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Book of Abstracts

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Acknowledgment

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Preface

Since 1992 scientists and engineers working in the field of guided wave theory and related numerical methods meet regularly to attend the International Workshop on Optical Waveguide Theory and Numerical Modelling (OWTNM), a forum for lively debates, intending to put forward new ideas in the field of theoretical optics and the respective numerical techniques. Basic physics and novel applications, artificially structured materials and new device concepts, elegant math and efficient numerics to tackle Maxwell's equations – these are the continuously evolving subjects which are discussed in a traditionally open and relaxed atmosphere.
This year the XVIIIth OWTNM workshop will take place in Jena, Germany, on April 17-18, 2009.
It is organized by the Solid State Optics Group of the Friedrich-Schiller-Universität and the Fraunhofer Institute for Applied Optics and Precision Engineering.
Topics of interest address the physical understanding and the mathematical description of light propagation and related effects in micro- and nanostructures. They include, but are not limited to: passive and active waveguide devices, photonic crystals, photonic nanostructures and metamaterials, optoelectronic devices, plasmonics, advances in numerical methods and multiphysics effects.

Since more than a decade OWTNM contributions have been regularly published in Special Issues of the Journal of Optical Quantum Electronics. The following remarks apply to this year's issue:
1. Regarding the high level of all contributions, no distinction will be made between oral and poster presentations given at the workshop. Every participant is encouraged to write and submit a manuscript based on the OWTNM contribution.
2. All papers should be submitted on-line via the Springer's Editorial Manager. Contributors shall personally submit their papers to Springer's electronic system and choose the article type "Special Issue OWTNM 2009".
Submission rules and guidance for authors can be found on the OQE official Web page
http://www.editorialmanager.com/oqel/default.asp
3. All papers will be reviewed by referees appointed by the Guest Editors, being Falk Lederer, Thomas Pertsch, Dirk Michaelis, and Christoph Wächter.
4. The submission deadline will be strictly on July 15, 2009 . The process of reviewing-revision-selection will be completed by October 31, 2009.

Jena, March 2009

The Local Organizing Committee of OWTNM09

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Local Organizing Committee OWTNM 2009

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OWTNM - History

The first International Workshop on Optical Waveguide Theory and Numerical Modelling has been held in Teupitz, Germany, in 1992 collocated with the ECOC.
Since then, the annual conference moved across Europe, with one detour to Australia:

2009, Jena, Germany,

2008, Eindhoven, The Netherlands,

2007, Copenhagen, Denmark,

2006, Varese, Italy,

2005, Sydney, Australia,

2005, Grenoble, France,

2004, Ghent, Belgium,

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2001, Paderborn, Germany,

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1999, Saint-Etienne, France,

1998, Hagen, Germany,

1997, Enschede, The Netherlands,

1995, Roosendaal, The Netherlands,

1994, Siena, Italy,

1993, Vevey, Switzerland,

1992, Teupitz, Germany

Programme

Workshop Schedule

Friday 17. 4. 2009

9.00 - 9.15	Opening
9.15 - 10.30	Session 1: Spatial and temporal light localization
10.30 - 11.00	*Coffee break*
11.00 - 12.15	Session 2: Photonic crystals
12.15 - 13.30	*Lunch*
13.30 - 15.00	Session 3: Numerical and Analytical Schemes
15.00 - 15.15	*Break*
15.15 - 16.15	Session 4: Device Modeling
16.15 - 16.45	*Coffee break*
16.45 - 19.00	Poster session
19.30	*Workshop Dinner*

Saturday 18. 4. 2009

8.30 - 10.00	Session 5: Lossy Waveguides & Plasmonics
10.00 - 10.30	*Coffee break*
10.30 - 12.15	Session 6: Plasmonics
12.15 -13.00	*Lunch*
13.00 - 14.45	Session 7: Fiber Geometries and Applications
14.45 - 15.15	*Coffee Break*
15.15 – 16.15	Session 8: Active devices
16.15	Closing of the workshop

Friday 17. 4. 2009

9.00 - 9.15	Opening
9.15 - 10.30	***Session 1: Spatial and temporal light localization*** Chair: Falk Lederer
9.15 - 9.45	D. Skryabin, C. Benton, A. Gorbach and J.C. Knight *(Invited)* *Nonlinear propagation in silicon photonic wires and slot waveguides*
9.45 - 10.00	S. Skupin, M. Grech and W. Krolikowski *Azimuthons in nonlocal nonlinear media*
10.00 - 10.30	N. Asger Mortensen, Jesper Goor Pedersen, Jure Grgic and Sanshui Xiao *(Invited)* *Slow-light in photonic crystals: how slow?*
10.30 - 11.00	***Coffee break***
11.00 - 12.15	***Session 2: Photonic crystals*** Chair: John Love
11.00 - 11.15	Rumen Iliew, Christoph Etrich, Thomas Pertsch and Falk Lederer *Modeling of Forward and Backward Second Harmonic Generation in Photonic Crystals using the Nonlinear Finite-Difference Time-Domain Method*
11.15 - 11.30	Manfred Hammer and Alyona Ivanova *On effective index approximations of photonic crystal slabs*
11.30 - 11.45	Lijun Yuan and Ya Yan Lu *Scattering from Periodic Arrays of Air-holes in a Slab*
11.45 - 12.00	C. Ciminelli, R. Marani and M. N. Armenise *Analysis of point-like and plane wave excitation in 2D photonic crystals by using Green's functions*
12.00 - 12.15	M. Vanwolleghem, K. Postava, L. Magdenko, B. Dagens, W. Smigaj, B. Gralak, P. Beavillain and J.-M. Lourtioz *Unidirectional transmission through a 2D magneto-photonic crystal*
12.15 – 13.30	***Lunch***

13.30 - 15.00 ***Session 3: Numerical and Analytical Schemes***
Chair: Hugo Hoekstra

13.30 - 13.45 Khai Q. Le, Peter Bienstman and G. Ronald Hadley
Fast wide-angle BPMs using complex Jacobi iteration

13.45 - 14.00 G. Ronald Hadley and David W. Peters
Complex Jacobi Iteration for 3D Helmholtz Analysis of Metallic Structures

14.00 - 14.15 Rosa Letizia and Salah Obayya
Dispersive Multiresolution Time Domain Scheme for Second Harmonic Generation Photonic Devices

14.15 - 14.30 R. Matzen
Design of Optical Circuit Devices Using Transient Topology Optimization

14.30 - 14.45 Alexandre Tishchenko and Alexey Shcherbakov
Rigorous modeling of 2D arbitrary shaped diffraction gratings with an analytical solution

14.45 - 15.00 Anurag Sharma and Hansa Chauhan
A New Analytical Model for the Field of Microstructure Optical Fibers

15.00 - 15.15 ***Break***

15.15 - 16.15 ***Session 4: Device Modeling***
Chair: Christoph Wächter

15.15 - 15.30 I. Gushchin, A.V. Tishchenko, O. Parriaux and H.J.W.M. Hoekstra
Ultrabroadband TM reflection from high contrast grating: why ?

15.30 - 15.45 Jiři Čtyroký
Asymmetric Complex Grating Coupler Modified to Ease Its Fabrication

15.45 - 16.00 Hung-Wen Chang
FD-FD analysis of dielectric waveguide crossings with two-fold symmetry

16.00 - 16.15 M.F.O. Hameed, S.S.A. Obayya, K. Al Begain, M.I. Abo el Maaty and A. M. Nasr
Characterization of Polarization Conversion in Nematic Liquid Crystal Photonic Crystal Fiber: Tolerance Study

16.15 - 16.45 ***Coffee break***

16.45 - 19.00 ***Poster session***

PO_01 Qiaoyin Lu, Weihua Guo, Diamuid Byrne and John F. Donegan
The Compact 2D FDTD Technique combined with the Padé Approximation Transform for the leaky modes analysis

PO_02 Daphné Duval and Bruno Bêche
Theoretical formulation to shape versatile propagation characteristics of 3-layer-tubular waveguides

PO_03 Irene Mozjerin, Shlomo Ruschin and Amos Hardy
Modeling, analysis and optimization of pulse-pumped unidirectional erbiumdoped waveguide ring lasers

PO_04 André Edelmann and Stefan Helfert
Three-dimensional analysis of hexagonal structured photonic crystals using oblique coordinates

PO_05 Nor Faridah Hanim Mat Junit, Jalil Ali, M. Fadhali and T. Saktioto
Breakdown voltage model of fusion SiO2 optical coupler switch

PO_06 Caterina Ciminelli, Francesco Dell'Olio Vittorio M. N. Passaro and Mario N. Armenise
Rigorous three-dimensional numerical modelling of scattering loss in high index contrast waveguides

PO_07 Elena Romanova and Andrey Konyukhov
Functionality in Mid-IR of Low-Contrast Periodic Structures in Highly Non-Linear Glass

PO_08 E. Gamet, F. Pigeon and O. Parriaux
Duty cycle tolerant high index phase masks

PO_09 O. Parriaux and A.V. Tishchenko
Analytical formulation and properties of the band edges of multilayers

PO_10 I. Gushchin and A.V. Tishchenko
Slanted boundary conditions in sliced gratings improve the accuracy of the RCWA

PO_11 Nataliya Sakhnenko, Ivan Trofimenko, Elena Semenova and Alexander Nerukh
Channeling Effect in Two-Layered Cylinder Composed from Double-Negative Materials

PO_12 Niklas Andermahr, Martin Schäferling and Carsten Fallnich
Gain-induced interaction of transverse modes in fiber amplifiers

PO_13 V.E. Babicheva1 and Yu.E. Lozovik
Extraordinary transmission through slit array in thin metallic film

PO_27 Thomas Paul, Christoph Menzel, Stephan Fahr, Carsten Rockstuhl and Falk Lederer
Adapted Fourier modal method for the analysis of higher harmonic generation in arbitrary bi-periodic multi-layer structures

PO_28 Pavel Kwiecien, Jan Fiala, Ivan Richter and Jiří Čtyroký
Advanced Modeling of Subwavelength Photonic Structures with Aperiodic Rigorous Coupled Wave Analysis

19.30 ***Workshop dinner***

Saturday 18. 4. 2009

8.30 - 10.00 Session 5: Lossy Waveguides & Plasmonics
Chair: G. Ronald Hadley

8.30 - 9.00 Christian Hafner
(Invited)
MMP modeling of lossy optical waveguides

9.00 - 9.15 Christian Helfert
The self-imaging effect in metallic waveguides

9.15 - 9.30 Rémi Pollès, Antoine Moreau, Jean-Pierre Plumey and Gérard Granet
Contra-directional Coupling Using Plasmons: the Plasmonic Light Wheel

9.30 - 9.45 Dmitry Fedyanin, Aleksey Arsenin, Vladimir Leiman and Anantoly Gladun
Zero-Group-Velocity Modes of Insulator-Metal-Insulator and Insulator-Insulator-Metal waveguides

9.45 - 10.00 Slobodan M. Vukovic
Dispersion of Plasmonic Modes in Nanolayer Composites

10.00 - 10.30 ***Coffee break***

10.30 - 12.15 ***Session 6: Plasmonics***
Chair: Jiři Čtyroký

10.30 - 11.00 Meir Orenstein
(Invited)
Nanoplasmonic waveguides

11.00 - 11.15 Jer-Shing Huang, Thorsten Feichtner, Paolo Biagioni and Bert Hecht
Impedance matching and power transmission in a complete optical circuit

11.15 - 11.30 Sven Burger, Daniel Lockau, Lin Zschiedrich and Frank Schmidt
Finite-element simulations of light propagation through subwavelength apertures in metal films

11.30 - 11.45 Stephan Fahr, Christoph Menzel, Thomas Paul, Carsten Rockstuhl and Falk Lederer
Periodic arrays of metallic nanoparticles as efficient intermediate reflectors in aSi:H-μcSi solar cells

11.45 – 12.15 Kosmas Tsakmakidis and Ortwin Hess
(Invited)
The Physics of Slow and Stored Light in nanophotonic Metamaterials

12.15 -13.00 ***Lunch***

13.00 - 14.45 ***Session 7: Fiber Geometries and Applications***
Chair: Olivier Parriaux

13.00 - 13.30 F. Ömer Ilday
(Invited)
Fiber laser modelling

13.30 - 13.45 John Love
Metal-Clad Optical Fibres

13.45 - 14.00 Uwe Langbein, Udo Trutschel, Andreas Unger and Michel Duguay
Rigorous Mode Solver for multilayer cylindrical Waveguide Structures using Constraints Optimization

14.00 - 14.15 Michael Kues, Nicoletta Brauckmann, Till Walbaum, Petra Groß, and Carsten Fallnich
Impact of feedback on femtosecond supercontinuum generation

14.15 - 14.45 Sergei K. Turitsyn
(Invited)
Statistical modelling of high-speed optical communication systems

14.45 - 15.15 ***Coffee Break***

15.15 - 16.15 ***Session 8: Active devices***
Chair: Peter Bienstman

15.15 - 15.45 Sergei V. Zhukovsky and Dmitry N. Chigrin
(Invited)
Bistable and multi-stable lasing in micro-cavities

15.45 - 16.00 A. G. Okhrimchuk, A.V. Shestakov, V. Mezentsev and I. Bennion
Modelling and Fabrication of Waveguide Saturable Absorber in Laser Crystals

16.00 - 16.15 Antti Laakso, Mihail Dumitrescu, Jukka Karinen, Jukka Viheriälä and Markus Pessa
Development of Narrow-Band Laterally-Coupled Distributed Feedback Lasers

16.15 Closing of the workshop

Nonlinear propagation in silicon photonic wires and slot waveguides

D. Skryabin, C. Benton, A. Gorbach, J.C. Knight

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Recent progress in the fabrication of nano-structures for photonics applications has stimulated research into light trapping and guiding on the subwavelength scale. Surface plasmon polaritons tightly confined to the metal-dielectric interfaces have been at the focus of recent efforts in this direction. Miniaturization of photonic circuits and nonlinear all-optical control can be addressed not only with metallic, but also with dielectric waveguides using, for example, more conventional semiconductor technology. In particular, silicon photonic wires have been recently promoted as promising and close to practical applications building blocks of photonic chips, where nonlinear and soliton effects have been already extensively researched.
The large refractive index of silicon (n ~3.5) allows for tight light confinement by the conventional total internal reflection mechanism, giving the simultaneous advantages of strong ultrafast Kerr nonlinearity ($n_2 \sim 4 \times 10^{-18} m^2/W$), controlled dispersion and manageable losses. Two photon and free career induced absorptions are traditionally thought of as hampering theattractiveness of silicon for nonlinear applications, but these often can be either lived with or managed, e.g. by the electrically removing free carriers from the waveguide core. In this talk I will review (with various degrees of details) the recent results of the Bath group on nonlinear optics in silicon photonic wires [1-3], which include

- Exerimental measurements and numerical modeling of spectral broadening and quasi-soliton propagation regimes in silicon-on-insulator photonic wire waveguides using 100fs pump pulses.

- Analysis of conditions for low-power spatiotemporal soliton formation in arrays of evanescently coupled silicon-on-insulator photonic wires. We have verified that pronounced soliton effects can be observed in the presence of realistic loss, two-photon absorption, and higher-order dispersions. A soliton in an N-wire array can excite N resonant frequencies, but some of these may be suppressed due to the soliton having zero projection onto the corresponding radiation supermodes. This results in pronounced differences between the radiation spectra observed from solitons excited at the edge and in the center of arrays.

- Group velocity dispersion (GVD) of the supermodes in a small array of silicon photonic wires can differ dramatically from the single wire GVD. This enables soliton propagation and frequency conversion to be seen at wavelengths where single wires have strongly normal GVD.

- A detailed analysis of the existence and stability of TE and TM nonlinear guided modes (spatial solitons) in one-dimensional sub-wavelength periodic silicon-silica structures. We have found that for small enough periods, TE solitons stop feeling the presence of the periodic structure. However TM solitons are demonstrated to sustain strongly

inhomogeneous field distribution for any small period of the structure, developing strong intensity peaks inside dielectric slots. Qualitative transformation in the structure of TM solitons occurs as the structure period is decreased, and is accompanied by the change in their stability properties, making somewhat unexpected prections about mobility of these structures. Results for single slot waveguides will also be discussed.

References

[1] W. Ding, C. Benton, A. V. Gorbach, W. J. Wadsworth, J. C. Knight, D. V. Skryabin, M. Gnan, M. Sorrel, and R. M. De La Rue, Opt. Express 16, 3310 (2008).

[2] C. J. Benton, A. V. Gorbach, and D. V. Skryabin, Phys. Rev. A 78, 033818 (2008)

[3] A. V. Gorbach, and D. V. Skryabin, http://xxx.lanl.gov/abs/0901.4288.

Azimuthons in nonlocal nonlinear media

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We discuss generic properties of self-guided rotating nonlinear wave solutions, the so called azimuthons, in nonlocal media. We link families of azimuthons to internal modes of classical non-rotating spatial solitons and provide a straightforward and exhaustive method to identify rotating soliton solutions.

Introduction

Spatial trapping of light in nonlinear media is a result of a balance between diffraction and self-induced nonlinear index change. While local nonlinearity cannot stabilize complex localized structures such as vortex beams, nonlocal nonlinearty can. In such media nonlinear response in a particular spatial location is typically determined by the wave intensity in a certain neighborhood of this location. Nonlocality often results from transport processes such as atomic diffusion or heat transfer. It can also be a signature of long-range interparticle interaction such as in nematic liquid crystals. Recently, it has been shown that nonlocal media can also support stable propagation of the rotating solitons, the so called azimuthons [1].

Results

In this work, we show that both, rotational frequency and intensity profile of the azimuthons can be uniquely determined by analyzing eigenmodes of the linearized version of the corresponding nonlocal problem. We consider physical systems governed by the two-dimensional nonlocal nonlinear Schrödinger equation

$$i\frac{\partial}{\partial z}\psi + \Delta_\perp\psi + \iint R(|\vec{r}-\vec{r}'|)\,|\psi(\vec{r}',z)|^2\,d^2\vec{r}'\psi = 0,$$

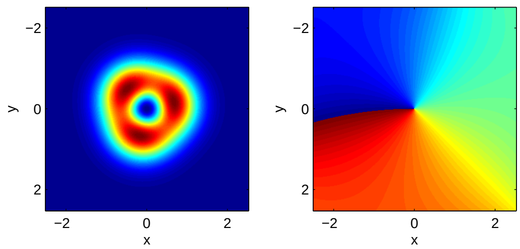

Fig. 1.: Amplitude and phase distribution of a rotating triple-hump azimuthon.

where R represents the spatially nonlocal nonlinear response of the medium. Its form depends on the details of a particular physical system. Azimuthons are a straightforward generalization of the usual ansatz for stationary solutions (solitons), $\psi(r,\phi,z) = U(r,\phi-\Omega z)\exp(i\lambda z)$ [2]. They are rotating structures involving an additional parameter, the angular frequency Ω. The most simple azimuthons are those connected to the single charged vortex soliton, i.e., they are are vortices with an amplitude modulation around the ring which rotates with Ω. We compute exact azimuthon solutions and their rotation frequencies numerically and show that in the limit of minimal azimuthal amplitude modulation, i.e., close to the vortex soliton, the rotation frequency is determined uniquely by eigenvalues of the bound modes of the linearized version of the respective stationary nonlocal solution. Moreover, the resulting azimuthon can be constructed from the corresponding linear eigensolution. Figure 1 shows an illustrative example using the Gaussian nonlocal model.

References

[1] S. Lopez-Aguayo *et al.*, Opt. Lett., **31**, 1100, 2006.
[2] A. Desyatnikov *et al.*, Phys. Rev. Lett., **95**, 203904, 2005.

Slow-light in photonic crystals: how slow?

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We discuss the slow-down limitations in the presence of photonic crystals composing absorption and/or disorder. Simple scalings of the minimum group velocities with the imaginary part of the dielectric function or, equivalently, the linewidth of the broadened states are presented.

Introduction

While ideal photonic crystals would support modes with a vanishing group velocity near the band edge, state-of-the-art structures have still only provided a slow down by roughly two orders of magnitude [1, 2]. We find that the induced density of states caused by lifetime broadening of the electromagnetic modes results in the group velocity acquiring a finite value above zero at the band-gap edges. This picture may be generalized to also waveguide modes, where the group velocity becomes slightly larger than in the ideal case with neither disorder nor absorption. Simple scalings of the group velocities with the imaginary part of the dielectric function or, equivalently, the linewidth of the broadened states are presented. The results obtained may conceptually be applied to any effect which results in a broadening of the electromagnetic states, such as loss, disorder, and finite-size effects.

Results

Consider the dispersion relation near $\omega(\kappa_0) = \omega_0$ where the band is approximated by the following Taylor expansion

$$\omega(\kappa) \simeq \omega_0 + \frac{\partial\omega}{\partial\kappa}(\kappa-\kappa_0) + \frac{1}{2}\frac{\partial^2\omega}{\partial\kappa^2}(\kappa-\kappa_0)^2 = \omega_0 + v_{g,0}(\kappa-\kappa_0) + \frac{\alpha}{2}(\kappa-\kappa_0)^2, \qquad (1)$$

thus ignoring any contributions from higher-order dispersion. From this expansion we may formally express the frequency-dependent group velocity in terms of $v_{g,0}$ and α. Next, consider the effect of a finite imaginary part ϵ'' of the dielectric function of either of the constituents of the photonic crystal. The finite imaginary part courses a finite broadening of the order $\epsilon''\omega$ of the electromagnetic modes. Thus, phenomenologically any effect causing such lifetime broadening may be mimicked by an effective ϵ'', and the analysis that follows is therefore entirely general and may be applied to, e.g., loss, disorder, or finite-size effects. We apply standard electromagnetic perturbation theory and find that to first order in the imaginary part of the dielectric function, the group velocity becomes

$$v_g(\omega_0) = \sqrt{v_{g,0}^2 + \alpha f \omega_0 \frac{\epsilon''}{\epsilon'}} \qquad (2)$$

which is a generalization of our result reported in Ref. [3] valid only near the band-edge where $v_{g,0} \to 0$ for symmetry reasons. Here, f is the filling fraction quantifying the electrical field overlap with material where ϵ'' is finite. This analysis is of course based on a perturbative approach and is only applicable in the case of small perturbations of an otherwise perfect photonic crystal. In particular, it does not apply in the limit of strong disorder, where Anderson localization will significantly alter the delay time statistics [4].

The main conclusion from the above analysis is that any broadening will limit the attainable slow down. In addition, our analysis reveals that structures with low group velocity dispersion, which have mainly been pursued with the interest of reducing pulse distortion, have the additional benefit of reducing the minimum attainable group velocity. Indeed, in the limit of vanishing GVD our analysis shows that the group velocity attains the ideal value of v_{g_0}, provided that any higher-order dispersion is negligible. In general, fulfilling the following criterium

$$\alpha \ll \frac{\epsilon'}{\epsilon''}\frac{v_{g,0}^2}{\omega_0} \tag{3}$$

will ensure that $v_g \simeq v_{g,0}$ so that the slow-down is insensitive to broadening. For simplicity we have here assumed that $f \sim 1$.

In the talk we discuss the consequences further and in particular we verify the above results by comparing to numerical simulations for a number of structures, such one-dimensional Bragg stacks, two-dimensional photonic crystals, and photonic crystal waveguide structures. Finally, we discuss the consequences in the context of experimental slow-light results reported in the literature.

References

[1] M. Notomi et al., *Phys. Rev. Lett.* **87**, 253902 (2001).
[2] H. Altug, and J. Vuckovic, *Appl. Phys. Lett.* **86**, 111102 (2005).
[3] J. G. Pedersen, S. Xiao, and N. A. Mortensen, *Phys. Rev. B* **78**, 153101 (2008).
[4] T. Schwartz, G. Bartal, S. Fishman, and M. Segev, *Nature* **446**, 7131 (2007).

Modeling of Forward and Backward Second Harmonic Generation in Photonic Crystals using the Nonlinear Finite-Difference Time-Domain Method

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Using the nonlinear finite-difference time-domain (FDTD) method we demonstrate efficient forward and backward second harmonic generation (SHG) in a photonic crystal (PhC) made of lithium niobate. We calculate the phasematching curves and compare them to a modal approach.

From the early days of nonlinear optics up until recently, due to the lack of computer power, modeling of parametric frequency conversion effects in nonlinear crystals was restricted to the numerical solution of modal equations. Hence the transverse spatial effects are separated by means of the unperturbed linear modes of the system, as plane waves in bulk media or the modes in optical waveguides. These modal approaches rely on a slow dynamics of the effects on the spatial and temporal scale. Also, only a limited number of *a priori* fixed modes and frequencies are accounted for, possibly neglecting conversion effects that could influence the performance of the device. The last decade has seen major advances in microphotonics with the emphasis on PhCs and metamaterials. Here the spatial variations of the dielectric structure and of possible nonlinear effects are comparable to the wavelength and smaller and modal approaches may cease to be valid.
We show results obtained from two-dimensional FDTD calculations for light propagation in quadratically nonlinear photonic crystals, where Maxwell's equations are discretized directly and without further approximation in time and space allowing for the treatment of wide-bandwidth optical effects and of effects on spatial scales below the wavelength. For our particular design of the crystal we show that efficient forward as well as backward SHG is possible.
The PhC consists of a hexagonal lattice of air holes in lithium niobate with a refractive index of 2.211 (realized in [1]). For TE polarization we obtained the phasematching curve for collinear forward SHG in ΓM direction shown in Fig. 1 from bandstructure calculations. The FDTD propagation simulations show an excellent agreement with this curve. In ΓK direction we obtain phasematching for collinear backward SHG. The power evolution for both cases is displayed in Fig. 1.

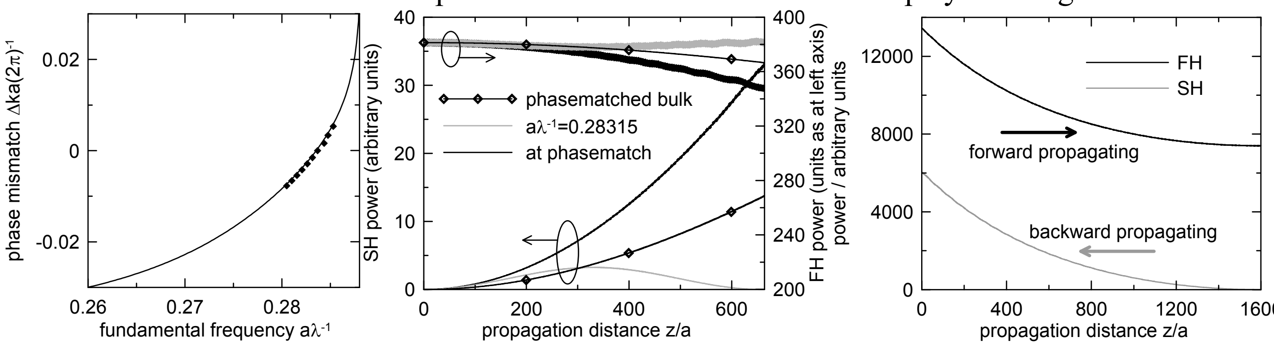

Fig. 1: Left: Phase mismatch versus frequency from bandstructure (solid line) and from FDTD (diamond symbols) calculations. Power evolution for forward (middle) and phasematched backward (right) SHG.

Rumen Iliew gratefully acknowledges a scholarship by the Carl Zeiss Foundation. The research was partly supported by the Bundesministerium für Bildung und Forschung.

