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Guiding Properties of Square-lattice Photonic Crystal Fibers

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In this paper we have investigated the guiding properties of photonic crystal fibers (PCFs) with a square-lattice of air-holes in the cladding. We have shown numerical results of PCFs with various air hole sizes and hole-to-hole spacings over a wide wavelength range. The group velocity dispersion, effective area and effective refractive index of PCF have been calculated numerically. The waveguide dispersion has greatly affected the group velocity dispersion when hole-to-hole spacing is about 1 μm. The effective area is quite flat over the wide spectral range whether the hole-to-hole spacing is large or ratio of diameter to pitch is large. From the field distribution, we found that the field is tightly confined within the core region of PCF when the pitch is 3 μm and the air-filling fraction is 0.9.

OCIS codes : 060.0060, 060.2400, 060.2270, 060.2310

I. INTRODUCTION

Photonic crystal fibers (PCFs), also called holey fibers or microstructured fibers, consist of an array of air-holes running through the entire fiber length. The PCFs consist of the core, which is formed by a solid silica defect instead of a missing hole, and the holey cladding region. The PCFs have many unique features such as the special optical properties of effective index, group velocity dispersion and band structure [1]. The guiding mechanisms of the fiber are explained by index guiding and photonic band-gap guiding: index guiding is so called as total internal reflection of the conventional step index optical fiber, whereas for photonic band-gap guidance the light can be confined to a solid defect region only and to propagates along a solid defect region because the existence of a photonic bandgap in the periodic photonic crystal cladding prohibits propagation though the transversal plane [2]. Owing to the structural difference of the cladding structure, the optical properties of PCFs are tailored by simply changing the structural parameters of the fiber to enhance or to degrade the high nonlinearity of the fiber, effective mode size, and group velocity dispersion [3].

Until now, PCFs with triangular or honeycomb lattice structures have been extensively studied to understand the optical characteristics and the special features, such as ultra-flattened dispersion over a wide wavelength range [4], polarization [5], very large or extremely small mode field size [6], and nonlinear properties [7], have been reported. Recently, a few works related to group velocity dispersion [8], second order mode cut-off [9], bandgap properties, and field distribution of the square-lattice PCF [10] have been reported, because they show different optical behaviors compared with other geometries.

In this paper, due to the lack of information on the optical properties, group velocity dispersion, effective area, and effective index in a wide wavelength range, for PCFs with square-lattice air-hole cladding structure, we will numerically show them with respect to the wide range of hole-to-hole distance (or pitch) Λ and the ratio of diameter of hole d to pitch d/Λ. We select the range of the structural parameters to investigate the fiber which d/Λ is 0.5~0.9 and pitch is 1~4 μm over the wavelength range from 600 to 1600 nm, because the optical properties of the PCF highly depend on the structural geometry such as air-filling fraction d/Λ and pitch, Λ.

II. OPTICAL PROPERTIES OF THE SQUARE-LATTICE PCFs

The dispersion properties of the square-lattice PCFs have already been analyzed within a limited wavelength and structural parameters with the finite-element method [8]. In this paper, we employed the numerical Galerkin method [11] with sine basis functions to solve the vectorial wave equation for lossless fused silica material below:

$$\nabla_t^2 \vec{E_t} + \left(n^2 k_0^2 - \beta^2\right)\vec{E_t} = -\nabla\left(\vec{E_t} \cdot \nabla \ln n^2\right), \quad (1)$$

where n is the refractive index of the fiber shown in Fig. 1, β is the propagation constant and k_0 is the wave number in a vacuum. The basic idea is that the solution is approximately expanded in terms of orthogonal basis functions inside a numerical boundary. The approximated solution is plugged into the original partial differential equation. Integrating over the given boundary after multiplying each basis function, we can convert the given vectorial wave equation problem into a matrix eigenvalue equation. To check the validity of the method, we compared the experimental result [12] with our numerical result having a hexagonal geometric structure with pitch and d/Λ equal to 7.5 µm and 0.43, respectively. The error in the group velocity dispersion was about 2%. The experimental result of the dispersion coefficient at 1.55 µm was 32 ps/nm-km, whereas our result was 31 ps/nm-km. Moreover, we compared with the result from the multipole method [13] which is the most accurate method, the dispersion coefficient is 31.5 ps/nm-km. So, the numerical Galerkin's method yields a very accurate value with about 2% marginal error.

