Highly Nonlinear Chalcogenide Decagonal Photonic Crystal Fiber for Mid-Infrared Supercontinuum Generation

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***Abstract*- The article is in attribute to introduce a decagonal photonic crystal fiber design which holds the linear and nonlinear property in application of supercontinuum generation. This photonic crystal fiber is 4 rings decagonal lattice fiber and it designed using chalcogenide (As_2S_3) as background material. This article shows the simulation of different parameters such as effective refractive index, chromatic dispersion, higher-order dispersion coefficients, effective mode area, non-linear coefficient. The purposed PCF has found effective area3.8623 µm^2 and very high nonlinear coefficient 2568.6 $W^{-1}km^{-1}$ at 1.9µm wavelength. The evaluated linear and nonlinear parameters are adequate to find satisfaction for further research and analysis for generating supercontinuum in range of wavelength (1.5µm-5.5µm).**

Keywords: Photonic crystal fiber; Chalcogenide material; Effective mode area; Nonlinearity; Chromatic dispersion; higher-order dispersion coefficient.

1. INTRODUCTION

Photonic crystal fibers also called holeyfibers or microstructuredfibers are one of the most entrancing and popular areas of research for years, due to its unique property.Optics and Photonics combinationsare the basic ideas behind photonic crystal fiber PCFs [1].It has two types offibers according to guiding mechanisms: index guiding fibers and photonic bandgap guidingfibers. In index guiding fiber or solid core PCF light guided by modified total internal reflection and in photonic bandgap or hollow-core PCF light guided by PBG method in which only a limited range of wavelength can enter in the cladding[2].PCF has various unique properties like low dispersion, highly nonlinearity, high birefringence, high effective area, low confinement loss,etc..Due to these properties PCFs differ from the optical fibers.

The nonlinear phenomenonin PCFs makesan environment for signal wave processing like optical amplification, compression of pulses, supercontinuum generation, etc. The nonlinearity of PCFs can enhance by enlarging the index of refraction of the core portion and also by reducing the core area. Thus, highly nonlinear refractive index materials can be used as a core material to enhance nonlinearity. Using pure silica material in the core, the nonlinear coefficient has a very small nonlinear refractive index.High index material can increase the nonlinearity of PCF. Chalcogenide material has a high nonlinear refractive index. Photonic crystal fiber has a good application in supercontinuum generation and it is an interesting area of studies for several years.

The non-linear phenomenon called as supercontinuum find when narrowband incident input pulse enter to very high nonlinear media of PCF and achieve extreme spectral broadening or broadband output pulse and it is caused by a various nonlinear process like self-steepening, self-phase modulation(SPM), Raman scattering, and four-wave mixing(FWM) [3].It is a super broad continuum pulse spectrum caused by nonlinear effects.It affected by chromatic dispersion,fiber length, nonlinear media, input pulse power, input pulse duration, central or pump wavelength. It has various unique applications in microscopy,spectroscopy, optical coherence tomography, etc.

In our purposed work, we use decagonal photonic crystal fiber with highly nonlinear index material chalcogenide to increase PCF nonlinearity. Comsol Multiphysics 5.3a software is used in this paper which based onthe finite element method for designing the PCF.The PCF properties like nonlinearity, effective area, chromatic dispersion are studied and simulated in the wavelength range (near to mid-infrared) 1.5µm-5.5µm.

2. PURPOSED PCFSTRUCTURE AND RESULT ANALYSIS

The crossectional view of purposed PCF with air hole distribution is shown in fig.1.The structure contains 4 rings decagonal lattice whose background is chalcogenide(As_2S_3) .The diameter of the air hole is d=1.1µm,core diameter D=2.7µm, and pitch p=1.9 µm.The background material of purposed decagonal PCF is select to chalcogenide (As_2S_3) whose wavelength-dependent refractive index has calculated by Sellimer equation by varying wavelength range 1.5 µm-5.5 µm shown below [4].Where λ is in µm, $B_1 - B_5$ and $C_1 - C_5$ coefficients value are mentioned in table 1.

$$n(\lambda) = \sqrt{1 + \frac{B_1\lambda^2}{\lambda^2 - {C_1}^2} + \frac{B_2\lambda^2}{\lambda^2 - {C_2}^2} + \frac{B_3\lambda^2}{\lambda^2 - {C_3}^2} + \frac{B_4\lambda^2}{\lambda^2 - {C_4}^2} + \frac{B_5\lambda^2}{\lambda^2 - {C_5}^2}} \quad (1)$$

Table.1. Sellimer equation coefficient of As_2S_3

B_1	B_2	B_3	B_4	B_5	C_1	C_2	C_3	C_4	C_5
1.898367	1.922297	0.87651	0.11887	0.95699	0.15	0.25	0.35	0.45	27.3861

In the fig.1 PCF,the cladding region contains 4 rings or air holes in a decagonal lattice arrangement.In purposed work, we take highly nonlinear index material chalcogenide to get high nonlinearity of PCF. Photonic crystal property depends on nonlinear material.

