Low Dispersion Nonlinear Polarization Maintaining Photonic Crystal Fiber Using Hybrid Cladding

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Abstract— **This paper presents and explores a new design hybrid cladding of nonlinear Photonic Crystal Fiber (PCF) with both very low dispersion and improved birefringence in a broad range of wavelength bands. The fundamental mode of birefringence and dispersion for such a PCF is analyzed numerically using the finite element method (FEM) with perfectly matched layer. Our proposed designed PCF contains a finite number of circular and elliptical air holes that are linearly placed to a straight line in a circle of boundary. It is demonstrated that our hybrid PCF can be used for different sensors and telecommunication applications cause it offers 0.0004 to 0.0009 birefringence and low dispersion (-4 to 8) ps/(km·nm) and nonlinear coefficient 7.8 to 3.7 $W^{-1}km^{-1}$ for a wide wavelength range 1.15 to 1.65 µm. Moreover our proposed design gives confinement loss $10^{-7.5}$ to $10^{-5.7}$ (dB/km) and effective area 1.45×10^{-11} to 2.1×10^{-11} μm^2 within this wide wavelength range.**

Keywords— Photonic Crystal Fiber, Dispersion, Birefringence, Nonlinear Coefficient, Effective Area and Finite Element Method.

I. INTRODUCTION

Index–guiding photonic crystal fibers (IG-PCFs) or holey fibers (HFs) or microstructured optical fibers (MOFs) are a single material optical fiber consisting of a microscopic array of air channels running down the entire fiber length that provides the confinement and guidance of light in the centre core [1]. Nowadays, the holey fiber has given attention in fiber optic communication due to its unique properties [2]. Airhole arrangement in the cladding can be tailored to get anomalous dispersion at wavelengths shorter than the zero material dispersion wavelengths. In such PCFs, more circular tightly confined optical field can be obtained with small effective area and high non-linearity which coupled with flat, anomalous dispersion has led to successful broadband supercontiuum generation (SCG) [3]. Due to the design freedom of PCFs, various laudable optical properties, such as ultra flat dispersion, high nonlinearity, large negative dispersion, ultra high birefringence and large effective mode area, etc have been demonstrated with PCFs which are not possible with conventional optical fibers [4-5]. Moreover highly birefrigent PCFs are used in optical devices such as fiber optic sensors. High modal birefringence can be achieved by creating asymmetrical design in the core region of PCFs. Beside these, High birefringence can be realized in various ways such as the fiber core can be designed to be asymmetrical , the air-holes in the cladding can be elliptical instead of circular [6], [7]. Moreover, the supercontinuum generation in PCFs has created attention in the current research work for designing highly nonlinear PCF [8]. At a zero dispersion wavelength, pumping with higher nonlinear PCF reduces its power requirement for generating broad supercontinuum power spectra [9]. Tailoring the dispersion to obtain flat, at near zero dispersion wavelengths with a high range is an important aspect in PCF for telecommunication purpose but here birefringence is not considered for design PCF [10]. Therefore, using hexagonal, octagonal and irregular design structures various index-guiding dispersion flattened with supercontinuum generation in PCFs have been published [11]. The designed S-PCF has achieved ultra high birefringence of 0.09 at 1550 nm which is higher for considering birefringence but given a negative dispersion [12]. Liang Wang et al and Dingjie Xu et al demonstrated only high birefringence without dispersion at the magnitude of 10^{-3} [20 - 21]. Jian Liang et al designed a PCF that offered birefringence at the magnitude of 10^{-3} and dispersion (5 to 30) ps/(km·nm) for wavelength range 1.0 to 2.05 µm [22]. In this paper, we propose a new designed hybrid PCF contains a finite number of air holes which are circular and elliptical in shape and linearly placed to a straight line in a circle of boundary that gives moderate birefringence 0.0004 to 0.0009, low dispersion (-4 to 8) ps/(km·nm), Nonlinearity 7.8 to 3.7 $W^{-1}km^{-1}$, effective area 1.45×10^{-11} to 2.1×10^{-11} μm^2, confinement loss $10^{-7.5}$ to $10^{-5.7}$ (dB/km) for a wide wavelength range of 1.15 to 1.65 µm that can be used for telecommunication purpose, sensor applications in visible and near infrared regions.

