Optica Applicata, Vol. XL, No. 3, 2010

Theoretical design of a large effective mode area microstructure optical fiber

S.M. Abdur RAZZAK[1, 2*], Yoshinori NAMIHIRA[1]

[1]Graduate School of Engineering and Science, University of the Ryukyus,
1 Senbaru, Nishihara, Okinawa 903-0213, Japan

[2]Department of Electrical and Electronic Engineering,
Rajshahi University of Engineering and Technology, Rajshahi 6204, Bangladesh

[*]Corresponding author: razzak91@yahoo.com

This paper presents a numerical design of a large effective mode area microstructure optical fiber. Using the finite difference time domain numerical simulation method it is shown that the proposed fiber can assume very high effective area of the order 122 to 252 μm^2, negative dispersion-flat properties around the 1550 nm wavelength, and very low confinement losses of the order 10^{-5} dB/km. A hexagonal eight ring silica-air microstructure is used with two air-hole dimensions and a common pitch. A microstructure optical fiber with large effective mode area, low confinement loss, and dispersion-flat property may be promising for next generation optical data transmission applications.

Keywords: microstructure optical fiber, large effective mode area, chromatic dispersion.

1. Introduction

Photonic crystal fibers (PCFs) [1] have drawn increased attention nowadays because of many of their attractive properties [2]; for example, very high or very low nonlinearity, wideband dispersion-flattened characteristics, high birefringence, endlessly single mode guiding, and many others. By modulating the parameters of the holey cladding, it is possible to design application specific guiding properties [3]. Until today, PCFs are being considered mainly for optical components and PCFs as high-speed optical transmission media are still under investigation [4–6]. This is mainly due to the high attenuation of these types of fibers [7]. Recently, the attenuation level has been lowered to the order 0.28 dB/km at the 1550 nm wavelength [7]. This fact eventually encouraged researchers to rethink the applicability of PCFs in signal transmission. Moreover, rapid progresses in fabrication technology are giving momentum to such thinking [8].

Optical transmission systems require PCFs with large effective mode area (LMA) [9]. The LMA PCF is required not only to support broadband optical transmission but also to minimize the coupling losses to standard single mode fibers (SMFs). Again, in broadband communications systems, fiber dispersion and confinement loss play very important roles. For example, in wavelength division multiplexing communication systems it is essential to maintain a uniform response in different wavelength channels. This is strictly achieved by ensuring ultra-flattened dispersion characteristics of fibers [10]. There are so many reports [9–16] in the literature dealing with dispersion-flattened PCFs. Some of which even warrant low confinement loss [14] as well. In spite of this fact, there are only few papers dealing with PCFs having both LMA and dispersion-flattened characteristics at the same time [8, 16].

MATSUI *et al.* [9] have proposed such an LMA PCF in 2005. They have theoretically achieved an effective mode area greater than 100 μm^2 using a double cladding structure characterized by two different pitch and air-hole dimensions. Although the confinement loss of this fiber is small, such PCF with a double cladding [9] sets a challenge on the fabrication issue. REEVES *et al.* [13] also have realized a PCF with effective area 44 μm^2. The PCF has a high confinement loss even with 11 rings. Moreover, the other design [16] contains arbitrary defected air-holes which are also difficult to fabricate.

In this paper, we propose a two layer cladding PCF characterized by a common pitch and two different air-hole dimensions. The structure can ensure LMA, dispersion--flat response, and low confinement loss in a wide wavelength range and is relatively simpler than the existing designs.

2. The LMA MOF design

Figure 1 shows the PCF designs. The two layer cladding is composed of a common air-hole pitch Λ and two different air-hole diameters d_1 and d_2, where d_1 is less than d_2. Air-holes of inner rings are chosen smaller to achieve larger mode area. Figure 1**a** has only one missing air-hole, *i.e.*, an air-hole has been removed from the center and Fig. 1**b** contains all air-holes, including the center air-hole.

