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小芯径光子晶体光纤中基于前向受激布里渊散射的超光速传输特性

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摘 要:理论研究了小芯径光子晶体光纤中基于前向受激布里渊散射的快光.利用前向受激布里渊散射三波耦合方程,通过傅里叶变换,计算小芯径光子晶体光纤中的群折射率和增益系数.用有限元法模拟了声场和光场的分布、信号光时间提前量和展宽因子.小芯径光子晶体光纤中光场与声场可以有效地重叠在纤芯中,增强了它们之间的非线性相互作用,导致强的受激布里渊散射和大的时间提前量.随着信号光传输距离的增加,时间提前量成非线性增长,与此同时,信号光被压缩.随着初始脉冲的增大,脉冲展宽因子逐渐趋于平稳.当传输距离为 70 m,初始脉冲宽度为 200 ns,泵浦功率为 600 mW,计算出时间提前量为 21.76 ns 和脉冲展宽因子为 0.77.

关键词:前向受激布里渊散射;光子晶体光纤;负增益;时间提前量;展宽因子

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Superluminal Propagation Induced by Forward Stimulated Brillouin Scattering in Small-core Photonic Crystal Fibers

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Abstract: The forward stimulated Brillouin scattering based fast light in small-core photonic crystal fibers is theoretically investigated. Three-wave coupled wave equations of forward stimulated Brillouin scattering in frequency domain were derived to calculate the group refractive index and gain coefficient in small-core photonic crystal fibers by Fourier transformation, then optical and acoustic field distribution, advancement and broadening factor of signal pulses induced by forward stimulated Brillouin scattering were simulated by the finite element method. Tight confinement of the optical fundamental mode and acoustic modes strengthens nonlinear interaction in the small-core photonic crystal fibers and results in strong SBS and large advancement of time. The time advancement grows nonlinearly with the transmission distance of signal light increasing, and the signal pulses are compressed. The pulse broadening factor gradually levels off with the growth of the initial pulse width. The time advancement of 21.76 ns and pulse broadening factor of 0.77 are evaluated at the transmission distance of 70 m, the initial pulse width of 200 ns and the pumping pulse power of 600 mW.

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Key words: Forward stimulated Brillouin scattering; Photonic crystal fibers; Negative gain; Time advancement; Broadening factor

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0 Introduction

Speeding up or slowing down the group velocity of light pulses in optical fibers has attracted considerable attention in optical community for more than one decade, and widely ranging applications have been proposed for optical fiber communication and optical sensing systems, i.e., optical delay lines, optical buffers, optical equalizers, signal processors and optical sensors and so on. Several ways have been implemented to achieve slow or fast light in optical fibers, such as Raman scattering^[1], Stimulated Raman Scattering (SRS)^[2], Raman-assisted parametric amplification^[3], and a combination of four-wave mixing and dispersion^[4] as well as Stimulated Brillouin Scattering (SBS)^[5-9]. The SBS based slow or fast light has been extensively investigated due to its potential advantages, such as operability at room temperature, simple structure, and e-compatibility with present optical communication systems.

The SBS is known as a nonlinear interaction between light and sound waves in dispersive media. According to the direction of scattered light (also called Stocks light) in fiber, SBS behaviors include Backward Stimulated Brillouin Scattering (BSBS) when the pump light counter-propagates with the scattered light, and Forward Stimulated Brillouin Scattering (FSBS) when they co-propagate^[7-8]. A large number of studies on slow and fast light of the BSBS have been conducted for the past few decades^[9-10], with many relevant applications having been exploited in optical communication and optical sensing systems, optical fiber laser and optical fiber amplifier. For example, the BSBS has been used to realize selective amplification of SSB signal and carrier suppression of microwave photon signals^[11], and measure temperature and strain^[12]. BSBS fiber lasers and fiber amplifiers have been reported^[13].