[1] F. Schrempel, T. Gischkat, H. Hartung, E.-B. Kley, W. Wesch, A. Tünnermann in Growth, Modification, and Analysis by Ion Beams at the Nanoscale, edited by Joerg K. N. Lindner, Marcel Toulemonde, William J. Weber, Barney L. Doyle (Mater. Res. Soc. Symp. Proc. 908E, Warrendale, PA, 2006), 0908-OO16-01.

On effective index approximations of photonic crystal slabs

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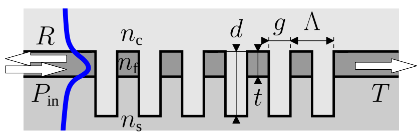
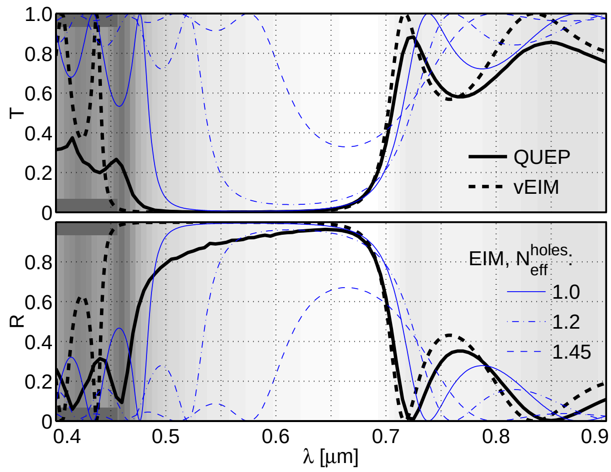
To assess the quality of effective index approximations for photonic crystal slabs, we consider a reduction of 2-D problems for waveguide Bragg gratings to 1-D, and compare with rigorous 2-D solutions. A variational procedure permits to establish reasonable effective indices even if locally no guided modes exist.

Summary

The propagation of light through slab-like photonic crystals (PCs) is frequently described in terms of effective indices (effective index method EIM, cf. e.g. Ref. [1]). One replaces the actual 3-D structure by an effective 2-D permittivity, given by the propagation constants of the slab modes of the local vertical refractive index profiles. Though the approach is usually described for the approximate calculation of waveguide modes, it is just as well applicable to propagation problems. Our aim is to check the approximation by analogous steps that reduce finite 2-D waveguide Bragg-gratings, which in turn can be seen as sections through 3-D PC membranes, to 1-D problems, which are tractable by standard transfer matrix methods. A 2-D Helmholtz solver (QUEP [2], reference) allows to solve the 2-D problem rigorously, i.e. to assess the quality of the EIM approximation. The EIM-viewpoint becomes particularly questionable if locally the vertical refractive index profile cannot accommodate any guided mode, as e.g. in the holes of a PC membrane. We check numerically a recipe [1, 3], based on a variational view on the EIM, to uniquely define an effective permittivity even then.

Our simulations (cf. also [4]) show clearly that a treatment of a propagation problem involving a high contrast PC membrane in terms of effective indices can hardly be expected to be more than a mere qualitative, or rather crude quantitative, approximation. Nevertheless, situations may arise where, for various reasons, there are no options but to restrict simulations of 3-D devices to 2-D. One should then at least invest the small effort to determine the variational correction term, and perform the 2-D calculation for the thus established effective permittivity profile (which may well turn out to be smaller than 1.0 locally, or even negative). At least for the given examples we could observe that the resulting variational effective index approximation (vEIM) comes closer to reality than any “conventional” EIM with educated guesses of effective indices for regions without local modes.





Deeply etched waveguide Bragg grating, rel. guided transmission T and reflection R versus vacuum wavelength λ; $N_{eff}^{slab} \in [1.87, 1.67]$, $N_{eff}^{holes} \in [0.82, 0.71]$ (vEIM); shading ∼ losses (QUEP); patches: multimode slab; $n_c : n_f : n_s = 1.0 : 2.0 : 1.45$, $\Lambda = 0.21\,\mu m$, $g = 0.11\,\mu m$, $d = 0.6\,\mu m$, $t = 0.2\,\mu m$.

References

[1] C. Vassallo. *Optical Waveguide Concepts*. Elsevier, Amsterdam, 1991.
[2] M. Hammer. *Optics Communications*, 235(4–6):285–303, 2004.
[3] E. W. C. van Groesen, J. Molenaar. *Continuum Modeling in the Physical Sciences*. SIAM, USA, 2007.
[4] M. Hammer, O. V. Ivanova. IEEE/LEOS Benelux, Proc. 13th Ann. Symp., Enschede, NL, 203–206 (2008).

Scattering from Periodic Arrays of Air-holes in a Slab

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For a photonic crystal (PhC) slab, we construct a matrix approximation to the Dirichlet-to-Neumann (DtN) map of its unit cells and use it to calculate the transmission and reflection spectra for propagating modes of the slab incident upon a finite number of air-hole arrays.

Introduction

PhC devices, such as waveguide bends and branches, give rise to boundary value problems in a large domain covering many unit cells. For ideal 2D PhC devices, efficient numerical methods have been developed based on the Dirichlet-to-Neumann (DtN) maps of the unit cells [1-3]. In this paper, we extend the DtN map method to PhC slabs.

The method and results

For PhC slabs with air-holes in a triangular lattice, a unit cell Ω is a 3D cylinder with hexagon cross section S. We truncate the vertical z-axis by perfectly matched layers and expand E_z and H_z in vertical modes. Inside Ω but outside the air-hole, we have $E_z = \sum \phi_j(z)\hat{E}_j(x,y)$ and $H_z = \sum \varphi_j(z)\hat{H}_j(x,y)$, where ϕ_j and φ_j are the TM and TE modes of the slab and $\hat{E}_j$ and $\hat{H}_j$ satisfy 2D Helmholtz equations. We define the DtN map Λ as the operator that maps $\hat{E}$ and $\hat{H}$ to their normal derivatives on ∂S (the boundary of S), where $\hat{E}$ is the vector of all $\hat{E}_j$, etc. If ∂S is sampled by K points and N modes are retained, Λ is then approximated by an $(NK) \times (NK)$ matrix. In this process, we use Fourier-Bessel expansions for $\hat{E}_j$ and $\hat{H}_j$ and match the tangential field components on the vertical walls of the air-hole. After Λ is obtained, we can solve the problem by working on the boundaries of the unit cells only. As an example, we consider 11 arrays of air-holes in a slab suspended in air. The air-holes form a triangular lattice with lattice constant L. The slab thickness is $0.6L$, the radius of the air-holes is $0.3L$ and the dielectric constant of the slab is $\varepsilon = 12.25$. For an incident wave whose vertical structure is the fundamental TE mode of the slab, we obtain the transmission and reflection spectra in Fig. 1. An interval of low transmission is clearly observed.

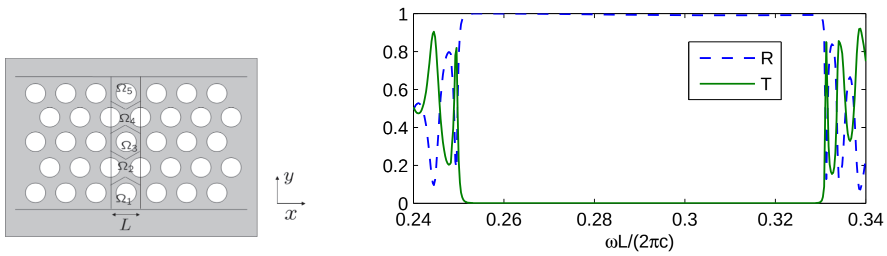

Fig. 1. Left: top view of five arrays of air-holes in a slab. Right: transmission and reflection spectra for 11 air-hole arrays and a TE incident wave at $\pi/6$ angle of incidence.

References

[1] Y. Huang, Y. Y. Lu, *J. Loghtwave Technol.* **24**, 3448-3453 (2006).
[2] Y. Wu, Y. Y. Lu, *J. Opt. Soc. Am. B* **25**, 1466-1473 (2008).
[3] Z. Hu, Y. Y. Lu, *Opt. Express* **16**, 17383-17399 (2008).

Analysis of point-like and plane wave excitation in 2D photonic crystals by using Green's functions

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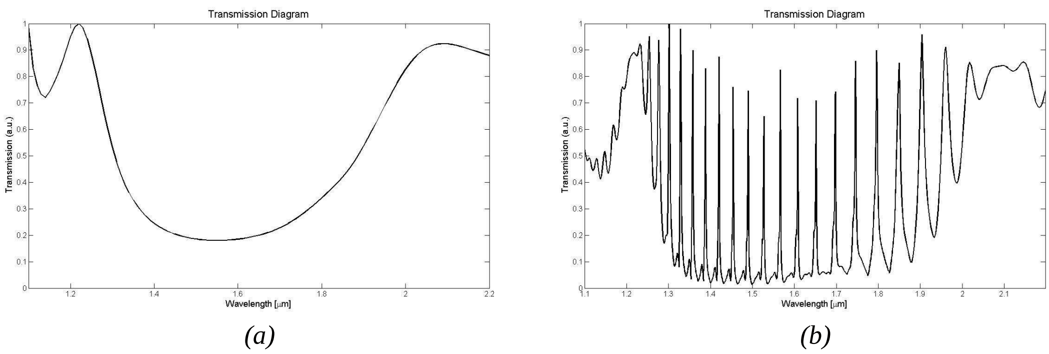
A new model for simulating wave propagation in photonic crystals is presented. Two-dimensional photonic band gap structures have been analyzed using Green's functions, rearranged to fit on the geometrical properties of the studied structure. The model is able to define all the physical effects occurring when a wave propagates inside the periodic structure, taking into account both physical and geometrical parameters. The results of the implemented model show a very good agreement with those expected, showing some significant advantages such as fast determination of the electromagnetic field distribution and band diagram and capability to analyze the effect of in-plane scattering, together with the possibility of evaluating also the field distribution in the rods of the periodic structure.

Referring to a 2D configuration composed by a finite number of dielectric cylinders in a homogeneous medium, the electromagnetic field that satisfies the Helmholtz wave equation in a plane region outside a generic cylinder can be expressed as a sum of two line integral around the contour of the region [1]. This yields to the evaluation of the electromagnetic field inside the structure as a superposition of Hankel and Bessel functions of the first kind. By deriving an appropriate form for the field representation in the device and imposing the boundary conditions, we are able to get a final matrix equation for the model in the case of Hankel excitation. The developed method also allows the characterization of physical effects due to a plane wave incidence. In this case, the plane wave is processed by using the Jacobi-Anger identity in order to get a new source coefficients formulation comparable with those obtained for the Hankel excitation.

The model has been implemented to simulate a photonic crystal device already analyzed [2]. The structure is a Fabry-Peròt extended filter whose mirrors are two-dimensional photonic crystals fabricated in a SOI ridge waveguide with triangular lattice whose constant *a* is 380 *nm*. The hole radius *r* of the cylinders that belong to the mirrors is 148 *nm*. Simulations have been performed for TE-polarization and the transmission diagram for the single mirror and the whole structure are reported, as an example, in Figs 1a and 1b, respectively. The total CPU time to analyze the mirror and the whole filter is about four times less than that required by the well-known FDTD method.



(a) *(b)*

Fig. 1: Transmission diagrams for the 2D photonic crystal mirror (a) and the extended Fabry-Peròt cavity (b).

References

[1] R. C. McPhedran *et al.*, *IMA Volumes in Mathematics and its Applications*, **96**, pp. 155-186, (1997)
[2] C. Ciminelli *et al.*, ECOC 2004 Conference Proceedings, Post-Deadline paper **Th. 4.2.6**, pp. 26-27, (2004)

Unidirectional transmission through a 2D magneto-photonic crystal

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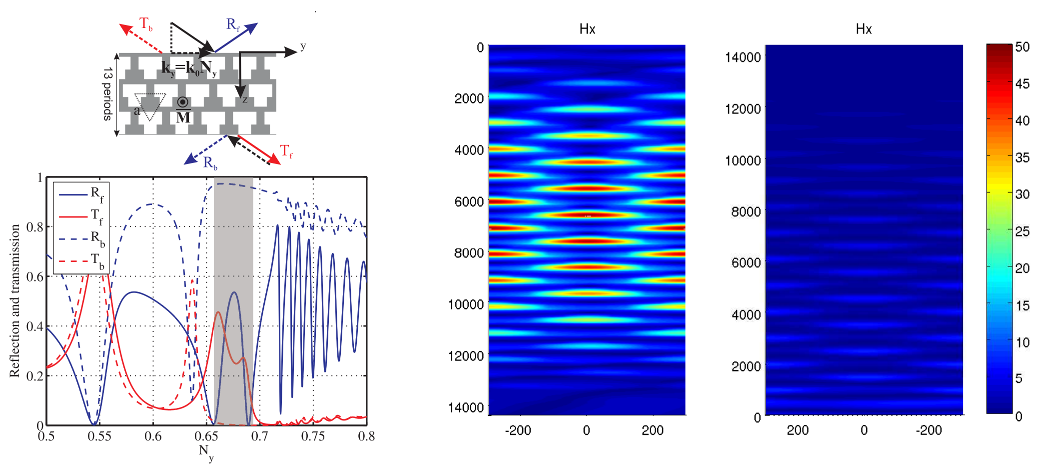
We propose a novel layout for a very compact integrated isolator based on the appearance of a unidirectional band gap in a 2D magnetophotonic crystal (MOPhC).

Introduction

The combination of magneto-optics and PhC layouts has been proven to lead to greatly enhanced optical non-reciprocity. We prove numerically that reducing the symmetry of the crystal motif can lead to strong non-reciprocity in uniformly magnetized PhC's. Previous reports used non-integrated 1D stacks and technological unfeasible antisymmetric magnetic domains [1].

Results

The figure shows a novel MOPhC structure consisting of a hexagonal lattice of a motif of air holes with a reduced pyramidal symmetry (square side= $0.4a$) etched in a transparent MO material ($Bi_3Fe_5O_{12}$ or BIG) in Voigt geometry ($\mathbf{M} \parallel x$). Using dichromatic magnetic plane group theory one can prove the non-reciprocal asymmetry of the TE bands and the eventual non-reciprocal misalignment of the band edges ($\mathbf{E} \parallel yz$). We confirm the existence of this unidirectional band gap with a model based on plane wave Fourier expansion of the field using anisotropic, magneto-optic RCWA [2]. The lattice constant is set at $a = 590$ nm, $\lambda = 1300$ nm, $\varepsilon_{xx}^{BIG} = 6.25$, $\varepsilon_{yz}^{BIG} = -\varepsilon_{zy}^{BIG} = 0.1\,i$, and 13 bi-layers are used. The MOPhC is surrounded by nonmagnetic BIG. The left subplot shows forward (full line) and backward (dotted line) reflection and transmission of the MOPhC as a function of $N_y = \sqrt{\varepsilon_{xx}}\sin\varphi$, where φ is the angle of incidence. For a certain range of parallel k_y a unidirectional band gap behaviour appears (gray zone). In this range a $10\log(\frac{T_f}{T_b}) \approx 25$ dB return isolation with less than 6dB diffraction loss is obtained. The field maps for H_x in forward and backward incidence at $N_y = 0.685$ clearly confirm the unidirectional TE transmission and the very compact integrated optical isolation.



References

[1] Z. Yu, Z. Wang and S. Fan, Appl. Phys. Lett. **90**, 121133 (2007).

[2] Š. Višňovský, *Optics in magnetic multilayers and nanostructures*, CRC Press, Taylor & Francis, 2006.

Fast wide-angle BPMs using complex Jacobi iteration

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We propose an adaptation to the recently introduced complex Jacobi iteration for the fast solution of wide-angle (WA) beam propagation methods (BPMs). The beam propagation equation is based on two approximant methods including the conventional Hadley(1,1) and the recently proposed KP(1,1) approximant.

Introduction

Efforts to improve the limitations of the paraxial approximation in the beam propagation method have so far made use of wide-angle formulations. Different treatments of WA-BPM based on the slowly varying envelope approximation (SVEA) have been developed. There exist real Padé approximant operators mentioned here as Hadley(m,n) [1] and complex Padé approximant operators [2]. In addition, treatments of WA-BPM without having to make the SVEAs have also been reported, including the series expansion technique of the propagator, the split-step of beam propagation equation and the rational KP(m,n) approximant we recently proposed [3].

For Hadley(1,1) and KP(1,1) approximant-based beam propagation of wave profiles within a 2D cross section, the beam propagation equation can be cast in terms of a Helmholtz equation with source term, but that equation needs to be solved efficiently since numerous propagation steps are routinely required during the course of a problem solution. For this purpose a recently introduced complex Jacobi iterative (CJI) method [4] is proposed for the solution of WA beam propagation and shown to be highly efficient.

Since the utility of the CJI technique depends mostly upon its execution speed in comparison with the traditional direct matrix inversion (DMI) method, we also present several speed comparisons. Numerical implementations are carried out for 3D optical waveguide structures.

Results

Via a quantitative comparison of runtimes between the traditional DMI and the new CJI method for 3D WA beam propagation, it is convincingly demonstrated that the CJI method is very competitive for demanding problems. The resulting runtimes of these methods for 3D optical waveguide structures are listed in Table 1.

TABLE 1
Quantitative comparison of runtimes of the DMI and the CJI for WA beam propagation based on Hadley (1,1) and KP(1,1) approximant in waveguide (WG) structure

Method \ Structure		3D Y-branch rib WG
DMI		5462.0 s
CJI	Hadley(1,1)-based WA-BPM	70.0 s
	KP(1,1)-based WA-BPM	46.9 s

References

[1] G. R. Hadley, *Opt. Lett.*, **17**, 1426-1428, (1992).

[2] Khai Q. Le, R. Godoy-Rubio, Peter Bienstman and G. Ronald Hadley, *Opt. Express*, **16**, 17021-17030, (2008).

[3] Khai Q. Le and P. Bienstman, *J. Opt. Soc. Am. B,* **26**, 353-356, (2009)

[4] G. R. Hadley, *J. Comp. Phys.*, **203**, 358-370, (2005).

Complex Jacobi Iteration for 3D Helmholtz Analysis of Metallic Structures

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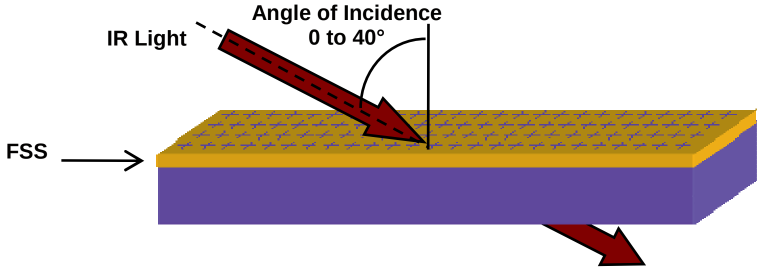
The recently-introduced complex Jacobi iterative method for Helmholtz Equation solution was developed and optimized for normal materials. Here we present an updated derivation for the convergence parameter that will produce convergent solutions for structures containing metals.

Introduction

The complex Jacobi iterative method was recently introduced[1] to provide iterative solutions of the Helmholtz Equation for three-dimensional problems where direct matrix inversion methods are prohibitive due to memory constraints. The previous derivation was appropriate for normal dielectrics, providing reasonable convergence rates for well-posed problems. However, the recent interest in metallic structures has led to the need to generalize this technique, since standard convergence parameter values result in divergent behavior. We have produced an updated derivation valid for metallic structures, and will present it here, along with solutions for an application of interest involving the propagation of infrared light through a sub-wavelength frequency-selective surface.

Application

We have employed the modified Jacobi iterative method to investigate the transmission properties of frequency-selective surfaces (FSS) for mid-IR imaging. FSSs offer a method for controlling the spectral transmission and polarization properties of a surface using a single metallic layer. While common in RF applications, their extension to the infrared is relatively recent and particularly challenging since the behavior of the (non-ideal) metal must be explicitly modeled, thus requiring a fine grid and very large dielectric constants. Such an FSS is shown in Fig. 1, produced by sub-wavelength patterning of a gold film on a dielectric substrate. We modeled the response of a single



pixel of this structure to incoming 5 μm light, and employed periodic boundary conditions at all lateral boundaries. Calculations performed for this structure have provided important information concerning phase distortion inside the dielectric, and will be discussed in detail.

References

[1] G. R. Hadley, J. *Comp. Phys*., **203**, 358-370(2005).

* Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Dispersive Multiresolution Time Domain Scheme for Second Harmonic Generation Photonic Devices

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Multiresolution Time Domain (MRTD) approach for the use of coarse grid resolutions in nonlinear problems without loss of accuracy is suggested here as alternative to conventional Finite Difference Time Domain (FDTD) method.

Introduction

Numerical dispersion effect in Finite Difference Time Domain (FDTD) typically demands a fine grid resolution in space with a cell size of 15-20 times less than the minimum simulated wavelength, which means λ_{sh}/15-20, with λ_{sh} the second harmonic wavelength when Second Harmonic Generation (SHG) is investigated. As an attempt to overcome this limit, a new Multiresolution Time Domain (MRTD) scheme is proposed here to study SHG in dispersive materials. Scaling functions are used as a complete set of basis functions to expand the electromagnetic field components in the context of method of moments, providing a high-order time-domain method [1]. The code has been rigorously extended to the analysis of SHG processes and Auxiliary Differential Equations (ADEs) applying the Lorentzian model, have been added to include the effect of chromatic dispersion [2].

Results

Results in a planar waveguide have shown the efficiency of MRTD compared to conventional FDTD, Fig. 1. Application of the presented approach is also given in a high-index contrast grating for phase matched SHG. In Fig. 2 the results of SHG efficiency for a grating of 20 periods are reported, which are shown to be in very good agreement with those reported in literature [3].

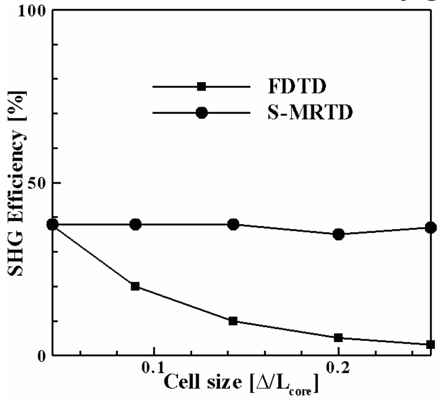

Fig. 1 Comparison of SHG efficiency variation with unit cell size Δ with FDTD and S-MRTD code.

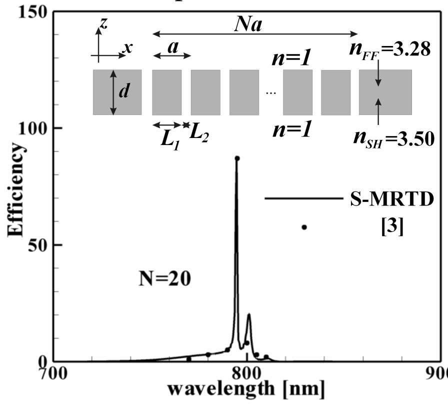

Fig. 2 SHG conversion efficiency calculated for N=20.

References

[1] M. Krumpholz and L. P. B. Katehi, *IEEE Trans. Microwave Theory Tech.*, **44**, 555 (1996).

[2] J. L. Young, and R. O. Nelson, *IEEE Antennas and Propag. Magazine*, **43**, 61 (2001).

[3] B. Maes, P. Bienstman, R. Baets, B. Hu, P. Sewell, and T. Benson, *Opt. Quant. Electron.*, **40**, 13 (2008).

Design of Optical Circuit Devices Using Transient Topology Optimization

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The design of channel drop filter is considered using transient topology optimization. The filter is based on a 2D PhC for TE modes with a point defect cavity. The optimization method is used to predict the material layout in the vicinity of the cavity such that field energy is maximized there.

Introduction

Designing ultra-compact optical devices based on 2D photonic crystal (PhC) structures has recently received much attention. Based on steady-state analysis, the method of topology optimization is used to design *bends* and *splitters* in [3]. A great interest in applying topology optimization to problems dealing with full transient behavior has recently emerged [1],[2]. This is due to the fact that optical structures can be optimized for broader frequency ranges by using modulated Gaussian wave pulses.

Results

Preliminary design proposals have been obtained for the channel drop filter and one appears in Fig. 1. The TE-modes is modeled by the scalar Helmholtz equation. This is solved by the finite-element time-domain (FETD) method for spatial and temporal discretization. The transient problem is solved by an explicit integration scheme with mass lumping to gain computational efficiency, albeit introducing an error in the FE solution. Further, the domain is truncated by ABC for normal incidence. Very recently, a particular type of the highly efficient perfectly matched layer, CFS-PML, has been successfully implemented as the wave absorber. Additionally, modified integration rules have been introduced to the mass lumped time integration reducing the dispersion error significantly. These improvements work in conjunction with the optimization technique that is facilitated by adjoint sensitivity analysis and mathematical programming. Thus, they are strongly believed to steer the optimization procedure towards more applicable designs.

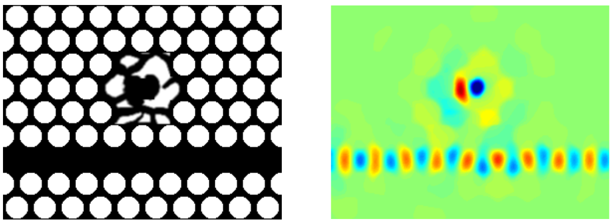

Fig. 1.: (Left) The optimized geometry of the cavity for the tuned resonance frequency $\omega = 0.30 \cdot 2\pi ac^{-1}$ with (Right) the corresponding state field. The PhC consists of the air-holes with radii $r = 0.4a$ embedded in dielectric material with $\varepsilon_r = 11.56$.

References

[1] Dahl J, Jensen JS, Sigmund O. Topology optimization for transient wave propagation problems in one dimension: Design of filters and pulse modulators. Struct. Multidisc. Optim, 36:585-595, 2008.

[2] Nomura T, Sato K, Taguchi K, Kashiwa T, Nishiwaki S. Structural topology optimization for the design of broadband dielectric resonator antennas using the finite difference time domain technique. Int J Numer Methods Eng, 71(11):1261-1296, 2007.

[3] Tetu A, Kristensen M, Frandsen LH, Harpøth A, Borel PI, Jensen JS, Sigmund O. Broadband topology-optimized photonic crystal components for both TE and TM polarizations. Optics Express, 13(21):8606-8611, (2005)

Rigorous modeling of 2D arbitrary shaped diffraction gratings with an analytical solution

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An analytical solution derived from the GSM for the S-matrix of 2D gratings gives rise to a dramatic reduction of the calculation time.

Introduction

The slicing technique together with S matrix recombination is the most general way to calculate diffraction from gratings of an arbitrarily profile. All existing methods like the RCWA perform very slowly when applied to 2D gratings since the calculation time is proportional to the cube of the number of diffraction orders taken into account.

