

The Influence of Air-hole Filling Fraction of Photonics Crystal Fibers on Stimulated Brillouin Scattering Slow Light

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Abstract— The influence of structural parameters of photonic crystal fiber (PCF) on the Stimulated Brillouin Scattering (SBS) slow light by the finite difference time domain method is investigated, the time delay and broadening factor of the pulse are studied for different air-hole filling fractions. The results indicate that time delay increases and broadening factor decreases with air-hole filling fraction increasing. Air-hole filling fraction has less effect on time delay and broadening factor for the same core diameter of PCF.

1. INTRODUCTION

Stimulated Brillouin Scattering (SBS) [1, 2] is a type of nonlinear optical phenomena in optical fiber. Because of the electrostrictive effect, it can lead to periodic modulation of refractive index of medium when the pump's power is greater than the Brillouin threshold power. The index grating generated by index modulation scatters the pump light. So Stokes wave is scattered by index grating and propagates in the opposite direction of the pump. SBS Slow light technology [3] has some advantages in comparison with the other slow light technologies in optical fibers, such as electromagnetic induction transparent (EIT), coherent population oscillation (CPO). Such as operating at room temperature, comparable with existing communication system, easy tailoring time delay and so on. The SBS slow light has great potential applications in fiber delay line, optical buffer and fiber optical sensor [4–6].

Photonics crystal fiber (PCF) is a new type of optical fiber with periodic arrangement of air hole on certain substrate materials. Due to the periodic cladding structures of PCF can be changed flexibly, the cladding-core refractive index difference of PCF is much larger than conventional doped fiber. It can improve the nonlinear property of PCF and enhance the SBS effect [7]. Dainese et al. [8] studied SBS in ultra core PCF, the results indicate that the Brillouin gain spectrum has multi-peak and Brillouin frequency shift is reduced to near 10 GHz as the diameter of PCF core is 70% of the incident light wavelength. This is due to a variety of acoustic mode couple in the PCF. J. Zhao et al. [9] observed SBS slow light in a high nonlinear PCF. They found that the high nonlinear PCF which compared with common fibers can effectively reduce its length and limit of pump power. Recently W. Wei et al. [10] used single pump and single-stage delay method to study SBS slow light in PCF which was generated by their own, they recorded the maximum of delay is 76 ns which is equivalent to 0.76 pulse width in length of 120 m high nonlinear microstructure fiber as pump power is 126.6 mW.

Based on previous research work [11] of our group, we used the finite difference method, and theoretically study the SBS process with the different structural parameters of PCF which influence on the delay time and broaden factor. We get the variation trend of delay time and broaden factor with the different air-hole filling fractions of PCF. The results shown that time delay increases and broadening factor decreases as the air-hole filling fraction increasing.

2. THEORETICAL ANALYSES

We stimulated the SBS process via solving the SBS three-wave coupled wave equations, which includes a forward pump wave, a backward Stokes wave and a forward acoustic wave. Under the slowly varying envelop approximation, the SBS three-wave coupled wave equations [12–14] is as follows

$$-\frac{\partial A_p}{\partial z} + \frac{1}{v_g} \frac{\partial A_p}{\partial t} = -\frac{\alpha}{2} + ig_2 A_s Q \quad (1)$$

$$\frac{\partial A_s}{\partial z} + \frac{1}{v_g} \frac{\partial A_s}{\partial t} = -\frac{\alpha}{2} + ig_2 A_p Q^* \quad (2)$$

$$\frac{\partial Q}{\partial t} + \left(\frac{\Gamma_B}{2} - i\Delta\omega \right) Q = ig_1 A_p A_s \quad (3)$$

where A_p is amplitude of pump wave, A_s is amplitude of Stokes wave, and Q is amplitude of acoustic wave. α is related to the loss coefficient of PCF. $\Gamma_B/2\pi = 40$ MHz is Brillouin gain bandwidth in silica. It is related to the lifetime of phonon. $\Delta\omega = (\omega_p - \omega_s) - \Omega_B$ is angular frequency which diverge from center of SBS gain spectrum. ω_p is angular frequency of pump wave, ω_s is angular frequency of stokes wave, and Ω_B is Brillouin frequency shift.

The actual gain is given by

$$G = \log(P_{out}/P_{in}) \quad (4)$$

where P_{in} is input stokes power and P_{out} is output stokes power.

Time delay T_d is defined as the time difference of stokes peak powers between in SBS and without SBS. Broaden factor B is defined as the ratio of FWHM of output stokes wave to FWHM of input stokes wave.

