Low Nonlinear Effects Index-Guiding Nanostructured Photonic Crystal Fiber

S. Olyaee, M. Seifouri, A. Nikoosohbat, M. Shams Esfand Abadi

Abstract—Photonic Crystal Fibers (PCFs) can be used in optical communications as transmission lines. For this reason, the PCFs with low confinement loss, low chromatic dispersion, and low nonlinear effects are highly suitable transmission media. In this paper, we introduce a new design of index-guiding nanostructured photonic crystal fiber (IG-NPCF) with ultra-low chromatic dispersion, low nonlinearity effects, and low confinement loss. Relatively low dispersion is achieved in the wavelength range of 1200 to 1600nm using the proposed design. According to the new structure of nanostructured PCF presented in this study, the chromatic dispersion slope is -30(ps/km.nm) and the confinement loss reaches below 10^{-7} dB/km. While in the wavelength range mentioned above at the same time an effective area of more than 50.2μm^2 is obtained.

Keywords—Optical communication systems, nanostructured, index-guiding, dispersion, confinement loss, photonic crystal fiber.

I. INTRODUCTION

THE photonic crystal fibers (PCFs) have attracted in many recent applications. PCFs with large effective mode area can strongly confine light in their hollow cores. PCFs with nearly zero and flat dispersion over a wide range of wavelengths are the suitable media for applications in wavelength-division-multiplexing (WDM) systems. It is imperative to maintain a uniform response at different wavelength channels, which requires that transmission happens within both very low chromatic dispersion and confinement loss regions. Thus, PCFs perform very well in telecom and non-telecom applications. In optical communication, chromatic dispersion plays an important role as it determines the information carrying capacity of the PCF. Therefore it becomes important to study the chromatic dispersion properties of PCF. In other hands, control of chromatic dispersion in PCFs is a very important problem for practical applications to optical communication systems, dispersion compensation, and nonlinear optics [1].

Usually, PCFs are constructed from silica glass which contains very tiny air holes. The air holes running through the length of the structure act as the cladding of the fiber and a defect at the center (done by removing the hole at the center of the structure) acts as the core [2]. Since in the index-guiding nanostructured photonic crystal fiber the average refractive index of the area surrounding core is lower than that of the core, subsequently, the transmission in this type of PCFs is due to the total internal reflection (TIR).

Up until now, several designs for PCFs have been proposed to achieve a very low chromatic dispersion and low confinement loss. Hansen proposed a PCF structure with three-fold symmetry which low dispersion and dispersion slope. However, the confinement loss was about 10^{-3} dB/km [3]. Nejad et al. presented a new PCF structure that controlled the chromatic dispersion very well. But, the confinement loss, was 10^{-4} dB/km [4]. In 2011, an ultra-flattened dispersion photonic crystal fiber with low confinement loss was proposed by Olyaee et al. [5], [6].

In designing PCFs, three optical parameters, namely, chromatic dispersion, confinement loss, and nonlinear effects are very important and they must have minimum values. By tuning physical parameters such as the diameter of the air holes, the shape of the holes, the defect at the center of the fiber, the number of holes rings in the area surrounding the core and the spacing between the adjacent air holes, one could have PCFs with desired properties [7].

In this paper, we introduce and simulate an index-guiding nanostructured photonic crystal fiber with improved optical parameters. In the proposed nanostructured PCF, low dispersion, low nonlinear effects and very low confinement loss are obtained.

II. CHARACTERISTICS OF PCFS

PCFs have some important optical parameters and each of which is crucial for high-speed optical communications. Important parameters in PCFs are as follows:

A. Confinement Loss

The confinement loss, L_c, is the light confinement ability within the core region. Increasing the number of air hole rings strengthen the confinement of light in the core region. This in turn results in smaller losses than those with less air hole rings. The confinement loss is calculated as [8], [10]-[12]:

$$L_c = \frac{(20*10^6)}{(L_n 10)} k_0 \mathrm{Im}[n_{eff}] \quad (1)$$

where, Im(n_{eff}) is the imaginary part of the n_{eff} and the unit of L_c is dB/m.

