Regular paper

Photonic crystal fibre characterisation with the method of lines

Igor A. Goncharenko and Marian Marciniak

Abstract — Photonic crystal fibres are longitudinally uniform fibres in which in lateral directions periodic refractive index changes occur. Two basically different light guiding mechanisms occur in crystal fibres: index guiding and bandgap guiding. In the paper different modelling methods have been evaluated when applied to photonic crystal fibres. In particular, the method of lines has been shown to be effective and reliable for both classes of photonic crystal fibres. High accuracy results for optical field distribution and dispersion characteristics in a photonic crystal fibre have been achieved with the method of lines.

Keywords — optical crystal fibres, photonic bandgap, method of lines.

1. Introduction

Optical fibres are actually regarded as the best available transmission medium in telecommunications. In addition, a growing number of very successful attempts to exploit fibres for optical signal processing purposes has to be noted recently. In silica glass fibres used actually in telecommunications the guiding of the light is assured by refractive index increase within the core region in comparison with surrounding cladding of the fibre. This is referred to in the literature as the "index guiding" principle and it results in specific transmission characteristics of the fibres as dispersion, single-mode vs. multimode transmission depending on the wavelength of the light, and several other.

Recently a new class of fibres based in "bandgap guiding" principle receive a lot of attention. Those are photonic crystal fibres, in which a new operational principle of optical fibres is possible, namely guidance due to photonic bandgap (PBG) effect [1–4]. Photonic bandgaps are forbidden photon energy intervals, which may be displayed by periodic dielectric structures (photonic crystals), and correspond to the electronic bandgaps of semiconductor crystals. Such PBGs may exist in periodic silica/air structures. One of the most promising application areas where photonic crystals are finding use is in optical fibre technology. These fibres of a new type are often called photonic crystal fibres (PCFs). PCFs are single material optical fibres with periodic array of air holes running along their entire length. Typical PCF cross section is shown in Fig. 1. PCFs have properties that can differ substantially from conventional step-index fibers, such as unusual dispersion characteristics (the "endlessly single mode" guidance could be achieved in a fibre with a periodic air-silica cladding), low or high effective nonlinearities, and many others.

In fibre like the one shown in Fig. 1, light can be guided using either one of two quite different mechanisms, so they can be divided into two very different groups [1–4]. The first is fibres having a high-index core (typically solid silica) surrounded by a two-dimensional photonic-crystal-

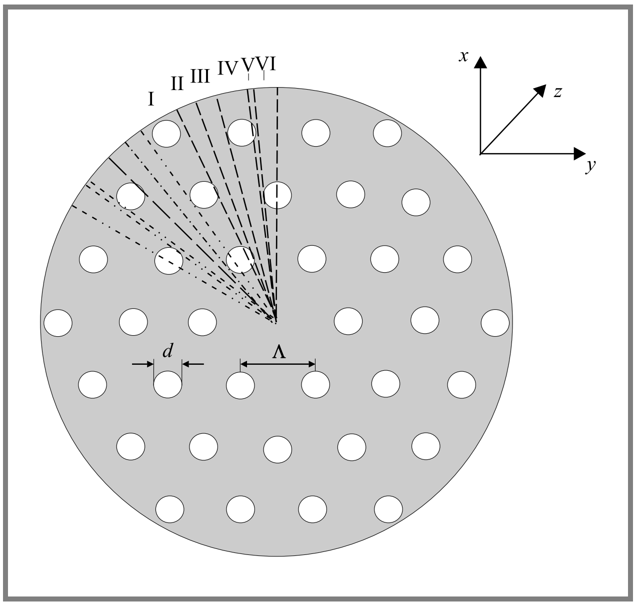

Fig. 1. Photonic crystal fibre cross-section; air holes are arranged in a hexagonal lattice in the cladding region.

cladding structure. These fibres have properties, which partially resembles those of conventional fibres due to the fact that the guidance is caused by total internal reflection (TIR). The higher refractive index of the core compared to the effective index of the photonic crystal cladding allows for traditional index guiding (effective index guidance). These fibres (TIR-PCFs) do not in fact rely on PBG effect at all.

