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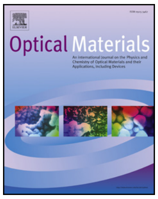

Extremely nonlinear carbon-disulfide-filled photonic crystal fiber with controllable dispersion

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ABSTRACT

In this paper, we present a new design of carbon-disulfide-filled photonic crystal fibers (CS_2-PCFs) by combining two unrelated optical properties, ultra high nonlinearity and tunable nearly-zero flattened disperion profile. Considering the fabrication challenges and using realistic hole dimensions, we design a CS_2-PCF with nonlinear coefficient of 7940 $W^{-1}km^{-1}$, confinement loss of 1×10^{-3} dB/km, total loss lower than 0.3 dB/m, nearly-zero dispersion of 0.00007 ps/(nm km) and a dispersion slope of 0.0000018 near 1550 nm. We demonstrate that the small changes due to fabrication imperfections does not have a significant effect on the dispersion characteristics or nonlinearity of the proposed PCF. In addition, we show that one can easily tune the dispersion profile of the proposed PCF by simply changing the core diameter. Therefore, the core diameter can be served as a controlling parameter to change the spectral range of flattened-dispersion profile of the CS_2-PCF. The proposed PCF is a promising candidate for numerous nonlinear applications which require high nonlinearity and/or specific dispersion characteristics including applications based on four-wave mixing.

1. Introduction

Since the major breakthroughs in the 1970s [1], optical fibers have evolved into many forms. Conventional fibers have been used for different important applications including telecommunications [2], sensing [3] and imaging [4]. However, conventional silica optical fibers have major limitations for realizing nonlinear processes because the fiber geometry and refractive index deviation of the core and cladding are restricted, and silica glass does not exhibit a high nonlinearity [5]. As a result, there is little incentive for considering conventional optical fibers for nonlinear applications. Photonic crystal fibers (PCFs) are a well-established class of optical fibers which consist of a core region surrounded by an array of air holes [6]. PCFs exhibit numerous unique features which are not available in silica fibers. For instance, one can realize ultra high nonlinearity in the PCFs due to the possibility of using nonlinear materials in the fiber core and tight mode confinement in PCFs [7]. As another example, the dispersion profile in PCFs can be controlled by changing the hole dimensions and the holes spacing (holes pitch) [8].

Dispersion Controllability in PCFs is an important issue for practical applications in nonlinear optics and optical telecommunications. In some nonlinear processes, for example four-wave mixing (FWM), maintaining phase matching between the pulses is the main concern [9–11]. The main source of the phase mismatch in optical fibers is the group velocity dispersion (GVD) which can significantly affect the efficiency of the nonlinear processes [10–12]. The magnitude of GVD, and even the slope of GVD curve has an important effect on the phase matching between pulses over a range of wavelengths [9]. The phase mismatch problem can exists in both long fibers and short fibers, even in 1 m long fiber with moderate dispersion [9,10]. Using highly nonlinear fibers with nearly-zero flattened dispersion characteristics, one can solve the phase matching problem in nonlinear processes. For example, using a flattened dispersion highly nonlinear PCF, wavelength conversion has been demonstrated in a wide frequency range via FWM [9,10].

To date, various PCFs with specific dispersion properties, such as ultra-flattened dispersion PCFs and multiple zero dispersion wavelength PCFS, have been studied both theoretically and experimentally [12–14]. On the other hand, PCFs with ultra high nonlinearity using chalcogenide glasses or highly nonlinear liquids have been reported. Using bismuth-oxide PCF (Bi-PCF), Chow et al. [10] obtained the nonlinear coefficient of 580 $W^{-1}km^{-1}$ at 1550 nm wavelength. The magnitude of nonlinear coefficient is about 100 times greater than that in silica fibers and 10 times greater than that in highly nonlinear silica-based PCFs. By filling a core of a hollow core PCF with a highly nonlinear liquid, one can increase nonlinear coefficients significantly due to

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high nonlinear refractive index of liquids and also tight mode confinement in PCFs. Previous studies on liquid filled PCFs, especially carbon-disulfide-filled PCFs, have shown that extremely high nonlinear coefficient magnitudes of the order of 2000–4000 $W^{-1}km^{-1}$ can be achieved [15–17].

