

**Research Article** 

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# Nonlinear Rectangular Photonic Crystal Fiber (PCF) for Optical Communication Exclusively Super Continuum Generation

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### Abstract

A rectangular PCF structure in BK7 glass with inner and outer cladding is used to investigate effective mode field area, high nonlinear coefficient, and confinement loss and dispersion property using 2D FDTD technique. The PCF structure is purposed to design with pitches and air hole diameter in a periodic array fashion. The different properties

of PCF structure like mode field area, nonlinear coefficient, confinement loss and dispersion are to be analyzed. The

variation is investigated with change of different parameters like  $\Lambda_1 \frac{d_1}{\Lambda_1}, \frac{\Lambda_2}{\Lambda_1}$ , and d1/d2 for a wide range of wavelength.

The proposed rectangular PCF structure has slightly more nonlinear coefficient ( $\gamma$ =36.98 W<sup>-1</sup>km<sup>-1</sup>) than the highly nonlinear silica photonic crystal fiber ( $\gamma$ =35 W<sup>-1</sup>km<sup>-1</sup>) at a wavelength of 1.55 µm with almost same mode field area (A<sub>eff</sub> ~ 2.8 µm<sup>2</sup>). This result seems to be important in super-continuum generation and nonlinear fiber optics.

**Keywords:** PCF; FDTD method; Kerr nonlinearity; Supercontinuum generation

## Introduction

Photonic crystal fibers also known as micro structured optical fibers have become a major topic of research over the last decade [1,2]. The kinds of fibers are fabricated mainly by a single material (glass or polymer). The cross-section of the fiber consists of a core area surrounded by a periodic array of holes, and air holes running along the length of the fiber, where the light can be either guided based on indexor band gap guidance mechanism depending on the refractive index contrast between the core and the cladding [3-5]. A holey cladding in PCFs control the nonlinear coefficient and dispersion property [6] in such way that, the conventional fiber does not do this. Such PCFs can control the chromatic dispersion keeping high nonlinear coefficient, which is most important application for nonlinear optics. Now a day, the highly nonlinear PCF is commonly used type. Their use are wide field of applications ranges from spectroscopy and sensor [7,8] to direct telecom. The high nonlinear coefficient and designable dispersion properties make these fibers attractive for many nonlinear applications of which super continuum(SC) generation has been the most intensively investigated and this has been used in application like optical coherence tomography, spectroscopy, metrology [9-11]. In a telecommunication era, the spectral slicing of broadband SC spectra has also been proposed as a simple way to create multiwave length optical sources for dense wavelength division multiplexing applications [12,13]. High nonlinear PCFs are good approach and used to generate super continuum generation pumped by ultrafast laser pulses and longer laser pulses, however super continuum generation in PCFs is restricted by dispersion properties. Mode field area of PCF is the key factor to generate the nonlinear coefficient i.e. as small as the mode field area, the increase in the nonlinear coefficient which leads to super continuum generation. Our research is aimed to design the rectangular PCF by adjusting suitable cladding variables to determine the high nonlinear coefficient and some dispersion properties. An interesting conclusion found from our simulation is that, the proposed rectangular PCF structure has slightly more nonlinear coefficient as compared to the highly nonlinear silica hexagonal photonic crystal fiber at a wavelength 1.55  $\mu m$  with same effective mode area [14]. So our proposed rectangular PCF is a suitable candidate for application like super continuum generation and nonlinear fiber optics.

## Structural Design

We propose to design a rectangular PCF of complex configuration with different circular air holes, which arranged in regular pattern. The nonlinearity and dispersion can be controlled by air hole diameter as well as pitch values. The PCF structure is in the form of inner cladding with small air hole and outer cladding with large air hole rectangular distribution as shown in Figure 1. Considering  $d_1$ ,  $\Lambda_1$  are the air hole diameter and the pitch of the inner cladding, while  $d_2$ ,  $\Delta_2$  are the air hole diameter and pitch of outer cladding respectively. The hole to hole spacing  $(\Lambda)$  can be chosen to minimize the value of effective mode area, however it is not always desirable to use the structure with smaller effective mode area because it exhibits high confinement loss. In addition by adding more ring of air hole to fiber cladding, it is possible to reduce confinement loss. Cladding region can be mostly comprised of air hole, Basically PCFs with small scale cladding feature and large air filling fraction (large value of  $d/\Lambda$ ) light can be confined extremely tightly with in the core, resulting in small mode field area and large value of nonlinear coefficient ( $\gamma$ ). The nonlinear coefficient of PCFs is tailored by changing the air filling rate of the cladding, while chromatic dispersion property can be obtained by varying air hole diameter and the pitch value. It is very difficult to obtain both high nonlinear coefficient and chromatic dispersion, if PCFs with same air

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hole diameter in entire cladding region. So it is necessary to implement cladding variables in PCF structure. Here we have considered BK7 glass as a background material, rather than silica material, because this PCF is also most suited for super continuum generation and nonlinear fiber optics in large extent.

