Designing a photonic crystal fibre with flattened chromatic dispersion

A. Ferrando, E. Silvestre, J.J. Miret, J.A. Monsoriu, M.V. Andrés and P. St. J. Russell

Using a full-vector modal method, the authors have identified a region of nearly zero flattened chromatic dispersion in a specially designed photonic crystal fibre. The approach permits an accurate control of the dispersion features of these fibres in terms of their structural parameters.

Introduction: Photonic crystal fibres (PCFs) were first proposed in 1995 [1]. They are thin silica glass fibres having a regular array of microscopic holes that extend along the whole fibre length. Any transverse section of the fibre has an identical periodic 2D structure. If one of these holes is absent, the transverse dielectric periodicity is broken and a defect appears. The known fact that light can be trapped at defects [2, 3] turns here into a propagation feature. The experimental feasibility of these fibres has been proven recently [4]. A robust singlemode structure was observed for an unusually wide range of wavelengths, a very remarkable property not present in ordinary fibres [5]. Our interest in this Letter is twofold. First, we give an appropriate treatment of the realistic problem of a PCF by modelling and solving efficiently its transverse 2D field structure. We consider a new approach in which the full-vector character of light propagation in fibres is taken into account. It is an adapted version of our biorthonormal-basis modal method [6]. Secondly, the dispersion properties of guided modes for different fibre structural parameters are calculated for the first time. In particular, several specially designed PCFs with nearly zero dispersion over a broad spectral range are presented.

Method: The modes of an inhomogeneous fibre verify a set of dimensionally reduced equations involving the transverse co-ordinates x and y exclusively. In terms of the transverse magnetic field, $h_T = (h_x, h_y)$, and a certain combination of components of the transverse electric field, $\bar{e}_T = (e_y^*, -e_x^*)$, these equations can be written as an eigensystem for the evolution operator L and its adjoint $L^\dagger$, namely, $Lh_T = \beta^2 h_T$, and $L^\dagger \bar{e}_T = \beta^{*2} \bar{e}_T$ [6]. It can be proven that the transverse fields h_T and $\bar{e} <_T$ verify what it is called the biorthogonal condition, $\langle \bar{e}_T^N | h_T^M \rangle = \delta_{NM}$. Because of this property the matrix elements of the L-operator can always be unambiguously defined in terms of the eigenvectors of an arbitrary $\{L', L'^\dagger\}$ system describing the wave propagation in an auxiliary fibre. The main goal of this approach is to transform the problem of solving the system of differential equations for h_T and $\bar{e}_T$ into an algebraic problem involving the diagonalisation of the L-matrix. Of course, the choice of an appropriate auxiliary basis is very important for an efficient implementation of the method. In the particular case of a PCF, realistic simulations can contemplate as much as nearly 100 2D step index individual structures (the air holes of the photonic crystal fibre). Therefore, a brute force computation of matrix elements can become useless in practice due to losses in numerical precision. This loss of precision call be critical in dispersion calculations, where results are extremely sensitive to error accumulation and, consequently, a very high accuracy in the numerical procedure is required. The implementation of the dielectric structure is carried out by putting the system into a finite 2D rhomboid box (of dimensions l_1 and l_2) and requiring the fields to fulfill periodic boundary conditions in the x_1- and x_2-directions defined by the rhomboid sides. This is equivalent to saying that we are choosing periodic plane waves in these two directions, as the auxiliary basis of our Hubert space. The calculation of the matrix elements corresponding to a single hole can be worked out analytically. Moreover, in this basis the sum over all the holes, and consequently the L-matrix of the whole dielectric structure, can also be analytically calculated due to the symmetry properties of the hexagonally-centred configuration of the PCF. In this way, the problem of critical loss of numerical precision in the calculation of the dispersion characteristics of the PCF can be overcome.