There were multiple attempts to increase nonliearity and control the dispersion characteristics of PCFs at the same time. PCFs with low effective area (in the order of $2\mu m^2$), high nonlinear coefficient (60.5–72 $W^{-1}km^{-1}$) and low dispersion (in the order of 0.3–0.7 ps/(nm km)) have been reported [11,12]. Although these PCFs show promise for nonlinear applications, the amount of dispersion slope can still lead to phase mismatch. Additionally, the amount of nonlinear coefficient can be significantly improve using a non-silica fiber. Poletti et al. [16] attempted to flatten the disperison curve of liquid-filled PCFs. They obtained a carbon-disulfide-filled PCF (CS_2-PCF) with $\gamma = 6548$ $W^{-1}km^{-1}$ and dispersion of 0.6 ps/(nm km) at 1550 nm wavelength. However, the PCF structure proposed in Ref. [16] has a relatively large filling fraction which makes the fabrication process of the PCF difficult, and also the amount of dispersion is problematic in most of the nonlinear processes.

In our previous work on liquid-filled hollow-core PCFs [17], we demonstrated the possibility of design of a liquid-filled PCF with large nonlinearity and high Brillouin gain for slow light generation. In this paper, we demonstrate a new possibility in designing nonliear CS_2-PCFs by combining two unrelated properties, ultra high nonlinearity and nearly-zero flattened disperion profile. We first design a highly nonlinear CS_2-PCF and show how the desired flat dispersion characteristics can be engineered. We then use the optimized PCF structure and show how we can control the dispersion profile using only a single design parameter.

2. PCF design

2.1. Nonlinear coefficient and loss

PCFs are usually designed and fabricated with a solid pure silica core, surrounded by periodic air holes that serve as a cladding [18]. Therefore, one can adjust the PCF core area to control the fiber nonlinearity [18]. First, we use silica as the cladding material for our proposed CS_2-PCF. In this study, we use Sellmeier's equation [19] to find the amount of linear refractive index of materials in different excitation wavelengths,

$$n^2(\lambda) = 1 + \sum_{j=1}^{k} \frac{A_j \lambda^2}{\lambda^2 - B_j^2} \tag{1}$$

where A_j and B_j are Sellmeier's coefficients, λ is the excitation wavelength in micrometers and $n(\lambda)$ is the wavelength-dependent linear refractive index of material. The Sellmeier's coefficients for CS_2 are $A_1 = 1.50387 \pm 0.00027$ and $B_1 = 0.03049 \pm 0.00008$ (μm^{-2}) [20]. Therefore, one can find refractive index of CS_2 as a function of wavelength using the following equation [20],

$$n_{CS_2} = \sqrt{1 + \frac{1.50387\lambda^2}{\lambda^2 - 0.03049}} \tag{2}$$

The material dispersion of CS_2 can be easily calculated using the dispersion formula, $D_{CS_2} = -\frac{\lambda}{c}\frac{d^2 n_{CS_2}}{d\lambda^2}$ [5,13]. The linear refractive index and material dispersion of CS_2 are shown in Fig. 1a and Fig. 1b as a function of wavelength.

Moreover, the refractive index of silica can be obtained using the following Sellmeier's equation [21,22].

$$n_{silica} = \sqrt{1 + \frac{0.6961663\lambda^2}{\lambda^2 - 0.0684043^2} + \frac{0.4079426\lambda^2}{\lambda^2 - 0.1162414^2} + \frac{0.8974794\lambda^2}{\lambda^2 - 9.896161^2}} \tag{3}$$

Our proposed PCF has a hexagonal lattice with five rings of air holes, surrounding a CS_2-filled-core in the center of the fiber. We chose CS_2 as the filling liquid as it exhibit an extremely large nonlinear refractive index ($n_2 = 320 \times 10^{-20} m^2/w$ at 1550 nm) and a nearly absorption free transmission spectrum in the spectral range extending from the visible to the midinfrared comparing to other nonlinear liquids such as nitrobenzene and toluene [16]. The design parameters of the CS_2-PCF are the hole diameter d, hole pitch Λ, and core diameter D. The cross section of the proposed CS_2-PCF is shown in Fig. 2.