The cross section of PCF is shown in Fig. 1. The circles in the figure are tiny air hole. d represents the diameter of air hole, d_c is effective core diameter and Λ is pitch between two air holes. The air-hole filling fraction f related to d and Λ is defined as

$$f = d/\Lambda \quad (5)$$

The definition of PCF fiber core diameter is:

$$d_c = 2\Lambda - d \quad (6)$$

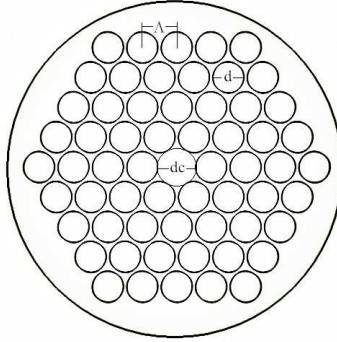


Figure 1: Cross section of PCF.

The variation of the air-hole filling fraction will affect the modal refractive index and area of core. These structure changes of PCF can influence on the SBS process. So we first achieve the results about the modal refractive index of core and calculate the area of the core by using the finite element method. Then we put the parameters into the Eqs. (1)–(3). The Stokes waveform can be solved by that set of equations. Finally we adopted the method [15], the required result can be obtained and be used to calculate the delay time and broaden factor.

3. NUMERICAL SIMULATIONS AND DISCUSSION

Setting PCF length L is 50 m. A 125 mW-power pump pulse with 1550 nm center wavelength and a full width at half maximum (FWHM) of 100 ns is injected in the fiber. Brillouin gain bandwidth is about 40 MHz, the gain coefficient is $g_0 = 5 \times 10^{-11}$ m/W.

Near the $G = 14$, the gain reaches saturation. The increase of delay becomes slower gradually as the gain continues to grown. Finally the time delay stops and slumps with pulse begin to compress. So we select $G = 10$, the delay increase steadily, and study the influence of the air-hole filling fraction on delay time and broaden factor.

3.1. The Diameter of Core Remains Unchanged

The influences of the air-hole filling fraction on delay time and broaden factor with $d = 1.7 \mu\text{m}$ and $G = 10$ are shown in Fig. 2 and Fig. 3. Fig. 2 shows time delay increases with the increase of air-hole filling fraction. The delay increases slowly under a small air-hole filling fraction. however, the delay increases quickly as $f > 0.5$. In Fig. 3, the broaden factor decreases when the air-hole filling fraction increases. The broaden factor decreases linearly as f from 0.4 to 0.6.

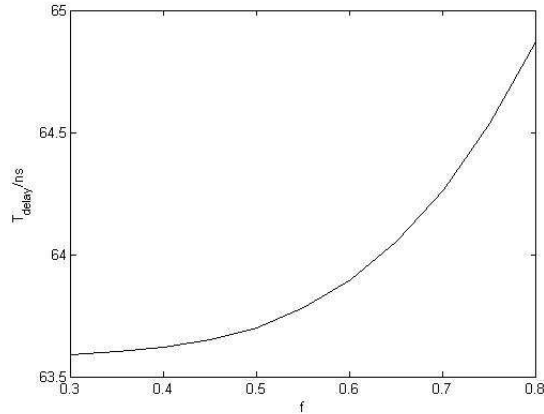


Figure 2: Variation of time delay and air-hole-fill fraction under the same air hole diameter.

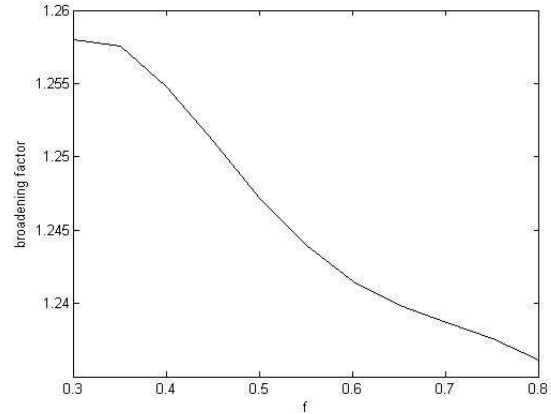


Figure 3: Variation of broadening factor and air-hole-fill fraction under the same air hole diameter.

3.2. The Pitch of the Air Hole Remains Unchanged

The influences of air-hole filling fraction on delay time and broaden factor with $\Lambda = 3\mu\text{m}$ and $G = 10$ are shown in Fig. 4 and Fig. 5. It can be seen that the delay time increases and broaden factor decreases linearly with the increase of air-hole filling fraction. The curve in Fig. 4 is more closer to linear than Fig. 2. But the total delay time is smaller. The relation between broaden factor and the air-hole filling fraction shown in Fig. 5 is more close to linear. But the broaden factor in Fig. 5 reduce from 1.257 to 1.205.

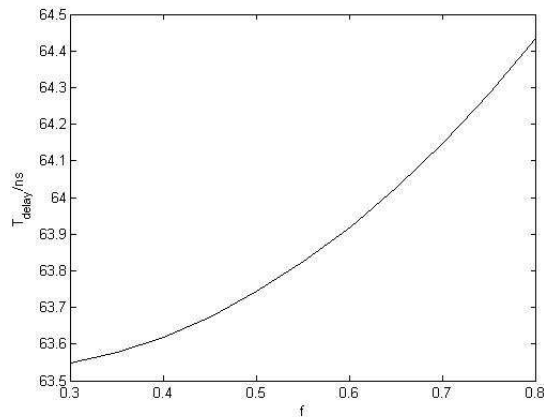


Figure 4: Variation of time delay and air-hole-fill fraction under the same air hole pitch.