Fig. 1 shows the schematic of the square-lattice PCF investigated in this paper, for which circular hole diameter and pitch along the vertical direction are the same as those along the horizontal direction. In the simulation, we used a 13-by-13 layer of holes and a solid defect at the center. In order for PCF to support the mode properly the modal profile is shown in Fig. 2 with a pitch of 3 µm and a fixed wavelength of 1.55 µm. As you can

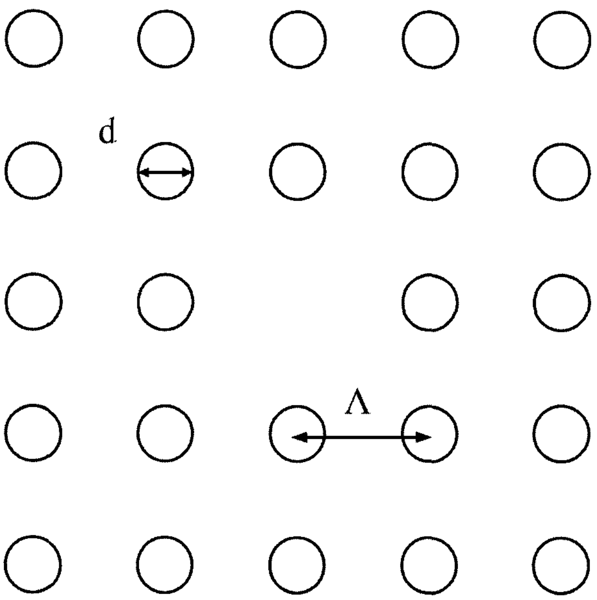


FIG. 1. Schematic of the photonic crystal fiber. The cladding consists of hole diameter d arranged in a square-lattice with pitch Λ. A missing air hole at the center confines the light within the fiber axis.

see the field is well formed and highly concentrated on the core region as d/Λ is increased from (a) 0.5 to (b) 0.9.

One of the important optical parameters of the fiber is the group velocity dispersion which determines the communication bandwidth to carry the capacity of the information. The group velocity dispersion D is calculated from the second derivative of effective index n_{eff} versus the wavelength.

$$D(\lambda) = -\frac{\lambda}{c}\frac{d^2 n_{eff}}{d\lambda^2}, \quad (2)$$

where c is the velocity of light in vacuum. Fig. 3 shows the group velocity dispersion of the square-lattice PCFs with different values of d/Λ for a pitch of (a) 1 µm, (b) 2 µm and (c) 8 µm, respectively. In Fig. 3 (a) the dispersion value at a wavelength of 1.55 µm is obtained as -278 ps/nm-km when d/Λ = 0.6 and the slopes of

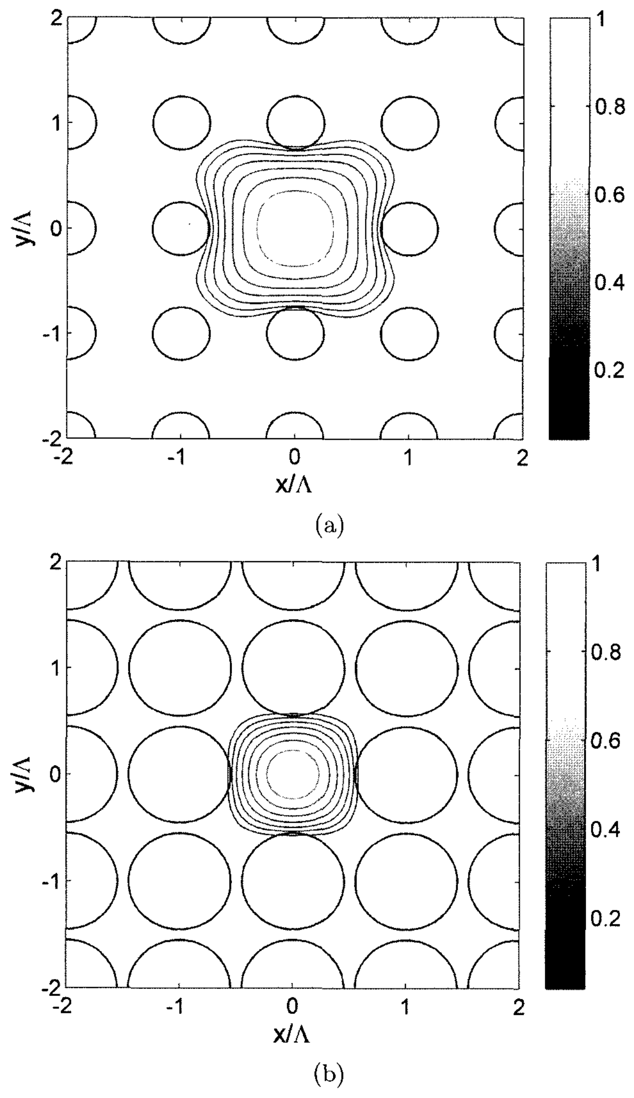


FIG. 2. Intensity distribution at 1.55 µm for the square-lattice PCF having Λ=3 µm, and d/Λ of (a) 0.5 and (b) 0.9.

