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RESEARCH ARTICLE

Highly nonlinear enhanced-core photonic crystal fiber with low dispersion for wavelength conversion based on four-wave mixing

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Abstract In this paper, a new structure of highly nonlinear low dispersion photonic crystal fiber (HN-PCF) by elliptical concentration of GeO_2 in the PCF core has been proposed. Using finite difference time domain (FDTD) method, we have analyzed the dispersion properties and effective mode area in the HN-PCF. Simulative results show that the dispersion variation is within ± 0.65 ps/(nm·km) in C-band, especially 0.24 ps/(nm·km) in 1.55 μm wavelength. Effective area and nonlinear coefficient are 1.764 μm^2 and 72.6 $W^{-1} \cdot km^{-1}$ respectively at 1.55 μm wavelength. The proposed PCF demonstrates high nonlinear coefficient, ultra small effective mode area and nearly-zero flattened dispersion characteristics over C-band, which can have important application in all-optical wavelength conversion based on four wave mixing (FWM).

Keywords dispersion, effective area, four wave mixing (FWM), wavelength conversion, photonic crystal fiber (PCF)

1 Introduction

In recent years, wavelength conversion has played a key role in providing wavelength flexibility in the optical telecommunication systems, especially, in the wavelength division multiplexing (WDM) systems [1,2]. Both theoretical and experimental works have showed that we can use four wave mixing (FWM) as a reliable technique for wavelength conversion according to its ultra fast response and high transparency to bit rate and modulation format [3]. FWM is one of main nonlinear optical processes, which can occur in optical fibers. It causes the generation of new frequency components, and has many applications in optical systems, such as all-optical signal amplification and all-optical wavelength conversion systems [4,5]. Recently, highly nonlinear fibers (HNLFs) with the appropriate design of low dispersion and small effective area have been used in wavelength conversion based on FWM systems [6]. Previous works on FWM based wavelength conversion using HNLFs [7,8], have shown good overall performances, but still it is required a long propagation distance and high pump power. Photonic crystal fibers (PCFs) are a new class of optical fibers, usually designed and fabricated with a solid pure silica core surrounded by periodic air holes which work as a cladding [9]. Air holes makeup in the cladding region of the PCF leads to unusual optical properties, such as nearly zero ultra flattened dispersion, low confinement loss, high birefringence, and large or small effective areas which results in the ability to control the amount of fiber nonlinearity [9,10]. In comparison with conventional optical fibers, PCFs can provide nonlinear properties and dispersion characteristics that can be strongly modified by designing air holes make up in the cladding region [11]. Moreover, FWM in PCFs can occur by relatively low pump powers and over short propagation distances, and also wavelength conversion can be possible in a much greater frequency range [12]. In addition, for generating effective FWM effect, maintaining phase matching between the signal and the pump is the main problem. Due to group velocity dispersion (GVD), it is very difficult to maintain phase matching in a long fiber or in a fiber with high GVD [13]. One solution for this problem is to use highly nonlinear PCFs (HN-PCFs) as the nonlinear medium with nearly zero flattened dispersion characteristics. According to previous researches on this field, the HN-PCFs can be designed by certain modifications such as reducing the core diameter [14]. On the other hand, the dispersion of PCF can be adjusted easily by changing size,

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pitch, shape and number of air holes in the cladding region [11]. A good number of PCF with moderate nonlinear property have been reported to date having flattened dispersion characteristics [15,16]. These PCFs have nonlinear coefficient less than 60.5 $W^{-1}\cdot km^{-1}$, while nonlinear coefficient of conventional fibers is only 1.3 $W^{-1}\cdot km^{-1}$ [16]. Although PCFs reported in Refs. [15,16] show a significant increment in the nonlinear coefficient (of the order 30 and 60.5 $W^{-1}\cdot km^{-1}$), these PCFs have too many design parameters, for example many different air-hole dimensions, that result in difficult fabrication process. However, using a PCF with same air holes diameter, it is difficult to control both the dispersion and nonlinearity in a wide range of wavelengths [17]. In this research, we present an enhanced core PCF with high nonlinearity and nearly-zero flattened dispersion as the suitable nonlinear media for generating effective FWM effect. We theoretically proposed a novel method for increasing fiber nonlinearity by elliptical enhancing the index of core region by doping germanium in the PCF core. The cross section of the proposed PCF and fundamental guided mode of the HN-PCF with holes diameter $d = 0.9$ µm, holes pitch $\Lambda = 2.3$ µm, width $a = 0.6$ µm and height $b = 2.2$ µm in operation wavelength $\lambda = 1.55$ µm are shown in Figs. 1 and 2.