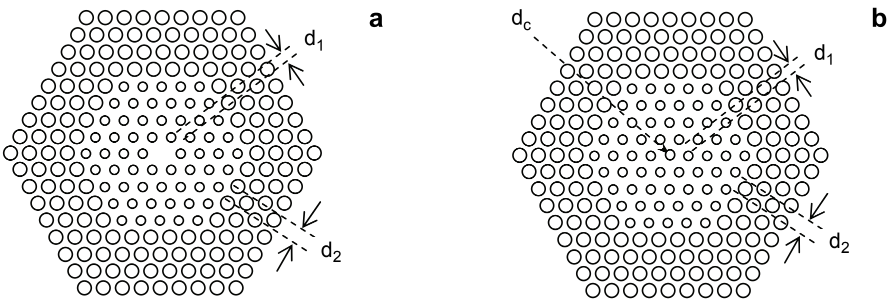

Fig. 1. PCF models: without center air-hole (**a**), and with center air-hole d_c (**b**).

For the purpose of comparison, all parameters of the two PCFs, one without the center air-hole d_c and the other with d_c, are chosen to be the same. Moreover, the dimension of d_c is the same as the dimension of defected air-holes d_1. We have investigated the dispersion and effective mode areas for different number of defected inner rings. A defected ring will mean a ring with air-holes having scaled down diameter. For example, a PCF with d_c and four defected rings will mean the PCF in Fig. 1**b** with $d_c = d_1$, where d_1 is the dimension of air-holes for the inner four rings and that $d_1 < d_2$.

3. Simulation method and equations

The finite difference method (FDM) [2, 17–19] with anisotropic perfectly matched layer (PML) boundary condition is used to simulate properties of the PCFs in Fig. 1. In addition to the PML boundary, a dense mesh is used for both the axes. A PML boundary is required to model the leakage and a dense mesh is required for the FDM to ensure high accuracy. The FDM directly solves the Maxwell equations to best approximate the value of the effective refractive index n_{eff}. Dispersion D, confinement loss L_c, and effective area A_{eff} can be obtained by using values of n_{eff} to the following equations [18]:

$$D = -\frac{\lambda}{c} \frac{\mathrm{d}^2 \mathrm{Re}[n_{\mathrm{eff}}]}{\mathrm{d}\lambda^2} \tag{1}$$

$$L_c = 8.686 \times \mathrm{Im}\Big[k_0 n_{\mathrm{eff}}\Big] \tag{2}$$

$$A_{\mathrm{eff}} = \frac{\left(\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} |E|^2 \mathrm{d}x\mathrm{d}y\right)^2}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} |E|^4 \mathrm{d}x\mathrm{d}y} \tag{3}$$

where $\mathrm{Re}[n_{\mathrm{eff}}]$ is the real part of n_{eff}, λ is the wavelength, c is the velocity of light in vacuum, k_0 is the free space wave number which is equal to $2\pi/\lambda$, and E is the electric field distribution. The material dispersion of silica obtainable from the Sellmeier formula [20] is directly included in the FDM calculation. Therefore, D in Eq. (3) corresponds to the total dispersion of the PCF.

4. Simulation results

We first set air-hole diameters of the outer cladding at $d_2/\Lambda = 0.75$. A high value is chosen for better field confinement. Then, we determine the dimension of air-holes of the inner cladding $d_1/\Lambda = 0.25$ examining the dispersion curves. Figure 2**a** shows effective mode area curves of the same PCF with and without the center air-hole d_c