II. DESIGN METHODOLOGY

Fig. 1 shows the geometry of the proposed low dispersion nonlinear polarization maintaining hybrid PCF with circular and elliptical shapes of air holes that are placed to a straight line in a circle of boundary. The elliptical air holes are designed on the base of elliptical ratio $q=q_1/q_2$ and circular air holes are designed with diameter d and radius r and a common pitch $p = \Lambda = 1.65$ µm. There are relationship between q, d, r and p. For ellipses the distance from two axis named as axis x = q_1 and axis y = q_2 are considered in design. There are seven lines are available in our design which contain respectively ellipses in line one are e_1 [elliptical ratio $q=q_1/q_2=(0.075\times p)/(0.15\times p)=0.5$], circles in line two have radius $r_1=0.3\times p/2$, ellipses in line three are e_2 [elliptical ratio $q=q_1/q_2 =(0.1875\times p)/(0.75\times p)=0.25$], circles in line four have radius $r_2=0.7\times p/2$, circles in line five have radius $r_3=0.75\times p/2$, circles in line six have radius r_4=0.8×p/2 and circles in line seven have radius r_5=0.9×p/2. Line 1 and line 3 contain ellipses. The circles are placed to a straight line in the square position. This design creates a higher air-filling ratio and a lower effective refractive index around the core, thereby providing strong confinement ability. The refractive index of background silica is set to be n_s = 1.45 and that of the air holes n_a = 1.00 are set to our simulation. The elliptical air holes in the line one and three are rotated by an angle of 0 (zero) degree for getting improved birefringence.

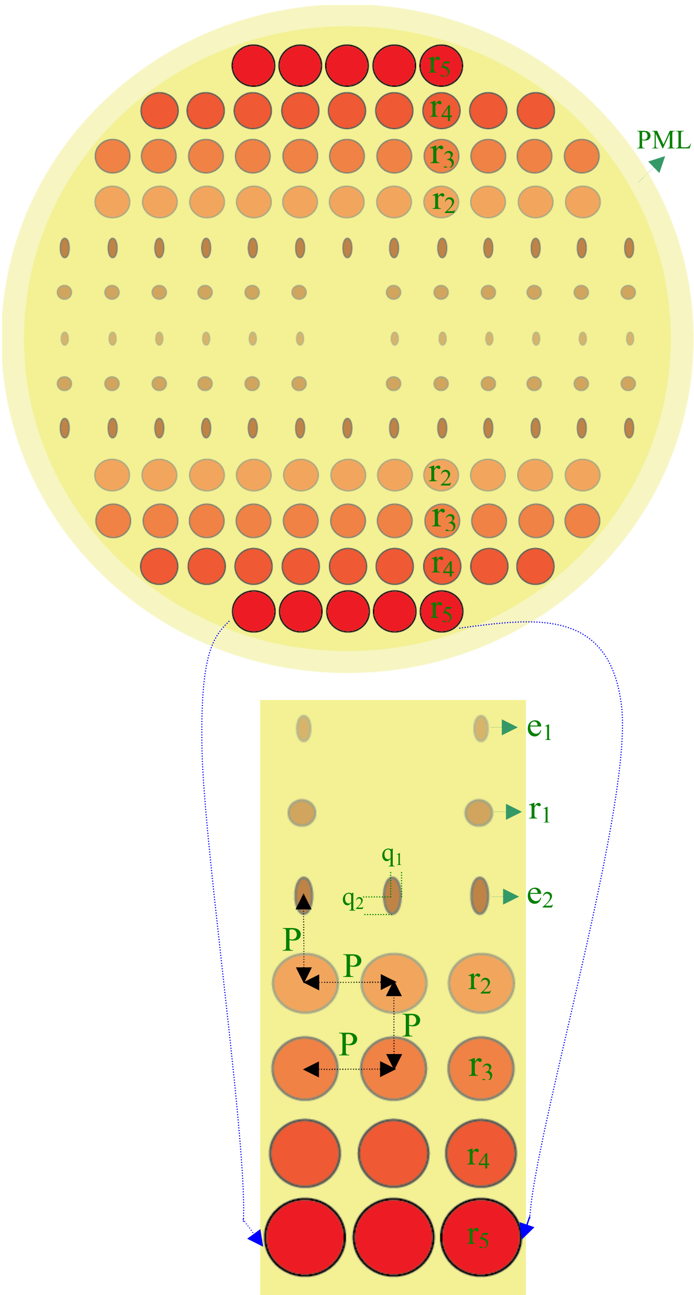


Fig. 1. Geometry model of our proposed HyPCF.
(a) Different lines with PML in our Proposed PCF
(b) Details of the core region and parameters of the design.