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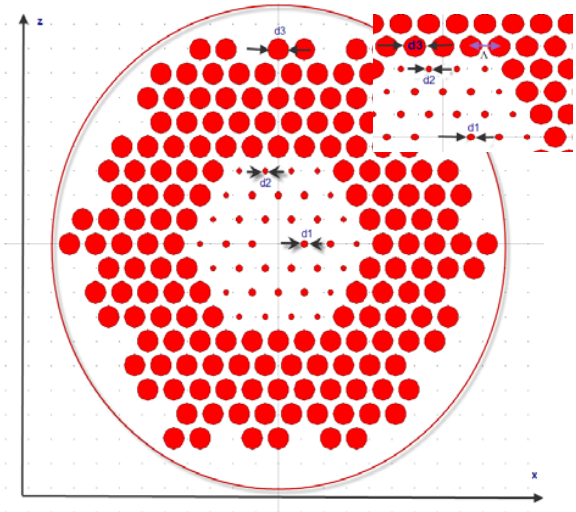


Fig. 1 The cross section of the proposed nanostructured PCF and its cross section of the proposed IG-NPCF structure in more details; with lattice constant being Λ1, the air-hole diameter of the 2nd ring is d1, the air-hole diameter of the 3rd ring is d2 and the diameter of air-holes in 4th to 8th rings is d3. d1=599.5nm, d2=449.65nm, d3=1798.6nm, Λ=2300nm

B. Chromatic Dispersion

An important parameter for designing PCFs is the total dispersion. The chromatic dispersion, $D(\lambda)$, is the sum of the material dispersion and the waveguide dispersion. Unlike conventional fibers, waveguide dispersion in PCFs may be difficult to control. But, material dispersion is controllable via suitable design of the cladding and its air-holes. The chromatic dispersion of PCF is computed from the real part of the effective mode index, n_{eff}, using the following [8]:

$$D(\lambda) = -\frac{\lambda}{C}\frac{d^2 Re[n_{eff}]}{d\lambda^2} \quad (2)$$

Here, λ is the operating wavelength in micro meter, C is the velocity of light in free space, and $Re[n_{eff}]$ is the real part of the n_{eff}. Therefore, the units for chromatic dispersion is ps/(nm.km). For a given wavelength, the effective mode index of a guided mode is obtained by solving the Maxwell's equations [9], using the FDTD method as explained in (3):

$$n_{eff} = \frac{\beta}{k_0} \quad (3)$$

where, β and k_0 are the propagation constant and the free space wave number, respectively.

C. Mode Effect Area

Mode effective area in PCFs, A_{eff} ,in units of mm^2 is given by:

$$A_{eff} = \frac{(\iint |E|^2 dxdy)^2}{(\iint |E|^4 dxdy)} \quad (4)$$

Here, |E| is the electric field distribution which derives from the eigenvalue problem drawn from Maxwell's equations [13]. By changing the geometric characteristics of the fiber-cross-section, such as large effective area, obtaining PCFs with various properties is possible [14].

D. Nonlinearity Effects

With high nonlinearity in PCFs, the confinement loss is increased rapidly. Subsequently, such PCFs are not used in long haul communications. Therefore the nonlinearity in PCFs must be minimized. Large mode area of PCFs can prevent unwanted nonlinear impairments [13]. On the other hand, low confinement losses or small effective mode area is required for some special applications including the nonlinear based phenomenon. The nonlinear effects can be written as follows:

$$N_{eff}\, \alpha\, (1/A_{eff}) \quad (5)$$

That N_{eff} and A_{eff} are the nonlinear effect and the effective mode area of PCFs, respectively.

III. IG-NPCF Design

The proposed IG-NPCF is made up of pure silica with a refractive index of 1.45. It has a triangular array of air holes formed along its length. This PCF consists of 8 air hole rings. The diameter of the holes in the second and the third inner rings and other rings are chosen to be 599.5nm, 449.65nm, and 1798.6nm, respectively. The lattice structure of the cladding is hexagonal and the pitch of the lattice, Λ (the spacing between the centers of two adjacent holes), is 2300nm. The transverse cross-section of the PCF is demonstrated in Fig. 1.

The air hole diameter-to-pitch ratio, (d/Λ), plays mainly a role in the design of IG-NPCF. By lowering d/Λ in the cladding, the chromatic dispersion reduces. But, on the other hand by increasing the d/Λ results in the reduction of the confinement loss. Therefore, the diameter of holes in the internal rings, have been selected to be smaller, whereas the diameter of holes in the external rings are selected to be larger. In the third ring, diameter of the holes is selected smaller than the two inner rings, because the chromatic dispersion can be improved using such structure, as shown in Fig. 1. By removing a number of the holes in the 8^{th} ring of the hexagon structure, the chromatic dispersion of PCF will be even less.