Our analysis is restricted to mode confinement through multiple total internal reflections (MTIR). Using a finite difference time domain (FDTD) analysis [22–24], we theoretically study the effective mode area, nonlinear coefficient and dispersion properties of the CS_2-PCFs. One of the most important characteristics of a highly nonlinear fiber is its nonlinear coefficient. The nonlinear coefficient γ is defined as [18,24].

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}}, \tag{4}$$

where n_2 is a nonlinear refractive index and A_{eff} is an effective area of the fundamental fiber mode, defined as [18,24].

$$A_{eff} = \frac{\int\int (|E|^2 dA)^2}{\int\int (|E|^4 dA)}. \tag{5}$$

Any nonlinear processes including FWM relies on the optical nonlinearities which act on the femtosecond and picosecond scales. The fastest of such nonlinearities is a regular electronic Kerr-type nonlinearity. For certain materials, especially highly nonlinear liquids, reorientational nonlinearity comes into play [25–27]. The mechanism for this type of nonlinearity is a reorientation of the liquid molecules each of which having a significant dipole moment caused by an applied external electric field [25,26]. Therefore this nonlinearity can be described as slow, since the modification of the refractive index depends not only on the intensity at the given moment but also on its past history [25,26]. CS_2 exhibits a strong non-instantaneous third-order response, arising from motions of the molecules. In fact, the nonlinear optical response of CS_2 varies by more than 1 order of magnitude in pulsed experiments. Previous studies show that n_2 of CS_2 will dramatically increases as the pulse duration increases from 110 fs to 75 ns dramatically (from $3 \times 10^{-15} cm^2/W$ to $4\times 10^{-14} cm^2/W$) [25]. However, the effect of the reorientational nonlinearity remains small for short pulses (below 50 fs) since the response does not have sufficient time to accumulate [25,26].

Additionally, due to a high refractive index contrast between silica and air, the PCFs offer a much tighter mode confinement and thereby a lower effective mode area than do conventional optical fibers [28]. In our case, this index contrast is even higher due to a large refractive index of CS_2 ($n_{CS_2} \approx 1.59$ at 1550 nm). We show the intensity profile of the fundamental guided mode in a PCF with a silica core (Fig. 3a) and CS_2-filled core (Fig. 3b) with a mode analysis using commercial software OptiFDTD [29]. The tight mode confinement in our proposed CS_2-PCF is due to large refractive index difference between core and cladding which results in a lower effective area and therefore higher nonlinear coefficient. This is one of the important advantages of CS_2-PCF over conventional silica PCFs. Another important factor which should be mentioned is the huge difference in nonlinear refractive index of silica and CS_2. The nonlinear refractive index of CS_2 is more than 2 orders of magnitude larger than silica. Combining the effect of tighter mode confinement and larger nonlinear index of CS_2, one can expect to see a huge difference in nonlinear coefficient of CS_2-PCF and regular silica PCF. This huge difference in nonlinearity is demonstrated in the Fig. 3c. As we can clearly see in this figure, the nonlinear coefficient of CS_2-PCF is nearly three orders of magnitude larger than the same PCF with silica.

