The 12th International Workshop on

# Optical Waveguide Theory and Numerical Modelling

March 22-23, 2004, Ghent, Belgium

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# Acknowledgements

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# Preface

We would like to welcome you to the 12$^{th}$ International Workshop on Optical Waveguide Theory and Numerical Modelling, held March 22-23 2004, in Ghent, Belgium.

As always, the aim of this workshop is to provide a forum for exchange of ideas and discussion of current problems in the field of optical modelling. This is done through a series of invited and contributed talks, but also through a poster session which allows for a wide interaction between the participants.

This year's workshop in Ghent continues the tradition of OWTNM workshops held annually in different places in Europe: 2003 in Prague, Czech Republic, 2002 in Nottingham, UK, 2001 in Paderborn, Germany, 2000 in Prague, Czech Republic, 1999 in St. Etienne, France, 1998 in Hagen, Germany, 1997 in Enschede, The Netherlands, 1995 in Roosendaal, The Netherlands, 1994 in Siena, Italy, 1993 in Vevey, Switzerland 1992 in Teupitz, Germany.

This series of workshops is supervised by the OWTNM technical committee, consisting of Trevor Benson (University of Nottingham, UK), Jirí Ctyroký (IREE AS CR, Czech Republic), Anand Gopinath (University of Minnesota, USA), Hans-Peter Nolting (HHI Berlin, Germany), Hugo J. W. M. Hoekstra (University of Twente, Netherlands), Olivier Parriaux (University of Saint Etienne, France), Reinhold Pregla (FernUniversität Hagen, Germany) and Christoph Wächter (Fraunhofer Inst. AOT Jena, Germany).

Papers from the workshop will appear in a special issue of Optical and Quantum Electronics. Details about the paper submission can be found on the OWTNM04 website http://photonics.intec.ugent.be/owtnm.

We acknowledge the Flemish Fund for Scientific Research (FWO – Vlaanderen) for their kind financial support.

We would also like to thank everyone that has contributed to this workshop, especially those people working behind the scenes. Without their efforts this workshop would never have been possible.

Ghent, March 2004

The local organisers

Peter Bienstman, Photonics group, Ghent University
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# Contents

# Solving the 3D Helmholtz Equation by Complex Jacobi Iteration

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Virtually every aspect of frequency-domain photonics modeling requires the solution of the Helmholtz Equation in some form. In particular, single-frequency excitation of structures that generate reflections can be effectively examined by solving the Helmholtz Equation over a region containing the test structure, together with appropriate absorbing boundary conditions or materials[1]. For 2D structures, the Helmholtz Equation can be solved reasonably quickly by direct matrix inversion. However, matrix inversion for 3D problems is impossible even for large computers for all but the smallest problems, and iterative methods are required.

Because the Helmholtz operator is indefinite, all the classical iterative techniques that achieved such popularity several decades ago for Laplace solution (i.e. ADI, SOR, etc.) do not converge. Presently, several iterative techniques are in use for Helmholtz solution that belong to a general family referred to as Krylov subspace methods. Included in this list is the better-known method of Conjugate Gradients. These techniques are fairly complex to program and therefore their use is often associated with a significant learning curve.

Here we propose a new and very simple iterative scheme based on the method introduced in 1845 by Jacobi. We generalize his method by the use of a complex iteration parameter $\alpha$ and consider the pair of iterations given by

$$H^{n+1/2} = H^n + \frac{\left(\nabla^2 + k_0^2\varepsilon\right)H^n}{2\alpha\left(\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} + \frac{1}{\Delta z^2}\right)}$$

$$H^{n+1} = H^{n+1/2} - \frac{\left(\nabla^2 + k_0^2\varepsilon\right)H^{n+1/2}}{2\alpha^*\left(\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} + \frac{1}{\Delta z^2}\right)}$$

where $\nabla^2$ is understood to be the standard finite-difference analogue of the Laplacian with grid sizes $\Delta x, \Delta y, \Delta z$, and $\varepsilon$ is the dielectric constant. This algorithm is stable for well-posed problems with adequate absorption, provided that $\alpha$ is properly chosen. Convergence rates depend on the effective absorption coefficient, the problem discretization and the iteration parameter, but not on overall problem size. We note in passing that the algorithm vectorizes immediately and so considerable speedups should be expected from the use of vector processors. We will discuss the method itself, pertinent applications, and demonstrate its use on some 3D problems of interest.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

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# Application of semi-analytic methods to boundary-perturbation problems in high-contrast waveguides

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Although brute-force simulations of Maxwell's equations, such as FDTD methods, have enjoyed wide success in modelling photonic-crystal and other strongly-confined optical systems, they are not ideally suited for the study of weak perturbations, such as surface roughness or gradual waveguide transitions, where a high resolution and/or large computational cells are required. Instead, we these important problems are ideally suited for semi-analytical methods, which employ perturbative corrections (typically only needing the lowest order) to the exactly understood perfect waveguide. However, semi-analytical methods developed for the study of conventional waveguides require modification for high index-contrast, strongly periodic photonic crystals, and we have developed corrected forms of coupled-wave theory and perturbation theory for this situation.

**Keywords:** perturbation theory, photonic crystals, coupled-mode theory

## Introduction

A large class of important perturbations to optical systems involves shifts in dielectric boundaries, from surface roughness to fiber acircularity to slow taper transitions. Because of the field discontinuity as such interfaces, however, well-known semi-analytic perturbative techniques can yield quantitatively or even qualitatively incorrect results in high-index-contrast systems with large discontinuities. Our new corrected theory [1] is fundamental to other approaches from coupled-mode theories to the volume-current method. In this correction, the usual $|\mathbf{E}|^2\Delta\varepsilon$ of perturbation theory is replaced by a term manifestly continuous across an interface: $|\mathbf{E}_{\parallel}|^2\Delta\varepsilon - |\mathbf{D}_{\perp}|^2\Delta\varepsilon^{-1}$.

The next step is the development of constant-frequency coupled-mode theories for periodic systems (photonic crystals), in two cases: slowly changing boundaries (e.g. tapers) where the total amount of change is arbitrary [2]; and changes of small magnitude where the rate of change is arbitrary (e.g. roughness) [3]. The former corresponds to the classical "local normal mode" basis, whereas the latter uses the modes of the ideal waveguide. In both cases, the bases are Bloch eigenmodes, which require a new coupled-mode theory because e.g. they are not orthogonal over a cross-section, nor is their choice necessarily even unique. Ultimately, however, we derive familiar-looking coupled-mode equations, and we show that they can be utilized for effective computations in systems where direct simulation is difficult, as well as to derive analytical results such as scaling laws and adiabatic theorems.

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# Peculiar Light

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The repeating wavelength-scale features – micro/nano-structured sheets, wires or dots – in a photonic crystal come into resonance or anti-resonance as the frequency of the light is changed. The resulting balance between energy storage and energy flow, which can be highly dependent on frequency and wavevector, fundamentally alters the electromagnetic dispersion relation, giving rise to counter-intuitive and sometimes even peculiar effects. These can be explained in terms of the dispersion (temporal and spatial) of photonic Bloch waves, whose band structure was studied both theoretically and experimentally in the early 1980s [1-4]. In this early work, which involved experiments on singly and doubly periodic "photonic crystal" waveguides (tantalum oxide on glass), many of the curious features of Bloch waves were observed and explained using photonic band structure. Examples include negative refraction [2], double refraction (Figure 1), strongly wavelength-dependent refraction [4] (rediscovered recently and called the super-prism effect [5]), negative diffraction and real and virtual interference [3]. Reviews of this early work are available [6-8].

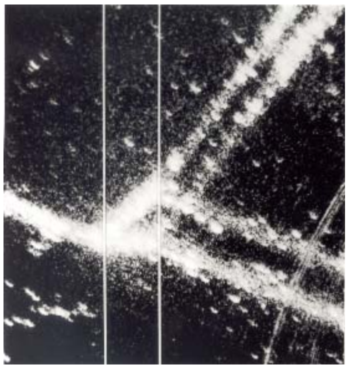

Figure 1: Double negative refraction in a thin photonic crystal strip ~1 mm thick [8]. The grating lines (300 nm pitch) run horizontally.

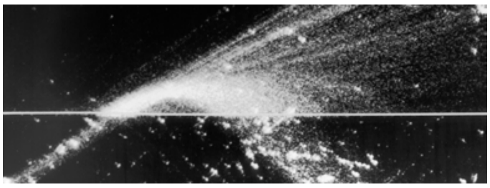

Figure 2: Bloch wave beam being turned around in a photonic crystal (grating lines horizontal) with graded properties [6].

Following early theoretical work on optical superlattices [9], the inverse Doppler effect was predicted and observed (at 1550 nm – 193 THz) in the mid 1990s [10] (despite this, recent observations at ~1 GHz frequency received considerable media attention [11]). In the experiment a fibre Bragg grating was modulated by a travelling acoustic wave, a negative Doppler shift being observed on the low-frequency side of the stop-band where the dispersion is anomalous.

In a separate study, a Hamiltonian optics model was developed [12] to explain observations made in photonic crystals with graded properties [6]. This used of the concept of photon effective mass, which can be infinite, negative or positive depending on the values of the reciprocal effective mass tensor elements. For example, it can be infinite against deflection at certain curvature-free points on the (constant frequency) wavevector surfaces.

The rich range of new possibilities offered by photonic Bloch waves is changing the menu of the possible in optical science and technology.

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# Bidirectional beam propagation method for the modeling of nonlinear microstructured waveguides

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We discuss the application of the bidirectional beam propagation method for the analysis of nonlinear microstructured waveguides. We review two different formulations of the nonlinear algorithm and we demonstrate the effectiveness of the method.

**Keywords:** beam propagation method, guided-wave optics, nonlinear optics, periodic structures

The time-harmonic bidirectional beam propagation method (Bi BPM) is a powerful numerical technique able to efficiently model multilayered devices. The linear transfer matrix Bi BPM algorithm [1] relates the output and the input fields by means of an operator T calculated through the alternated application of wide-angle BPM propagators in homogeneous regions and interface operators at the dielectric discontinuities. We have extended this algorithm for the analysis of second-order nonlinear effects, and in particular Second-Harmonic Generation (SHG) [2]. The transfer matrix nonlinear Bi BPM exploits the split-step technique in order to divide the linear and the nonlinear problems and an iterative procedure that permits to consider the nonlinear forcing terms as known values. Nevertheless, the transfer matrix formulation can suffer from instability problems when the eigenvalues of the operators are complex. This is an unacceptable limitation, because the modeling of microstructured waveguides requires complex propagators for the damping of the evanescent field and perfectly matched layers boundary conditions to absorb the radiation field. The linear Bi BPM based on scattering operators [3] represents a good solution for these problems. The algorithm is based on the backward propagation of two scattering operators R and T and shows good stability for the cases of interest, because the evaluation of the operators does not involve the inversion of the propagators. We have extended this method to study structures with second and third-order nonlinearity [4]; the governing equations are the same as in [2] but we have modified the scattering operator formulation in order to model the nonlinear interactions. The resulting method can be applied to study nonlinear microstructured waveguides exhibiting high index contrast. During the presentation we will show numerical examples that demonstrate the efficiency and the effectiveness of the algorithm for the modeling of challenging structures with practical applicability.

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# A New Approach to Bend Loss Minimisation in Single-mode Optical Fibres

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When a single-mode optical fibre or waveguide is bent, it must necessarily radiate power from its fundamental mode into the cladding because of the change from translational invariance. The description of this loss has been described traditionally in terms of two components covering: (i) transition loss associated with the relatively abrupt change in curvature at the beginning and end of the bent section; and (ii) pure bend loss associated with radiation from a bend of constant curvature. These loss mechanisms have been quantified approximately and various strategies have been devised in the literature over the years to minimise the loss due to either of these mechanisms.

Recently, we have developed a totally new approach to understanding and thereby minimising bend loss by focusing on (i) the evolution of the fundamental mode field as it propagates into, along and out of the bend, and (ii) the minimisation of the coupling of its power to cladding modes. This development is very analogous to the propagation of the fundamental mode along an approximately adiabatic single-mode taper.

Unlike tapers, real fibres have a coating to protect the cladding. Our loss minimisation model takes into account the interaction of the fundamental-mode field with the coating as the former is displaced laterally along the bend and leads to a simple requirement on the real part of the coating index.

Simulations of bent fibres will demonstrate the effectiveness of the new approach and show how it is possible to design a bend that has an arbitrarily small radius and yet exhibits negligible loss.

# Numerical Modelling Techniques Applied to Slanted-Angle Rib Waveguides

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We summarize our recent studies of finite difference, finite element and boundary element approaches to rib waveguide modelling.[1-4] The finite element method is then applied to slanted angle semiconductor on insulator (SOI) rib waveguides, yielding novel design techniques.

**Keywords:** optical waveguide theory, numerical modelling, guided-wave optics, integrated optics.

In work performed with Tao Lu, Henghua Deng, Derek Dumas and Magnus Wik, the suitability of various numerical methods for rib waveguide, and especially slanted-angle rib waveguide calculations was assessed.[1-4] A comparative study was performed of vector finite-difference methods, which have been shown, e.g. in [5], to be sufficiently accurate to be used in polarization converter fabrication. Here it was found that effect of suppressing the errors arising from the boundary conditions at abrupt waveguide interfaces, which can be achieved through techniques of various theoretical sophistication,[6,7] is generally far smaller than the influence of the procedure chosen to set the values taken for the refractive index values at each grid points.[1] Next, we applied vector finite element procedures based on mixed elements[8] to slanted-angle silicon on insulator waveguides for polarization converters.[9,10] This yielded algebraic formulas that can be immediately employed to design SOI converters with the correct rotation angle and modal behaviour.[2] Finally, we analyzed electromagnetic fields at dielectric corners.[3,4] In particular, we extended to the formalism of [11-13] through a comprehensive series solution that we applied to $6^{th}$ order.[3] While for practical reasons our first results employ the vector boundary element method, extensions to other numerical procedures are being developed.

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# Modelling nanophotonic components

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**Keywords:** modelling, nanophotonics, plasmons, Green's tensor

The difficulty of localizing and manipulating light at the sub-micron scale is a major reason that has prevented optical integration to achieve the performances of electric integration. Fortunately, tremendous technological developments over the last few years have made possible the realisation of new structures that can confine and guide light at the nanoscale. From a modelling point of view, the study of these nanophotonic components is quite challenging, as they often include high dielectric contrasts and lead to rapid variations of the electromagnetic field over short distances, while long distance effects – related e.g. to the substrate – can still influence the overall field distribution and the device response.

In this presentation we will describe an approach based on the Green's tensor technique, which appears to be very well suited for the simulation of nanophotonic components. Simulations of high permittivity photonic wires and resonators will be completed with near-field microscopy images which allow the direct measurement of the field distribution at the vicinity of the optical structures.

Special emphasis will be put on the utilisation of surface plasmon-polaritons for optical signal processing. These electromagnetic waves are supported by a metallic surface and can be excited at optical and telecom frequencies. Since they are localized by the metal surface, their propagation is limited in two dimensions and scattering losses can be extremely small. We will present different configurations for moulding their flow at the nanoscale, hence introducing a completely new approach to optical information processing in integrated circuits.

# Electromagnetic modelling of circular microresonator-based devices

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"Rigorous" modal methods for the calculation of vectorial electromagnetic fields of eigenmodes of 2D (planar) and 3D circular ring and disk microresonators and bent guides will be briefly reviewed. The applications of electromagnetic modelling for the determination of "system parameters" like resonant frequency, finesse, free spectral range, and coupling strength between the circular microresonator and the straight "port" waveguide will be discussed.

**Keywords:** optical waveguide theory, numerical modelling, guided-wave optics, microresonators, film mode matching, coupled mode theory.

## Introduction

Microresonator-based devices are important candidates for building blocks of future VLSI photonic guided-wave devices for telecom applications [1]. For their efficient design, novel modelling methods are to be developed. Accurate modelling of microresonator-based devices is rather challenging for the following reasons: omnidirectional wave propagation in the resonator, leaky character of microresonator eigenmodes due to radiation from the bends, necessity of a full-vectorial treatment due to large refractive-index contrast of both the resonator and port waveguides, and a complex character of the coupling between the straight port waveguide and the bent (leaky) guide of a microresonator. Strong polarisation dependence of both the (group) effective indices of the resonator and of the coupling strength is often encountered, too.

## Modelling of microresonator-based devices by modal methods

For accurate vectorial 'electromagnetic' modelling of microresonator-based devices we have chosen "igorous" modal methods based on film mode matching technique. The film-mode matching bend mode solver is now being developed [2] in our laboratory using the immittance approach, in a very similar way as described by Sudbø [3,4] for straight waveguides. As it has been shown [5], for the calculation of microresonator eigenfrequencies, the corresponding mode field distributions, free spectral range, and finesse of an unloaded microresonator, the complex frequency approach is well suited. A promising approach how to accurately calculate the coupling between the straight and bent guide in the 2D approximation has recently been presented in [6]. It is based on the reciprocity and variational principle [7]. The applicability of the calculated 2D and 3D field distributions for accurate modelling of "system pararmeters" like resonant frequency, finesse, free spectral range, and coupling strength between the circular microresonator and the straight "port" waveguide will be discussed.

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# A Propagator-$\theta$ Beam Propagation Method

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A new wide-angle beam propagation method is developed for better modeling of both propagating and evanescent modes. It brings in a parameter $\theta$ to connect the $[(p-1)/p]$ and $[p/p]$ Padé approximants of the one-way propagator.

**Keywords:** beam propagation method, rational approximation, one-way operator

The standard beam propagation method (BPM) is derived from the slowly varying envelope approximation (SVEA). It gives rise to a differential equation that is first order in the propagation direction $z$. Typically, the Crank-Nicolson (CN) method is used to solve this equation as an initial value problem in $z$. Sometimes, CN produces large errors since it cannot suppress the evanescent modes. These modes are excited at the longitudinal interfaces when a slowly varying waveguide is approximated by a piecewise uniform waveguide. They may also be present in the starting field. When CN fails, the $\theta$ method can be used. It brings the CN and backward Euler methods into one framework. The parameter $\theta$ can be adjusted to balance the conflicting requirements of the propagating and evanescent modes.

Wide-angle BPMs can be derived from rational approximants of a square root operator or its exponential [1, 2]. In the latter approach, the two steps (approximating the square root operator and marching in $z$) are replaced by a single step of approximating the exponential of the square root operator, i.e., the propagator. In this paper, we present a $\theta$-method for the propagator-based wide-angle BPM. Again, the parameter $\theta$ is used to balance the conflicting modeling requirements of the propagating and evanescent modes.

Let $\phi$ be the envelope associated with some field components, such that the fast $z$ dependence $e^{ik_0 n_* z}$ is removed for some $k_0 n_*$. Most BPM models can be derived from the ideal one-way equation: $\partial_z \phi = ik_0 n_* (\sqrt{1+X} - 1)\,\phi$ assuming time dependence is $e^{-i\omega t}$. Here, $X$ is a transverse operator or matrix of operators (if $\phi$ is a vector). Although the envelope $\phi$ is involved, SVEA is not used here. A step from $z_j$ to $z_{j+1} = z_j + \Delta z$ can be discretized as

$$\phi_{j+1} = P\,\phi_j, \quad \text{for} \quad P = e^{is(\sqrt{1+X}-1)},$$

where $s = k_0 n_* \Delta z$ and $X$ is evaluated at the midpoint $z_j + \Delta z/2$. The propagator $P$ can be approximated by its $[p/p]$ Padé approximant for some integer $p$, but the evanescent modes will be incorrectly modeled. The $[(p-1)/p]$ Padé approximant of $P$ can damp the evanescent modes, but it is less accurate for the propagating modes, although accuracy increases as $p$ increases. Our propagator-$\theta$ method connects the $[(p-1)/p]$ and $[p/p]$ Padé approximants of $P$ through a parameter $\theta$. It relies on a rational approximant $R_p(\theta)$ such that $R_p(0)$ and $R_p(1)$ are the $[(p-1)/p]$ and $[p/p]$ approximants, respectively. Numerical examples indicate that a suitable choice of $\theta$ can increase the accuracy of the solution, especially for small $p$.

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# A Novel Mode-Solver for Photonic Crystal Fibres

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With the huge recent surge of interest in photonic crystal fibres (PCF) there is a pressing need for simulation codes that can solve accurately and efficiently for the modes of propagation in fibres with arbitrary shapes of glass and air regions. We have developed a novel computational scheme which has a number of features that make it particularly suitable for the modelling of both solid-core and hollow-core PCF (an outline of the method is given in [1]). Our code is based on solving the governing equation for electromagnetic waves propagating along a fibre that is uniform along its length in the $z$ direction [2]:

$$\left(\nabla^2 + k_0^2 n^2\right) \mathbf{h} + \nabla(\ln n^2) \times (\nabla \times \mathbf{h}) = \beta^2 \mathbf{h}. \qquad (1)$$

Here, $\mathbf{h}(x, y)$ is the transverse component of the magnetic field, $n^2(x, y)$ represents the dielectric function of the fibre, $ck_0$ is the angular frequency of the radiation, and $\beta$ is the wavevector component along the fibre axis. The code uses a plane-wave representation of $\mathbf{h}(x, y)$ but, unlike other plane-wave methods which solve for frequencies $k_0$ at a fixed $\beta$ [3], we solve (1) directly for the modes that are characterised by their propagation constant $\beta$ at a fixed frequency $k_0$. This has the obvious advantage that a fixed-frequency method represents the experimental situation better than a fixed $\beta$ method. Another significant advantage is that, because our method is designed to work with non-Hermitian systems, it is straightforward to include a complex dielectric function and thus to calculate complex values of $\beta$ for a given input frequency. It is therefore possible to model fibres that contain lossy dielectrics or which include metallic components. A feature that makes the code particularly suitable for modelling hollow-core PCF is a novel method for singling out the modes nearest to any selected value $\beta_0$. For example, by choosing $\beta_0$ close to $k_0$ we can home in on modes that are localised in the central air-hole of a bandgap-guiding, hollow-core fibre [1]. As well as describing the theoretical background of the code, a number of applications will be discussed [1,4].

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# Rigorous Design Optimizations of Photonic Devices

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As optical technology has reached a high level of maturity during the last two decades, the nature of the associated devices has, in parallel, themselves become more complex. The optimization of such advanced devices requires an accurate knowledge of their lightwave propagation characteristics and their dependence on the system fabrication parameters. Unfortunately, analytical techniques are not adequate to model lightwave devices without significant approximations. Therefore, the optimization of existing, realistic designs or the evaluation of new designs for optoelectronic devices and sub-systems has created significant interest in the development and use of effective numerical methods.

Of the different numerical approaches for modal solutions reported so far, the finite element method (FEM) [1] has now been established as one of the most powerful and versatile methods. Over the last two decades this technique has been used to characterise a wide range of waveguides, such as semiconductor ridge [2], titanium diffused anisotropic $LiNbO_3$ [1], stress induced highly-birefringent silica fibres [3] and ion exchanged glass waveguides, multiple quantum well devices [4], surface plasmon modes with loss [5], and second [6] and third order [7] nonlinear optical waveguides. In the finite element approach, the problem domain is suitably divided into a patchwork of a finite number of sub-regions called elements. Each element can have a different shape and size and by using many elements, a complex problem can be accurately represented. A wide range of optical devices can be modeled as each element can be considered to have different optical parameters such as refractive index, anisotropic tensors, nonlinearity, and loss or gain factors.

