Chalcogenide glass Photonic Crystal Fiber with flattened dispersion and high nonlinearity at telecommunication wavelength

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Abstract— **A highly nonlinear photonic crystal fiber with eight ring octagonal structure is proposed. Chalcogenide glass of As_2S_3 is used as the material for this photonic crystal fiber structure. The finite-element method with perfectly matched boundary layer is employed to analyze the guiding properties. Non linearity of 13,584.5 per W-km is obtained at 1.55 µm with reasonable flattened dispersion of -25 ps/nm-km to -28 ps/nm-km. Confinement loss achieved is of the order of 10^{-6} dB/km. Large negative dispersion is also obtained ranging from wavelength of 0.85 µm to 1.95 µm, which can be used for dispersion compensation in fiber optic communication. This Photonic Crystal Fiber structure can also be used for nonlinear applications like ultra short soliton pulse transmission, optical parametric amplification, supercontinuum generation.**

Keyword- Chalcogenide glass, Chromatic dispersion, Finite element method, Large negative dispersion, Photonic crystal fiber, Supercontinuum.

I. INTRODUCTION

Photonic crystal fibers (PCFs) are holey fibers made up of large number of air-holes in its cladding [1]. They have been very attractive nowadays because we can easily control the dispersion [2], confinement loss [2] nonlinearity [3], [4] etc. by varying the structural parameters of the PCF. Controlling dispersion and achieving high nonlinearity along with low confinement loss is very crucial in PCFs. PCFs are used in applications like parametric amplification, wavelength division multiplexing, soliton transmission, gas sensing, dispersion compensation, supercontinuum generation etc.

Our PCF is showing large negative dispersion so that it can be used as dispersion compensation in optical communication [5]. Flattened dispersion along with high nonlinearity is reported at the telecom wavelength of 1.55 µm. This property can be used to generate Supercontinuum [6], [7], [8]. Supercontinuum is the spectral broadening caused to a ultra short light pulse, while propagating in the fiber. We consider As_2S_3 based chalcogenide glass as the material for our PCF [9]. This type of glass possess very high nonlinearity with large negative dispersion. Our unique structure provides waveguide dispersion in such a manner that this waveguide dispersion will cancel some of the negative dispersion and provides a more flattened dispersion for using this PCF in the telecom wavelength of operation. Numerical simulations show that we have achieved ultrahigh nonlinearity of almost 100 times than that of silica with dispersion variation of 3.9 ps/nm-km at 1.55 µm.

II. PCF STRUCTURE

We propose an octagonal symmetric structure**,** with the inner ring hole diameter varying to form three different cases of the PCFs. The air-hole diameter of the first ring is d1, while air-hole diameter of the second to eighth ring is d2. The pitch distance between circles on adjacent rings is pitch1 and pitch distance between circles on same ring is pitch 2. The structure is shown in Fig.1.

The parameters are d2=0.5246 µm, pitch1=0.86 µm and pitch2=0.765 * pitch1=0.6579 µm. By keeping other parameters constant, we are considering three cases of d1. That is the 'first case' with d1=0.13115 µm, the 'second case' with d1= 0.2623 µm and the 'third case' with d1=0.5246 µm.

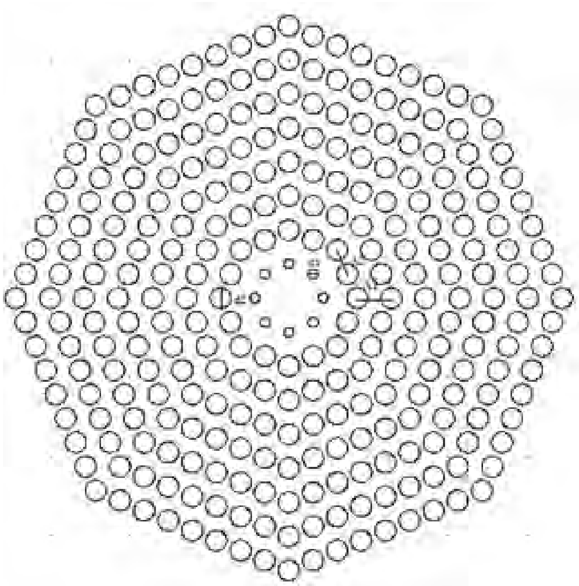

Fig 1. Proposed eight ring octagonal PCF structure.

III. SIMULATION RESULTS

COMSOL MULTIPHYSICS is used for the simulation of our proposed PCF structure.Two dimensional output of light confinement obtained is shown in Fig. 2. The effective mode index (n_{eff}) and electric field component (E), for a range of wavelengths from 0.85 µm to 1.95 µm is obtained. Chromatic dispersion, Confinement loss, Effective area and Nonlinearity are calculated and plotted using MATLAB.

