A New Design of As_2Se_3 Chalcogenide Glass Photonic Crystal Fiber with Ultra-Flattened Dispersion in Mid-Infrared Wavelength Range

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ABSTRACT
In this paper, we report a new design of As_2Se_3 chalcogenide glass photonic crystal fiber (PCF) with ultra-flattened dispersion at mid-infrared wavelength range. We have used the plane wave expansion method (PWE) for designing the structure of As_2Se_3 glass PCF at different wavelength windows. In the proposed structure with hole to hole spacing $\Lambda_1 = 3\mu m$ and $\Lambda_2 = 18\mu m$, the negative dispersion is -1025 ps/nm/km at the wavelength of 1.55µm, and also an ultra-flattened dispersion is achieved at the wavelength range of 3.5-18µm. Hence such PCFs have a high potential to be used as dispersion compensating fibers at 1.55µm wavelength in optical communication systems. The ultra-flattened dispersion at the wavelength range of 3.5-18µm can be employed to achieve high power super-continuum generation. The nonlinear coefficient of the proposed PCF is 1.5 $W^{-1}m^{-1}$ at the wavelength of 1.55µm. Chalcogenide glasses are known to have both high transparency and nonlinearity in a wide range of infrared wavelengths compared to silica glasses.

KEYWORDS: Chalcogenide Glass, Photonic Crystal Fiber, Flattened Dispersion, Compensation, Super-Continuum Generation.

1. INTRODUCTION

In recent years, infrared light sources have received much attention due to their applications in sensors, optical communications, military technology and medicine [1], [2]. Materials with features such as high transparency and nonlinearity in a wide range of infrared wavelengths can be used in the manufacture of optical fibers. Many non-linear optical processes such as four-wave mixing and Super-continuum generation require a medium with high nonlinearity. Amongst the materials that are used in the manufacture of optical fibers, chalcogenide compounds are the key materials in the infrared wavelength range [3]-[5]. Chalcogenide glasses are combinations of two or more of the following elements; As, Ge, P, Te, S, and Se. As_2Se_3 is amongst the known chalcogenide glasses. These compounds have high transparency and non-linearity in a wide range of infrared wavelengths. Some combinations of chalcogenide glasses have nonlinearity 100-1000 times greater than that of silica glasses. Refractive indices of chalcogenide glasses range from 2.4 to 3 [4]. The above properties, have led chalcogenide glasses to be considered as suitable materials for the production of optical fibers which are employed in the infrared region. The chalcogenide glasses are used in the manufacture of devices, such as lenses, infrared cameras, lasers, optical switches and chemical sensors [6], [7]. In order to compare the efficiencies of various optical fibers, optical characteristics such as dispersion, nonlinearity, confinement loss and the effective area should be considered. Depending on the application, optical fibers should have optical characteristics with appropriate features. For conventional optical fibers, to achieve low and flat dispersion at a wide range of wavelengths is very difficult. For this reason, in recent years many studies have been carried out on a specific type of optical fiber known as photonic crystal fiber (PCF). This type of optical fiber is made up of a core and an array of air holes which are drawn around the core. Light guidance in such PCFs is based upon the principle of total internal reflection [8]-[12]. In order to confine light inside the core, a large contrast between the refractive index of the core and the cladding is required. A large refractive index difference between the core and the cladding creates two main advantages for PCFs. 1- In such PCFs, managing optical characteristics such as dispersion is much simpler than the conventional fibers. 2- Due to a strong confinement of light in the core, nonlinearity increases [13]-[16]. Furthermore, due to the high flexibility in the design of the core diameter, number and shape of the air holes in the cladding in PCFs, controlling the optical properties in these fibers is much easier than the conventional fibers. One of the characteristics of PCFs is the single-mode behavior at a wide range of wavelengths. This behavior depends on the diameter and the distance between the air holes (pitch) [17], [18]. Many PCFs with silica cores have been presented by various research groups, but recently the core of PCFs are designed with chalcogenide glasses due to their certain optical characteristics that are mentioned above [19]. In structures that have been proposed up until now, Optical characteristics of PCFs have been managed by changing their geometric parameters such as the air hole diameter (*d*), the distance between the centers of the adjacent air holes (*Λ*), the shapes of the air holes, filling holes with other materials (hybrid PCFs) and finally causing defects in the array of air holes in the cladding. PCFs applications include fiber optic communications, medical, military and metrology applications. They can also be used as dispersion compensating fibers (DCFs). In optical communication systems, data bit rates are limited by dispersion and distance. For dispersion compensation in optical communication fibers and hence enhancing data bit rate, DCFs with high negative dispersion have been used [20], [21].

