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High - Birefringent Nanowire Embedded Photonic Crystal Fiber for Optical Switching

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Abstract*— We design a novel waveguide structure of sub-wavelength core diameter called photonic nanowire (PN) and study the different optical properties, namely, dispersion, birefringence and nonlinearity. We design a PN with elliptical core that exhibits a very high birefringence of about $\approx$0.037049, 0.068264, 0.190803, dispersion of about $\approx$ 1850, 2300 and 3250 ps/(nm km) and nonlinearity of about $\approx$ 606,467 and 294 W-1m-1at 0.850,1.06 and1.55 µm wavelengths respectively and with circular air-holes located in the cladding. This property would highly useful for switching, sensing, etc.

Index Terms*— Photonic Crystal Fiber, Photonic Nanowire, Birefringence, Finite Element Method.

I. INTRODUCTION

In recent times, a novel design of the waveguide structure has come into existence. This is called photonic nanowire (PN) which has sub-wavelength core diameter. It is fabricated from a variety of materials including silica glass, SF6 glass, chalcogenide glass, silicon, InGaAs, etc. Although, functionally, it is again an optical fiber, it is different from the conventional fibers, at least in two aspects. First, PNs have a core radius 10 to few 100 nm as against the case of optical fibers with radius 8 to 12 µm. The next, more importantly, the high refractive index contrast between core and cladding (approximately, 0.5) compared with the conventional fiber (0.1 to 0.01). PNs have many merits compared with the conventional fibers. To name a few are the tight mode confinement and strong waveguide dispersion. These features truly have attracted tremendous amount of interest due to the accessibility of new fabrication techniques for a myriad of materials, which might result in realizing high performance photonic devices. Ademgil et al [1] reported that the model birefringence and the beat length Lb as a function of wavelength. We observed from this report that the relatively large birefringence in the order of 10-3 is achieved by varying Λ (pitch). It can clearly be seen that the birefringence is sensitive to variation of the wavelength λ. Birefringence increases as the wavelength increases. The beat length decreases as the wavelength increases. Daru Chen and Linfang Shen [2] has demonstrated that elliptical air holes in the core region contribute to increase the birefringence. We proposed an improved structure of high birefringence PN.

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The high refractive indexed silicon core yields a very high dispersion. Due to the nature of PN the value of effective mode area decreases, so that the nonlinearity gets increased.

II. PROPOSED DESIGN

In this paper, we design a nanowire embedded photonic crystal fiber with high birefringence using the finite element method (FEM). The core of the proposed nanowire embedded PCF is made of silicon which provides a better confinement of light owing to its high refractive index. The cladding possesses the number of circular air holes. High birefringent PN can be achieved by having asymmetric core. The asymmetric core can be achieved either by altering the air hole sizes near the core area, or by distorting the shape of the air holes. With this motivation, this work proposes a highly birefringent PN with by introducing a six circular ring-air cladding with an elliptical core of hexagonal structure.

Figure 1 shows geometrical structure of the proposed structure. This PN consisting of six rings of air holes arranged silica background with central core refractive index is silicon 3.5. The unique nature of PN allows to analysis of the optical properties by precise tuning of design parameters such as diameter of air holes and the hole-to-hole spacing (pitch). The diameter of air holes and hole-to-hole spacing is denoted with d and Λ, respectively. Here, we keep the diameter of the circular air holes in the first ring to be the same as that of pitch and diameter is reduced slightly in the second ring. The diameter is further reduced in the third ring and maintained constant up to the fifth ring. The structure is terminated by the sixth ring wherein the diameter is restored to the case of first ring. We clearly demonstrate that the variations in the diameter of this nature helps catch up with an appreciable birefringence, which, in turn, results in better light confinement. We study the waveguiding properties using five different pitches such as 1.8, 2.0, 2.2, 2.6 and 3.2 µm for the wavelength range 0.4 to 1.8 µm.