the dispersion in all cases have negative values in C and L communication windows. So it can be used as a dispersion compensating fiber. When the pitch is greater than 2 μm the dispersion increases monotonically with a positive value in the communication windows as shown in Fig. 3 (b)-(c). Also the dispersion curves are almost independent on d/Λ, when the pitch is greater than 7 μm.

For the cases of $d/\Lambda = 0.5$ and pitch $\Lambda = 3$ μm, the triangular PCFs have been studied [14] [15]. The dispersion of square-lattice PCF is higher than that of the triangular case when the pitch is small ($\Lambda = 1$ μm). On the contrary, when $\Lambda = 3$ μm, triangular PCFs have higher dispersion parameter than that of the square case.

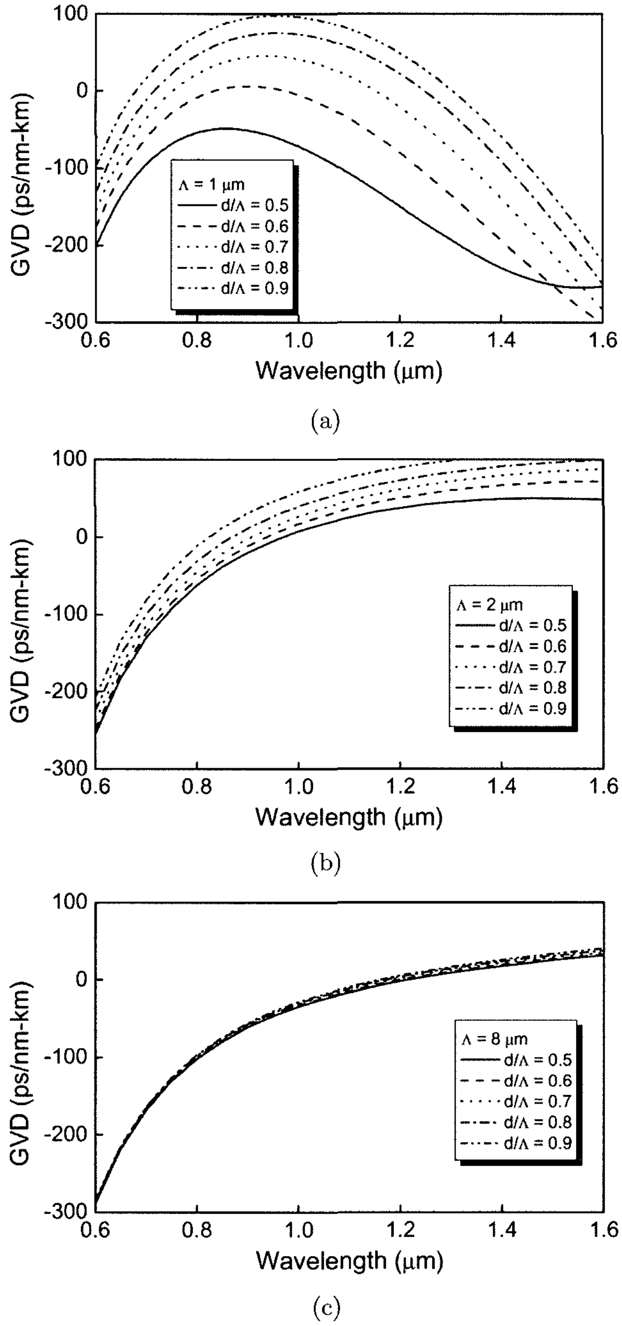


FIG. 3. Group velocity dispersion of the square-lattice PCF with a pitch (a) 1 μm, (b) 2 μm, and (c) 8 μm.