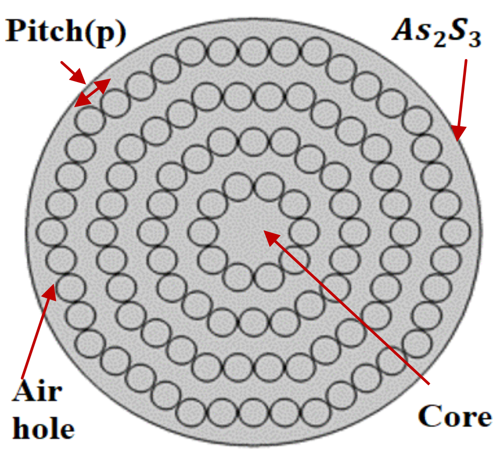
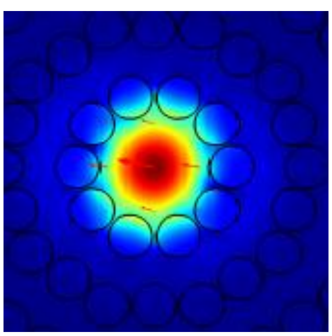


Fig.2.(a).structure of decagonal PCF

The simulated output of purposed PCF is shown in fig.2(b) and fig.2(c). which shows the electric field distribution x -polarised and y- polarised view at 1.55µm wavelength.



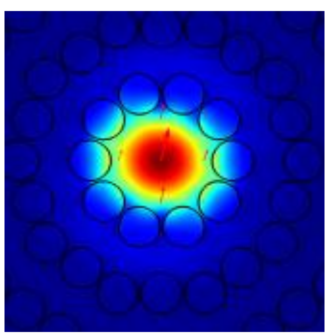


Fig.2.(b). Electric field distribution of decagonal PCF x- polarized mode

Fig.2.(c). Electric field distribution of decagonal PCF y- polarized mode

The plot of the refractive indexconcerning wavelength is shown in fig.2.(d). In this paper, we varying the pitch from 1.8µm to 2.0µm and fixed the diameter of air holes.Total chromatic dispersion is a combination of material and waveguide dispersion. Material dispersion is always a concern with the material of the fiber on the other hand waveguide dispersion depends on the fiber property. The dispersion plot concerning the wavelength of purposed PCF is shown by fig.2(e). There are two zero-dispersion observed at 1.9µm and 5.2µm wavelength with pitch 1.8µm. Chromatic dispersion can be calculated as,

In (2) n_{eff} is a real part of mode index at wavelength λ and c is speed of light.β_2 is second-order dispersion.

$$D(\lambda) = -\frac{\lambda}{c}\frac{d^2 n_{eff}}{d\lambda^2} = -\frac{2\pi c}{\lambda^2}\beta_2, \quad (2)$$

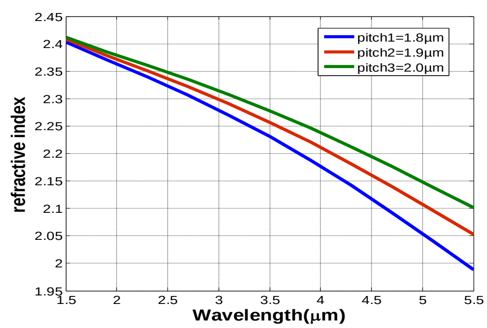


Fig.2.(d).Effectiverefractive index plotwith varying pitch 1.8µm,1.9µm,2.0µm of decagonal PCF