Results

We develop a new technique based on the generalized source method (GSM) scheme [1]. First, all elements of the S matrix of a thin grating slice are found in an analytical form. At this stage, we apply the slanted boundary conditions proposed in [2] to avoid the dangerous artifacts of a staircase approximation of the actual profile. A specific implementation of the slanted boundary conditions results in a notable improvement of the capabilities of the method.
In a second step, all S matrices are combined together analytically under the GSM scheme. This allows for the direct calculation of the diffraction efficiencies without matrix multiplication. The diffraction problem is thereby expressed algebraically as a linear system of equations. Analytical expressions are obtained in a very simple form and can be decomposed into products of Toeplitz and diagonal matrices. As a consequence the Fast Fourier technique [3] together with the GMRES method [4] can be naturally implemented. This leads to a very short computation time which is linearly proportional to the number of slices and diffraction orders. Finally, an asymptotic method is applied which increases the calculation accuracy by several orders of magnitude.
With these new developments the analytical approach becomes not only a powerful tool for grating calculations but also a promising method for modeling nonperiodic micro- and nanostructures.

References

[1] A.V. Tishchenko, Opt. Quantum Electron., **32**, 1971-1980 (2000)

[2] E. Popov, M. Neviere, J. Opt. Soc. Am. A, **17**, 1773-1784 (2000)

[3] B.T. Draine, J.J. Goodman, Opt. Lett., **16**, 1198-1200 (1991)

[4] Y. Saad, M. H. Schultz, SIAM J. Sci Stat. Comput., **7**, 856-869 (1986)

A New Analytical Model for the Field of Microstructure Optical Fibers

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We propose a new analytical for the field of index-guided microstructured optical fibers. We show that this model is better, both in terms of capability and accuracy, than the widely used effective-index model (EIM).

Introduction

Microstructured optical fibers (MOFs) are known to have many interesting properties like endlessly single mode operation [1], unusual dispersion properties etc. Many numerical techniques have been developed for their study, which are computationally intensive. The effective-index model, based on the equivalent step-index, has been widely used to model the field as well as to obtain other characteristics of these fibers. This model does not include the important azimuthal variation of the field and is limited in accuracy. Our model represents a significant improvement of these two counts.

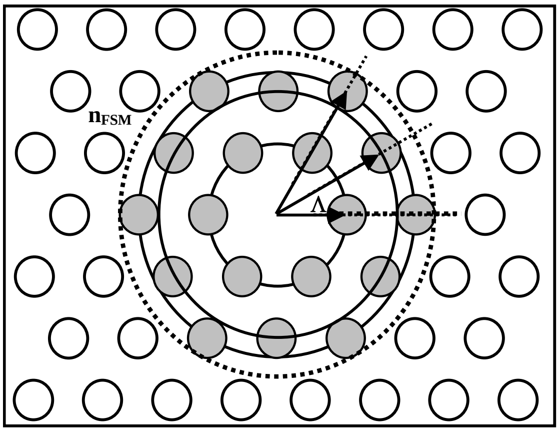

Fig.1 Basic MOF structure

The Model and Results

MOFs can be viewed, without any change in the structure, as an arrangement of air-holes in a certain angular symmetry in which the holes are distributed in different concentric rings are at an angular separation of $\pi/3$ (Fig. 1). In our model, we assume that the lattice structure beyond the third ring (*i.e.*, beyond the dotted line in Fig.1) is replaced by a uniform cladding of the index of the fundamental space-filling mode [1]. We use the following field:

$$\psi(r,\phi) = e^{-\alpha r^2} - Ae^{-\alpha_1 (r-\sigma*\Lambda)^2}(1+\cos 6\phi) \quad (1)$$

where A, α, α_1 and σ are the parameters which are optimized using the variational principle for the propagation constant. Figure 2 shows the variation of modal index of the fundamental mode with wavelength. The results have been compared with scalar FEM [2] and EIM and show that our results are much closer to FEM. Figure 3 shows that the intensity pattern obtained using our model possess an azimuthal variation which is similar to the one obtained experimentally. This feature is totally missing in the EIM field.

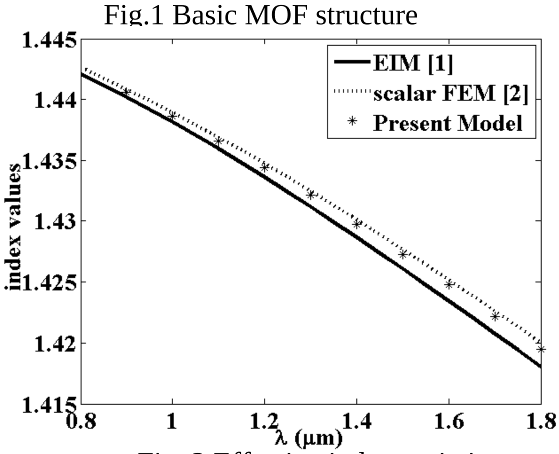

Fig. 2 Effective index variation

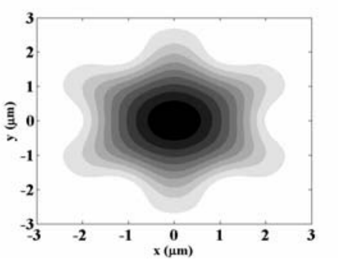

Fig. 3 Field intensity contour plot

References

[1] T. A. Birks, J.C. Knight, and P.St. Russell, *Opt. Lett.* **22**, 961-963 (1997)
[2] V.H. Aristizabel, F.J. Velez, and P. Torres, *Opt. Express* **24**, 11848-11854 (2006)

Ultrabroadband TM reflection from high contrast grating: why ?

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A grating mode analysis of the unusually broadband TM reflection from a high contrast binary grating sheds light on the origin of this effect. This interpretation will be submitted to the workshop attendance.

Introduction

There has been a high interest lately in the unusually wide, close to 100% reflection spectrum of a normally incident, TM-polarized plane wave from a high index contrast binary grating or segmented waveguide [1]. All modeling results have been obtained by applying the RCWA numerical technique and although there was some attempt to give a phenomenological interpretation of the effect, the question of the wide bandwidth character of the reflection spectrum remains unanswered.

Results

We have first analyzed the phase of the reflection spectrum to discover that there is only one guided TM mode propagating along the segmented waveguide. Resonant reflection can therefore not explain the broadband character although it does participate in the effect.
We have taken up this problem on the basis of the two excited grating modes (TM_0 and TM_2) propagating up and down the vertical walls and slits of the structure and examined what may be responsible for a broadband destructive interference in the transmission medium. The two conditions for such effect to occur are a wavelength independent propagation constant difference between the two excited grating modes and a wavelength independent balanced excitation of these two modes. We will show that a TM mode close to cut-off exhibits a change of sign of the dispersion curve curvature, and that such feature is already present in a high contrast single slab waveguide. This leads to the possibility of achieving a parallelism between the TM_0 and TM_2 dispersion curves over a rather wide part of the spectrum. Examining the variation of the TM modal fields in this part of the spectrum teaches that the balanced excitation of the two modes by a plane wave can be kept over the same section of the spectrum.
This broadband effect will be discussed at depth and the interpretation submitted to the attendance.

References

[1] C.F.R. Mateus et al., *IEEE Photonics Tech. Lett.*, Vol. **16**, 518-520, (2004)

Asymmetric Complex Grating Coupler Modified to Ease Its Fabrication

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We suggest a modification of an asymmetric grating coupler that could possibly lead to its easier fabrication. Results of a using bi-directional mode expansion algorithm but stimulated by a simple physical considerations based on the coupled mode theory will be presented.

Introduction

A very unusual waveguide device – an asymmetric complex grating coupler – has been proposed and rather thoroughly analzyed in [1-4]. In [5, 6], specific practical applications of an asymmetric graring coupler were proposed and analyzed. However, very intriguing properties of this device have not been practically exploited so far probably due to its very difficult fabrication. In this contribution we present a numerical study of a modified device that might be easier to fabricate unless its unusual properties are completely destroyed.

Modified Design and Numerical Results

The principle of the complex grating coupler rests on the arrangement of the grating: their positive and negative spatial harmonics strongly differ in magnitudes. In the „classical" arrangement, each grating period is composed of four segments with permittivity variations positioned in all four quadrants on a circle centered in the origin in the complex plane. It makes the fabrication of the device extremely demanding. In our modified design, the grating is purely passive while the active region is concentrated into a single longitudinally uniform stripe along the coupler. The structure of the (not fully optimized) device and the field distributions under excitation into the lower and upper waveguide are plotted in Fig. 1. The field distributions were calculated using the bi-directional mode expansion tool BEXX [7, 8].

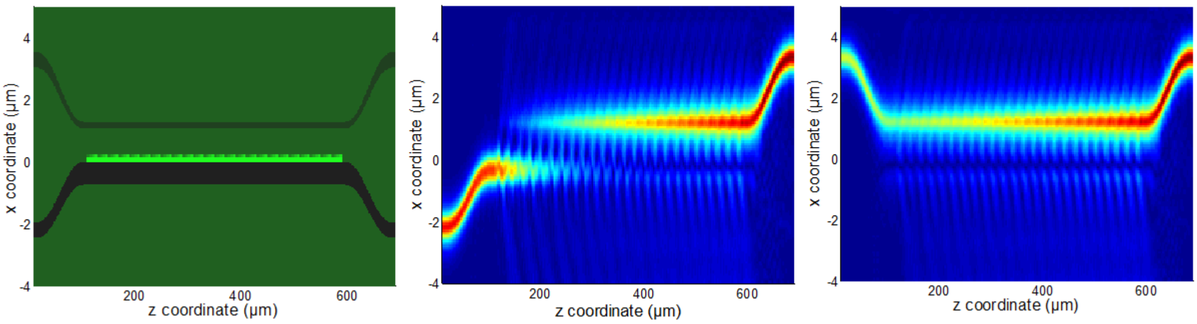

Fig. 1. Modified complex grating structure (left) and its behaviour under excitation into lower and upper waveguides (middle and right figures, respectively).

References

[1] L. Poladian, *Phys. Rev. E*, **54**, 2963-2975, (1996).
[2] M. Greenberg and M. Orenstein, *Optics Express*, **12**, 4013-4018, (2004).
[3] M. Greenberg and M. Orenstein, *Optics Letters*, **29**, pp. 451-453, (2004).
[4] M. Greenberg and M. Orenstein, *IEEE J. Quantum Electron*, **41**, 1013-1023, (2005).
[5] M. Kulishov *et al*, *Optics Express*, **13**, 3567-3578, (2005).
[6] M. Kulishov *et al*, *Optics Express*, **13**, 3068-3078, (2005).
[7] J. Čtyroký, *J. Lightwave Technol.*, **25**, 2321-2330, (2007).
[8] J. Čtyroký, *J. Lightwave Technol.*, **27**, (2009), in print.

FD-FD analysis of dielectric waveguide crossings with two-fold symmetry

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By exploiting the symmetry of a crossing waveguide along two diagonally intersecting lines, we obtain, through four independent FD-FD calculations, reflection, transmission and cross-coupling coefficient matrices for an unbound dielectric crossing waveguide.

Introduction

Active and passive integrated optical devices such as the optical filters, optical add-drops and WDM devices contain many crossing waveguides. One of the critical criterions for designing a crossing waveguide is the less than .5 dB of radiation and cross coupling loss at each stage. This tight accuracy requirement makes it hard to analyze an unbound dielectric crossing waveguide.

Results

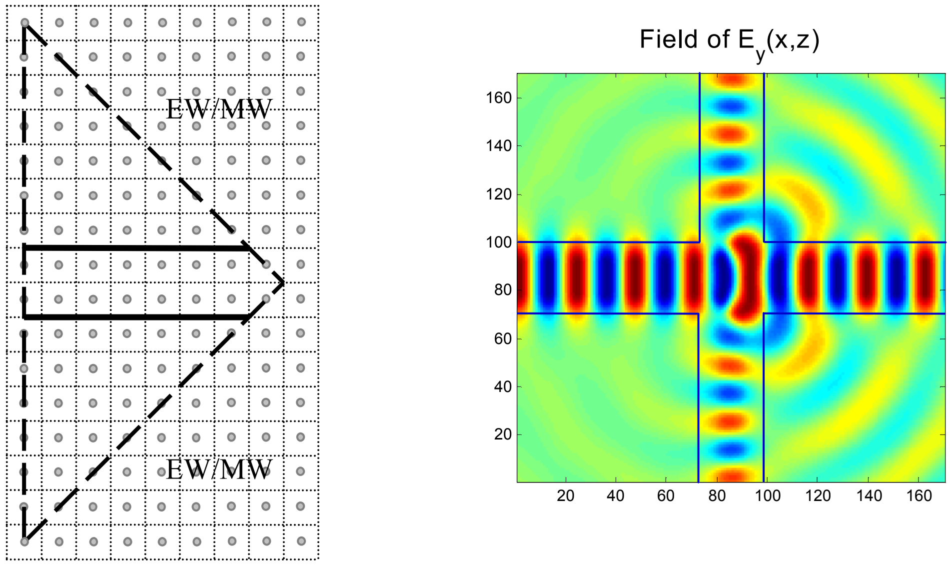

Figure 1 Illustration of a crossing waveguide showing two diagonal symmetry lines (left) and the 2D field snap shot (right).

By exploiting the symmetry along two diagonal planes passing through the center of the waveguide (Fig 1, left), the problem is reduced to calculating four reflection coefficient matrices of a straight waveguide with two perfect boundary conditions (electric/magnetic walls, EW/MW). We use FD-FD method with a high-quality layer-mode based transparent boundary condition [1] for the reduced problems. The unknowns are assigned right on the two 45 degree boundaries so that simple modification of FD coefficients can be derived for these points. In this way, the total field distribution and scattering matrices of the original problem can be computed (Fig 1, right) with high numerical accuracy. Thus, the higher-order effects in a crossing waveguide can be studied.

References

[1] Hung-Wen Chang and S.-M. Wang, "Large-Scale Hybrid FD-FD Method for Micro-Ring Cavities," FiO-LS 2005, FWE6 (2005).

Characterization of Polarization Conversion in Nematic Liquid Crystal Photonic Crystal Fiber: Tolerance Study

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In this paper, the expected performance of a novel polarization rotator (PR) based on nematic liquid crystal photonic crystal fiber (NLC-PCF) is reported. The simulation results are obtained using full vectorial finite difference beam propagation method which is able to deal accurately with anisotropic materials.

Introduction

The suggested polarization rotator (PR) as shown in Fig.1 is a photonic crystal fiber (PCF) [1] whose holes (gray area) are infiltrated with a nematic liquid crystal (NLC) of type E7. The holes are arranged in a soft glass background of type SF57. The refractive index of SF57 is higher than the ordinary n_o and extraordinary n_e refractive indices of the NLC which guarantees the index guiding of the light through the NLC-PCF. In addition, the use of the soft glass offers optical properties that cannot be provided by silica, such as high rare earth solubility, mid-infrared transmission and high nonlinearity. Moreover, the director orientation of the NLC molecules as shown in Fig.1 can be controlled using a static electric filed which can be used to produce complete polarization conversion.

Results

Fig.2 illustrates the variation of the converted power P_x and the crosstalk (CT) with the rotation angle φ of the NLC at $z=L_\pi$ (the minimum longitudinal distance at which maximum polarization conversion occurs) and at z=1072µm (the device length of the proposed PR). It is evident from this figure that φ has a great impact on P_x and the corresponding crosstalk. At $\varphi= 45^o$, the proposed PR offers 99.813% polarization conversion ratio with a relatively short device length of 1072µm. As φ changes from 42^o to 48^o, P_x and the crosstalk at the designed length 1072µm will be always better than 0.9872 and -19dB respectively. In addition, the numerical results revealed that the polarization conversion would be more than 99% over the 1.53µm-1.6µm wavelength range. Moreover, n_o and n_e of the NLC changes with the temperature variation therefore, the effect of the temperature on the PR performance is presented. Furthermore, the influence of the waveguide geometrical parameters on the overall polarization conversion and polarization crosstalk is reported. To the best of the authors' knowledge, it will be the first time to use the PCF for polarization conversion. More results will be presented in the conference.

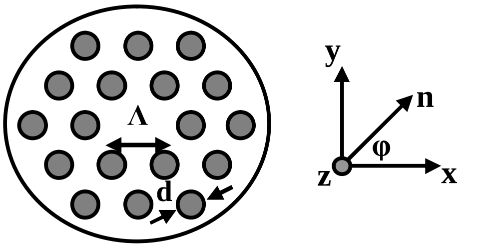

Fig.1.Cross section of the proposed NLC-PCF. The director of the NLC is shown at the right

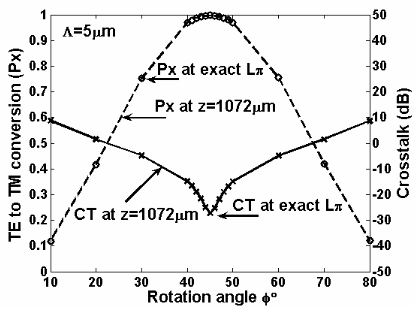

Fig.2 The variation of the converted power (P_x) and the crosstalk (CT) at $z=L_\pi$ and at z=1072µm with the rotation angle φ of the NLC.

[1] J. Broeng et al, *Opt. Fiber Technol*, **5**, 305-330, (1999).

The Compact 2D FDTD Technique combined with the Padé Approximation Transform for the leaky modes analysis

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The compact 2D FDTD technique combined with the Padé approximation transform has been presented to solve the leaky modes in optical waveguides. To show the effectiveness of the proposed approach, we analyze a 3D leaky waveguide structure and compare the results with the frequency domain mode solvers.

Introduction

To optimally design optical devices using semiconductor deep-ridge waveguides such as arrayed waveguide gratings (AWGs) and Mach-Zehnder (MZ) modulators, the leaky modes in these deep-ridge waveguides should be well analyzed. Several methods have been proposed to calculate the leaky mode loss [1]-[3], which are generally based on complex root searching in the frequency domain and could be initial-guess sensitive. In this work, an efficient time domain method based on the compact 2D FDTD technique and the Padé approximation transform is implemented to analyze the leaky modes. To efficiently truncate the FDTD lattices the uniaxial anisotropic perfectly matched absorption layers (UPMLs) is adopted. The 3D waveguide is treated as a 2D cavity of which the resonant modes represent the 3D propagation modes of the waveguide. Using the Padé approximation transform the FDTD data is transferred into the frequency domain to calculate the corresponding mode spectra. A Lorentzian fitting can be used to find the mode frequency f_0 and the 3-dB bandwidth Δf. The mode quality factor can then be calculated as $Q = f_0/\Delta f$. Further the real part of the mode effective index and the mode loss (the imaginary part of the mode effective index) can be calculated as $n_{\mathrm{eff}} = \beta/k_0$, $\alpha = n_g k_0/Q$ ($n_{\mathrm{i}} = \alpha/2k_0$). (where k_0 is the free-space wave number, n_{eff} and n_i are the real and imaginary parts of the effective index, respectively, n_g is the group index.)

Results

In order to confirm the validity of the proposed model, we consider a 3D leaky waveguide with the same structure as analyzed in [1]. 1-μm-thick UPMLs are used in the simulation and the uniform space cell size used is 0.0125 μm. Table I shows the imaginary part mode indices of five TE modes at the wavelength of 1.064 μm calculated by this modal and other methods. It is seen that for four of the five modes, the results obtained from different methods agree with each other well. However, for the TE_{20} mode, the results between [2] and [3] differ massively and our result is closer to the result in [3].

Table I. Comparison of the imaginary parts of the complex mode indices of TE modes.

Mode	This model	SIM [1]	FEIDBPM [2]	Edge-element [3]
TE_{00}	$j1.693\times10^{-7}$	$j1.697\times10^{-7}$	$j1.698\times10^{-7}$	$j1.712\times10^{-7}$
TE_{01}	$j5.447\times10^{-5}$	$j5.481\times10^{-5}$	$j5.482\times10^{-5}$	$j5.569\times10^{-5}$
TE_{02}	$j8.407\times10^{-4}$	$j8.841\times10^{-4}$		$j8.831\times10^{-4}$
TE_{20}	$j4.676\times10^{-6}$		$j1.691\times10^{-6}$	$j6.786\times10^{-6}$
TE_{21}	$j1.083\times10^{-4}$		$j1.232\times10^{-4}$	$j1.154\times10^{-4}$

References

[1] G. M. Berry, et al., *Electron. Lett.*, **29**, 1941-1942, (1993).
[2] Y. Tsuji, et al., *J. Lightwave Technol.*, **18**, 618-623, (2000).
[3] S. Selleri, et al., *Opt. Quantum Electron.*, **33**, 359-371, (2001).

Theoretical formulation to shape versatile propagation characteristics of 3-layer-tubular waveguides

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This study introduces an analytical formalism to shape the quantification of photonic modes devoted to global 3-layer-tubular waveguides (including hollow cylindrical structures). Thereby we have implemented such an overall frame and focus on the asymptotic behavior and the cut-off limit discussions.

Introduction

Owing to their high aspect ratio, sub-wavelength nanotubes are promising building blocks for extreme miniaturization of optical components [1, 2]. In this study, we present a generalized formalism for the whole optical modes of 3-layer-tubular waveguides based on the exact solution of Maxwell's equations. The tubular configuration of interest consists of two regions of infinite length with refractive index n_1 and n_2 embedded in a third infinite media of refractive index n_3 ($n_2 > n_1$ and $n_2 > n_3$). The internal and external radius are respectively noted a and b.

Results

In each region, the six field components have been deduced. By using the boundary conditions, two characteristics equations have been achieved (1). These equations contain two unknown ratios, a_4/a_2 and b_4/b_2, that are obtained by applying Cramer's rule to the eight equations of the boundary conditions. Propagation constants for hybrid modes are obtained by solving simultaneously the two characteristic equations (1) with the proper forms of a_4/a_2 and b_4/b_2.

$$\left\{\begin{aligned}
\left(\frac{\beta\nu}{k_0 n_1}\right)^2\left(\frac{1}{p_{11}^2}+\frac{1}{p_{21}^2}\right)^2 &= \left(\frac{\nu}{p_{11}^2}+\frac{I_{\nu+1}(p_{11})}{p_{11}I_\nu(p_{11})}+\frac{\frac{\nu}{p_{21}}J_\nu(p_{21})-J_{\nu+1}(p_{21})+\frac{b_4}{b_2}\left(\frac{\nu}{p_{21}}Y_\nu(p_{21})-Y_{\nu+1}(p_{21})\right)}{p_{21}\left(J_\nu(p_{21})+\frac{b_4}{b_2}Y_\nu(p_{21})\right)}\right)\times \\
&\left(\frac{\nu}{p_{11}^2}+\frac{I_{\nu+1}(p_{11})}{p_{11}I_\nu(p_{11})}+\frac{n_2^2}{n_1^2}\frac{\frac{\nu}{p_{21}}J_\nu(p_{21})-J_{\nu+1}(p_{21})+\frac{a_4}{a_2}\left(\frac{\nu}{p_{21}}Y_\nu(p_{21})-Y_{\nu+1}(p_{21})\right)}{p_{21}\left(J_\nu(p_{21})+\frac{a_4}{a_2}Y_\nu(p_{21})\right)}\right) \\
\left(\frac{\beta\nu}{k_0 n_3}\right)^2\left(\frac{1}{p_{22}^2}+\frac{1}{p_{32}^2}\right)^2 &= \left(\frac{\nu}{p_{32}^2}-\frac{K_{\nu+1}(p_{32})}{p_{32}K_\nu(p_{32})}+\frac{\frac{\nu}{p_{22}}J_\nu(p_{22})-J_{\nu+1}(p_{22})+\frac{b_4}{b_2}\left(\frac{\nu}{p_{22}}Y_\nu(p_{22})-Y_{\nu+1}(p_{22})\right)}{p_{22}\left(J_\nu(p_{22})+\frac{b_4}{b_2}Y_\nu(p_{22})\right)}\right)\times \\
&\left(\frac{\nu}{p_{32}^2}-\frac{K_{\nu+1}(p_{32})}{p_{32}K_\nu(p_{32})}+\frac{n_2^2}{n_3^2}\frac{\frac{\nu}{p_{22}}J_\nu(p_{22})-J_{\nu+1}(p_{22})+\frac{a_4}{a_2}\left(\frac{\nu}{p_{22}}Y_\nu(p_{22})-Y_{\nu+1}(p_{22})\right)}{p_{22}\left(J_\nu(p_{22})+\frac{a_4}{a_2}Y_\nu(p_{22})\right)}\right)
\end{aligned}\right. \tag{1}$$

The quantification of families of optical modes have been implemented in the case of silica nanotubes ($n_1 = n_3 = 1$, $n_2 = 1.5$ at $\lambda = 670nm$). Two studies of such eigenvalue quantifications are depicted: 1. the internal radius a is fixed and the external radius b ranges around $[a, 10a]$, with $a = [\lambda/10;\ \lambda/2;\ \lambda]$; 2. the external radius b is fixed and the internal radius a ranges around $[0, b]$, with $b = [\lambda/2;\ \lambda;\ 10\lambda]$. The opposite of the effective refractive index has been plotted and studied as a function of the radius (internal or external) normalized to the wavelength. The asymptotic behavior of the curves are particularly discussed as well as the cutoff limits of the optical modes. A map of the different areas (monomode and multimode) has been dressed as a function of the internal and external radius normalized to the wavelength for versatile tubular structures.

References

[1] D. Duval, et al., *Electron. Lett.*, **44**, 1135–1136 (2008).
[2] E. Pouget, et al., *Nature*, **6**, 899–900 (2007).

Modeling, analysis and optimization of pulse-pumped unidirectional erbium-doped waveguide ring lasers

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Dynamics of pulse-pumped erbium-doped waveguide ring lasers is analyzed using a time-dependent rate-propagation equation model. Laser configuration is optimized for obtaining highly unidirectional operation.

Introduction

Erbium-doped waveguide lasers can find numerical applications in DWDM communication systems, sensing, medicine, metrology etc. Ring lasers can be operated in a unidirectional regime that allows increased power extraction from the gain medium and better potential to single-frequency operation. The main obstacle for developing highly unidirectional erbium-doped waveguide ring lasers (EDWRLs) is the absence of integrated optical isolators compatible with the silica-on-silicon or glass technology [1]. Earlier we analyzed several methods for achieving unidirectional operation of continuous-wave (CW) EDWRLs [2]-[4]. These methods are based on employing special asymmetric elements in laser configuration, such as an S-crossover waveguide or an integrated Bragg grating with an asymmetric profile. We also studied the inherent tendency of one-end-pumped CW EDWRLs to unidirectional lasing, and its influence on application of these methods. The analysis was carried out using a time-dependent rate-propagation equation model. Only the steady-state solutions, corresponding to CW operation of EDWRLs, were considered in the previous study. Now we extend our study to consideration of pulse-pumped EDWRLs. We discuss applicability of the model for description of laser dynamics, analyze the mechanism of the counter-directional wave suppression in pulse-pumped EDWRLs and optimize laser parameters and the pump power for obtaining highly unidirectional operation.

Results

The counter-directional wave suppression in unidirectional EDWRLs shows relaxation-oscillation behavior, synchronous with oscillations of the lasing power, in response to a stepwise change of the pump power. Oscillations of the suppression produced by pumping asymmetry have longer relaxation time and larger amplitude than those caused by asymmetric elements. Assuming rectangular pump pulses with a given power, pump energy consumption can be optimized for producing laser pulses with simultaneously the highest peak power and the strongest suppression. At the same time, the counter-directional wave suppression remains almost constant during the laser pulse. The suppression caused by pumping asymmetry reaches maximum as a function of the pump power. The suppression caused by the asymmetric elements is independent of the pump power. Furthermore, for the one-end-pumped EDWRLs, optimization of laser and pump pulse parameters allows achieving highly unidirectional operation with no asymmetric elements.