For better control of the chromatic dispersion, the confinement loss, and nonlinearity, unequal diameters for air holes can be selected. In this design, the pitch is chosen to be constant. Therefore, by increasing or decreasing the diameter the air holes in the proposed IG-NPCF, the chromatic dispersion, the confinement loss, and the nonlinearity change.

IV. Simulation Results

The chromatic dispersion curve of our design is demonstrated in Fig. 2. The chromatic dispersion over the measured wavelength range of 1000-4600nm is low and suitable. The chromatic dispersion of the proposed IG-NPCF is -32.152ps/(nm.km), at the wavelength of 1550nm. The minimum of the chromatic dispersion is related to the wavelength range of 900-1000nm which has negative dispersion of -7ps/(nm.km). This is a very low value. In the proposed IG-NPCF, over the wavelength range of 1200-1600 nm, the average of chromatic dispersion is -30ps/nm.km, which is a low value. In the other ranges of wavelengths, the IG-NPCF has a low negative dispersion and in longer wavelengths, the negative dispersion decreases. The best chromatic dispersion is achieved with Λ=2300nm.

The loss characteristic of the presented index-guiding nanostructured photonic crystal fiber within the wavelength range of 1000-4200nm is plotted in Fig. 3. As can be seen from the figure, the loss of the designed PCF is 2.02×10^{-7}dB/km at the wavelength of 1550nm. This value is extremely low and very proper. In addition, the PCF shows the losses of $1.63\times10^{-7} \sim 1.96\times10^{-7}$dB/km in the wavelength range of 1200-1600nm and less than 10^{-6}dB/km over other wavelength ranges.

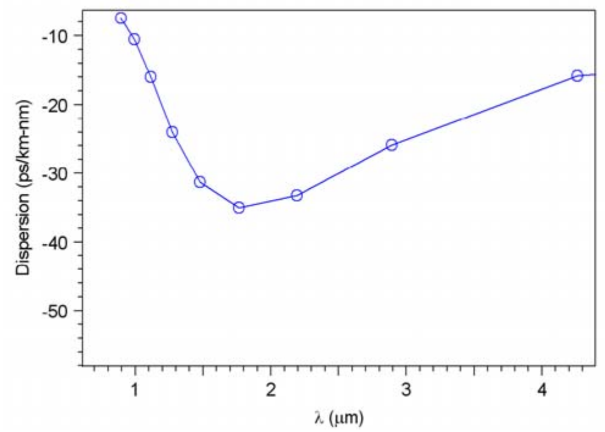


Fig. 2 The chromatic dispersion curve of the proposed nanostructured PCF as a function of wavelength

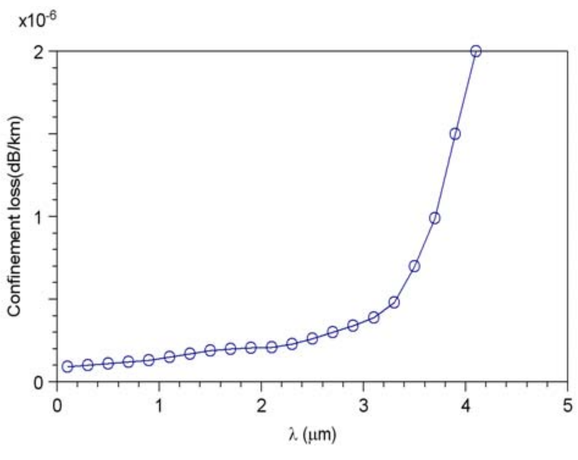


Fig. 3 The confinement loss curve of the proposed nanostructured PCF as a function of wavelength

The effective index curve of the proposed IG-NPCF within the frequency range of 10^{13}-3.5×10^{14} Hz is shown in Fig. 4. As shown in Fig. 4, the effective index increases with increasing frequency. Therefore in longer wavelengths, the effective index decreases.

Fig. 5 illustrates the variation of the n_{eff} with respect to the wavelength in the proposed index-guiding nanostructured photonic crystal fiber. The effective index curve of the proposed IG-NPCF within the wavelength of 0.4-4.6μm is shown. As shown in Fig. 5, the effective index decreases by increasing the wavelength.

In the proposed design, a strong confinement of light in the core of the IG-NPCF is obtained. The mode field is mainly distributed and guided in the silica core region. The light is well trapped at the center of the structure and the mode effective area of 50.2μm^2 is achieved at 1.55μm. In order to visualize and support our results, we calculated the first-order mode for the index-guiding nanostructured photonic crystal fiber ($|E|^2$ and $|E|$) at $\Lambda/\lambda = 2.53906$ as shown in Fig. 6. This is a large mode area. In the proposed structure, with such a large mode area, the unwanted nonlinear impairments are prevented and hence, nonlinear effects are decreased.

