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Slow light generation via stimulated Brillouin scattering in liquid-filled photonic crystal fibers

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ABSTRACT

We theoretically investigate slow light generation using stimulated Brillouin scattering (SBS) in a short highly nonlinear liquid-filled photonic crystal fiber (PCF). We study optical properties of hollow-core PCFs, filled with liquids exhibiting strong optical nonlinearities. We propose a design of carbon-disulfide-filled fiber with an effective area of 1.8 μm^2, nonlinear coefficient larger than 7300 W^{-1} km^{-1}, confinement loss of 0.007 dB/km and total loss lower than 0.3 dB/m over the C-band. Relative to standard single mode fibers, the proposed fiber reduces power $\times$ fiber length requirement for a given gain (delay) by nearly three orders of magnitude (830 times). Furthermore, using just a 1-m long fiber, we demonstrate that pulses can be slowed down to c/50 with a required power level of only 25 mW. We show that our PCF is about 7 times more efficient than the previously reported fiber designs.

1. Introduction

The group velocity of light control has attracted much attention in both academia and industry because it provides optically controllable pulse delays for applications such as data synchronization, optical memory, optical buffering, and optical signal processing [1]. The prevalent protocols for slowing down optical pulses in bulk media and semiconductor devices include the electromagnetically induced transparency and coherent population oscillations [1]. However, slow light generation inside optical fibers can be realized at room temperature with a good deal of flexibility and rather simple configurations via stimulated Brillouin scattering (SBS) [2,3]. The SBS slow light generation makes use of an optically controlled narrowband gain in a fiber, thus the group velocity of optical pulses can be tuned continuously by simply controlling the pump power level. There are two main research trends around the world in this area. First, optimizing SBS pump profiles for increasing the bandwidth, reducing pulse distortions, and overcoming inherent SBS line width limitations [4,5]. The second amounts to SBS slow light realization in highly nonlinear fibers. The SBS gain coefficient in silica fibers is just about 5×10^{-11} m/W. Thus, we cannot attain a considerable change of group velocity using SBS in short span standard fibers or with low pump powers [6]. Okawachi et al. [6], have achieved a 25 ns long slow light delay of signal pulses along a 500 m long SMF-28e fiber. Using shorter fiber lengths has a benefit for overall performance of the system in terms of minimizing the inherent latency of the device [7]. In recent years, SBS slow light generation has been carried out in chalcogenide glass, bismuth oxide glass, tellurite glass fibers and PCFs [5,7,8]. Nonstandard fibers, made of nonlinear glass materials, could support the SBS interaction that is 2–3 orders of magnitude stronger than that obtained in standard silica fibers. For example, J. Misas et al. [7] substantially

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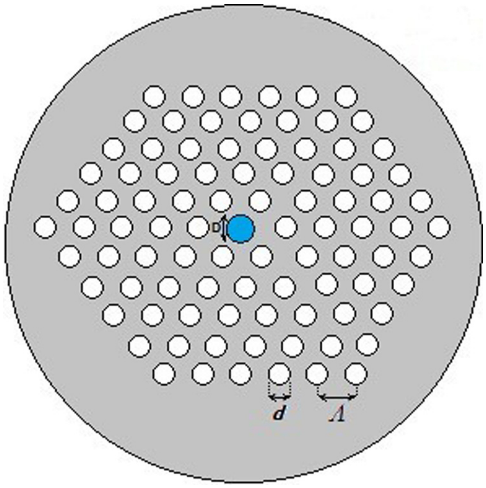

Fig. 1. Cross section of the liquid-filled PCF with hole dimension (d), hole pitch (Λ) and core diameter (D).