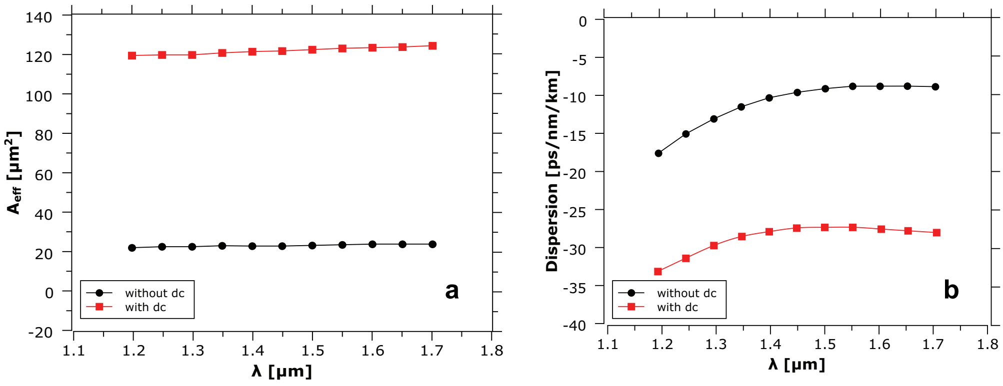

Fig. 2. Properties of PCF with and without d_c; effective mode area (**a**), chromatic dispersion (**b**).

for a same set of parameters. It shows that the PCF without a central defect can assume larger mode area than the other for the same parameters. This is due to the fact that presence of the central air-hole makes the entire defected region as the fiber core. For $d_1/\Lambda = 0.25$, $d_2/\Lambda = 0.75$, $\Lambda = 2.8$ μm, the effective area at 1550 nm wavelength is 122 μm^2 with d_c and it is only 25 μm^2 without d_c.

Figure 2**b** shows dispersion curves for the two cases. For the same aforesaid parameters, the dispersion at 1550 nm is a –8.6 ps/nm/km without d_c and a –27.2 ps/nm/km with d_c. It is clear from the figure and it confirms some previous study [21] that air-core index-guiding PCFs assume flatter dispersion characteristics. Moreover, the central defect d_c has the effect of lowering the dispersion curve which is also consistent. Since this paper intends to design LMA PCFs, from this point forward we will examine PCF characteristics with d_c only. Figure 3 shows the effects of defected number of rings on the effective area and dispersion curves of the PCF

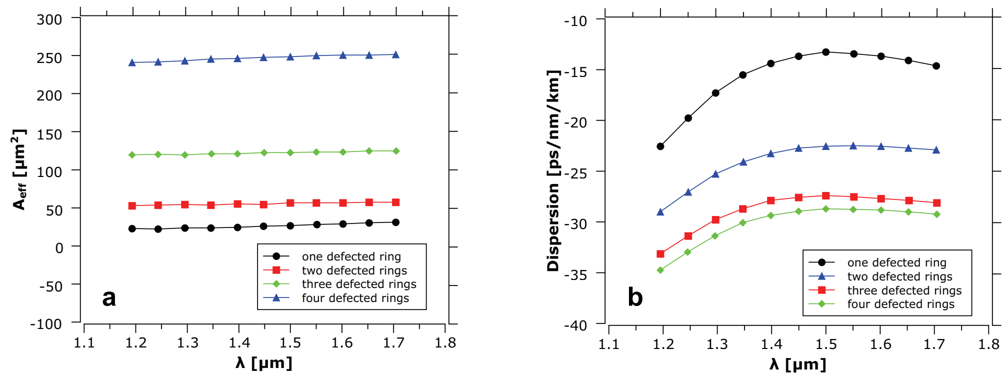

Fig. 3. Effects of defected number of rings on the effective mode area and chromatic dispersion characteristics; effective mode area (**a**), dispersion (**b**).

with d_c (PCF in Fig. 1**b**). It shows that the effective area increases (Fig. 3**a**) with the increased size of the inner cladding having smaller d/Λ. The effective area for a defected first ring is only 31 μm^2 at 1550 nm while it increases to 252 μm^2 for defects up to fourth rings. If we have a look at the dispersion characteristics (Fig. 3**b**), we see that dispersion curves become flatter with increasing defected rings. It becomes ultra-flat at a value of –28.1 ps/nm/km, *i.e.*, the variation of a 0.6 ps/nm/km over 300 nm wavelength centered at 1550 nm wavelength ("three defected rings" line) takes place.

We see that for both three and four defected rings, the PCF can assume very high effective mode areas, greater than 100 μm^2 (122 μm^2 for three defected rings and 252 μm^2 for four defected rings). Dispersion in both cases is very flat around 1550 nm wavelength. Even the PCF with two defected rings can assume an effective area of 55 μm^2 at 1550 nm, which is larger than that of the PCF [13].