We further examine the effect of hole dimension on nonlinearity of our proposed CS_2-PCF. The dependence of the nonlinear coefficient on

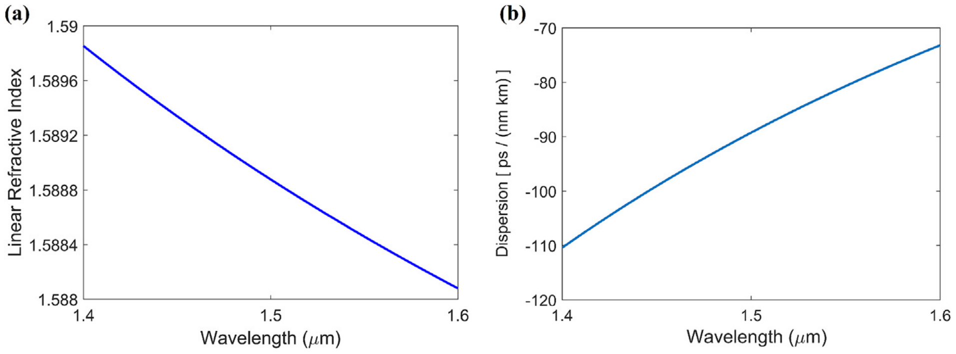

Fig. 1. (a) Linear refractive index of CS_2 and (b) material dispersion of CS_2 as a function of wavelength.

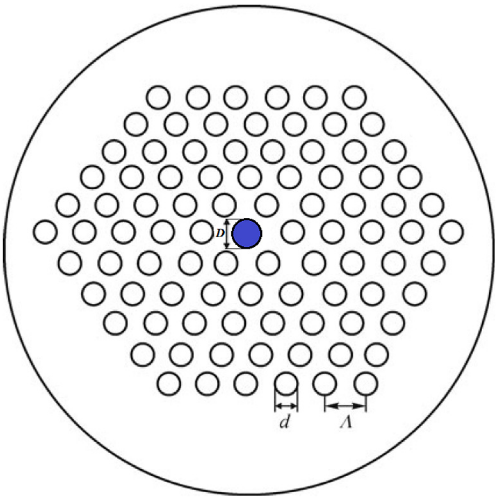

Fig. 2. Cross section of the CS_2-PCF with holes dimension (d), holes pitch (Λ) and core diameter (D).

the core diameter D is shown in Fig. 4 for $d/\Lambda = 0.7$ and $\Lambda = 1.2\,\mu m$, as the core filling fraction D/Λ varies from 0.4 to 0.8 in steps of 0.2. It is obvious that by decreasing the core diameter, the nonlinear coefficient increases dramatically due to tight mode confinement in a reduced size core. Also, the value of nonlinear coefficient decreases gradually with the wavelength.

The amount of confinement loss in the proposed fiber design for CS_2 is really low (in order of 10^{-3} dB/km). However, the total fiber loss will be likely dominated by absorption and scattering losses in the liquid. Fortunately, CS_2 boasts a nearly absorption free transmission spectrum in visible to the midinfrared spectral regions [16]. Therefore, we can expect an overall loss lower than 0.3 dB/m for our CS_2-filled fiber [16,17]. Although it is possible to achieve even higher nonlinearity using, for example, a chalcogenide glass PCF [30], low loss transmission of light and dispersion tunability are the main advantages of using a CS_2-filled PCF over other nonlinear PCFs [31–33].

2.2. *Dispersion characteristics*

Fiber dispersion is another important parameter. The total dispersion is calculated as the sum of waveguide and material dispersion [24]. In our calculations, the material dispersion, quantitatively described by Sellmeyer's formula, has been taken into account. Due to large material dispersion of CS_2, we should compensate material dispersion using waveguide dispersion of the PCF. The waveguide dispersion in PCFs can be easily controlled by varying the air hole diameter, shape, number and pitch. In our CS_2-PCF, we can control dispersion not only by adjusting the hole dimensions in the cladding, but also by adjusting core dimensions or changing the background material. In order to achieve