## Numerical Analysis

In order to obtain, the field distribution of rectangular photonic crystal fiber (PCF) cladding, we have used 2-dimensional finite difference time domain (FDTD) method. Considering the material is isotropic, linear, and lossless, the time dependent Maxwell's equations can be written as

$$\frac{\partial H}{\partial t} = \frac{1}{\mu(r)} \nabla \times E \tag{1}$$

$$\frac{\partial E}{\partial t} = \frac{1}{\varepsilon(r)} \nabla \times H - \frac{\sigma(r)}{\varepsilon(r)} E$$
(2)

E, H are electric field and magnetic field.

Where  $\epsilon(r)$ ,  $\mu(r)$ ,  $\sigma(r)$  are permittivity, permeability and conductivity of the material and all are in the function of position.

Equations (1) and (2) can be discretized using Lee's technique. Considering spatial and time discretization, equations (1) and (2) can be written for TE polarization as follows

$$H_{x(i,j)}^{n+1/2} = H_{x(i,j)}^{n-1/2} - \frac{c\Delta t}{\mu\Delta y} \left( E_{z\left(i,j+\frac{1}{2}\right)}^{n} - E_{z\left(i,-\frac{1}{2}\right)}^{n} \right)$$
(3)

$$H_{y(i,j)}^{n+1/2} = H_{y(i,j)}^{n-1/2} + \frac{c\Delta t}{\mu\Delta x} \left( E_{z\left(i+\frac{1}{2},j\right)}^{n} - E_{z\left(i-\frac{1}{2},j\right)}^{n} \right)$$
(4)

$$E_{z(i,j)}^{n+1} = E_{z(i,j)}^{n} + \frac{c\Delta t}{\varepsilon\Delta x} \left( H_{y\left(i+\frac{1}{2},j\right)}^{n+\frac{1}{2}} - H_{y\left(i-\frac{1}{2},j\right)}^{n+\frac{1}{2}} \right) - \frac{c\Delta t}{\varepsilon\Delta y} \left( H_{x\left(i,j+\frac{1}{2}\right)}^{n+\frac{1}{2}} - H_{x\left(i,j-\frac{1}{2}\right)}^{n+\frac{1}{2}} \right)$$
(5)

For stability, the time step  $\Delta t \leq \frac{1}{c\sqrt{\Delta x^{-2} + \Delta y^{-2}}}$  where  $\Delta t$  the time

increment, c is the velocity of light,  $\Delta x$  be the lattice increment in x direction,  $\Delta y$  be the lattice increment along y direction. Considering equation (3), (4) and (5), we have calculated the field distribution of PCFs in TE polarization mode.

For a nonlinear optical waveguide having Kerr type nonlinearity

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related permittivity  $\varepsilon_r$  depends on electric field  $E_v$  and can be expressed as

$$\varepsilon_r = \varepsilon_{r\perp} + \alpha \pm \left| E_y \right|^2 \tag{6}$$

Where  $\varepsilon_{r,L}$  is the linear relative permittivity and  $\alpha$  is the nonlinear coefficient. A hybrid implicit FDTD method [10], is used to simulate the field for 2D PCS with nonlinear rods. The overall stability of this hybrid FDTD scheme is determined by the stability in the linear medium regions. Consequently, nonlinearity in the structure does not affect stability and hence the grid size and time step. The nonlinear coefficient of PCFs and dispersion control are rested with the design of the cladding structure parameters that is flexibility and comparative freedom, the cladding structure parameters mostly include air hole diameter d, pitch  $\Lambda$  and air filling rate f of cladding. The nonlinear coefficient  $\gamma$  ( $\lambda$ ) of PCFs can be expressed as

$$\gamma(\lambda) = \frac{2\pi n_2}{\lambda A_{eff}} \tag{7}$$

Where  $A_{eff}$  is model effective area and  $n_2=2.497 \times 10^{-20}$  m<sup>2</sup>/W, is the nonlinear index of BK7 glass.