Many important photonic devices, such as optical modulators, filters, polarization splitters, polarization rotators, power splitters, etc may be fabricated by combining several butt-coupled uniform waveguide sections. To design and analyse such photonic devices, it is important to use a junction analysis program in association with a modal analysis program. One of the most rigorous approaches, the least squares boundary residual (LSBR) method [8] has been developed by the authors. In this approach the continuity of the tangential electric and magnetic fields is imposed globally over the interface to obtain the scattering coefficients at the junction. Alternatively, to simulate the propagation of optical waves through a *z*-dependent linear or nonlinear structure, the finite element-based beam propagation method (BPM) has been developed [9] using a fully vectorial approach with a difference scheme along the axial directions. Such a method is particularly useful in the characterization of tapered sections, Y and X junctions and nonlinear optical devices.

Numerically simulated results for many important guided-wave photonic devices, using the full vectorial finite element-based approaches, will be presented, such as high-speed modulators [10], optical filters [11], power splitters [12], spot-size converters [13], surface plasmon modes [5], compact bends [14], second harmonic generations [6], all optical switches [7], optical polarizers [15], single polarization guide [16] polarization rotators [17], and polarization controllers.

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# Transparent-Influx Boundary Conditions for FEM based modelling of 2D Helmholtz problems in Optics

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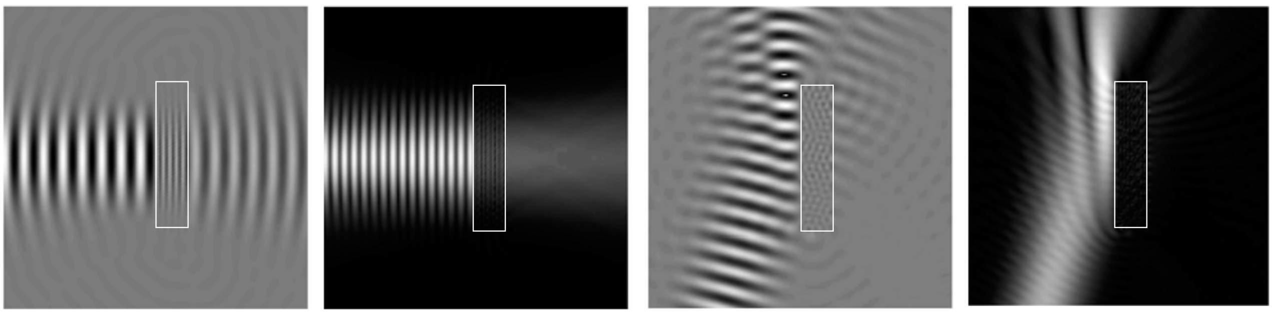
A numerical method for the analysis of the 2D Helmholtz equation is presented, which incorporates Transparent-Influx Boundary Conditions into a variational formulation of the Helmholtz problem. For rectangular geometries, the non-locality of those boundaries can be efficiently handled by using Fourier decomposition. The Finite Element Method is used to discretise the interior and the nonlocal Dirichlet-to-Neumann operators arising from the formulation of Transparent-Influx Boundary Conditions.

**Keywords:** TIBCs, Dirichlet-to-Neumann operator, Helmholtz problems, FEM.

Usually, when numerically computing the solution of optical problems in an unbounded domain, artificial boundaries are introduced to confine the infinite domain to a finite computational window. For reasons of efficiency, this window should be as small as possible. The corresponding boundary conditions must be chosen such that the reflectionless propagation of waves through this boundary can be modeled and that arbitrary influx can be prescribed. At present, Perfectly Matched Layers (PMLs) are the most common approach [3]. The application of this type of boundary condition requires additional computational time and memory. Boundary integral methods, infinite element methods and non-reflecting (transparent) boundary methods are also widely used. Our aim is to realize these Transparent Boundary Conditions (TBCs) in any numerical method, but we will show here the application in the framework of FEM simulations. We use variants of the Dirichlet-to-Neumann operator [1,2], which basically requires the solution of the exterior problem. The boundary conditions for the confined variational formulation of the Helmholtz problem are obtained by matching a representation of the external field in terms of Fourier decompositions to the unknown internal field. The problem can then be solved by standard FEM discretization. The properties of those boundary conditions depend only on the behaviour of the solution in the exterior domain, such that the problem inside the computational window can be arbitrary complex. These TBCs guarantee reflectionless propagation of waves through the boundary, and are less expensive than PMLs as they contain no adjustable parameters and no artificial layer of a specific thickness.



FEM computation of a 2-D problem: A computational window of 16 $\mu m \times 16$ $\mu m$ surrounded by TIBCs. The plots show the real part and absolute value of the field distribution. For TE polarized waves with a vacuum wavelength of 1 $\mu m$, a dielectric rectangle ($1 \times 4$ $\mu m^2$) with refractive index $n_2 = 3.25$ is placed at the center, surrounded by air. A centered Gaussian beam of width 2 $\mu m$ is lauched horizontally (left plots) or vertically, tilted at an angle of $15^0$.

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# Analysis and design of efficient coupling into photonic crystal circuits

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**Keywords:** photonic crystals, electromagnetic scattering by periodic structures, mode-matching, eigenmode expansion.

**Abstract**

Efficient coupling into and out of photonic crystal (PhC) circuits is one of the main challenges to achieve reliable micro-scale photonic integrated circuits based on the PhC technology. Therefore, the knowledge of analytic expressions for the transmission and reflection at an interface between an external medium and a PhC circuit can be very useful when testing novel designs and studying the influence of different parameters on the coupling efficiency. Previously, closed-form expressions were derived for an interface between a dielectric waveguide and a semi-infinite PhC waveguide [1]. In this paper, transmission and reflection matrices are obtained for the (reverse) interface between a semi-infinite PhC waveguide and a dielectric waveguide (see Figure 1(a)). Different from the previous work, in this case both forward and backward propagating Bloch modes inside the PhC waveguide need to be considered. The reflection as a function of different parameters is analyzed and we show the differences from the reflection that occurs at the interface between a dielectric and PhC waveguide. Furthermore, the transmission efficiency as a function of the dielectric waveguide width is also analyzed and maximized by choosing the optimum interface among the different cuts that can be chosen within the basic period of the photonic crystal. To optimize the totally transmitted power, the width of the dielectric waveguide is chosen much broader than that of the PhC waveguide. As a consequence several dielectric waveguide modes get excited. A specially designed coupler then converts this excitation with a high efficiency into a single-mode excitation of the dielectric waveguide. Therefore, a transmission efficiency of 98% from the input to the output dielectric waveguide is achieved.

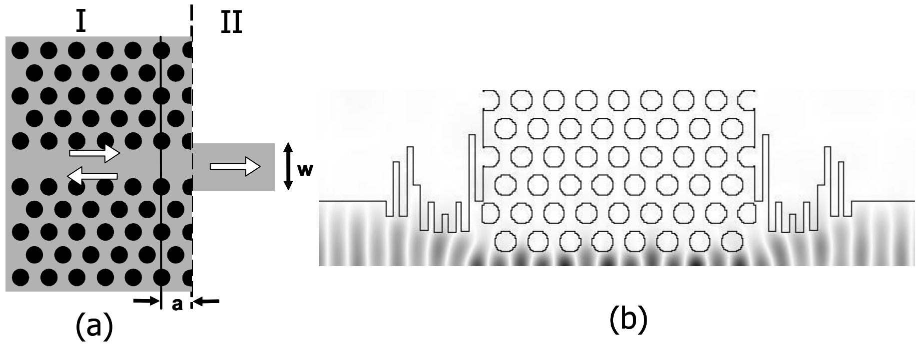


Figure 1.- (a) Analyzed structure and (b) Highly efficient coupling into and out of a finite PhC

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# Fourier modal method for the analysis of photonic-crystal microcavities?

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The Fourier modal method used in grating theory for many years is applied to the study of the electromagnetic properties of photonic-crystal microcavities.

**Keywords:** optical waveguide theory, numerical modelling, guided-wave optics, photonic crystals, Bloch Waves, Fourier modal method

## Introduction

One challenge in photonics is to strongly confine light in small volumes to increase light-matter interaction. Presently, an intense research activity is devoted to designing and fabricating high Q and small V photonic microcavities. Recently, we have studied two types of microcavities and will report on their electromagnetic properties at the conference.

## Pillar microcavities

Pillar microcavities have played a major role in the development of several optoelectronic devices, including vertical cavity surface emitting lasers [1]. We present the results of an exact electromagnetic modelization of the Q and Purcell factors of GaAs/AlAs pillar microcavities in the small-diameter limit, which reveals amazing novel phenomena. Both factors display indeed a fast oscillatory variation as a function of the pillar diameter, and Q reaches values well in excess of the quality factor of the reference planar cavity. A simple approximate model will be introduced to interpret the physical origin of this unexpected behaviour.

## Photonic-crystal microcavities

Recently, a new concept based on tailoring the Fourier spectrum of cavity modes has been proposed [2] for increasing their lifetime. It has been alleydedly validated through the achievement of a surprising $\approx$10-times Q enhancement by finely tuning the mirror hole geometry in a photonic-crystal nanocavity with a Q factor as high as 45,000. We will argue that the concept is not warranted, and that the Q improvement is due to an increase of the impedance wave-matching at the cavity edges and to a slow-wave effect. This interpretation is confirmed by 3D computational results and by an approximate based on a Fabry-Perot model using the bouncing of the Bloch mode of a one-row missing photonic crystal waveguide.

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# Adiabatic excitation of slow light states in 1D

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**Keywords:** optical waveguide theory, numerical modelling, photonic crystals, periodic structures, slow light

**Abstract**
We present a design strategy for adiabatic excitation of slow light (SL) states near the band edge of 1D gratings. For this, we developed the standard coupled mode theory (CMT) to handle the 1D gratings with modulation in grating strength via Bloch-mode basis. Later on, the CMT will be employed for optimisation of SL device. We show that the optimised SL structure produces the strong enhancements and high transmission of the SL modes, in a relatively short length. The study is meant to be the basis of further research of 2D and 3D SL structures.

**Adiabatic excitation of SL 1D gratings**
Since the properties of incoming wave of a uniform medium are very different from the one of the SL grating mode, direct excitation of SL devices will cause high losses (large back reflection.) [1,2]. In order to overcome this problem, adiabatic excitation will be carried out. Hereby the modulation depth of the fraction is chosen to increase such that the coupling between forward and backward moving grating modes is kept constant. According to the developed CMT, the aforementioned tapering of the mode depth leads to a tapering formed by

$$\frac{\partial n_m}{\partial z} \propto C(n_{m,gap}^2 - n_m^2)^{3/2}$$

where $n_m$ is the modulation depth, z is the propagation direction, and $n_{m,gap}$ the index corresponds to the band edge. With the procedure, a power enhancement of about 160 was achieved for a taper length of 1 mm.

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# Diffraction Losses, Cavity Modes and Exciton Polaritons in Photonic Crystal Slabs

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In this work we report on the theoretical results obtained for photonic crystal slabs, also known in the literature as waveguide gratings for the 1D case, both in airbridge and Silicon-on-insulator (SOI) configurations.

These systems are characterized by the existence of truly guided modes, which lie below the light line of the cladding material, and quasi-guided modes lying above the light line, the latter being subject to intrinsic radiation losses owing to the periodicity in the plane of the waveguide. The method adopted for the calculation relies on an expansion of the magnetic field on the basis of the guided modes of the effective planar waveguide with averaged dielectric constant [1]. The radiation losses are calculated by taking into account the coupling to leaky modes of the effective homogeneous waveguide by perturbation theory. The effects of structural imperfections of the system are considered by using a supercell with a gaussian distribution of the air fraction in the plane of periodicity to model the disorder-induced out-of-plane diffraction. The radiation losses are related to the spectral linewidth of the photonic eigenmodes, e. g. in reflectance or transmittance experiments.

A detailed study of photonic band dispersions and gap maps is made for 1D photonic structures, and compared to the reference ideal 1D system. A proper study of gap formation is of crucial importance in the design of structures containing localized defect modes. Single defect cavities embedded in SOI waveguide gratings are theoretically studied with the finite-basis expansion method discussed above, and the results show very good agreement with a modal expansion method [2] and also with preliminary experimental data. The conclusion is that the quality factor of the cavity can be experimentally probed by variable angle reflectance.

When a quantum well with a strong excitonic resonance is inserted in the core layer of a photonic crystal slab (e. g. a GaAs membrane with InGaAs quantum wells), the interaction between excitons and the photonic eigenmodes in the grating may lead to the existence of mixed polaritonic states. A full quantum mechanical theory of these *photonic crystal polaritons* is developed [3]. We present the results for the dispersion of these quasi-particles and discuss the conditions leading to their formation.

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# Determination of Floquet–modes in asymmetric periodic structures

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It will be shown how the Floquet modes in asymmetric periodic structures can be determined.

**Keywords:** periodic structures,Floquet's theorem, method of lines

Periodic structures like Bragg–gratings are important components in optical circuits. Paricularly, an efficient algorithm for the analysis of symmetric structures (with respect to the direction of propagation) has been described in [1]. For this purpose Floquet's theorem has been introduced. The stable determination of Floquet modes for this case has been presented recently [2], [3].

Besides the symmmetric periodic structure also devices which are not symmetric with respect to the direction of propagation are important. Examples are multilayer or blazed gratings (see Fig. 1). Another example is a dielectric antenna that has been proposed in [4]. An algorithm for analyzing also these asymmetric periodic structures has been described in [5]. A problem remains the determination of the Floquet modes. The transfer matrix expressions used in [5] are stable only for short periods and low losses. One way of determining the Floquet-modes in a stable way was shown in [6]. In this contribution we present an extension of the algorithms given in [2] and [3]. First, we derive an impedance or admittance relation for the electric and magnetic fields on the two sides of one period (plane A, B in Fig 1):

$$\begin{pmatrix} \mathbf{H}_{\mathrm{A}} \\ -\mathbf{H}_{\mathrm{B}} \end{pmatrix} = \begin{bmatrix} \boldsymbol{y}_{11} & \boldsymbol{y}_{12} \\ \boldsymbol{y}_{21} & \boldsymbol{y}_{22} \end{bmatrix} \begin{pmatrix} \mathbf{E}_{\mathrm{A}} \\ \mathbf{E}_{\mathrm{B}} \end{pmatrix} \qquad (1)$$

From this expression a matrix difference equation system can be developed resulting in an explicite matrix eigenvalue problem. The solution of this eigenvalue problem finally gives the Floquet–modes. It should be mentioned that the size of the matrices is doubled compared to the symmetric case in [2] [3]. Hence the numerical effort is higher, here.

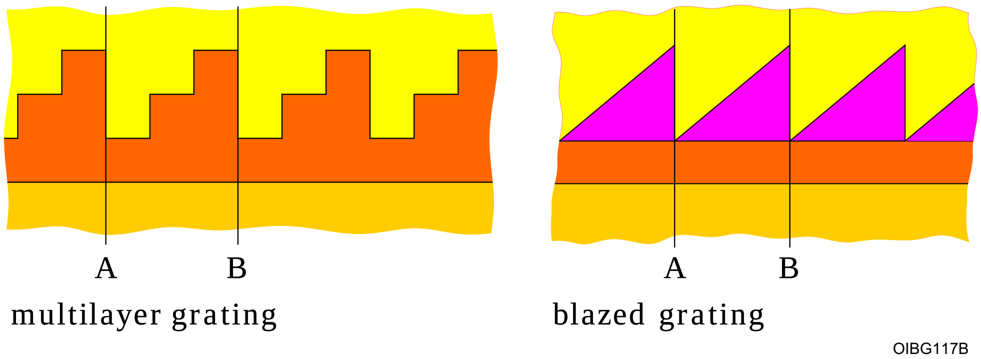


Fig. 1: Examples of asymmetric periodic structures

The numerical results show that the forward and backward propagating modes in case of isotropic structures have identical propagation constants, while the field distribution is different.

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# Fourier analysis of Bloch wave propagation in photonic crystals

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We propose an original description of Bloch wave propagation in photonic crystals based on their Fourier decomposition into series of pseudo-electromagnetic plane waves. This model provides a new physical understanding of negative refraction.

**Keywords:** photonic crystal, Bloch wave, Fourier analysis, negative refraction, left-handed material

Although phenomena such as negative refraction, high dispersion or self-collimation have been numerically modeled and experimentally observed in Photonic Crystals (PhCs), there is as yet very little published work on the physical understanding of such effects. Yet, the design of new optical devices based on these phenomena requires a thorough understanding of light propagation in PhCs. Electromagnetic Bloch waves are the standard representation of the optical field propagating in periodic media and we will present an original description of these waves based on their Fourier transform.

We will first consider an electromagnetic Bloch wave propagating in a PhC and expand separately its electric, magnetic and electric flux density fields in Fourier series. Using Maxwell's equations, we will show that the relationships between their $n^{th}$ Fourier components correspond to the case of an electromagnetic plane wave. Pursuing a similar analysis on the Poynting vector and the group velocity, we will demonstrate that Bloch waves can be decomposed into series of pseudo-electromagnetic plane waves. The special properties of these constitutive plane waves will be discussed, as well as their individual contributions to the total energy and group velocity of the global Bloch wave. The validity of the decomposition will be explained in the one- and two-dimensional case for TE and TM waves.

This original approach brings a new insight for fundamental understanding of light propagation in PhCs because light properties in homogenous or modulated media can be described with the same model. The analysis of the vanishing modulations case will highlight important characteristics of Bloch waves. For example, we will demonstrate that the energy of Bloch waves located in the second transmission band is mainly stored in the second Brillouin zone. Consequently, the wave vector best characterizing Bloch waves is not necessarily located in the first Brillouin zone. We will discuss how our approach resolves inconsistencies resulting from the artificial band folding for vanishing modulations, which were pointed out by *Notomi et al.* [1]. Finally, we will show that our model provides a new physical understanding of negative refraction phenomena and clarifies the origin of the left-handed material behaviour observed in PhCs.

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# Resonnant transmission through two dimensionnal photonic crystal with line defects

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We study numerically the resonant transmission of plane waves through two dimensional photonic crystal with line defects. By using the Fourier modal method, it is shown that two kinds of waveguide modes can contribute to the transmission.

**Keywords:** photonic crystal, defect modes, modal analysis.

Photonic crystals have inspired great interest because of their potential ability to control the propagation of light [1],[2]. It is well known that when a line defect is introduced in a perfect photonic crystal that exhibits a band gap, waveguides in which guided modes are allowed may be created. In the present paper, we investigate the transmission properties of a finite size two dimensional plotonic crystal in which slits are periodically etched. It is numerically observed that resonant transmission occur. Such anomalous effects are of importance because they have potential application in novel photonic devices. By using the Fourier modal method, we can calculate the effective index of the modes inside the slits and the coupling of these modes with the reflected and transmitted order. The modal analysis reveals that two kinds of waveguide modes can exist inside the slits. The line shape of the resonance is closely related with the mode present in the slit. Fig 2 shows the spectral transmission for a structure with the following parameters (arbitrary units): $d_1=d_2=1$, $a=b=0{,}5$ , $h=6$, $\Lambda=4{,}7$ , $w_1=1{,}2$ , $w_2=0{,}7$ , $\varepsilon_1=3{,}5$ , $\varepsilon_2=1.5$ . The two cases (a) and (b) correspond to two different defect modes. Furthermore, in the case of conical incidence the structure can be designed in such a way that the response is independent of the polarisation of the incident plane wave.

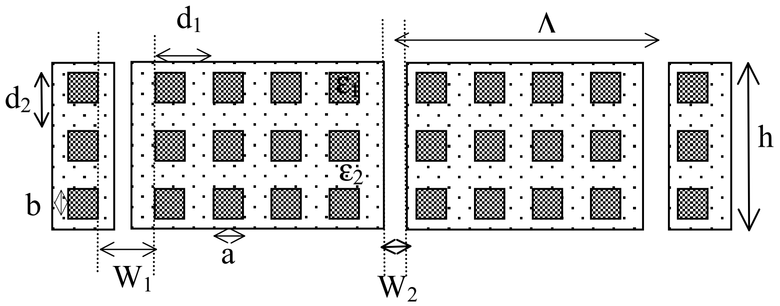


**Figure 1: Geometric configuration of a two dimensional photonic crystal with line defects**

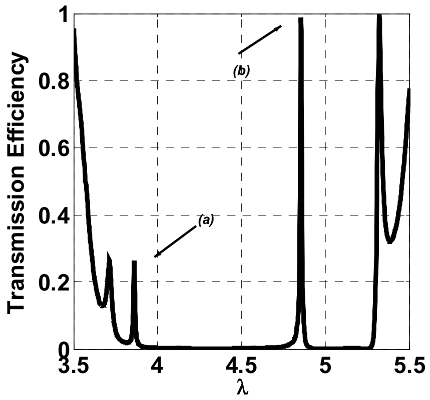


**Figure 2 :Transmission efficiency versus wavelength of a stack of 6 periodic layers with an air slit under normal incidence**

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# Phenomenological representation of deep and high contrast lamellar gratings by means of the modal method

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Deep and high index contrast lamellar gratings exhibit a number of interesting effects such as sharp resonant reflection [1], high extinction wide band polarization [2], wide band total reflection [3], narrow band total transmission [4]. These effects have long been identified and analyzed by means of numerical techniques. It is however still difficult to make the synthesis of a structure exhibiting a desired optical function.

The modal method naturally offers a simple and very physical understanding of the interference phenomena taking place in these deep high contrast structures. The modes propagating up and down are described by analytical formulae, and there are very few of them in most cases of interest where the period is of the order of the wavelength. These modes are excited by an incident free space wave and they radiate forward and backward depending on their relative propagation constants along the grooves and slabs of the grating and depending on their mutual coupling at the grating top and bottom.

Some remarkable effects will be analyzed at the light of this "vertical mode" representation such as resonant reflection and wide band total reflection, and the general methodology of this phenomenological representation will be presented.

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# Finite Difference Time Domain code for second harmonic generation in photonic crystals

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**Abstract:** A simple 2D nonlinear finite difference time domain code is used to investigate second harmonic generation in a 1D and 2D photonic crystals in waveguide configuration.

Finite Difference Time Domain (FDTD) codes were recently extended to describe field propagation in 2D photonic crystals (PCs) having a sizeable second order nonlinear tensor[1]. The nonlinear FDTD method we developed constitutes an intuitive alternative solution able to analyze the SHG in an arbitrary 2D structure with a reasonable time consumption at expend of loosing generality (non-depleted pump approximation and intra-pulse chromatic dispersion neglected) [2]. It is based on the implementation of two parallel linear FDTD codes. The first operating at fundamental field (FF) wavelength and the second at second harmonic field (SH) wavelength. The quadratic nonlinearity is only taken into account for the SH, which is not coupled back at the FF wavelength. Chromatic dispersion is considered simply by taking the actual refractive index at FF and SH wavelengths. This artificial separation of FF and SH propagation allows to easily identify FF and SH distribution and other relevant physical parameters. We apply the code to the estimation of SHG efficiency in 1D and 2D nonlinear PCs.

**I- 1D photonic edge waveguides: the role of diffractive losses:** A schematic view of a typical phase matched and doubly resonant (FF and SH) NL 1D-PC is shown in Fig. 1. The results obtained as a function of the number of period N (until N=20) for h=2µm and H=3µm are represented in squares in Fig. 2. In order to fully understand the role of losses in SHG and to predict the efficiency as N is further increased, we develop an equivalent double resonant cavity model which takes into account heuristically diffractive losses both at FF and SH wavelength (full lines).