References

[1] M. Levy, *IEEE J. of Selected Topics in Quantum Electronics* **8**, 1300-1306 (2002)

[2] I. Mozjerin, S. Ruschin and A. Hardy, *Electronics Letters*, **41**, 1119-1121 (2005)

[3] I. Mozjerin, A. Hardy and S. Ruschin, *IEEE J. of Quantum Electronics*, **42**, 600-607 (2006)

[4] I. Mozjerin, *Ph.D. Thesis*, Tel-Aviv University, Tel-Aviv (2006)

Three-dimensional analysis of hexagonal structured photonic crystals using oblique coordinates

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We consider hexagonal structured photonic crystals and use oblique coordinates to calculate their band structure. In particular, three-dimensional vectorial calculations were performed.

Introduction

The elementary cells of hexagonal structured photonic crystals are described by parallelograms. Oblique coordinates are used to express the boundaries. These are introduced into the Method of Lines (MoL) and the calculations of the band structure were done. In particular three-dimensional vectorial calculations have to be performed. The theoretical background and results for the two-dimensional case can found in [1] and [2].

Results

The underlying photonic crystal is designed as array of hexagonal holes in a substrate and can be found in [3]. In Fig. 1 we can see a) the odd- and b) the even-Modes of the photonic crystal. The calculations show a good agreement up to certain frequencies. For higher frequencies the approximations must be done more precisely.

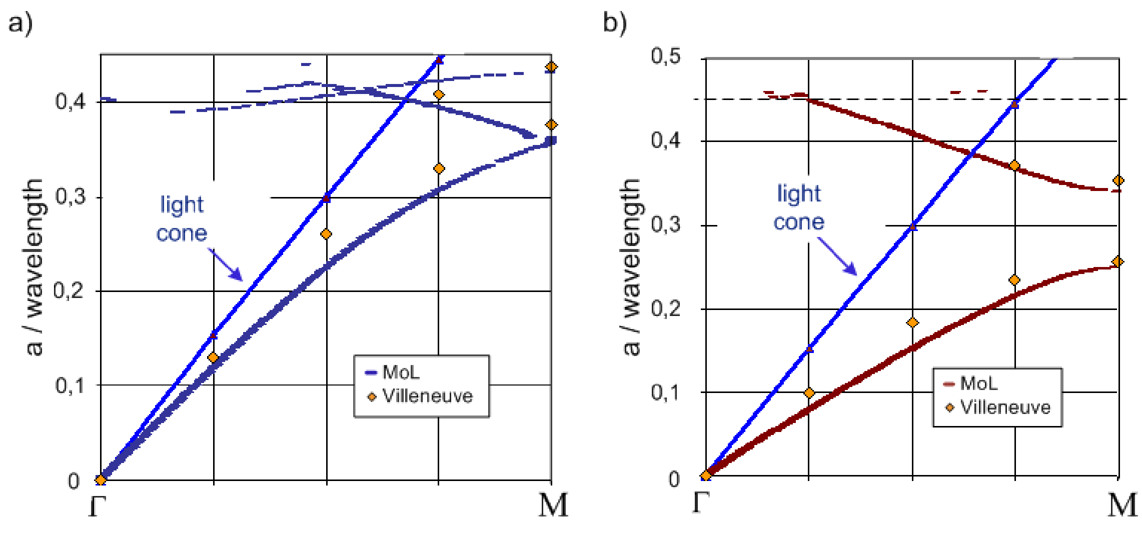

Fig. 1. Calculated (MoL) Γ-X Band of a) odd-Modes and b) even-Modes and the literature values from [3] (Villeneuve) as reference

References

[1] S. F. Helfert, "Introducing Oblique Coordinates in Numerical Methods, Applied to the Computation of Band Structures", in *ICTON Conf.*, Rome, Italy, vol. 2, pp. 80–83, 2007
[2] S. Helfert, *Progress in electromagnetic Research PIER 61*, pp. 271–278, 2006.
[3] P. R. Villeneuve and S. Fan and S. G. Johnson and J. D. Joannopoulos, *IEE Proc.-Optoelectron.*, vol. 145, no. 6, pp. 384–390, 1998.

Breakdown voltage model of fusion SiO_2 optical coupler switch

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Abstract
This paper describes the breakdown voltage of SiO_2 fiber using the Pockel's effect and empirical equation. The model is evaluated by using the coupling coefficient and the changes in the refractive index. Increasing the value of coupling coefficient between the electrodes lead to a reduction in the breakdown voltage.

Introduction

Switching technology exhibits a large electro-optic effect causing a change in the optical properties in response to a slowly varying electric field. The successful operation was demonstrated [1]. Directional coupler switches can be built by fabricating coupler on an electro-optic material. A voltage is then applied through sectioned electrodes along the coupling length. A 1X2 Single Mode SiO_2 fiber coupler has been fabricated [2]. A simplified model of breakdown voltage to drive the switch is then developed. The change of refractive index due to linear electro-optic, Pockels effect [3] and an empirical equation are used to calculate the value of coupling coefficient, κ, via the equation,

$$V_{dc} = \left[n_1 \left(2 - 2\sqrt{1-\delta} - \delta \right)^{\frac{1}{2}} \right] \left[\frac{2x}{r\, n_1^3} \right]$$

where n_1 is the refractive index of core, δ is the fractional refractive index change, x is the distance between the electrodes, and r is the electro-optic coefficient.

Results

The result shows that the changes of the refractive index increase exponentially as a function of separation fiber axis from 5 to 8 x 10^{-6} *m.* The breakdown voltage and δ depict a linear relationship. The increment of κ shows that the value of voltage is reduced.

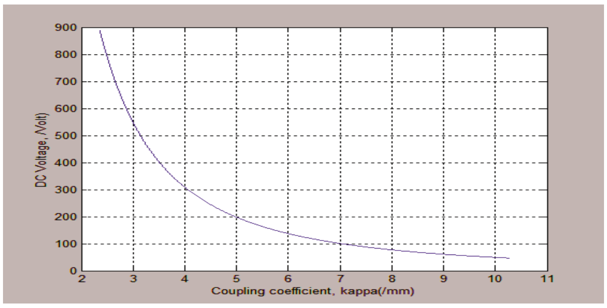

Figure 1: Voltage breakdown at 1 atmospheric pressure

References

[1] H. Kogelnik and R. V. Schmidt (1976). Switched directional couplers with alternating $\Delta\beta$. *IEEE Journal of Quantum Electronics.* Vol. QE-12(7), pp. 396-401.
[2] Saktioto, Ali, J., Fadhali, M., Zainal, J. (2008). Estimation of coupling power parameter of fused coupled fibers. *Journal of Nonlinear Optical Physics and Materials*. Vol. 17(1), pp. 111-120.
[3] Tarek S. El-Bawab (Ed.) (2005). *Optical Switching*. New York: Springer Science+Business Media, Inc.

Rigorous three-dimensional numerical modelling of scattering loss in high index contrast waveguides

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Introduction

Scattering loss minimization has a key role in optical waveguides design and optimization because it often limits the photonic device performance. Then, analytical and numerical algorithms can be very useful to predict scattering loss of a specific waveguide and to point out geometrical and physical parameters that can be adjusted to minimize this loss contribution.

Recently, two different three-dimensional (3D) models have been developed to estimate sidewall roughness induced loss [1-2]. In [1], the coupled mode theory has been used to evaluate the coupling between guided and radiation modes (derived by an approximated semi-analytical method) induced by sidewall roughness induced coupling In [2], the volume current method has been employed to calculate scattering loss in Silicon-on-Insulator, Silicon Oxynitride/SiO_2 and Si_3N_4/SiO_2 rectangular waveguides. In [2], the electromagnetic field generated by the current distribution simulating the presence of sidewall roughness has been computed by using the dyadic Green's functions and by approximating the rectangular guiding structure with a planar one.

In this paper, scattering loss suffered by high index contrast waveguides has been modelled by means of a rigorous numerical 3D algorithm based on volume current method. The algorithm does not introduce any approximation except that due to 3D finite element method (FEM) utilization. Results obtained by our model have been compared to experimental ones reported in literature, demonstrating a very good agreement.

Results of validation procedure

To validate our modeling technique we have used it to calculate scattering loss (α_{sc}) suffered by a high-index waveguide. This waveguide is a InP-based photonic wire exhibiting an index contrast larger than 70 % [3]. Scattering loss of this waveguide has been calculated by our model. The radiation pattern of current distribution equivalent to sidewall roughness has been evaluated by 3D FEM. Obtained results for the waveguide reported in [3] is α_{sc} = 15.1485 dB/cm. This value is very close to that one experimentally measured (relative error less than 1 %).

References

[1] C. Poulton, C. Koos, M. Fujii, A. Pfrang, T. Schimmel, J. Leuthold, and W. Freude, *IEEE J. Sel. Topics in Quantum Electron.*, **12**, 1306-1321 (2006).

[2] T. Barwicz and H. A. Haus, *J. Lightwave Technol.*, **23**, 2719-2732 (2005).

[3] M. Lesecq, S. Maricot, J.-P. Vilcot, and M. Beaugeois, IET Optoelectronics, **2**, 69-75 (2008).

Functionality in Mid-IR of Low-Contrast Periodic Structures in Highly Non-Linear Glass

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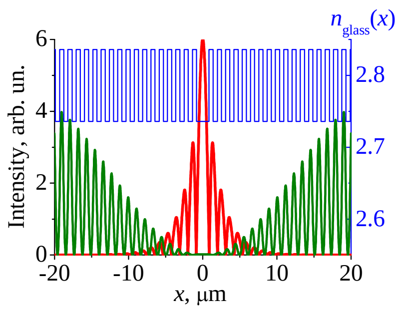
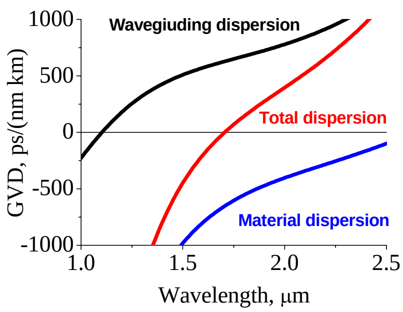
Introduction

Among non-linear optical materials, chalcogenide glasses stand out because they have third-order non-linearity 2-3 orders of magnitude greater than that of fused silica. However large positive dispersion of these glasses in the spectral range 1–2 microns cancels observation of the soliton effects and significantly reduces the efficiency of supercontinuum generation (zero of the group velocity dispersion is usually located in the Mid-IR spectral range). In modern photonics, 2D arrays of parallel waveguides have wide range of promising applications [1]. Defect modes can be used for efficient dispersion compensation. The waveguide arrays can be high-contrast (ridge waveguides in air) or low-contrast (lattices with different refractive index). In this work, we report theoretical efforts aimed at understanding the efficiency of using low-contrast periodic waveguiding structures as non-linear devices in Mid-IR.

Our theoretical approach in analysis of the spatio-temporal non-linear dynamics of the ultra-short optical pulses uses the classic theory based on the solution of a 2D+T linear parabolic wave equation in frequency domain with rigorous account of the dispersion consisting of both the waveguiding and material part. Non-linear effects are evaluated in time domain. To analyse dispersion properties of the waveguide arrays, we solve the eigenvalue equitation for TE modes.

Results





In our results, we demonstrate some ways to manage dispersion and, in this way, spatial, temporal and spectral characteristics of non-stationary light beams propagating as defect modes inside the periodic structures. Dispersion of the structure and material is accounted for rigorously [2]. Optimal conditions for efficient excitation of defect modes are analysed. The structure, shown in Fig.1, can significantly reduce large positive dispersion of chalcogenide glass ($D=-700$ps/(nm km)) and shift zero dispersion wavelength from 4.5 microns to 1.8 microns. Spatiotemporal dynamics of the defect mode at central wavelength in the range 1.5-3mirons shows applicability of the structure for soliton formation and spectrum broadening over relatively short distances of propagation. The results are related to development of compact wide-band laser sources and pulse compressors in Mid-IR. Exploration of Mid-IR range would provide a real breakthrough in spectroscopy, security and medicine issues.

References

[1] G. Bartal *et al.*, "Spatial photonics in nonlinear waveguide arrays, " Opt. Express, 13, 1780 (2005).

[2] Y. Ohmachi, "Refractive index of vitreous As_2Se_3, " J.Opt. Soc. Am., 63, 630 (1973)

Duty cycle tolerant high index phase masks

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An all-normalized modal formalism gives the condition for a duty cycle tolerant cancellation of the 0th transmitted order in any high index contrast phase mask.

Introduction

Phase masks used to print large area planar gratings of submicron period have to fulfil conditions which differ from the phase masks used to write fibre Bragg gratings: the printing wavelength is close to the grating period. Under such condition, the requirement of extinction of the 0^{th} transmitted order can not be satisfied in silica based phase masks, therefore the binary corrugation must be made in a high index layer. The cancellation of the 0^{th} order imposes a given grating depth and, what is more difficult to achieve, a given line/space ratio.

Results

In the present contribution the conditions are found for a phase mask structure where the 0^{th} order can be canceled over a relatively wide domain of the line/space ratio, thus releasing the fabrication constraints. The search for the high tolerance phase mask structure is made once for all for the TE polarization after the structure parameters have been reduced to only three by proceeding to the most condensed normalization: the index contrast, the wavelength/period ratio and the line/space ratio.
A universal chart defines the domain of the normalized parameters giving rise to tolerant fabrication.

Analytical formulation and properties of the band edges of multilayers

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Revisiting the old concept of multi-dielectric-layer mirrors at the light of the modes they can propagate along the layers gives a clearer understanding of their properties

Introduction

Dielectric multilayers have long been envisaged as free space wave transmissive and reflective structures, and more recently as 1D photonic crystals. However, as soon as a periodic microstructure is defined in one of, or all layers, the modes propagating along the layers must be considered.

Results

An analytical formulation is given for the angles and the wavelengths at which the reflection of a dielectric multilayer composed of alternate quarter wave layers under normal incidence falls to zero. A modal representation of the field at the band edges of the reflection spectrum permits to render the properties of such simple structures more intelligible and to design them more efficiently as soon as they contain coupling microstructures.

Slanted boundary conditions in sliced gratings improve the accuracy of the RCWA

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The use of slanted boundary conditions at the walls of the slices of a staircase-decomposed arbitrary profile corrugation grating greatly improve the accuracy of the RCWA.

Introduction

The RCWA is widely used in grating modeling thanks to its usefulness and ease of implementation. When applied to corrugations of arbitrary profile, it requires a slicing approach whereby the grating region is finely sliced in the form of a staircase approximation of the actual corrugation. Such approximation of a continuous profile is not advisable since the field matching between slices involves high diffraction orders to account for an artifact which does not exist in reality.

Results

Popov et al [1] suggested to apply oblique boundary conditions at the edges of a slice, the slope of the edges coinciding with the slope of the tangent to the corrugation profile at the level of the considered slice. We adapted this approach to the RCWA and found out that it fits very well with the formalism of the FMM analysis and always leads to exact solutions except in metallic gratings under TM incidence.

In the presentation we will describe how naturally the slanted boundary condition is applied, and discuss the possible further improvements that it can bring to the RCWA as well as in other methods.

References

[1] E. Popov et al., *J.Opt. Soc. Am.A*, **17**, 1773-1784, (2008)

Channeling Effect in Two-Layered Cylinder Composed from Double-Negative Materials

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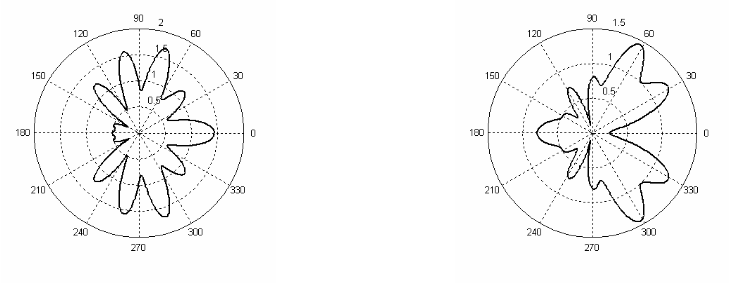
This paper theoretically investigates a 2D electromagnetic problem of the line source radiation scattering from the two-layered cylindrical structure that consists of the materials with the positive/negative permittivity and the positive/negative permeability.

Introduction

Metamaterials have got a great amount of researcher's interest recently. A very interesting case of this composite materials is so-called double-negative (DNG) materials with simultaneously negative values of the permittivity ε and the permeability μ [1] especially opposite to double-positive (DPS) materials that are characterized by positive ε and μ. This paper presents theoretical results of the harmonic line source field scattering from the two-layered cylinder. The scatterer consists of the cover with the parameters ε_1, μ_1 and the radius a and the core with the parameters ε_2, μ_2 and the radius b. The problem is solved theoretically on the base of the rigorous mathematical approach that provides an analytical solution which is presented in the form of an eigenfunction expansion.

Results

This configuration with DPS core and DNG cover demonstrates features associated with refocusing of the radiation and appearing of the source image at the inner point. The possibility of the wave channeling is another interesting feature of the structure composed from two metamaterials with different parameters. Fig. 1 demonstrates the far-field distributions in the two cases of the DNG structure which is illuminated by the source placed on right-hand side from the scatterer. Its distance from the cylinder center is 1.5a and the radiation wavelength is $\lambda = a$. The cylinder is nearly opaque for the radiation in homogeneous DNG structure shown in Fig. 1a and it is transparent for the radiation in the case of layered structure that is shown in Fig. 1b.



a) $\varepsilon_1 = \varepsilon_2 = -2,$ $\mu_1 = \mu_2 = -1$

b) $\varepsilon_1 = -1,\ \mu_1 = -1,$ $\varepsilon_2 = -2,\ \mu_2 = -1, b = 0.5a$

Figure 1. The far-field patterns of the scattered fields.

References

[1] V.G. Veselago, "The electrodynamics of substances with simultaneously negative values of ε and μ.", *Usp. Fiz. Nauk*, vol. 92, no. 3, pp. 517-526, 1967.

Gain-induced interaction of transverse modes in fiber amplifiers

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We model transverse mode propagation in a fiber amplifier by solving the Fresnel wave equation. Local gain saturation causes an interaction between transverse modes, which influences the modal polarization and modal power. The numerical results are compared with recent experiments.

Introduction

The impact of transverse modes has become an important topic in the field of high power fiber amplifiers and lasers. Although single-mode fibers provide an excellent beam profile, often large mode area (LMA) fibers have to be used for high power applications. LMA fibers reduce the power density in the core and thereby the nonlinearities, but in general allow the propagation of higher order modes (HOM). At the limits of highest power it is important to analyze the impact of HOM and to understand their interactions.

Recent experiments have shown that transverse modes in a fiber amplifier prefer to have orthogonal polarization states at high gain [1]. Our simulations agree with the experimental results and give an insight to the physical reasons of the interaction [2].

Numerical model and results

The propagation of the electrical field $\vec{E}$ can be described by the Helmholtz equation

$$\vec{\nabla}^2 \vec{E}(\vec{r}) + k^2(\vec{r})\vec{E}(\vec{r}) = 0. \tag{1}$$

The real part of the wave number $k(\vec{r})$ describes the local variation of the refractive index $n(\vec{r})$ and the imaginary part the variation of the local intensity-dependent gain $\alpha(\vec{r}, I(\vec{r}))$:

$$k(\vec{r}) = n(\vec{r})k_0 - i\frac{\alpha(\vec{r}, I(\vec{r}))}{2}. \tag{2}$$

Transverse modes interact, as the gain saturates in dependence on the local intensity $I(\vec{r})$:

$$\alpha(\vec{r}) = \frac{\alpha_{\mathrm{ss}}(\vec{r})}{1 + I(\vec{r})/I_{\mathrm{sat}}}, \tag{3}$$

where α_{ss} is the small signal gain and I_{sat} the saturation intensity.

We solve the wave equation using the slowly-varying-envelope-approximation. From the calculated electrical field the modal powers and modal polarizations are derived for each z-position in the fiber. In good agreement with the experimental results of [1] it is found that the transverse modes tend towards orthogonal polarization states with increasing gain. Our approach can be extended to model further influences on the transverse beam profile like bending of the fiber or different gain profiles.

References

[1] N. Andermahr and C. Fallnich, *Opt. Express* **16**, 8678 (2008).
[2] N. Andermahr and C. Fallnich, *Opt. Express* **16**, 20038 (2008).

Extraordinary transmission through slit array in thin metallic film

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Extraordinary transmission of electromagnetic wave through the array of subwavelength slits in metal film is considered. The numerical simulations for different systems show significant accordance with theoretical predictions based on Fabry-Perot formula. Comparison of results for silver and ideal metal films is presented.

Introduction

Since the problem of extraordinary transmission is difficult for analytic studying, then the numerical experiment with the least number of simplifications is very important. We made the numerical simulation of this phenomenon with the help of Finite-Difference Time-Domain Method [1]. The realizing of the extraordinary transmission nature is our task. In particular determining of the surface plasmon-polariton (SPP) resonances role in this phenomenon.

Results

The numerical simulations of extraordinary transmission for different systems show significant accordance with predictions based on Fabry-Perot formula. There are all types of peaks earlier described in theoretical and quasianalytic models [2–4]. The origin of these peaks is shown in [2] for extremely thin films within the bounds of the single-mode approximation with Fabry-Perot formula. The peaks of absorption are placed at the same wavelengths as the transmission resonances. The absorption peaks magnitude decreases with the rise of wavelength. To establish a nature of extraordinary transmission and SPP role in this nature we have carried out investigation of electromagnetic wave transmission for both real metal and ideal metal (in the same geometry as for real metal – silver). Since origin of resonances at wavelength close to the period of the structure causes the greatest interest we carried out investigation of extraordinary transmission for thin films. The reason is that only one type of resonances in thin film is observed namely resonances at wavelength close to the period. Wavelength λ which equals 605.5 nm there corresponds to extraordinary large transmission in ideal metal at wavelength very close to the period of the structure $P = 600$ nm. Two resonances at wavelength 601.8 nm and 662.8 nm which are close to the period of the structure are observed for silver. It was found that position and amplitude of resonances of extraordinary transmission can be explained within the single-mode approximation and don't require introduction of SPP resonances which are absent in ideal metal.

References

[1] A. Taflove and S. C. Hagness, *Computational Electrodynamics: The Finite-Difference Time-Domain Method*, 3rd. ed., (Artech House, 2005).
[2] A. Moreau, C. Lafarge, N. Laurent, K. Edee and G. Granet, *J. Opt. A: Pure Appl. Opt.* **9**, 165 (2007).
[3] J. A. Porto, F.J. Garcia-Vidal and J.B. Pendry, *Phys. Rev. Lett.* **83**, 2845 (1999).
[4] F. J. Garcia-Vidal and L. Martin-Moreno, *Phys. Rev. B* **66**, 155412 (2002).

Coupling Characteristics Of Liquid Crystal Photonic Crystal Fiber Coupler

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The coupling characteristics of a novel soft glass photonic crystal fiber coupler infiltrated with a nematic liquid crystal (NLC-PCF) are presented in this paper. The analysis is carried out using full vectorial finite difference method as well as full vectorial finite difference beam propagation method.

Introduction

The proposed coupler as shown in Fig.1 depends on infiltrating the holes (gray area) of double core photonic crystal fiber (PCF) [1] with a nematic liquid crystal (NLC) of type E7. The infiltrated holes are arranged in a soft glass of type SF57 (white area) which offers optical properties that cannot be provided by silica, such as high rare earth solubility, mid-infrared transmission and high nonlinearity. The refractive index of the SF57 is higher than the ordinary and extraordinary refractive indices of E7. Therefore, the propagation through the suggested coupler has been taken place by the modified total internal reflection. In addition, the director orientation of the NLC molecules as shown in Fig.1 can be controlled using a static electric filed which produces unique and uncommon polarization and coupling properties. Moreover, the performance of the proposed coupler is affected by the temperature (T) variation.

Results

The influence of the coupler geometrical parameters, temperature and rotation angle of the director of the NLC on the coupler performance is investigated. The numerical results reveal that the suggested NLC-PCF coupler will be suitable for designing short single polarization NLC-PCF couplers with low crosstalk. Moreover, the possibility of using the suggested NLC-PCF coupler as a multiplexer demultiplexer is also discussed. Fig.2 illustrates the variation of the coupling length (L_C) of the two polarized modes with the temperature at different rotation angles φ. It is evident from this figure, that L_C of the TE modes at $\varphi=0^o$ and 30^o increase with increasing temperature however, L_C of the TM modes are nearly constants. At $\varphi=60°$ and $90°$, L_C of the TM modes increase with increasing temperature however, L_C of the TE modes are nearly unchanged. To the best of the authors' knowledge, it is the first time that an index guiding soft glass NLC– PCF coupler with low cross talk is proposed and analyzed. More results will be presented in the conference.

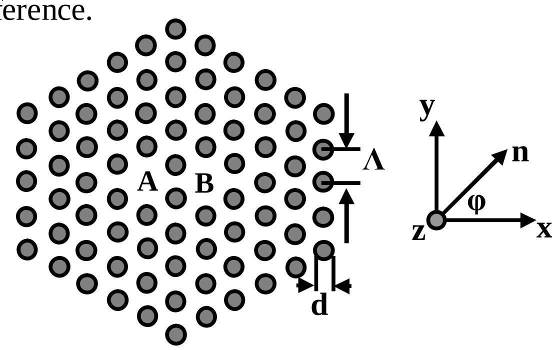

Fig.1. Cross section of the proposed NLC-PCF coupler. The director of the NLC is shown at the right

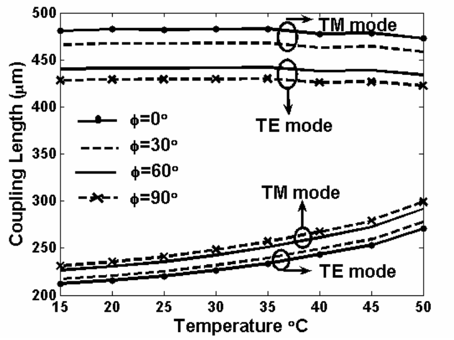

Fig.2. The variation of the coupling length of the two polarized modes with the temperature at different rotation angles φ of the NLC.

[1] J. Broeng et al, *Opt. Fiber Technol*, **5**, 305-330, (1999)

Analysis of a 3×1 Demultiplexer PhC Using CE-ADI-FDTD

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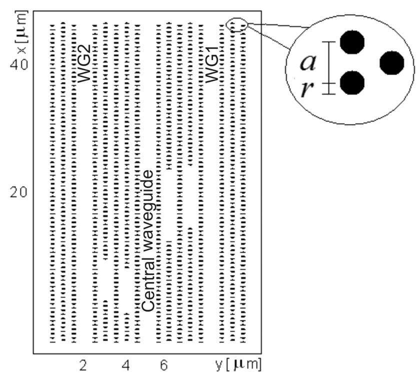
The Complex Envelope Alternating Direction Implicit (CE-ADI) Finite Difference Time Domain (FDTD) method is used to design a novel Photonic Crystal (PhC) 3×1 Multiplexer/Demultiplexer (MUX/DEMUX).

Introduction

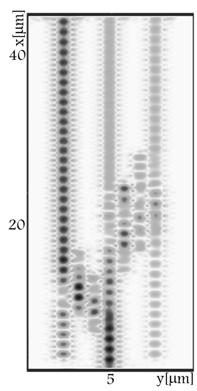
A 3×1 MUX/DEMUX is presented based on careful geometric considerations of microcavity design. Cavities are imbedded within the coupling region that separates three waveguides in a triangular lattice. The designed device has been thoroughly analysed using the CE-ADI-FDTD method. Furthermore, the performance of the applied Perfectly Matched Layers (PML) boundary conditions has been improved thanks to the minimisation of the discretisation error.