The FSBS has attracted much more attention in optical communities in recent years. It is well known that the FSBS can be sufficiently realized when optical waves and transverse acoustic waves are tightly confined and interacted in small-core optical fibers. The acoustic fields of the FSBS include TR_{2m} torsional and R_{0m} radial modes, and their Brillouin frequency shift are at the megahertz range in standard Single Mode Fibers (SMFs). Moreover, the FSBS also known as Guided Acoustic-Wave Brillouin Scattering (GAWBS) in optical fibers was first proposed by SHELBY R M et al^[14-15], and then it has been extensively studied in small core optical fibers. The Brillouin Frequency Shift (BFS) of the FSBS at the gigahertz frequency range in a small-core (diameter $\sim 2\ \mu\text{m}$) Photonic Crystal Fibers (PCFs) was explored by KANG M S et al^[16], in which the Stokes and anti-Stokes scattering induced by the R_{0m} radial modes were enhanced, and the frequency of acoustic radial mode R_{0m} could be reach up to the gigahertz frequency range suitable for application, compared with the frequency of longitudinal modes of the BSBS^[17]. The acoustic waves of the FSBS have a flat dispersion curve at the zero axial wave vector, which allows phase matching of the three-wave coupled equations including the two co-propagating optical waves and the transverse acoustic waves to be excited^[18-19].

Herein the fast-light induced by the FSBS in small-core PCFs was theoretically investigated and the gain coefficient, refractive index, group index and time advancement were derived from the three-wave coupled wave equations of the FSBS. The characteristics and fast light of the FSBS were simulated by the finite element method. An experimental setup on fast light of the FSBS was proposed for its explanation. The results indicate that the time advancement and broadening factor of the pulse can be customized by initial pulse width, pump pulse power, and transmission distances. It is of theoretical significance for designing fast-light based optical components for optical communications or optical sensing.

1 Theory

1.1 The FSBS fast light

FSBS can be described by the interactions between the two co-propagating optical and the transverse acoustic waves, the three-wave coupled equations are expressed as^[20]

$$\left\{ \begin{array}{l} \frac{\partial E_p(z, t)}{\partial z} + \frac{n_{\text{eff}}}{c} \frac{\partial E_p(z, t)}{\partial t} = \frac{i\omega_p \gamma_e Q_0}{2n_{\text{eff}} c \rho_0} E_{\text{as}}(z, t) U^*(z, t) \\ \frac{\partial E_{\text{as}}(z, t)}{\partial z} + \frac{n_{\text{eff}}}{c} \frac{\partial E_{\text{as}}(z, t)}{\partial t} = \frac{i\omega_{\text{as}} \gamma_e Q_0}{2n_{\text{eff}} c \rho_0} E_p(z, t) U(z, t) \\ 2i\Omega \frac{\partial U(z, t)}{\partial t} + (\Omega^2 - \Omega_a^2 + i\Omega \Gamma_B) U(z, t) = \epsilon_0 \gamma_e Q_1 E_p^*(z, t) E_{\text{as}}(z, t) \end{array} \right. \quad (1)$$

where $E_p(z, t)$, $E_{\text{as}}(z, t)$ and $U(z, t)$ are the slowly varying amplitudes of the pump wave, the anti-Stokes and the acoustic wave, respectively. $Q_1 = 2\pi \int \nabla_{\perp}^2 E_0^2(r) U_0(r) dr$, $Q_0 = 2\pi \int E_0^2(r) U_0(r) dr$, Γ_B denotes the Brillouin linewidth; n_{eff} is the effective index, c is the velocity of light in vacuum; ϵ_0 is the electric permittivity in vacuum; ω_p is the optical frequency of pump light; ω_{as} is the optical frequency of anti-Stokes light; Ω_a is the frequency of the acoustic mode; γ_e and ρ_0 are the electrostrictive constant and the mean density of fibers, respectively; ∇_{\perp}^2 is the transverse Laplacian; $E_0(r)$ is the normalized transverse field distribution of the fundamental optical mode, and $U_0(r)$ is that of the acoustic field R_{01} .