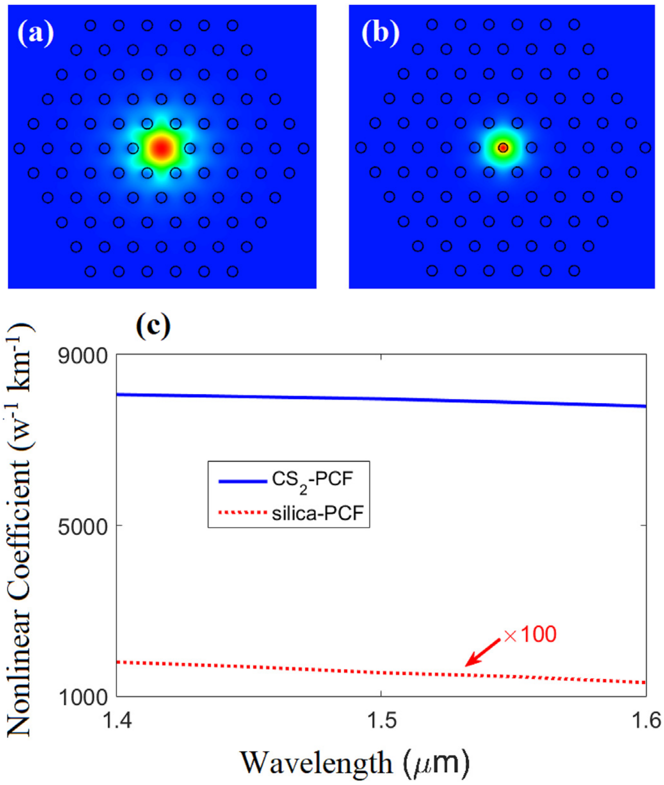

Fig. 3. Intensity profile of fundamental guided mode in a PCF with $d/\Lambda = 0.7$, $D/\Lambda = 0.6$ and $\Lambda = 1.2\,\mu m$ with (a) silica core and (b) CS_2-filled core. (c) The nonlinear coefficient of silica core and CS_2-filled core PCF as a function of the wavelength. Nonlinear coefficient of silica-core PCF is enhanced by a factor of 100 to facilitate visualization.

large waveguide dispersion –with the opposite sign to material dispersion– we need to increase either the core size or air hole dimensions. There is a threshold for a filling fraction in the PCF design. Specifically, the fabrication of large filling fraction PCFs (d/Λ larger than 0.8) is known to be quite challenging because of potential fiber core or air hole deformations. If the d/Λ value is larger than 0.9 (filling fraction being larger than 90%), the fabrication of the PCF is almost impossible with the current fabrication technology. Thus, we should keep our d/Λ and D/Λ sufficiently small (no larger than 0.8). The GVD parameter of a fiber is usually calculated in terms of the dispersion parameter Di, defined as [5,13].

$$Di = -\frac{\lambda}{c}\frac{d^2 n_{eff}}{d\lambda^2}. \tag{6}$$

The dispersion parameter Di and GVD parameter β_2 are related to each other as [13].

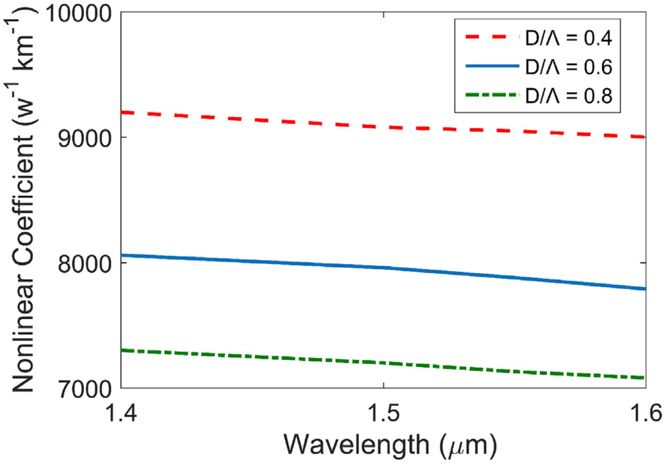

Fig. 4. Nonlinear coefficient of the CS_2-PCF with d/Λ = 0.7 and Λ = 1.2 μm and different core diameters as a function of wavelength.