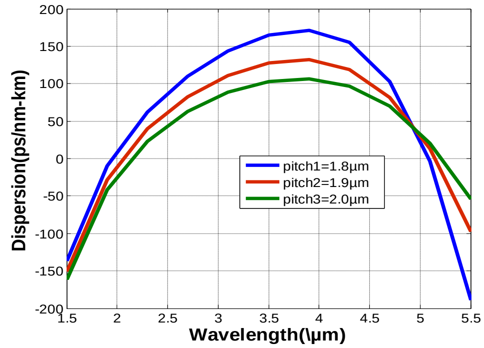


Fig.2.(e). Dispersion curve with varying pitch 1.8μm,1.9μm,2.0μm

The plot of the effective area concerning wavelength is shown in Fig.2(f).A_{eff} is an effective area that helps in calculating the nonlinear coefficient. Effective area calculated by (3).

$$A_{eff} = \frac{(\iint |E^2| dxdy)^2}{\iint |E|^4 \, dxdy} \quad (3)$$

Purposed PCF exhibit A_{eff} is $3.8623 \mu m^2$ at 1.9 μm. It shows in fig.2.(g). nonlinear coefficient concerning wavelength. The nonlinear coefficient is calculated by (4),

$$\gamma = \frac{2\pi}{\lambda} \frac{n_2}{A_{eff}} \quad (4)$$

Where n_2 the nonlinear refractive index of background material. The obtained very high non-linear coefficient value γ is $2568.6 W^{-1} km^{-1}$ at the wavelength of 1.9μm.

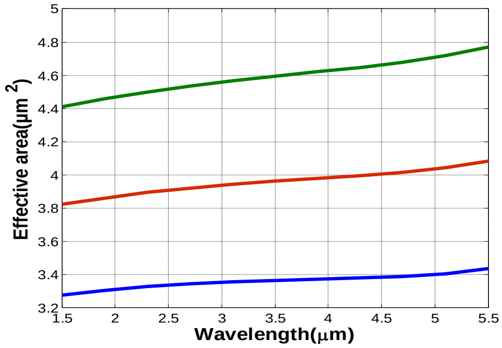


Fig.2.(f).The effective area of purposed PCF with varying pitch blue line indicates 1.8μm pitch, red indicates 1.9 μm, green 2.0μm pitch

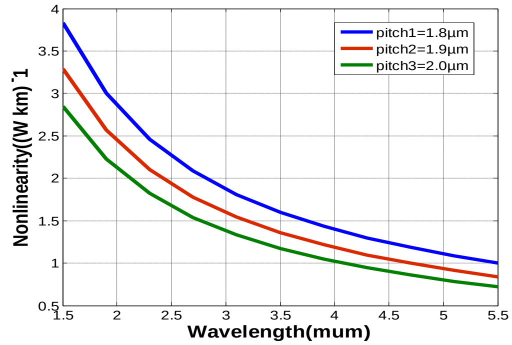


Fig.2.(g). nonlinear coefficient as a function of wavelength with varying pitch

The higher-order dispersion coefficient β_k values calculated by (5) at wavelength 1.9μm, where, w isthe angular frequency, k shows degree of derivation and β is propagation constant of mode which can calculated as(6).In,(6) c is the speed of light and $n(w)$ shows the refractive index concerning frequency w. All coefficient are related to each other as β_2 is found by the derivative of β_1 .Decagonal purposed PCF is plots of all coefficient shown below as a function of wavelength.