Due to the Fourier transformation $\partial E_{\text{as}}(z, t)/\partial t \sim i(\omega_{\text{as}} - \omega) E_{\text{as}}(z, \omega)$, Eq. (1) can be transferred to the form in the frequency domain

$$\frac{\partial E_{\text{as}}(z, \omega)}{\partial z} + i \frac{n_{\text{eff}}}{c} (\omega_{\text{as}} - \omega) E_{\text{as}}(z, \omega) = \frac{i\omega_p \gamma_e Q_0}{2n_{\text{eff}} c \rho_0} E_p(z, \omega) U(z, \omega) \quad (2)$$

Suppose the propagation of acoustic phonons $\partial U(z, t)/\partial z \approx 0$, the steady-state $\partial U(z, t)/\partial t = 0$ sound field amplitude $U(z, \omega)$ is expressed as

$$U(z, \omega) = \epsilon_0 \gamma_e Q_1 \frac{E_p^*(z, \omega) E_{\text{as}}(z, \omega)}{\Omega^2 - \Omega_a^2 + i\Omega \Gamma_B} \quad (3)$$

Substituting Eq. (3) into Eq. (2), then

$$\frac{\partial E_{\text{as}}(z, \omega)}{\partial z} + i \frac{n_{\text{eff}}}{c} (\omega_{\text{as}} - \omega) E_{\text{as}}(z, \omega) = i \frac{\epsilon_0 \omega_p \gamma_e^2 Q_1 Q_0}{2n_{\text{eff}} c \rho_0} \frac{P_p E_{\text{as}}(z, \omega)}{\Omega^2 - \Omega_a^2 + i\Omega \Gamma_B} \quad (4)$$

If an anti-stokes light travels along z direction, $\frac{\partial E_{\text{as}}(z, \omega)}{\partial z} = i[\beta_{\text{as}}(\omega) - \beta_{\text{as}}(\omega_{\text{as}})] E_{\text{as}}(z, \omega)$ can be compared with the Eq. (4) to achieve the propagation constant

$$\beta_{\text{as}}(\omega) = n_{\text{eff}} \frac{\omega}{c} + \frac{\epsilon_0 \omega_p \gamma_e^2 Q_1 Q_0}{2n_{\text{eff}} c \rho_0 \Omega_a} \frac{2\Omega^2(\Omega - \Omega_a) - i\Omega^2 \Gamma_B}{4\Omega^2(\Omega - \Omega_a)^2 + \Omega^2 \Gamma_B^2} P_p = \frac{\omega}{c} \tilde{n}_s \quad (5)$$

Then the complex index of refraction can be given as

$$\tilde{n}_s = n_{\text{eff}} + \frac{\epsilon_0 \gamma_e^2 Q_1 Q_0}{2n_{\text{eff}} \rho_0 \Omega_a} \frac{2\Omega^2(\Omega - \Omega_a) - i\Omega^2 \Gamma_B}{4\Omega^2(\Omega - \Omega_a)^2 + \Omega^2 \Gamma_B^2} P_p \quad (6)$$

The real part of the complex refractive index is the refractive index, and the imaginary part is related to absorption. In the FSBS fast light behavior, the refractive index and the gain spectrum are expressed respectively as

$$n(\omega) = \text{real}(\tilde{n}_s) = n_{\text{eff}} + D \frac{\delta\omega/\Gamma_B}{1 + 4\delta\omega^2/\Gamma_B^2} \quad (7)$$

$$g_s = -\frac{\omega}{n_{\text{eff}} c^2 \epsilon_0} \text{Im}(\tilde{n}_s) = \frac{g_0 \Gamma_B^2 P_p}{4(\Omega - \Omega_a)^2 + \Gamma_B^2} \quad (8)$$

Because the group index $n_g = n + \omega(dn/d\omega)$, then the group index is given as

$$n_g(\omega) = n + \frac{D\omega}{\Gamma_B} \frac{1 - 4\delta\omega^2/\Gamma_B^2}{(1 + 4\delta\omega^2/\Gamma_B^2)^2} \quad (9)$$

where $D = 2c^2 \epsilon_0 n_{\text{eff}} g_0 P_p / \omega$, $g_0 = \omega \gamma_e^2 |Q_1 Q_0| / (2n_{\text{eff}}^2 c^2 \rho_0 \Omega_a \Gamma_B)$, $\delta\omega = \Omega - \Omega_a$, P_p is the pump power.