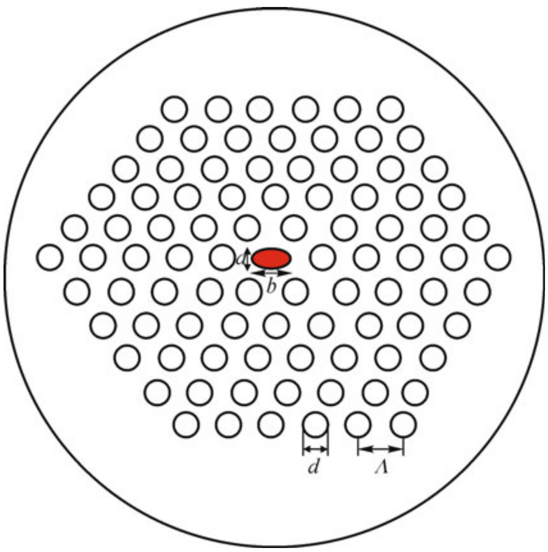

Fig. 1 Cross section of HN-PCF with holes diameter d, holes pitch Λ, width a, and height b of ellipse of the germano-silicate high index core

2 Theories

2.1 Guiding mechanism

There are two guiding mechanisms for the confinement of light in the PCF core. These mechanisms are called index guiding mechanism and band-gap guiding mechanism. In

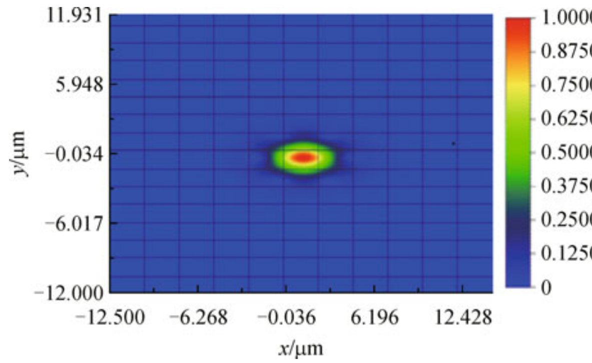

Fig. 2 Fundamental guided mode of HN-PCF with $d = 0.9$ µm, $\Lambda = 2.3$ µm, $a = 0.6$ µm and $b = 2.2$ µm in operation wavelength $\lambda = 1.55$ µm

the conventional fiber optics, the diversity of refractive index between core and cladding causes confinement of light in the fiber core. The same thing happens in the index guiding mechanism in PCFs. The core refractive index (n_{core}) is greater than the average refractive index of the cladding (n_{clad}), and light is guided by a modified form of internal reflection, which is usually referred to the modified total internal reflection (MTIR) guiding mechanism. Recent researches have obviously shown when pure silica is used as the material, n_{core} reducing to the index of pure silica. As a result, the guided light has an effective index (n_{eff}) that satisfies the following condition: $n_{clad} < n_{eff} < n_{core}$. Under these circumstances, PCFs can be designed to be endlessly single mode (ESM), which just supports propagation of the fundamental mode in all conditions [18].

2.2 Core refractive index

The refractive index of the pure silica is 1.446 at 1.55 µm wavelength [19], but the refractive index of enhanced core PCF can be calculated according to GeO_2 concentration (mol%) level. The refractive index relationship with the concentration level and the wavelength is given by Sellmeier's equation [20]:

$$n^2 = 1 + \sum_{i=1}^{k} \frac{a_i \lambda^2}{\lambda^2 - b_i}, \tag{1}$$

where k is equal to 3, represents that this is a three term Sellmeier's equation. λ is in a unit of micron (µm). In this equation, a certain set of parameters a_i and b_i are corresponding to a specific type of material such as pure silica or GeO_2 doped silica glass.