$$\beta_k = \frac{d^k \beta}{dw^k} \quad (5)$$

$$\beta = \frac{n(w)}{c} \times w \quad (6)$$

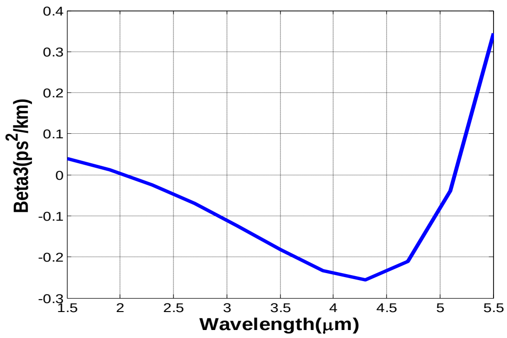


Fig.2.(h) $\beta_3 = 0.0118ps^3/km$ at $\lambda = 1.9\mu m$

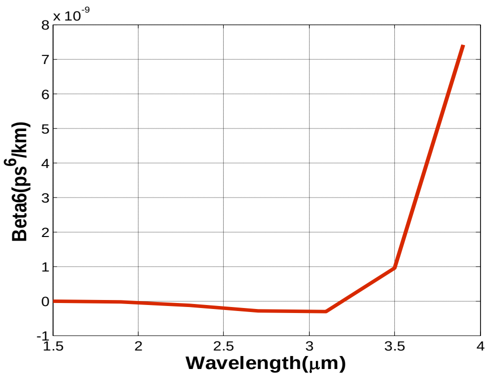


Fig.2(l) β_6=-3.6$\times 10^{-10} ps^6/km$ at $\lambda = 1.9\mu m$

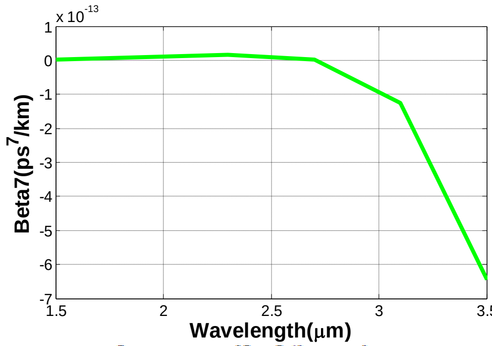


Fig.2.(m) β_7=8.8*$\times 10^{-12} ps^2/km$ at $\lambda = 1.9\mu m$

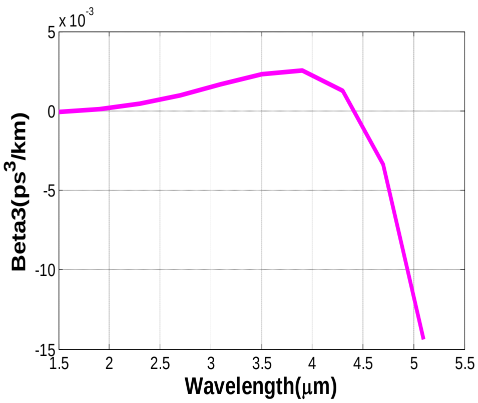


Fig.2.(i) $\beta_2 = 1.0 \times 10^{-2} ps^2/km$ at $\lambda = 1.9\mu m$

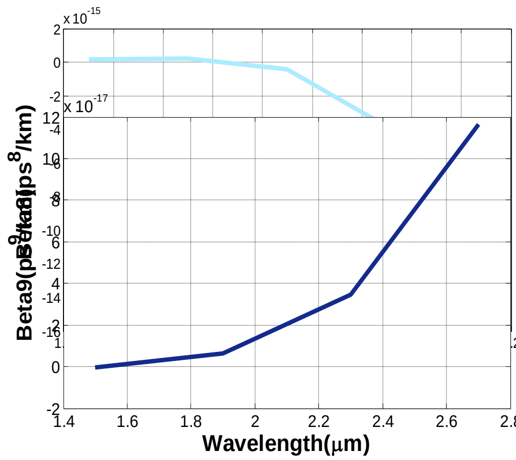


Fig.2.(o) $\beta_9 = 0.63 \times 10^{-17} ps^2/km$ at $\lambda = 1.9\mu m$

In, table (2), comparison of dispersion at a wavelength and various parameters like effective area and nonlinearity of photonic crystal fiber is present, which shows a comparative analysis of PCF property. PCF properties like chromatic dispersion, effective area, nonlinearity affected by the structure of the fiber, geometry, wavelength and also PCF material. Here, we compared evaluated results with previous work articles of different materials used PCF