III. SIMULATION METHODOLOGY AND EQUATION

The simulation tool used for this work is COMSOL software of version 4.2 and an efficient finite element method (FEM) with circular perfectly matched layer (PML) has been used to characterize the performance of the PCF. The fiber cross section representation is very accurate as the domains are divided into sub-domains with triangular or quadrilateral or square shapes where any refractive index profiles can be properly represented [13]. In order to evaluate confinement loss of the mode, an anisotropic perfectly matched layer is employed as a boundary condition at computational domain edges [14]. Dispersion D (λ) in optics is a phenomenon which causes separation of a wave into its spectral components and is defined as the change in pulse width per unit distance of propagation (i.e., ps/km/nm), where c is the velocity of light in vacuum, λ is the wavelength. The effective area A_{eff} (λ) is the area where the beam intensity drops to 13.5% of its' maximum value and the diameter of which is called the mode field diameter (MFD). Confinement loss L_c is treated as the loss of leaky modes. n_x and n_y are the mode indices of the two polarized axes. The effective refractive index of the base mode is given as n_{eff} =β/k_0 , where v_g is the group velocity, n_r is the real part of modal effective index n_{eff} of the fundamental mode, β is the propagation constant, k_0=2π/λ is the free-space wave number. Once the modal effective indexes n_{eff} is solved then birefringence B, confinement loss Lc and nonlinear coefficient γ, effective area A_{eff}, disperson D can be obtained by the following equatins [15-16].

$$D(\lambda)=d/d\lambda(1/v_g(\lambda)) = -(\lambda/c)d^2 n_r / d\lambda^2 \ \ \text{ps/(km·nm)} \tag{1}$$

$$B=|n_x-n_y| \tag{2}$$

$$Lc = 8.686 \times k_0 \,\mathrm{Im}[n_{eff}] \times 10^3 \ \text{dB/km} \tag{3}$$

$$A_{eff}(\lambda)=\frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left(|E_x(x,y)|^2+|E_x(x,y)|^2\right)dxdy]^2}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left(|E_x(x,y)|^2+|E_x(x,y)|^2\right)^2} dxdy \ \ \mu m^2 \tag{4}$$

$$\gamma=(2\pi/\lambda)\left(\frac{n_2}{A_{eff}}\right)\times 10^3 \ \ W^{-1}km^{-1} \tag{5}$$

IV. FLOW CHART OF THE SIMULATION WORK

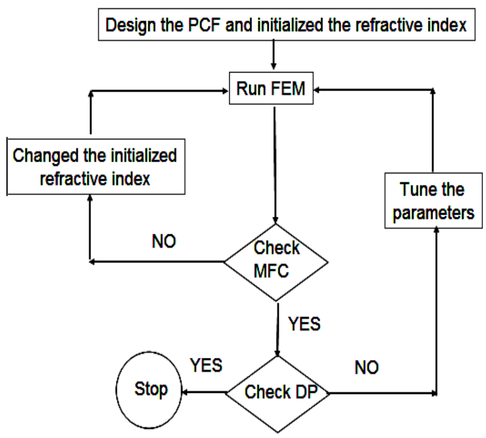
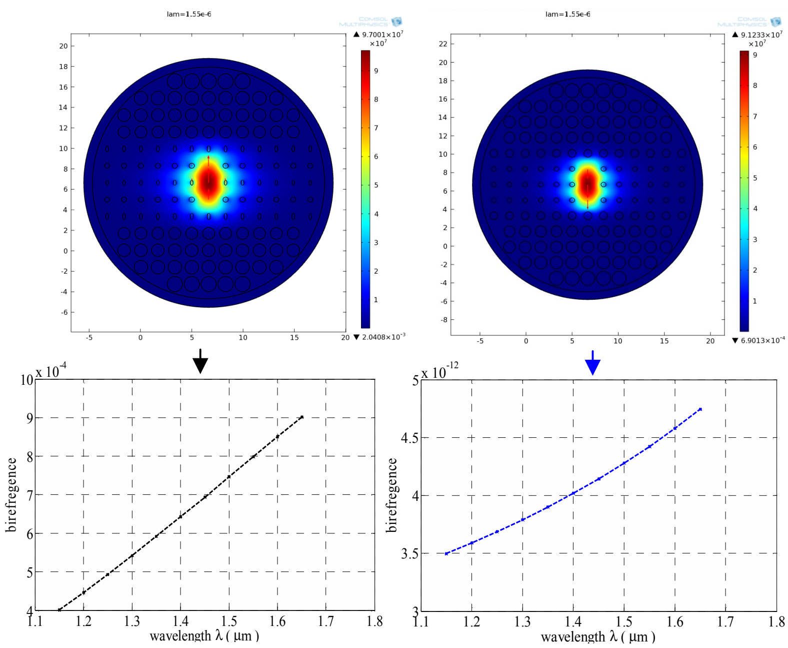