Radically different to TIR-PCFs are fibres, where photonic-crystal-cladding structure is exhibiting PBG effect, and where this effect is utilised to confine light in core region. A full 2D photonic band gap can be created when the holes are arranged in a hexagonal lattice as in Fig. 1 or in honeycomb configuration, i.e., there exists a frequency range in which light cannot propagate in the transverse plane. Numerical simulations show that a band gap only forms when the air holes are quite large, that is when the air hole diameter d is at least 40% of the hole separation Λ. When a defect is introduced into such a structure (for instance, the absence of the hole in the centre), a localised state is created within the bandgap, and so it becomes possible for

PCF to guide light along the length of the fibre making use this state. These fibres, PBG-PCFs, show remarkable properties among which being the ability to confine and guide light along a core region having refractive index below that of the cladding structure. It was recently proven that it is possible to guide light almost entirely within an air-core using PBG fibres. The transmission losses in such fibres (in case they have the ideal structure) are in 10–100 times lower than the one in conventional fibres.

2. Review of modelling methods

The appearance of the new class of optical waveguides represented by photonic crystal fibres not only have opened up for new waveguiding properties, but it has also placed new and stronger demands on fibre modelling.

The effective-index approach should primarily be seen as a rapid method for gaining a qualitative impression of the waveguiding properties of TIR-PCFs [5–8]. In this model, the waveguide consists of a core and cladding region that have refractive indices n_{co} and n_{cl}. The core is pure silica, but the definition of the refractive index in microstructured cladding region is defined in terms of the propagation constant of the lowest order mode that could propagate in the infinite cladding material. This cladding mode field, ψ, is determined by solving the scalar-wave equation within a unit cell centred on one of the holes. By reflection symmetry the boundary condition at the cell edge (at radius $\Lambda/2$) is $\mathrm{d}\psi/\mathrm{d}s = 0$, where s is the coordinate normal to the edge. The propagation constant of the resulting fundamental space-filling mode, β_{FSM}, is used to define the effective index of the cladding as $n_{ef} = \beta_{FSM}/k$ (where k is the free-space propagation constant of light with wavelength λ). Now having determined the cladding- and core-index values, the approximate propagation properties of the PCF may be calculated as for step-index fibre with core index n_{co}, core radius $\Lambda/2$, and cladding index $n_{cl} = n_{ef}$. The cladding-index model can be modified by the addition of a wavelength dependent refractive index for silica through the Sellmeier formula. The dispersion properties of the PCFs are calculated by numerical differentiation.

However the effective-index approach ignores the complex refractive index profiles within PCFs. Hence, this reduced model is unable to accurately predict modal properties, which depend critically on the arrangement and size of the air holes.

To accurately model PCFs with large air holes, it is crucial to use a full vector model. In full vector technique based on plane-wave expansion method, the modal fields and refractive index profile are decomposed into plane wave components, and by doing this the wave equation is reduced to an eigenvalue problem [4, 8, 9]. This equation is then solved to find the modes and their corresponding propagation constants. As this approach can account for any kind of complicated cladding structure, it can accurately model PCF. However it is not efficient, as it does not take advantage of the localisation of the guided modes, and so many terms are needed to obtain an accurate description. Also, this technique involves defining the refractive index profile over a restricted region and using periodic boundary conditions to extend the structure over all space in the transverse plane. Hence, an additional periodicity is imposed on the system (i.e., a periodic distribution of both defects and air holes), which therefore somewhat restricts its applicability to TIR-PCFs, which, unlike PBG-PCFs, do not need to be periodic.

To overcome these disadvantages some alternative approaches have been proposed. One of them is based on modal decomposition using Hermite-Gaussian functions (localised function method) [10–13]. This technique takes advantage of mode localisation, and so can be more efficient than the plane-wave method. However, it cannot be accurate unless the refractive index is also represented well. In multipole method modal expansion on cylindrical functions is used [14–17]. However the localisation function method and multipole method cannot efficiently describe an extended hexagonal lattice structure. Biorthogonal modal method is based on the non-self-adjoin character of the electromagnetic propagation in a fibre [18, 19]. This technique is somewhat complicated as well as numerical method based upon the calculation of the multiple scattering between all the air holes that form the cladding of the PCF [20].

A 3D full-vectorial beam propagation method is successfully applied to investigate longitudinally varying structures or propagation and polarisation effects, which are of practical interest for advanced optical applications [21, 22].

Another method based on space-domain-division-type technique, such as finite element method (FEM) with locally variable mesh is also useful for design and modelling PCFs [23–26]. Contrarily to others computational methods, the FEM does not need any approximation. It models the propagation characteristics of the field taking into account the actual structure of the guide. In order to obtain a precise description of the field distribution over PCF cross-section, and especially near the holes, the classical Maxwell differential equations system must be solved for a large set of properly chosen elementary subspaces, taking into account the conditions of continuity of the fields. The first step consists in splitting the cross section of the modelled guide into distinct homogeneous subspaces. This parcelling results in a mesh of simple finite elements (triangles and quadrilaterals in the 2 dimensions case). For a better description of the fields, the shorter distance of the subspaces to the centre is, the smaller their dimensions are chosen. Then, the Maxwell equations system is discretised for each element, leading to a set of elementary matrices. The combination of the latter creates a global matrix system for the whole studied structure. Finally, the effective index, the distributions of the amplitudes and of the polarisations of the modes are numerically computed, taking into the conditions of continuity at the boundary of each subspace. However finite element method is strictly numerical and very time consumable. In calculations by the pure numerical methods casual solutions can appear besides the right ones. Thus, the additional efforts have to be spent for definition of the correct solution between the number of solutions obtained.