Results and discussion: We have simulated a PCF characterised by a triangular distribution of air-filled holes with a central defect. The hole radius a, the horizontal distance between the centre of two consecutive holes, or pitch Λ, and the wavelength of light λ are free parameters we have changed at will. The dimensions of the rhomboid box are fixed by the pitch, $l_1 = l_2 = 7\Lambda$. Our simulation allows us to calculate the modal dispersion relations for the fibre under consideration over a wide range of wavelengths extending from $\lambda = 300$ to 1600 nm.

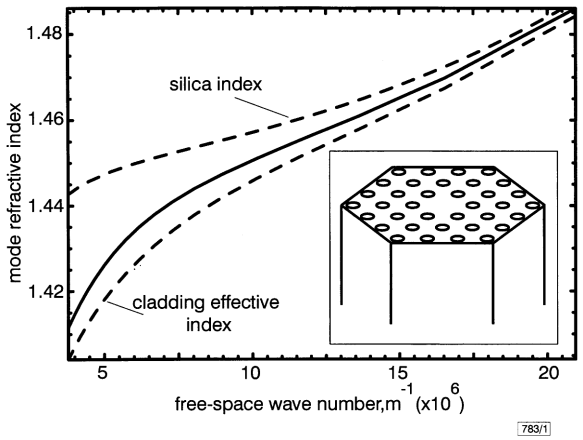

Fig. 1 *Modal dispersion relation for PCF of ratio $a/\Lambda = 0.42/2.3$ and $\Lambda = 1.776\mu m$*

Dispersion curves for both polarisations coalesce in a single plot

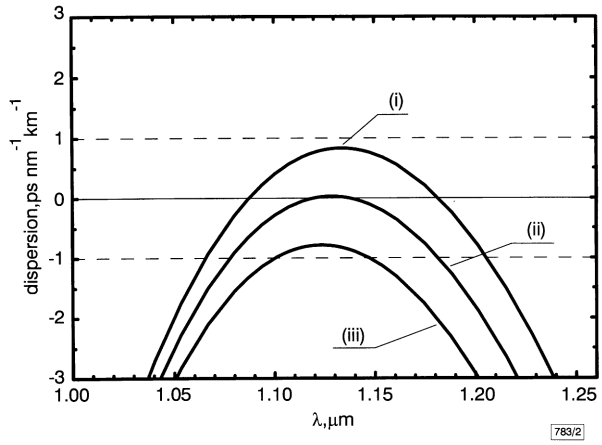

Fig. 2 *Dispersion against λ for fixed ratio $a/\Lambda = 0.42/2.3$ (equivalent filling fraction of air, $f = 13.97\%$) and $\Lambda = 1.74$, 1.73 and 1.72 μm*

(i) $\Lambda = 1.74\mu m$
(ii) $\Lambda = 1.73\mu m$
(iii) $\Lambda = 1.72\mu m$

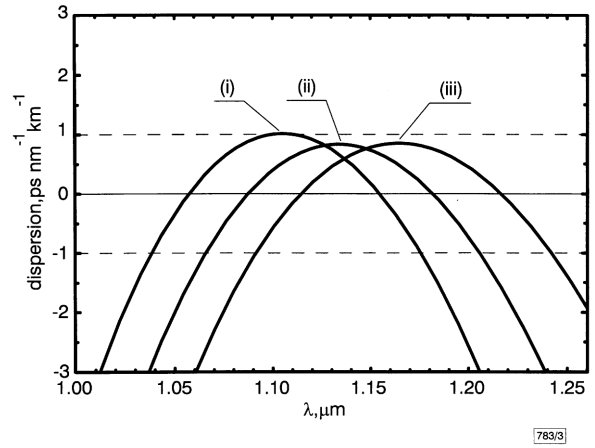

Fig. 3 *Dispersion against λ for some selected combinations of a/Λ (with equivalent filling fraction of air f) and Λ*

(i) $a/\Lambda = 0.44/2.3$ ($f = 15.33\%$), $\Lambda = 1.65\mu m$
(ii) $a/\Lambda = 0.42/2.3$ ($f = 13.97\%$), $\Lambda = 1.74\mu m$
(iii) $a/\Lambda = 0.40/2.3$ ($f = 12.67\%$), $\Lambda = 1.84\mu m$

The dispersion of modal refractive index in an experimentally realisable structure is given in Fig. 1. The dispersion of the pure silica has been directly included in the calculation. In general terms,

our results agree with previous experimental results as they account for the existence of a robust singlemode structure at all wavelengths.