The time advancement of the signal pulse can be described as

$$\Delta T = \frac{L_{\text{eff}}}{c} (n_g - n) = \frac{2c\varepsilon_0 n_{\text{eff}} \Gamma_B G}{\omega} \frac{1 - 4\delta\omega^2/\Gamma_B^2}{(1 + 4\delta\omega^2/\Gamma_B^2)^2} \quad (10)$$

where the $G = g_0 P_p L_{\text{eff}}$, the effective length $L_{\text{eff}} = \alpha^{-1} [1 - \exp(-\alpha L)]$, $\alpha = 0.2$ dB/km.

The broadening factor B is given as^[21]

$$B = \frac{\tau_{\text{out}}}{\tau_{\text{in}}} = (1 - \frac{16\ln 2}{\tau_{\text{in}}^2 \Gamma_B^2} G)^{1/2} \quad (11)$$

where τ_{in} and τ_{out} are the full width at half maximum of the input and output signal light, respectively.

1.2 The FSBS acoustic field

It should be noted that the acoustic field of the FSBS is full of elastic waves at the core range of the small-core photonic crystal fiber. For the radial acoustic mode R_{0m} , its characteristic equation is expressed as^[14,22]

$$(1 - \kappa^2) J_0(y_m) - \kappa^2 J_2(y_m) = 0 \quad (12)$$

where J_0 and J_2 are the Bessel functions; y_m and κ are defined as

$$\begin{cases} y_m = \frac{\Omega_m a}{V_T} \\ \kappa = \frac{V_T}{V_L} = \sqrt{\frac{(1 - 2\nu)}{2(1 - \nu)}} \end{cases} \quad (13)$$

where Ω_m is the angular frequency of the R_{0m} mode; ν is the poisson's ration; a is the fiber core radius; V_L and V_T are the longitudinal and transverse sound velocities severally.

The filed distribution of the acoustic mode R_{0m} is described as^[14,22]

$$\begin{cases} U_r(r) = C_R J_1(y_m r/a) \\ U_\varphi = 0 \\ U_z = 0 \end{cases} \quad (14)$$

where C_R is the amplitude of a thermally excited low-frequency vibration calculated from the equipartition theorem and is proportional to $(KT)^{1/2}$ ^[14]; KT is the total vibrational energy for a single mode.

2 Numerical simulation

2.1 The proposed small-core PCFs

The profile of the proposed small-core Total-Internal Reflection Photonic Crystal Fiber (TIR-PCF) is shown in Fig. 1. The matrix material is silica and the air holes are hexagonally arranged along the fiber periodically in the cladding. In addition, air hole is absent at the center of the fiber to form the core. Then the effective refractive index of the cladding is less than that of the core, to that light is guided into the core by total-

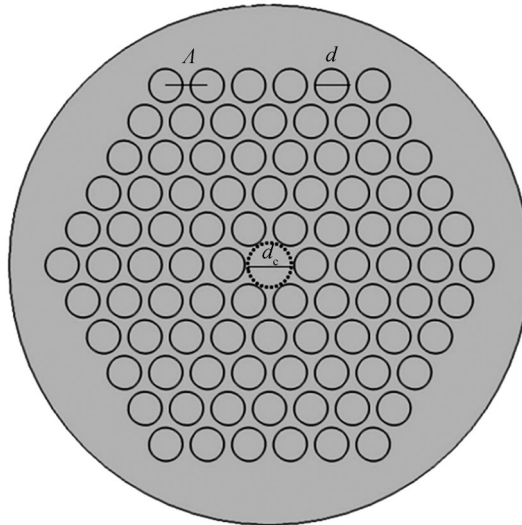


Fig.1 The index profile of the proposed photonic crystal fiber

internal reflection. The diameter of the air hole is d ; the pitch of the air hole Λ is the distance between the two adjacent air hole centers; $d_c = 2\Lambda - d$ is the effective core diameter.

The other parameters of the proposed small-core PCF are shown in Table 1. Herein V_L is the longitudinal velocity; V_T is the transverse velocity and ρ is the density in the fiber.