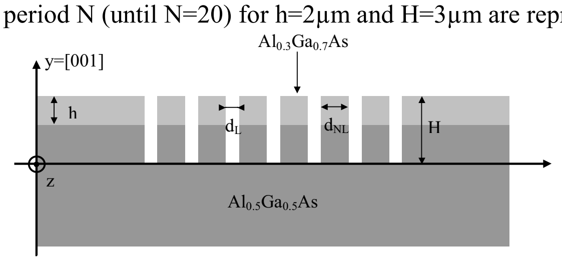
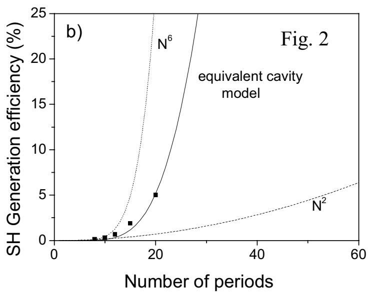



Fig. 1. Schematic of the 1D structure - $d_L$ and $d_{NL}$ are the thickness of the linear (air) and nonlinear layers




**II - Phase-matching in W1 2D photonic crystal waveguide:**
The structure is designed (Fig. 3) in order to have photonic bandgaps around the FF frequency for the H polarization and around the SH frequency for the E polarization. It thus supports waveguide modes at FF and SH wavelengths. We use our NLFDTD code to calculate the generated SH. Figure 4 represents the normalized (to the incident FF spectrum) SH spectrum (thick line). The linear response of the structure around SH wavelength obtained with usual FDTD is also plotted (thin line). The SHG spectrum clearly shows maxima at expected phase-matched wavelengths $\lambda_0$ and $\lambda_1$. In addition, NLFDTD code gives rich information on SHG that takes into account several interesting effects: 1) The presence of a mini gap between $\lambda_0$ and $\lambda_1$ and resonances around it. 2) An additional resonance at $\tilde{\lambda}_0$, non predicted by the simulation of the infinite equivalent structure, is also observed. 3) The maximum of SHG is obtained at $\lambda_0$-mode that, in addition to phase-matching, takes benefit both from a good FF/SH overlapp and small FF group velocity.

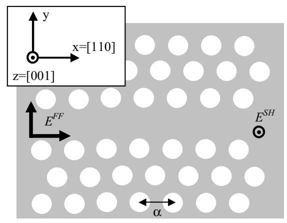



Fig. 3. Schematic of the 2D structure

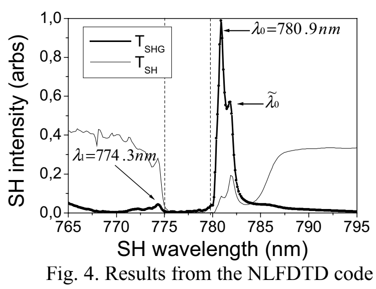



Fig. 4. Results from the NLFDTD code

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# Modeling Second Harmonic Generation with Mode Expansion

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We present an accurate and efficient method using eigenmode expansion to model second harmonic generation in two-dimensional structures.

**Keywords:** numerical methods, mode expansion, second harmonic generation, periodic structures

## Introduction

In future all-optical WDM networks nonlinearities will necessarily play an important role in switches or wavelength converters. One of the simplest schemes for the latter is second harmonic generation (SHG). In order to design efficient integrated SHG components new numerical tools are needed.
Most of the methods available focus on a plane wave or single mode approach. Full transverse effects are only modeled with FDTD or BPM. Our technique extends a plane wave method [1] in order to handle a number of eigenmodes. With the non-depleted pump wave approximation we construct a matrix formalism, extending upon CAMFR [2], to calculate the generated second harmonic in one run.

## Method

We write the fields at ω and 2ω as a superposition of eigenmodes and put them in the SH differential equation. By applying mode orthogonality and approximations (slowly varying envelope, non-depleted pump) we find the respective SH mode amplitudes:

$$B_k(z) = B_k(0) + \gamma \sum \frac{e^{j\Delta\beta z} - 1}{\Delta\beta} A_i^2 \langle i | k \rangle .$$

The sum indicates the separate contributions of the fundamental modes, determined by three factors: a phase matching factor ($\Delta\beta = 2\beta_i^{\omega} - \beta_k^{2\omega}$), the fundamental mode amplitude squared and a mode profile overlap integral. With this expression we can derive a bidirectional scattering matrix formalism, thus taking multiple reflections into account.
As is evident from the equation above, coupling between e.g. high order SH radiation modes and fundamental guided modes can become negligible. Therefore our tool allows choosing the subsets of fundamental and second harmonic modes that take nonlinear generation into account. With the rest of the modes scattering linearly, this speeds up calculations.
Because the formalism is analogous to the linear case, the same dramatic decrease in calculation time and memory, compared to FDTD or BPM, is present. Especially in photonic crystal devices, we can effectively reuse many calculations (mode profiles, overlap integrals...).
In conclusion, our method efficiently simulates SHG in two-dimensional stuctures with high index contrast.

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# Transition Between Dark and Antidark Soliton-like Solutions in A Finite Deep Nonlinear Bragg Grating with Mirror

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We have studied the existence of soliton-like solutions in a system consisting of a finite deep nonlinear Bragg grating and a metallic mirror. Transition of the admitted dark and antidark soliton-like solution is shown to be induced by either varying the input optical intensity or the mirror position.

**Keywords:** deep nonlinear Bragg grating, soliton

## Introduction

We report the result of our study on a system consisting of a finite deep nonlinear Bragg grating and a metallic mirror as a model for the creation of a standing light pulse in the form of dark or antidark solitons. Our study is conducted on the basic of a general coupled mode equation for a deep nonlinear Bragg grating which accommodates the case of narrow and finite gap in an infinite grating [1,2]. We have demonstrated in ref. [1] that the grating system admits the so-called "in-gap" dark or antidark soliton solutions if the coefficients of all the nonlinear terms are of the same order of magnitude. We examine, in the finite system considered, the characteristics of those solitonic solutions and the transition between them induced by changing the light intensity of the source or shifting the mirror position.

## The Finite Grating System

The system is similar to the one proposed previously in ref. [3] as depicted in figure (1), which consists of a c.w light source (*s*) with frequency $\omega$, a deep nonlinear Bragg grating (*g*) with length, $L = M\Lambda$, and a metallic mirror (*m*) positioned at a distance $D$ from the grating. The presence of the metallic mirror is aimed to assure the zero energy flow condition and to fix or regulate the phase mismatch between the forward and backward field at the grating end on the mirror side. Since the electric field at the mirror surface is zero, one can simply write $E_{mirr.surf.} \equiv f_m\left[\exp(i\pi/2) + c.c\right]$. Consequently, the field on the grating end facing the mirror is given by $E_m = f_m\left[\exp(i\phi_m) + c.c\right]$, where, $\phi_m = \pi/2 - k_m D$. While the field on the source end of the grating is given by $E_s = f_s\left[\exp(i\phi_s) + c.c\right]$. Here, $\phi_m$ and $f_s$ are externally controllable parameters.

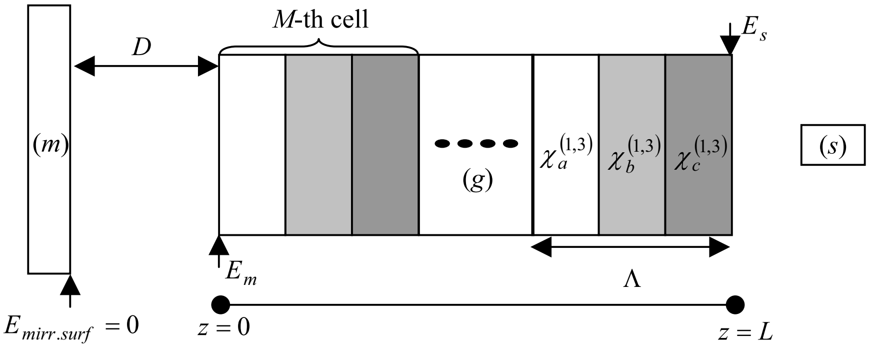
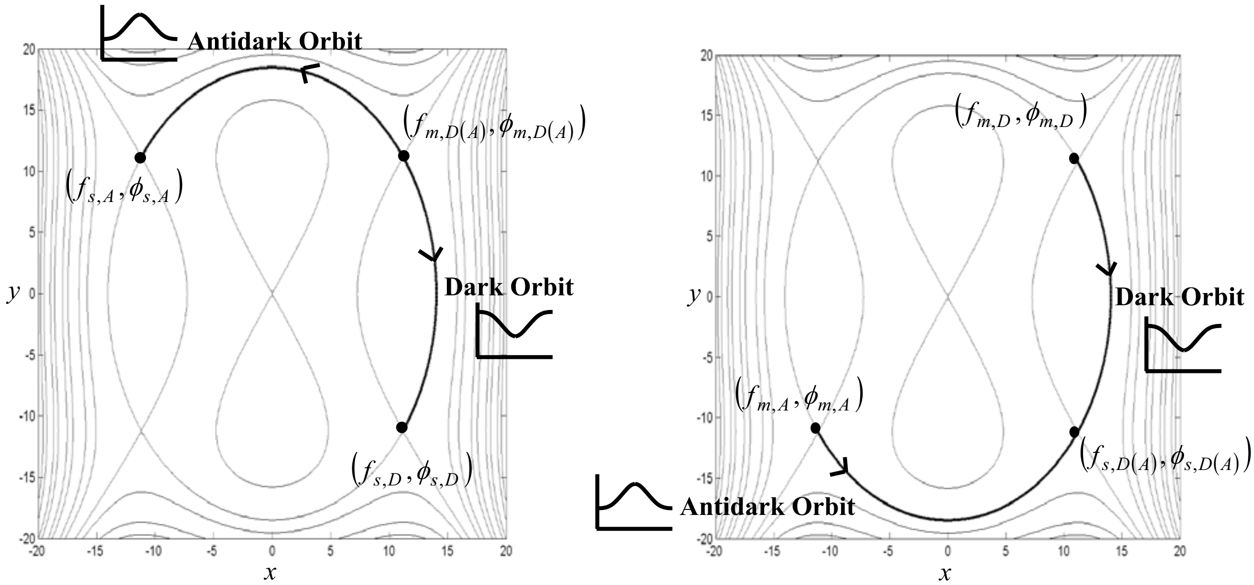



Fig. 1. Schematic drawing of the system considered

## The Results

Based on the phase plane analysis, we found that two different states of dark and antidark solitons associated with different branches on the corresponding phase portraits, can be connected either optically by changing the intensity of the source or mechanically by changing the mirror position as shown schematically in figures (2a) and (2b) respectively.




(a) (b)

Fig. 2. The dark to antidark soliton transition induced by (a) changing light source intensity where in general $f_{s,D} \neq f_{s,A}$ while keeping $\phi_{m,D} = \phi_{m,A}$ (b) changing the mirror position where $\phi_{m,A} \neq \phi_{m,D}$ , while keeping $f_{s,D} = f_{s,A}$ The subscripts *s* and *m* refer respectively to the grating ends facing the source and mirror respectively, while *A* and *D* refer respectively to Dark and Antidark solitons. The small graphs at the figure illustrate the corresponding dark and antidark amplitude profiles as functions of *z*.

A numerical calculation has been carried out to solve the associated coupled equations. The result shows that the optically induced transition process generally follows a hysteresis loop, while the mechanically induced transition is free from the hysteretic effect. This result suggests the desirability for a further study on its potential for photonic applications.

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# Time Domain Simulation of All-Optical Limiter Using Kerr and Duffing Models

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The behaviour of an all-optical limiter is simulated using both the Kerr and Duffing models of optical non-linearity. It is shown that the Duffing model, only, can take full account of the non-linear and dispersive character of the limiters.

**Keywords:** Non-linear materials, Kerr non-linearity, Duffing non-linearity, time domain modelling.

**Introduction**

Fibre Bragg Gratings have emerged as one of the more important components in non-linear optics. The non-linear nature of the gratings allows dynamic tuning of the band gap, and thus gives rise to a varied range of applications, including optical switching, limiting [1], soliton propagation, and dispersion-compensated pulse shaping. Due to the complex interplay of dispersion and non-linearity in these systems, however, analytical treatments are restricted to a few simplified cases. More complex problems require the use of a suitable numerical tool, such as the Finite Difference Time Domain method (FDTD) [2], or Transmission Line Method (TLM) [3], to provide further insight into the nature of these complex phenomena. In the present paper, we focus on the application of the TLM method to the analysis of non-linear phenomena in all-optical devices. In particular, we compare results obtained using two different formulations of the non-linearity– the Kerr model and a Duffing model.

In the Kerr model the polarisation function can be described by:

$$P = \varepsilon_0 (n_0^2 - 1)E + \varepsilon_0 2 n_0 n_2 E^3 \qquad (1)$$

where $n_0$ is the linear refractive index of the material, $n_2$ is the non-linear coefficient and $E$ is the applied electric field. The Duffing model, on the other hand, is a more realistic model of the electronic polarisation in a dispersive, non-linear, dielectric and is given by [4]:

$$\frac{\partial^2 P}{\partial t^2} + 2\delta \frac{\partial P}{\partial t} + \omega_0^2 (1 + \alpha P^2) P = \varepsilon_0 \Delta\chi_e \omega_0^2 E \qquad (2)$$

where $P$ is the polarisation, $\delta$ is the damping frequency, $\omega_0$ is the resonant frequency, $\alpha$ is the non-linear coefficient and $\Delta\chi_e$ is the susceptibility contrast. In the Kerr model, the polarisation remains unsaturated for large applied electric fields, and this may lead to instability. The Duffing model, however, takes into account the dispersive nature and saturation of the dielectric and is therefore more generally applicable than the Kerr model [4]. Parametric analyses of the two models are performed and results so-obtained are compared for the case of a plane wave propagating in non-linear and dispersive dielectrics. The two models are applied to simulate an all-optical limiter consisting of layers having alternate positive and negative non-linearity coefficients [1]. It is shown that full account of the non-linear and dispersive character of the optical limiters can only be obtained using the Duffing model.

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# Time domain Bi BPM for ultrashort nonlinear pulse propagation

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We developed a time domain bidirectional beam propagation method able to deal with pulse propagation in nonlinear periodic structures. This algorithm permits to analyze the reduction of second-harmonic generation efficiency with ultrashort pump pulses.

**Keywords:** bidirectional beam propagation method, second-order nonlinearity, pulse propagation.

Recently a time-harmonic bidirectional beam propagation method (Bi BPM) based on scattering operators has been proposed to model nonlinear interactions in photonic bandgap (PBG) waveguides [1]. This numerical method has been reformulated to obtain a time domain Bi BPM (Time Bi BPM) able to investigate short pulse propagation in PBG. This technique, which stems from the Bi BPM, is able to address the problem of Second-Harmonic Generation (SHG) in periodic structures pumped with ultrashort pulses. Assuming the propagation along the $z$ direction, we define $A^{\pm}(t,z) = u^{\pm}(t,z)\exp(\mp i\bar{k}_{rif}z)$ as slowly varying functions in the time domain, then the electric field is the sum of two counterpropagating components identified by the superscripts "+" and "−". This assumption permits us to write the governing equations in the linear regime as

$$\mp 2i\bar{k}_{rif}\partial_z u^{\pm}(t,z) + \left(k^2(z) - \bar{k}_{rif}^2\right) u^{\pm}(t,z) - 2ik\partial_\omega k\partial_t u^{\pm}(t,z) - k\partial_\omega^2 k\partial_t^2 u^{\pm}(t,z) = 0 \qquad (1)$$

where the two derivatives with respect to $\omega$ are evaluated in $\omega_0$. Supposing also that the refractive index is stepwise, i.e. $n(z) = n_j$ for $z_{j-1} < z < z_j$, we can write formal solutions of (1). From these we are able to find the operators $P$ and to write the continuity conditions at the interfaces in $z = z_j$ [2]. Our tool is based on a scattering operator formulation [2] extended to treat second-order nonlinear problems. The reflection and transmission operators read as

$$R_p(z)\,A_p^+(t,z) + W_p(z) = A_p^-(t,z); \qquad T_p(z)\,A_p^+(t,z) + K_p(z) = A_p^+(t,a^+) \qquad (2)$$

where $a$ is the length of the analyzed structure. The operators $W_p$ and $K_p$ take into account of the nonlinear energetic exchanges between components centered in $p = \omega_0$ and $p = 2\omega_0$. We propose a method to determine the operators $R_p(0^-)$, $T_p(0^-)$, $W_p(0^-)$ and $K_p(0^-)$ at the input, step-by-step, from their known values at the output [$R_p(a^+) = 0$, $T_p(a^+) = I$, $W_p(a^+) = 0$ and $K_p(a^+) = 0$]. The algorithm has been successfully used to study the SHG efficiency in periodic structures pumped with ultrashort pulses, and will be used for the analysis of the process of Difference Frequency Generation (DFG), which is the basis of wavelength conversion in PBG.

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# 3D Time Domain Integral Equation Model

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A 3D vector time domain algorithm has been derived from a time domain integral formulation of the physics of light in complex and time varying media. The scheme has proved both accurate and stable.

**Keywords:** time domain analysis, 1D and 3D model, numerical algorithm

## Introduction

Modelling the physics of time varying problems by means of Volterra integral equations has previously led to the development of a 1D numerical algorithm with certain computational advantages over the FDTD approach, [1-4]. Specifically, the need to directly discretise fields only in discontinuity regions where the structure under consideration differs from a simple background structure yields significant scope for memory reduction. An example of such a situation is provided by the case of a micro-resonator in a uniform or stratified space. To date, only the 1D algorithm had been developed. Here we present a full 3D vectorial algorithm, which promises to significantly extend the practical range of structures which can be simulated.

## Theory

In general, the electric field in a 3D structure satisfies a Volterra integral equation [4]

$$\mathbf{E} = \mathbf{E}_0(t,r) + \int_0^{\infty} dt' \int_{V(t')} dr' \left[ \frac{1}{4\pi} \left( \nabla\nabla - \frac{\partial^2}{v^2 \partial t^2} \right) \frac{\delta\left(t - t' - \frac{1}{v}|r - r'|\right)}{|r - r'|} \left( \frac{\varepsilon_1(t') - \varepsilon_b}{\varepsilon_b} \right) \right] \mathbf{E}(t', r') \quad (1)$$

where $V(t)$ is a spatial integration region, $\varepsilon_b$ and v are the relative permittivity and speed of light in the background material, here assumed to be a simple uniform dielectric. $\varepsilon_1$ is the relative permittivity of the discontinuity region $V(t)$ and may be time varying, non-linear and dispersive in general. $E_o$ is the excitation field and t and r =(x,y,z) are the time and space coordinates. Equation (1) is discretised onto a Cartesian mesh and the 4D integrals reduced to 3D using the properties of delta functions. By means of careful discretisation of the spatial and time derivatives in (1) it has proved possible to obtain a stable scheme that gives the present value of electric field at any point in space in terms of the time history of the fields only in the discontinuity region.

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# Modelling of Microstructured Waveguides using Finite Element based Vectorial Mode Solver with Transparent Boundary Conditions

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Finite element vectorial optical mode solver is used to analyze microstructured waveguides in a relatively small computational domain. The presentation will consider the computational method, as well as the applications of it on a number of waveguides with 2-D cross section where microstructures are employed.

**Keywords:** finite element method, transparent boundary conditions, microstructured optical waveguides

Since the introduction of holey fiber[1], various waveguiding structures that utilize the arrangement of holes or thin layers have been proposed. The large variety of possible hole shapes and arrangements demand the use of numerical methods that can handle arbitrary cross section to analyze the structure. In this work, we use vectorial optical mode solver[2] based on Galerkin finite element method furnished with 1$^{st}$-order Bayliss-Gunzburger-Turkel-like transparent boundary conditions to model various kinds of microstructured waveguides. Due to the boundary conditions, the structure can be analyzed in a relatively small computational domain and depending on the structure, guided or leaky modes computation can be carried out. The structures being considered include those with index or bandgap effect to guide light, and those that use holes to tune among others, the dispersion properties of an ordinary fiber.

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# Fourier Based Method-of-Lines Beam Propagation Method to analyse optical waveguide discontinuities

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In this work we propose a Fourier based method-of-lines beam propagation method with PML absorbing boundary conditions for analysing abrupt discontinuities in 2D and 3D optical waveguides. The method has been applied to study abrupt longitudinal discontinuities of slab and fiber waveguides.

**Keywords:** global numerical methods, fourier series expansion, perfectly matched layers, method-of-lines, optical waveguides, beam propagation method, discontinuities.

## Introduction

The method-of–lines (MOL) is a well known technique that has been successfully used in the last years to analyse all kind of problems in microwave and optics [1]. Traditionally, the transversal discretisation necessary to apply the MOL has been done by using finite-difference methods (FDM), although discretisation schemes based on finite-element methods (FEM) have also been presented in the bibliography [2]. In this work we propose to apply the Galerkin method with Fourier basis functions instead of the FDM or FEM techniques. This strategy has recently been used to achieve an efficient and robust Fourier Based 3D-Full Vectorial Beam Propagation Method with PML boundary conditions [3]. To test the proposed Fourier based method-of lines, different 2D and 3D optical discontinuities have been simulated. In Fig.1 is represented the power reflectivity of an abrupt coupling of slab waveguide to air versus the core thickness, while in Figs.2-3 the problem of a weakly guiding optical fiber with an abrupt termination in air is analysed. In both cases, the obtained results are in agreement with those previously published in the bibliography [4]-[5], and confirm that accurate results can be achieve with a reduced number of harmonics.

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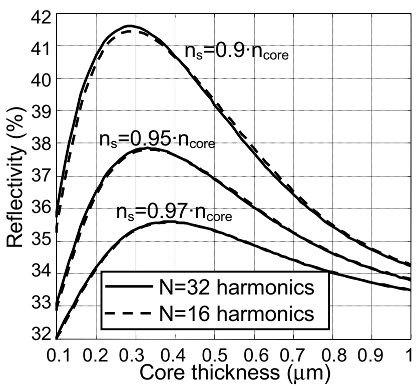


**Figure 1.** Power reflectivity of the fundamental mode of a slab waveguide with an abrupt termination in free space. Parameters: $n_{core}$=3.6, $\lambda_0$=0.86μm

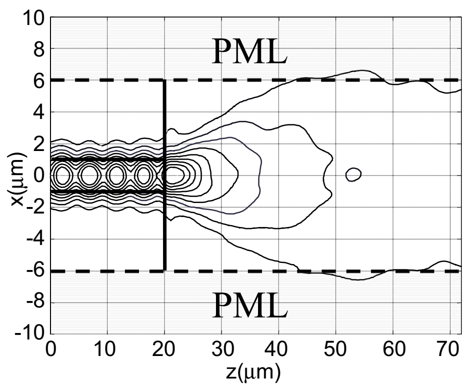


**Figure 2.** Contour map of the electric field around an abrupt fiber-air discontinuity. Parameters: Core radius 0.98μm, $n_{core}$=1.46, $n_{cladding}$=1.4162, $\lambda_0$=1.3μm. $N_x$=$N_y$=16

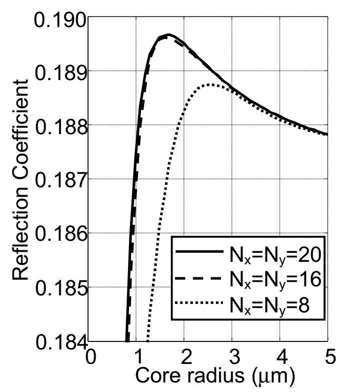


**Figure 3.** Reflection coefficient of the fundamental mode versus the core radius. Same case as Figure 2.

# The Single Mode Condition for Large Cross-Section Optical Rib Waveguides.

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Widely used design criteria are shown insufficient to ensure the single mode behaviour of large cross-section rib waveguides. The importance and implications of this finding are discussed and other designs based on ARROW waveguides investigated.