3. Method of lines

To reduce the numerical efforts another technique, co-called method of lines, can be applied for calculation of parameters and field distribution of the guided modes in PCFs. Method of lines (MoL) introduced first by Reinhold Pregla [27] is a special finite difference method, which make it possible to analyse the wave propagation in multilayer waveguide structures. This method uses the semi-analytical approach, which yields accurate results with less computational effect compared to other techniques. In the MoL the mode coupling is automatically taken into account. Non-physical or spurious modes do not appear, and the method has no problem with relative convergence phenomena [28, 29]. Disadvantage of the MoL is in reduced flexibility: different geometries require new algorithms.

Following the MoL we divide the cross-section of PCF into a sequence of regions (layers) homogeneous in angular direction for any fixed radial coordinate (see Fig. 1).Then we look out for a solution of system of coupled partial differential equations in each layer:

$$-j\varepsilon[\mathbf{E}] = \bar{r}^{-1}\frac{\partial}{\partial\phi}[\mathbf{H}] + \begin{bmatrix} D_z \\ -\bar{r}^{-1}D_r\bar{r} \end{bmatrix}\widetilde{H}_\phi\,, \qquad (1)$$

$$-j\mu[\mathbf{H}] = \bar{r}^{-1}\frac{\partial}{\partial\phi}[\mathbf{E}] - \begin{bmatrix} \bar{r}^{-1}D_r\bar{r} \\ D_z \end{bmatrix}E_\phi\,, \qquad (2)$$

where $\mathbf{H} = \left[-\widetilde{H}_z^t, \widetilde{H}_r^t\right]^t$, $\mathbf{E} = \left[E_r^t, E_z^t\right]^t$, superscripts t stand for matrix transposition, $\widetilde{H}_{r,z,\phi} = \eta_0 H_{r,z,\phi}$,$\bar{r} = k_0 r$, k_0 and η_0 are the wave number and wave impedance of free space, $E_{r,z}$ and $H_{r,z}$ are the components of electric and magnetic fields respectively, ε and μ are dielectric and magnetic permittivities, $D_z = jn_{ef}$, $D_r = \partial/\partial r$, n_{ef} is the effective refractive index of the fibre mode. These equations can be easily derived from Maxwell's equations. The azimuthal fields components are obtained from

$$\widetilde{H}_\phi = j\mu^{-1}\left[D_z, -D_r\right][\mathbf{E}]\,,$$
$$E_\phi = -j\varepsilon^{-1}\left[D_r, D_z\right][\mathbf{H}]\,. \qquad (3)$$

After some mathematical manipulation system (1)–(2) can be rewritten in matrix notation as

$$\frac{\partial^2}{\partial\phi^2}[\mathbf{H}] + \left[Q_H^\phi\right][\mathbf{H}] = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \qquad (4)$$

$$\frac{\partial^2}{\partial\phi^2}[\mathbf{E}] + \left[Q_E^\phi\right][\mathbf{E}] = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \qquad (5)$$

with

$$Q_{E11}^\phi = D_r\varepsilon^{-1}\bar{r}D_r\varepsilon\bar{r} + \mu\bar{r}D_z\mu^{-1}\bar{r}D_z + \varepsilon\mu\bar{r}^2,$$
$$Q_{E12}^\phi = D_r\varepsilon^{-1}\bar{r}D_z\varepsilon\bar{r} - \mu\bar{r}D_z\mu^{-1}\bar{r}D_r\,,$$
$$Q_{E21}^\phi = D_z\varepsilon^{-1}\bar{r}D_r\varepsilon\bar{r} - \mu\bar{r}D_r\mu^{-1}\bar{r}D_z\,,$$
$$Q_{E22}^\phi = D_z\varepsilon^{-1}\bar{r}D_z\varepsilon\bar{r} + \mu\bar{r}D_r\mu^{-1}\bar{r}D_r + \varepsilon\mu\bar{r}^2 \qquad (6)$$