Table 1 The parameters of the proposed small-core PCF

Parameter	Units	Value
d	μm	1.67
Λ	μm	2.07
ρ	kg/m^3	2.20×10^3
Γ_B	MHz	$2\pi \times 15$
ω_P	THz	$2\pi \times 194$
V_L	m/s	5 944
V_T	m/s	3 749
n		1.458

2.2 The optical and acoustic field distribution

The acoustic radial fundamental mode R_{01} and the optical fundamental mode LP_{01} are taken into account, because other acoustic field modes are eliminated or reduced^[23]. Fig. 2(a) illustrates the optical field distribution of the LP_{01} mode, indicating that the light is tightly confined in the core of the PCF, which can easily induce SBS. The acoustic field distribution of the R_{01} mode is shown in Fig. 2(b), which indicates that the acoustic wave is mainly confined in the core of the fiber, but less acoustic energy is distributed in the center of the fiber core and the cladding. Thus the optical and the acoustic waves are overlapped in the core of the PCF so as to enhance the interaction of acoustic and optical waves. While the R_{01} mode in conventional single-mode fiber has much wider spatial distribution than the optical field distributes in the proposed PCF, so the spatial overlap between guided acoustic waves and optical waves in the fiber is much weaker^[24].

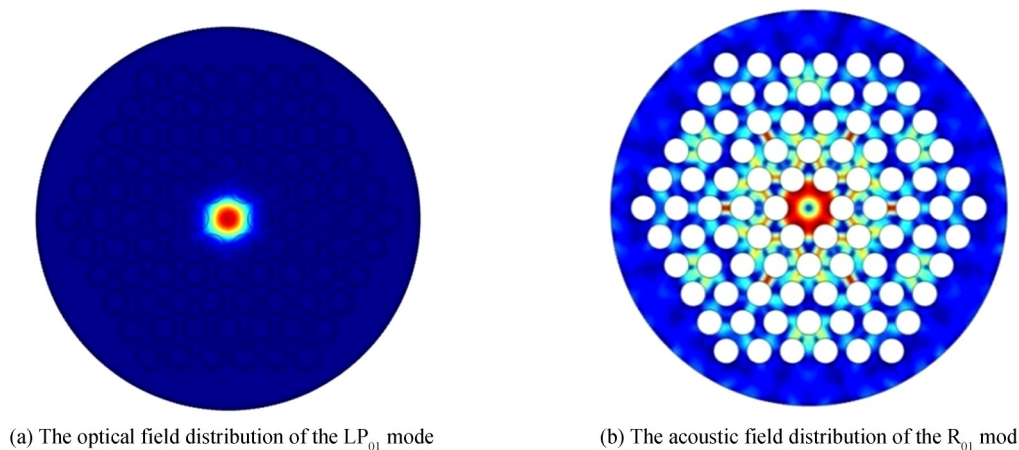


Fig.2 The optical field and the acoustic field distribution

2.3 The gain coefficient, refractive index and group index with the frequency

The normalized gain coefficient is depicted in Fig.3. It can be seen that the gain is negative, which means that this is an absorption spectrum where the anti-Stokes light occurs. As shown in Fig.4, the normalized refractive index (red curve) falls at the range of $d\omega/\Gamma_B$ from -0.4 to 0.4 , so the slope of the refractive index curve is negative ($dn(\omega)/d\omega < 0$) and very steep. According to the group index $n_g = n(\omega) + \omega dn(\omega)/d\omega$, the group velocity $v_g = c/n_g = c/(n(\omega) + \omega dn(\omega)/d\omega)$ can exceed the light speed c in vacuum. It also can be seen that refractive index and refractive velocity of the group can reach up to the maximum at $\delta\omega/\Gamma_B = 0$, the group velocity of the signal pulse of anti-stokes ($v_g \gg c$) leads to fast-light propagation. So the fast propagation of the light can be achieved on the basis of the FSBS.