2.3 Nonlinear refractive index of HN-PCF

From Ref. [21], the nonlinear refractive index for pure silica is 2.507×10^{-20} m^2/W and the relationship between relative index difference and the nonlinear refractive index in GeO_2 doped glass can be experimentally expressed as

$$n_2 = 2.507 + 0.505\Delta. \tag{2}$$

We define the relative index difference as [20]

$$\Delta = (n_1^2 - n_0^2)/2n_1^2,$$

where n_0 and n_1 denote the refractive indexes of pure SiO_2 and the doped glass, respectively. Note that the above mentioned relationship is obtained for operating wavelength of 1550 nm. As the wavelength changes, n_2 has a slight variation. However, the variation is smaller by two orders of magnitude and need not be taken into account for simplicity.

2.4 Effective area

All of the nonlinear processes in optical fibers are dependent upon the intensity of the electromagnetic field in the core of the fiber. The optical power leaving an optical fiber is indeed the integral of the intensity distribution over the whole of the fiber cross section. We assume a uniform intensity distribution (I_u) over area of the core (A_{core}). It is known that the intensity could be calculated from the measured power ($P_{measured}$) using:

$$I_u = \frac{P_{measured}}{A_{core}}. \tag{3}$$

However, the field in a single mode fiber (SMF) or PCF is not equally distributed. Thus, we cannot assume a uniform intensity in the core. So, the effective mode area parameter has been defined for the calculating nonlinear effects in optical fibers that do not have a uniform intensity distribution [18,22]. The effective mode area is a quantity with high matter and many applications. It was originally introduced as a measure of nonlinearities. Indeed, a low effective mode area gives a high density of power needed for nonlinear processes and a high effective mode area gives a low density of power that ignores nonlinear effects. A useful definition for effective mode area of the optical fiber is [18,22]

$$A_{eff} = \frac{\iint (|E|^2 dA)^2}{\iint (|E|^4 dA)} = \frac{\iint (|I| dA)^2}{\iint (|I|^2 dA)}, \tag{4}$$

where E is the electric field amplitude and I is the optical intensity. However, If the mode field is well approximated by a Gaussian function of radius w at the 1/e amplitude points, the effective mode area can also be related to the spot size (w) through $A_{eff} = \pi w^2$, where $2w$ is the mode field diameter (MFD) of the fiber. The effective mode area is also important in the measurement of the confinement loss, bending loss, splicing loss, modal field diameter and numerical aperture [18,22].

2.5 Nonlinear coefficient

The nonlinearity coefficient (γ) is given by [6,22]

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}}, \tag{5}$$

where n_2 is the nonlinear index coefficient in the nonlinear part of the refractive index. Several methods have been proposed for the measurement of nonlinearity coefficient. It can be measured by using a number of techniques based on fiber nonlinear effects such as FWM [22]. The quantity of A_{eff} is an important starting point in the understanding of nonlinear processes in PCFs. Due to the high refractive index contrast between pure silica and air, the PCFs offer a much tighter mode confinement over a wide range of wavelengths and thereby a lower effective mode area compared to conventional optical fibers. Thus, for nonlinear processes, such as four wave mixing and Raman amplification, PCF is a suitable transmission media that allow engineers to increase nonlinearity coefficient.

2.6 Dispersion

One of the most important optical properties of a PCF is its manageable dispersion. The total dispersion can be easily controlled by varying the air holes diameter, shape, number and pitch. The effective refractive index of the fundamental guiding mode is provided by $n_{eff} = \beta/k_0$, where β is propagation constant and $k_0 = 2\pi/\lambda$ is the free space wave number. So, the total dispersion can be calculated from [23]

$$D(\lambda) = -\frac{\lambda}{c}\frac{d^2 n_{eff}}{d\lambda^2}, \tag{6}$$

where c is the velocity of light in vacuum and λ is the wavelength. The material dispersion provided by Sellmeier's formula [8] has been taken into attention in the calculation. The total dispersion is calculated as the sum of the waveguide dispersion and the material dispersion in the first order calculation [23]:

$$D(\lambda) = D_w(\lambda) + \Gamma(\lambda) D_m(\lambda), \tag{7}$$

where Γ is the confinement factor in silica, $D_m(\lambda)$ is material dispersion, and $D_w(\lambda)$ is the waveguide dispersion. The waveguide dispersion in PCFs can be calculated the same as the total dispersion, but under new circumstances that the new material, which is used in the structure, must be non dispersive [23].