In order to investigate the optical properties of BK7 glass rectangular PCF, we have given stress for dispersion property and the confinement loss of the same optical fiber. The chromatic dispersion play an important role in optical communication is calculated as:

$$D(\lambda) = -\lambda / c \frac{d^2 \operatorname{Re}(n_{eff})}{d\lambda^2}$$
(8)

Where Re  $(n_{aff})$  is the real part of the refractive index in cladding.

The confinement loss of optical fiber can be calculated using fundamental formula, which is given bellow.

Confinement loss=  $8.686 k_0 \text{Im} [n_{eff}] dB/km (9)$ 

Where Im is the imaginary part,  $n_{eff}$  is the effective index of x polarized and y polarized fundamental mode.

Similarly, effective mode area can be expressed as

$$Aeff = \frac{\left(\iint |E|^2 \, dx \, dy\right)^2}{\iint |E|^4 \, dx \, dy} \tag{10}$$

This integration is calculated over the cross-section of the fiber and the electric field intensity E is given by

$$E = \sqrt{E_x^2 + E_y^2} \tag{11}$$

Where  $E_x$  is the x-component of the electric field and  $E_y$  is the y-component of the electric field.

#### **Simulation Analysis**

To investigate the possible application of the proposed rectangular PCF cladding structure for supercontinuum generation, we implement 2D FDTD technique, where the excitation is initiated at the centre of above mentioned structure without no defect. We have adjusted suitably the cladding structure parameters  $d_1$ ,  $d_2$ ,  $\Lambda_1$  and  $\Lambda_2$  for high nonlinear coefficient ( $\gamma$ ) and dispersion property. For this, we analyze nonlinear coefficient and dispersion of PCF cladding with respect to various structure parameters. In order to achieve optimum structural parameters, we investigate the nonlinear coefficient and dispersion property almost suited for super continuum generation using 2D

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FDTD simulation. Choosing the parameters:  $\frac{\Lambda 2}{\Lambda 1}$ =1.6, d1/d2=1.6,  $\frac{d_1}{\Lambda 1}$ 

=0.8 fixed and varying one parameter the small air hole pitch ( $\Lambda_1$ =0.6 0.8 1.0 1.2) in our simulation and these parameter have most significant influence on the fiber properties. First, we simulate effective mode area, nonlinear coefficient, dispersion and confinement loss using above data with wide range of wavelength shown in Figures 2-5. Figure 2 shows the effective mode area with respect to wavelength for different  $\Lambda_1$  and all other parameter fixed. The result predicts that, the effective mode field area  $(\mathrm{A}_{_{\mathrm{eff}}})$  is gradually increasing with increasing of wavelength.  $\mathrm{A}_{_{\mathrm{eff}}}$  is large for  $\Lambda_1$ =1.2 µm and least for  $\Lambda_1$ =0.6 µm. Mode field area becomes almost same at 1.5  $\mu$ m. A<sub>eff</sub> is the most important key factor for nonlinear coefficient which leads to super continuum generation. Figure 3 shows that nonlinear coefficient as a function of wavelength for different value of  $\Lambda_1$  while other parameters are kept constant. By increasing the value of wavelength, nonlinear coefficient decreases exponentially except for  $\Lambda_1=0.6 \ \mu m$ , where there is a sudden rise in the nonlinear coefficient at  $\gamma$ =1.0 µm. The nonlinear coefficient, for 1.5 µm from Figure 3. is calculated as  $\gamma$ =36.98 W<sup>-1</sup>km<sup>-1</sup> and is more than the values in reference [14] for the same wavelength. Figure 4 is the waveguide dispersion versus wavelength under same parameter as Figures 2 and 3. It is in general observed that, with increasing wavelength, dispersion property increase, while for large value of  $\Lambda_1$ , dispersion increase sharply after the wavelength of 1  $\mu$ m and small value of  $\Lambda_1$ , the curve of dispersion become steep. So for small value of  $\Lambda_1$ , the nonlinear coefficient  $\gamma(\lambda)$ 