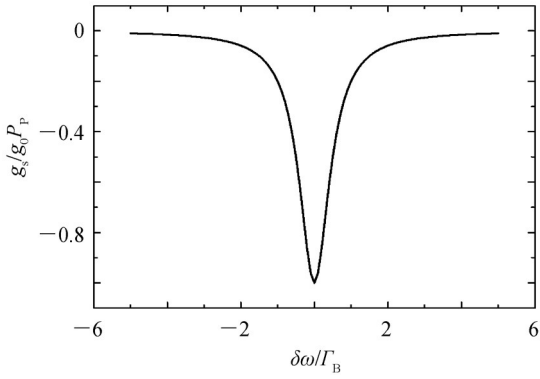


Fig.3 The normalized gain coefficient of FSBS

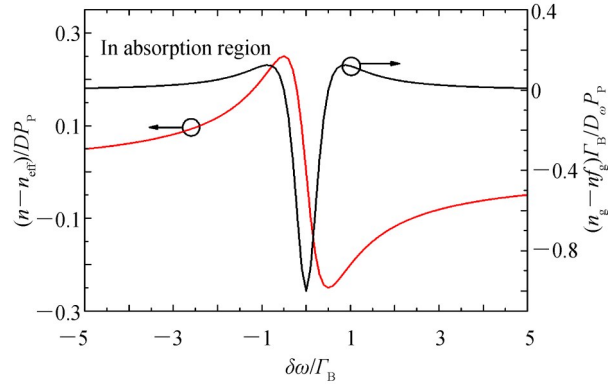


Fig.4 The normalized refractive index and the group index of FSBS.

2.4 Time advancement of the fast light

The fiber parameters are shown in Table 1 and the finite element method is used to calculate the BFS of acoustic mode R_{01} , the effective refractive index, the gain coefficient. The time advancement is obtained from Eq.(10) and the curves are shown in Fig.5.

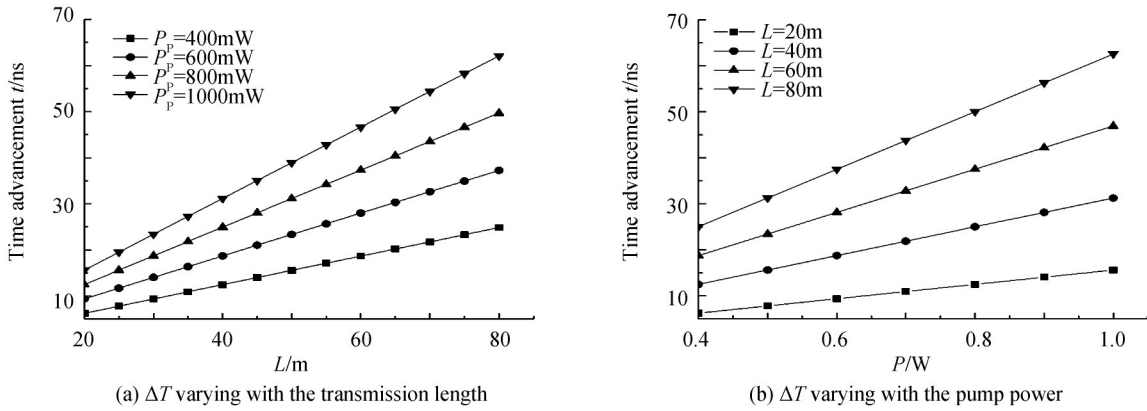


Fig.5 Dependence of the time advancement on the transmission length and pump power

Fig.5(a) shows the time advancement varying with the transmission distance in terms of different pump power. It can be seen that the time advancement linearly rises as the transmission distance increasing at a given pump power, and the larger the pump power is, the steeper slope of the line becomes, thus larger time advancement is caused. This conclusion deduced from Fig.5(b) indicates that the time advancement grows with the increase of the pump power in terms of different transmission distances. The time advancement presents linear growth with the increase of the pump power at a given transmission distance, so larger time advancement can be obtained by increasing the transmission distance and the pump power. However, a large distance will lead too low optical power to trigger. In addition, a large pump power will generate other nonlinear effects, i.e., occurrence of stimulated Raman scattering, and worse distortion of optical pulses. Following sections focused on addressing the mentioned issues.

2.5 Distortion of optical pulses induced by the fast light

The distortion of the optical pulse is demonstrated by broadening factor which is defined as Eq.(11). Fig.6 (a) indicates the broadening factor is below 1, which means that the optical pulses are all compressed. The broadening factor upsurges with the rise of initial pulse width under a given pump power, but in terms of larger width of initial pulses, i.e., larger than 280 ns, the broadening factor gradually level off to near 1 with the increase of initial pulse width under all pump powers. This is because the pulse linewidth is narrower than Brillouin linewidth, and the pulse can be significantly compressed. Fig.6 (b) indicates the pulse broadening factor gradually decrease and the signals are compressed with the increase of pump power. The smaller the initial pulse width is, the more obvious the signal compression becomes.