Fig. 2. Flow Chart of the Simulation by Comsol software

V. Simulation Results and Discussion

According to the simulation, it is seen that x and y axis polarized modes are strongly bounded in the high-index core region, giving the birefringence at the exciting wavelength λ=1.55μm, B = $|n_x - n_y|$ = 0.0008 for our proposed design and the birefringence B = $|n_x - n_y|$= 4.4 × 10^{-12} for the design of all circles only than those obtained from a conventional step index fiber 10^{-4} [17], circular air holes 10^{-3} [18] and elliptical hollow PCF 10^{-3} [19] and our design is better considering low dispersion of (-4 to 8) ps/(km·nm) for a wide wavelength range of 1.15 to 1.65 μm.



(a) (b)

(a) Proposed hybrid design with circular and elliptical air holes have parameters p=Λ=1.65 μm, e_1 (q=0.5), r_1=0.3×p/2, e_2 (q=0.25), r_2=0.7×p/2, r_3=.75×p/2, r_4=0.8×p/2, r_5=0.9×p/2

(b) Only all circular air holes having parameters p=Λ=1.65 μm, e_1 = r_1=0.3×p/2, e_2 = r_3=0.5×p/2, r_2=0.7×p/2, r_3=0.75×p/2, r_4=0.8×p/2, r_5=0.9×p/2

Fig.3. Fundamental mode field pattern at wavelength of 1.55μm and Figure of Birefringence at wavelength range from 1.15 to 1.65μm

Disperson of our proposed design is shown in the fig. 4. It is observed that dispersion is very low for a broad wavelength range from 1.15 to 1.65 μm as it is (-4 to 8) ps/(km·nm) and 7.7 ps/(km·nm) for the excitation wavelength of λ = 1.55 μm. So it can be used for original band (O band (1260-1360) nm), Extended (E band (1360–1460) nm), Short wavelength (S band (1460–1530) nm), Conventional erbium window (C band (1530–1565) nm), Long wavelength (L band (1565–1625) nm), Ultra long wavelength (U band (1625–1675) nm) bands and also suitable for Infrared region and telecommunication purpose.

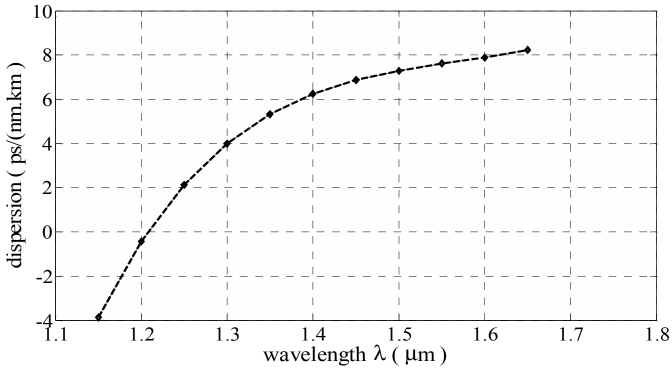


Fig.4. Chromatic Dispersion of our proposed Hybrid design

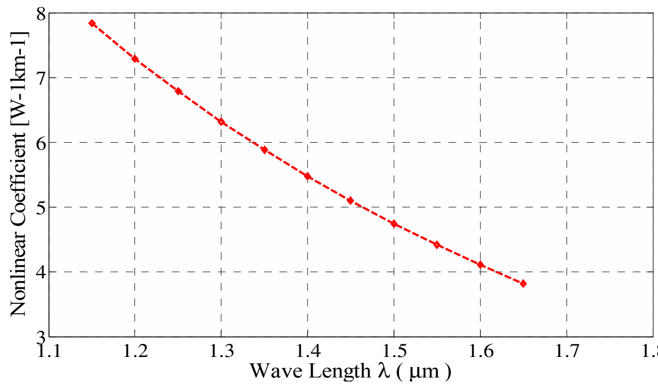


Fig.5. Nonlinear Coefficient of our proposed Hybrid design

From the fig. 5 it is observed that our desire hybrid PCF is a nonlinear fiber and nonlinear coefficients for 1.15 to 1.65 μm are 7.8 to 3.7 $W^{-1}km^{-1}$. Again from fig. 6 the effective areas for 1.15 to 1.65 μm are 1.45 × 10^{-11} to 2.1×10^{-11} $μm^2$ and 1.925× 10^{-11} $μm^2$ at excitation wavelength 1.55 μm which is greater than the previous design [10].