$$Di = -\frac{2\pi c}{\lambda^2}\beta_2. \tag{7}$$

In Fig. 5a, we show dispersion as a function of the hole diameter d for different operation wavelengths, ranging from 1.4 μm to 1.6 μm in steps of 0.05 μm. It can be seen from Fig. 5a that the proposed PCF has a negative dispersion slope in the wavelength range around 1.55 μm. Upon increasing the filling fraction from 0.75 to 0.83, the amount of dispersion increases and a zero dispersion wavelength (ZDW) of the fiber will shift slightly to the right. Next, fixing d/Λ = 0.7 and Λ = 1.2 μm, while varying the core filling fraction D/Λ, we further analyze the dependence of dispersion on the wavelength. It is manifest in Fig. 5b that three dispersion curves have nearly the same shape in a spectral region around 1.55 μm. In this neighbourhood, dispersion increases with D, as we vary D/Λ from 0.76 to 0.81. Moreover, dispersion decreases gradually with the wavelength over the telecommunication band. Thus, the core diameter adjustment can affect dispersion (mostly its magnitude) while the hole diameter controls both the dispersion magnitude and dispersion curve shape.

We infer that liquid-filled PCF dispersion strongly depends on the core as well as hole diameters. We can find an optimized value for the nearly zero flattened dispersion curve but the problem is the magnitudes of d/Λ and D/Λ are relatively large (filling fraction is near 80%) which makes the fabrication process rather formidable. The proposed CS_2-filled PCF of Poletti et al. [16] has a relatively large filling fraction as well (d/Λ = 0.75 in one case and D/Λ = 0.9 in the other case). To overcome the fabrication challenge, we propose to replace the background material with an optical soft glass. We inspected a range of commercial borosilicate glasses from Schott Company for this purpose [34]. We use BK10, BK7 and BAK2 which have the following linear refractive indices at 1550 nm: 1.482, 1.500 and 1.523 respectively [34]. We display the CS_2-filled soft-glass PCF dispersion analysis in the Fig. 6a. Using BK10 soft glass we can achieve a nearly-zero ultra-flattened dispersion (ultra small dispersion slope or S_0) near 1550 nm wavelength. By optimized design of PCF with d/Λ = 0.7, D/Λ = 0.58 and Λ = 1.2 μm, we obtain ultra-flattened dispersion with a variation between ± 0.005 ps/(nm.km) over a 60 nm wavelengths range (1530–1590 nm). We illustrate this flattened dispersion curve in more detail in the Fig. 6b. This dispersion is also easily adjustable by adjusting hole dimensions. We obtain $\gamma = 7740$, $Di = 7\times 10^{-5}$ ps/(nm km) and $S_0 = \partial Di/\partial\lambda = 1.8\times 10^{-6}$ ps/(nm^{2}km) at 1550 nm. The proposed PCF with a high nonlinearity and low flattened dispersion at 1550 nm can result in efficient FWM-based applications, for example a wideband wavelength conversion.

2.3. Dispersion tunability

One of the most interesting features of our proposed CS_2-PCF is the possibility of controlling the dispersion profile with only one design parameter. By changing the core diameter, one can easily control the ultra-flattened dispersion region without changing any other parameter of the PCF. As we can see in Fig. 7, by increasing core filling fraction D/Λ from 0.52 to 0.68, the flattened-dispersion region will shift from lower O-band (around 1200 nm) to U-band and higher (around 1700 nm).

This interesting property can be used to optimize the PCF design for applications which require flattened dispersion profile over a specific spectral range, for instance mid-infrared or visible ranges. Table 1 summarizes the optical parameters of the proposed CS_2-PCF, bismuth-oxide PCF in Ref. [10], chalcogenide glass PCF in Ref. [30] and commonly used highly nonlinear silica fiber. The main advantages of our CS_2-PCF is a moderate overall loss (as opposed to usually high optical losses in bismuth oxide, tellurite and chalcogenide glasses), nearly-zero and tunable dispersion, and a large nonlinearity at telecommunication wavelengths.