Results

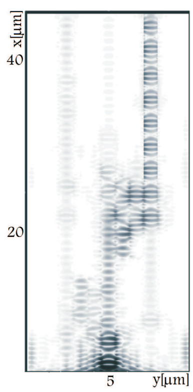
This PhC is a 75×19 triangular lattice arrangement of dielectric rods of radius $r = 0.2a$ in air, where a is the lattice constant. There are four embedded cavities, the rods surrounding the cavities adjacent to the central waveguide (CWG) are set at $r = 0.208a$. With dielectric material of dielectric constant 12, the photonic bandgap ranges from the normalized frequency units (a/λ) 0.286 to 0.429, where λ is the wavelength in vacuum. Fig.1(a) shows the schematic of the MUX/DEMUX designed to channel selected frequencies at coupling lengths $L = 10$ and 16. Fig.1(b) and Fig.1(c) illustrate the resulting patterns of the propagating electric fields for two continuous wave signals centred at $\lambda = 1.55\mu$m and $\lambda = 1.417\mu$m, respectively. This design has a crosstalk of $18dB$ difference between the required output and the CWG, and a transmission rate of 95%. This successful novel design of a PhC 3x1 MUX/DEMUX is competitive in terms of performances when compared to other designs suggested in literature [1]. More results will be presented in the conference.



(a) 3×1 PhC MUX-DEMUX Schematic



(b) E-field propagation at $\lambda = 1.55\mu m$



(c) E-field propagation at $\lambda = 1.417\mu m$

References

[1] S. Haxha, et al, *Analysis of wavelength demultiplexer based on photonic crystals*, IEE proceedings. Optoelectronics, vol. 152, no. 4, pp. 193198, (2005).

Closed-form one-way, multi-mode theory for micro-ring cavities with MMIs

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We combine EMET (eigen-mode expansion technique), FD-FD method to form a closed-form transfer function expression for modeling optical micro-ring cavities (MRC) with multi-mode interferometers (MMI) couplers. Improved tolerance of MRC parameters is demonstrated.

Introduction

A single mode one-way, multiple-looping theory is adequate to describe how the MRC device works. Although radiation loss can be incorporated in this theory, the simple model does not account for the apparent higher-order effects of this device. The standard MRC coplanar directional coupler is very sensitive to the gap distance and to the core/cladding index variation. Recently, the used of MMI as an alternative waveguide coupling element in the ring has been proposed for having better processing tolerance. These MRCs are too large to be accurately modeled by FD-TD or FD-FD methods [1,2]. Thus a new approach is needed to model the MRC with MMI coupler.

Results

We propose an improved model over the single-mode theory. The MRC is divided into sections—the MMI, two bending and one straight waveguide sections. Within each section, forward propagating multi-modes wave fields are assumed. These vector modes are related by coupling (**K**) and propagation (**T**) matrices below: The analysis of the MMI section is done by a modified EMET [1]. The bending, radiation and other higher-order effects (**P**) are computed by FD-FD method [2]. The closed-form expression of the MRC transfer function can be obtained using **T,P,K** matrices. The computational costs are much less than FD-TD or FD-FD methods. The accuracy and performance of this model will be examined and verified against the full coupled TMIE method.

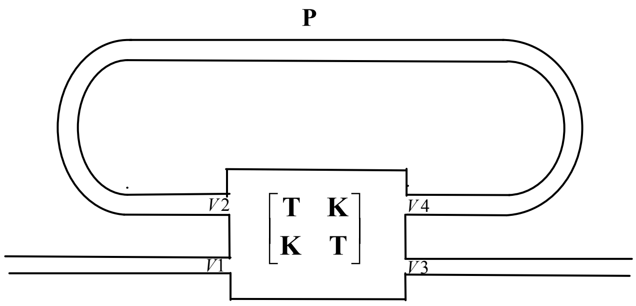

Fig.1 Single-track micro-ring cavity with a MMI

$$\begin{bmatrix} \bar{V}_3 \\ \bar{V}_4 \end{bmatrix} = \begin{bmatrix} \mathbf{T} & \mathbf{K} \\ \mathbf{K} & \mathbf{T} \end{bmatrix} \cdot \begin{bmatrix} \bar{V}_1 \\ \bar{V}_2 \end{bmatrix}, \quad (1)$$

$$\bar{V}_2 = \mathbf{P}\bar{V}_4, \quad (2)$$

$$\bar{V}_3 = [\mathbf{T} + \mathbf{K}(\mathbf{I} - \mathbf{PT})^{-1}\mathbf{PK}]\bar{V}_1. \quad (3)$$

References

[1] Zheng-Wei Lin, "Analysis of 2D optical waveguide structures using frequency-domain finite-difference method," Master Thesis, Institute Elctro-Optical Engineering, National Sun Yat-sen University, Taiwan, (2004).

[2] Hung-Wen Chang and S.-M. Wang, "Large-Scale Hybrid FD-FD Method for Micro-Ring Cavities," FiO-LS 2005, FWE6 (2005).

Finding Optimal Gradient-Index Profile of Multimode Planar Waveguides for Dispersion-Free Short Pulse Propagation

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Semi-analytical optimization technique is used to model an optimal gradient refractive index profile of a planar optical waveguide to provide better conditions for short pulse propagation. It is shown how dispersion along the propagation depends on parameters of the transverse profile.

Summary

Multimode waveguides are efficient in transmitting higher amount of information and are able to accept light from incoherent broad spectral width source, also being generally easier for injecting optical signal into them due to larger core diameter. However, their main disadvantage is high level of dispersion leading to sufficient pulse broadening.

Most popular method of dispersion compensation used to correct this disadvantage is based on using non-linear materials. Alternative way is to construct a waveguide with non-uniform core and/or cladding using linear materials.

It had been noticed since 1976 [1] that graded-index fibers are potential in controlling propagation dispersion. However, to get optimal result one needs a very particular profile of refractive index.

With widened usage of gradient-index materials like plastic or polymer ones, possibilities of optimal waveguide construction also widened significantly. On the other hand, greater choice of materials makes it impossible to arrange those into optimal combination using iterative improvements or experimental search, and theoretical methods of optimum search are needed.

Here we use rigorous semi-analytical approach to optimise profiles of refractive index in gradient-index planar optical waveguides using Shift Formulae Method (SFM) [2-4]. The profile is described by mathematical model with the shape determined by three parameters. The model used to describe the profile [5] is flexible enough to represent smooth profiles as Gaussian one, complementary-error function profile and many others, including those with hollow centre. To find an optimum profile, desired values of propagation constants for different modes are used as an input data.

References

[1] R. Olshansky and D.B. Keck, *Appl. Optics*, **15**, 483-491 (1976)

[2] V.V. Shevchenko, *Sov. J. of Commun. Technology and Electronics*, **31**, No 9, 28 (1986)

[3] N.E. Nikolaev and V.V. Shevchenko, *Proc. XI International Workshop on Optical Waveguide Theory and Numerical Modelling*, April 4-5, Prague, Czech Republic (2003)

[4] N.E. Nikolaev and V.V. Shevchenko, *Optical and Quantum Electronics*, **39**, No 10-11, 891-902 (2007)

[5] N.E. Nikolaev and V.V. Shevchenko, *J. of Commun. Technology and Electronics*, **43**, No 6, 651-654 (1998)

Simple and Fast Method for Approximation of Optical Fiber Chromatic Dispersion

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Simple method for calculation of optical fiber chromatic dispersion approximate estimates is presented. This approach is based on the combination of Gaussian approximation method and spectral Laguerre method. Proposed approach numerical results, FEM numerical results and experimental data are compared.

We propose a simple and fast method for calculation of optical fiber mode chromatic dispersion approximate estimates. Represented approach is adopted for optical fiber with an arbitrary coaxial index profile. Introduced method is based on the combination of Gauss approximation method [1] and spectral Laguerre method [2]. According to improved approach field function is represented as expansion:

$$\psi(r) = \sum_m \left(\frac{r}{r_0}\right)^l \cdot L_{m-1}^l\left(\frac{r^2}{r_0^2}\right) \cdot \exp\left(-\frac{r^2}{r_0^2}\right),$$

where r – coordinate; r_0 – mode field radius.

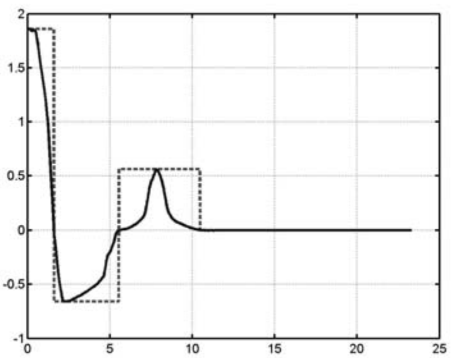

Figure 1. Profile of optical fiber sample.

To estimate an accuracy of proposed method, following sample of optical fiber was considered [3]. Refractive index profile of this sample is shown on Fig. 1. Core and claddings refraction indexes, their derivatives with respect to wavelength are calculated by method based on Sellmeier equation [4]. Also the same fiber sample chromatic dispersion was computed by FEM algorithm [5]. Measured sample data [3], calculation results been obtained by proposed method and FEM are presented on Tabl.1. A good agreement between proposed approach numerical results, FEM numerical results and experimental data is demonstrated.

Table 1.

Parameter	Proposed method	FEM	Sample measured data
Dispersion, ps/(nm·km)	-101	-106	-107
Dispersion slope, ps/(nm^2·km)	-1,02	-1,16	-1,18

References

[1] A. W. Snyder and J. D. Love, *Optical Waveguide Theory*, London, Chapman and Hall (1983).
[2] B.G Mikhailenko *Spectral Laguerre method for the approximate solution of time dependent problems*, Appl. Math. Lett. **12**, 105–110 (1999).
[3] L. Jiang et al., Patent USA 6731848 (2003).
[4] V. Burdin *Method for material dispersion account for optical fiber chromatic dispersion calculation*, Infocom.Tech. **6**(2), 37-41 (2006).
[5] K. Okamoto, *Fundamentals of optical waveguides*, Sun Diego, Academic Press (2000).

Simulation of a Few-Mode Signal Propagation over Long Period Weakly Tapered Multimode Optical Fiber

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Simulation results of an excited by VCSEL few-mode Gaussian pulse propagation over the long period weakly tapered silica multimode fiber with graded refractive index profile are represented.

Summary

We present simulation results of a few-mode Gaussian pulse propagation over long period weakly tapered (LPWT) multimode optical fiber. Silica weakly-guiding irregular multimode fibers with axial-symmetric graded index profile under central defect, local fluctuations and single outer cladding are considered. It is supposed, the core diameter is periodically tapered and decreased from it's nominal value 62,5 to 20 μm. The total period length of each taper zone is 80 m. Solution is based on recently proposed [1] time domain model of piece-wise regular multimode fiber link under few-mode signal propagation, excited by laser source. Model takes into account differential mode delay, higher-order mode chromatic dispersion, mode mixing and power diffusion. To estimate mode transmission parameters, including mode field radius, group velocity, dispersion parameter etc., and mode coupling coefficients at the boundaries of regular spans, we apply extension of modified Gaussian approximation [2, 3] for analysis of multimode fibers with arbitrary axial-symmetric index profile. Gaussian pulse with initial width 40 ps excited by VCSEL (λ=850 nm) under transversal offset 4 μm was considered. Some computation results of pulse dynamics during propagation over described LPTW fiber with length 320 m are represented on Fig 1.

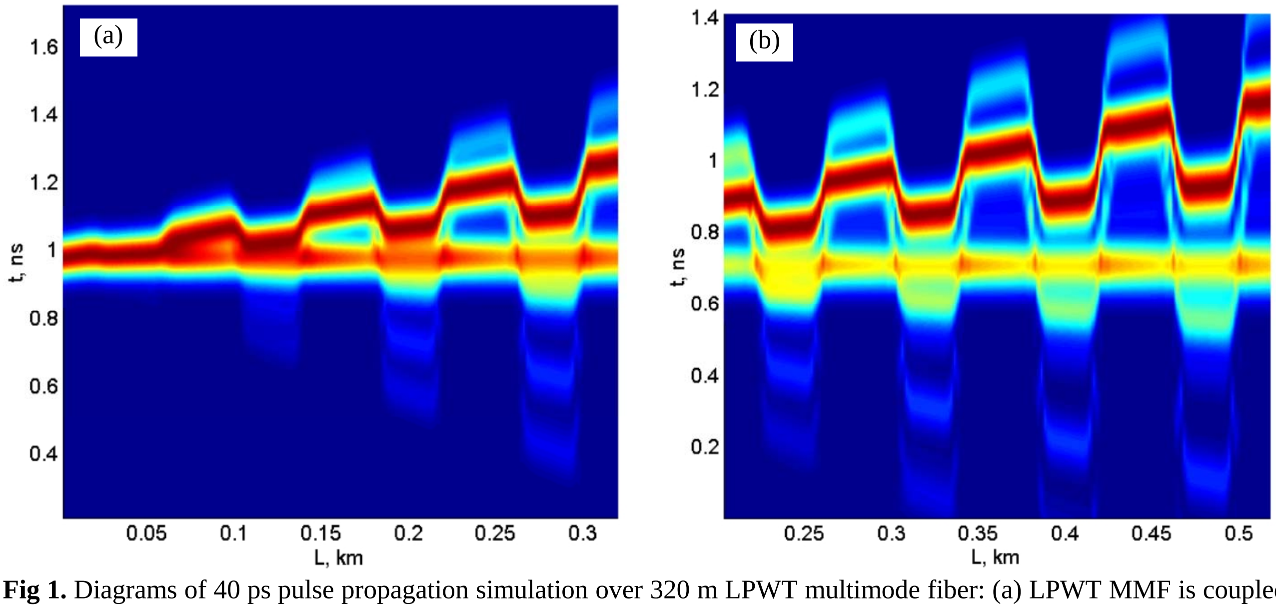

Fig 1. Diagrams of 40 ps pulse propagation simulation over 320 m LPWT multimode fiber: (a) LPWT MMF is coupled direct to VCSEL under offset 4 μm; (b) LPWT MMF is jointed to the output of 200 m conventional graded index multimode fiber 62,5/125, excited under the same launch conditions.

References

[1] A.V. Bourdine, V.A. Burdin., *Proc. of OWTNM 2008*, 35 (2008).
[2] A.V. Bourdine, *Proc. of SPIE*, **6605**, 660509-1 – 660509-13 (2006)
[3] A.V. Bourdine, *Proc. of SPIE*, **7026**, 702606-1 – 702606-14 (2008).

Dispersion and Stability Properties of a Wide-Angle Runge-Kutta Beam Propagation Method

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We propose a Wide-Angle Runge-Kutta Beam Propagation Method based on the Taylor series expansion of the scalar propagation operator. Transversal discretization has been performed using two approaches, Finite Difference and Fourier expansion. Analytical expressions to calculate dispersion and stability are presented.

Introduction

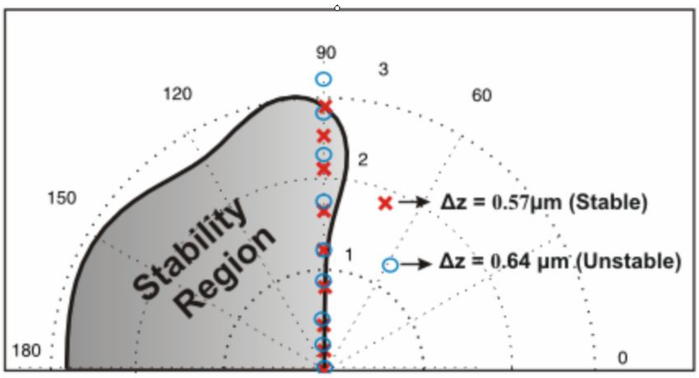
Beam Propagation Methods (BPMs) have shown to be efficient techniques to characterize sinusoidal steady-state behaviour of linear and nonlinear photonics devices. Although BPM techniques are quite mature, research is still being carried out mainly concerning Wide-Angle capabilities, or increasing the computational efficiency with alternative techniques for the discretization of the longitudinal operator [1].

In this field, authors have recently proposed a novel dispersion and stability analysis for the Runge-Kutta Finite Difference Beam Propagation Method (RK-FDBPM) under paraxial approximation [2], [3]. The proposed stability and dispersion criterion helps to adequately set the numerical mesh step sizes, avoiding time-consuming trial and error iterative processes.

In this work, we propose a Wide-Angle RK-BPM based on the n-order Taylor series expansion of the exact scalar Helmholtz propagation operator. It must be noticed that this approach is quite different to the usual one, based on the Padé expansion of the square root operator and the application of the Crank-Nicolson scheme. We have performed the transversal discretization using two alternative techniques, Finite Difference and Fourier series expansion [4]. Closed expressions to analyse dispersion and stability of the new techniques are established. Finally, different linear and nonlinear photonic devices have been studied to asses and compare the proposed methods.

Results

The proposed stability criterion is based on the position of the eigenvalues of the discretized system matrix. The figure below shows, for a singlemode waveguide solved by the Wide-Angle Fourier method (128 harmonics and two different longitudinal step sizes Δz), the eigenvalue locations superimposed over the Runge-Kutta (4,4) stability region.



References

[1] S. Sujecki, *J. Opt. Soc. Am. A*, **25**, (2008)

[2] J. de-Oliva-Rubio, Ph. D. Thesis (in Spanish), ISBN: 84-690-3321-2, Univ. Málaga, (2006).

[3] J. de-Oliva-Rubio, et al., *Opt. Express*, **16**, 8755-8768 (2008).

[4] J. M. López-Doña, et.al., *IEEE Phot. Tech. Lett.*, **17**, (2005).

Frequency Change of Partial Spherical Waves Owing to Time Change of the Medium Permittivity

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Transformation of a plane harmonic wave in a spherical symmetric medium with the time-varying permittivity is investigated via solution of this problem constructed by virtue of time-spatial matrices based on the longitudinal and transverse spherical vector eigen-functions.

Introduction

A wide range of structures including nanospheres and nanoshells as well as plasmonic resonators, optical nanoantennas, super lenses, deep sub-wavelength size resonators can be reduced in some approximation to such a simple structure as a layered spherical region. In the proposed paper the solution to the initial electromagnetic problem for Maxwell's equations in spherical symmetric medium is investigated by virtue of the mathematical tool developed to be convenient for this problem.

Results

To solve a 3-D initial spherical symmetric problem for Maxwell's equation in a medium which permittivity change in time an approach using the well known method [1, 2] is developed. This approach allows to reduce the problem to three independent scalar equations by virtue of the constructed transfer matrix based on the longitudinal and transverse spherical vector eigen-functions $\mathbf{L}_{mn}(\mathbf{x},\mathbf{p})$, $\mathbf{M}_{mn}(\mathbf{x},\mathbf{p})$ or $\mathbf{N}_{mn}(\mathbf{x},\mathbf{p})$. Here, $\mathbf{x}=(t,\mathbf{r})$, $\mathbf{p}=(m,n,p,s)$ where p is a complex variable of the Laplace transform and s is a real variable of the Hankel transform.
A solution to the problem is sought as a sum of three terms corresponding to the appropriate eigen-vectors

$$\mathbf{E}(\mathbf{x}) = \int d\mathbf{p}\left(\mathbf{L}_{mn}B_1(\mathbf{p}) + \mathbf{M}_{mn}B_2(\mathbf{p}) + \mathbf{N}_{mn}B_3(\mathbf{p})\right)e^{pt}s^2 \quad (1)$$

where $\int d\mathbf{p} = \sum_{n=-\infty}^{\infty}\sum_{m=-n}^{n}\int_{\sigma-i\infty}^{\sigma+i\infty}\frac{dp}{2\pi i}\int_0^{\infty} ds$, and $B_i(\mathbf{p})$ is the function satisfying the scalar equations

$$B_i(\mathbf{p}) = B_{0i}(\mathbf{p}) + \int d\mathbf{p}' K(\mathbf{p},\mathbf{p}')B_i(\mathbf{p}'). \quad (2)$$

Analysis of the exact solution shows that the time change of the permittivity transforms the initial plane harmonic wave in a set of the partial spherical harmonics. One set corresponds to evanescent waves and the other to harmonic ones with frequencies determined by a number of the spherical harmonic. This effect can be used for the frequency transformation of the waves with special spatial distribution.

References

[1] P.M.Morse and Feshbach H., Methods of theoretical physics. (McGraw-Hill, New York, 1953).

[2] C. Gerassimos, Kokkorakis and John G. Fikioris, IEEE Trans. on Antennas and Propag., vol. 55, 3178-3190 (2007).

Tuning Confined Electromagnetic Modes in Microdiscs with Liquid Crystals

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We present numerical results of confined electromagnetic modes in microdiscs embedded in a liquid crystal calculated with the finite difference time domain method (FDTD) using an anisotropic dielectric material model.

Abstract

The effect of different phases of the liquid crystals on the confined electromagnetic modes in microdiscs is investigated. Above a critical temperature the liquid crystal undergoes a transition from the isotropic phase to the nematic phase. In the latter case, the liquid crystal posesses an unaxial optical anisotropy and can be oriented by applying an external electric field.

Varying the refractive index of the liquid crystal shifts the resonant wavelength of the electromagnetic modes [1]. We investigate, whether the modes with smaller or larger wavelength are coupling stronger to the liquid crystal.
In the experiment InAs quantum dots are embedded in microdiscs. We reproduce the experimental results with numerical calculations. The model for the nonlinear quantum dots was already used in a FDTD code successfully [2]. Here, we combine this approach with a treatment of an anisotropic dielectric material model and investigate investigate the nonlinear coupling dynamics of the quantum dots and the resonant electromagnetic field, which is confined in the microdisc and tuned to the resonance of the quantum dots via the liquid crystal.

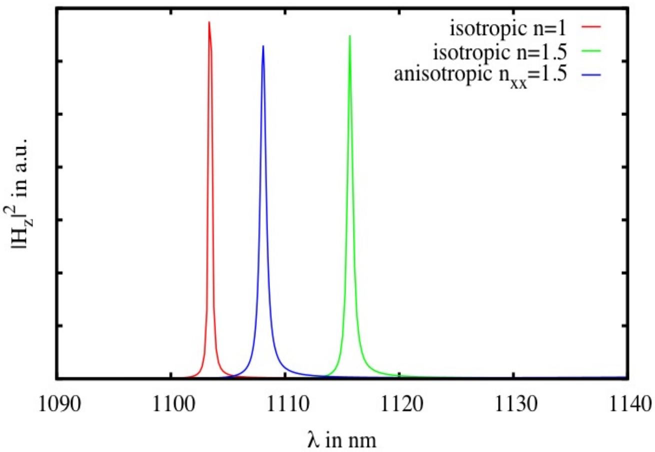

Fig. 1. Resonant modes of the electromagnetic field in a GaAs microdisc for isotropic (red: $n = 1$, green: $n = 1.5$) and anisotropic phase ($n_{xx} = 1.5$) of the liquid crystal.

References

[1] Karoline A. Piegdon, Heinrich Matthias, Cedrik Meier, and Heinz-S. Kitzerow, *Tunable optical properties of photonic crystals and semiconductor microdisks using liquid crystals*, Proc. SPIE 6911 (2008).

[2] C. Dineen, J. Förstner, A.R. Zakharian, J.V. Moloney, S.W. Koch, *Electromagnetic field structure and normal mode coupling in photonic crystal nanocavities*, Optics Express 13, 4980 (2005)

A Tool for Automatic Grating Design

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We present a tool that allows automated design of gratings. The core engine uses a Fourier Eigenvector Expansion Method with coordinate-stretching type PML and Bloch-mode computation. A novel fiber-chip grating coupler design with micrometer dimension is demonstrated as an application example.

Introduction

One of the most challenging problems in integrated optics today is the efficient coupling between fiber and planar waveguides made in high index contrast materials, such as Silicon on Insulator (SOI). Although gratings have been widely used in the past to inject light into nanophotonic devices [1, 2], we have not find references which cover the problem of efficiently coupling to micrometric devices (e.g. based on SOI rib waveguides).

In order to succeed at designing these devices, we need a tool computationally efficient and highly automated. Commercial solutions are discarded as they show serious problems with PMLs and because automation is not allowed. Therefore, we have developed an in-house tool based on the Fourier Eigenvector Expansion Method [3, 4]. It includes coordinate-stretching type PML [5] and Bloch-mode computation [6]. Our design tool has proved to be efficient and accurate. It shows a very good behaviour when PMLs are used and, as it is self developed, allows the required capability of automation.

Results

Using the aforementioned tool, we have designed a coupling grating based on micrometric rib waveguides made in SOI technology. The features of the grating have been summarized in Table I, whereas Fig. 1 shows the electric field distribution as offered by the application. Comparisons with FDTD simulations have been done to check the accuracy of the obtained results.

Table 1. Grating characteristics

		Radiation efficiency	80 %
Reflectivity	1 %	Directivity	89 %
Substrate radiation	10 %	Radiation angle	-13.2º

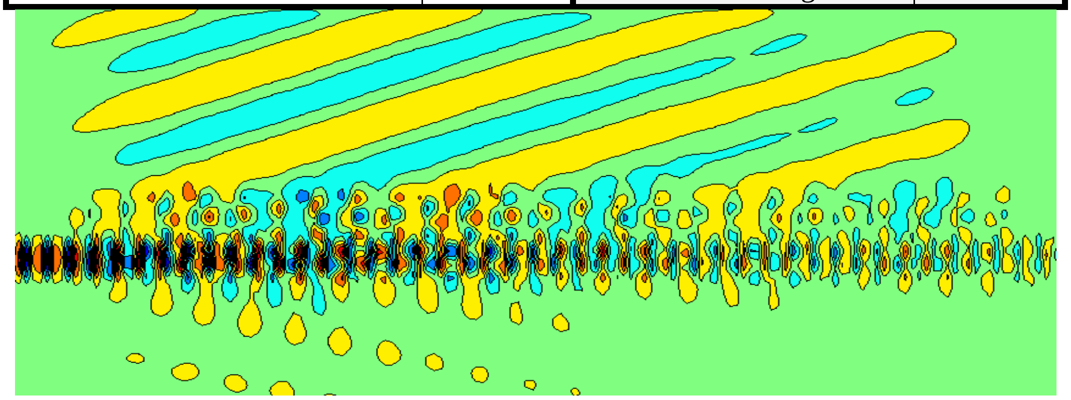

Figure 1. Electric field distribution of the designed micrometric grating.

References

[1] P. Cheben, et. al., *Optics Express* **14**, 4695-4702, (2006).
[2] G. Roelkens, et. al., *Opt. Lett.*, **32**, 1495-1497, (2007).
[3] P. Lalanne et al., *Opt. Lett.*, **25**, 1092-1094, (2000).
[4] A. Ortega-Moñux et al., *Opt. Quant. Electr.*, **37**, 213-228, (2005).
[5] W. C. Chew et al., *Microw. Opt. Tech. Lett.*, **7**, 599-604, (1994).
[6] Q. Cao et al., *J. Opt. Soc. Am. A*, **19**, 335-338, (2001).

Retrieving Effective Parameters of Anisotropic Metamaterials

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We introduce a procedure to retrieve anisotropic effective parameters of metamaterials at oblique incidence. We show that such a homogenization fails near plasmonic resonances for all reasonable aspect ratios and discuss possible implications.