**Keywords:** Finite difference method, beam propagation method, waveguide modes.

Single-mode semiconductor rib waveguides are critical components in planar photonic circuits realized in many materials systems. Single-mode rib waveguides that also possess large cross-section dimensions (typically several microns high and several microns wide) are particularly desirable since they permit efficient optical coupling to fibres [1]. The widely used geometrical constraints for the single-mode behavior of large cross-section rib waveguides presented in [1] and [2] (and later discussions of rib waveguides with sloped walls, [3]) are based upon the cut-off equation for the $HE_{01}$ and $EH_{01}$ modes. In this paper, results from detailed numerical analyses of the modal characteristics of large cross-section rib waveguides show that satisfying these widely used criteria is not sufficient to ensure single-mode behaviour. In particular, many geometries predicted single-mode for each polarization are shown to support low-loss higher-order vertical modes. Fortunately we can also identify large cross-section rib geometries that remain effectively single mode for each polarization. Our findings, and their importance, are clearly confirmed by performing further simulations using a Finite Difference Beam Propagation Method. (FD-BPM). Early experimental results on silicon-on-insulator waveguides, [4], provide some additional support. The implications of our findings on multi-waveguide photonics components such as arrayed waveguide gratings will also be discussed before we briefly show how the use of ARROW waveguides can increase the design options for large-cross section single mode rib waveguides.

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# Roughness-induced propagation loss in ultra-small square SOI waveguides

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Numerical investigations of scattering loss induced by side-wall roughness is performed as a function of the size of SOI square strip waveguides. Propagation loss are strongly correlated to field confinement and are maximum for a 260nm×260nm waveguide. They are quite small for a 150nm×150nm waveguide which is well suited to very low loss light coupling from and to a single-mode fiber.

**Keywords:** optical waveguide, SOI, side-wall roughness, propagation loss, optical telecommunications

## Modelling

The side-wall roughness is the main source of propagation losses in submicron strip waveguides. Scattering loss effects are calculated. A model derived from a planar waveguide [1] has been used and extended to the case of 2D structures. Thus, the propagation loss coefficient can be written in dB/cm as $\alpha = 4.34 \frac{\sigma^2}{k_0 \sqrt{2} d^4 n_1} g(V).f(L_c, \gamma)$ where $g(V)$ and $\gamma$ depend on the waveguide geometry, $k_0$ is the wavenumber in vacuum and $n_1$ the core index whereas the standard deviation $\sigma$ and the correlation length $L_c$ characterize the roughness.

## Results

The waveguide width 2d ranges from 150nm to 500nm (Fig. 1). The corresponding calculated propagation loss are reported versus 2d in fig. 2 for $\lambda$=1.55µm with $L_c$=50nm and $\sigma$=2nm [2]. The simulations show that when 150nm<2d<250nm, the propagation loss decreases due to a lower optical mode confinement. Thus, for a 150nm ×150nm cross-section, the expected propagation loss does not exceed 0.5 dB/cm for a predicted mode diameter of 4µm at $1/e^2$. Such a result is of prime importance for optical telecommunications since a 2D tapered waveguide ended by a strip waveguide section with low confinement provides efficient coupling with a single mode optical fiber [3].

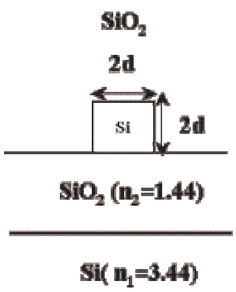


*Fig. 1 - Cross-section of the strip waveguide*

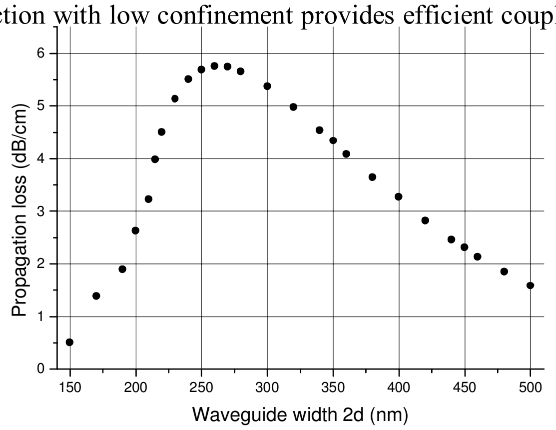


*Fig. 2 - Calculated propagation loss versus waveguide width*

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# Waveguide Bends: Accurate Mode Matching Modeling of Mode Fields

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A rigorous fully vectorial Film Mode Matching (FMM) analysis of mode field of bent waveguides is presented. Similarities and differences between the formulations of the FMM for straight and bent waveguides are clearly identified. A simplified semivectorial solver is easily obtained by neglecting TE-TM mode coupling terms.

**Keywords:** optical waveguide theory, numerical modeling, mode matching, bend mode solver

### Introduction

Microresonators are promising devices for many applications in integrated optics. Their design can be optimized using mode solvers that are often based on eigenmodes of a bent waveguide. Rotational symmetry of the structure implies that the mode field distribution in a radial direction is analytically described in terms of Bessel functions with both complex order $\nu$ and argument. In the bent guide with the radius of curvature $R$, the longitudinal phase factor $\exp(ik_0N_z z)$ for the case of a straight waveguide is substituted with the azimuthal dependence $\exp(i\nu\varphi) = \exp(ik_0N_\varphi R\varphi)$. Leaky character of the eigenmode due to radiation leads to complex $N_\varphi$ and thus to complex $\nu$.

### Modes of bent waveguide

FMM is a semianalytical method which belongs among the most accurate and fastest mode solvers. Our prime was to extend this method to circularly bent waveguides. Applying Hertz vectors with a single axial component allows us to express mode field in each radially uniform segment ("slice") as a superposition of modes of a multilayer planar waveguide. Even if the propagation constant of a bend is complex, the effective indices of planar 'slice' modes are real, which allows for using very fast methods for their locating. Amplitudes of eigenmodes in the expansion are then determined as solutions of a nonlinear eigenvalue problem – dispersion relation which is formed by matrices that consist of cylindrical functions. Projection of the orthonormal basis from one slice to another (neighboring) one is done by means of overlap integrals that are obtained from continuity conditions of tangential components of electric and magnetic intensity vectors.

Semivectorial version of the mode solver can be obtained in a straightforward way – by omitting overlap matrices mutually mixing the TE and TM slice modes. The benefits – reduction of matrices' dimension, increased speed, and simplification of mode spectra – outweigh the cost – lower accuracy of propagation constant and mode fields – for large class of waveguides.

Our derivation closely follows the procedure for a straight mode solver, providing a one-to-one correspondence between these two. Serious numerical difficulties caused by the appearance of cylindrical instead of trigonometric functions are believed to be essentially overcome.

Financial support by the European Commission (project IST-2000-28018, 'NAIS') is gratefully acknowledged.

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# A New Approach to the Computation of Leaky Modes

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We propose a new algorithm to compute leaky modes of waveguides. The algorithm is applicable to both 1D and 2D waveguide cross sections.

**Keywords:** leaky modes, eigenmodes, arrow waveguides

## Introduction

Most of the work dealing with the computation of leaky modes is based on the model of planar multilayer waveguides. The reason is that the popular transfer matrix method supplies a convenient way to derive implicit dispersion relations whose zeros correspond to bound and leaky modes of the waveguide. The search of zeros in the complex plane can be a difficult task, and so some methods are proposed to either circumvent this direct computation of zeros, e. g. [1], or to make this search both simple and robust, e. g. [2]. These methods work very well but they are limited by the fact that they rely on a 1D model - the multilayer structure of the waveguide.

## Pole Condition Approach

Our approach is based on a new understanding of wave propagation on unbounded domains [3]. Originally devoted to solve scattering problems on unbounded domains, it turns out that it can be applied as well to the computation of leaky modes. The main construction is as follows. First the 2D plane is decomposed into two domains. One of them, the interior domain, is bounded (say a circle or a rectangle) and contains the waveguide. The other domain is the remaining unbounded exterior domain. The interior domain may be discretized by any method, as a standard we use a finite element discretization. The exterior is discretized in a special manner by ray-like objects which cover the whole unbounded domain. On these rays a condition is posed that we call pole condition. The pole condition guarantees that asymptotically only outgoing waves exist. Interior and exterior solutions are glued together via the boundary conditions on the separating boundary. Altogether, the whole approach ends up with an algebraic non-hermitian eigenvalue problem which can be solved by standard Arnoldi packages as for example implemented in Matlab. The main features of the approach are the natural applicability to two dimensional cross sections, the simplicity of locating closely spaced eigenvalues and the certainty that all eigenvalues in a specified region of the complex plane are found.

We acknowledge support from the *DFG Research Center "Mathematics for key technolgies"* and the BMBF under contract No. 13N8252 (*"HiPhoCs")*.

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# Optimization of the Wallplug-Efficiency of Laser Diodes by an Electro-Optical-Thermal Black-Box Model

R. März, M. Behringer, C. Hanke, M. Kamp, and, B. Stegmüller

A black-box model for the optimization of the wallplug efficiency by choosing appropriate "external" parameters of an edge emitting laser -- resonator length, operating current -- is presented and applied to a high-power laser and a communication laser. The model is realistic, i.e., it correctly describes the thermal roll-over of the device.

Among the long list of laser parameters, the wallplug efficiency (and its optimization) often plays a minor role compared to others such as emitted power, differential efficiency and threshold current. For certain applications such as high-power lasers and sources for optical interconnects, the optimization of the wallplug efficiency has more significance by itself. It should be noted, however, that a device operated far away from its optimum wallplug efficiency produces, irrespctive from the underlying application, always an unnecessary thermal loading of the device and its environment resulting in potential aging problems.

Black-box models are interesting not only for laser manufacturers, but also for system oriented engineers who intend to simulate a laser within their system context and to derive from those simulations well justified requirement specifications.

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# Computation of Optical Modes in Microcavities by FEM and Applications in Opto-Electro-Thermal VCSEL Device Simulation

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Optical modes of microcavities are determined by solving Maxwell's vectorial wave equation subject to an open boundary. Using a continuation scheme the optical problem can be solved self-consistently with the electro-thermal device equations.

**Keywords:** optical mode computation, finite element method, numerical device simulation

## Optical Modes in Microcavities

The optical modes are determined accurately by solving Maxwell's vectorial wave equation, subject to an open boundary, taking into account diffraction and absorption of electromagnetic waves. Perfectly matched layer absorbing boundaries are used to model the open microcavity.

Combined 2D edge / node finite elements of first and second polynomial order are employed to formulate the optical problem. Expansions are in cylindrical coordinates assuming rotational symmetry of the device structure [1]. The accuracy of the result is assessed by benchmark examples.

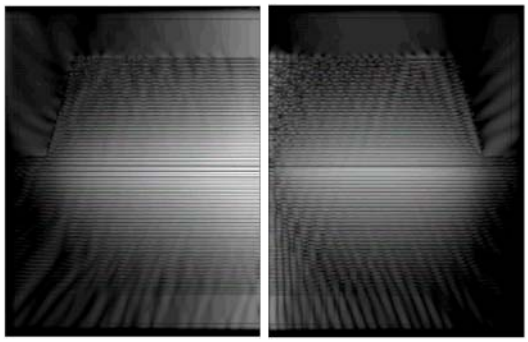

Fig. 1. HE11 and TE01 modes, normalised intensity, logarithmic grey scale

## Opto-Electro-Thermal VCSEL Device Simulation

Self-consistent opto-electro-thermal simulation of vertical-cavity surface-emitting laser (VCSEL) devices is presented. The simulator model is based on semiclassical microscopic laser theory. The model self-consistently describes spatially resolved quantities, namely, electrical potential, electron and hole densities, local temperature, and mean optical intensity. The input parameters to the model equations are the topology and the local physical material parameters.

The efficient computation of the optical modes based on a continuation scheme allows, for the first time, that Maxwell's vectorial wave equation, subject to an open boundary, can be solved self-consistently with the electro-thermal device equations [2].

The model is suitable for the analysis of a wide range of VCSEL device types with realistic device structures and sizes. Multi-mode simulation results are compared to measurements and show excellent agreement for a VCSEL with narrow oxide confinement. The practical use of the simulator as a computer aided design tool is demonstrated.

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# Modeling of polarization behavior of elliptical surface relief VCSELs

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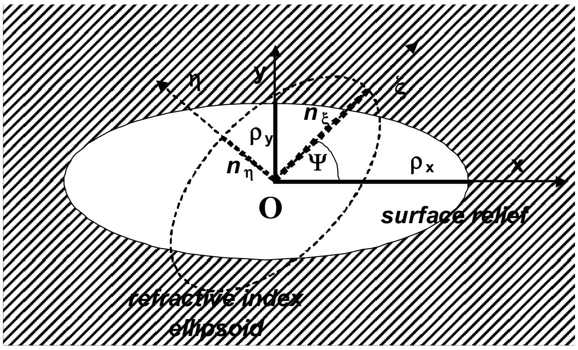
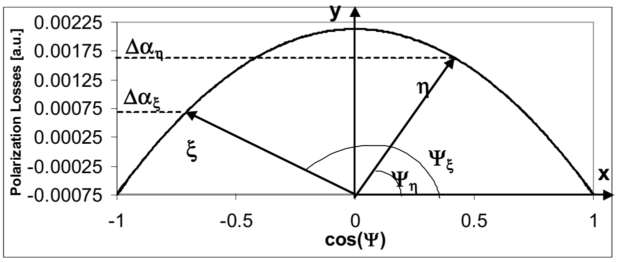
Many efforts have been made to ensure single transverse-mode operation of VCSELs. The general idea is either to reduce the transverse optical waveguiding or to introduce additional mode-selective losses. In the first case one, i.e., reduces the thickness of the AlAs layer or places it at a field node. One can even introduce antiguiding by post-growth, selective oxidation or radial change of the cavity length. In the second case, one modifies the lateral gain, introduces a. saturable absorber, uses external lens or curved micromirror or introduces a shallow surface relief. Lots of research was also devoted to introducing polarization dependent waveguiding or modal gain/loss. These include etching of rectangular mesa or aperture, growth on misoriented substrates, asymmetric current injection. One technique that affects both the modal and the polarization behavior is elliptical surface relief. The ellipse of the surface relief is oriented along the co-ordinate system Oxy while the index ellipsoid orientation depends on the strain present in the cavity – see Fig.1. The theoretical description of such birefringent VCSEL is quite intricate. In order to get physical insight




into the mechanism of polarization stabilization we assume separable longitudinal (z) and the transverse (x,y) field. Our first approach is variational, we consider only the two fundamental VCSEL modes with either ξ or η polarization and filed amplitude $E_{\xi/\eta}$. We assume a Gaussian approximation for the two LP modes and a weak guidance approximation and obtain the mode spot sizes and the polarization corrections to the propagation constant from variational expression for the effective propagation constant of the LP modes. In fig.2 we show the polarization dependent losses in the shallow etched VCSEL as a function of the polarization angle Ψ. The LP mode losses are given by the projection of the arrows ξ or η on the y-axis. It is clear from this figure that the polarization contribution to the mirror losses for the two LP modes is the same when they are oriented at π/4 to the axis of the elliptical surface relief. From the elasto-optic effect calculations we obtained that the dominant




orientation of the refractive index ellipsoid is along [110]. We can therefore conclude that the largest polarization anisotropy and the best polarization stabilization is achieved for elliptical surface relief oriented along the [110] crystallographic directions. Indeed, we confirm this conjecture experimentally.

As a second approach we use more refined numerical technique based on solving the vectorial rate equations by a plane wave decomposition method with periodic boundary conditions. It is however developed for isotropic optical waveguiding media and we therefore, only compare the two limiting case in Fig.2, namely the light polarizied along x and y axis. More results concerning the comparison of the different methods will be presented at the conference.

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# Design and Analysis of Nonlinear Optical Waveguide Sensors

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**Abstract:**

Recent years have shown increased interest in the investigation of integrated optical sensors [1-4] due to their miniature, high sensitivity, small size, immunity to electromagnetic interference and low price. Biochemical and biomedical sensors are examples of using planar integrated optical wave guide in their structures in both homogenous and surface sensing. In the past few years, there was [5-7] a significant amount of work regarding the applications of lasers and nonlinear optical materials in a large number of opto-electronics devices. The changes of the refractive index in nonlinear media may be used to control the sensitivity of nonlinear wave guide sensors. Abadla, Shabat, and D.Jäger [8,9] have shifted the study of linear wave guide sensors to nonlinear wave guides sensors.

This paper presents our recent works on nonlinear wave guide sensors. Novel nonlinear wave guide sensors are designed for the first time. We derive an extensive theoretical analysis of nonlinear wave guide structure sensors and the conditions for the maximum achievable sensitivity. In homogeneous sensing, the wave guide sensor structure consists of a dielectric film sandwiched between a linear substrate and a nonlinear cladding. An extra very thin layer is added above the film in surface sensing. In both cases, the nonlinear cladding is considered to have an intensity dependent refractive index. Computer programs based on the derived mathematical modeling are developed to analyze the propagation characteristics of various integrated optical nonlinear wave guide structures. The theoretical requirements for reaching high sensitivity of the proposed nonlinear waveguide sensor are determined. A comparison between linear and nonlinear sensor structures has been made. Some suggestions for optimizing the structure of the nonlinear wave guide sensors will also be derived.

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# Circuit-Oriented Modelling of Ring-Resonators

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A circuit-oriented analysis of ring-resonator based devices allows to easily take into account the effect of coupler imperfections and polarisation mode coupling. The precision of the proposed modelling is confirmed by experimental results.

**Keywords:** circuit analysis, numerical modelling, ring resonators.

The rigorous electromagnetic analysis of a single integrated-optic ring resonator or a ring-based filter is a difficult, if not impossible, issue. Apart from very small microring resonators with few microns of overall dimensions, rings with diameter hundreds of micron are extremely time and memory consuming for the majority of electromagnetic solvers such as FEM, EME, FDTD, etc. These methods are essential to calculate the transmission matrices of the building blocks such as couplers and bent waveguide sections. The circuit behaviour can thus be calculated by using these matrices on a circuit-oriented basis.

In this contribution we show the advantages deriving from this approach, in particular we have investigated the single ring behaviour taking into account the effect of a differential mode attenuation in the couplers and the polarisation mode coupling in the curved sections. Comparisons with experimental results confirm the validity of the model.

In a directional coupler, as a consequence of the imperfections in the coupling region, the odd and even modes may experience slightly different losses. By solving the coupled mode equations taking into account this differential attenuation, one finds that fields at the coupler output ports have a phase relation $\Delta\varphi$ dependent on the attenuation itself [1]. The phase shift produces a distortion of the spectral behaviour as shown in fig. 1 for a ring resonator phase shifter with coupling coefficient equal to 0.5 and roundtrip attenuation of 0.75 dB. The three curves correspond to $\Delta\varphi$=0, –2.5 and –5 deg, roughly corresponding to a differential attenuation of 0, 0.4 and 0.7 dB. This explains distortions often observed experimentally.

Also the polarisation mode coupling can be included in a circuit based approach, confirming how much flexible, reliable and powerful is such an approach in the analysis and syntheses of integrated optic circuits.

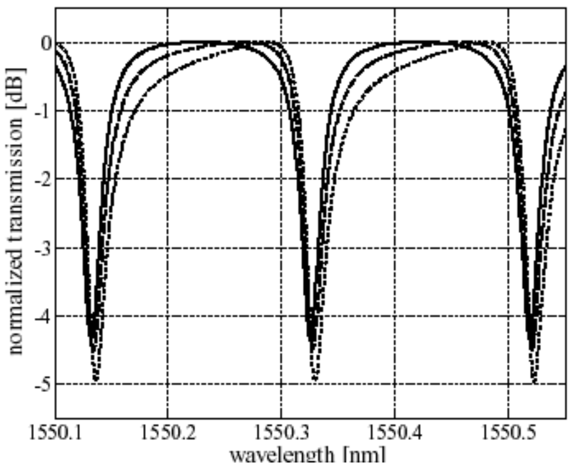


Fig. 1 – Spectral response of a ring-resonator

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# Coupled Mode Theory Based Modeling of 2D Cylindrical Integrated Optical Microresonators

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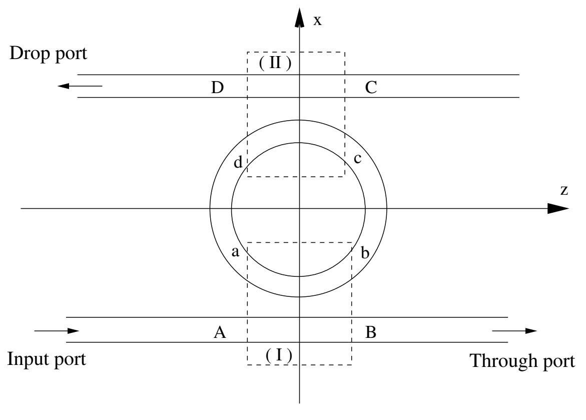
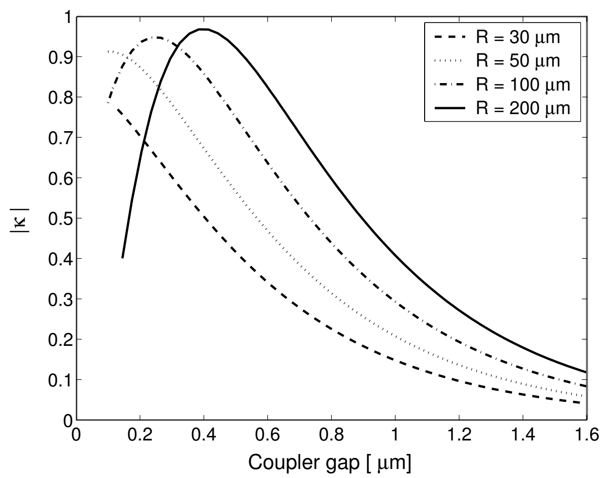
Optical microring resonators (MRs) are among the concepts at the focus of the current research on large scale integration of photonic devices. Conventionally, the ring resonator elements are described in the framework of a frequency domain model. A MR is functionally decomposed into two bend-straight waveguide couplers and the two bend waveguide (cavity) sections which internally connect the two couplers. Each coupler is externally connected to straight waveguides, which act as input/output ports. The advantage of this decomposition is that the modeling of a MR reduces to the modeling of the bent waveguides and the modeling of the bend-straight waveguide couplers.

The above formulation is crucially dependent on accurately and efficiently calculated bend modes. For this purpose, we developed a 2 D semi analytic planar bend mode solver. Having access to the analytic representation of the bend modes, we formulated and implemented a spatial coupled mode theory (CMT), which is based on variational principles (functional/reciprocity techniques), to model the bend-straight waveguide coupler. Solving the coupled mode equations numerically on a suitable computational window and taking the projection onto the (straight waveguide) port modes allows us to compute the scattering matrix of the coupler regions.

We obtain stable and surprisingly accurate results, even for quite compact and rather radiative cavities (see figure). The CMT results are compared with finite difference time domain results. It turns out that, for an accurate computation of the coupling constants, quite a large part of the radially extending basic bend mode profile has to be taken into account. The coupler scattering matrix obtained in this way forms the basis for the MR description. An extension of the model to unsymmetrical MRs or to resonators with multimode cavities should be straightforward.




Left: Schematic decomposition of the MR into two coupler regions I and II, connected by the segments of the ring cavity. Right: CMT results for 2 D MRs. Variation of the absolute value of the straight waveguide to bend waveguide coupling coefficient ($\chi$) for various disk radii ($R$) versus the coupler gap. Specifications: Bend waveguide and straight waveguides with core refractive index 1.6 and width 1 $\mu m$, background refractive index 1.45, TE polarised light with a vacuum wavelength 1.55 $\mu m$.

# (1+1)D vectorial simulation method for light propagation in bulk liquid crystal cells with voltage-biased nonlinear optical field induced director reorientation

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**Keywords:** liquid crystals, optical nonlinearity, spatial optical solitons, vectorial beam propagation method

## Introduction

Spatial optical solitons (SOS) are self-confined beams and they can occur when the material has an optical nonlinear response that acts like a self-focusing mechanism for the light. Recently they have been observed in nematic liquid crystals (NLCs), with a thermal nonlinear effect [1], but also with the nonlinear effect of optical field-induced director reorientation [2]. The director of the liquid crystal is reoriented by the optical electric field, similar to the reorientation by the field from an applied voltage over the cell as in liquid crystal displays. In [3] the director orientation is simulated in the approximation of only one optical field component and the light propagation is simulated by a scalar BPM algorithm, neglecting the optical anisotropy. NLCs are uniaxial materials and in this abstract, a simulation method is presented that incorporates the full vectorial calculation of the problem.