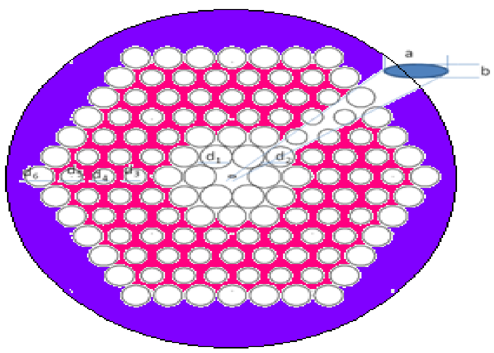

Fig.1 Design of proposed PN structure

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The field distribution of the fundamental mode of the elliptical core for the Λ=2.2 µm is shown in Fig.2

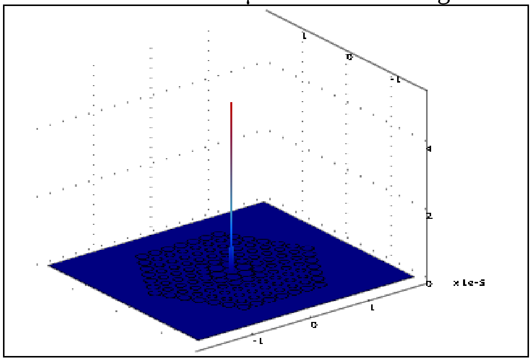
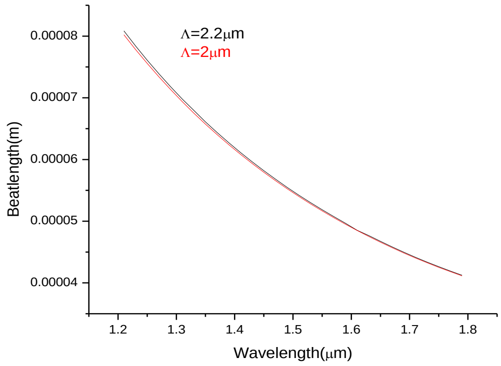


Figure.2 Field distribution of the fundamental mode.



III. RESULTS AND DISCUSSION

Linear Properties

Birefringence:

Birefringence is defined as the difference between two refractive indices of the polarization mode. It is calculated by

$$B = |n_{eff}^{x} - n_{eff}^{y}|$$

where n_{eff}^{x} is the refractive index of x polarized mode and n_{eff}^{y} is refractive index of y polarized mode. Figure 4 shows the variations of the birefringence as a function of wavelength for the proposed design.

Beat length:

The beat length is calculated by

$$L_b = \lambda / B$$

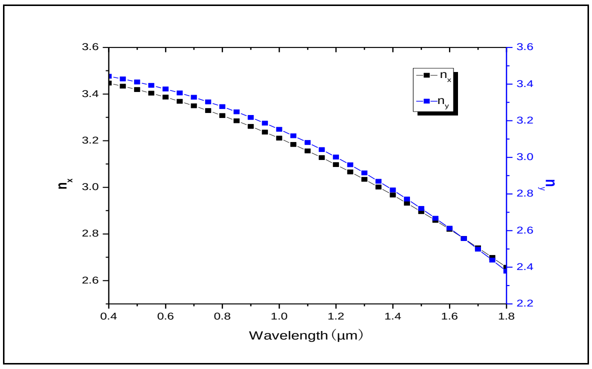


Fig.3 Variation of effective refractive index of the x and y polarized modes with respect to wavelength of the proposed design.

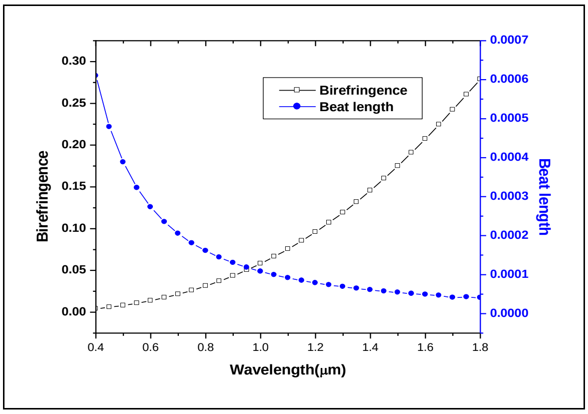


Figure 4 shows the variations of the birefringence and beat length for different wavelength of the proposed design.

Birefringence increases and beat length decreases as the wavelength increases.

Dispersion of the proposed structure:

Dispersion calculated using the following formula

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

Where λ = wavelength of the light, C = velocity of the light n_{eff} = effective indices

Fig.8. Dispersion of proposed structure at pitch 2 µm for broad wavelength range

The dispersion increases with respect to wavelength. At 1550 nm dispersion is ≈ 1300 ps/nm km for the pitch 2µm. The dispersion at first decreases and after 1480 nm the dispersion get increases.