3 Results and discussion

At present, PCF containing highly GeO_2 doped core has been reported [19]. Our proposed PCF has the linear refractive index of n = 1.47 and so the relative index difference is 1.3% which is achievable. According to Eq. (2), the amount of the nonlinear refractive index in our proposed PCF is 3.1635. Using finite difference time domain (FDTD) method [24,25], we theoretically investigated the effective mode area and dispersion properties of the HN-PCFs. First, the dependences of the dispersion on the holes diameter d is simulated and shown in Fig. 3 with fixed holes pitch Λ = 2.3 μm and size of doping concentration ellipse a = 0.6 μm and b = 2.2 μm, while changing d from 0.68 to 0.71 μm in steps of 0.01 μm. Chromatic dispersion in optical telecommunication systems is related to the variation in group velocity of optical pulses in the fiber. The dispersion is said to be anomalous when the chromatic dispersion value is less than zero. In these circumstances, shorter wavelengths propagate faster than longer wavelengths [11]. On the other hand, the dispersion regime is said to be normal when dispersion value being greater than zero. In this case, longer wavelengths propagate faster than shorter wavelengths. As above mentioned, maintaining phase matching in a long fiber is difficult due to GVD. Previous research shows that the phase mismatch even exists in less than 1 meter fibers [12]. In order to obtain an efficient wavelength conversion based on FWM, we can use HN-PCFs with modified dispersion characteristics. It can be seen from Fig. 3 that the proposed PCF has a nearly-zero dispersion parameter and a negative dispersion slope in the wavelength range near 1.55 μm, which demonstrates an excellent dispersion property for nonlinear processes. The value of the dispersion increases gradually with wavelength in a shorter wavelength and decreases gradually in a longer wavelength range. On the other hand, by increasing holes diameter from 0.68 to 0.71 μm, the amount of dispersion increases and zero dispersion wavelength (ZDW) of the fiber will move slightly to the right.

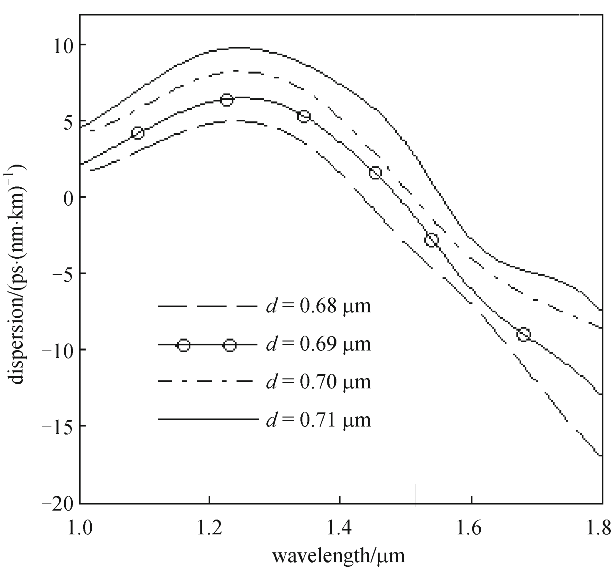

Fig. 3 Dispersion curves of HN-PCF with Λ = 2.3 μm, a = 0.6 μm and b = 2.2 μm as function of wavelength

Next, the dependences of the nonlinear coefficient on the holes diameter d is simulated and shown in Fig. 4, with fixed holes pitch Λ = 2.3 μm and size of doping concentration ellipse a = 0.6 μm and b = 2.2 μm, while changing d from 0.4 to 0.9 μm in steps of 0.1 μm. As shown in Fig. 4, the nonlinear coefficient of the HN-PCF is strongly depends on the holes diameter. In order to obtain the greater nonlinear coefficient in the wavelength range around 1.55 μm, the relative holes size (d/Λ) and consequently, air filling fraction must be increased. Air filling fraction will determine the effective index of the guiding modes in PCFs and also has a key role in determining the confinement loss of the fiber [18]. By increasing holes diameter d, the relative holes size (d/Λ) increases and consequently, air filling fraction will be increased dramatically. It is known that by increasing air filling fraction, nonlinear coefficient of the PCF increases and confinement loss will be reduced. From Fig. 4, it is obviously shown that by increasing holes diameter, the nonlinear coefficient increases dramatically. Also, the value of nonlinear coefficient decreases gradually with an increase of wavelength.