The effective mode area as a measure of nonlinearities is a very important property to understand the guided mode. Small effective area gives a high power density required by non-linear effects [16]. Moreover, the effective area $A_{eff} = \pi\omega^2$ is related to the spot size ω, which is an important parameter related to the confinement loss of a fiber [17]. The effective area of triangular PCFs have been already shown in Ref. [15]. The effective area A_{eff} over the wavelength range from 0.6 to 1.6 μm is calculated using the following formula:

$$A_{eff} = \frac{\left(\iint |\vec{E}_t^2| dxdy\right)^2}{\iint |\vec{E}_t|^4 dxdy} \tag{3}$$

where $\vec{E}_t$ is the component of the transverse electric field. Fig. 4 shows the effective area of the fundamental mode as a function of wavelength regime of 0.6~1.6 μm for the pitch of (a) 1 μm and (b) 2 μm. In Fig. 4 (a) the effective area decreases as the air-filling fraction is incr-

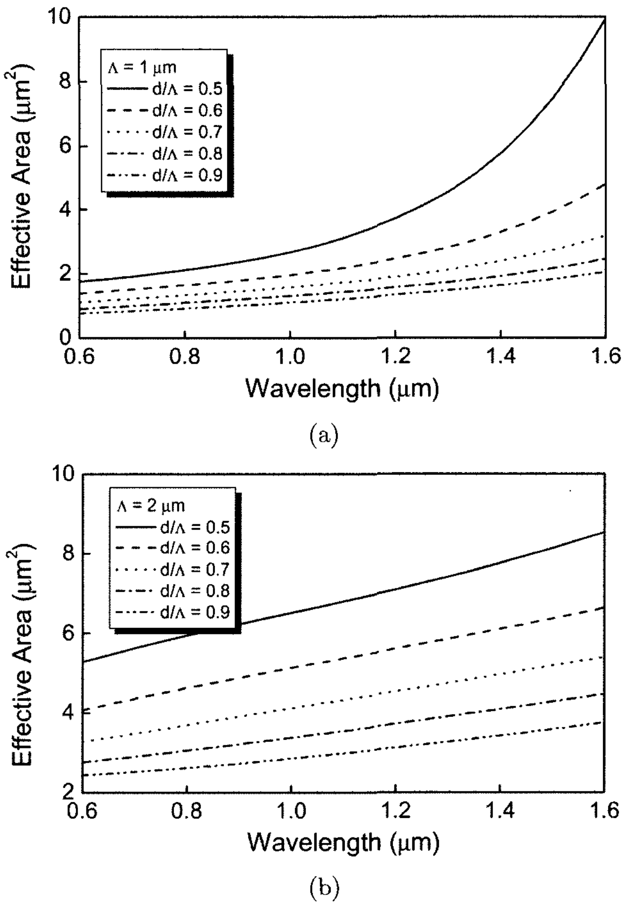
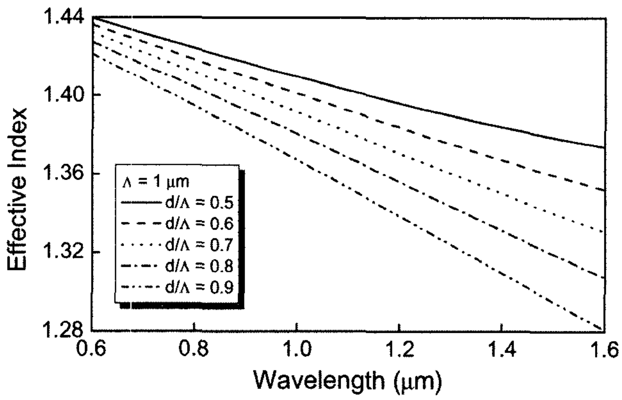


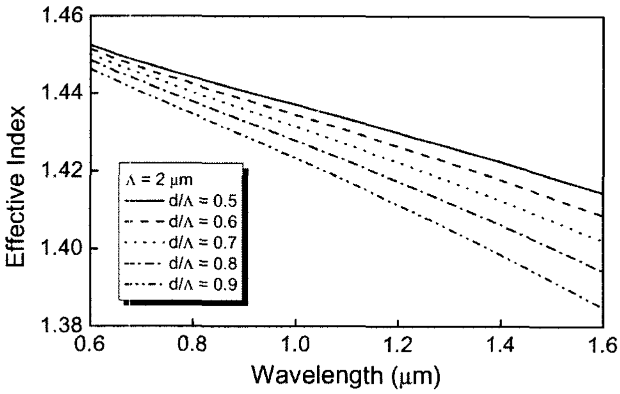
FIG. 4. The effective area as a function of wavelength for different hole sizes with the pitch (a) 1 μm and (b) 2 μm.

eased. The values of the effective area of the square-lattice PCFs are larger than those of the triangular case [8], which is caused by the geometrical difference due to the air-filling fraction [8]. When the pitch is small and the air-hole spacing is large, the effective area of the PCF has a small value of about 1.9 μm^2.