In this paper, plane wave expansion method (PWE) is employed for designing a new PCF structure with flattened dispersion properties in mid-infrared wavelength windows. Our structure consists of 5 air hole rings, embedded in As_2Se_3 chalcogenide glass. Two sets of *Λ*s with values of $\Lambda_1 = 3\mu m$, $\Lambda_2 = 18\mu m$ are used. By using different sizes of air holes with different hole to hole spacing (*Λ*) in the cladding, various dispersion properties can be achieved. Hence, we use two different air hole diameters in the structure to obtain not only flattened dispersion at the wavelength range of 3.5-18μm, but also to achieve a high negative dispersion with the value of -1025 ps/nm/km at the wavelength $\lambda = 1.55\mu m$. The nonlinear coefficient of the proposed PCF is $1.5 W^{-1} m^{-1}$ at the wavelength of 1.55μm.

2. THEORY AND CONCEPT

In this section, the numerical method known as plane wave expansion (PWE) that is used in our simulations is described. We have also reviewed optical characteristics such as dispersion, confinement loss, effective mode area and nonlinear coefficient.

2.1. Plane Wave Expansion Method

In order to design PCFs with specific optical characteristics, a numerical approach is required to determine the propagation of light through them. Using numerical techniques, one can compute frequencies at which light can propagate in PCFs and also can get an insight into the field distribution of each light frequency. Up until now, various numerical methods such as FEM, FVEIM and PWE are applied. In this paper, PWE method is used for our design purposes [4]. PWE is a method for solving Maxwell's equations in electromagnetics.

This method is employed for frequency band and dispersion calculations in PCFs [22].

Effective index of a guided mode for a given wavelength is obtained by solving the eigenvalue problem drawn from the Maxwell equations using the plane wave expansion method. The effective index, n_{eff} , can be obtained as [20]:

$$n_{eff} = \frac{\beta}{K_0} \quad (1)$$

where β is the propagation constant and K_0 is the free apace wave number,

$$K_0 = \frac{2\pi}{\lambda} \quad (2)$$

The refractive index can be obtained by the sellmeier equation as follows [5]:

$$n(\lambda) = \sqrt[2]{\left(1 + \frac{A\lambda^2}{\lambda^2 - D} + \frac{B\lambda^2}{\lambda^2 - E} + \frac{C\lambda^2}{\lambda^2 - F}\right)} \quad (3)$$

2.2. Chromatic Dispersion

The main property of PCFs, namely chromatic dispersion is studied. Thus a brief introduction to this property is presented in this section. Dispersion is broadening of pulse when propagates through optical fibers. The wavelength dependence of both material refractive index and propagation constant leads to chromatic dispersion. Chromatic dispersion $D(\lambda)$ is the sum of both waveguide $D_w(\lambda)$ and material dispersions $D_m(\lambda)$ .Total chromatic dispersion can be calculated from [4]:

$$D(\lambda) = D_m(\lambda) + D_w(\lambda) \quad (4)$$

Here the chromatic dispersion characteristic of PCF, D (λ) with unit of ps/nm/km is calculated from the second derivative of the real part of the effective index as shown below [4]:

$$D(\lambda) = -\frac{\lambda}{c}\frac{d^2 Re\left[n_{eff}\right]}{d\lambda^2} \quad (5)$$

Where, $Re\left[n_{eff}\right]$ is the real part of n_{eff}, λ is the wavelength, and C is the velocity of light in free space. If $D(\lambda) < 0$, PCF has a negative dispersion, otherwise it has an anomalous dispersion. Negative dispersion is obtained over a broad wavelength range due to large index contrast between core and cladding. Major factor in telecommunication systems that limits data bit rates, is the broadening the optical pulse when propagates within the optical fiber. This is known as anomalous dispersion. The simplest technique to compensate dispersion is to employ fibers with high negative dispersions. These fibers are known as dispersion compensating fibers (DCFs). DCFs are usually connected to the end of the telecommunication fibers. Based on Equation (6), the higher negative dispersion, the smaller length of DCF is needed [20]-[21].

$$D_T = D_f \times L_f + D_{DCF} \times L_{DCF} \quad (6)$$

Where D_f and L_f are dispersion and length of telecommunication fiber respectively, while D_{DCF} and L_{DCF} are dispersion and length of DCF.