Nonlinear Properties:

Effective nonlinearity calculated from Effective mode area of PN.

$$A_{eff} = \left(\int |E|^2 dA \right)^2 \Big/ \int |E|^4 dA$$

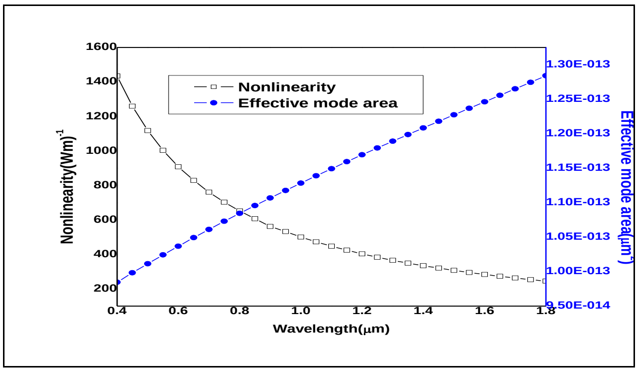


Fig.10 Variation of effective mode area and non-linearity with respect to wavelength for pitch is 2µm

The effective mode area increases with increase in the wavelength. Small effective mode area producing high nonlinearity it is calculated using the formula

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}}$$

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Where n_2= nonlinear index coefficient
λ=wavelength of the light
A_{eff} = effective mode area
The non-linearity decreases with increasing the wavelength. The nonlinearity of about ≈ 606,467 and 294 $W^{-1}m^{-1}$at 0.850,1.06 and1.55 µm wavelengths respectively.

Table 1 shows all the the parameter for different values of pitch at 0.85µm wavelength.

Pitch(µm)	B	Dispersion (ps/nm-km)	Nonlinearity $(Wm)^{-1}$
Λ=1.8	0.036778	-650	607.2845712
Λ=2.0	0.037049	-640	606.8326801
Λ=2.2	0.036623	-675	607.5456061
Λ=2.6	0.03662	-685	607.1037450
Λ=3.2	0.036663	-650	607.8319694

Table 2 shows all the the parameter for different values of pitch for 1.06µm wavelength.

Pitch(µm)	B	Dispersion (ps/nm-km)	Nonlinearity $(Wm)^{-1}$
Λ=1.8	0.068043	-925	467.483105
Λ=2.0	0.068264	-900	467.340821
Λ=2.2	0.067933	-905	467.598607
Λ=2.6	0.067888	-950	467.351895
Λ=3.2	0.068008	-950	467.750624

Table 3 shows all the parameters for different values of pitch at 1.55µm wavelength.

Pitch(µm)	B	Dispersion (ps/nm-km)	Nonlinearity $(Wm)^{-1}$
Λ=1.8	0.190742	-1450	294.811966
Λ=2.0	0.190803	-1400	294.8352487
Λ=2.2	0.190701	-1405	294..841997
Λ=2.6	0.190607	-1425	294.743329
Λ=3.2	0.190881	-1425	294.895092

From above tables, we conclude that optical properties are not varying with designing parameter over wide wavelength ranges.This highly birefringent photonic nanowire very much suitable for chemical sensors, bio-sensor, optical switching and telecommunications.

IV. CONCLUSION

In this study, we have proposed and demonstrated a design of high-birefringent photonic nanowire using full-vector FEM. The effective refractive index, the birefringence, beat length, dispersion, nonlinearity were analyzed. From the above discussions, we conclude that the birefringence increases with increase in wavelength. The birefringence is ≈ 0.187835 at 1550 nm wavelength 2.2µm pitch. Beat length decreases with increase in wavelength. At 1550nm wavelength the beat length will be ≈ 5.18483 at 2.2µm pitch. The dispersion at first decreases and after 1.48 µm the dispersion gets increases. The effective mode area increases with increase in the wavelength. At 1550 nm wavelength the effective mode area is ≈ 0.1236 at 2.2 µm pitch. The non-linearity decreases with increase in the wavelength. At 1550 nm wavelength the non linearity is ≈ 294$W^{-1}m^{-1}$ at 2.2µm pitch. The applications are as switches, sensors, wideband supercontinuum as polarization controllers.

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