Fig. 5 shows the effective refractive indices of the fundamental mode as a function of wavelength for the pitch of (a) 1 μm and (b) 2 μm. As the d/Λ increases, the variation of the effective index is also increasing. By changing the air filling fraction of the PCFs with three kinds of air hole spacing as shown in Fig. 6. The effective area, the effective index, and the dispersion are shown at a wavelength of 1550 nm with respect to d/Λ. In Fig. 6 (a) the effective area decreases as the air-filling fraction increases, whereas the effective area with pitch of 1 μm, and d/Λ of 0.5 increases as the air-filling fraction decreases due to almost the same value of the effective core index and the effective cladding index. The effective index is decreasing as the air-filling fraction increases due to lowering the effective cladding index as shown in Fig. 6 (b). According to Fig. 6 (c), group velocity dispersion has a strong negative dispersion at the smallest pitch and d/Λ of 0.55 approximately. When the pitch is large compared to the wavelength, the effect of the waveguide dispersion is weakened.



(a)

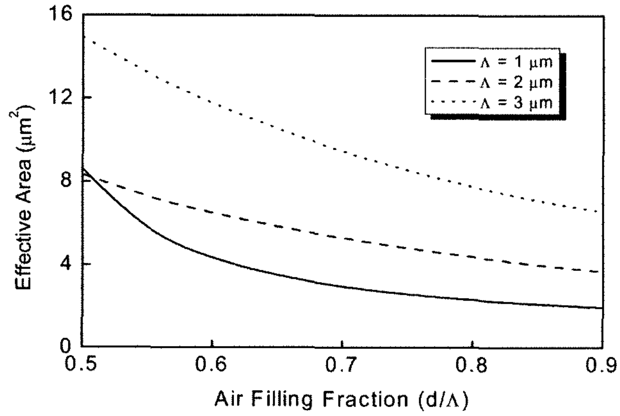


(b)

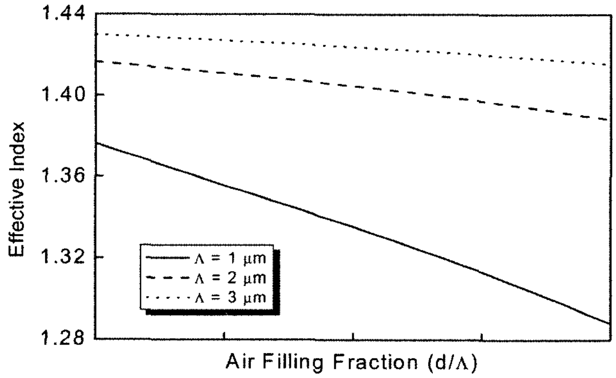
FIG. 5. The effective refractive index as a function of wavelength with the pitch (a) 1 μm and (b) 2 μm.

III. DISCUSSION AND RESULTS

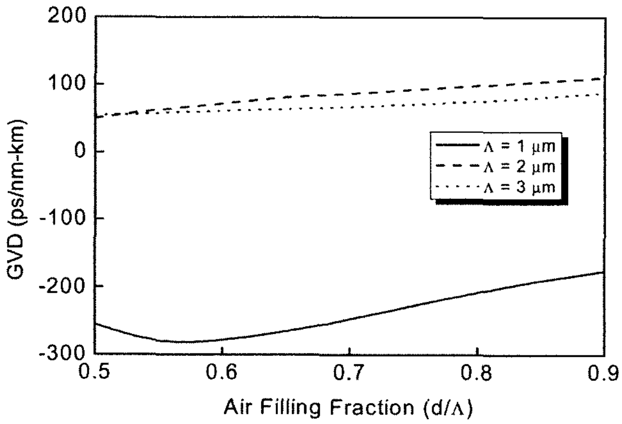
We have shown several optical properties of the square-lattice PCFs such as modal profile, group velocity dispersion, effective area, and effective index. The minimum group



(a)



(b)



(c)

FIG. 6. It shows that (a) effective area, (b) effective refractive index and (c) dispersion with respect to air-filling fraction at a wavelength of 1.55 μm.

velocity dispersion was obtained about -300 ps/nm- km when $d/\Lambda = 0.55$ at the wavelength 1.55 μm with a pitch of 1 μm with high negative dispersion and strong field confinement, such PCF can be used as dispersion compensating fiber. When the PCF has the pitch of 1 μm and d/Λ is 0.9, the effective area and the group velocity dispersion have a minimum value of about 1.9 μm^2 and a strong negative dispersion, respectively. The effective area is larger than that of the triangular case, which is caused by the geometric difference. When the pitch is 3 μm, together with the maximum air-filling fraction, the modal field distribution is quite confined in the first ring of holes.