Up until now, various techniques have been employed to manage fiber dispersion, such as multi-ring PCF [5], chalcogenide/tellurite hybrid micro-structured optical fiber [13], [16]. These structures use various geometric dimensions, shapes and sizes of the air hole around the core to manage fiber dispersion characteristics.

2.3. Confinement Loss

Light leaking out from the core into the cladding region is known as the confinement loss. With increasing the number of rings of the air holes around the core and also with air holes having greater diameters in the inner ring of the cladding, losses can be reduced drastically. The confinement loss L_c, in unit of dB/m., is calculated from the following equation [23]:

$$L_c = \frac{20}{ln10} \times \frac{2\pi}{\lambda} Im(n_{eff}) \quad (7)$$

where $Im\left(n_{eff}\right)$ is the imaginary part of effective refractive index.

2.4. Effective Mode Area

Another important characteristic of our structure is the effective mode area. Effective mode area in unit of μm^2, is calculated as [23]:

$$A_{eff} = \frac{\left(\iint |E|^2 dxdy\right)^2}{\iint |E|^4 dxdy} \quad (8)$$

where $|E|$ is the electric field distribution. Effective mode area can be increased by enlarging the pitch, while keeping the diameter of the air holes constant.

2.5. Nonlinearity

Nonlinearity becomes important, when light with high intensity is coupled with the core of the proposed PCF. Effective mode area has an inverse relationship with nonlinearity. PCF with a large core can have a low nonlinearity. Nonlinear coefficient in unit of $W^{-1}m^{-1}$ is calculated as [23]:

$$\gamma = \left(\frac{2\pi}{\lambda}\right)\left(\frac{n_2}{A_{eff}}\right) \quad (9)$$

where n_2 is the nonlinear index, which for As_2Se_3 chalcogenide glass is $2.4\times10^{-17} m^2/W$, and for air is $2.9\times10^{-23} m^2/W$ [14].

It should be noted that nonlinear coefficient in DCF is an important parameter. High nonlinearity in DCF, certainly affects the nonlinear characteristics, such as four-wave mixing in the telecommunication fibers. Cores with small diameters increase the nonlinear characteristics of PCFs. But on the other hand, cores with small diameters limit the power transfer. Solution this limitation, is to use a core with high nonlinear material such as chalcogenide glasses.

3. DESIGN PRINCIPLE AND RESULTS

The preliminary design of the proposed PCF is illustrated in Fig.1. This PCF consists of 5 air hole rings, embedded in As_2Se_3 chalcogenide glass with refractive index of 2.82. The diameter of the air holes and the distance between the centers of the adjacent air holes are d and Λ respectively. The dimensions of d and Λ affect PCF optical characteristics such as dispersion and confinement loss. By adjusting the number of air holes and the ratio of d/Λ, the confinement loss can be managed effectively. For large d/Λ, confinement losses are low [4]. To obtain flattened dispersion for a broadband of wavelengths, small diameters of air holes in the cladding are needed. But small dimensions of the air holes make the PCF fabrication relatively difficult. Our proposal to obtain flattened dispersion in a wide band of wavelengths is to use 4 hexagonal rings of air holes with same diameter away from the PCF core and 6 air holes near the core. The diameter of the holes in the inner ring is chosen to be 3μm and that of the four outer rings is 1μm. The lattice structure of the cladding in this PCF is hexagonal and the spacing between the centers of the adjacent holes of the four outer rings, Λ_1 , is 3µm and the spacing between the centers of adjacent holes of the inner rings, Λ_2, is 18µm. Fig. 2 shows that our design can confine the light inside the PCF core.

To study optical characteristics for the proposed structure, firstly the effective refractive index is calculated. The effective refractive index as a function of wavelength (λ) is shown in Fig.3. As illustrated in Fig.3, in the wavelength range of 3.5-18µm, the effective refractive index change is minimal. Fig. 4 shows the dispersion as a function of wavelength in the proposed design. It illustrates that the proposed structure have flat dispersion with value close to zero at 3.5-18µm wavelength range while the dispersion value of the structure in [5], has fluctuations around zero at wavelengths larger than 2.5µm. Air holes with small diameter in the cladding, have created the flattened dispersion. Flat dispersion in a wide range of wavelength is an advantage that can be used for nonlinear processing such as Super-continuum generation [3]. Hence, our structure has a strong potential to be used for Super-continuum generation at the wavelength range of 3.5-18µm. Fig. 5 shows the dispersion of our PCF at $\lambda = 1.55\mu m$. This figure illustrates that the proposed PCF at $\lambda = 1.55\mu m$ has negative dispersion with a value of -1025 ps/nm/km, while the negative dispersion in the PCF presented in