and

$$Q_{H11}^\phi = \varepsilon\bar{r}D_r\varepsilon^{-1}\bar{r}D_r + D_z\mu^{-1}\bar{r}D_z\mu\bar{r} + \varepsilon\mu\bar{r}^2,$$
$$Q_{H12}^\phi = \varepsilon\bar{r}D_r\varepsilon^{-1}\bar{r}D_z - D_z\mu^{-1}\bar{r}D_r\mu\bar{r}\,,$$
$$Q_{H21}^\phi = \varepsilon\bar{r}D_z\varepsilon^{-1}\bar{r}D_r - D_r\mu^{-1}\bar{r}D_z\mu\bar{r}\,,$$
$$Q_{H22}^\phi = \varepsilon\bar{r}D_z\varepsilon^{-1}\bar{r}D_z + D_r\mu^{-1}\bar{r}D_r\mu\bar{r} + \varepsilon\mu\bar{r}^2. \qquad (7)$$

These partial differential equations have to be discretised with respect to the radial coordinate using finite differences. This results in a system of ordinary differential equations, which can be solved analytically. In this case, all potentials and dielectric permittivities, as well as, the radial coordinate r have to be discretised. To fulfil the interface conditions the discretisation is done on two different line systems.

In transform domain the discretised wave equations are

$$\frac{d}{d\,\phi^2}\overline{\mathbf{F}} - \Gamma^2\overline{\mathbf{F}} = \mathbf{0}\,, \qquad (8)$$

where $\mathbf{F}$ is $\mathbf{H}$ or $\mathbf{E}$, $\mathbf{H} = \mathbf{T}_H\overline{\mathbf{H}}$, $\mathbf{E} = \mathbf{T}_E\overline{\mathbf{E}}$, Γ is the vector of eigenvalues and derived from eigenvalue problem

$$\mathbf{T}_{H,E}^{-1}Q_{H,E}^\phi\mathbf{T}_{H,E} = -\Gamma^2. \qquad (9)$$

General solution of the Eqs. (8) is

$$\overline{\mathbf{F}} = A\cosh\left(\Gamma\phi\right) + B\sinh\left(\Gamma\phi\right). \qquad (10)$$

Coefficients A and B can be obtained from the relation between magnetic and electric fields.

The analytical solution should be performed in ϕ-direction. The electric and magnetic fields components should be matched at the boundaries of the layers. Thus we can transform fields components from inner side of the layer VI (see Fig. 1) to its outer side. By such a way determinant equation for defining effective refractive index n_{ef} is derived. The computation efforts can be reduced if we take into account the azimuthal periodicity of the structure and will use the Floquet's theorem.

4. Modelling and results

In the following we present preliminary results as the proof of applicability of MoL for calculation of PCFs structures. Figure 2 shows the dispersion characteristics of fundamental mode of PCF (curve *1*) with $\Lambda = 2.3$ μm, $d = 0.6$ μm, refractive index $n = 1.46$. Curve *2* presents dispersion characteristics of conventional fibre with cladding refractive index n_{cl}, where $n_{cl} = (nS_s + S_h)/(S_s + S_h)$, S_s and S_h are the cross-section squares of silica and air holes respectively.

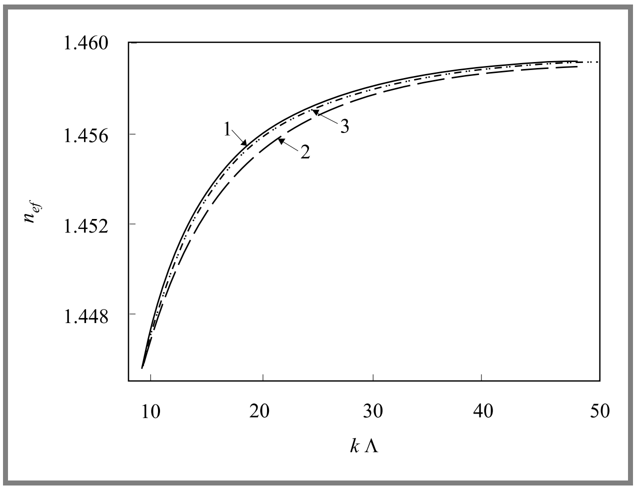

Fig. 2. Dispersion characteristics of fundamental modes of PCF (curve *1*) and conventional fibre (curve *2*), calculated by MoL. Curve *3* presents the dispersion characteristic of the same PCF obtained by full-vector method in [19].