Fig.2.(n) $\beta_8 = 0.2 \times 10^{-14} ps^2/km$ at $\lambda = 1.9\mu m$

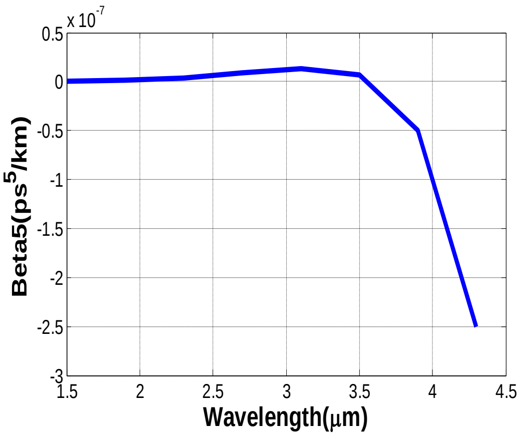


Fig.2.(k) β_5 =1.2 $\times 10^{-8} ps^5/km$ at $\lambda = 1.9\mu m$

Table.2 comparison table of different PCF property for supercontinuum generation

Ref.	Non-linear medium	Wavelength (μm)	Dispersion (ps/km-nm)	Effective area A_{eff} (μm^2)	Nonlinear coefficient γ ($W^{-1}km^{-1}$)
[5]	Silica glass PCF	1.55	-1528.5	1.48	84.80
[6]	Silica glass PCF	1.55	-0.60	2.38	52
[7]	$SF57$ glass PCF	1.55	-4 and zero dispersion at 1.56 μm wavelength	1.7	151
[8]	$Ga_8Sb_{32}S_{60}$ PCF	4.5	Zero dispersion at	15.23	970
[9]	As_2S_5b BorosilicatePCF	2.5	Zero dispersion at 2.08 μm wavelength	5.16	1460
[10]	As_2S_3 PCF	2	Zero dispersion at 1.985 μm	3.98	2362
Present work	As_2S_3 PCF	1.9	Zero dispersion wavelength at	3.8623	2568.6

3.

4. CONCLUSION

The design of a decagonal chalcogenide-based photonic crystal fiber is presented in this paper.We studied photonic crystal fiber design and its application for supercontinuum generation. We numerically studied and simulate properties of decagonal photonic crystal fiber like chromatic dispersion, higher-order dispersion, effective area, nonlinear coefficient. The calculated value of the effective area and nonlinear coefficient are 3.8623 μ $\mathbf{1.}$? and 2568.6$\mathbf{1.}$ $W^{-1}km$ at wavelength 1.9μm.We calculated all higher-order dispersion coefficient $\mathbf{1.}$ β_2 *to* β.The result of this photonic crystal fiber design is adequate and more suitable for further research work on the generation of supercontinuum spectrum in mid-infrared wavelength range 1.5μm to 5.5μm.

REFERENCES

[1]. Nidhi Sharma, Neetu Rajawat, Kavita Agrawal, February 2015, “Photonic Crystal Fiber Characteristics Benefits Numerous Applications”, International Journal of Scientific &Engineering Research,Volume 6, Issue 2, ISSN 2229-5518.

[2]. NehaMahnot, Shikha Maheshwary, Rekha Mehra, February 2015, “Photonic Crystal Fiber- An Overview”,International Journal of Scientific &Engineering Research, Volume 6, Issue 2, ISSN 2229-5518.

[3]. John M.Dudley, Gorey Genty, Stephane Coen,2006, “Supercontinuum generation in photonic crystal fiber” Reviews of Modern Physics, volume 78, DOI:10.1103/RevModPhys.78.1135.

[4]. L. Shuo and L. Shu-Guang,2013,“Numerical analysis of photonic crystal fiber with chalcogenide core tellurite cladding composite

microstructure,", Chin. Phys. B, volume. 22, number. 7, p. 074206.

[5]. Md.Ibadul Islam,Kawsar Ahmed,Shuvo Sen,Bikash Kumar Paul,2017, "Proposed square Lattice Photonic Crystal Fiber for extremely High Nonlinear, Birefringence, and Ultra-High Negative Dispersion Compensation", Journal of communication, DOI:10.1515/joc.2017.0095.

[6]. Feroza Begum, PgEmeroylariffion Abas, 2019, "Near-Infrared Supercontinuum generation in silica used photonic crystal fiber", Progress in Electromagnetic Research C, Vol.89,149-159.

[7]. Mohit Sharma, SwapanKonar, KaisarR.Khan, 2015, "Supercontinuum generation in highly nonlinear Hexagonal photonic crystal fiber at very low power", Journal of Nanophotonics,DOI: 10.1117/1.JNP.9.093073.

[8]. A. Medjouri, D. Abed, Z. Becer,2019, "Numerical investigation of a broadband coherent supercontinuum generation in $Ga_8Sb_{32}S_{60}$ chalcogenide photonic crystal fiber with all-normal dispersion", optoelectronics review 27, https://doi.org/10.1016/j.opetre.2019.01.003.

[9]. Amine Ben Salem, Mbaye Diouf, Rim Cherif, AhmadouWague, Mourad Zghal, 2016,"Ultraflat-top midinfrared coherent broadband supercontinuum using all normal As_2S_5 -borosilicate hybrid photonic crystal fiber", Opt. Eng. 55(6), 066109, DOI: 10.1117/1.OE.55.6.066109.

[10]. Redwan Ahmad, Matej Komanec,Stanislav Zvanovec,2016, "Circular Lattice Photonic Crystal Fiber for Mid-IR Supercontinuum Generation", IEEE Photonics Technology Letters, DOI 10.1109/LPT.2016.2615657.