We have also simulated a number of different fibre designs by changing the pitch Λ and the hole radius a. The high accuracy required to calculate the group velocity dispersion of such singlemode fibres is fully provided by our method. In this way, by analysing the dispersion curves of these differently-designed fibres, we have found that it is possible to control their dispersion characteristics. In fact, a proper selection of the above geometrical parameters can yield frequency-independent, i.e. flattened, group velocity dispersion.

In Fig. 2 we present some examples of such flattened dispersion designs and show the effect of scaling simultaneously the pitch arid the hole radius while keeping the a/Λ ratio constant. We can appreciate how the dispersion curves shift upwards and broaden slightly as the scaling factor increases (notice that this is equivalent to increasing Λ). If, instead, we change the a/Λ ratio while fixing the pitch, we also produce a vertical shift but we simultaneously obtain a substantial displacement of the flattened dispersion curves along the wavelength axis. An appropiate fine-tuning of both effects permits excellent control over the wavelength window within which we can obtain nearly zero flattened dispersion structures, as shown in Fig. 3.

Conclusions: In this Letter we have identified PCF designs with an achromatic dispersion behaviour. Simultaneously, we have established an operative procedure to control the dispersion properties of PCFs in terms of their structural parameters. The high accuracy needed to guarantee the fine control of these properties is achieved because the vector character of light propagation is fully and properly taken into account by our numerical procedure. In this way, we have at our disposal a very efficient tool to exploit the wide set of potentially interesting features shown by PCFs.

Acknowledgment: This work was financially supported by the Generalitat Valenciana (grant GV96-D-CN-05141), Spain. J.J. Miret gratefully acknowledges financial support from this institution.

11 November 1998
Electronics Letters Online No: 19990189
DOI: 10.1049/el:19990189

A. Ferrando, E. Silvestre, J.J. Miret, J.A. Monsoriu (*Departament d'Òptica, Universitat de València, E-46100 Burjassot* (*València*), *Spain*)

M.V. Andrés (*Institut de Ciència dels Materials, Universitat de València, E-46100 Burjassot* (*València*), *Spain*)

P. St. J. Russell (*Optoelectronics Group, Department of Physics, University of Bath, Bath BA2 7AY, United Kingdom*)

References

1 ST. J. RUSSELL, P., BIRKS, T.A., and LLOYD-LUCAS, F.D.: 'Photonic Bloch waves and photonic band gaps' *in* 'Confined electrons and photons: New physics and applications' (Plenum Press, New York, 1995)

2 JOHN, S.: 'Strong localization of photons in certain disordered dielectric superlattices', *Phys. Rev. Lett.*, 1987, **58**, pp. 2486–2489

3 YABLONOVITCH, E., GMITTER, T.J., MEADE, R.D., RAPPE, A.M., BROMMER, K.D., and JOANNOPOULOS, J.D.: 'Donor and acceptor modes in photonic band structures', *Phys. Rev. Lett.*, 1991, **67**, pp. 3380–3383

4 KNIGHT, J.C., BIRKS, T.A., RUSSELL, P.ST.J., and ATKIN, D.M.: 'All-silica singlemode fiber with photonic crystal cladding', *Opt. Lett.*, 1996, **21**, pp. 1547-1549 (See also Errata, *Opt. Lett.*, 1997, **22**, pp. 484–485)

5 BIRKS, T.A., KNIGHT, J.C., and RUSSELL, P.ST.J.: 'Endlessly single-mode photonic crystal fiber', *Opt. Lett.*, 1997, **22**, pp. 961–963

6 SILVESTRE, F., ANDRÉS, M.V., and ANDRÉS, P.: 'Biorthonormal-basis method for the vector description of optical-fibre modes', *J. Lightwave Technol.*, 1998, **LT-16**, pp. 923–928