slowed down pulses over a distance of just 2 m using a pump power level of 400 mW in a BiO_2 nonlinear fiber. However, the loss in this type of glasses is really high within the optical communication window. Thanks to small effective mode areas in photonic crystal fibers (PCFs), we could also achieve an enhanced SBS interaction there. The highly nonlinear PCFs (HNPCFs) made with silica have nonlinear coefficients less than 60.5 W^{-1} km^{-1}, while nonlinear coefficients of the conventional SMFs are only around 1.3 W^{-1} km^{-1} [9]. For example, using a 50 m long PCF, Yang et al. [10] demonstrated a delay of a half a pulse length. One way to enhance both nonlinear and Brillouin gain coefficients of a fiber is to infiltrate PCFs with highly nonlinear liquids. The technique to fill in the hole of a hollow-core PCF with a liquid has already been developed and utilized experimentally [11–13]. In recent years, researchers have worked on designing liquid-filled optical fibers filled by highly nonlinear liquids such as carbon disulfide (CS_2) and nitrobenzene. Previous studies on liquid filled PCFs have shown that extremely high values of nonlinear coefficients of the order of 2000–4000 W^{-1} km^{-1} can be achieved [12–14]. Poletti et al. [15] proposed theoretically a highly nonlinear CS_2-filled PCF with the nonlinear coefficient of 6548 W^{-1} km^{-1} at 1550 nm. However, their proposed PCF structure has a relatively large filling fraction, which makes the PCF fabrication process rather difficult. Combining small effective areas in PCFs and large Brillouin gain coefficients of nonlinear liquids can result in minimizing power and length requirements for a given delay and, at the same time, increase the delay time. In this work, we will present a comprehensive study of liquid-filled PCFs with different materials and different structural parameters. We then demonstrate how the novel fiber design becomes highly advantageous for slow light generation using SBS.

2. PCF design

We will now present our liquid-filled hollow-core PCF design and optimize its parameters for slow light generation. The liquids that we use in our simulations are CS_2, nitrobenzene, toluene, benzene, chloroform and methanol, and the corresponding linear refractive indices at 1550 nm are 1.59, 1.524, 1.477, 1.476, 1.433, 1.317 respectively. PCFs are a class of optical fibers, usually designed and fabricated with a solid pure silica core, surrounded by periodic air holes which serve as a cladding [16]. The air holes makeup in the cladding region of the PCF leads to tailored optical properties such as nearly zero flattened dispersion and low confinement loss; further, one can adjust the PCF core area to control the fiber nonlinearity [16,17]. For example, by increasing the number of air holes in the cladding region, we can decrease the confinement loss of the fiber dramatically. Although we use only six liquids for our investigations, our studies can be extended to other liquids as well. The cladding material of our proposed PCF is silica with the linear refractive index of $n = 1.446$ at 1550 nm. Our proposed PCF has a hexagonal lattice with five rings of air holes surrounding a liquid-filled core in the center of the fiber. Thus, the design parameters of the liquid-filled PCF are the hole diameter d, hole pitch Λ, and core diameter D. The cross section of the proposed liquid-filled PCF is shown in Fig. 1.

Our analysis is restricted to mode confinement through multiple total internal reflections. We do not consider the bandgap guiding mechanism in hollow-core PCFs because it would greatly restrict benefits of the high nonlinear index of the liquid. Using a finite difference time domain analysis [17,18] applied with OptiFDTD commercial software [19], we theoretically study the effective mode area, nonlinear coefficient and confinement loss properties of the liquid-filled PCFs. One of the most important characteristics of a highly nonlinear fiber is its nonlinear coefficient which contains information about both mode confinement (effective mode area) and the nonlinear refractive index of the medium. The nonlinear coefficient γ is defined as [17,20]

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}}, \tag{1}$$

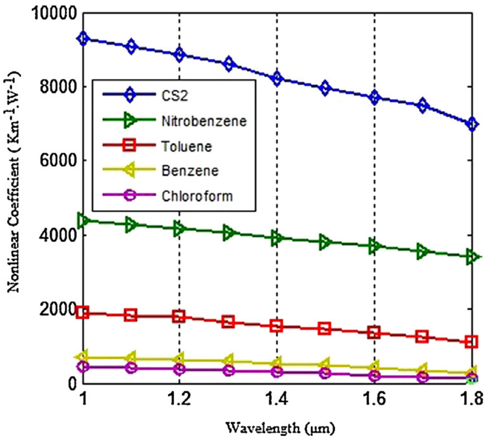

Fig. 2. Nonlinear coefficient of the liquid-filled PCF with $\Lambda = 1.5$ µm, $d/\Lambda = 0.66$ and $D/\Lambda = 0.53$ and different core filling liquids as a function of wavelength.

where n_2 is a nonlinear refractive index and A_{eff} is an effective area of the fundamental fiber mode, defined as [17,20]