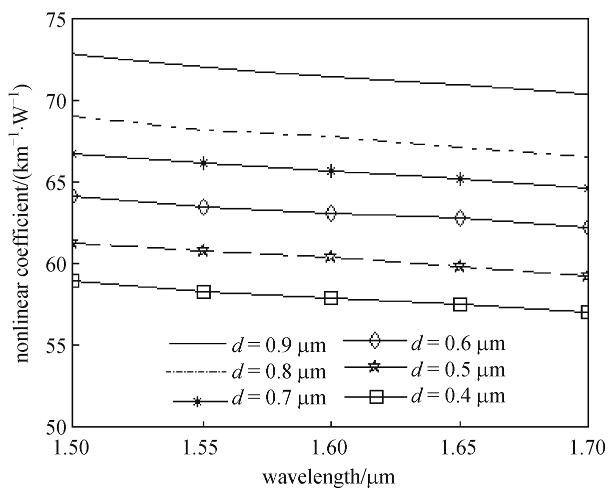

Fig. 4 Nonlinear coefficient curves of HN-PCF with Λ = 2.3 μm, a = 0.6 μm and b = 2.2 μm as function of wavelength

And then, fixing d = 0.7 μm, Λ = 2.3 μm and b = 1.0 μm while changing relative concentration ellipse size a/b, the dependences of dispersion on wavelength is further analyzed. It can be seen clearly from Fig. 5 that three dispersion curves are very close to each other near 1.55 μm wavelength range. In this operation wavelength range, the value of dispersion decreases with increase of a, while changing a from 0.3 to 0.7 μm in steps of 0.2 μm. Moreover, the value of dispersion decreases gradually with wavelength near 1.55 μm wavelength.

Furthermore, we investigate the influence of the geometric parameters d, and Λ on the effective area for the HN-PCFs while fixing a = 0.6 μm, b = 2.2 μm. The

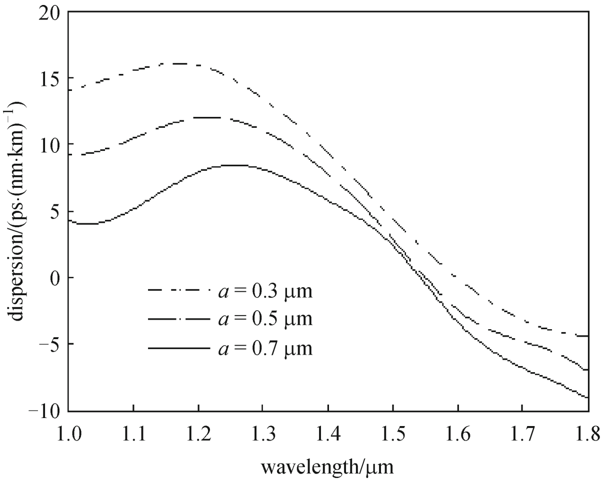

Fig. 5 Dispersion curves of HN-PCF with d = 0.7 μm and Λ = 2.3 μm as function of wavelength

results of these simulations are shown in Fig. 6. According to Eq. (5), by decreasing effective area, nonlinear coefficient will be increased dramatically. So, we must optimize design parameters of HN-PCF to achieve low effective area. In recent years, PCFs with low effective area have been reported [16]. These PCFs have effective area about 2 μm^2, while the effective area of conventional HNLFs are only 3.5 μm^2 [12,15]. It can be seen clearly from Fig. 6 that our proposed fiber can exhibit an ultra low effective area near 1.55 μm wavelength (about 1.75 μm^2) by optimizing relative holes size. Also, the value of effective area increases gradually with an increase of wavelength and decreases with increase of relative holes size (d/Λ).

Finally, we compare the optical properties of the proposed HN-PCF with conventional HNLFs. PCFs with