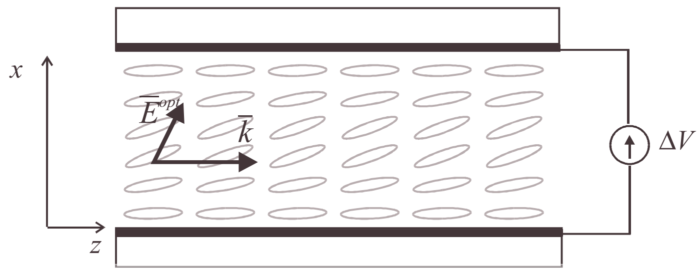


Fig. 1. Geometry and axes

## Geometry and simulation method

The director orientation is calculated for the geometry shown in fig. 1 for a one-dimensional situation in the one-constant ($K$) approximation for the distortion free energy. The different electric fields give rise to a torque on the molecules, leading to:

$$K\frac{\partial^2\theta}{\partial x^2}+\frac{1}{2}\Delta\varepsilon^{DC}\sin 2\theta\left|E^{DC}\right|^2+\frac{1}{2}\Delta\varepsilon^{opt}\left[\sin 2\theta\left(\left|E_x^{opt}\right|^2-\left|E_z^{opt}\right|^2\right)+\cos 2\theta\left(E_z^*E_x+E_zE_x^*\right)\right]=0$$

The DC-field in this equation is calculated from $\partial/\partial x.(\overline{\overline{\varepsilon}}^{DC}.\overline{E}^{DC})=0$ arising from the static Maxwell's equations. The propagation of the optical fields is calculated by a full vectorial finite difference BPM. Maxwell's equations are solved for the $H_y$-field and the calculation is done in the paraxial approximation. The beam propagation and the director calculation have to be calculated iteratively due to the nonlinearity until desired accuracy is achieved.

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# Polarisation splitter/combiner based on antiresonant directional couplers

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We present a study of a new class of polarisation splitters based on directional couplers. Our device includes a highly polarisation sensitive mirror by introducing Brewster angle reflections in it. Coupling characteristics are confirmed by a mode analysis that identifies the details of the modes responsible for the power transfer in both polarisation and allow to specify the parameters to optimise the performance.

**Keywords:** optical waveguide theory, Bragg reflector waveguide, polarisation splitters

## Introduction

Integrated polarisation control devices are of great interest in different fields of technology extending from optical communications to sensors. Passive polarisers can exploit different phenomena such as the material birefringence, metallic layers or the reflection at the Brewster angle. For example, metal layers can easily eliminate one polarisation but more sophisticated integrated polarisers should be designed to split and conserve both polarisations. The present splitter/combiner has been inspired from the works on Bragg fibres in which Brewster angle considerations have been used to select the polarisation state [1].

## Coupler description and results

The two waveguides (WG) in Fig 1 are separated by an antiresonant mirror [2] of high reflectivity for the TE polarisation. At the same time, the index of the core is chosen such that the TM wave impinges on the mirror layers at the Brewster angle. When this condition is met, the mirror becomes a coupling region for the TM polarisation and facilitates its transfer into the second guide as in a conventional directional coupler. The transfer characteristics of our splitter have been analysed by a simple modal analysis. The choice of Si and $Si_3N_4$ as material in the coupling region fixes the effective index to 1.73; a material of a slightly higher index is needed to match this value and get the best performance as shown on Fig. 2 where coupling lengths are given for both polarisations. The difference in coupling lengths of two orders of magnitude will ensure a high extinction ratio to the device.

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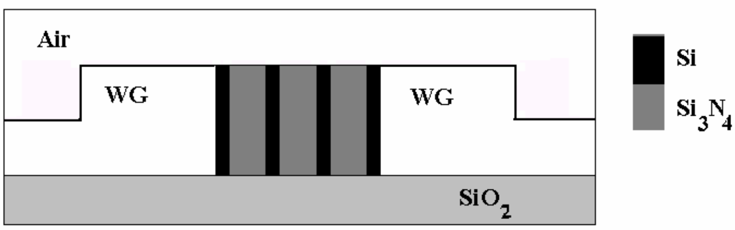


*Fig 1.* Proposed polarisation splitter

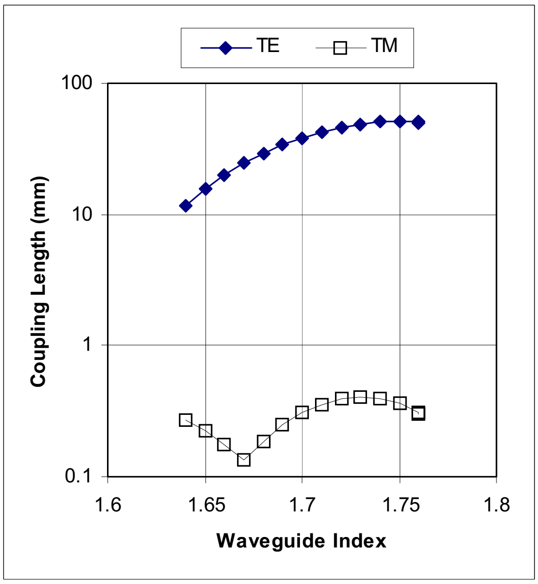


*Fig 2.* Coupling characteristic vs guide core index

# Efficient evaluation of spontaneous emission rates in planar structures

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**Keywords:** optical waveguide theory, modelling, guided-wave optics, spontaneous emission, density of modes, Greens functions.

**Summary**:
The effect of the structural environment on the density of modes, and so on the spontaneous emission rates of molecules, can be calculated by considering the power radiated by a classical dipole in such a structure [1-3]. The presentation will show that for planar structures the latter can be calculated quite efficiently by evaluating a single integral along a well-chosen path in the complex $k_{//}$ plane. Here $k_{//}$ is the in-plane wavenumber of the light. Hereby, the effect of both radiation and guided modes are taken into account automatically, without the necessity of applying mode-searching routines. We will further present computational results of applications of the theory on appealing examples, as well as closed form expressions for the Green's functions for layered structures.

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# Automatic Simulation Trade-off within Optoelectronic Device Optimisation

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Judicious use of a range of simulation tools within global optimisation is shown to synthesise device designs quickly and to a user specified accuracy.

**Keywords:** Synthesis, Optimization, FSRM, Thin-films, CAD

## Introduction

The design of increasingly complex optoelectronic components such as photonic crystal structures and facet coatings has led to the use of multidimensional optimisation methods to synthesise new designs. Using global methods such as Evolutionary Algorithms or Simulated Annealing a user-defined figure of merit can be minimised over a large problem space, automatically obtaining a structure with desired operating characteristics [1].

Global optimisation comes at a price; the requirement for numerous highly accurate numerical simulations leads to increasingly long runtimes. For those with the infrastructure, this can be overcome with large-scale parallel computing resources and distributed optimisation. The alternative to this is to use the existing simulation tools more effectively within the global optimisation. To do this we require the designer to specify not only the bounds of the practical problem but also the simulation accuracy to which they require the result.

In this work we show how the use of a hierarchy of both simulation and optimisation tools can allow for the most effective use of computational resources. By the management of the simulation acuracy during the optimization process the most appropriate simulation technique is actively determined at each stage. This automatic trade-off between simulation accuracy and runtime allows a design of user specified accuracy to be obtained with a reduced number of accurate simulations hence reducing the overall design time.

Our methodology is applied to the efficient design of thin-film optical filters. In the initial stages of global optimisation a plane wave model is used to develop the problem space for an optical filter with the desired operating parameters. When sufficient convergence towards a solution has occurred, the method used changes to the more accurate semi-analytical Free Space Radiation Mode (FSRM) method in 2-D and similarly, in the latter stages of optimisation to a full 3-D vector FSRM technique. This example enables us to obtain accurate designs quickly and efficiently. We describe how the principle could be extended further for use with alternative hierarchical simulation schemes and how solutions may be used to seed structures investigated with numerical techniques, resulting in novel, highly effective designs.

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# Bandwidth Maximisation in Few-Mode Optical Fibres

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**Keywords:** optical waveguide theory, guided-wave optics.

## Introduction

A classical problem in the propagation of light pulses along optical fibres is the minimisation of dispersion in order to maximise the bandwidth of the fibre over a given distance. For most long-distance terrestrial and submarine applications, weakly guiding, single-mode fibres are deployed. The refractive-index profile and materials used in these fibres are chosen so that the dispersion of the fundamental mode due to the profile and the material dispersion essentially offset one another exactly at and close to the operating wavelength, typically 1,300 or 1,550 nm.

With the introduction of wavelength division multiplexing (WDM) into long-distance optical transmission systems, especially within the 1,550nm optical amplifier window, the capacity of a single-mode fibre can be increased by more than a hundred-fold by exciting the fundamental mode at a number of closely spaced wavelengths (DWDM). The multiplexing (superposition) and de-multiplexing (separation) of such a large number of channels with minimal cross talk between them is normally achieved using an arrayed waveguide grating (AWG).

Here we investigate an alternative strategy for increasing bandwidth capacity based on a fibre supporting only a small number of modes. In this scheme each mode is excited separately and detected at the beginning and end of the fibre, respectively. For example, in the case of a two-mode fibre, the fundamental and second modes would be introduced into the fibre from separate laser sources using an asymmetric, 2-mode Y-junction. Similarly a special type of coupler fabricated from a single-mode and the two-mode fibre could be used to separate the two modes at the end of the fibre. A similar strategy would be used for a 3-mode fibre system.

To maximise the overall bandwidth of a few-mode fibre, the bandwidth for each mode should also be maximal. Here we show, by using a simple, equivalent infinite parabolic profile model of a fibre, it appears to be possible to achieve this goal by suitably choosing the excitation wavelength for each mode. An advantage of the infinite parabolic profile model is that an exact analytical expression for the combined effects of mode and material dispersion for each mode can be derived that provides insight into the interaction of the two forms of dispersion. In the case of a practical few-mode fibre, however, dispersion cannot be expressed in an analytical form and the maximum bandwidth profile would need to be determined numerically.

By analogy with the wavelength multiplexing of the fundamental mode of a single-mode fibre, it would also be possible to excite a large number of closely spaced wavelength channels within each modal channel and hence produce a few-mode fibre with a very large overall bandwidth.

# Silica glass bend waveguide assisted by two-dimensional Photonic Crystals

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**Keywords:** glass waveguides, bend, photonic crystals, finite difference time domain (FDTD) method, plane wave expansion (PWE) method

## Introduction

In this paper we report on the modelling of low index contrast silica glass ridge bend waveguides assisted by a two-dimensional photonic crystal. The performance of the 2D-PC bend structure is compared to that of a classical bend and the phenomenon of light confinement is critically observed.

## Design and modeling of silica glass bend waveguide

In low index contrast silica glass bend planar waveguides, the light confinement is ensured by total internal reflection (TIR), but strong radiation losses can be induced when the curvature of the waveguide increases. To improve the light confinement we have introduced 2D Photonic Crystals (2D-PCs), acting as efficient mirrors, along the boundaries of the ridge. In this case the mechanism of light confinement which sets up along the bend waveguide is similar to that described in [1-2], where it is shown that the propagation in a photonic crystal bend occurs without significant radiation losses, even at sharp 90° bends.

The numerical analysis has been performed for both the bend ridge waveguide, having a Ge-doped 2.5 µm-thick and 4.4µm-wide $SiO_2$ core and silica cladding, whose size was chosen in order to have the fundamental mode propagating, and the same structure assisted by 2D-PCs consisting of a triangular lattice of Ge-doped $SiO_2$ pillars in air. At the wavelength of 1.3 µm the refractive index of core and cladding are $n_{core}$=1.4855 and $n_{cladding}$=1.448, respectively.

The geometrical parameters of the 2D-PC structure, without considering the ridge waveguide, have been calculated by the effective index and the 2D Plane Wave Expansion (2D-PWE) methods. A photonic band gap for TM polarization extends from 0.5059 to 0.5371 in the normalized frequency ($a/\lambda$), while no band gap exists for TE polarization. The simulations indicate that Ge-doped $SiO_2$ pillars with radius r=0.28a and lattice period a=678nm, result in a normalized frequency of 0.5215 inside the photonic band-gap. These geometrical parameters have been used in a 3D Finite-Difference Time-Domain (3D-FDTD) based computer code in order to evaluate the transmission characteristics of the bend ridge waveguide. The phenomenon of light confinement is critically observed, by considering different values of the bend radius.

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# Band Structures in Nonlinear Photonic Crystal Slabs

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The three-dimensional (3-D) finite-difference time-domain (FDTD) method is applied to analyze band structures in Kerr-nonlinear photonic crystal slabs (PCS). Results show that the calculated bands are dynamically red-shifted with regard to the bands in linear PCS.

**Keywords**: photonic crystal slab, Kerr-nonlinear material, 3-D FDTD, red-shift

Linear PCS were extensively studied, both theoretically and experimentally (see e.g. [1]). Nonlinear PCS have recently been of particular interest to researchers because of their promising applications in integrated optical devices [2]. Nonlinear PCS, which consist of Kerr-nonlinear materials (e.g. semiconductors, glasses and polymers), can be applied to nonlinear optical devices such as low threshold limiting, all-optical switching, etc. In these devices, the nonlinear phenomena mentioned are achieved by modifying the incident intensity. With the FDTD method, the mechanism of modification was first studied in infinite photonic crystals by Tran [3]. In the present study, the band structures in the Kerr-nonlinear PCS are calculated in accordance with Tran's method and group theory. An absorbing boundary condition is posed in the vertical direction. A random number generator and a delta pulse with intensity $I$ are used for excitation.
The triangular lattice of circular air rods ($a=1, r=0.24a$) in a Kerr-nonlinear material is considered. The slab is suspended in air, its thickness is $d=0.3a$. The dielectric constant of the slab is intensity-dependent and can be written as $\varepsilon=\varepsilon'+\chi^{(3)}\left|\vec{E}\right|^2$, where $\varepsilon', \chi^{(3)}$ and $\vec{E}$ are the dielectric constant in the linear regime ($\varepsilon'=12$), the Kerr coefficient ($\chi^{(3)}=0.01$) and the electric field vector, respectively. The calculated band structures (even modes) and the incident intensities (in arbitrary units) used for calculation are presented in Figure 1. This figure shows that the band structures in the nonlinear PCS are red-shifted with regard to the linear case and that the red-shift increases as the incident intensity increases.

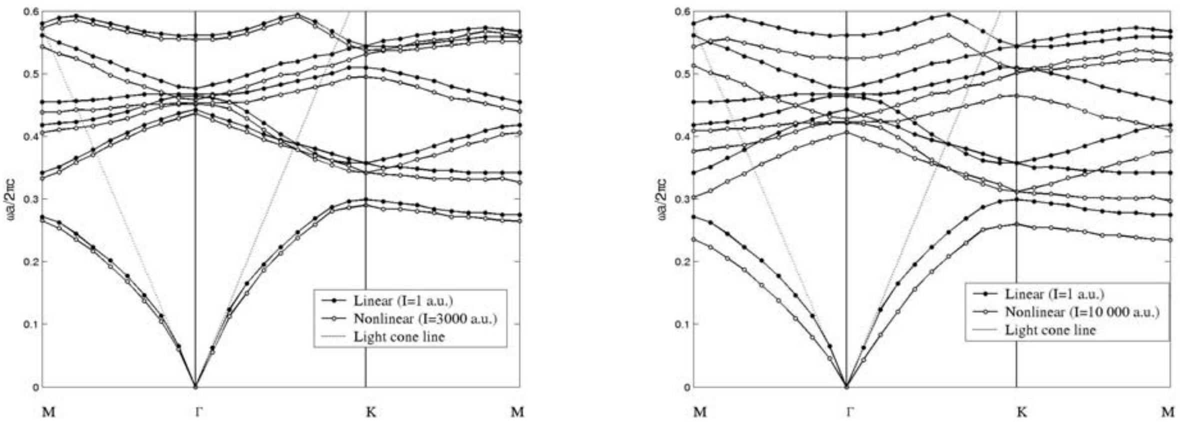


Figure 1. Comparison of band structures in the linear and nonlinear PCS.

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# PBS Solver and FDTD Solver – versatile tools for modeling 2D photonic crystals

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Two computer modeling tools, based on the plane wave and finite difference time domain method, for two-dimensional photonic crystal simulations have been developed and applied to various modeling tasks.

**Keywords:** two-dimensional photonic crystals, photonic band gap, plane-wave method, finite difference time domain method, periodic boundary conditions, perfectly matched layers.

To study behavior and properties of 2D photonic crystals (PhC) we have used two complementary methods: Plane Wave Expansion (PWE) method and Finite-Difference Time-Domain (FDTD) method. Concerning the PWE approach, the PBS Solver software tool developed for calculating photonic band structures (PBS) of two-dimensional dielectric photonic crystals (2D-PhC), has been developed, using the Matlab® environment [1]. Our PBS Solver can be applied to compute PBS of very general classes of 2D-PhC structures (general definitions of lattices as well as basic building objects, including their combinations). Two approaches have used for numeric calculations, analytical method for simpler structures, and numerical FFT method for general and more complex structures (case of overlapping building objects). Defining new structures, setting computational parameters, and data management are very easy by using powerful Matlab's graphical user interface. The program also allows computing of one- and two-dimensional parametric dependencies in a very general form, and thus offers optimization of the structure for various parameters. The validity of our computation has been verified using the MPB code [2]. Several interesting examples of analyzed 2D-PhC will be shown and discussed. Next, the FDTD method was also implemented using Matlab® environment, with standard 2D Yee algorithms, and several types of boundary conditions implemented: Perfect electric conductor (PEC), periodic boundary condition (PBC), and perfectly matched layers (PML) in its uniaxial form [3]. Various numerical aspects of the implementation have been approached, including numerical dispersion relation of a 2D grid, anisotropy of numerical phase velocity, the overall numerical stability and validity of the code, effectivity of used PML boundary conditions, limitations of our FDTD code, etc. Then, a comparison of both approached for various 2D simulations (PBS computation, the influence of defects using either the method of initial field or the method of transmission spectrum) will be given. Based on our practical experience, we can summarize the advantages and disadvantages of both methods for different types of simulations. Finally, several interesting results of 2D-PhC simulations will be shown.

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# FDTD characterization of nanopillars photonic crystal waveguides

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We present numerical characterization of photonic crystal waveguides composed from dielectric nanopillars. Guided modes are classified by their symmetry. An excitation of specific mode with a possible application of the waveguide as a laser resonator is discussed.

**Keywords:** numerical modelling, FDTD, photonic crystals waveguides

We found that N rows of periodically placed nanopillars in the air form a waveguide channel with strong localization of fields in the space region filled with dielectric inclusions. Such nanopillar photonic crystal waveguides (PCW) have been analysed by 2D FDTD method. The lowest group of modes is guided by total internal reflection. The number of modes in the group is equal to the number of nanopillars rows N. The modes are classified as even and odd relatively to the vertical plane passed through the axis of the waveguide (Fig.1). All of these modes are lying within the continuum of surface modes of semi-infinite photonic crystal with the corresponding Bravais lattice. Changing the filling fraction, dielectric constant and the ratio of sides of rectangular Bravais lattice as well as the type of the lattice, can vary the dispersion properties of modes. Thus the fine positioning of modes in frequency can be obtained.

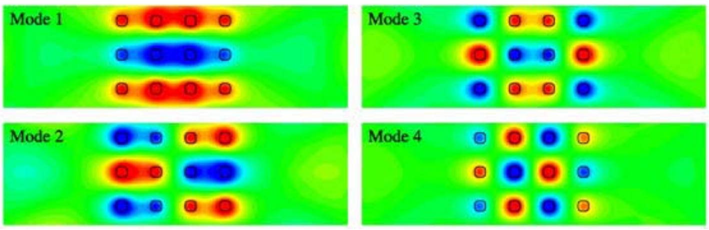

Fig. 1 Field patterns of the 4 lowest guided modes of 4-rows PCW. Modes 1 and 3 are even, 2 and 4 are odd. Modes propagate from the bottoms to the tops of the pictures

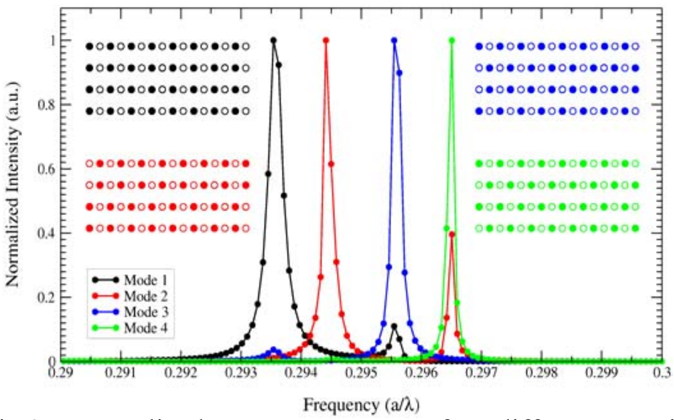

Fig.2 Normalized energy spectra for different spatial patterns of the excitation for the 20 periods long W4 PCW. Spatial patterns of excitation modes are shown in insets by filled circles

The PCW is multimode. An implementation of incident gaussian-shaped pulse with the symmetry of the particular mode gives a transmission spectrum, which reflects the frequency position of the mode on the dispersion diagram. Having in mind a possible forthcoming application of a nanopillar PCW as a laser resonator with *ab-initio* inserted distributed feedback, we put point dipole sources inside the dielectric nanopillars. The arrangement of the sources repeats the field distribution of certain mode like showed on Fig.1. Normalised energy density spectra of the fields inside the waveguide volume are plotted in Fig.2. The excitation of the given mode is clearly seen. Comparatively small cross-talks visible on the plots between modes with the same parity can be overcome by increasing the length of the waveguide and by optimising the arrangement of dipoles.

# Mach-Zehnder interferometers in photonic crystals

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**Keywords:** photonic crystal, optical waveguides, Mach-Zehnder interferometer, wavelength demultiplexer.

## Introduction

Photonic crystal (PhC) technology allows to implement optical waveguides with low sharp-bending losses and very low group velocity. This last property is particularly interesting for optical devices based on the controlled modification of the optical phase of the signals traveling through the waveguides. Among these devices the Mach-Zehnder interferometer acquires fundamental importance as it is used as a building block of more complex optical devices and functionalities such as optical filters, wavelength demultiplexers, switches and optical gates.

## Mach-Zehnder interferometers

Mach-Zehnder interferometers (MZIs) are optical devices that make use of the interference between two optical signals from a same origin propagating through different effective path lengths. The difference between the effective lengths may be induced by inserting two waveguides with identical amplitude response and different physical lengths. This configuration can be used to implement filters or demultiplexers as it can resolve different wavelengths at the MZI outputs.