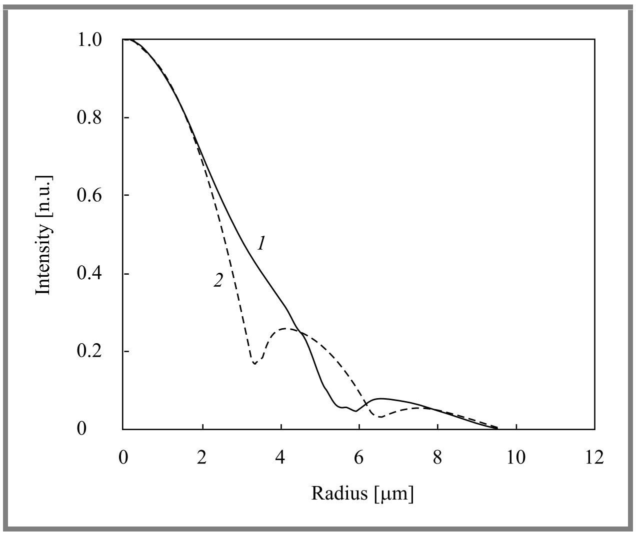

Fig. 3. Radial distribution of the transverse electric fields of fundamental mode of PCF in x (curve *1*) and y (curve *2*) directions.

Curve *3* presents the dispersion characteristic of the same PCF calculated by full-vector method in [19]. As can be seen from the figure, the results obtained by MoL are in very good agreement with those obtained by full-vector analysis. Moreover, the comparison carried out in [21] shows the good agreement between the dispersion values from [19] and the ones obtained by full-vector BMP method in [21]. Figure 3 shows the radial distribution of transverse electric field of fundamental mode in x- and y-directions.

5. Conclusions

Photonic crystal fibres have been classified with respect to basics of guiding mechanism, index guiding or bandgap guiding. Different modelling methods have been evaluated when applied to photonic crystal fibres with special emphasis to the method of lines. Mathematical background of the method of lines has been discussed, and the method has been successfully implemented for calculation of the parameters of modal fiend distribution and dispersion characteristics in photonic crystal fibres. It has been shown that results obtained by the method of lines are in a good agreement with the ones obtained by other full-vector numerical methods.

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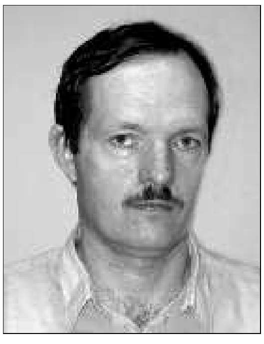

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He has been appointed to Management Committees of all those Projects as the Delegate of Poland. In addition, he has been appointed as the Evaluator of the European Union's 5th Framework Program proposals in the Action Line *All-Optical and Terabit Networks*. He is a Delegate to the International Telecommunication Union, Study Group 15: *Optical and Other Transport Networks*, and to the International Electrotechnical Commission, Technical Committee 86 *Fibre Optics* and its two sub-Committees. He served as a member of Polish Delegation to the World Telecommunication Standards Assembly WTSA 2000. From 2002 he participates in the work of the URSI – *International Union of Radio Science, Commission D – Electronics and Photonics*. In 2000 he originated and actually serves as the Chairman of the Technical Committee 282 on *Fibre Optics* of the National Committee for Standardisation. Since May 2003 he serves as the Vice-President of the Delegation of Poland to the Intergovernmental Ukrainian-Polish Working Group for Co-operation in Telecommunications. He is the originator and the main organiser of the *International Conference on Transparent Optical Networks* ICTON starting in 1999, and a co-located events the *European Symposium on Photonic Crystals* ESPC and *Workshop on All-Optical Routing* WAOR since 2002. He is the Technical Program Committee Co-Chair of the *International Conference on Advanced Optoelectronics and Lasers* CAOL, and he participates in Program Committees of the *Conference on the Optical Internet & Australian Conference on Optical Fibre Technology* COIN/ACOFT, the *International Conference on Mathematical Methods in Electromagnetic Theory* MMET, the *International Workshop on Laser and Fiber-Optical Network Modeling* LFNM, and the *International School for Young Scientists and Students on Optics, Laser Physics and Biophysics/Workshop on Laser Physics and Photonics*. He serves as a reviewer for several international scientific journals, and he is a Member of the Editorial Board of *Microwave & Optoelectronics Technology Letters* journal, Wiley, USA, and the *Journal of Telecommunications and Information Technology*, National Institute of Telecommunications, Poland. Languages spoken: Polish (native), English, French, and Russian. His biography has been cited in Marquis *Who's Who in the World, Who's Who in Science and Engineering*, and in the *International Directory of Distinguished Leadership of the American Biographical Institute*.

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