3. Effect of fabrication imperfections

PCF fabrication using stack-and-draw technique is a well-established method and widely used by different manufacturers and research groups around the world [35–37]. In addition, there are several different techniques to fill the holes of a hollow-core PCF with a liquid, including fusion splicing techniques, which have already been taken into practice [38–40]. One interesting method is utilizing different flow speeds of the liquids in the holes with different sizes to fill liquid in the core or cladding holes in hollow-core PCFs [40]. Another method is to use the photo-lithographic masking technique [41] which makes it possible to block unwanted air holes at the end-face of fiber and obtain the selective filling. No matter which method one is used to fabricate the PCF and fill the hollow core with liquid, there are always

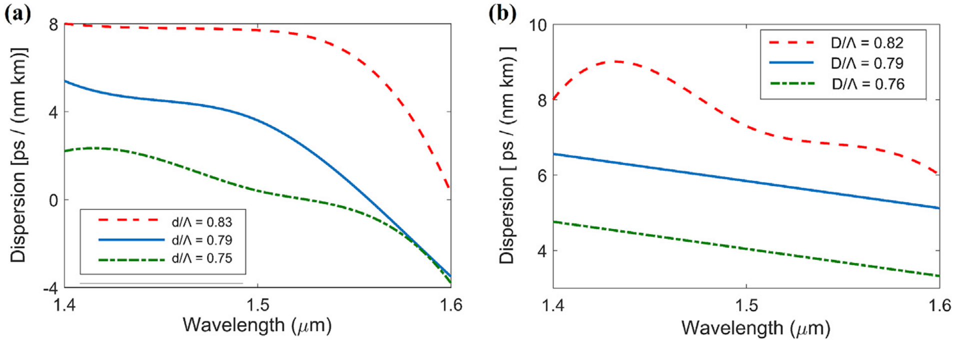

Fig. 5. Dispersion of the CS_2-PCF with fixed hole pitch Λ = 1.2 μm, (a) with D/Λ = 0.8 and different d/Λ as a function of the wavelength, (b) with d/Λ = 0.7 and different D/Λ as a function of the wavelength.

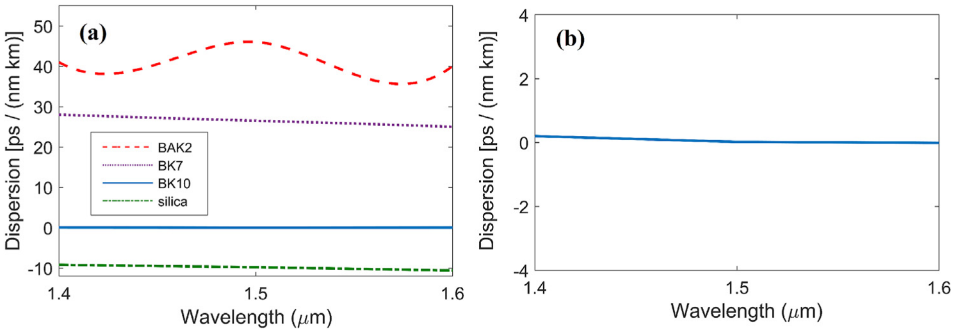

Fig. 6. (a) Dispersion of the CS$_2$-PCF with d/Λ = 0.7, D/Λ = 0.6 and Λ = 1.2 μm and different background materials as a function of wavelength. (b) Flattened Dispersion of CS$_2$-PCF with BK10 as a background material.

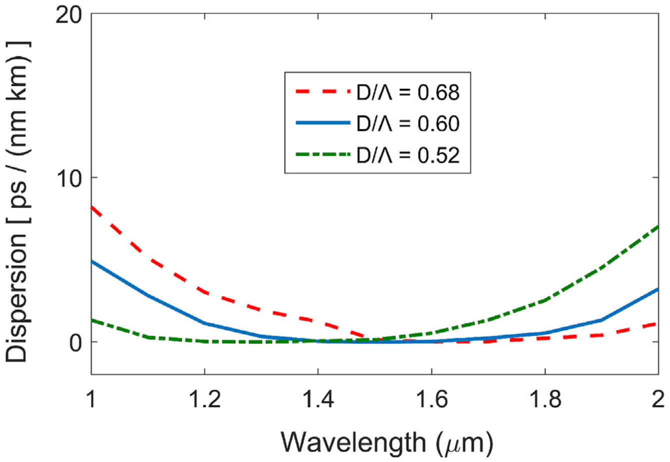

Fig. 7. Dispersion of the CS_2 PCF with d/Λ = 0.7 and Λ = 1.2 μm and different core diameters as a function of wavelength.