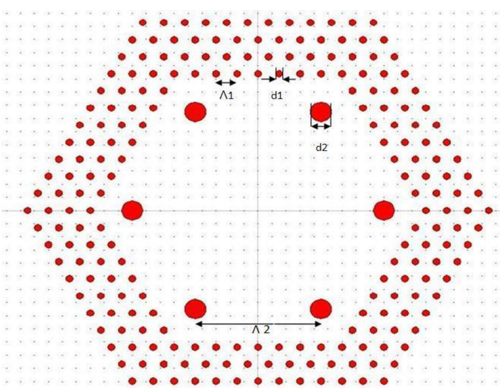

Fig. 1. The cross section of the proposed PCF

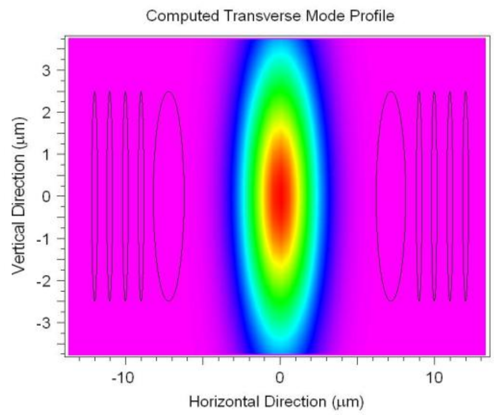

Fig. 2. Mode field distribution of the proposed PCF

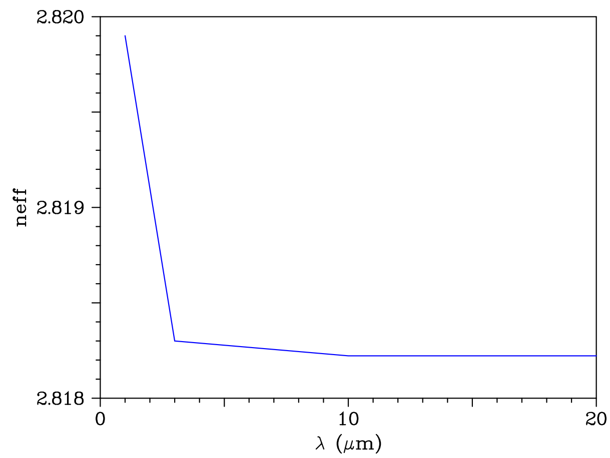

Fig. 3. Effective refractive index versus wavelength for the proposed PCF

[18] is -723.1ps/nm/km. 1.55µm wavelength is very important in the optical communication systems, hence at this wavelength, the fiber dispersion should have low anomalous dispersion. However, low anomalous dispersion in long optical fibers, has an adverse effect on data bit rates. DCF can be used in order to reduce this effect in optical transmissions.

DCF should have high negative dispersion at $\lambda = 1.55\mu m$. Subsequently, the proposed PCF in this paper can be employed as a DCF at the communication wavelength of 1.55µm. Confinement loss is another important optical characteristic in optical fibers. Confinement loss versus wavelength for the proposed PCF is shown in Fig. 6. Confinement loss of the structure in [5], is negligible at the wavelength range of 1 to 8µm, while confinement loss of our PCF is negligible at a wider range of wavelengths, 1 to 12.5µm. Effective mode area (A_{eff}) is also studied in this paper. A_{eff} of our PCF versus wavelength is shown in Fig.7.