V. Conclusions

In this paper, a new index-guiding nanostructured photonic crystal fiber based on pure silica is designed and simulated. According to the results, lower values for chromatic dispersion, nonlinear effects, and confinement loss can be acquired by reducing of the size of the holes in the inner rings and increasing the diameters of the holes in the outer rings. The results show that negative dispersion can be obtained. The main advantages of the proposed nanostructured PCF are ultra-low chromatic dispersion, low confinement loss and low nonlinearity effects with large mode area.

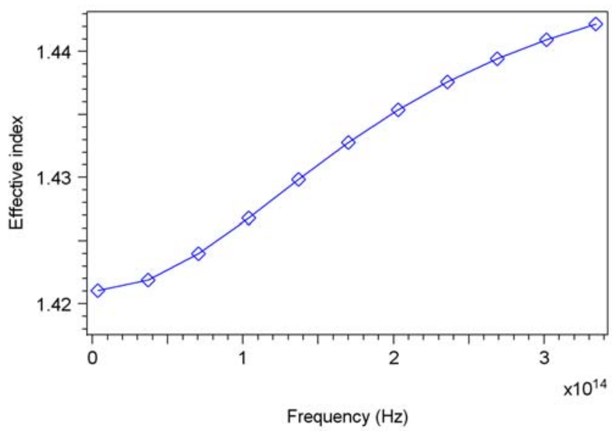


Fig. 4 The effective index curve of the proposed nanostructured PCF as a function of frequency

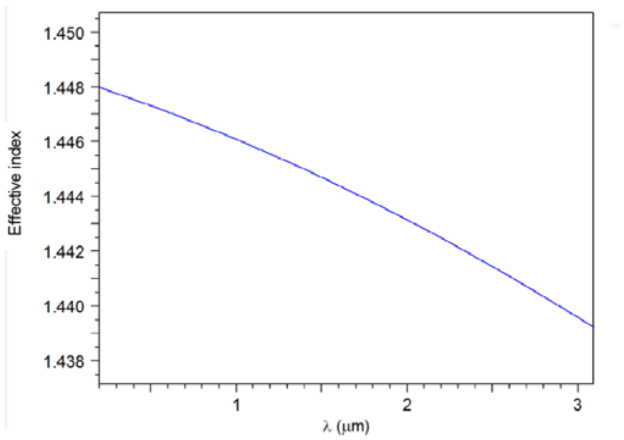
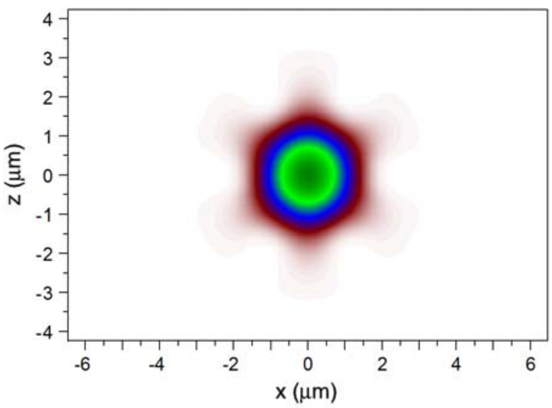
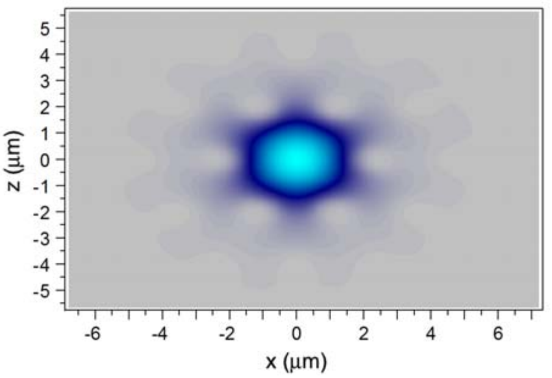


Fig. 5 The effective index curve of the proposed nanostructured PCF as a function of wavelength



(a)



(b)

Fig. 6 The field distribution of the first-order mode (a) $|E|^2$ and (b) $|E|$ for the proposed nanostructured PCF at $\Lambda/\lambda = 2.53906$. At this value, n_{eff} is 1.4417

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