## MZI employing coupled-cavity waveguides

Coupled-cavity waveguides (CCWs) can be introduced in a PhC as a chain of evenly-spaced high-Q cavities [1]. CCWs seem to be a good choice to guide light through photonic integrated circuits due to two main reasons [1]: (i) bending losses are negligible over the entire waveguide bandwidth, and (ii) the dispersion relation of the guided modes can be modeled from the tight-binding formalism employed in solid-state physics, so there is an analytical tool that can make easier the design of devices based on this kind of waveguides. In addition, guided modes in CCWs have also a very low group velocity, so devices based on such guides can become extremely small. All these interesting properties of CCWs can be used to implement ultra-small MZIs [2]. The power transfer function of a CCW-based MZI can be written as a closed-form expression. In this paper a CCW-based MZI is analyzed in detail by means of simulations using a finite-difference time-domain method. The results shown that the model theoretical model is valid although the design of efficient power combiners that do not alter the spectral response of the MZI becomes a key step to achieve a proper performance. It is shown that the difference in the number of cavities that form each CCW is the key parameter in the design of the MZI. Moreover, the use of coupling techniques that allow an efficient power injection (extraction) to (from) the CCW-based MZI seem to be fundamental to avoid the amplitude ripple of the transmission spectrum. Anyway, it is shown that CCW-based MZIs can be good candidates to implement channel interleavers and demultiplexers that can be used in high-speed optical networks.

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# Numerical Modeling of Photonic Crystal Filters and Couplers

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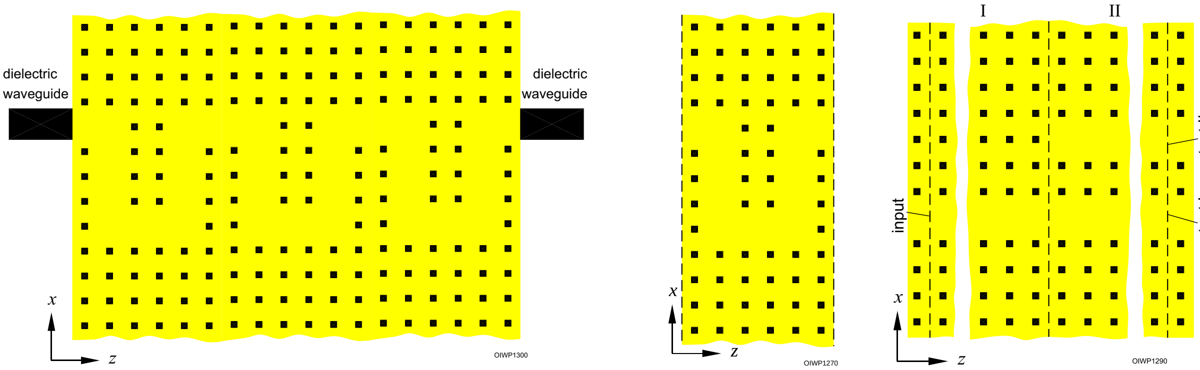
Numerical modeling of new photonic crystal devices will be shown.

**Keywords:** photonic crystal devices, Floquet's theorem, method of lines

The interest in photonic crystals and bandgap structures is still increasing. In the modern technology is important to design new devices and understand their behaviour [1]. Several different properties of couplers can be useful in new circuits. Under our consideration are various kinds of photonic crystal structures. Meander-line connected with dielectric waveguides and the fundamental period of a meander-line are shown in Fig. 1a,b. In Fig. 1c we can see an example for a 3 dB coupler.




(a) (b) (c)

Fig. 1. (a) scheme of meander-lines consisting of 3 periodic blocks ,(b) fundamental periodic block of the meander-line ,(c) scheme of 3 dB coupler

To understand the fundamental properties of photonic crystal meander-lines, we started our examination with one basic periodic block. Following this the number of periodic blocks increased. We have to mention here that the meander-lines can contain a large number of such periodic blocks. In our work we modeled also other devices like: 3 dB couplers and the concatenation of meander-lines with photonic or dielectric waveguides. For the analysis of the structure the MoL [2] [3] with Floquet's theorem was implemented [4] [5]. The meander-lines and their concatenations with various structures might allow to design new filters.

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# FDTD Analysis of Photonic Crystal Defect Layers Filled with Liquid Crystals

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**Keywords:** photonic crystals, liquid crystals, FDTD method.

**Abstract** – In the present study, the Finite Difference Time Domain method is applied to investigate the properties of 2-D photonic crystal structures, combined with liquid crystal defect layers.

### FDTD algorithm and indicative numerical results

Photonic Crystal (PC) devices containing Liquid Crystal (LC) defects have recently attracted much attention for telecom applications due to their wide tuning range and low operating voltages [1], [2]. Such a structure is studied using the Finite Difference Time Domain (FDTD) method. The geometry, shown in Fig. 1(a), consists of a triangular lattice of circular air-voids with cross-section radius 0.3*a* in GaAs ($\varepsilon_r$=11.7). A defect layer in the range of 1μm, made of a typical nematic LC material like E7, is inserted between two blocks of the photonic crystal.
The device is analysed using an anisotropic formulation of the FDTD method [3]. Periodic boundary conditions are used in the upper and lower sides, while the material-independent Perfectly Matched Layer absorber minimises the reflections at the left and right boundaries. Furthermore, the LC director orientation profile along the *x*-axis is determined using a free-energy minimisation technique which leads to an Euler equation, solved numerically taking into account the appropriate boundary conditions. In Fig. 1(b), the resulting profile of the tilt angle between the LC director and the *y*-axis is illustrated for four different values of the applied voltage.
Due to the variation of the effective refractive index presented by the LC layer, the defect mode frequency alters with the electric field amplitude. This is clearly demonstrated in Fig. 1(c), where the transmission coefficient for four voltages is depicted. It should be noted, that the corresponding wavelengths of the second group of modes in Fig. 1(c) are located between 1500 nm and 1600 nm for *a*=480 nm, rendering the device suitable for optical communication applications.
The defect mode frequency shift will be further examined varying the PC lattice parameters and the LC layer thickness. Moreover, the case of bistable ferroelectric LC defect layers will be studied.

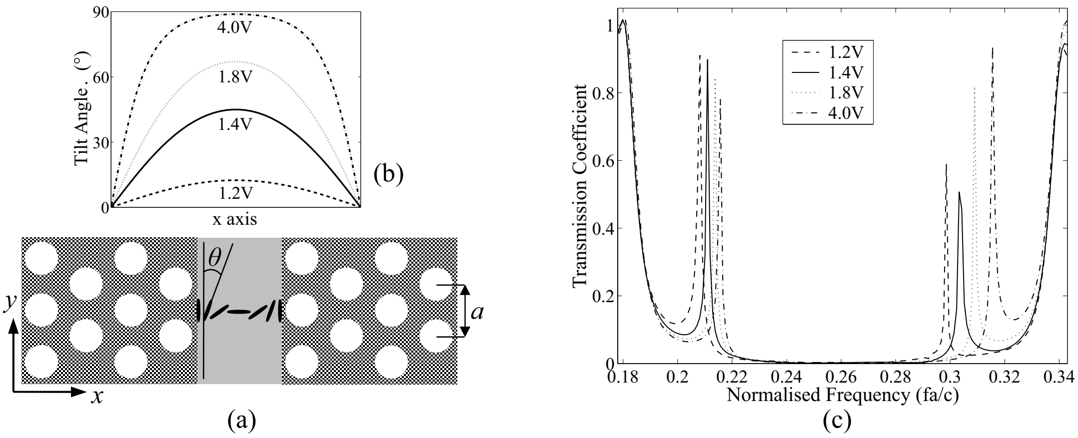


Fig. 1 (a) PC structure, (b) director orientation profile and (c) transmission coefficient.

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# Analysis of Photonic Crystal Waveguides as Dispersion Compensators

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A theoretical study of the possibilities of photonic crystal waveguides as dispersion compensators is presented. One of the unique features of this kind of waveguides is that group velocity at band edges tends to zero, which results in very large values of group velocity dispersion (GVD). With the use of a short-length section of waveguide the dispersion induced by a previous waveguide with opposite sign GVD is compensated.

**Keywords:** photonic crystal waveguides, pulse propagation, dispersion compensation

## Introduction

One of the most interesting properties of PhCs is the possibility of achieving waveguides with low group velocity and very large group velocity dispersion at their band edges [1]. This last property, together with the possibility of obtaining GVDs of both signs, is used in this work to compensate the dispersion induced by a previous PhC waveguide (although it could be an optical fiber) [2].

The structure used throughout the study consists of a 2D periodic array of high-index rods ($\varepsilon_H$) in a low-index background ($\varepsilon_L$). A single row of rods is removed in order to create the waveguide. The normalized dispersion parameter $\beta_2$ is obtained deriving the band diagram of the waveguide.

An optical pulse of width 134.625 ($a/c$) is launched into a first waveguide with dispersion parameter $\beta_2$ = -77.56 ($a/c^2$). The output pulse width is 180.2 ($a/c$) when the waveguide is 80 periods long. If a second waveguide with normalized period $a'$ = 1.2867$a$ is introduced following this first section, the dispersion parameter will be $\beta_2$ = 100.1752 ($a/c^2$). This value of $\beta_2$ determines an optimum compensation length of 48$a'$, achieving an output pulse width of 139.7 ($a/c$). The pulse shapes is shows in the Fig. 1. The final pulse is wider than the source one because of the second order dispersion $\beta_3$ which can not be compensated in the second waveguide.

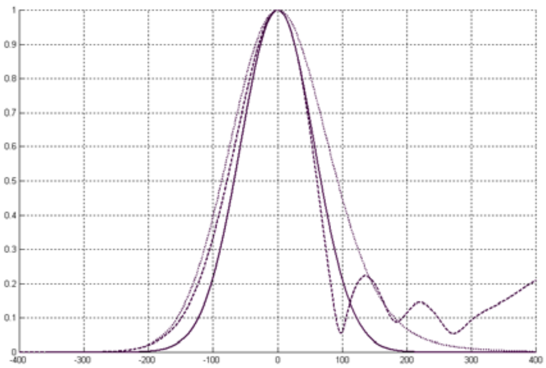


Fig. 1. Evolution of pulse shapes (solid line – source pulse, dotted line – spread pulse, dashed line – compensated pulse)

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# Analytical Evaluation of Chromatic Dispersion in Photonic Crystal Fibers

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We present a fast and accurate procedure for the evaluation of chromatic dispersion in photonic crystal fibers. It combines an iterative Fourier technique to compute the propagation constant at any wavelength and an analytical approach to calculate its derivatives.

**Keywords:** guided-wave optics, photonic crystal fibers, chromatic dispersion

In this contribution, we present an extremely efficient —very fast and accurate— procedure to calculate the chromatic dispersion in realistic photonic crystal fibers. For each wavelength $\lambda$ we are interested in, the solution is found in two steps. First we calculate the propagation constant $\beta$ and the transversal components of the magnetic field using an iterative two-dimensional procedure inspired by Ref. [1]. Second, we use some closed relations to compute the propagation-constant derivatives.

In order to carry out the first step, we recast the two-dimensional wave equation for the transversal components of the magnetic field (see Ref. [2]) in such a way that an iterative Fourier algorithm can be applied. This approach allows us to deal with arbitrary refractive-index distributions. This point is very important since real photonic crystal fibers differ considerably from ideal designs. In this way, we improve both the memory and computing time requirements since the diagonalization process is carried out without explicit representation of the operator defined by the wave equation. Additionally we take advantage of the main characteristic of two-dimensional schemes, material dispersion and losses due to both absorption and radiation can be introduced trivially into the diagonalization process.

In the second step we derive some analytical expressions to compute $\beta_1$ and $\beta_2$, i.e., the first and second derivative, respectively, of $\beta$ with respect to frequency $\omega$. This fact permits to speed up noticeably the calculation of the chromatic dispersion in these non-trivial guiding structures.

This new scheme is extremely useful for both the analysis and design stages. In the first case, results for any kind of fiber can be obtained in quasi-real time. In the second one, and combined with a suitable design procedure (see Ref. [3]), structures with group velocity dispersion extremely flattened —with zero third- and forth-order dispersion— can be easily predicted, as well as design with very high anomalous dispersion.

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# Numerical analysis of Bragg gratings in Photonic Crystal Fibers

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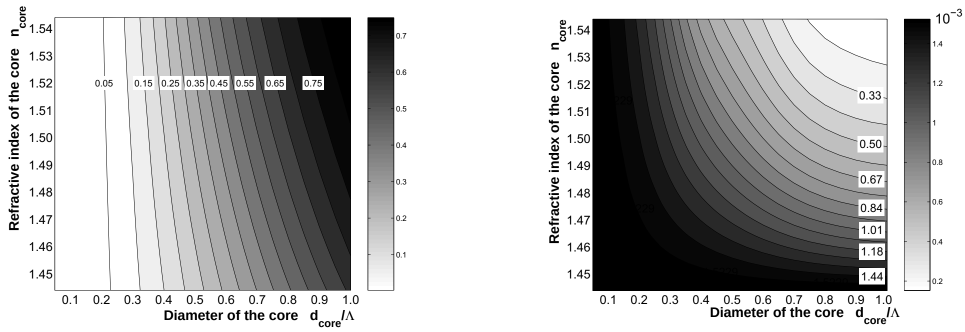
We present a combined method of numerical analysis of Bragg gratings written in Photonic Crystal Fibers. Our approach is based on fully vectorial plane-wave mode solver and Coupled Mode Theory. We analyze influence of the fiber geometry on the grating's coupling properties.

**Keywords:** photonic crystal fibers, Bragg gratings, mode solvers, Coupled Mode Theory

Although fiber Bragg gratings in conventional fibers have played major role in many applications, in recent years there have been only a few attempts to incorporate a Bragg grating in PCF. First experiments with this type of structures have been demonstrated by Eggleton *et al.* in 1999 [1] but the numerical methods of simulations presented there were based on scalar approximation and therefore did not cover such phenomena as polarization mode dispersion. In this paper we use our fully vectorial mode solver which is a variation of the plane-wave method [2]. Propagation of light through a fiber Bragg grating in PCF is in general a three dimensional problem. However, by treating the grating as a perturbation over original structure of a PCF, we can solve separately the two dimensional equations describing behavior of light in unperturbed translationally invariant fiber and the one dimensional problem describing influence of refractive index perturbation on the guided light.

We analyze impact of the doped core on the properties of PCF, in particular boundaries of single mode operation and value of birefringence. We also show how the overlap integral $\eta_{11}$ responsible for the self coupling of the fundamental mode depends on the parameters of the doped region (Fig.1). These results allow for future design of Photonic Crystal Fiber Bragg Gratings with precisely tailored parameters.




(*a*) (*b*)

Fig. 1. Dependence of the a) mode's overlap integral with the grating and b) fundamental mode birefringence on the parameters of the doped core region

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# Photonic Crystal Fibers with Anisotropic Refractive Index

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**Keywords:** photonic crystal fibers, birefringence, numerical modelling

## Summary

We describe an efficient numerical method for the calculation of the modal structure of microstructured fibers consisting of anisotropic materials. With this method we are solving the fully vectorial wave equation for the transverse magnetic field and the respective propagation constants. The method is based on the plane-wave approach, leading to a nonhermitian algebraic eigenproblem, with the propagation constants given as eigenvalues and the transverse fields as eigenvectors. In this respect our approach is similar to other works [1-3], however it accounts for material anisotropy.

For simple fiber cross-profiles, such as consisting of e.g. elliptical, or polygonal sub-elements of constant dielectric tensor, the elements of the matrix which defines the eigenproblem are given with analytical expressions. We solve the eigenequation numerically for a limited number of modes using Arnoldi's algorithm. This allows to save computer memory, since the matrix does not need to be fully stored at any moment. Instead, it is only needed to calculate how it acts on a given vector. At this point, we make use of the convolution theorem and instead of the direct calculation of the convolution terms that appear, we find them using FFT. It is only necessary to carefully treat the effects related to the difference between the ordinary two-dimensional convolution and circular convolution that results from the discrete FT. Another advantage of the approach based on separate treatment of 2-D convolution terms, is that it allows to avoid the cumbersome rearrangement of the two-dimensional Fourier representation of the dielectric tensor and fields in one-dimensional vectors. Instead it is possible to use the natural two-dimensional representation, with more obvious index arithmetic.

The purpose of the present study is twofold. First, we are interested in photonic crystal fiber sensors. The response of the fiber to mechanical strain, as opposed to the thermal response[4], requires to consider anisotropic materials. Moreover, the same applies to EM field sensors consisting of holey fibers with holes filled with a liquid crystal. On the other hand, we apply the same numerical method to study certain polarization properties of VCSELs. The latter topic is presented in a separate paper.

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# Approximate Analysis of MMI Couplers with Large Port Counts

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This paper proposes approximate solutions to Maxwell's equations for multimode interference structures having large port counts. In this way, a greater understanding of the limitations of these devices and of the relative importance of key parameters can be gained.

**Keywords:** optical waveguide theory, multimode interference couplers, numerical modelling

## Introduction

Low order multimode interference (MMI) couplers, for example 2x2 couplers, show good performance and are widely used in optical communication systems. However, in practice, the performance of MMI couplers deteriorate as the number of input and output ports increase. The usual methods of analysis and design of these devices rely on either simplified analytical approaches or computationally intensive numerical solutions. This paper, instead, looks at explicit approximate formulae for the two dimensional modal analysis of MMI structures.

## Current analytical methods

The most common approach [1] to analysing MMI guided structures relies on a modal propagation analysis of a one dimensional waveguide cross-section. This model assumes perfectly reflecting walls and a square law variation of the propagation constant. Another approach [2] also treats the MMI as a waveguide with a one-dimensional cross-section but uses a numerical solution for the dispersion equation.

## Approximate Solution

It is possible to obtain approximate solutions to the dielectric waveguide problem by using a separation of variables approach or the effective index method. This requires two consecutive solutions to the dispersion equation in one dimension. Even in the one-dimensional case, it is difficult to derive analytical approximations that can cope with both near cutoff and far from cutoff cases.
One type of approximate explicit solution [3] examined in this paper has the form

$$U = U_\infty \frac{V}{V+1}\left(1 - \sum_i \frac{a_i}{(V+1)^{2i+1}}\right)$$

where $U$ is the modal parameter in the lateral direction and $U_\infty$ is its value far from cutoff. $V$ is the dimensionless frequency parameter that has to be modified to take into account the effect of the other transverse direction. The terms $a_i$ are functions of the mode number $n$. Such an approach shows some promise in moving towards an adequate approximate analytical solution to the fields in wide MMI devices.

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# The modal method in deep metal-dielectric gratings : the decisive role of hidden modes

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The modal method is well adapted for the modeling of deep groove, high contrast gratings of short period, possibly involving metal parts. The presence of metal in the case of the TM-polarization is known to cause numerical problems [1] in most methods. The modal method also meets difficulties although the modes propagating up and down the rectangular grooves and slabs of the grating seem to represent a natural basis for the expansion of the grating fields. The modal method gives correct results if all the modes are taken into account. It is usually believed on the basis of early fundamental work [2] that the modes of a lossless lamellar grating have either real or imaginary eigenvalues. Applying this statement in a lamellar grating comprising lossless metal parts leads to wrong results. We show here that some modes exhibiting a complex eigenvalue even in lossless structure [3] must be considered. Once this is made, the modal method gives diffraction efficiencies of a lossy grating extremely fast and with high accuracy.
This will be reported in the case of 1D gratings. The case of 2D gratings will also benefit from this step ahead and receives soon a very fast and accurate solution.

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# Modeling of photon scanning tunneling microscopy by 2D quadridirectional eigenmode expansion

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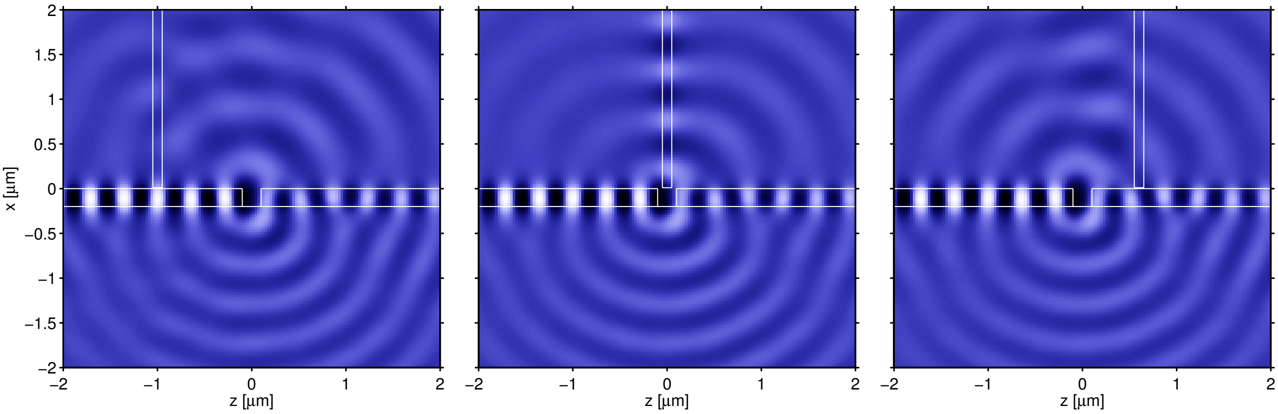
Photon scanning tunneling microscopy (PSTM) becomes increasingly popular as a tool to study the local optical electromagnetic field close to the surface of devices from integrated optics / photonics. A recent example is the mapping of the field evolution in waveguide Bragg gratings [1]. The microscope probes the optical field by detecting the optical power that is transferred via evanescent or radiative coupling to the tapered tip of an optical fiber close to the surface of the sample. Scanning the tip across the surface leads to a map of the evanescent optical field. For the present contribution we looked at a highly simplifying 2D model of the microscope that includes the sample as well as the probe tip. Corrugated slab waveguides (cores with slits, short Bragg gratings) serve are samples. A half infinite piece of waveguide, oriented perpendicularly to the axis of the sample structures, represents the probe tip. The propagation of light with fixed frequency and definite polarization is to be analyzed.

A recently proposed semianalytical simulation algorithm (quadridirectional eigenmode propagation, QUEP) [2] constitutes a convenient tool for virtual experiments with this model, as an alternative to usually computationally quite expensive rigorous numerical computations (FD / FEM discretization of Maxwell equations, see e.g. [3]). Our simulations are based on bidirectional expansions of the electromagnetic field into eigenmodes associated with the piecewise constant refractive index structure, along each of the two relevant Cartesian coordinate axes. After a brief overview of the computational approach, a series of results for the PSTM model are discussed. The examples allow to estimate how the signal detected via the fiber is related to the field intensity at the probe tip, and how the presence of the probe in uences the field distribution within the sample. Despite the simplicity of the model, we observed a reasonable qualitative agreement between these computations and a previous experimental PSTM investigation of a waveguide Bragg grating [1].




*Snapshots of the electric field $E_y$ for TE light propagation through the 2D microscope model, for three different probe positions. A slab waveguide (thickness $0.2\,\mu$m, refractive indices: $1.45$, $2.0$, $1.0$) with a $0.2\,\mu$m hole forms the sample. The vertical core (width $0.1\,\mu$m, refractive index $1.5$) represents the fiber tip. The sample is illuminated from the left by the fundamental mode (vacuum wavelength $0.633\,\mu$m) of the horizontal channel. QUEP simulation with $80 \times 80$ expansion terms on a $6\,\mu m \times 6\,\mu m$ computational window.*

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# Modeling of Pulse Propagation in Microresonator Devices

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The effective method for the calculation of propagation of an optical signal in microresonator (MR) structures is presented. Propagation of short pulses with lengths comparable with MR roundtrip time is examined.

**Keywords:** optical microresonators, numerical modeling, optical waveguides, Fourier transform.

The propagation of an optical wave in MRs is usually modeled with the FDTD method. In the 3D case, this approach provides very realistic results. Time consumption for such calculation, however, makes this method often unusable for design needs even in the 2D approximation.

Another possibility is to use a system-based modeling [1] with the help of the FFT. But, for typical optical frequencies, an extremely large number of samples of the signal must be used. This complication may be overcome by using the Fourier Transform of a periodical signal with a known spectrum. Then, a number of frequency (wavelength) samples can be drastically reduced. It is a well-known property of a modulated optical signal that its spectrum is formed by a (double-side) spectrum of the pulse envelope centered at the optical (carrier) frequency. Thus, in the frequency domain, only the spectrum of the *modulation* signal is treated. The resultant output time-dependent optical signal is obtained as a sum of the Fourier components in which the optical frequency is properly taken into account.