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

Due to the high refractive index contrast between silica and air, the PCFs offer a much tighter mode confinement over a wide range of wavelengths and thereby a lower effective mode area than do conventional optical fibers. In our case, this index contrast is very high, especially in the case of CS_2 and nitrobenzene, due to a large liquid core refractive index. First, the dependences of the nonlinear coefficient on the core filling liquids are simulated and shown in Fig. 2, with the fixed hole pitch $\Lambda = 1.5$ µm, $d/\Lambda = 0.66$ and $D/\Lambda = 0.53$ while changing the operation wavelength from 1 µm to 1.8 µm in steps of 0.2 µm. As we can see in Fig. 2, the CS_2 has the highest γ due to its huge nonlinear refractive index ($n_2 = 320 \times 10^{-20}$ m^2/W at 1550 nm) and a rather tight mode confinement which results in the ultra small effective mode area ($A_{eff} = 1.8$ µm^2 at 1550 nm). These exceptional values lead to the magnitude of γ between 7300 and 8000 over the S-, C- and L-bands (1460–1625 nm). We note that n_2 decreases and A_{eff} increases with the wavelength for nonlinear liquids. Therefore, we expect γ to decrease with the wavelength according to Eq. (1). As we can see in Fig. 2, γ decreases gradually with the wavelength and agrees well with the theoretical prediction. We also notice that the rate of decrease of γ with the wavelength is faster for CS_2 and nitrobenzene than for the other liquids we examine.

The second critical parameter of a highly nonlinear fiber is its energy loss. We examine different kinds of filling liquids in the PCF and compare the amount of confinement loss for fixed structural parameters. Confinement loss of a liquid-filled PCF with fixed hole pitch $\Lambda = 1.5$ µm, $d/\Lambda = 0.66$ and $D/\Lambda = 0.53$ at the operation wavelength of 1550 nm for different core filling liquids is simulated and displayed in Fig. 3. As we can see in the figure, confinement loss strongly depends on the filling liquid type. The amount of confinement loss in the proposed fiber design for CS_2 and nitrobenzene is really low (in order of 10^{-3} dB/km), and for liquids like toluene and benzene is low (in order of 10^{-2} dB/km). Losses will increase dramatically (larger than 5 dB/km) for low index liquids such as methanol, ethanol and water. Due to nearly-zero confinement loss of CS_2-filled

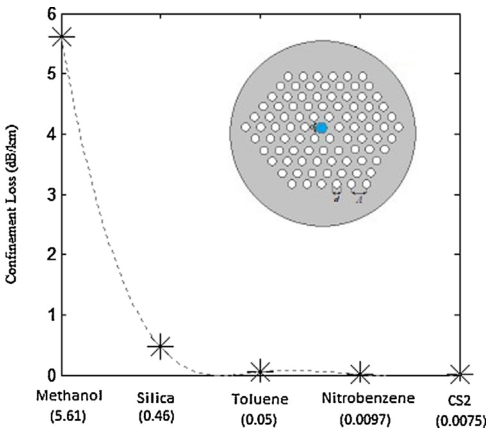

Fig. 3. Confinement loss of the liquid-filled PCF with $\Lambda = 1.5$ µm, $d/\Lambda = 0.66$ and $D/\Lambda = 0.53$ as a function of core filling liquid.

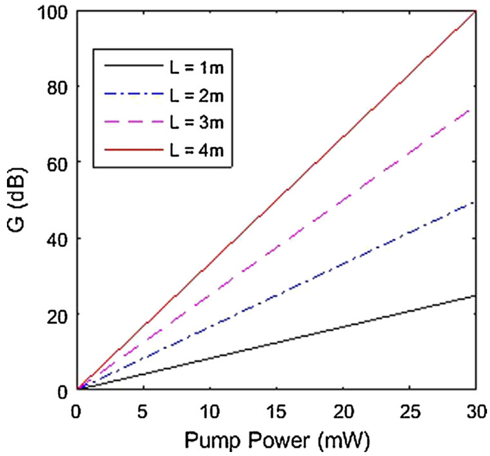

Fig. 4. Amount of Brillouin gain as a function of the pump power in the CS_2-filled PCF for different fiber lengths.

PCF, however, the total fiber loss will be likely dominated by absorption and scattering losses in the liquid. Fortunately, the CS_2 transmission spectrum is almost absorption peak free in the spectral range extending from the visible to the midinfrared [15]. Therefore, we can expect an overall loss lower than 0.3 dB/m for our CS_2-filled fiber [15]. The proposed fiber with ultra-high nonlinearity and relatively low loss, can have other applications in nonlinear devices. We can use the proposed fiber as a nonlinear medium for wavelength conversion based on four-wave mixing, frequency comb generation, supercontinuum generation and other nonlinear processes.