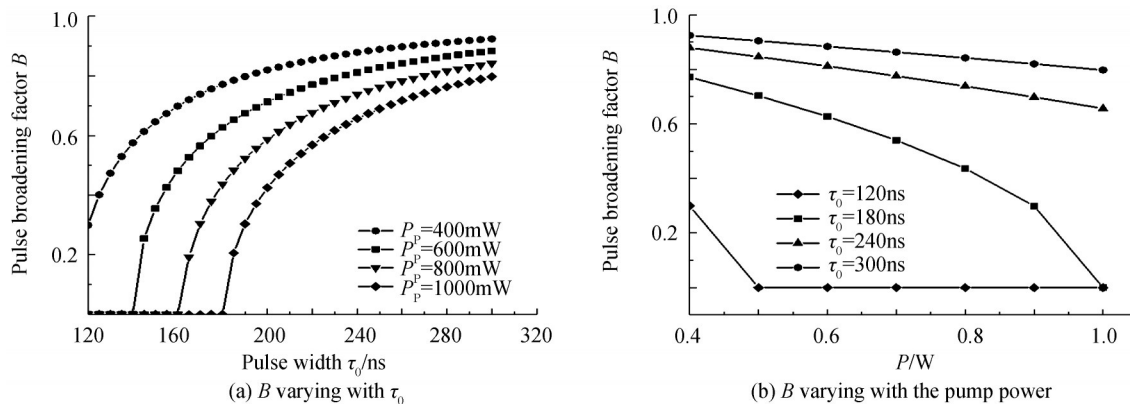


Fig.6 Dependence of the pulse broadening factor B on the initial pulse width and the pump power

2.6 The normalized waveforms of output

The normalized waveforms of output are plotted in Fig.7 without or with SBS under different pump power. It can be seen from this figure that the time advancement of the output wave grows with increasing pump power. This conclusion is consistent with that mentioned above. However, the output waves are compressed under all pump powers. The trailing edge of the output wave becomes flattening, compared with the leading edge, and when pump power increases, the pulse broadening factor falls; that is, the output pulse waves are compressed. When the transmission length, pump power and initial pulse width are optimized, the time advancement $\Delta T = 21.7576$ ns and pulse Broadening factor $B = 0.77$ can be evaluated when $L = 70$ m, the initial pulse width $\tau_0 = 180$ ns and $P_p = 600$ mW.

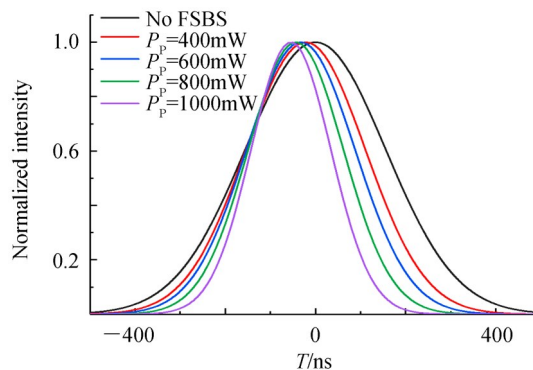


Fig.7 The waveforms of output induced by fast light of FSBS

3 Conclusion

In summary, the refractive index, group index, gain and BFS can be derived from the three-wave coupled wave equations of FSBS. The time advancement, broadening factor, gain and output waveforms can be simulated by the finite element method. The results reveal that the time advancement is more sensitive to the pump power than the transmission distance. The pulse can be significantly compressed when its linewidth is much lower than Brillouin linewidth. The larger the pump power increases at different initial pulse width, the more the signal pulse is compressed. The time advancement $\Delta T = 21.7576$ ns and pulse Broadening factor $B = 0.77$ can be evaluated when $L = 70$ m, the initial pulse width $\tau_0 = 180$ ns and $P_p = 600$ mW. This implementation shows that the proposed PCF can be one of the best candidate media for designing optical components based on SBS fast light.

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