An interesting problem of propagation of a pulse shorter than the MR round trip time was recently discussed , e.g., in [2]. The round-trip time can be expressed as

$$t_g = L\frac{N_g}{c_0} = \frac{\lambda_0^2}{c_0}\cdot\frac{1}{FSR}, \tag{1}$$

where $L$ is the round-trip path length inside the MR, $N_g$ is the group effective index, $c_0$ is the velocity of light, $\lambda_0$ is the vacuum wavelength, and $FSR$ is the free spectral range. The results for the pulse length 1.2 ps propagating through the structure with $t_g \approx 1.6$ ps and with modules of amplitude coefficients of coupling and transmission [1] equal to 0.7 are depicted in Fig. 1. It

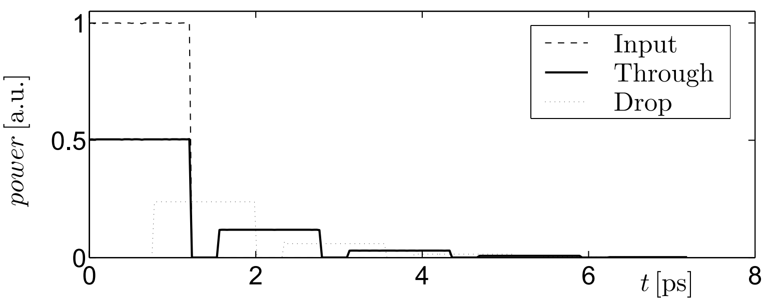


Fig. 1. The power of the input and output signals.

is obvious that the input signal is only divided between the throughput port and the MR ring guide with the ratio of the coupling coefficients. In addition, the results are not influenced by the position of the center wavelength of the signal to a resonant wavelength of the MR.

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# Novel Subgriding Technique for the Analysis of Optical Devices

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A novel and simple subgridding technique for the Method of Lines (MoL) is presented. High-accuracy is achieved by second order finite difference operators.

**Keywords:** Method of Lines, Subgriding, second order accuracy, characterisation methods

The idea of subgridding is not new, the considerable number of papers published in the literature over the last twenty years suggest big interest in this subject. In the first attempts of introducing subgridding scheme, either linear interpolation of missing boundary field components [1] or approximation it with wave equation [2] was used, giving reflection from the subgridding boundary about -40 dB or worse. Lower reflection from subgridding boundary (about −60 to −75 dB) can be achieved using algorithms presented in [3] (only for refinement factor of two) and [4] (only for odd refinement factors and with linear interpolation).

In this paper a simple high-accurate subgridding technique for the Method of Lines (MoL) is presented. It is the first paper dealing with subgridding problem in the MoL. The implemented subgridding algorithm involves interpolating of missing field components on the fine/coarse mesh boundary as well as determining of first and second derivatives with second-order accuracy. The proposed formulation enables to increase mesh density by any integer factor. The suggested algorithm is based on the formulation previously used with the MoL. Therefore, to extend standard MoL discretization scheme with subgridding, only moderate programming effort is required.

The algorithm will be applied to the structure in Figure 1. Two very different waveguides are coupled. One of the waveguides has a periodic varying cross section and the other one has in comparison to the first one extreme dimensions (small thicknes, great width). Furthermore, its field has a wide distribution. Therefore, the analysis is difficult. Although this paper is addressed to introduce subgridding into MoL discretization scheme, most of the given formulation is quite general and can be used with other FD methods as well.

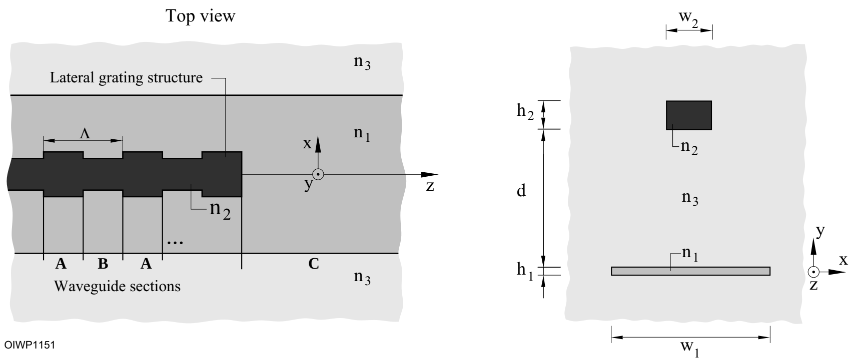


Fig. 1. Coupling of two very different waveguides: One waveguide with periodic varying cross section and the other with extreme dimensions.

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# Accurate 3D Photonic Band Gap Computation Based on $\vec{k}$-modified Whitney Elements and Fast Multilevel Methods

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We report on our C++ finite-element-implementation for the computation of Bloch-type eigenmodes in three-dimensional photonic crystals. The algorithm makes use of eigensolvers based on subspace iteration with multi-level preconditioning. This allows to solve large problems on unstructured grids with linear complexity. Another special feature is adaptive mesh refinement, steered by a posteriori error estimation, to account for geometric features on different scales.

**Keywords:** finite-elements, Whitney elements, guided-wave optics, photonic crystals, periodic structures, characterisation methods

The design of photonic crystal devices calls for simulation tools with high accuracy, speed and reliability. We use higher order, $\vec{k}$-modified Whitney finite-elements [1] on unstructured tetrahedral grids to discretize the time-harmonic vectorial Maxwell's equations. Such discretization leads to a discrete counterpart to the de Rham complex of differential forms. This results in the suppression of spurious modes. Non-physical eigenmodes appear as the kernel of the $\left(\nabla \times +i\vec{k}\times\right)$ operator [1]. This way the non-physical solutions are well isolated from the true eigenmodes fulfilling the divergence condition. Further, the discrete de Rham complex allows the construction of a fast multilevel preconditioner [2, 3]. We use subspace iteration algorithms relying on minimizing the Rayleigh quotient [3]. To avoid that the iteration tumbles into the non-physical kernel of the $\left(\nabla \times +i\vec{k}\times\right)$ operator we project the iterates onto the divergence-free subspace. Again this is done by a fast multilevel method. With this, the computational time and the memory requirements grow linearly with the number of unknowns. Moreover, we have implemented an error estimator and adaptive mesh refinement for the precise determination of localized modes.

We present 3D bandstructure calculations of Bloch modes in photonic crystal slab structures, which can be formed by etching a 2D periodic pattern into a high-index dielectric guiding slab. The convergence of the obtained results towards an accurate solution is analyzed.

We acknowledge support from the *DFG Research Center "Mathematics for key technologies"* and by the BMBF under contract No. 13N8252 ( *"HiPhoCs"*).

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# Hybrid mode finder for waveguides with a 2D cross-section

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In order to build an efficient three-dimensional (3D) optical model based on eigenmode expansion, it is of crucial importance to have a fast method to find the propagation constants and mode profiles of the vectorial eigenmodes of waveguides with an arbitrary two-dimensional (2D) cross section. Ideally, the method should be robust enough to deal with structures that have material losses, as well as deal with structures where radiation losses are modelled through perfectly-matched layer (PML) boundary conditions. Therefore, the technique has to be able to locate progation constants in the complex plane in a robust and efficient way.

Here, we present an efficient two-stage hybrid method which combines the virtues of plane-wave expansion methods and mode-matching methods. In a first stage, a plane-wave method is used to construct a single eigenvalue problem which provides an estimate of all the eigenmodes of the structure. These estimates are subsequently refined in the second stage using a technique based on vectorial eigenmode expansion. We opt for a vectorial eigenmode expansion technique because evidence suggests that it can deal more accurately with discontinuities and singularities which inevitably occur in the field profiles of these eigenmodes. By using this hybrid method, we get improved convergence compared to the case where we would only use a single method.

This hybrid method will be illustrated with a number of examples (propgation loss in photonic wires, radiation loss in photonic crystal fibres, ...). Its convergence properties will be discussed and compared to other methods.

# LINEAR AND NONLINEAR OPTICAL PROPERTIES $Zn_{1-x}Mg_xSe$ LAYERS

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**Abstract:**
Refractive index and TPA of $Zn_{1-x}Mg_xSe$ compounds grown by MBE and PLD methods were investigated as a function of Mg composition. We studied linear and nonlinear optical properties using photoreflection spectroscopy and nonlinear transmission, respectively.

**Keywords:** linear and nonlinear refractive index, absorption coefficient, two-photon absorption, degenerate four wave mixing, photoreflection

## Introduction

Novel ZnMgSe semiconductors are very attractive materials for full colour visible optical devices in wide wavelength range and for the cladding layer of II-VI laser diodes. Their optical properties such as the energy gap, linear refractive index, absorption coefficient and lattice constant can be changed with increasing Mg composition [1]. For the practical application linear and nonlinear optical characterizations such as the two-photon absorption (TPA), linear and nonlinear refractive index are an important aspect. A practical motivation to measure the magnitude of the two-photon absorption coefficient ($\beta$) is that the performance of a device based on nonlinear refraction is strongly affected by the eventual nonlinear absorption.

## Experimental results

The energy gap and linear refractive index of these materials increase with Mg content, hence the nonlinear optical processes such as two-photon absorption (TPA) and nonlinear refraction index can be modified [2, 3]. We can see that all studied samples reveal a relatively strong nonlinear absorption, which increase with an increase of Mg composition. Our results were compared with materials deposited on different substrates with different lattice constants (ZnTe, GaAs and Si) [4]. Influence of tensile and compressive stress on fundamental energy gap and refractive index were observed.

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# The enhanced effective index method for high-contrast photonic crystal slabs

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This paper presents the new approach for determination of the band structure in two-dimensional photonic crystal slabs using the enhanced effective index approximation. The proposed method remains valid in the wide frequency range even for high-index-contrast heterostructures.

**Keywords:** photonic crystals, material dispersion, effective index method

## Introduction

Determination of the photonic band structure in photonic crystals (PCs) is one of the crucial steps for numerical simulations of all PC devices including two dimensional photonic crystal slabs, which are of particular interest because of their easy fabrication and suitability for a wide range of applications. While exact numerical modelling of such PC slabs requires fully vectorial 3D calculations, it can often be reduced to the simpler 2D ones using the effective index method [1, 2]. Such an approach proved recently to be of a good exactness for low-index-contrast heterostructures [2]. However, in high-contrast heterostructures, the effective index varies signi cantly with the frequency and hence the classical techniques for PC band structure determination, in which permittivity is assumed to be constant, cannot be used.

In our work the classical frequency-domain nite-dif ference method for 2D PCs analysis is enhanced to allow for a strong refractive index dispersion which consequently makes it possible to analyse properly photonic crystal slabs with high-index-contrast heterostructures.

## Method and results

In the effective index method, the 3D pro le of refractive indices in a multilayer slab is replaced with the single effective index of an unperturbed waveguide. Then the 2D calculations can be performed for determination of photonic eigenmode frequencies for a given wavevector. In our enhanced method, we determine the eigenfrequencies pro le for an arbitrary range of effective indices. Then, being able to compute the structure effective index as a function of frequency, we can solve for the frequencies which appear in the real device.

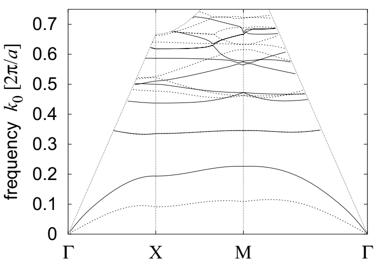


Fig. 1. Calculation results

The sample photonic band structure of even TE modes is presented at the Fig. 1 (solid lines). We carried out calculations for the square structure of air-holes in the three-layer $SiO_2$/Si/$SiO_2$ PC slab. The core and cladding refractive indices were 3.6 and 1.5, respectively, and the effective index varied strongly in this range. For comparison, we presented the band structure (dashed lines) obtained with the classical approach assuming constant effective index 2.95, which is the value for the frequency of the second (almost horizontal) band. The signi cant difference in those results shows that classical method are not satisfactory and in high-index-contrast multilayered slabs our enhanced approach should be used.

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# Non-Linear Modes in Step-Index Dielectric Waveguides with Spatial Discontinuities: a Dynamic Model

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It is shown numerically that paraxial components of radiation field excited on non-linear discontinuity of a dielectric waveguide form a lateral part of non-linear mode. The lateral power flow oscillates without attenuation along the exterior side of the core/cladding boundary. Time-harmonic and non-stationary light beams are considered.

**Keywords:** non-linear phenomena, numerical modelling, beam propagation method, radiation field

Non-linear modes in step-index dielectric waveguides are usually referred to as solutions to the non-linear Helmholtz equation for transverse distributions of time-harmonic light fields. Spatial profiles of the modes in planar waveguides have been derived, their stability has been analysed [1].

In this paper, another type of non-linear modes is described. The analysis is based on numerical solution of the scalar paraxial wave equation for the field envelope of a light beam propagating through a nonlinear discontinuity consisting of consecutively joint linear and non-linear step-index waveguides of the same width. The Finite-Difference Beam Propagation Method is used.

Spatial dynamics of the time-harmonic basic mode behind the discontinuity in non-linear waveguide reveals that paraxial component of radiation field excited on the discontinuity remains in the cladding and propagates without attenuation along the exterior side of the core/cladding boundary. In this region, transverse power flow changes its sign periodically along the propagation distance. Outside this region in the cladding and also inside the core the transverse power flow is zero. Longitudinal power flow is stable and has a lateral part.

These results give a reason to identify the fields as dynamic non-linear modes. Contrary to solutions to the non-linear Helmholtz equation, they have oscillating lateral power flows in the cladding. Total power remains constant over a propagation length.

Spatiotemporal dynamics of the non-stationary basic mode with initial gaussian time envelope is considered in a quasi-static approximation. The spatiotemporal distribution becomes stable far from the discontinuity in non-linear waveguide. It has a lateral part, a pulse that propagates without attenuation along the exterior side of the core/cladding boundary. The pulse is formed by paraxial components of the radiation field, its mean squared duration $T$ is much less here than in the core in comparison with the initial duration $T_0$ (Fig.1). Increase of $T$ over some range of transverse coordinates is due to the pulse shape variation. Pulse duration measured by intensity averaging over finite area in a cross-section behind the discontinuity depends on the area dimensions and has minimum value on the waveguide axis.

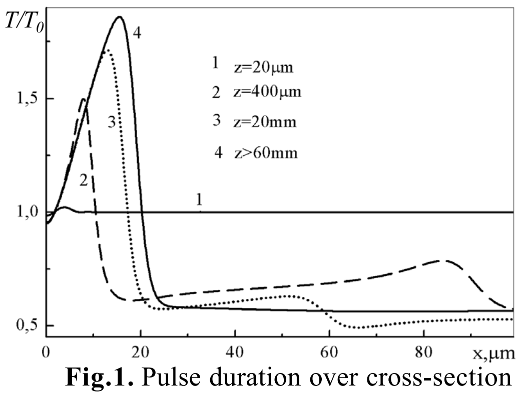


**Fig.1.** Pulse duration over cross-section of non-linear mode in planar waveguide; $z$ - distance from the discontinuity; core halfwidth = 3.0$\mu m$.

Transformation of the non-linear modes on sharp discontinuities of planar and cylindrical non-linear waveguides is also investigated and will be discussed in the report.

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# Parallel Evolution of Electromagnetic Signal Complexity with the Medium Change

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Effect of parallel evolution of an electromagnetic signal complexity is shown on signals with different initial complexity for various rules of a medium parameter changing.

**Keywords**: Electromagnetic transients, signal complexity, time-varying medium.

A 'statistical complexity' of an electromagnetic signal is a measure of its information content [1]. This measure changes in a time-varying medium when the signal propagates in it. The influence of the subsequent sharp time changes of the medium in the form of rectangular pulses on a complexity of electromagnetic signals has been investigated in previous works [2]. Here, the influence of various laws of the medium change on different initial signals is investigated and an effect of a saturation of a signal complexity is shown.

Three groups of signals with different initial complexity are considered. Signals of a hump-like and Gaussian-like forms: $f_1 = 4\left(e^{-10|t-x|} - e^{-5|t-x|}\right)$; $f_2 = 4(e^{-10|t-x|} - e^{-5|t-x|})\sin 50(t-x)$; $f_3 = e^{-10(t-x)^2}$; $f_4 = e^{-10(t-x)^2}\cos 50(t-x)$; $f_5 = 4e^{-10(t-x)^2}\left(\sin 11(t-x) - \sin 9(t-x)\right)$;

signals of a Lorentz-like form: $f_6 = \dfrac{1}{50(t-x)^2+1}$; $f_7 = \dfrac{75(t-x)}{1000(t-x)^2+1}$; $f_8 = \dfrac{1.7\sin 11(t-x)}{50(t-x)^2+1}$; $f_9 = \dfrac{75(t-x)\cos 11(t-x)}{1000(t-x)^2+1}$;

and signals described by the Laguerre polynomials: $f_{11} = 3.5e^{-20(t-x)/2}L_1(20(t-x))$; $f_{12} = 1.75e^{-20(t-x)/2}L_2(20(t-x))$; $f_{13} = 0.7e^{-20(t-x)/2}L_3(20(t-x))$; $f_{14} = (1/3.5)e^{-20(t-x)/2}L_4(20(t-x))$.

Transformation of the complexity of these signals in the medium which permittivity changes step-wise by various rules is shown in Fig. 1. The signal transformation is calculated exactly and its complexity is calculated using Crutchfield's 'computational mechanics' approach [3]. The initial value of the signal complexity depends on the signal form and the interval width in which this signal is considered. Investigations show that, independently of the initial value, the complexity changes in time in parallel. This is evident for the weak variations of the medium permittivity, Fig. 1a, and implicit in Fig. 1b when the great variation of the permittivity leads to a saturation effect.

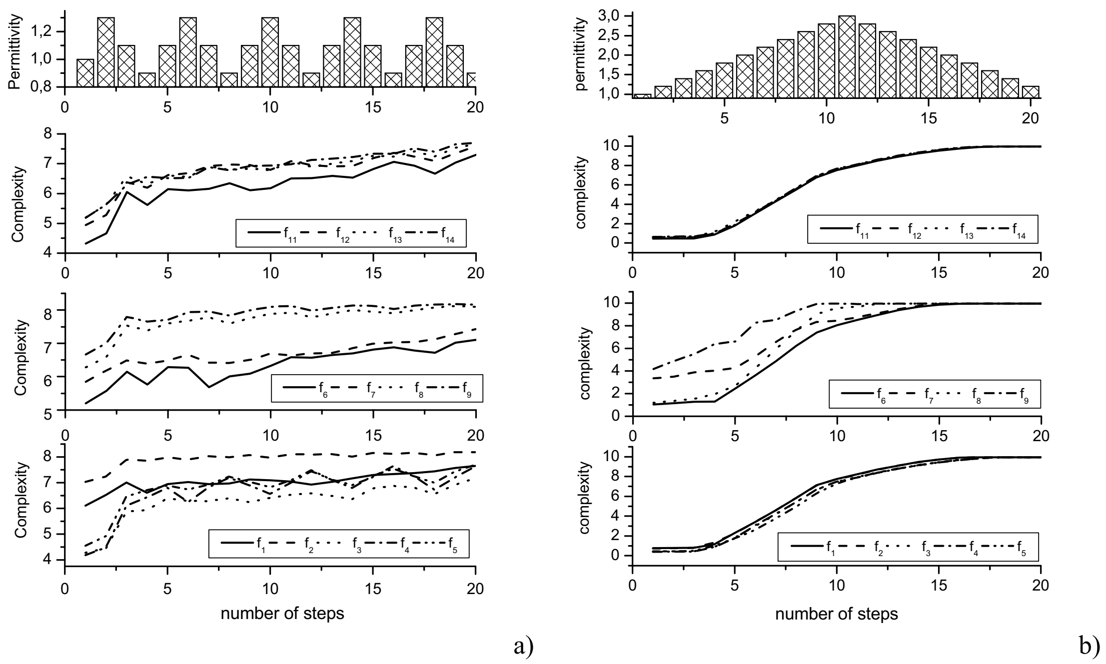


Fig.1. Evolution of the signal complexity: a) periodic changes and b) a raise and a fall of the permittivity.

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# Some Features of the $HE_{1n}$ Modes of Cylindrical Dielectric Waveguides Below the Cutoff Frequency

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Behaviour of dispersion curves of the $HE_{1n}$ modes of step-index waveguide is analysed below the cut-off frequency on a Riemann surface of a complex plane of transverse wavenumber in cladding. Asymptotic analysis of the results obtained with account of material losses helps to explain some features of $HE_{1n}$ modes of lossless waveguide.

**Keywords:** optical waveguide theory, radiation field, leaky modes

In spite of spectral theory of step-index dielectric waveguides has been developed quite well, behavior of the $HE_{1n}$ modes below the cutoff frequency of a lossless waveguide is not quite clear. It was shown analytically [1] that approximate characteristic equation obtained by the Taylor expansion of the rigorous one near the cutoff frequency had no solutions in some range of frequencies just below the cutoff. This result is in accordance with the results obtained in [2] via numerical solution of the rigorous characteristic equation for $HE_{1n}$ modes.

In this paper, we analyze behavior of the roots of approximate and rigorous characteristic equations for $HE_{1n}$ modes on a complex $w$-plane of the transverse wavenumber in cladding. Riemann surface of the $w$-plane has infinite number of sheets. The analysis reveals that the roots of characteristic equations for $HE_{1n}$ modes of a lossy waveguide "rotate" around the center of the $w$-plane, the number of turns depending on the magnitude of material losses. Analytical continuation of a dispersion curve below the cutoff frequency is located on a sheet with some definite number $N$. Dispersion curves of lossless waveguide have analytical continuation below the cutoff frequency just on the infinite sheet of the $w$-plane.

For a lossy waveguide, we clarify the meaning of the term "cutoff". A region of cutoff is defined, which corresponds to a range of frequencies between the first and the last crossings of a dispersion curve with the imaginary axis of the $w$-plane. For a lossless waveguide the region tends asymptotically to the point of cutoff $w=0$, $u'=V$.

In spite of there are no analytical continuation of dispersion curves of a lossless waveguide on any sheet with a finite number, there are other curves of the leaky modes on every sheet. Account of the dispersion curves degeneration results in a conclusion that there is no any gap below the cutoff frequency of $HE_{1n}$ modes of a lossless waveguide. In Fig.1 we use the same representation of the results as in [2], Fig.24.3, and show the roots located on the sheets with number $N$ just below the cutoff frequency $V_c$ (dashed curves).

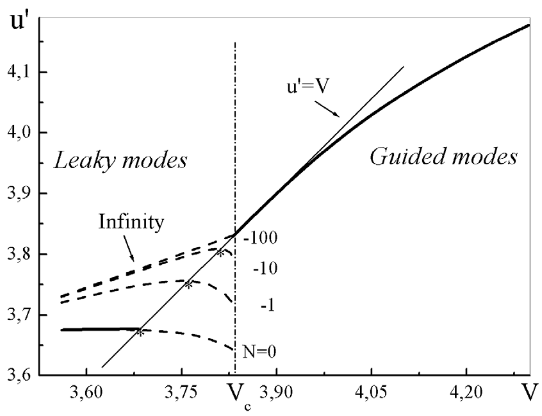


Fig.1. Real part of the wavenumber in the core depending on characteristic frequency. Solid lines – Snyder's curve on the zero sheet [2]; $V_c \approx 3.83$.