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REFERENCES

[1] J. C. Knight, "Photonic crystal fiber: putting new life into an old hat," *Technical Digest of the LEOS Summer Topical Meetings*, pp. 3-4, 2003.

[2] J. C. Knight and P. St. J. Russell, "New ways to guide light," *Science*, vol. 296, pp. 276-277, 2002.

[3] J. C. Knight, A. Benabid, W. Reeves, T. Birks, and P. Russell, "Holey optical fibers: cages for light," *Optical Fiber Communications Conference*, vol. 2, pp. 693-694, 2003.

[4] W. H. Reeves, J. C. Knight, and P. St. J. Russell, "Demonstration of ultra-flattened dispersion in photonic crystal fibers," *Opt. Exp.*, vol. 10, no. 14, pp. 609-613, 2002.

[5] M. Szpulak, J. Olszewski, T. Martynkien, W. Urbanczyk, and J. Wojcik, "Polarizing photonic crystal fibers with wide operation range," *Opt. Comm.*, vol. 239, pp. 91-97, 2004.

[6] J. C. Knight, T. A. Cregan, P. St. J. Russell, and J. P. de Sandro, "Large mode area photonic crystal fibre," *IEEE Electron. Lett.*, vol.34, no. 13, pp. 1347-1348, 1998.

[7] A. Ferrando, M. Zacares, P. F. de Cordoba, D. Binosi, and A. Monsoriu, "Spatial soliton formation in photonic crystal fibers," *Opt. Exp.*, vol. 11, no. 5, pp. 452-459, 2003.

[8] A. H. Bouk, A. Cucinotta, F. Poli, and S. Selleri, "Dispersion properties of square-lattice photonic crystal fibers," *Opt. Exp.*, vol. 12, no. 5, pp. 941-946, 2004.

[9] F. Poli, M. Foroni, M. Bottacini, M. Fuochi, N. Burani, L. Rosa, A. Cucinotta, and S. Selleri, "Single-mode regime of square-lattice Photonic crystal fibers," *J. Opt. Soc. Am. A*, vol. 22, no. 8, pp. 1655-1661, 2005.

[10] M. Y. Chen, and R. Yu, "Square-structured photonic bandgap fibers," *Opt. Comm.*, vol. 235, pp. 63-67, 2004.

[11] J. Kim, U. -C. Paek, D. Y. Kim, and Y. Chung, "Analysis of the dispersion properties of holey optical fibers using normalized dispersion," *Optical Fiber Communication Conference*, WDD86, 2001.

[12] B. Zsigri, C. Peucheret, M. D. Nielsen, and P. Jeppesen, "Transmission over 5.6 km large effective area and low-loss (1.7 dB/km) photonic crystal fibre," *IEEE Electron. Lett.*, vol. 39, no. 10, pp. 796-798, 2003.

[13] T. P. White, B. T. Kuhlmey, R. C. McPhedran, D. Maystre and G. Renversez, C. Martijin de Sterke, L. C. Botten, "Multipole method of microstructured optical fibers. I. Formulation," *J. Opt. Soc. Am. A*, vol. 19, no. 10, pp. 2322-2330, 2002.

[14] B. T. Kuhlmey, R. C. McPhedran, C. M. de Sterke, P. A. Robinson, G. Renversez and D. Maystre, " Microstructured optical fibers: where's the edge?," *Opt. Exp.*, vol. 10, no. 22. pp. 1285-1290, 2002.

[15] N. A. Mortensen, "Effective area of photonic crystal fibers," *Opt. Exp.*, vol. 10, no. 7, pp. 341-348, 2002.

[16] G. P. Agrawal, *Nonlinear Fiber Optics* (Academic Press, San Diego, 2001).

[17] T. P. White, R. C. McPhedran, C.M. de Sterke, L. C. Botton, and M. J. Steel, "Confinement losses in microstructured optical fibers," *Opt. Lett.*, vol. 26, no. 21, pp. 1660-1662, 2001.