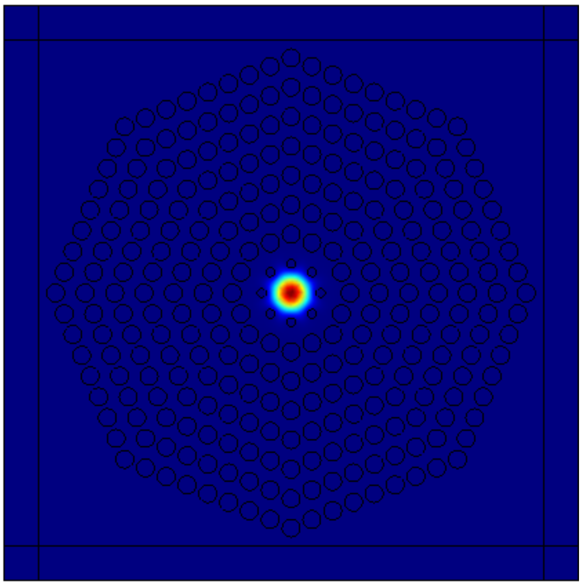

Fig 2. Two-Dimensional plot of light confinement.

A) Dispersion

Chromatic dispersion is the sum of material and waveguide dispersion [9]. Material dispersion is calculated from the simpler form of Sellemeier equation, which is known as Cauchy's equation, showing the relation of material of the chalcogenide glass with the refractive index [10]. This relation is shown in the table 1. Cauchy's equation is given by

$$n(\lambda)= (a+b/\lambda^2+c/ \lambda^4)^{1/2} \quad (1)$$

where, a=5.14, b=0.20 µm^2, c=0.14 µm^4 and λ is the wavelength

TABLE I
Refractive index of As_2S_3 at different wavelengths.

Wavelength (μm)	Refractive index
0.85	2.4423
0.95	2.4111
1.05	2.3909
1.15	2.3772
1.25	2.3676
1.35	2.3605
1.45	2.3552
1.55	2.3511
1.65	2.3478
1.75	2.3453
1.85	2.3432
1.95	2.3414

From the wavelength dependence of refractive index, we calculate the total chromatic dispersion which includes material and waveguide dispersion as given by the equation

$$D(\lambda) = -\frac{\lambda}{c}\frac{\left(d^2 Re(neff)\right)}{d\lambda^2} \text{ ps/(nm-km)} \quad (2)$$

Where Re(neff) is real part of effective mode index, λ is the wavelength and c is the velocity of light. Dispersion curves are shown in Fig. 3. Dispersion variation is from -149 ps/nm-km to -178 ps/nm-km for the first case, from -211 ps/nm-km to -225 ps/nm-km for the second case and from -25 ps/nm-km to -28 ps/nm-km for the third case. In spite of large negative dispersion of chalcogenide glass we have obtained the required flattened dispersion for super continuum generation at 1.55 μm.

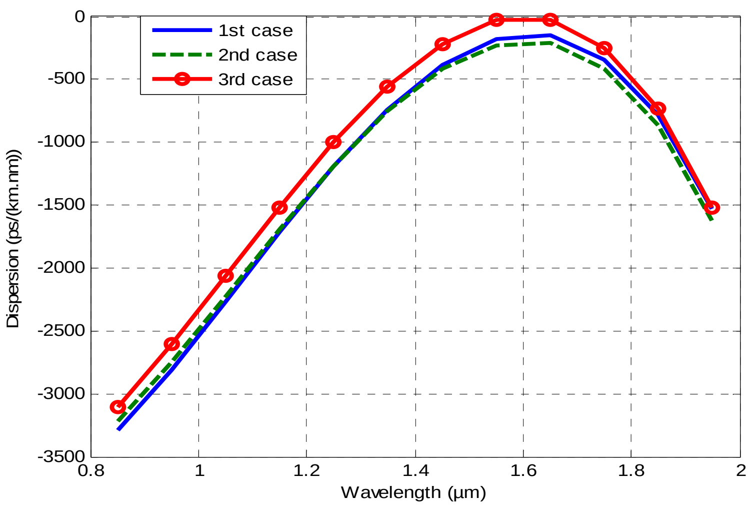

Fig 3 Variation of Chromatic dispersion with wavelength.

B) Confinement Loss

Confinement loss can be calculated by using the equation

$$Lc = 8.686 k_0 Im(neff) \text{ dB/m} \quad (3)$$

where Im is the imaginary part of effective mode index , and k_0 is the free space wave number, which is equal to 2π/λ . Our structure provides fine reduced values of confinement loss of the order of 5.46 X 10^{-8} dB/km, 3.70 X 10^{-7} dB/km and 5.51 X 10^{-7} dB/km for our first, second and third cases respectively, at the telecommunication wavelength of 1.55 μm.