Summary

The assignment of effective material parameters has become an important issue in the field of metamaterial (MMs). It is an extremely valuable concept since it allows to describe light propagation in complex nanostructured media by a few quantities only such as, e.g., the effective permittivity and the effective permeability. Usually such an assignment is only performed at normal incidence, parallel to the main axes of periodically arranged unit cells. Their usefulness is then often doubtful since almost all MM designs proposed so far are anisotropic and suffer from strong spatial dispersion. A lot of discussion came up concerning their physical meaning and interpretation. Following these doubts it is obviously necessary to retrieve effective parameters for all angles of incidence to test particularly for spatially dispersive features.

We will use the inversion of Fresnel coefficients to directly calculate effective parameters for almost arbitrary angles of incidence for the simple case of periodically arranged metallic bricks. Here the effective parameters will be shown to be strongly spatially dispersive, hence angular independent material parameters cannot be resolved uniquely. For different incident planes and polarization states different effective material parameters are obtained as soon as they do explicitly depend on the vectorial wave vector [Fig.1]. The stronger the solutions are deviating the stronger are the effects of spatial dispersion. In particular for MM composed of metallic unit cells an effective description in terms of angular independent material tensors will completely fail in the near of plasmonic resonance, as is commonly the case of interest.

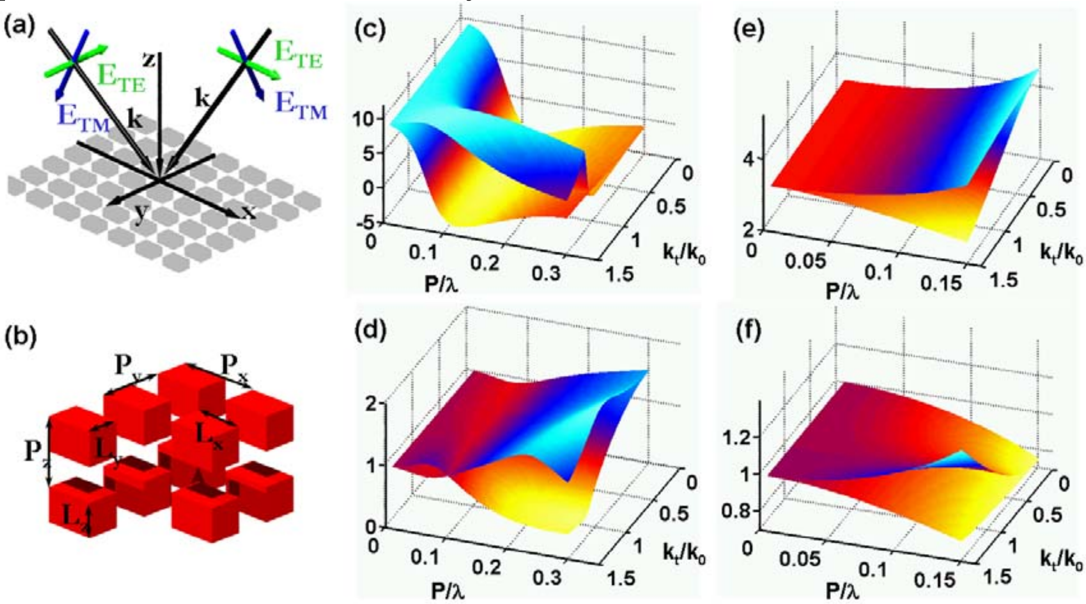

Fig. 1: (a,b) Sketch of the principle geometry and the simulated scattering scenarios together with the geometrical parameters. Real parts for both measurements (i.e. different direction/polarization states) for λ=0.5µm of ε_x (b), μ_y (c) and for λ=1 µm of ε_x (e), μ_y (f). Note that different wavelengths yield different values for P/λ for the same actual particle size.

Femtosecond Microfabrication and Characterization of Curvilinear Waveguides in Borosilicate Glass

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We present the results of microfabrication and characterization of curvilinear waveguides inscribed by high repetition rate femtosecond oscillator in BK7 glass. Low loss (4 dB/cm) curvilinear waveguides (with R=3mm)are demonstrated.

Curvilinear waveguide is an ultimate building blocks for any integrated optics circuit. In this paper we explore a femtosecond microfabrication technology for inscription of buried curvilinear waveguides. High repetition rate regime of the fs laser [1] produces superior results in terms of waveguide quality and inscription speed compared to the best ones previously reported using 1 kHz repetition rate. We report on the operational parameters that are required to fabricate low-loss waveguides from an 11 MHz repetition rate 800 nm Ti:Sa femtosecond laser. The optimization of a range of experimental parameters yields a propagation loss in a straight waveguide of 0.2 dB/cm at the wavelength 633 nm and 0.6 dB/cm at a wavelength of 1550nm. The waveguides appear to have smooth circular symmetric shape. The distribution of the refractive index is found using inverse Abel transform of the experimentally measured phase of the transmitted light. The resulting waveguides are multimode up to 1.2÷1.3 μm. Numerically calculated modes are compared to those experimentally observed.

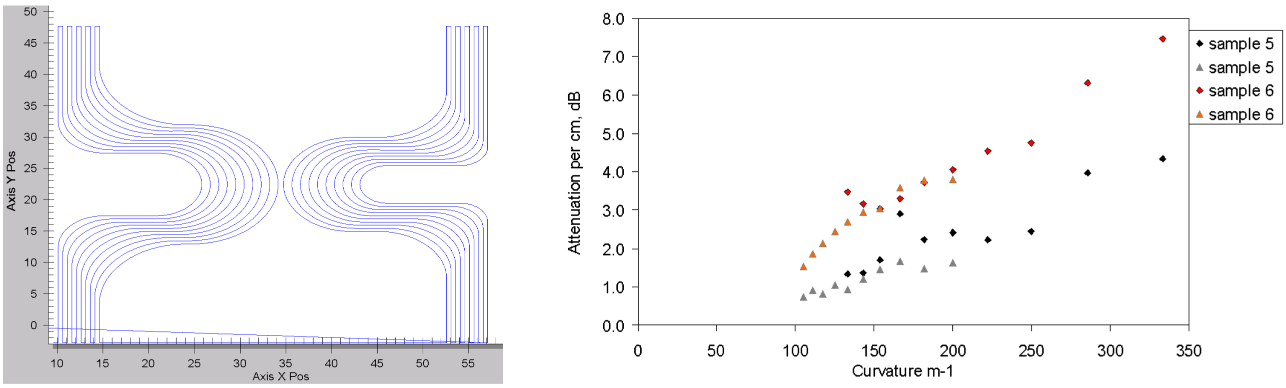

Figure 1. Left: Inscribed tracks. Right: Measurements of waveguide losses for different series.

In this work we use optimum regimes found while manufacturing straight waveguides to inscribe curvilinear tracks. The length of all tracks remains constant after polishing. Coupling losses (1÷ 2 dB) were estimated based on mode-field diameter measurements at 1550 nm.

We present both analytical model and numerical simulation results to support experimental data. A comparison of our results with those produced elsewhere [1] using different femtosecond lasers (laser wavelength, pulse energy, pulse duration, pulse repetition rate, and focusing conditions) suggests that the heat accumulation effect has purely thermal nature.

References

[1] S. M. Eaton, Mi L Ng, J. Bonse, A. Mermillod-Blondin, H. Zhang, A. Rosenfeld, P.R. Herman, *Applied Optics*, **47**, 2089 (2008).

Efficient simulation of plasmonic structures for solar cells

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We present a numerical method for accurate and efficient simulation of near field enhancement through the excitation of localized plasmon polaritons at metal nanostructures in solar cells.

It has been proposed to use metallic nanostructures for efficiency enhancement of energy conversion in solar cells. In a recent publication, Rockstuhl et al. have numerically investigated the dependence of absorption enhancement on geometrical properties of 1D and 2D periodic metallic gratings embedded into solar cells [1]. For simulating Maxwell's equations the authors have used a Fourier model method. Part of their computations were performed on an IBM p690 supercomputer. The authors state that a comprehensive analysis of a larger class of plasmonic devices for efficiency enhancement would require computational resources that seem to be not available at present. This encourages the development of fast and accurate Maxwell solvers.

We present a dedicated finite-element (FEM) solver for nanooptical problems [2]. We apply the solver to simulate light scattering off periodic arrays of silver nanodiscs on a layer of amorphous silicon (*a*-Si) [1]. The convergence behaviour of FEM is investigated for this example. We show that very well converged results can be obtained in short times on a personal computer. Figure 1 shows part of the discretization of the computational domain, a convergence plot and the absorption spectrum. The convergence was investigated for light with a wavelength of 500 nm and perpendicular incidence. The different values were obtained using finite-element ansatz functions of polynomial order $p = 1 \ldots 5$. Results with a relative error as low as 1% are obtained on a PC in roughly 10 s with a memory consumption of RAM$\approx$ 0.6 GB. Speed and accuracy advantages of FEM compared to standard methods allow for design optimizations of metallic nanostructures on solar cells on a larger parameter space.

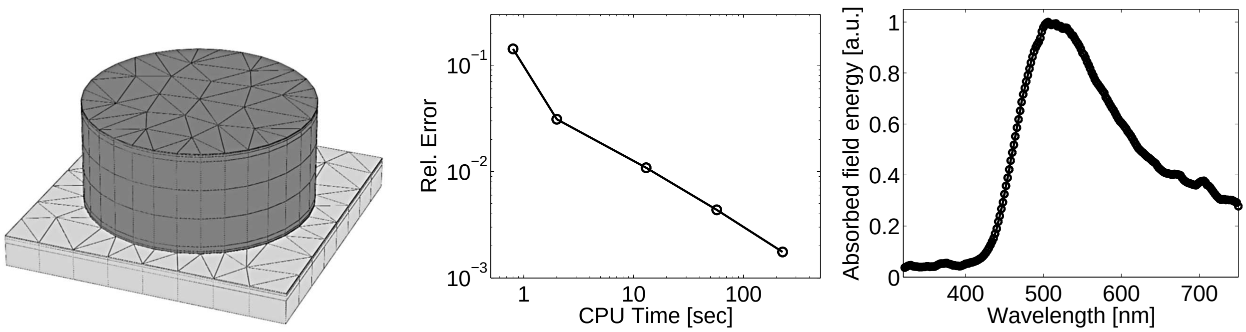

Fig. 1. Left: Discretized geometry of a silver nano-disc (diameter: 140 nm, height: 65 nm). Middle: Relative error of the simulated absorption in *a*-Si vs. total computation time on a standard PC (single-processor usage, up to 4 GB RAM). Right: Plasmon enhanced energy absorption spectrum, weighted with a sum of direct and circumsolar spectrum.

References

[1] C. Rockstuhl, S. Fahr, F. Lederer, *J. Appl. Phys.* **104**, 123102 (2008).
[2] J. Pomplun et al.,*phys. stat. sol. (b)* **244**, 3419 (2007).

Adapted Fourier modal method for the analysis of higher harmonic generation in arbitrary bi-periodic multi-layer structures

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We present an adapted Fourier modal method (FMM) which allows for the analysis of nonlinear wave interactions on arbitrarily distributed, 2D-periodic, multilayer structures. Example calculations are shown for second harmonic (SH) generation on metallic arrays deposited on a lithium niobate substrate.

Summary

With the development of nanofabrication technology in the last decades a novel class of artificial materials for the optical frequency range - as there are i.e. photonic crystals and optical metamaterials - attract an ever-increasing amount of interest. Especially for optical metamaterials the linear optical properties are widely investigated, while the nonlinear once enjoy increasing attention only recently. The method presented in this paper is a rigorous solution formalism for 2D-periodical multi-layer structures. It extends the well-known ordinary FMM to nonlinear interaction processes. The example of second harmonic generation shall state the case in the following. Thus, we assume to have two interacting monochromatic fields ($\sim \exp(-i\omega_n t)$) at frequency ω_1 and $\omega_2 = 2\omega$. Inside the grating structure we assume the linear material properties to be represented by the permeability and permittivity tensors μ_{ij} and ε_{ij}. Additionally, the nonlinear electrical polarizability of the material is represented by the second order susceptibility tensor χ^{ijk}. By considering Maxwell's equations (MEs) for the fields at ω_1 and ω_2 and by applying the undepleted pump approximation MEs will decouple into a set of linear but inhomogeneous partial differential equations. Expanding the electromagnetic field into a Floquet-Bloch-series allows to derive a rigorous solution. As an example we have numerically calculated SH generation on an onedimensional metallic grating structure deposited on a lithium niobate substrate, which is assumed to be the exclusive nonlinear material in the system. The geometrical parameters of the structure are tuned such that a plasmonic resonance at the pump frequency can be observed in the considered frequency range. Due to the strong field concentration of the pump field around the metallic stripes within the plasmonic resonance an enhanced second harmonic signal can be observed, too. Careful investigations show, that the resonance for ω_2 is only observable within the first diffraction order (see Fig.1), whereby the zeroth diffraction order is characterized by a lowered signal strength. Overall, we are able to explain these characteristics by the special near field distribution of the generated SH signal which prevents a coupling to the zeroth diffraction order.

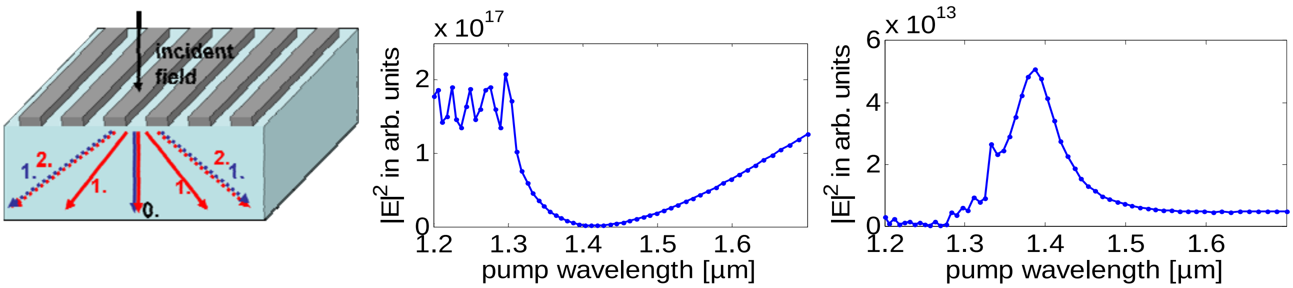

Fig. 1: left: Principle sketch of a metallic grating structure deposited on a lithium niobate substrate. The blue (pump field) and red (second harmonic field) arrows indicate the appearing diffraction orders in transmission. Furthermore, the transmissions of the zeroth order pump field (middle) and the first order of generated SH field (right) are shown.

Advanced Modeling of Subwavelength Photonic Structures with Aperiodic Rigorous Coupled Wave Analysis

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The aperiodic rigorous coupled wave analysis (ARCWA) method with the complex coordinate transformation and adaptive spatial resolution is applied as an efficient modeling tool to calculate the performance of various subwavelength photonics structures, with the concentration given to subwavelength apertures. A comparison with other models and methods, especially with the BEXX method, is also made.

Summary

Photonic and plasmonic structures (photonic crystals, wires, diffractive structures, etc.), especially those with high-index contrast and subwavelength feature sizes, are very attractive in many areas of optics and photonics. Such structures, due to their specific properties and characteristics, have already enabled to develop many functional devices with new functionalities, and the research towards fully functional subwavelength high-contrast photonic structures successfully continues. In this contribution, we will concentrate on several aspects. First, the attention will be given to the Fourier modal methods, i.e. the modal methods based on the Fourier expansions, namely the ARCWA method [1,2] and to its latest developments, in comparison with the bi-directional mode expansion propagation algorithm (BEXX) [3]. Following the original Lalanne's idea [1], the modification has been achieved by introducing a virtual periodicity and incorporating artificial absorbers (perfectly-matched layers and especially the nonlinear coordinate transformation) at the boundaries of the elementary cells of corresponding periodic structures. Our ARCWA implementation (Matlab-based effective numerical tool applicable to the two-dimensional structures) has included all modern techniques and approaches (as e.g. the proper Fourier factorization rules, scattering and enhanced transmittance matrix algorithms) as well a range of other important algorithm expansions, necessary for an accurate effective modeling. Especially the approach, known as adaptive spatial resolution (ASR) algorithm [4,5], as implemented into the ARCWA method, will be discussed. It will be shown how the proper implementation of this approach can effectively overcome the typical disadvantages connected with the application of the Fourier methods to real problems: a large number of diffraction orders (wave harmonics) needed to achieve the desired accuracy, connected with the presence of the Gibbs phenomenon. A study of the numerical performance of the method with the ASR implemented will be presented, as well as a comparison with the BEXX method and approaches, the attention will be given to convergence study, as well as to the effect of boundary condition selection. Finally, several simulation and optimization examples of photonic nanostructures will be discussed, with the attention also directed towards the simulation of light interaction with various classes of subwavelength apertures and /or slit-groove diffraction problems (the effect of transmission enhancement).

References

[1] E. Silberstein et al., *JOSA A*, 18, 2865 (2001).
[2] J. Čtyroký, I. Richter, P. Kwiecien, *Proceedings of SPIE*, 7099, 70991K:1-11, (2008).
[3] P. Kwiecien, I. Richter, Photonics Prague, August 2008, Prague, Czech Republic (2008).
[4] J. Čtyroký, *Journal Ligtwave Technology*, 25, 2321-2330 (2007).
[5] G. Granet, *JOSA A*, 16, 2510-2516 (1999).
[6] T. Vallius, M. Honkanen, *Opt. Exp.*, 10, 24-34 (2002).

MMP modeling of lossy optical waveguides

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The Multiple Multipole Program (MMP) is a semi-analytic boundary discretization method which provides insight into physical phenomena. It is highly valuable for demanding waveguide problems, where both material losses and radiation losses are involved.

Introduction

The analysis of loss-free cylindrical waveguides is a well-studied and well-understood topic in electrodynamics. The time dependence and the dependence of the field along the waveguide may be separated from the field dependence in the transverse plane. One then writes

$$Field(u,v,z,t) = \mathrm{Re}\left(F(u,v)\cdot e^{i(\gamma z-\omega t)}\right), \quad \gamma = \beta + i\alpha \,, \tag{1}$$

where the propagation constant γ becomes real, i.e., $\alpha = 0$ as long as no losses are present. This separation leads to the widely known two-dimensional Helmholtz equation

$$\left(\Delta + \kappa^2\right)F(u,v) = 0, \quad \kappa^2 = k^2 - \gamma^2 = \omega^2\mu\varepsilon \,. \tag{2}$$

This equation establishes an eigenvalue problem, formulated in the transverse plane (coordinates u, v) of the waveguide. There are various methods to solve this problem. First, one may either consider the frequency ω as fixed and search for the corresponding propagation constant $\gamma(\omega)$ or one can choose γ and search for $\omega(\gamma)$. Second, one may apply either domain discretization or boundary discretization methods. The latter only discretize the one-dimensional boundaries in the (u,v) plane, which typically leads to rather small but dense homogeneous matrix equations of the form

$$\mathrm{M}(\omega,\gamma)\ \mathrm{A}(\omega,\gamma) = 0, \tag{3}$$

where M is a known matrix and A the eigenvector.

Such matrix equations are also present in simple cases, where analytic solutions are available. The eigenvalues are then determined using the condition $\det(\mathrm{M}(\omega,\gamma))=0$ for obtaining non-trivial solutions with $\mathrm{A} \neq 0$. Finding zeros of this determinant may however cause severe problems, depending on the properties and size of M.

The Multiple Multipole Program (MMP) [1] closely follows the analytic procedure until a matrix equation of form (3) is found. It models the field in each domain of a waveguide as a superposition of analytic solutions of the Helmholtz equation (2), with a certain preference of multipole expansions. In order to avoid numerical problems, an overdetermined system of equations is derived, where M becomes rectangular. As a consequence, the matrix equation (3) only has trivial solutions. In order to reestablish a condition for computing the eigenvalues, a residual vector $\mathrm{E}(\omega,\gamma)$ is introduced on the right hand side of (3), and the matrix equation is then solved in such a way that the square norm of E is minimized under the additional condition that the "amplitude" of each mode is equal to 1. In fact, there are various methods for defining the amplitude. The best one is the total power flux in z direction, but in simple cases, one may also simply set one of the elements of the vector A equal to 1. This high flexibility is cumbersome for simple, user-friendly codes, but it allows one to obtain more information and experience. In general, one obtains a non-linear search function $f(\omega,\gamma)$. The minima or maxima of this function then determine the eigenvalues $\gamma(\omega)$ or $\omega(\gamma)$. In order to increase the efficiency, several eigenvalue tracing techniques were developed, which are similar to path-following techniques known from finite elements.

Material losses and material dispersion

When losses are present in any of the materials constituting the waveguide, ε or μ is complex. In this case, it is no longer possible to find real eigenvalues. The two search procedures $\gamma(\omega)$ or $\omega(\gamma)$ then lead to different solutions because either γ or ω becomes complex while the other variable is kept real. In physics, ω is usually considered as the eigenvalue, which then becomes complex. In engineering, one considers the measurement setup, where the source that excites the waves is clearly described by a real ω. Then one prefers letting γ be complex. The situation becomes more complicated because lossy materials are usually dispersive, i.e., their properties are frequency dependent. Then $\varepsilon(\omega)$ and $\mu(\omega)$ are known from measurements with real ω. Thus, searching for a complex $\gamma(\omega)$ with real ω is natural.

As a consequence, the search function f, mentioned above, is defined in the complex γ plane for a given frequency ω, which is determined by the source at the input of the waveguide. Although the search for minima or maxima of f in the complex plane is rather demanding, the procedure itself remains the same as with loss-free materials.

Radiation losses and periodic waveguides

Guided modes in waveguides are usually considered as radiation-free. In the case of open waveguides, where the field extends to infinity in the (u,v) plane, this is usually guaranteed by imposing the Sommerfeld radiation condition. By imposing this condition, it is no longer possible to find any radiating mode, which does not mean that radiating modes do not exist.

A typical example of radiating modes is obtained when modes along photonic crystal (PhC) waveguides [2] are considered. Usually, such waveguides are analyzed by means of the super-cell method [2], which in fact ignores radiation. Realistic PhC waveguides always exhibit radiation loss because their walls consist of finite PhCs, which always have some transmittance. The analysis of PhC waveguides is rather demanding because they have periodic symmetry in z direction rather than cylindrical symmetry. As a consequence, equation (1) must be replaced and finally, the field must be computed in a three-dimensional cell of width d equal to the period in z direction. Beside this, the eigenvalue search procedure remains the same.

Cylindrical waveguides actually support radiating modes as well. Typically, guided waves become radiating below their cutoff frequency. Thus, it is desirable to compute radiating modes as well. As a consequence of radiation loss, the propagation constant becomes complex even when no material losses are present. Furthermore, the Sommerfeld radiation condition may no longer be imposed. Essentially, the field of a non-radiating mode decays exponentially with the distance from the waveguide, whereas for radiating modes, it increases exponentially with the distance. Thus, the ansatz for modeling the field in domains extending to infinity must be modified. For semi-analytic methods, such as MMP, this is relatively easy. It can be done for simple slab waveguides, for cylindrical waveguides, and for periodic waveguide structures. Results obtained from the latest MMP implementation contained in the MaX-1 software package [3] illustrate this.

References

[1] Ch. Hafner, *Post-modern Electromagnetics*, John Wiley & Sons, Chichester (1999).

[2] J. Smajic, et al., *PIERS, Pisa, March 28-31*, (2004), available on http://alphard.ethz.ch/Smajic/PDFdocs/36_04.pdf.

[3] Ch. Hafner, MaX-1, *A Visual electromagnetics platform,* John Wiley and Sons, Chichester (1998).

The self–imaging effect in metallic waveguides

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In this presentation we examine the wave propagation in metallic waveguides. Particularly, we are interested in the self–imaging effect in such devices.

Introduction

Metallic waveguide structures may play an important rule in photonics in the future. In this presentation we examined the wave propapagation in these devices in order to study the self–imaging effect. Self–imaging means that an input field distribution repeats itself in a certain distance. In dielectric waveguides it could be used to design couplers (see e.g. [1]).

Results

Since the self–imaging effect can be best understood with the knowledge of the eigenmodes one important point of the presentation is a comparison of the eigenmodes in metallic structures and dielectric waveguides to see the differences and common behavior. The magnetic field distribution of the fundamental mode of these devices is shown in Fig. 1. It can be observed that the maximum of the fields appears at the interface between metall and the surrounding dielectric on the left. As well known, in the dielectric waveguide (right) the field is concentrated inside the higher refractive index media. However, if we examine the fields in planes where they are maximum we obtain very similar curves. If we take look at the wave propagation in metallic waveguides we see a decrease of the fields due to losses. Therefore, we also investigate how configurations with sufficiently low losses can be designed (see also [2]).

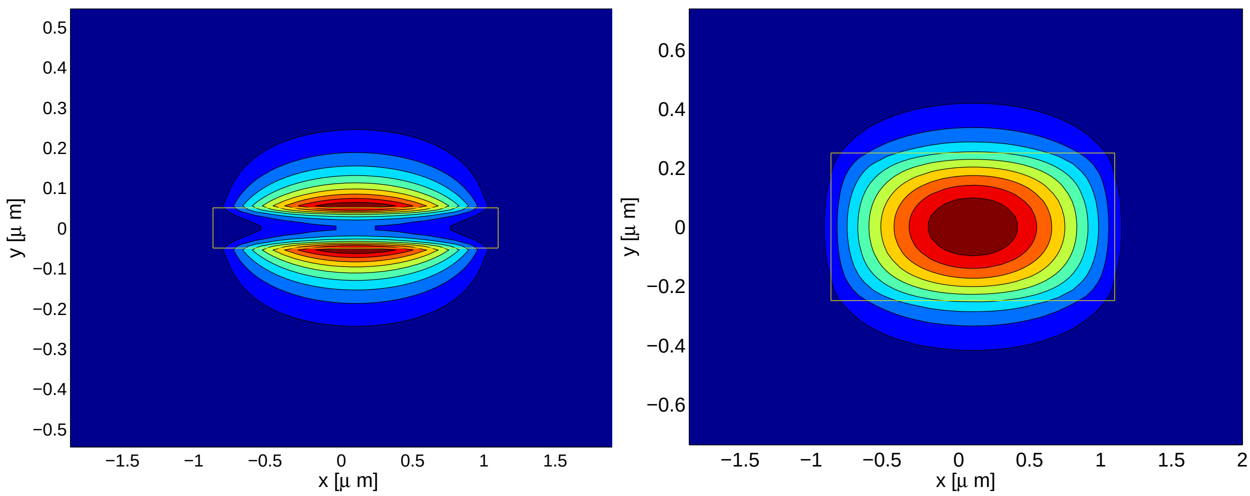

Fig. 1. Magnetic field distribution of the fundamental even–mode in a metallic–structure (left), and a dielectric–waveguide (right)

References

[1] L. B. Soldano and E. C. M. Pennings, *J. Lightwave Technol.*, vol. 13, pp. 615–627, 1995.
[2] P. Berini, *Phys. Rev. E*, vol. 61, pp. 10484–10503, 2000.

Contra-directional Coupling Using Plasmons: the Plasmonic Light Wheel

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Backward plasmonic modes of a metal-film are studied in order to obtain contra-directional coupling with a dielectric waveguide. A light wheel can be finally excited.