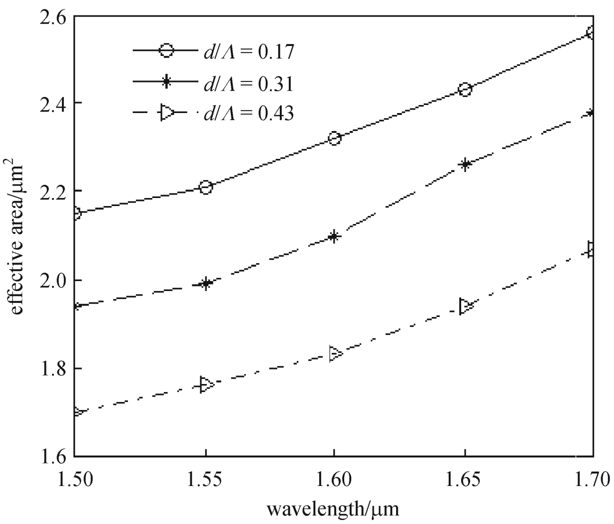

Fig. 6 Effective area of HN-PCF with a = 0.6 μm, b = 2.2 μm and Λ = 2.3 μm as function of wavelength

high nonlinearity and modified dispersion properties have been reported to date [15,16]. According to previous researches on this field, by modified design of air-holes or doping some materials in the PCF core, we can obtain specific optical properties, such as low effective area and flattened dispersion characteristics [12,19]. Recently, a PCF with low effective area (in order of 2 μm^2), high nonlinear coefficient (60.5 W^{-1}·km^{-1}) and low dispersion (in order of 0.7 ps/(nm·km)) by modified design of air-holes in a rectangular lattice structure for four-wave mixing has been reported [16]. Although this PCF has a great performance for four-wave mixing process, but the nonlinear coefficient and dispersion of the PCF can still be improved. Previous works show that this value of dispersion can still leads to phase mismatch [26]. Furthermore, it has many design parameters such as different air-holes diameters which make fabrication process of the PCF more difficult. In order to reduce phase mismatch and enhance FWM performance, it is required to using a fiber with nearly zero dispersion. Positive fourth-order dispersion or negative dispersion can also enhance the performance of wavelength conversion based on FWM process [26]. In this paper, we proposed an ultra high nonlinear PCF with modified dispersion and low effective area, which can have an important application in nonlinear processes such as FWM. Analyzing Figs. 3–6, it is found that the proposed PCF has optimal dispersion curves and better nonlinearity when the fiber parameters are optimized as follows: Λ = 2.3 μm, d/Λ = 0.42, a/b = 0.36. Hence, the optimized PCF with the high nonlinear coefficient and low flattened dispersion will have the opportunity to have an important application in wavelength conversion based on FWM. Simulative results in the optimized PCF show that the dispersion variation is within ±0.65 ps/(nm·km) in C-band, especially 0.24 ps/(nm·km) in 1.55 μm wavelength. Effective area and nonlinear coefficient are 1.764 μm^2 and 72.6 W^{-1}·km^{-1} respectively at 1.55 μm wavelength. Table 1 summarizes the optical parameters of conventional highly nonlinear photonic crystal fibers (C-HNPCF), rectangular lattice highly nonlinear photonic crystal fiber (R-HNPCF), which is reported in Ref. [16] and our proposed HN-PCF.

4 Conclusions

In this paper, we reported a new structure of highly nonlinear low dispersion photonic crystal fiber (HN-PCF) by elliptical concentration of GeO_2 in the PCF core. We used finite difference time domain (FDTD) method for our simulations. We analyzed the dispersion properties and effective mode area in the HN-PCFs in different situations and obtained great results by modifying air-holes and also concentration area. Numerical results show that the dispersion variation is within ±0.65 ps/(nm·km) in C-band, especially 0.24 ps/(nm·km) in 1.55 μm wavelength,

Table 1 Optical properties of fibers at $\lambda = 1.55$ μm wavelength

property	C-HNPCF	R-HNPCF	Our HN-PCF
effective area	3.5 μm^2	2 μm^2	1.76 μm^2
dispersion	3.2 ps/(nm·km)	0.7 ps/(nm·km)	0.24 ps/(nm·km)
n_2	2.507×10^{-20}	3×10^{-20}	3.16×10^{-20}
nonlinear coefficient	$29\ W^{-1} \cdot km^{-1}$	$60.5\ W^{-1} \cdot km^{-1}$	$72.6\ W^{-1} \cdot km^{-1}$

and effective area and nonlinear coefficient are 1.764 μm^2 and 72.6 $W^{-1} \cdot km^{-1}$ respectively at 1.55 μm wavelength. The proposed PCF demonstrates high nonlinear coefficient, ultra small effective mode area and nearly-zero flattened dispersion characteristics over C-band which can have important application in all-optical wavelength conversion based on four wave mixing.

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