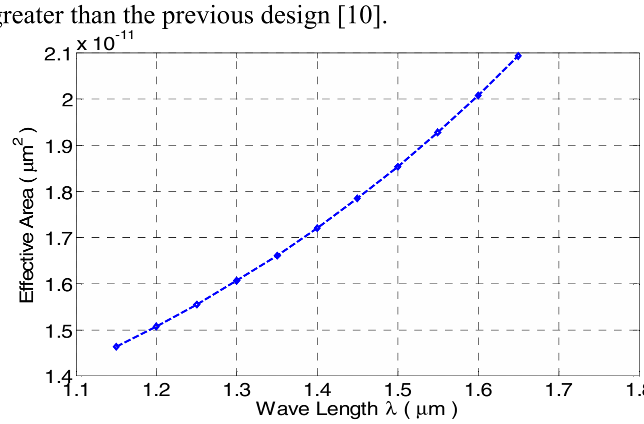


Fig. 6. Effective area of our proposed Hybrid design

It is observed from fig. 7 that for the wavelength range 1.15 to 1.65 μm confinement losses are $10^{-7.5}$ to $10^{-5.7}$ (dB/km) respectively means as the wavelength increases also confinement loss increases. Fig. 8 shows the dispersion accuracy by increasing and decreasing e_1, r_1 and e_2 by 1% or ±0.01. The parameter for our desire design is accurate for simulation work like fig.1 and also fig. 9 shows pitch changing by equation (Λ/P×1)%.

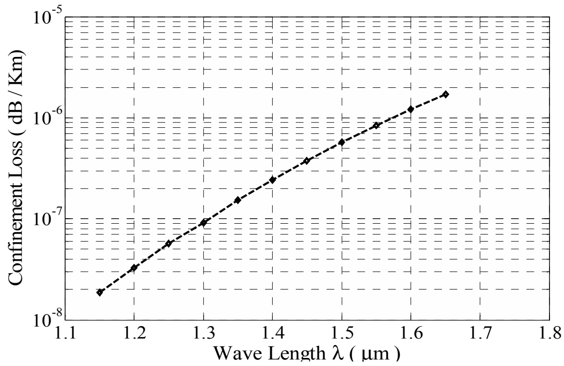


Fig. 7. Confinement Loss of our proposed Hybrid design

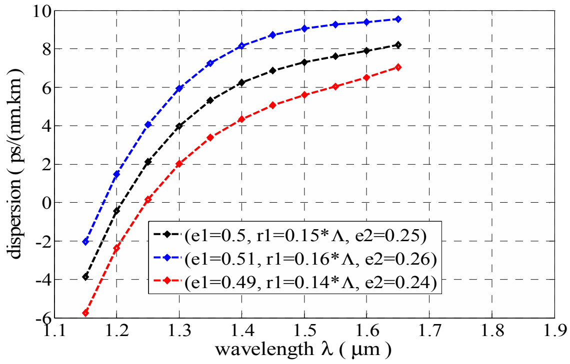


Fig. 8. Changing circular and elliptical air holes in the core region of our proposed design by ±1%

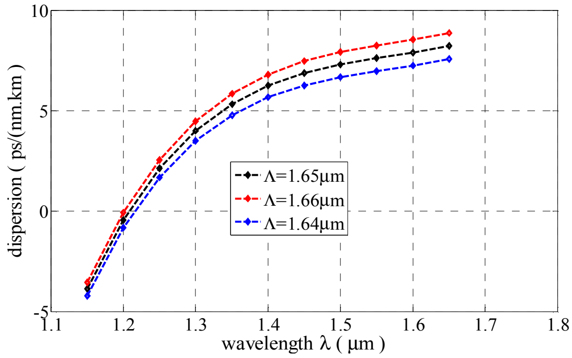


Fig. 9. Changing the pitch of our proposed design by ±1%

Conclusion

A relatively simple polarization maintaining low dispersion nonlinear fiber has been reported. The highest birefringence 0.0008, low dispersion 7.7 ps/(km·nm), nonlinear coefficient 4.5 $W^{-1}km^{-1}$, effective area 1.93×10^{-11}, confinement loss $10^{-6.5}$ can be achieved at the exitation wavelength 1.55μm with only few airholes in the fiber cladding. This design can be improved further research for getting better birefringence with ultra dispersion flat 0±0.5 ps/(km·nm) and for very high nonlinear fiber. Photonic crystal fibers having novel properties such as high birefringence for optical fiber based sensors, nonlinearity for nonlinear optics applications and ultra dispersion flat are crucial for telecommunication.

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