Figure 4**a** shows effects of defected rings on the confinement losses in a 1200 to 1700 nm wavelength. Although the optical loss of PCFs, like in the conventional fiber, comprises the Rayleigh scattering loss, scattering due to imperfections, OH absorption loss, and infrared absorption losses. These losses can be minimized by using high-purity silica glass and precise control of air-hole geometry and contaminations during the fabrication process. In addition to the above mentioned losses, PCFs suffer from confinement losses too. Especially, they significantly contribute to the total loss when the fiber core becomes small. As the air-hole diameter and pitch, and number of rings play important role in reducing this loss component, we compute the confinement losses of the PCFs in discussion. Figure 4**a** shows that confinement losses are much lower than the Rayleigh scattering limit for all the four categories.

Figure 4**b** shows both coupling losses to conventional single mode fibers (SMFs). It is seen from the figure that the splice losses [18] are very small with a value of 0.19 dB at 1550 nm. It should be pointed out that we have considered the mode field

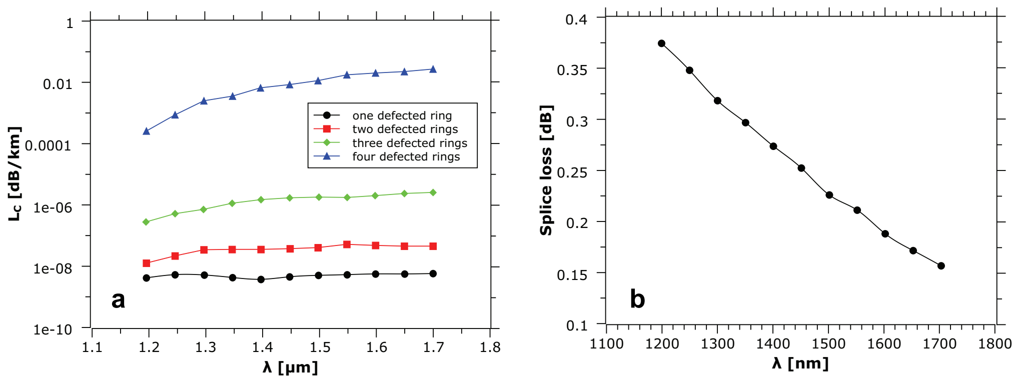

Fig. 4. Confinement losses of the PCFs with d_c as a function of wavelength (**a**), splice loss (**b**).

diameter of the SMF to be 10 μm. Thus we see that it is possible to design wideband ultra-flattened dispersion LMA PCF with low confinement losses without artificial defects [16] or a double pitch double-clad configuration [9].

5. Conclusions

A large mode area dispersion-flat microstructure optical fiber with low confinement losses has been proposed. The coupling loss of such a fiber with conventional single mode fibers has also been calculated. Fibers with large effective mode area, flatter dispersion, and low confinement losses are crucial for future generation high-speed reconfigurable transmission systems.

References

[1] KNIGHT J.C., *Photonic crystal fibers*, Nature **424**, 2003, pp. 847–851.

[2] RAZZAK S.M.A., NAMIHIRA Y., BEGUM F., *Ultra-flattened dispersion photonic crystal fibre*, Electronics Letters **43**(11), 2007, pp. 615–617.

[3] SAITOH K., FLOROUS N.J., KOSHIBA M., *Ultra-flattened chromatic dispersion controllability using a defect-core photonic crystal fiber with low confinement losses*, Optics Express **13**(21), 2005, pp. 8365–8371.

[4] NIELSEN M.D., JACOBSEN C., MORTENSEN N.A., FOLKENBERG J.R., SIMONSEN H.R., *Low-loss photonic crystal fibers for transmission systems and their dispersion properties*, Optics Express **12**(7), 2004, pp. 1372–1376.

[5] TAJIMA K., JIAN ZHOU, NAKAJIMA K., SATO K., *Ultralow loss and long length photonic crystal fiber*, Journal of Lightwave Technology **22**(1), 2004, pp. 7–10.