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# Time-Domain Diffraction from 3D Irregular Structure


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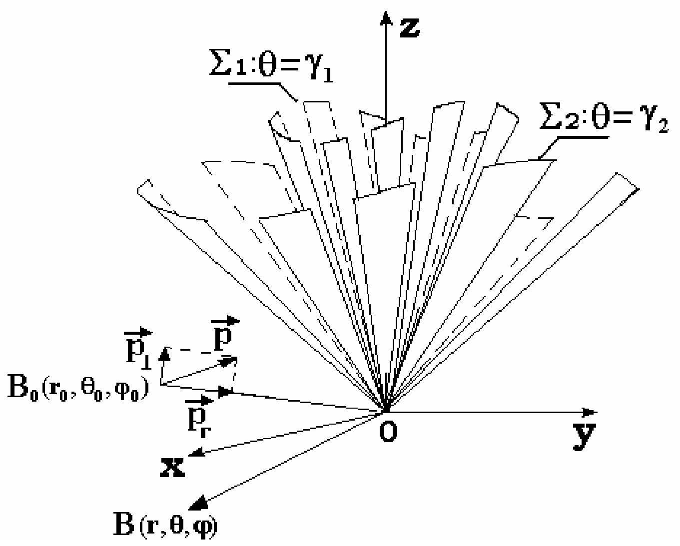


*Irregular structure.*

A slotted bicone structure is a model of a transmission line. A harmonic excitation problem for a semi-infinite perfectly conducting circular cone with periodical longitudinal slots has been considered in [1]. The problem of transient wave diffraction from isotropic perfectly conducting cone has been investigated in [2]. The next step of investigation is to construct mathematical model for solving electromagnetic transient excitation of an infinite slotted bicone structure with an inside conical screen. Slots and isotropic cone effects are of special interest. The paper is devoted to investigation of the simulation problem of exciting the bicone with periodical longitudinal slots and an isotropic inside screen by a dipole whose field arbitrarily varies in time. A method for problem solution uses the Laplace transform, the Kontorovich-Lebedev transforms and the semi-inversion method. The original transient electromagnetic problem is reduced to solving algebraic equations system of the second type. The system can be solved by the iteration method and the reduction one both. The analytical solution is obtained for an alone slotted cone. Simple solution representation is given for a long time regime.

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# The leaky modes calculation of weak guidance optical waveguides with complex transverse section.

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The combined finite element – integral equation method is developed to calculate the leaky modes of weak guidance arbitrary shape inhomogeneous optical dielectric waveguides including coupled structures, Bragg fibers, waveguides with defects.

**Keywords:** leaky modes, optical waveguide theory, numerical modelling, finite element method, integral equation method, losses, Bragg fibers.

### Introduction

The calculation of leaky modes of optical dielectric waveguide is important for such promising applications as optical sensors, Bragg fibers, integral optics structures, dielectric antennas and emitters. The usage of the traditional numerical methods leads to difficulties due to specific features of the problem, especially in the case of arbitrary shape inhomogeneous waveguide. As a solution of this problem, the combined method of finite element - integral equation is suggested.

### Results

The dispersion, the radiation losses, the field power distribution are calculated for scalar leaky modes in the following structures:

a) Circular and elliptical optical dielectric waveguides below the cutoff (first higher mode).
b) Circular and elliptical inverted dielectric waveguide, where the core index is lesser than cladding index (fundamental mode).
c) 3-layer Bragg fiber (fundamental mode) with the following modifications:
d) Elliptical Bragg fiber with $a/b$ ratio varying from 1.1 to 5.0 (fundamental mode).
e) Bragg fiber with excentrical layers (fundamental mode).
f) Coupled Bragg fibers.

The comparison with analytically obtained results shows high accuracy of the developed method.

The work was partially supported by the RFBR (Grant 03-02-16161).

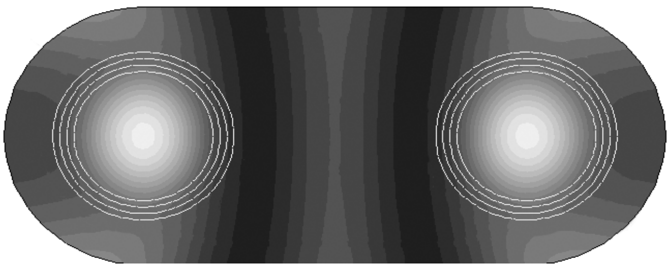

Fig.1. The field power distribution for coupled 3-layer Bragg fiber.

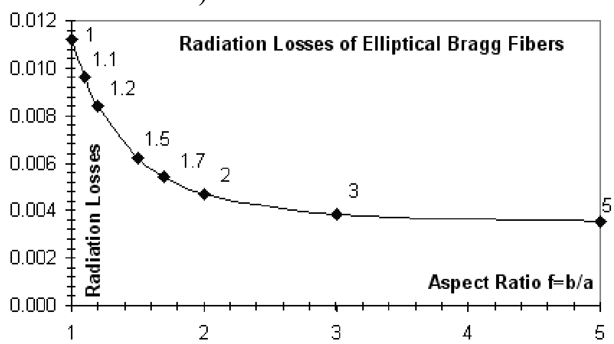


Fig.2. The radiation losses as function of aspect ratio of elliptical Bragg fiber.

# Narrow Band Optical Filter Based on Fabri-Perot Interferometer with Waveguide Grating Mirrors

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Fabri-Perot interferometer with one or two waveguide grating mirrors is considered as a narrow pass band filter. Influence of losses in the waveguide mirror on the filter performance is studied.

**Keywords:** Fabri-Perot interferometer, abnormal reflection, waveguide grating mirror, narrow band filter

Earlier [1] we analysed the work of the narrow band filter based on Fabri-Perot interferometer with one waveguide-grating mirror. It was shown that the strong spectral dependence of the phase of wave reflected from the corrugated waveguide determines the narrow (δλ~1Å) linewidth of the filter. In this work we present the results of the study of loss influence on the performance of the filter as well as investigation of the Fabri-Perot interferometer comprising two waveguide-grating mirrors with losses.

First, we have shown that if choose the buffer thickness so that $R_{mm} \neq R_w$ in the resonance (in particular $R_{mm} < R_w$) then the filter transmission is decreased and the shape of transmission line become more asymmetric. As a result when the buffer thickness corresponds to resonance at the maximum of reflection of the waveguide grating mirror the filter has a reflection peak with the width depending on the difference between $R_{mm}$ and $R_w$. If there is no loss in the waveguide mirror then the reflection peak reaches 100% which is not surprising. The peak disappears when the loss level in the mirror exceeds some critical level.

When two identical waveguide-grating mirrors are used in the interferometer then their reflection coefficients are equal at any wavelength so the existence of the transmission peak is determined solely by the buffer layer thickness. If the losses exist in the mirror then the width and the amplitude of the peak depend on the distance from the peak to the maximum of reflection of waveguide grating mirror. Both parameters increase when the resonance position moves away from the maximum. An interesting feature is the dependence of resonance peak shape and position on the relative phase of gratings in two waveguides when the buffer layer thickness is small ($h_b \sim 2\mu m$). When the buffer layer increases the dependence becomes less noticeable and disappears completely at large thickness.

At large buffer layer thickness shape of the reflection band of the Fabri-Perot interferometer becomes very irregular but the irregularity disappears close to the maximum of waveguide-grating mirror reflection that in some cases can lead to narrowing of the reflection peak. Such an affect can be useful in laser applications and spectroscopy.

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# Novel Finite Element Based Time Domain Propagation Analysis of Photonic Devices

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The beam propagation method (BPM) has been considered in the last two decades as one of the most popular methods used for the simulation of wave propagation in various photonic devices. However, the BPM has the inherent limitation of treating forwardly propagating waves only, and the class of reflecting optical structures cannot be treated using the conventional BPM methods. On the other hand, the finite difference time domain (FDTD) method is a very powerful technique in dealing with arbitrarily reflecting optical devices. However, the FDTD, although general and rigorous, demands an intensive use of the computer resources, and also relying on a uniform mesh that makes it less efficient for relatively long optical structures. Recently, some research effort has been devoted towards improving the efficiency of the FDTD by introducing what is called finite difference time domain beam propagation method (FDTDBPM). Knowing that the modulation frequency of the propagating wave is much less than the carrier frequency, therefore, by removing the high frequency carrier, an efficient finite difference based time domain propagation algorithm has been developed to track the slowly varying amplitude with much larger time steps compared to the conventional FDTD. However, being based on the finite differences, the FDTDBPM still suffers from the inherent limitation of the finite difference discretization problems such as , e.g, straicasing. Alternatively, very efficient implicit finite element based time domain beam propagation methods (FETDBPM) to deal with wideband [1] and full band [2] cases, respectively, have been recently presented in the literature. Although versatile by relying on non-uniform distribution of the nodes, the implicit FETDBPM proposed in [1,2] ends up with a linear system of equations to be solved at each time step. This would be very demanding in terms of execution time when dealing with full wave analysis of three-dimensional integrated optical structures where the number of unknowns can be tens of millions. In this paper, a numerically efficient explicit finite element based time domain beam propagation method (FETDBPM) is presented. By lumping the global mass matrix into a diagonal matrix, an efficient FETDBPM can be derived where the only operations needed at each time step is just a matrix-vector product. As shown in Fig. 1, the accuracy of the proposed FETDBPM is demonstrated through the analysis of the $90^o$ sharp bend. These results are in excellent agreement with their counterparts obtained using the FDTD method [3]. The main advantage of the newly proposed algorithm is that it combines the beauty of the explicit nature of FDTD methods and the robustness and flexibility of the finite element method in meshing. In the presentation, detailed mathematical analysis of the proposed time domain method and simulation results of various reflecting optical waveguiding structures will be presented and compared against those published in the literature.

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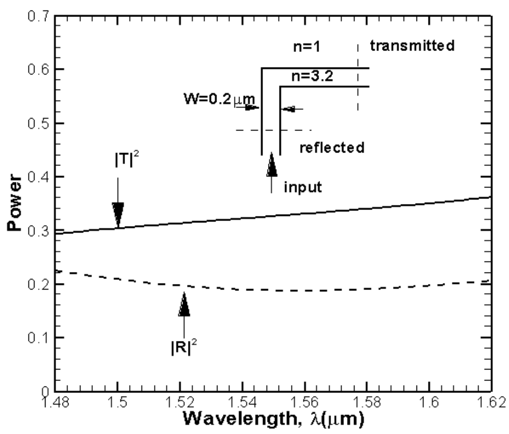


Fig. 1 Transmitted, $|T|^2$, and reflected, $|R|^2$, power spectra around a $90^o$ sharp bend whose structure is shown as an inset.

# Development of Shift Formulae Method for the Problem of Gradient Index Planar Waveguide Synthesis

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The paper considers the synthesis of gradient index planar waveguides using Shift Formulae Method. The advantage of Shift Formulae Method is shown compared with other methods.

**Keywords:** gradient index optics, planar waveguides, optical waveguide theory, refractive index, shift formulae method, numerical modelling, synthesis of planar waveguides

The determination of the refractive-index profile of a planar waveguide is an important problem. The profiles of different forms can be reconstructed. The number of required numerical data depends highly on the form of profile. The method used for the profile reconstruction is also very important. The WKB-method [1] gives good results for refractive-index profiling of multi-mode waveguides and fails when applied to single-mode waveguides.

We use the Shift Formulae Method (SFM) [2] which can be applied to single-mode waveguides. In this work the SFM is realized with the use of very convenient mathematical model [3], that describes a refractive-index profile of a waveguide. This model is suitable for representation of smooth profile. Flexibility of the model allows to describe a great variety of profiles using only few parameters.

The profile of gradient index planar waveguide is characterized by several parameters: its maximum value, depth, and parameters determining its shape. So at least three effective indexes are required for the profile reconstruction. To obtain these values of effective indexes for single-mode waveguide one have to measure them at three different frequencies. Another way is to consider the waveguide with the same profile but with other external refractive indexes [4–5]. The combination of both cases gives good result and allows to find the exact refractive-index profile of a waveguide using less values of effective indexes. The results are illustrated on diagrams.

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# Numerical Modelling of Absorbing and Amplifying Reflective Microresonator by the Method of Single Expression

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To model a reflective microresonator an advanced method of single expression (MSE) is used. A multilayer structure consisting of a highly reflective mirror as a substrate and an absorbing (or amplifying) layer sandwiched between dielectric layers is considered. For the metallic mirror an optimal thickness providing high reflectivity and low loss in accordance with the Hagen –Rubens relation is suggested. For the absorbing and amplifying microresonators the corresponding reflection spectra, distributions of the electric field amplitude and power flow density across the structures are obtained. Resonant configurations for the absorbing and amplifying reflective structures are defined.

**Keywords:** reflective microresonator, metallic mirrors, resonant absorption and amplification, method of single expression, numerical modelling

The correct wavelength scale numerical modelling of the reflective microresonator (Gires-Tournouis resonator) is carried out by the non-traditional method of single expression (MSE) [1,2]. The optimal thickness of highly reflective silver mirror is chosen to be corresponding to the minimal loss and the saturated value of the reflectivity of infinitely thick metallic layer. The execution of the Hagen-Rubens relation corresponding to the saturated minimal value of loss in the metallic half-space is shown. An absorbing microresonator with a bismuth semitransparent layer (serving as a second mirror), as well as a model of a semiconductor amplifying microresonator consisting of p-layer / active transient layer / n-layer on a metallic substrate are considered.

For the absorbing microresonator the reflection spectral dependences on the distance between two mirrors have an oscillating character. At the specific thickness of the semitransparent mirror and for certain distances from the highly reflective mirror very low reflection is obtained corresponding to the high absorption of the incident energy. Distributions of the electric field amplitude and power flow density across the reflective microresonator are obtained at the points of minimal and maximal reflection. For the minimal reflection the absorbing bismuth layer will be located close to the loop of the standing wave and at the node, in the opposite case.

For the amplifying microresonator the reflection spectral dependences on the distance between the highly reflective mirror and the active transient layer have also an oscillating character. However now the values of maximal reflection are higher than one. These maxima correspond to the resonant amplification (generation) and are possible at certain values of the active layer thickness. The loop of the standing electric field amplitude will be in the active layer for the resonant amplification.

Outside of the microresonators the travelling and standing waves formed by the incident and reflected waves are observed.

In the summary the resonant configurations for the absorbing and amplifying microresonator structures are defined and proper physical explanation is given.

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# Method of Lines for Modelling Second Order Nonlinear Phenomena in Planar Optical Waveguides

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The method of lines is used for the analysis of second order nonlinear interactions in a planar optical waveguide. Modelling of second harmonic generation, as well as four frequencies nonlinear interaction in optical waveguide is performed. Obtained results are in a good agreement with the existing ones and prove the energy exchange between the fundamental and second harmonic fields in the both cases.

**Keywords:** second order nonlinear phenomena, optical waveguides, numerical modelling, method of lines

## Introduction

Second harmonic generation (SHG) is an interesting, widely spread and technologically significant nonlinear optical phenomenon. SHG has many potential applications such as frequency conversion, optical witching, generating coherent radiation at new frequencies for spectroscopy, nonlinear optics, remote sensing, optical radar, and various other applications [1].

The method of lines (MoL) [2] has been used as a modelling tool for investigation of the SHG process in a waveguide structure. The MoL is a semi-analytical algorithm for solving partial differential equations and has been successfully used for many years for the modelling of different types of microwave and optical structures. In the previous years the MoL was used to solve some problems of nonlinear optical phenomena [3-5].

Basic formulas for the SHG with the transmission line equations have been derived to analyse nonlinear interaction of fields in optical waveguide. Investigations have been done for different values of incident field amplitude and parameters of the waveguide structure. Well-known energy exchange between the fundamental and second harmonic fields is observed. The obtained results are compared properly with the literature [6]. It was interesting to analyse the nonlinear interaction of more frequencies and by that reason the general formulas for the nonlinear interaction of arbitrary number of frequencies have been also developed in the terms of the MoL. The computation has been done for the four frequencies nonlinear interaction where instead of two coupled differential equations now the coupled wave equations for the four interacting frequencies are involved. The analysis has been done for different values of fundamental field amplitude. The intensity of the doubled frequency field is monotonously increased by the corresponding decreasing the intensity of the single frequency original field. Main interaction takes place between the first two frequencies however the last two frequencies also exchange their intensities.

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# Transformation of Ultra-Short Pulse in a Nonstationary Dielectric Waveguides

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Analytic-numerical approach for investigation of short pulses transformation in a planar dielectric waveguide with time-varying or nonlinear properties is considered.

**Keywords:** dielectric waveguide, nonlinear medium, integral equations methods in time domain, transients.

According to the approach developed in [1] and applied to the problems in nonstationary dielectric waveguides in [2], electromagnetic field in the waveguide is described by the Volterra integral equation and for the case when the core's medium parameters change abruptly the solution is found exactly using resolvent operator. An arbitrary change of the core's medium permittivity, for instance owing to its nonlinearity, is approximated by a sequence of step-wise functions, that allows to construct an exact solution on each time step. Further, transformation of the field on the sequence of the steps is calculated numerically.

Analysis of the exact solution shows the transformation of an initial guided mode caused by an abrupt change in the core permittivity. In the early stages of the transient the initial wave splits into two guided waves with new frequencies, which propagate into opposite directions. At this stage of the process the waveguide walls have no influence yet. The influence reveals itself at subsequent stages when a significant complication of a field structure appears. Two new kinds of guided waves appear. One of these waves has the same frequency as the initial field but a new transverse wavenumber which satisfies the dispersion equation corresponding to the new permittivity in the core. The second wave has a new frequency but the same transverse wavenumber as the initial wave. There are also separate waves in the core that has an irradiated character because its outer field presents itself a propagating non-decaying wave. Besides the guided waves, a continuous spectrum of waves is also excited during transient process.

All such phenomena also reveal themselves during electromagnetic pulse propagation, calculation of which is shown on Fig.1, 2.

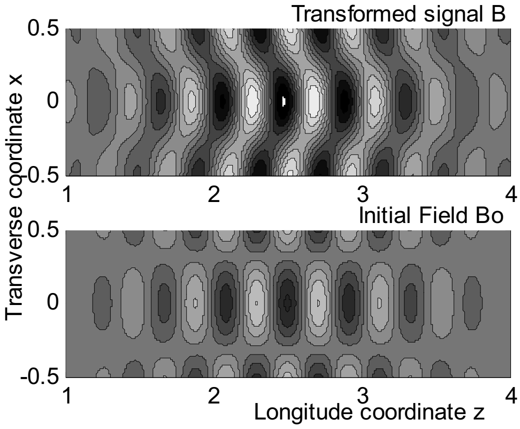


Fig. 1 – Transformation of the signal's spatial structure after step-change of the core's medium permittivity. *t*=3 in dimensionless units.

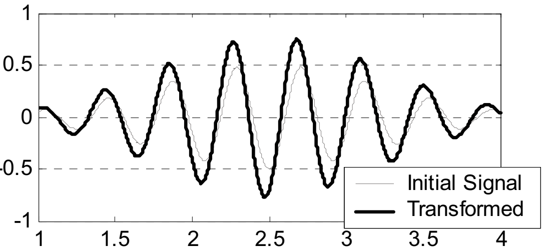


Fig.2. – Transformation of the field amplitude in the middle of the waveguide's core. (t=3)

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# Resonance Properties of Transient Plasma Inclusion in Waveguide

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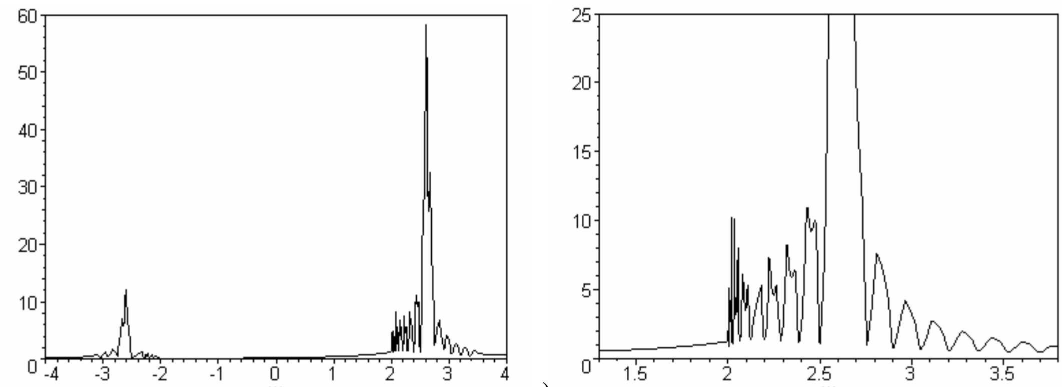
We apply Volterra integral equation approach to investigate analytically electromagnetic wave interaction with a transient plasma microcavity. Spectrum change of the origin wave is demonstrated.

**Keywords:** time-varying media, Volterra integral equation method.

Influence of an active medium on an electromagnetic wave is a problem of great interest because of its potential application for frequency conversion. Instant ionization of the unbounded medium leading to the plasma forming gives splitting of the origin wave into forward and backward propagating ones that have new frequency $\omega_1 = \sqrt{\omega_0^2 + \omega_e^2}$. Here $\omega_e$ is plasma frequency, $\omega_0$ is the frequency of origin wave [1, 2]. Interaction with plasma bounded transient region leads to the quality new results. In this paper we analytically solved the problem of normal incidence of the plane monochromatic wave on the 2D transient plasma cylinder that orthogonal to the perfectly conducting plates of the plate parallel waveguide. It is supposed that at a some moment of time an external source forms instantly plasma inside the cylinder of a finite radius which is a model of a microcavity.

Transformed field inside the plasma inclusion depends on the correlation between the plasma frequency and the frequency of the original wave. For $\omega_e > \omega_0$ we can observe, except of the shifted wave, oscillations on all possible eigenfrequencies of the plasma microcavity (Fig 1). When $\omega_e < \omega_0$, besides the wave of the shifted frequency, the wave with the original frequency survives. In both case there are a transient in the electromagnetic field.




a) b)

Fig.1. Spectrum of the electromagnetic field transformed by plasma time change in microcavity: a) the general view; b) the detailed view in the narrow interval.

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# Electromagnetic Wave Scattering on a 3D Unclosed Structure

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This paper is devoted to investigation the 3D excitation problem with conical geometry. The structure under consideration is a semi-infinite circular cone with longitudinal slots. It's well known that periodic structures are of significant interest in many fields of science, including optoelectronics. The field behavior studying near the structure singularities, such as the cone tip or edges, is important for an efficient computation of the scattered fields from conical structure.

**Keywords**: cone tip singularity, 3D conical structure, slots

The source of an incident field is a harmonic dipole (electric or magnetic) or a plane wave. The method for solving the correspondent electromagnetic problem is a combination of the Kontorovich-Lebedev integral transforms and the semi-inversion method. In previous works we have obtained the numerical results for the case, when the source is placed to the cone axis [1].

The main task of this work is to obtain the numerical solution for arbitrary structure parameters, provided that the source is at any point of the space. The problem parameters effects are analyzed by virtue of given scattered field patterns. The field behavior near the tip of a conical structure is studied. In the present paper we focus our attention on the singularity of the electric and magnetic excitation types at the tip of a perfectly conducting cone with longitudinal slots.

It's common knowledge that the singularity of the electric field proportional to $r^{-1+\mu}$, where $\mu$ depends on structure parameters. There are many interesting particular cases of this conical unclosed structure, such as a cone with a slot, plane angular sector (the opening angle is equal to $\pi/2$, one arbitrary width slot). The obtained results for the plane sector coincide with the values published in the work [2], that demonstrate the accuracy of the given results.

The numerical results show that for an electrical radial dipole excitation singularity near the tip increases through the increasing the slot width. On the contrary, the tip singularity decreases by means of the increasing the slot width for the magnetic dipole excitation. The opening conical angle varying leads to revising the field behavior near the cone tip too. So, the electrical dipole excitation increases and magnetic dipole excitation decreases singularity near the cone tip when the opening angle decreases.

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