3. Slow light generation

The SBS process can be described as an interaction of a strong pump and counter-propagating weak probe waves. An acoustic wave will be generated if the frequency-matching condition is satisfied, $\Omega_B = \Omega_p - \Omega_s$, where Ω_B is the Brillouin frequency, Ω_p is a pump frequency and Ω_s is a probe frequency. The Brillouin gain bandwidth is usually very small in optical fibers; for example, it is about 30 MHz in conventional optical fibers. Thus, we can view SBS as a narrowband amplification process. In this process, a strong pump wave produces a narrowband gain in a spectral region around $\Omega_p - \Omega_B$ and a loss around $\Omega_p + \Omega_B$ [5,8]. The group index of a pulse is defined as $n_g = n + \omega \frac{dn}{d\omega}$. The group index change can serve as a control parameter to realize an optical time delay [5]. These changes in the group index can be used as a controllable optical time delay. The linear Brillouin gain along a fiber can be expressed as [6]

$$G = \frac{g_0 L_{eff} P_{pump}}{A_{eff}}, \tag{3}$$

where L_{eff} is an effective fiber length, $L_{eff} = 1 - e^{\alpha L}/\alpha$, where L is the physical length of the fiber, α is the loss coefficient of the fiber and P_{pump} is the pump power. The center-line gain coefficient g_0 depends only on the fiber core material [21]. In our calculations, we take $g_0 = 1.5$ m/GW, an estimate for CS_2 known from the literature [21]. Using realistic physical dimensions and an optimized design for the proposed CS_2-filled PCF with $d/\Lambda = 0.75$, $D/\Lambda = 0.58$ and $\Lambda = 1.2$ μm, we exhibit the Brillouin gain of the proposed fiber for different pump powers and fiber lengths in Fig. 4.

As we can see in the figure, G strongly depends on the fiber length and pump power. Thanks to the small effective area and high g_0 of CS_2, we can achieve a relatively high exponential gain (around $G = 20$) at a very low power level in a quite short fiber. We note that the gain parameter G is limited by the exponential gain threshold of the fiber G_{th} due to spontaneous Brillouin scattering. For $G = G_{th}$, photons spontaneously scattered from thermal phonons are exponentially amplified which leads to the Stokes field generation at the output that saturates the pump field [22]. For bulk media it has been shown that G_{th} is approximately constant [23]. For CS_2 bulk material, G_{th} is measured to be 22.8 at 1060 nm [23]. In optical fibers, G_{th} depends on the experimental parameters such as input pulse, material, length and numerical aperture (NA) of the fiber [6,23]. However, it can be shown that in a very short fiber with a moderate numerical aperture, G_{th} tends to its value in the bulk material [23]. In our case, we utilize a very short fiber (only 1 m long) with NA = 0.5, thus we can expect G_{th} to be around 20–28, depending on the experimental parameters. Moreover, G_{th} is generally taken to be equal to 21 in optical fibers [23,24]. Therefore, we may estimate the pump power threshold as [24]

$$P_{th} = \frac{G_{th} K_B A_{eff}}{g_B L_{eff}}, \tag{4}$$

where K_B is a constant depending on the polarization property of the fiber which is equal to 1 if the fiber is polarization maintaining and 1.5 otherwise [24]. Considering $G_{th} = 21$ and $L = 1$ m, we obtain $P_{th} = 25.2$ mW for the proposed fiber. Table 1 shows all of the simulation parameters and optical characteristics of the proposed PCF for slow light generation via SBS.

Table 1
Simulation parameters and optical properties of the proposed PCF at $\lambda = 1.55\ \mu m$.

A_{eff} (μm^2)	γ ($W^{-1}\ km^{-1}$)	α (dB/m)	g_0 (m/W)	L (m)	P_{pump} (mW)
1.8	7300	0.3	1.5×10^{-9}	1	25

Table 2
Optical properties of different fibers near $\lambda = 1.55\ \mu m$ for SBS slow-light generation.

Property	SMF-28 Silica fiber	Tellurite fiber [8]	As_2S_3 fiber [5]	CS_2-filled PCF
g_0 (m/W)	5×10^{-11}	2.16×10^{-10}	6.08×10^{-9}	1.5×10^{-9}
α (dB/m)	0.2×10^{-3}	0.51	0.84	~0.3
n	1.44	2.3	2.8	1.59
A_{eff} (μm^2)	50	9.2	~30	1.8
FOM	0.0007	0.011	0.079	0.528