Table 1
Optical properties of commonly used highly nonlinear fiber, bismuth-oxide PCF in Ref. [10], chalcogenide glass PCF in Ref. [30] and the proposed $CS_2 - PCF$ near $\lambda = 1.55 \mu$m.

Property	common HNLF	BiO$_2$-PCF [10]	chalcogenide PCF [30]	CS$_2$-PCF
Di[ps/(nm km)]	1.7	−9.9	–	0.00007
α(dB/m)	0.2 × 10^{-3}	1.9	–	~0.3
n	1.44	2.02	–	1.59
A_{eff} (μm^2)	11	3.71	1.2	1.63
γ (W^{-1}km^{-1})	15.5	580	4.72 × 10^4	7940

fabrication-induced imperfections and disorder in PCF fabrication and manufacturing process [42].

To this end, we further study the tolerance of the design to variations in geometry due to fabrication imperfections. We investigate the change in dispersion profile as well as nonlinear coefficient, as a function of wavelength, when fiber filling fraction (d/Λ) is varied from 0.69 to 0.71 (which is a possible range of variation due to fabrication imperfections in fabrication process of PCFs). It can be seen from Fig. 8 that the small changes due to fabrication imperfections does not have any significant effect on the nonlinear coefficient, and dispersion profile of the proposed PCF near 1.55 μm. It can be inferred from Fig. 8 that the proposed PCF has a good tolerance to variation in geometry due to fabrication imperfections.

4. Conclusion

We have theoretically demonstrated a design of highly nonlinear carbon-disulfide-filled photonic crystal fiber (CS$_2$-PCF) with tunable dispersion profile. We design a CS$_2$-PCF with nonlinear coefficient of 7940 W^{-1}km^{-1}, total loss lower than 0.3 dB/m, nearly-zero dispersion of 0.00007 ps/(nm km) and a dispersion slope of 0.0000018 near 1550 nm. We show that the proposed PCF has a good tolerance to fabrication imperfections. Emphasizing the potential of the proposed CS$_2$-PCF, it should also be noted that the ability to control the dispersion profile of the fibers makes it possible to design new fibers for specific nonlinear applications in which high nonlinearity and flattened-dispersion profile in a specific spectral region is needed.

Declaration of interest

None.

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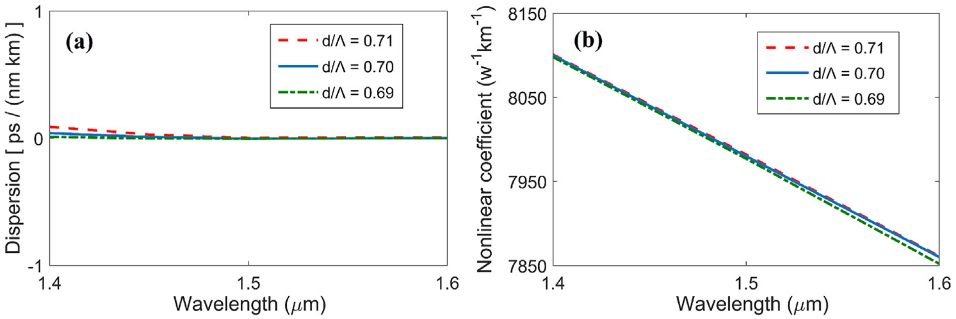

Fig. 8. Dispersion (left) and nonlinear coefficient (right) of the CS$_2$-PCF with D/Λ = 0.6 and Λ = 1.2 μm and different d/Λ, as a function of wavelength.

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