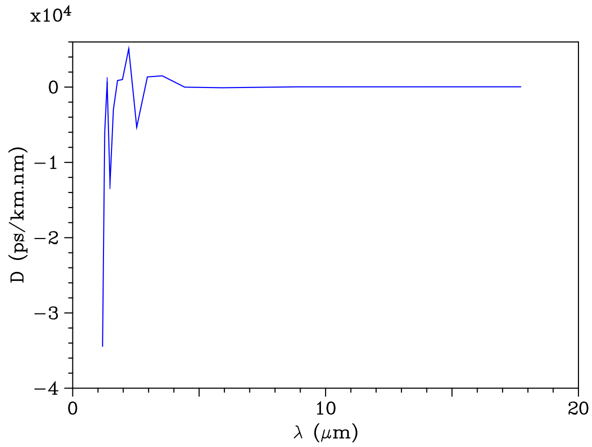

Fig. 4. Dispersion versus wavelength for the proposed As_2Se_3 glass PCF

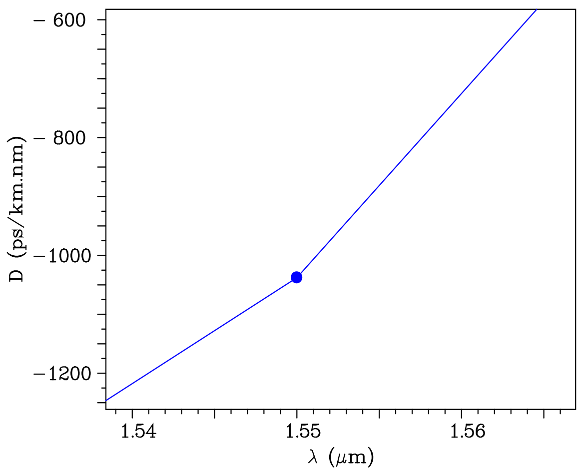

Fig. 5. Dispersion versus wavelength for the proposed PCF at $\lambda = 1.55\mu m$