[6] NAKAJIMA K., JIAN ZHOU, TAJIMA K., KUROKAWA K., FUKAI C., SANKAWA I., *Ultrawide-band single--mode transmission performance in a low-loss photonic crystal fiber*, Journal of Lightwave Technology **23**(1), 2005, pp. 7–12.

[7] JIAN ZHOU, TAJIMA K., NAKAJIMA K., KUROKAWA K., FUKAI C., MATSUI T., SANKAWA I., *Progress on low loss photonic crystal fibers*, Optical Fiber Technology **11**(2), 2005, pp. 101–110.

[8] ROBERTS P.J., COUNY F., SABERT H., MANGAN B.J., WILLIAMS D.P., FARR L., MASON M.W., TOMLINSON A., BIRKS T.A., KNIGHT J.C., RUSSEL P.ST.J., *Ultimate low loss of hollow-core photonic crystal fibers*, Optics Express **13**(1), 2005, pp. 236–244.

[9] MATSUI T., JIAN ZHOU, NAKAJIMA K., SANKAWA I., *Dispersion-flattened photonic crystal fiber with large effective area and low confinement loss*, Journal of Lightwave Technology **23**(12), 2005, pp. 4178–4183.

[10] FERRANDO A., SILVESTRE E., MIRET J.J., ANDRES P., *Nearly zero ultraflattend dispersion in photonic crystal fibers*, Optics Letters **25**(11), 2000, pp. 790–792.

[11] TZONG-LIN WU, CHIA-HSIN CHAO, *A novel ultraflattened dispersion photonic crystal fiber*, IEEE Photonics Technology Letters **17**(1), 2005, pp. 67–69.

[12] FERRANDO A., SILVESTRE E., ANDRES P., MIRET J., ANDRES M., *Designing the properties of dispersion--flattened photonic crystal fibers*, Optics Express **9**(13), 2001, pp. 687–697.

[13] REEVES W.H., KNIGHT J.C., RUSSELL P.ST.J., ROBERTS P., *Demonstration of ultra-flattened dispersion in photonic crystal fibers*, Optics Express **10**(14), 2002, pp. 609–613.

[14] SAITOH K., KOSHIBA M., HASEGAWA T., SASAOKA E., *Chromatic dispersion control in photonic crystal fibers: Application to ultra-flattened dispersion*, Optics Express **11**(8), 2003, pp. 843–852.

[15] RENVERSEZ G., KUHLMEY B., MCPHEDRAN R., *Dispersion management with microstructured optical fibers: Ultra-flattened chromatic dispersion with low losses*, Optics Letters **28**(12), 2003, pp. 989–991.
[16] FLOROUS N., SAITOH K., KOSHIBA M., *The role of artificial defects for engineering large effective mode area, flat chromatic dispersion, and low leakage losses in photonic crystal fibers: Towards high speed reconfigurable transmission platforms*, Optics Express **14**(2), 2006, pp. 901–913.
[17] KANESHIMA K., NAMIHIRA Y., ZOU N., HIGA H., NAGATA Y., *Numerical investigation of octagonal photonic crystal fibers with strong confinement field*, IEICE Transactions on Electronics **E89-C**, 2006, pp. 830–837.
[18] RAZZAK S.M.A., NAMIHIRA Y., BEGUM F., MIYAGI K., KAIJAGE S., HAI N.H., KINJO T., ZOU Z., *Dispersion-flattened modified hexagonal photonic crystal fibers with low confinement loss*, Optical Review **14**(4), 2007, pp. 165–168.
[19] RAZZAK S.M.A., NAMIHIRA Y., *Tailoring dispersion and confinement losses of photonic crystal fibers using hybrid cladding*, Journal of Lightwave Technology **26**(13), 2008, pp. 1909–1914.
[20] AGRAWAL G., *Nonlinear Fiber Optics*, 3rd Edition, Academic Press, 2001, pp. 5–10.
[21] JINGYUAN WANG, CHUN JIANG, WEISHENG HU, MINGYI GAO, *Properties of index-guiding PCF with air-core*, Optics and Laser Technology **39**(2), 2007, pp. 317–321.

Received November 19, 2009
in revised form April 30, 2010