In order to compare optical fibers as SBS slow light media, it is necessary to define a proper figure of merit for evaluation. According to the previous experimental and theoretical analyses of the SBS process, the slope of the time delay versus Brillouin gain only depends on the inverse of the gain bandwidth [5]. However, this bandwidth can be arbitrarily extended in the broadband scheme by pump dithering [5]. Thus, the gain coefficient and effective area are the only parameters that will scale the efficiency in the time delay generation. Response speed and the stability are other significant parameters [5]. These parameters are inversely proportional to the refractive index of the fiber. Therefore, we can define the Brillouin figure of merit (FOM), following the FOM in the [5] as

$$\mathrm{FOM} = \frac{G}{P_{pump} L_{eff}\, n} = \frac{g_0}{n A_{eff}}. \tag{5}$$

As our analysis is restricted to very short fibers, we can neglect fiber birefringence and the effect of random polarization change along the fiber. Using realistic physical parameters and optimized design for the proposed CS_2-filled PCF with $d/\Lambda = 0.75$, $D/\Lambda = 0.58$ and $\Lambda = 1.2\ \mu m$, and considering $L = 1$ m, we can obtain total loss lower than 0.3 dB/m, $A_{eff} = 1.8\ \mu m^2$, $P_{th} = 25.2$ mW and B-FOM = 0.528 dB/mW/m. For a sufficiently weak Stokes field which is the case for most of the SBS slow light experiments, a continuous-wave (cw) pump is undepleted. Using the undepleted CW pump approximation and following the procedure of [22], we can obtain the expression for the group index of a probe pulse as

$$n_g(\omega) = n_{fg} + \left(\frac{c g_0 P_{pump}}{\Gamma_B A_{eff}}\right) \frac{1 - 4\delta\omega^2/\Gamma_B^2}{(1 + 4\delta\omega^2/\Gamma_B^2)^2}, \tag{6}$$

where $\Gamma_B/2\pi$ is a FWHM bandwidth of Brillouin gain, n_{fg} is the group index of the fiber mode and $\delta\omega$ is the frequency detuning between the Stokes pulse (Ω_s) and the line center of the SBS gain bandwidth ($\Omega_p - \Omega_B$). The SBS-induced group index change ($n_g - n_{fg}$) depends on the fiber type and the pump power. Assuming 1 mW pump power, the group-index change in the proposed CS_2-filled fiber is 1.9 while it is equal to 3.4×10^{-4} in the standard SMF-28-e fiber. In order to achieve the maximum delay, the frequency difference between the pump and Stokes waves is set to the Brillouin shift of the fiber ($\delta\omega = 0$). For CS_2, $\Gamma_B/2\pi = 52.3$ MHz at 694 nm and it is proportional to ω^2 [21]. Thus, we can estimate $\Gamma_B/2\pi = 21$ MHz at 1550 nm. Assuming $P_{pump} = 25$ mW, we obtain a group index of 49.3 which approximately corresponds to the group velocity of c/50. Comparing this with the group velocity of c/10 in BiO_2 fiber, which is reported in [8], we can achieve 5 times greater delay in the proposed PCF at a lower pump power and shorter length of the fiber. As we can see from Table 2, FOM in the proposed fiber has improved significantly as compared with the standard silica fibers or non-standard nonlinear glasses. The FOM of the proposed fiber is about 750 times greater than that of the conventional silica fibers and about 7 times larger than that in the As_2S_3 fiber considered in [5]. The main reasons for these improvements are high SBS gain coefficient of CS_2, low effective area and relatively low loss of our proposed fiber. Our results also suggest that the proposed fiber reduces the power to fiber length ($P_{pump} \times L$) requirement for a given gain (delay) by nearly three orders of magnitude (830 times) relative to standard single mode fibers. Note that in our case, the pump power is only 25 mW and length of the fiber is only 1 m.

4. Conclusion

In this paper, slow light generation using stimulated Brillouin scattering (SBS) in a short highly nonlinear liquid-filled photonic crystal fiber (PCF) has been investigated. We studied optical properties of hollow-core PCFs, filled with highly nonlinear liquids such as nitrobenzene and carbon-disulfide. We proposed a design of carbon-disulfide-filled fiber with an effective area of 1.8 μm^2, nonlinear coefficient larger than 7300 $W^{-1}\ km^{-1}$, confinement loss of 0.007 dB/km and total loss lower than 0.3 dB/m over the C-band. Relative to standard single mode fibers, the proposed fiber reduces power × fiber length requirement for a given gain (delay) by nearly three orders of magnitude (830 times). Furthermore, using just a 1-m long fiber, we demonstrate that pulses can be slowed down to c/50 with a required power level of only 25 mW. We show that our PCF is about 7 times more efficient than the previously reported fiber designs.

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