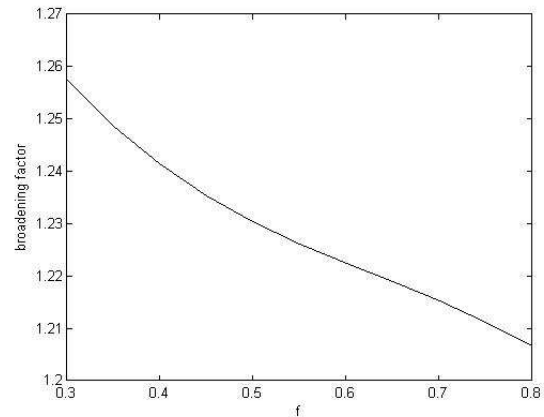


Figure 5: Variation of broadening factor and air-hole-fill fraction under the same air hole pitch.

4. CONCLUSION

The influence of the SBS slow light for the different structural parameters of PCF is theoretically studied by using the finite difference time domain method. We discuss the influence of the air-hole filling fraction on the delay time and broaden factor. The results show that the delay time increases and the broaden factor decreases with increase of the air-hole filling fraction. They have linear change as the pitch of PCF is fixed. When the diameter of core is fixed the change of air-hole filling fraction has little effect on delay time and broaden factor.

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REFERENCES

1. Agrawal, G. P., *Nonlinear Fiber Optics*, Academic Press, California, 1995.
2. Zhaoming, Z., D. J. Gauthier and R. W. Boyd, “Stored light in an optical fiber via stimulated brillouin scattering,” *Science*, Vol. 318, 1748–1751, 2007.
3. Zadok, A., A. Eyal, and M. Tur., “Stimulated Brillouin scattering slow light in optical fibers,” *Applied Optics*, Vol. 50, No. 25, 38–49, 2011.
4. Song, K. Y., M. G. Herráez, and L. Thévenaz, “Obvervation of pulse delaying and advancement in optical fibers using stimulated Brillouin scattering,” *Opt. Express*, Vol. 13, No. 1, 82–88, 2005.
5. Wu, Y., L. Zhan, and Y. Wang, “Low distortion pulse delay using SBS slow-and fast-light propagation in cascaded optical fibers,” *Opt. Soc. Am. B*, Vol. 8, No. 11, 2605–2610, 2011.
6. Chin, S. and L. Thévenaz, “Tunable photonic delay lines in optical fibers,” *Laser Photonics Rev.*, Vol. 6, No. 6, 724–738, 2012.
7. Mcelhenny, J. E., R. K. Pattnaik, and J. Toulouse, “Unique characteristic features of stimulated Brillouin scattering in small-core photonic crystal fibers,” *Opt. Soc. Am. B*, Vol. 25, No. 4, 582–593, 2008.
8. Dainese, P., P. St. J. Russell, and N. Joly, “Stimulated Brillouin scattering from multi-GHz-guided acoustic phonons in nanostructured photonic crystal fibres,” *Nature Phys.*, Vol. 2, No. 6, 388–392, 2006.
9. Zhao, J., X. Yang, and Y. Li, “Stimulated Brillouin scattering slow light in photonic crystal fiber,” *Acta Optic Sinica*, Vol. 30, No. 8, 2437–2440, 2010.
10. Wei, W. and X. Zhang, “Slow light based on stimulated Brillouin scattering in microstructured fiber,” *Acta Physica Sinica*, Vol. 62, No. 18, 184208–184212, 2013.
11. Hou, S., H. Li, and S. Li, “Inluence of Stokes pulse shapes on SBS slow light in fibers,” *Acta Optic Sinica*, Vol. 31, No. 6, 0606008–0606012, 2011.
12. Schneider, T., R. Henker, and K. Lauterbach, “Distotion reduction in slow light systems based on stimulated Brillouin scattering,” *Opt. Express*, Vol. 16, No. 11, 8280–8285, 2008.
13. Zhu, Z. and D. J. Gauthier, “Numerical study of all-optical slow-light delays via stimulated Brillouin scattering in an optical fiber,” *Opt. Soc. Am. B*, Vol. 22, No. 11, 2378–2384, 2005.
14. Winful, H. G., “Chirped Brillouin dynamic gratings for storing and compressing light,” *Opt. Express*, Vol. 21, No. 8, 10039–10047, 2013.
15. Cao, Y., P. Lu, and Z. Yang, “An efficient method of all-optical buffering with ultra-small core photonic crystal fiber,” *Opt. Express*, Vol. 16, No. 18, 14142–14150, 2008.