Introduction

Using the nonconventional behaviour of Left-Handed Materials (LHM), contra-directionnal coupling between a guided mode supported by a dielectric slab and a backward mode supported by a LH slab has been studied [1]. An exotic mode, called light wheel, is excited for which the light rotates in the lamellar structure. Backward modes also exists in metal films [2, 3] and contra-directional coupling based on these modes seems possible [4]. We present here the study of a light wheel using the backward plasmonic mode of a thin metal film instead of a LH slab: the plasmonic light wheel.

Results

The backward modes of a thin metal film are of two type: (i) coupled surface plasmons when an interface alone actually supports plasmons and (ii) thin film modes when the permittivities of the metal and the surrounding medium do not allow such a mode.
We have then studied the contra-directional coupling between a thin metallic film and a dielectric waveguide by a complex plane analysis, using the dispersion relation of the whole structure. The plasmonic light wheel can be excited using evanescent coupling (fig.1).

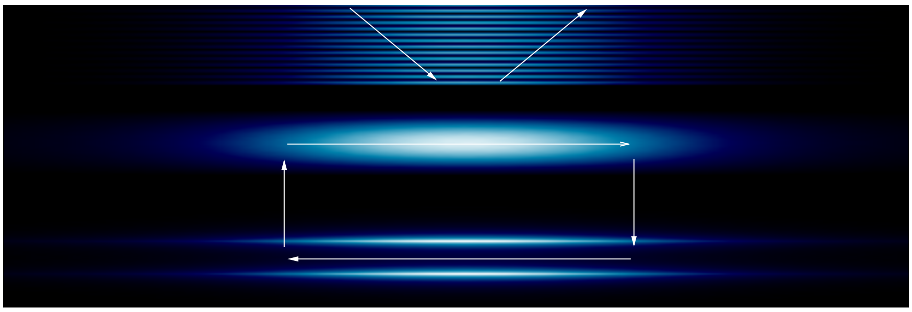

Fig. 1. The plasmonic light wheel: the light is heading to the right in the dielectric slab and to the left in the metal-film

After having exposed these purely theorical considerations, we will adopt a more realistic approach, in terms of permittivities values, giving some suggestions for future experimentation.

References

[1] P.H. Tichit, A. Moreau and G. Granet, *Opt. Express* **15**, 14961-14966 (2007).
[2] P. Tournois and V. Laude, *Optics Communications*, **137**, 41-45 (1997).
[3] A. Alù and N. Engheta, *J. Opt. Soc. Am. B* **23**, 571-583 (2006).
[4] Y. Wang, R. Islam and G.V. Eleftheriades, *Opt. Express* **14**, 7279-7290 (2006).

Zero-Group-Velocity Modes of Insulator-Metal-Insulator and Insulator-Insulator-Metal waveguides

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Explicit analytical formulas for the conditions of existence of waves with zero group velocity are obtained in insulator-metal-insulator (IMI) and insulator-insulator-metal (IIM) waveguides in the case of low losses. Also we establish the conditions taking into account the influence of losses using the numerical technique.

Introduction

It's well known that dispersion relation of Surface Plasmon Polariton (SPP) guided by thin metal film splits into two branches for both “unsupported” films (the two bounding insulator media are identical) and “supported” films (the two insulator media have different permittivities) [1, 2]. The group velocity of the high-frequency (antisymmetric) mode can be positive, zero and negative depending on the wave vector. As for IIM waveguide structures, a thin insulator layer deposited on metal slab changes the dispersion relation of SPP and also may lead to the arising of zero and negative group velocities [3].

Results

We consider IMI and IIM structures under the assumption that metal is described by Drude-Zener model ($\varepsilon(\omega)=\varepsilon_r-\omega^2/(i\Gamma\omega+\omega^2)$, where ε_r is the high frequency dielectric constant due to interband transitions of electrons and Γ is the damping term resulting from electron-phonon and electron-electron collisions) and permittivities of insulator media weakly depend on frequency. Firstly, we have obtained clear analytical solution for existence conditions of waves with zero group velocity in the case of low losses in the system and, secondly, have used numerical technique and have taken into account the influence of losses upon the dispersion relation of SPP. A comprehensive analysis of zero-group-velocity modes of IMI and IIM waveguides is given by means of consideration structures consisted of silver with combinations of different dielectric materials (Al_2O_3, ZrO_2 and SiO_2). The efficiency and possibilities of excitation of such modes is considered and the further application to design of high Q-factor plasmonic micro- and nanocavities [4] is discussed.

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References

[1] E.N. Economou, *Phys. Rev.,* **182**, 539-554 (1969).

[2] V.M. Agranovich and D.L. Mills, *Surface Polaritons* (North-Holland Publishing Company, Amsterdam, NewYork, Oxford, 1982).

[3] Shou Xian She, *J. Opt. Soc. Am. A*, **7**, 1582-1590 (1990)

[4] M. Ibanescu, et al., *Opt. Lett.,* **30**, 552-554 (2005).

Dispersion of Plasmonic Modes in Nanolayer Composites

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Dispersion of surface and bulk eigenmodes of a stack of metal-dielectric nanolayers has been studied in details. It is shown that inside the light cone, an entire family of TE and TM polarized Tamm plasmon-polaritons appears, while the TM modes survive outside the cone as bulk or surface plasmon-polaritons.

Introduction

Conventional surface plasmon-polaritons (SPPs) have TM polarization and dispersion that lies outside the light cone, i.e. their in-plane wavevector exceeds that of light in vacuum. Consequently, SPP cannot be directly excited by light that is simply incident on metal-dielectric surface. However, a simple, planar multilayer structure has been recently used for the experimental creation of surface waves at the boundary between a metal and a dielectric Bragg mirror that can have a small or even zero, in-plane wave vector [1]. Therefore, such low-index modes that have been called Tamm plasmon-polaritons (TPPs) can be produced by direct optical excitation. Moreover, those modes can be formed in both TE and TM polarizations. Their in-plane dispersion is parabolic and the splitting between TE and TM polarized modes increases quadratically with the in-plane wavevector.
On the other hand, highly confined, TM polarized optical modes in nanoscale planar metal-dielectric multilayer have been analyzed both theoretically and experimentally in Ref. [2]. It has been shown that, in addition to the conventional symmetric and anti-symmetric SPPs supported by thin films, there exist high-index guided modes that are strongly confined within the bulk of the multilayer. Those modes have been called bulk plasmon-polaritons (BPPs). However, the dispersion relation has been derived (but not analyzed) for the highest-order and the lowest-order modes in approximation of an infinite number of layers, only.
Here, both high-index and low-index plasmonic modes in a stack of finite number of nanolayers have been studied theoretically and numerically. Direct connection among BPPs, TPPs and SPPs has been established.

Results

The modes supported by a nanoscale planar multilayer structure designed to consist of alternating N (N>1) dielectric layers and N+1 metalic layers sandwitched by dielectric cladings have been analysed. It is demonstrated that outside the light cone there exist 2(N-1) BPPs and 1 or 2 SPPs depending on the tickness of metalic layers. All the modes are TM polarized and divided into two groups, the upper and the lower one in the (ω, κ) plane, of N or N-1 modes. Inside the light cone, however, N modes can be identified as TM polarized TPPs . Exactly the same number of TE polarized TPPs appear. For zero wave vector both TM and TE modes coincide at N points, as expected. As the wave vector κ increases, splitting between TE and TM modes quadratically increases, for small κ , in full agreement with the basic properties of TPPs. However, dispersion of the TE polarized modes remains within the light cone, while dispersion curves of the TM polarized TPPs smoothly pass through the light cone and continue as the upper (N-1) BPPs and 1 SPP outside.

References

[1] M. E. Sasin, et al., *Appl. Phys. Lett.*, **92,** 251112, (2008)

[2] I. Avrutsky, et al., *Phys. Rev. B*, **75**, 241402 (R), (2007)

Nanoplasmonic waveguides

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Plasmonic waveguides and cavities are forming an entrance avenue of photons into the nano-world, due to the unique characteristics of plasmon polaritons – e.g. their slow wave characteristics.

We intend to present the issue of plasmonic guiding and storing (cavities) covering the range of full wave regime to quasistatic fields. We analyze the detailed mechanisms of wave and light slowing in plasmonics, light stopping and the branching, leading to a negative index branch. In addition the interesting plasmonic regime of near zero index is discussed.

When going to nano-dimensions – we show unique plasmonic guiding configurations – differentiating it from dielectric waveguides. We look at detailed analysis of plasmonic guiding on wedge structures – and the guiding on compound structures as an hybridization (coupling) of edge and wedge guiding. We study in details the slot plasmonic configuration and discuss the efficiency of transfer of power from photons to nano plasmons.

We examine approximated methods of analysis – e.g. the effective index method, and their validity for plasmonic modeling, showing the emergence of novel type of modes. The seamless transfer of plasmons polaitons (propagating plasmons) to quasistatic particle plasmons is discussed with some surprising result on high Purcell factor nano-cavities.

Finally – if time allows, we intend to discuss nonlinear waves in the plasmonic arena, such as plasmon-soliton and ponderomotive plasmonic waves.

Impedance matching and power transmission in a complete optical circuit

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We report a prototype optical circuit consisting of a plasmonic two-wire transmission line and two optical antennas. We study the impedance matching and power transmission using classical transmission line theory. We also use an open stub as a passive element to modify the impedance matching and the emission spectrum.

Introduction

Miniaturization and packaging density of integrated optics based on dielectrics is limited by the wavelength scale modal profiles of guided modes [1]. Surface plasmon enables sub-wavelength manipulation and distribution of optical fields and advances applications ranging from optical sensing, quantum information processing to novel nanophotonic devices [2, 3]. It has been shown that resonant optical antennas can efficiently couple far-field photons into sub-wavelength spatial domains [4]. Here, we propose an experimentally realizable prototype optical circuit consisting of a plasmonic two-wire transmission line and two optical antennas. We show by finite difference time domain (FDTD) simulation that using optical near-fields, antenna input impedance and the power transmission are nicely described by classical theory [5].

Results

The proposed circuit is made of gold and situated in air on top of a glass half space. The cross section of the transmission line wire is 30 × 30 nm^2 and the separation between wires is 10 nm as well as the feed gap of the antenna. We illuminate the receiving antenna with a tightly focused Gaussian beam (λ=830 nm) and simulate the near-field enhancement. Emitting antennas (loads) of various dimensions are attaching to the other end of the transmission line. We evaluate the voltage reflection coefficient (Γ_v) at the feed point of the load by analyzing the experimentally accessible near-field standing wave patterns. The load impedance is then described in terms of Γ_v and the characteristic impedance of the transmission line (Z_0). Using the concept of power wave [6], we obtain the power reflection at the load and the overall power transmission efficiency of the circuit. We also connect a passive open stub to modify the impedance matching and the emission spectrum of the load. Results obtained from FDTD simulations and classical transmission line model show nice agreement. Our work clearly shows that systems of interconnected nanooptics elements can be optimized by applying concepts of impedance matching which may also be applied to understand and control the coupling between single quantum emitters and metallic nanostructures.

References

[1] A. Yariv, *Optical Electronics in Modern Communications*, 1997, Oxford University Press, Oxford, UK, ISBN-10: 0195106261
[2] W. L. Barnes, et al., *Nature*, **424**, 824-830, (2003)
[3] E. Ozbay, *Science*, **311**, 189-193, (2006)
[4] P. Mühlschlegel, et al., *Science*, **308**, 1607-1609, (2005)
[5] D. K. Cheng, *Field and Wave Electromagnetics*, 1983, Addison Wesley, New York, USA, ISBN-10: 0201128195
[6] K. Kurokawa, *IEEE Trans. Microw. Theory Tech.* **13**, 194-202, (1965)

Finite-element simulations of light propagation through subwavelength apertures in metal films

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We use the finite-element method for simulating light transmission through a 2D-periodic array of rectangular apertures in a film of highly conductive material. We discuss numerical convergence for various geometries, including corner and edge roundings. This allows to reach accurately converged results on standard PCs and workstations.

Experimental investigations of light transmission through subwavelength apertures in metallic films have found unexpected phenomena like enhanced transmission [1]. For a fully quantitative understanding and for a functional design of these structures, accurate numerical simulations of Maxwell's equations with full 3D geometry are desired [2]. We develop adaptive, higher-order finite-element methods (FEM) in the frequency domain for Maxwell-type scattering, eigenvalue and resonance problems [3]. Granet and Li have carefully investigated enhanced light transmission through a 2D periodic array of holes in a silver film with a dedicated adaptive Fourier-modal method [2]. We have revisited this simulation problem using FEM [4]. Figure 1 (left) shows the dependence of the obtained relative error in transmissivity on the number of unknowns, N, of the discretized Maxwell's equations for the different polynomial degrees of the finite-element ansatz-functions, p. As can be seen from the figure, we obtain accuracies which are about one order of magnitude higher than the highest obtained accuracies reported by Granet and Li [2]. Figure 1 (right) displays the dependence of computation time (on a standard workstation) on N for the data set with $p = 2$. We will further discuss the critical influence of geometry parameters, like corner roundings, on enhanced transmission.

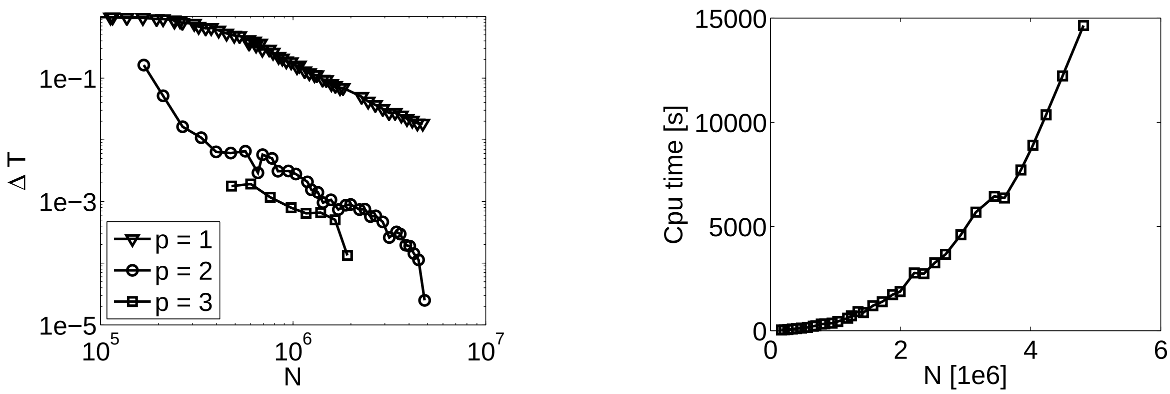

Fig. 1. Convergence study for simulated transmissivity; computational effort/CPU-time.

References

[1] T. W. Ebbesen et al., *Nature* **391**, 667 (1998).
[2] G. Granet and L. Li, *J. Opt. A: Pure Appl. Opt.* **8**, 546 (2006).
[3] J. Pomplun et al., *phys. stat. sol. (b)* **244**, 3419 (2007).
[4] D. Lockau et al., *arXiv:*0902.2862 (2009).

Periodic arrays of metallic nanoparticles as efficient intermediate reflectors in aSi:H-µcSi solar cells

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The use of appropriately designed metallic nanoparticles embedded in a dielectric matrix as an intermediate reflector in aSi:H-µcSi solar cells with the aim to significantly enhance absorption is studied numerically.

Summary

Current aSi:H-µcSi tandem cells suffer from the low diffusion length of electron-hole pairs in the aSi:H top cell, which limits their possible thickness. It causes a significant degradation of the efficiency to absorb light at wavelengths approximately above 600 nm. If this absorption could be significantly increased, the overall current as well as the cell efficiency would increase too. Intermediate reflecting layers (IRL) can enhance the back reflected light and therefore the current in the top-cell. Recent research on IRLs concerned, e. g., dielectric (ZnO, SiO_x) layers. By modifying their thickness a reflection peak can be tuned towards the spectral domain of interest.

In this contribution we study the use of appropriately tailored metallic nanoparticles embedded in a dielectric matrix as IRLs [see fig. 1a)]. The investigation is done by relying on rigorous diffraction theory. By carefully choosing the geometrical parameters of the nanoparticles their plasmonic resonance can be used to red-shift the absorption edge of the aSi:H top cell. Ideally, light with wavelengths below the resonance wavelength is already absorbed within the aSi:H top layer. Wavelengths around the plasmonic resonance will be reflected efficiently, thus nearly doubling the path length inside the top cell and thus its absorption. Light with longer wavelengths will be scattered efficiently into the forward propagating direction, e.g. into the bottom cell, with only minor losses. Thus, metallic nanoparticles promise to serve as spectrally selective IRLs with extraordinary quality [see fig. 1b)].

Results for periodic arrangements of infinite nanowires and bi-periodic nanodiscs will be presented. The number of absorbed photons could be increased by a factor of 1.11 assuming normal incidence of unpolarized light, when compared to cells with optimized purely dielectric intermediate reflector layers.

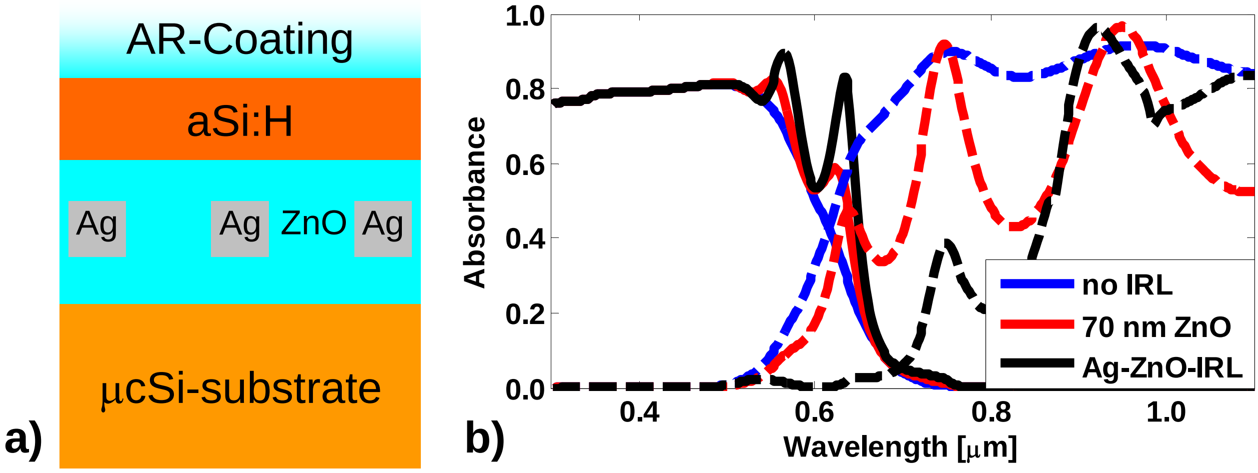

Fig. 1: a) Principle sketch of the considered solar cells. b) Absorbance of the top (solid lines) and the bottom cells (dashed lines) for different IRLs.

The Physics of Slow and Stored Light in Nanophotonic Metamaterials

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In this contribution we will discuss the physics of the recently discovered 'trapped rainbow' principle allowing to realize slow and stored broadband light in nanophotonic metamaterials by exploiting negative Goos-Hänchen phase-shifts.

Introduction

A far-reaching development in modern nanophotonics and nanoengineering has been the conception and practical implementation of materials exhibiting simultaneously negative electric permittivity and magnetic permeability, known also as left-handed metamaterials (LH-MMs). Their conceivable strong economic and social impact, owing to their potential applicability in diverse realms of science, such as telecommunications, radars and defence, nanolithography with light, microelectronics, medical imaging, and so on, has lately prompted an overwhelming excitement within the scientific community [1]-[3]. In parallel to the impressive advances in metamaterials, the aim of producing "slow" or completely "stopped" light, i.e. electromagnetic waves in the optical and telecommunication regimes with extremely small group velocities compared to the speed of light in vacuum ($v_g << c$), has attracted enormous interest [4]. The ability to controllably decelerate, stop, store and regenerate / release optical pulses in a low-loss regime, will conceivably have important potential applications, ranging from quantum memories for photons and storage of light, to the realisation of optical buffers for photonic communication networks.

Until now, a variety of methods have been proposed as a means of producing "slow" or "stopped" light, including electromagnetically induced transparency (EIT) [5], quantum-dot semiconductor optical amplifiers (QD-SOAs) [6], photonic crystals (PCs) [7], coherent population oscillations (CPOs) [8], stimulated Brillouin scattering (SBS) [9] and surface plasmon polaritons (SPPs) in metallodielectric waveguides [10, 11]. However, so far, most of these methods bear inherent limitations that may hinder their practical deployment. For instance, EIT uses ultracold atomic gases (e.g. a cloud of sodium atoms at a temperature of 0.9 μK) and not solid state materials, QD-SOAs usually allow for only modest delays but for potentially ultra-broadband light pulses, CPOs and SBS are very narrowband (typically, several MHz) owing to the narrow transparency window of the former and the narrow Brillouin gain bandwidth of the latter, SPPs are very sensitive to surface roughness and are relatively difficult to excite, while PCs may be highly multimodal; this, combined with the strong impedance mismatch in the "slow-light regime" makes launching the incoming light energy to a single, slow mode alone overly difficult.

In this contribution, we will discuss the physics of the 'trapped rainbow' principle that was recently introduced [12]. We will show that the trapped-rainbow method allows realizing slow and stored broadband light in nanophotonic metamaterials by exploiting negative Goos-Hänchen phase-shifts. Since it does not rely on group index resonances it is inherently broadband and allows for large delay-bandwidth products (since a wave packet can be completely stopped and buffered indefinitely) and high, almost 100%, in/out-coupling efficiencies. By nature, the presented scheme invokes solid-state materials and, as such, is not subject to low-temperature or atomic coherence limitations. A wave analysis, which demonstrates the halting of a monochromatic field component travelling along the heterostructure, will be followed by a pertinent ray analysis, which unmistakably illustrates the trapping of the associated light-ray and the formation of a double light-

ray cone ('optical clepsydra') at the point where the ray is trapped. Importantly, we shall explain that this method for stopping light is resilient in the presence of material losses, i.e. even in the presence of high material losses there are still guided electromagnetic modes, characterised by a *real* propagation constant and *complex* frequency, which can assume a zero group velocity and be excited in a time-domain experiment. We shall also review recent progress in the realm of slow/stopped light in metamaterial waveguides and will present a variety of structures that have recently been proposed towards achieving complete stopping of light in such structures.

The 'trapped-rainbow' principle in metamaterial heterostructures

In order to establish the working principle of the metamaterial-waveguide enabled method for stopping light, let us consider a translationally slowly-varying nonuniform waveguide that has a core of negative refractive index (NRI) material ($n < 0$), bounded asymmetrically by two positive-index media. The waveguide is adiabatic to prevent back reflections and scattering, so that we may assume the *total*, i.e. forward plus (the absolute value of the) backward power of a local mode to be conserved. In the presentation we shall explain that the principal conclusions of the analysis do not depend on the dimensionality of the problem nor on Imn, so long as we consider a supported guided mode having *real* propagation constant and *complex* frequency [13, 14]. Clearly, the assumption of slow variation is very accurate provided that the length of each tapered waveguide segment is large compared with the biggest length scale for the fields, i.e. the largest distance over which the total field may change significantly owing to phase differences between the various local modes.

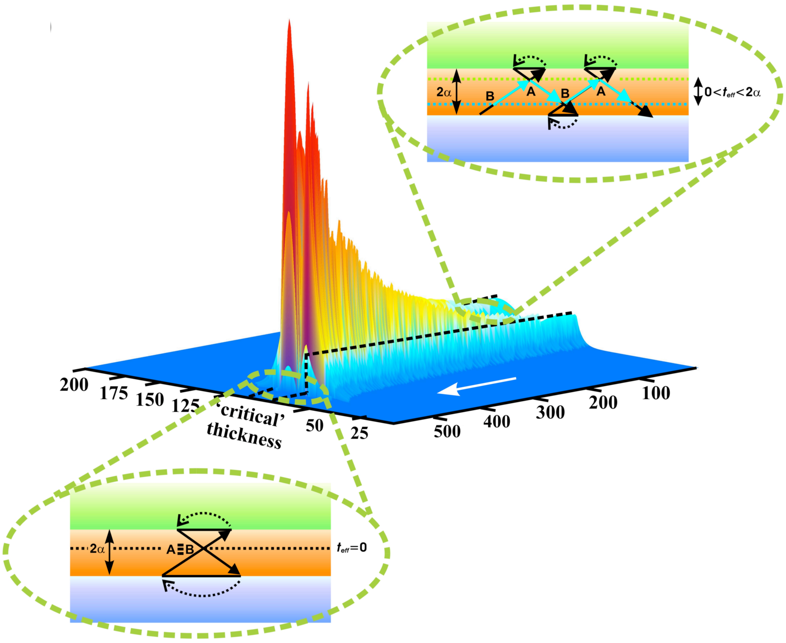

Figure 1. Association of wave propagation inside the adiabatically tapered negative refractive index waveguide with the corresponding zigzag ray analysis for different guide widths.

The optical parameters of the NRI heterostructure are chosen such that all surface plasmon polariton (SPP) modes are totally suppressed, i.e. $\sigma_\varepsilon^{\text{LHH}} = 0.1 < \rho_\varepsilon^{\text{LHH}} = 0.5$, $\sigma_\mu^{\text{LHH}} = \rho_\mu^{\text{LHH}} = 1$ (i.e. the cladding layers are non-magnetic) [12-14]. Detailed computations then reveal that at a 'critical' point along the structure (see Fig. 1) the guided light signal is completely stopped, with its group and energy velocities reducing to zero [12].

Pursuing a ray-tracing analysis that accurately incorporates the Goos-Hänchen phase shifts experienced by a guided light-ray upon total (internal) reflection, we can further show that, in stark contrast to conventional dielectric waveguides, in NRI heterostructures the effective guide thickness t_{eff} is always *smaller* that the core physical thickness 2α, and can become zero or even negative. An example of zero effective NRI waveguide thickness is illustrated in the bottom left inset of Fig. 1, showing a ray becoming permanently 'trapped' owing to the negative Goos-Hänchen phase shifts that it experiences upon hitting the two media interfaces.

Using impedance matching arguments, one finds that for the NRI heterostructure analysed above and for a conventional optical waveguide with $n_{core} = 1.25$, $n_{cladding2} = 1.2$ and $n_{cladding3} = 1.1$, we can achieve complete impedance matching for a reduced guide thickness, ak_0, equal to approximately 12.77 [12]. In addition to the impedance and thickness matching at that point, it also swiftly turns out that the two structures have very similar magnetic field distributions (mode matching). As a result, a wave launched from the conventional dielectric waveguide to the left-handed heterostructure will only experience minimal reflection, mainly owing to minute mode-mismatch.

Outlook: A world of 'trapped rainbows'

The 'trapped rainbow' method for stopping light relies critically on the presence of negative Goos-Hänchen phase shifts, as well as on the occurrence of mode-degeneracy [13,14] points in the modal dispersion diagrams, both of which require media with negative optical parameters, e.g., negative permittivity – but *not* necessarily negative refractive index. For instance, a plasmonic waveguide having a core of a material with negative (real part of) permittivity in the optical regime supports surface plasmon polaritons (SPPs) whose cycle-averaged power flow inside the negative-ε core is negative (owing to the negativeness of ε). This can result in zero total cycle-averaged power flow, P_{tot} [13,14], at a particular (mode-degeneracy) point along the waveguide and, accordingly, in zero group (or energy) velocity at that point. In addition to the initially proposed, negative-index based, method towards broadband, 'trapped rainbow'-stopping of light, scientists have now theorized a number of alternative (metamaterial) structures and geometries that can also achieve negative phase shifts.