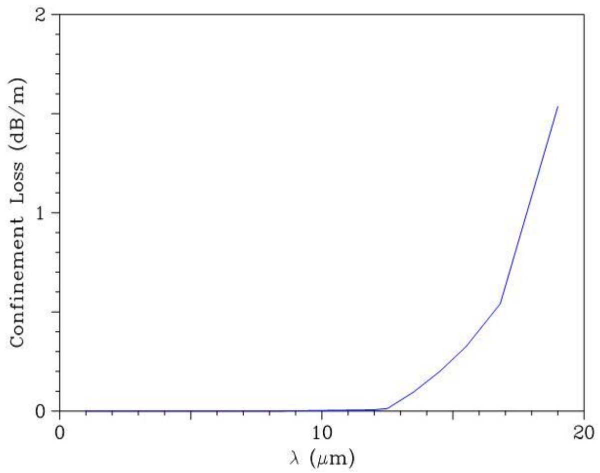

Fig. 6. Confinement loss curve of the proposed PCF

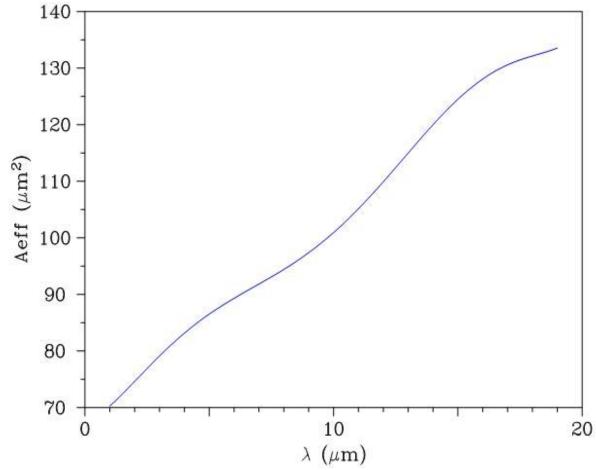

Fig. 7. The effective mode area as a function of wavelength

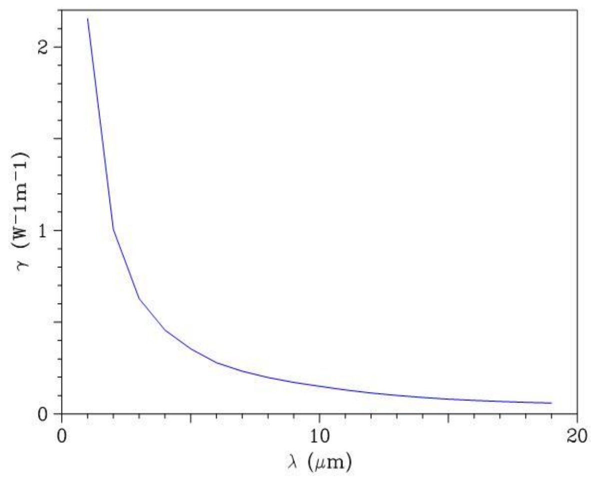

Fig. 8. Nonlinear coefficient as a function of wavelength

In all wavelengths, the proposed PCF has larger A_{eff} than the structure studied in [5]. For example, at $\lambda = 10\mu m$ our PCF has $A_{eff} = 100\mu m^2$, while the PCF in [5] has $A_{eff} = 80\mu m^2$. The effective mode area in our structure at $\lambda = 1.55\mu m$ is $73\mu m^2$. Larger A_{eff} is an important parameter in high power transmission. Last optical characteristic that is mentioned in this section is the nonlinear coefficient (γ). Nonlinear coefficient as a function of wavelength is shown in Fig. 8. Nonlinear coefficient at $\lambda = 1.55\mu m$ in our structure is $1.5 W^{-1}m^{-1}$, while for the PCF presented in [5], it has a value of about $0.2095 W^{-1}m^{-1}$. The nonlinear coefficient in multi-ring structure in [5] is smaller than that in our structure. To study the effect of geometrical dimensions on PCF dispersion and simulations have been carried out with different values of Λ, d.

Fig. 9 shows the PCF dispersion for $d = 0.8\mu m$. It can be seen that air holes with small diameters cause the flat dispersion to shift to longer wavelengths than 6μm. Λ is a parameter that has an influence on dispersion. Fig.10 illustrates the dispersion for $\Lambda_1 = 4\mu m$. It can be observed the larger the value of Λ_1 makes the flat dispersion to shift to longer wavelengths than 8μm.

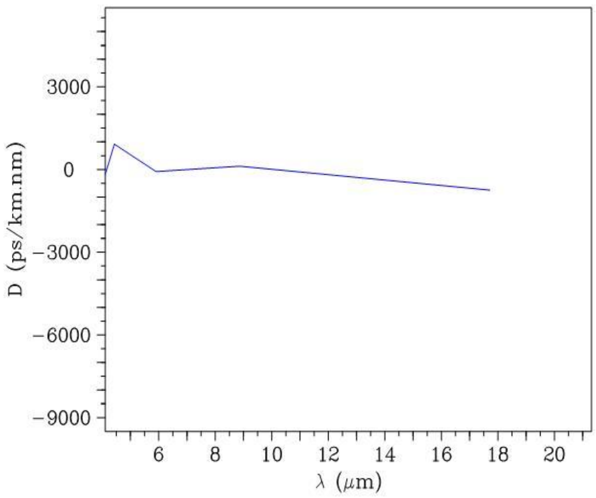

Fig. 9. PCF dispersion with $d = 0.8\mu m$

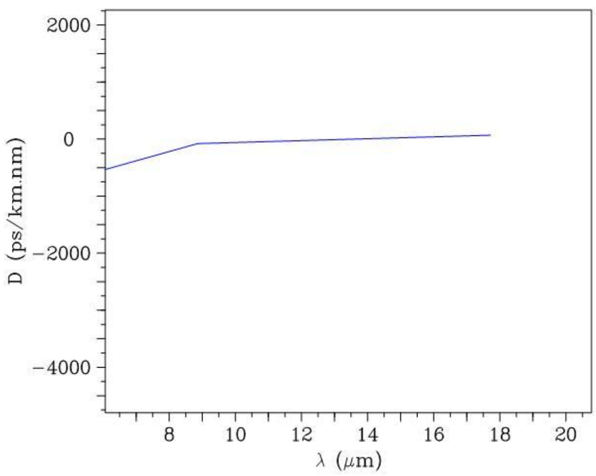

Fig. 10. PCF dispersion with $\Lambda_1 = 4\mu m$

4. CONCLUSION

This paper presents a new kind of As_2Se_3 chalcogenide glass PCF. This new structure has flattened dispersion in 3.5-18μm wavelength range and also has a high negative dispersion at 1.55μm wavelength. Hence such PCFs have high potential to be used as dispersion compensating fibers at 1.55μm wavelength in optical communication systems. The ultra-flattened dispersion at the wavelength range of 3.5-18μm can be employed to achieve high power Super-continuum generation. Therefore, using our design, there is a strong potential to not only achieve high power Super-continuum generation at the wavelength range of 3.5-18μm but also to fabricate high performance dispersion compensating fibers at 1.55μm wavelength range for optical communication systems. The nonlinear coefficient of the proposed PCF is $1.5W^{-1}$ m^{-1} at 1.55μm wavelength. Confinement loss of our PCF is negligible at a wider range of wavelengths, 1 to 12.5μm.

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