C) Effective Area

Effective area is given from the equation

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

where E is the electric field of the light wave. We have achieved a reduced effective area of 2.86 μm^2, 1.79 μm^2 and 0.87 μm^2 for our first, second and third cases respectively, as shown in Fig. 4.

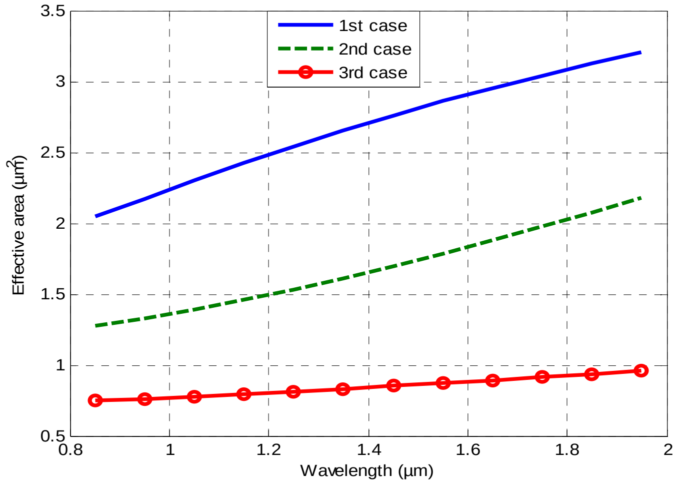

Fig 4. Variation of effective area with wavelength

D) Nonlinearity

Nonlinear coefficient given by the equation

$$\gamma = \left(\frac{2\pi n_2}{\lambda A_{eff}}\right) \ W^{-1}m^{-1} \quad (5)$$

where n_2 =2.92 X 10^{-18} m^2/W, which is the nonlinear refractive index of As_2S_3 based glass. Usually nonlinear coefficient of chalcogenide glasses is around 100 to 1000 times larger than that of silica glasses [9]. At telecommunication wavelength, nonlinear coefficients in the order of 4136.6 $W^{-1}km^{-1}$, 6616.7 $W^{-1}km^{-1}$ and13,584.5 $W^{-1}km^{-1}$ respectively are obtained for our three cases, as shown in Fig. 5.

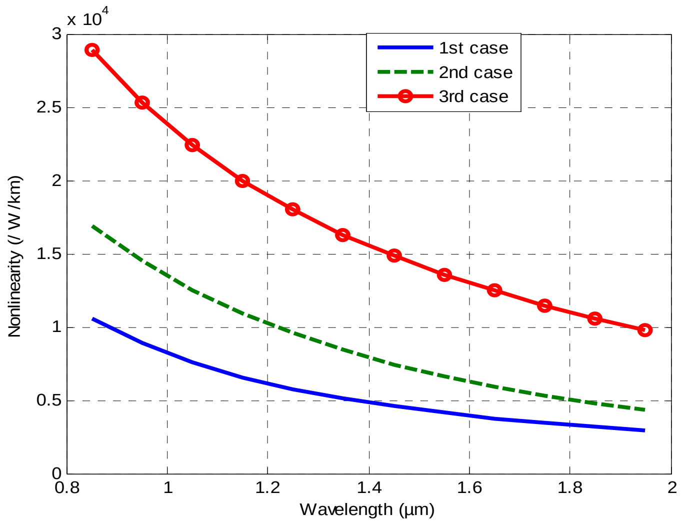

Fig 5. Variation of nonlinear coefficient with wavelength.

Advantage of our PCF is that only four structural parameters are required for its design. More over we have obtained flattened dispersion with ultra large nonlinearity and low confinement loss. Our PCF shows large negative dispersion in a considerably large wavelength range so that it is a promising structure as a dispersion compensating device in long haul fiber optic links. The ultra flattened dispersion with ultra high nonlinearity can be used for generating supercontinuum. Moreover high nonlinearity can be used in parametric amplification, soliton pulse transmission and wavelength conversion..

IV. CONCLUSION

We propose three different cases of PCFs with octagonal structure, by varying the inner most ring of air-holes. Large negative as well as flattened dispersion with low confinement loss is obtained. Flattened dispersion in the range of -25 ps/nm-km to -28 ps/nm-km and nonlinearity of 13,584.5 $W^{-1}km^{-1}$ is obtained at telecommunication wavelength of 1.55 µm. By this remarkable property of ultra high nonlinearity and flattened dispersion, our proposed PCF structure can be used for Supercontinuum generation.

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