A first approach relies on the use of extremely anisotropic metamaterial wire waveguides made up of alternating metallic and dielectric discs [15]. In these structures the effective permittivity of the metamaterial wire is negative in the transverse direction but positive in the longitudinal direction, leading to zero group velocity (mode degeneracy) points for the supported oscillatory modes similar to those appearing in a negative-index waveguide. The light-stopping is achieved by an adiabatic increase of the wire radius to the zero-v_g point. Another scheme uses, so called, 'spoof' SPPs in engineered metallic gratings in the THz regime (where the metallic losses are very small) to bring them to a complete halt at different points along the grating, depending on the frequency of the guided SPP wave [16,17]. The authors of that work have, thus, showed that different 'colours' of light can adiabatically be stopped at different waveguide thicknesses, forming (THz) 'trapped rainbows'. In a different approach, He *et al.* demonstrate that using a waveguide with a photonic crystal in its negative-refraction regime can, also, lead to halting of individual light frequencies at distinct points along the waveguide [18]. An advantage of this scheme is that, being all-dielectric, is almost insensitive to material dissipative losses. 'Trapped rainbow' stopping of light inside a hollow, air waveguide with anisotropic metamaterial cladding has been demonstrate numerically by Jiang *et al.* [19], while slow light propagation with very low group velocity dispersion in a negative-index waveguide with plasmonic claddings was reported by Dong *et al.* [20]. Finally, it is worth pointing out that negative Goos-Hänchen shifts can exist not only for electromagnetic waves, but also for acoustic waves, as well as for matter (e.g., electron or atom) waves [21,22]. This opens

up the remarkable possibility of 'trapped rainbow'-stopping of *matter* waves by means of *light* (e.g., laser 'slabs'), i.e. the reverse of 'trapped rainbow'-stopping of light in meta-material waveguides.

References

[1] T. J. Yen, W. J. Padilla, N. Fang, D. C. Vier, D. R. Smith, J. B. Pendry, D. N. Basov, and X. Zhang, *Science* **303**, 1494 (2004).

[2] A. N. Grigorenko, A. K. Geim, H. F. Gleeson, Y. Zhang, A. A. Firsov, I. Y. Khrushchev, and J. Petrovic, *Nature* (London) **438**, 17 (2005)

[3] V. M. Shalaev, *Nature Photonics* **1**, 41 (2007).

[4] P. W. Milonni, *Fast light, Slow Light and Left-Handed Light* Chs. 5 & 6 (Institute of Physics, Bristol, 2005).

[5] C. Liu, Z. Dutton, C. H. Behroozi, and L. V. Hau *Nature* (London) **409**, 490 (2001).

[6] E. Gehrig, M. van der Poel, J. Mørk, and O. Hess, *IEEE J. Quantum Electron.* **42**, 1047 (2006).

[7] Y. A. Vlasov, M. O'Boyle, H. F. Hamann, and S. J. McNab, *Nature* (London) **438**, 65 (2005).

[8] M. S. Bigelow, N. N. Lepeshkin, and R. W. Boyd, *Science* **301**, 200 (2003).

[9] Y. Okawachi, *et al.*, *Phys. Rev. Lett.* **94**, 153902 (2005).

[10] M. I. Stockman, *Phys. Rev. Lett.* **93**, 137404 (2004).

[11] A. Karalis, E. Lidorikis, M. Ibanescu, J. D. Joannopoulos, and M. Soljačić, *Phys. Rev. Lett.* **95**, 063901 (2005).

[12] K. L. Tsakmakidis, A. D. Boardman, and O. Hess, *Nature* (London) **450**, 397 (2007).

[13] K. L. Tsakmakidis, A. Klaedtke, C. Jamois, D. P. Aryal, and O. Hess, *Appl. Phys. Lett.* **89**, 201103 (2006).

[14] K. L. Tsakmakidis, C. Hermann, A. Klaedtke, C. Jamois, and O. Hess, *Phys. Rev. B* **73**, 085104 (2006).

[15] Y. J. Huang, *et al.*, *Phys. Rev. A* **77**, 063836 (2008).

[16] Z. Fu, *et al.*, *IEEE J. Select. Top. Quantum Electron.* **14**, 486 (2008).

[17] Q. Gan, *et al.*, *Phys. Rev. Lett.* **100**, 256803 (2008).

[18] J. He, *et al.*, *Opt. Express* **16**, 11077 (2008).

[19] T. Jiang, *et al.*, *Opt. Express* **17**, 170 (2009).

[20] J. W. Dong and H. W. Wang, *Appl. Phys. Lett.* **91**, 111909 (2007).

[21] L. Zhao and S. F. Yelin, arxiv:0804.2225v2 [cond-mat.other], 11 Dec. 2008.

[22] J. Huang, *et al.*, *Phys. Rev. A* **77**, 063608 (2008).

Modeling of Ultrafast Fiber Lasers Operating in Different Mode-locking Regimes

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Fiber lasers receive much attention due to their attractive features for applications. Indeed, these lasers are governed by extremely rich dynamics arising from an interplay of gain, nonlinearity and dispersion. This talk will discuss the physics of the many mode-locking regimes of fiber lasers.

There is much progress on mode-locked fiber lasers, motivated by their great potential for use in applications of ultrafast pulses. Perhaps most importantly fiber lasers robust enough that little to no user interference is required during prolonged operation. These applications include material processing, biomedical imaging, optical frequency metrology, and generation of THz pulses, among others. Not long ago, fiber lasers were limited to typical pulse energies of ~ 1 nJ. The latest results now report more than 30 nJ in 80 fs pulses using regular fiber-optics components [1] and up to 265 nJ using specialty fibers [2]. These developments are partly a result of improvements in technology and components, but to a larger extend are enabled by improved understanding of the underlying pulse formation dynamics and to the discovery of new pulse shaping mechanisms. The intellectually rich dynamics governing mode-locked fiber oscillators is a result of the intricate interplay of gain, strong nonlinear effects, dispersion. These include the similariton [3], all-normal dispersion [4] regimes as well as the hybrid regime of soliton-similaritons [5], adding to the list of all well-known regimes of soliton-like [6], stretched-pulse (also known as dispersion-managed soliton-like) [7] regimes. Given the complex nature of these dynamics, the best tool is numerical simulations of the governing equations.

Our approach to the modeling of mode-locked fiber lasers is based on a generalized nonlinear Schrödinger equation (NLSE) describing pulse propagation. This model has been continuously evolving over the last decade and has been successful in describing all the known mode-locking regimes. The model includes second and third order dispersion, self-phase modulation, and the Raman correction. Gain is assumed to saturate over a large number of pulses with a response response time much longer than the cavity roundtrip time and has a frequency dependance, modeling the gain filtering effect. The saturable absorber effect is modeled by various transfer functions. Intra-cavity elements such as a bandpass filter or an output coupler are included. Recently we have developed a graphical user interface which allows easy use of all the functionalities of the numerical model.

In conclusion, the main purpose of the talk will be to discuss the similarities and differences between the underlying physics characterizing each of the known mode-locking regimes of fiber lasers. A secondary goal of the talk will be the discussion of the technical details of the numerical model we have developed in order to make it accessible to the use of the optics community.

References

[1] K. Kieu, W. H. Renninger, A. Chong, and F. W. Wise, *Opt. Lett.* **34**, 593 (2009).
[2] B. Ortac, *et al.*, *Opt. Express* **45**, 10725 (2007).
[3] F. Ö. Ilday, J. R. Buckley, W. G. Clark, and F. W. Wise, *Phys. Rev. Lett.* **92**, 213902 (2004).
[4] A. Chong, J. Buckley, W. Renninger, and F. W. Wise, *Opt. Exp.* **14**, 10095 (2006).
[5] B. Öktem , C. Ülgüdür, F. Ö. Ilday, *CLEO*, May 2008.
[6] I. N. Duling III, *Electron. Lett.* **27**, 544 (1991).
[7] K. Tamura, J. Jacobson, H. A. Haus, E. P. Ippen, and J. G. Fujimoto, *Opt. Lett.* **18**, 1080 (1993).
[8] E. Verhagen, *Opt. Express* **45**, 45–57 (2008).

Metal-Clad Optical Fibres

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In the optical frequency domain, metals can be regarded as dielectric materials, albeit with a relatively large imaginary part to the refractive index that represents the opacity and is normally much larger than the real part. The guidance provided by a metal-clad, dielectric-core fibre is more easily understood in terms of the respective dielectric constants rather than the refractive index values.

Because of the large variation between dielectric constants, Maxwell's equations are necessarily employed to determine modal propagation characteristics and their solution is generally numerically intensive. An exact, explicit analytical solution is available for the single TM-polarised surface plasmon propagating along a planar dielectric-metal interface. This result can also be anticipated from simple considerations of continuity.

Perturbation solutions are possible when only a small fraction of modal power propagates within the metal. Examples will be presented for the cases of (i) a tapered, metal-clad, single-mode fibre used for scanning near-field optical microscopy (SNOM) application, and (ii) multimode propagation inside a hollow, multimode silver capillary for laser light delivery in surgery.

Rigorous Mode Solver for multilayer cylindrical Waveguide Structures using Constraints Optimization

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A rigorous mode solver module for multilayer fiber configurations ("ATSOS" [1]) is presented based on a generalized transfer matrix algorithm combined with a Constraint Optimization Method [2]. Guided and leaky Modes of three unconventional fiber structures (Hollow-core-ARROW-Fiber, Metal-Coated Fiber, Directional Radial Fiber Coupler) are calculated to demonstrate the performance of this approach.

Introduction

The problem of mode finding in multilayer cylindrical waveguide structures based on a complex dispersion relation is redefined as a minimization problem with constraints. This presented fully vectorial approach avoids local minima restricting the search direction by means of constraints. As a result, complex dispersion charts together with modal field profiles can be calculated conveniently even for systems with strong absorption and radiation effects and without any reference to a discretization scheme and/or a computational window.

Results

This presented algorithm includes the following steps: 1. Decompose the given structure into a set of homogeneous cylindrical layers, bounded by a core and a cladding region; 2. Derive and solve the cylindrical HELMHOLTZ-equation in the core and cladding region analytically, and for all fiber layers analytically or numerically; 3. Apply boundary conditions to connect the field components on both sides of each interface. Be advised about the mutual coupling of electric and magnetic field components at each interface [3]; 4. Formulate a modified Modal Dispersion Function to be minimized under the constraints for electric and magnetic fields imposed by the continuity conditions; 6. Solve the resulting set of algebraic Equations using Constraints Optimization methods.
The mode solver module ATSOS comes with a JAVA-based intuitively to handle graphical user interface and an underlying C++/Fortran computational core. Its performance includes high computational speed even for large numbers of cladding layers, parameter scans for every parameter of the set up complemented by a permanent, mouse driven, access to field and intensity profiles associated with a given parameter selection.
Using several application examples, we will show the typical transitions from anti-resonant to resonant mode condition in the complex dispersion chart of an ARROW fiber, the propagation characteristics of short and long range plasmons as well as surface plasmons coupled to guided modes in a metal coated fiber, and the coupling mechanism in a directional fiber coupler in terms of supermode interference.
The presented concept can be extended easily to graded index- and nonlinear materials using a Runge-Kutta procedure to solve the HELMHOLTZ-equations inside the fiber layers. Additional applications of our rigorous mode solver are in the areas of coaxial fibers, Bragg fibers and Plasmonic structures.

References

[1] Analysis Tool for Stratified Optical Systems (ATSOS), www.doos.de

[2] D. Luenberger, Linear and Nonlinear Programming, Addison-Wesley Publishing 1984

[3] M. Boerner, G. Trommer, Lichtwellenleiter, Teubner Stuttgart 1989

Impact of feedback on femtosecond supercontinuum generation

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We have numerically analyzed the effect of feedback on femtosecond supercontinuum generation in photonic crystal fiber and have observed system behavior varying from steady-state, via period multiplication and limit cycles up to chaos. These system states are characterized, also with perturbations included in the numerical model.

Introduction

Supercontinuum (SC) generation describes the process of spectral broadening of an ultra-short laser pulse and is known since 1970, but has been boosted by the advent of photonic crystal fibers. After the SC generation process and the contributing effects were in principle well understood, further investigations have focused on improving the stability of generated SC, since numerous applications, like coherent anti-Stokes Raman microscopy, coherence tomography and precision frequency metrology require a good suppression of fluctuations. In order to achieve this goal, we numerically study the supercontinuum evolution in a ring cavity synchronously pumped with fs-pulses from a titanium:sapphire laser, as we expect a self-stabilization leading to a reduction of phase- as well as amplitude fluctuation from the incorporation in a cavity.

Results

In order to describe the single pulse propagation inside a photonic crystal fiber, the generalized nonlinear Schrödinger equation was numerically implemented using of a split-step Fourier method. The feedback was realized numerically by superimposing a fraction of the SC generated in the PCF, with the next following pump pulse. The model and its implementation have been verified by comparing results from simulations to performed experimental measurements, which show reasonable agreement.

Here, we will present results of these simulations with feedback. Substantial impact of feedback on SC evolution can be observed, depending on initial parameters like effective pump power or temporal delay between the generated SC pulses and the following pump pulses. In a certain parameter range the investigated feedback system exhibits a convergence of consecutive SC spectra into a steady-state solution. In a different parameter range, the system shows periodic solutions, i.e., the system state is not reproduced after every iteration, but after every second or third roundtrip or after some other number of feedback iterations. In addition, for yet another range of initial parameters, the system exhibits a further system state with reduced stability, called limit cycle, which is expressed in a closed orbit in phase space. A chaotic system behavior can be observed for even higher pump pulse powers.

Finally, noise was included in our simulations in order to model experimentally realizable conditions. These simulations show, that the above observed system states are retained despite of perturbations.

The investigated system exhibits nonlinear dynamical behavior just as many other nonlinear optical systems, which show self-stabilization. From these results, we expect a parameter range in which the stability as well as the coherence can be improved.

Statistical modelling of high-speed optical communication systems

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Summary: Recent developments in the optimization and modelling of high-bit-rate fibre communication systems and high-speed all-optical signal processing will be discussed.

The growing demand on capacity of high-speed optical communication systems is leading to the continuous development of new transmission techniques. Ultimately, the benefits of novel engineering approaches are measured in terms of the achievable bit-error-rate (BER) over the targeted distance, subject to economic and/or technological constraints. The design of modern complex high-speed fibre communication links requires the optimisation of multiple system/signal parameters, making the direct comprehensive measurement of BER impractical. In this regard, it is obvious that accurate modelling of BER in high-speed fibre communication links is vitally important for the optimum system design. In order to accurately estimate BER, one needs knowledge of the signal and noise statistics that accounts for both the amplified spontaneous emission and the nonlinear transmission effects. The analysis of the statistical properties of signals in modern high-speed optical communication systems is a complex nonlinear problem. The problem is further complicated by the fact that information is coded and transmitted using a variety of modulation formats in a range of fibre system configurations. Statistics for modulation formats using optical phase for coding and transmission of information is fundamentally different from the traditional on-off-keying (OOK) format. For example, in OOK transmission, the phase variation in signal pulses has no impact on the detected electrical signal. In the so-called differential phase shift-keying (DPSK) transmission, any variation of the phase between adjacent bits has immediate impact on the signal after demodulation. In DPSK transmission systems, linear phase noise is introduced through amplifier spontaneous emission from optical amplifiers, and nonlinear phase noise arises when amplitude noise is converted to phase noise through fibre nonlinearity, commonly known as the Gordon-Mollenauer effect. As a result, the statistics of DPSK signals differ substantially from that of conventional OOK data [1-3]. Therefore, reliable, simple and accurate estimation of the BER in DPSK systems, which correctly accounts for complex signal statistics including both amplitude and phase noise is a challenging and yet unsolved problem. A practically important example of the growing complexity of design appears in the optical transmission systems using distributed amplification. Distributed amplification introduces new degrees of freedom for the system optimization, making a search for the best possible configuration a daunting task. A new optimisation approach recently proposed in [4] will be discussed in the lecture. This new strategy allows us to determine many of the important optimal parameters without the need to perform time-consuming transmission simulation based on the signal amplitude equations. Another important application of statistical modelling is in the area of optical data processing. Photonic technologies for data processing in the optical domain are expected to play a major role in future high-speed communications. The full potential of all-optical data processing is still to be realized in a variety of possible applications. In this talk, I will overview our recent studies on the design of high-speed fibre communication systems, the modelling of signal statistics and the development of novel approaches to all-optical signal processing.

References

[1] B. Slater et al, Optics Express **15 (17)**, pp. 10999-11007 (2007)

[2] S. K. Turitsyn at al, *Optics Communications,* **277(2)**, 264 (2007)

[3] B. Slater, S. Boscolo, A. Shafarenko and S. K. Turitsyn, *J. of Optical Networking* **6 (8)**, 984 (2007)

[4] J. D. Ania-Castanon et al, Opt. Express **14**, 8065 (2006)

Bistable and multi-stable lasing in micro-cavities

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As recently demonstrated, microlasers can support bi- and multi-stable operation, giving rise to, e. g., ultrafast wavelength switching. We outline the general theoretical principles of designing a multistable microlaser and carry out a numerical demonstration of its operation in a variety of coupled microcavity geometries.

Physics of microlasers is substantially different from that of bulk-cavity lasers since the smaller cavity size (comparable with the operating wavelength) limits the number of modes and makes modes heavily dependent on a cavity shape. As a result, the operation of microlasers becomes more sophisticated, featuring an increased variety in the mode dynamics. For example, bistable operation in photonic crystal microlasers has been recently reported, allowing wavelength switching by up to 20 nm on a picosecond time scale [1]. This can be employed in a design of multiple-wavelength integrated coherent light sources or optical flip-flop (memory) cells [2].

In this work, a systematic study of bi- and multistability in microcavity-based lasers is carried out. We start from the Maxwell-Bloch equations and formulate the coupled mode theory without assuming any specific form for the cavity modes. Governing equations for the mode dynamics are then obtained for all laser dynamics classes. The introduction of those classes itself is revisited in the multimode case as opposed to single-mode case [3].

In the simplest class-A dynamics, subject to a relatively easy analytical description, we have found out that bistability originates from an interplay between incoherent (spatial hole burning) and coherent (population inversion pulsations) mode interaction processes. Due to a good matching of in-cavity intensity between coupled-cavity modes (as opposed to different-order longitudinal or transverse bulk-cavity modes) bistable lasing can be achieved for modes with frequency spacing $\Delta\omega$ several orders of magnitude greater than previously deemed possible.

In the more complicated class-B and class-C dynamics, the same principles were seen to hold. Increasing the pumping beyond near-threshold values was seen to cause bistable operation. A good agreement is demonstrated between the predictions of the coupled mode theory and direct numerical FDTD simulations. In a proof-of-the-principle structure based on coupled defects in a photonic crystal lattice, numerical results indicate a possibility for ultrafast (10-20 ps), large (20 nm apart) wavelength switching. Multistable operation was observed in systems involving more than just two modes. These results were demonstrated in a variety of coupled cavity geometries, including coupled nanopillar waveguides and coupled microdisks.

References

[1] S. V. Zhukovsky, D. N. Chigrin, A. V. Lavrinenko and J. Kroha, "Switchable lasing in multimode microcavities," *Phys. Rev. Lett.*, **99**, 073902, (2007).

[2] M. Hill, H. J. S. Dorren, T. de Vries et al., "A fast low-power optical memory based on coupled micro-ring lasers," *Nature*, **432**, 206, (2004).

[3] S. V. Zhukovsky, D. N. Chigrin, J. Kroha, "Bistability and mode interaction in microlasers," *Phys. Rev. A*, in press, (2009), arXiv:0804.3758.

Modelling and Fabrication of Waveguide Saturable Absorber in Laser Crystals

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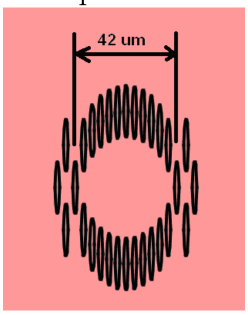
In this paper we present the concept, modeling, and the first demonstration of the Waveguide Saturable Absorber (WSA) fabricated in the bulk of the YAG:Cr^{4+} crystal.

Waveguide design of laser components is a very attractive option in integration with fiber components. For example, 1 μm Q-switched fiber lasers appear very promising in a range of applications for material processing. A reliable and cost effective saturable absorber is needed for such a laser. YAG:Cr^{4+} crystal appears as the most suitable material. Indeed, it is the most popular solution for saturable absorber for solid state lasers. However reliable integration of the widely available bulk saturable absorber in a fiber laser is a serious challenge. We present a novel waveguide design for a saturable absorber based on the YAG:Cr^{4+} crystal. A waveguide is designed to be compatible with conventional fibers.



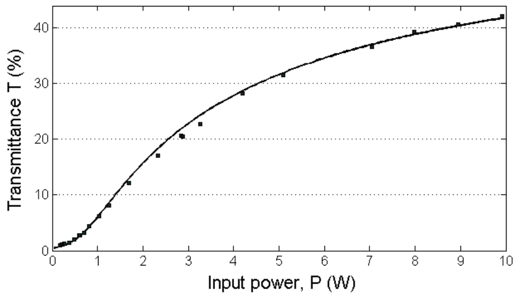


Figure 1. Left: Schematic design of the depressed cladding waveguide. Right: Transmittance of WSA upon power of CW laser beam entering into the waveguide (the points - experiment, solid line - theory).

We fabricated a waveguide with a depressed cladding in YAG:Cr^{4+} under a crystal surface. Femtosecond laser beam was used for waveguide microfabrication [1]. Schematic cross-section of the waveguide is shown in Fig.1. Modified regions of the crystal have refractive index lower by 3×10^{-3} compared to unperturbed value. They are shaped as rods with oval cross section and all together form a waveguide cladding. A core is formed by a non-perturbed region of the crystal. To characterize the WSA we coupled a 1.064 μm CW Gaussian laser beam. The nonlinear transmittance of the WSA is shown on the right in Fig.1. We compared these measurement with numerical simulations taking into account well known model of tetrahedrally coordinated Cr^{4+} [2]. We used known values of saturable absorption cross sections and un-saturable losses for the YAG:Cr^{4+} crystal when numerically solved rate equations for field intensity and level populations of the Cr^{4+} ions. A very good agreement between theory and experiment was found for the excited state lifetime equal to 2.9 μs, and a coupling efficiency of 87%. We believe that the WSA could be used for efficient Q-switching of Yb^{3+} and Nd^{3+} fiber lasers.

References

[1] A.G.Okhrimchuk, A.V.Shestakov, I. Khrushchev, J. Mitchell, *Optics Letters*, **30**, 2248–2250 (2005).
[2] A.G.Okhrimchuk and A.V.Shestakov, *Phys. Rev.*, **61(2)**, 988–995 (2000).

Development of Narrow-Band Laterally-Coupled Distributed Feedback Lasers

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The paper presents design principles for laterally-coupled distributed feedback lasers. The variations in threshold current density, modulation bandwidth, side-mode suppression ratio and linewidth are discussed. The principles have been used for designing distributed feedback lasers for 894 and 980 nm.

Summary

We have fabricated laterally-coupled distributed feedback (LC-DFB) lasers (Fig. 1a) using nanoimprint lithography and achieved 50 dB side-mode suppression ratio (SMSR) [1].

A stable single-transverse-mode (STM) operation in ridge waveguide lasers as well as in LC-DFB lasers depends on ridge geometry. The ridge profile can be designed by solving the 2D scalar Helmholtz equation for the weighted-average transverse refractive index distribution and using the value of $(\Gamma_1-\Gamma_2)(\Gamma_1-\Gamma_3)/\Gamma_1^2$, where Γ_m is the under-the-ridge confinement factor for the m-th mode, as a figure of merit indicating the likelihood of STM operation [2]. The values for the un-etched cladding layer thickness, *t*, the width of the middle ridge section, *W*, and the width of the lateral extension of the gratings, *D*, that are most likely leading to STM operation are obtained as a result (stars in Fig. 1b).

The coupling coefficient, κ, which has a significant influence on the device characteristics, is also dependent on the ridge geometry (Fig. 1c). SMSR increases as a function of κL, where L is the device length. Value of κ defines the possible range for L, because high κL causes spatial hole burning, whereas for low κL there isn't enough modal selectivity. For fixed L, threshold current, I_{th}, increases and threshold current density, J_{th}, decreases as W gets wider. However, mirror loss coefficient, α_m, increases as L decreases and therefore very high κ (narrow W or wide D) results in substantial increase in I_{th} and J_{th} (Fig. 1d). On the other hand, low κ values lead to long devices with limited modulation bandwidths, $f_{3\ dB}$ (Fig. 1e). The linewidth, $\Delta\upsilon$, decreases as α_m decreases. Furthermore, α_m decreases when κ and/or L increases. However, for the 894 and 980 nm LC-DFB lasers, the reduction in $\Delta\upsilon$ (as well as in J_{th}) is small when W is wider than 1.5 μm and κL is larger than 1.5 (Fig. 1f), whereas $f_{3\ dB}$ decreases for W wider than 1.5 μm and κL larger than 1.5.

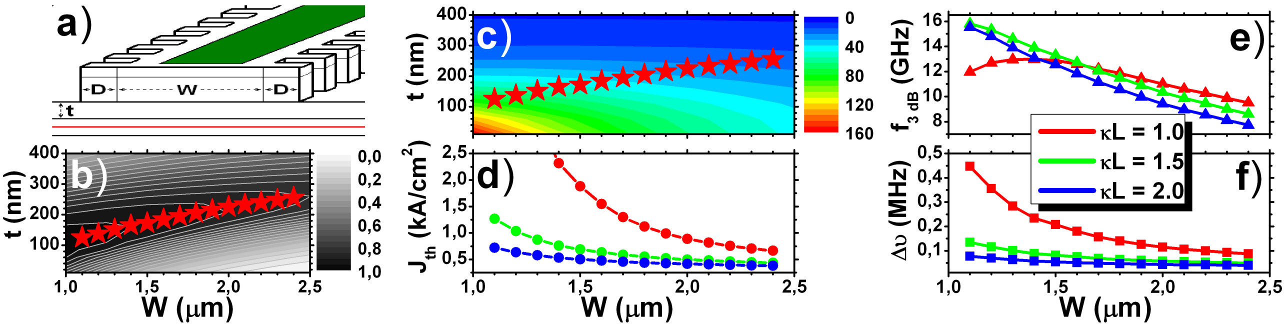

Fig. 1. HR/AR -coated LC-DFB laser operating at 894 nm: a) sketch of the structure, b) $(\Gamma_1-\Gamma_2)(\Gamma_1-\Gamma_3)/\Gamma_1^2$, c) κ for the third-order grating (cm^{-1}), d) J_{th}, e) $f_{3\ dB}$, and f) $\Delta\upsilon$. Bias current is 100 mA, κL is either 1.0, 1.5 or 2.0, and D is 0.5 μm. The values of t and W used when evaluating J_{th}, $f_{3\ dB}$ and $\Delta\upsilon$ are marked with red stars.

References

[1] J. Viheriälä et al., *Microelectron. Eng.*, doi:10.1016/j.mee.2008.10.010, Article in press

[2] A. Laakso et al., *Opt. Quantum Electron.*, OWTNM'08 Special Issue, Under review