is high but the curve of waveguide dispersion is steep. Similarly Figure 5 shows the variation of confinement loss with wavelength of PCF cladding under same condition (Figure 5). It shows, confinement loss falls rapidly with increase in wavelength, and seen that it is high for  $\Lambda_1$ =0.6 µm, Basically small core PCFs can offer light mode confinement and are more useful for high nonlinear application and confinement loss significantly degrade the performance of device based on such small core fiber. In general every propagating mode is intrinsically leaky, so it experiences confinement loss, and can be reduced by carefully optimization. Secondly we have investigated the case  $\Lambda_1$  is fixed for different value of  $\frac{d_1}{\Lambda 1}$  (0.5 0.6 0.7 0.8) and  $\frac{\Lambda 2}{\Lambda 1}$ , d1/d2 are set to fix as 1.6. In Figures 6 and 7 we plotted nonlinear coefficient versus wavelength and dispersion versus wavelength under abovementioned conditions. In Figure 6, when we increase  $\frac{d_1}{\Lambda l}$ , the nonlinear coefficient also increase, while in Figure 7, increase  $\frac{d_1}{\Lambda 1}$ , dispersion curve increase but hump arises soon after a wavelength 1 µm. We observed here for large value of  $\frac{d_1}{\Lambda 1}$ ,  $\gamma$  ( $\lambda$ ) is also high. Lastly we investigate the case  $\Lambda_1$ ,  $\frac{d_1}{\Lambda 1}$  and  $\frac{\Lambda 2}{\Lambda 1}$  are kept fixed (their values as 1.0µm, 0.8µm and 1.6) and changing one parameter d2/d1=0.5 0.6 0.7 0.8 respectively, and

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simulation results shows in below figure. The Figure 8 shows the variation of nonlinear coefficient with wavelength while variation of the waveguide dispersion with wavelength is shown in Figure 9. The nonlinear coefficient falls suddenly with change of wavelength, but dispersion increase with increase of wavelength. Analysis made so for lead us to conclude that, the cladding structure parameters:  $\Lambda_1$ ,  $\frac{d_1}{\Lambda 1}$  and d1/d2 effect on the nonlinear coefficient and waveguide dispersion.



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The hole to hole spacing i.e. pitch has most dominate key factor that influence the nonlinear coefficient and waveguide dispersion curve,  $\frac{d_1}{\Lambda l}$  also effect on nonlinear coefficient and size, position of waveguide dispersion. Reducing the pitch value  $\Lambda_1$  or increasing  $\frac{d_1}{\Lambda l}$  or by properly increasing d1/d2, we can obtain the high nonlinear coefficient and maintain the dispersion to be little flattened.

#### Conclusion

We investigated the nonlinear coefficient and dispersion properties of a rectangular PCF cladding structure in BK7 glass using 2D FDTD method. The PCF structure is composed of inner and outer cladding with different pitch value and air hole diameter, where the small air hole pitch  $\Lambda_1$  has most significant role for dispersion curve and  $\frac{d_1}{\Lambda_1}$  is another parameter which influence the size and position of waveguide dispersion. One can achieve high nonlinear coefficient of rectangular PCF, either by reducing  $\Lambda_1$  or by increasing  $\frac{d_1}{\Lambda_1}$ . In reference [14], for a conventional fiber, the maximum nonlinearity can be enhanced to 35 W<sup>-1</sup>km<sup>-1</sup>, whereas in the proposed structure the nonlinearity can be increased to higher value 36.98  $W^{\mbox{-}1} \mbox{km}^{\mbox{-}1}$  for  $\Lambda_1 \mbox{=} 0.6 \ \mbox{\mum},$  37.67  $W^{\mbox{-}1} \mbox{km}^{\mbox{-}1}$ for  $\frac{d_1}{\Lambda 1}$  =0.5 and 36.13 W<sup>-1</sup>km<sup>-1</sup> for  $\frac{d_2}{\Lambda 2}$  =0.5. Similarly dispersion coefficient of proposed PCF is 2.235 ps.km<sup>-1</sup>.nm<sup>-1</sup> for  $\Lambda_1$ =1.2 µm, 2.853 ps.km<sup>-1</sup>.nm<sup>-1</sup> for  $\frac{d_1}{\Lambda l}$ =0.8 and 2.53 ps.km<sup>-1</sup>.nm<sup>-1</sup> for  $\frac{d_2}{\Lambda 2}$ =0.8 which is greater than the corresponding values in literature [14]. Thus the nonlinearity and dispersion coefficient can be suitably optimized for a given application by changing the value of either  $\Lambda_1$  or  $\frac{d}{\Lambda}$  ratio. The importance of this investigation is the increase of nonlinearity and increase the dispersion coefficient without affecting the mode field diameter. So our proposed PCF structure may be suitable for super continuum generation and nonlinear fiber optics.

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