Study of SBS slow light based on nano-material doped fiber*

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A novel optical fiber doped with nano material InP is manufactured by the modified chemical vapor deposition (MCVD). The slow light based on stimulated Brillouin scattering (SBS) in the optical fiber is studied. The results show that a time delay of ~738 ps is obtained when the input Stokes pulse is 900 ps(FWHM) and the SBS gain is ~15. It shows that a considerable time delay and an amplification of the input light can be achieved by this novel optical fiber.

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The optical pulse, whose propagation speed in medium is slowed down, is called the slow light[9]. It is widely used as the key elements of all optical communication such as the optical buffering, routing, optical memories, and single processing, etc. Especially, the slow light based on stimulated Brillouin scattering (SBS) shows several advantages including wide range of wavelengths, compatibility with all fiber type, low pump powers and high delays. In this paper, a novel optical fiber doped with nano material InP is manufactured and applied in the SBS slow light system, which makes a progress in slow light with nano-technology and even becomes a promising medium for slow light in the future optical communications. The numerical model of the SBS slow light is studied based on the three coupled wave theory [2], whose key element is a novel nonlinear optical fiber doped with InP nano particles. The result shows that a considerable delay and amplification can be achieved.

In the model of the SBS slow light system based on three coupled wave equations, there are three waves: a pump light wave, a Stokes light wave and the acoustic wave, which propagate along the fiber in -z,+z and -z directions, respectively. If the particular phase matching conditions are met, an acoustic wave is generated. This acoustic wave scattering photons from the pump to the Stokes wave, stimulate the SBS process. The phase matching expression is given:

$$\omega_{\mathrm{p}} = \omega_{\mathrm{s}} + \Omega_{\mathrm{B}} \ , \tag{1}$$

where ω_{p} (ω_{s}) is the angular frequency of pump(Stokes) wave, Ω_{B} is the SBS frequency shift.

In order to highlight the effects of SBS in slow light, we neglect the detuning off the SBS gain line-center, the three coupled wave equations are given as:

$$\begin{aligned} -\frac{\partial A_p}{\partial z} + \frac{n}{c}\frac{\partial}{\partial t}A_p &= -\frac{\alpha}{2}A_p + \frac{g_B}{2A_{eff}}\left|A_s\right|^2 A_p + ig_2 A_s A_a \ , \\ \frac{\partial A_s}{\partial z} + \frac{n}{c}\frac{\partial}{\partial t}A_s &= -\frac{\alpha}{2}A_s - \frac{g_B}{2A_{eff}}\left|A_p\right|^2 A_s + ig_2 A_p A_a^* \ , \\ \frac{\partial A_a}{\partial t} + \frac{\Gamma_B}{2}A_a &= ig_1 A_p A_s^* \ , \end{aligned} \tag{2}$$

where α is the loss coefficient of the fiber; $\Gamma_{\mathrm{B}}=1/\tau_{\mathrm{B}}$ is the bandwidth(FWHM) of the Brillouin resonance, τ_{B} is longevity of the phonon; g_{B}, g_1 and g_2 are Brillouin gain coefficient, electric field coupling coefficient and acoustic wave field coupling coefficient, respectively; γ is the electrostriction coefficient of the fiber; υ_a is the speed of acoustic wave in the fiber, ρ_0 is the material density.

From Eq.(2), we can conclude that the process of SBS is a narrowband amplification process, in which a continuous-wave pump produces a narrowband gain in a spectral region around ω_s.

Using Eq.(2), n_{g} at the peak of the Brillouin gain is obtained as follows:

$$n_{\mathrm{g}} = \frac{cg_0 I_p}{\Gamma_{\mathrm{B}}} \ , \tag{3}$$

where g_0 is the SBS gain factor, I_{p} is the pump intensity. Thus the maximum delay is given as:

$$\Delta T_d = \frac{n_g L}{c} = \frac{G}{\Gamma_{\mathrm{B}}} \ , \tag{4}$$

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where L is the fiber length of SBS process, $G = g_0 I_p L$ is the SBS gain parameter.

Using this optical fiber doped with InP nano-material, the experimental configuration for the slow-light is illustrated in the Fig.1.

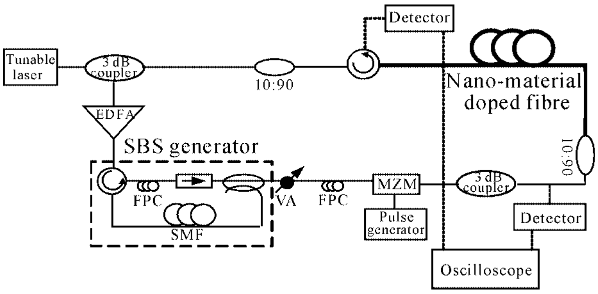

Fig.1 Experimental setup of SBS slow light

The signal generated by a tunable laser is split into two through a 3 dB couple[3]. One of the signals is sent into the SBS generator consisting of a 1-km length of SMF-28 fiber, which makes use of the Brillouin self pulsing to generate the Stokes signal that matches the input automatically[4]. Then the amplified Stokes signal is modulated to be a Stokes pulse. In the nano- material doped fiber, the Stokes pulse and pump pulse produced by another signal interact with each other, which induces the SBS slow light.

The novel optical fiber, whose Si-core is doped with InP nano-material, is manufactured[5, 6] by two stages. Modified chemical vapor deposition (MCVD) method is used to make a cylindrical preform firstly, then the preform is drawn into a fiber using the drawbench device.

The model of the distribution of InP nano-material doped in the Si-core is obtained appropriately and shown in Fig.2. Calculating this structure, the effective area of this fiber is A_{eff}= 10.01 μm^2, which is lower than that of normal fiber (20-100 μm^2). The nonlinear coefficient is given:

$$\gamma = \frac{n_2 \omega_0}{c A_{eff}} \quad , \tag{5}$$

where n_2 is the nonlinear refractive index parameter, ω_0 is the center frequency of optical field. Considering the influence on optical material features due to adulterating InP material, when $n_2 = 2.6 \times 10^{-20}$ m^2/ W , the nonlinear coefficient γ=10.53 W^{-1} • km^{-1}, which is higher than that of normal fiber.

The three-dimensional energy distribution for electric field with the propagation constant $\beta = 5.67898 \times 10^6$ is simulated by using the FEM(Finite Element Method)[7] and the result is shown in Fig.3.

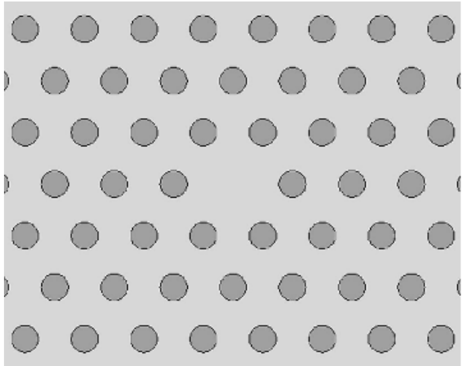

Fig.2 The structure of the core

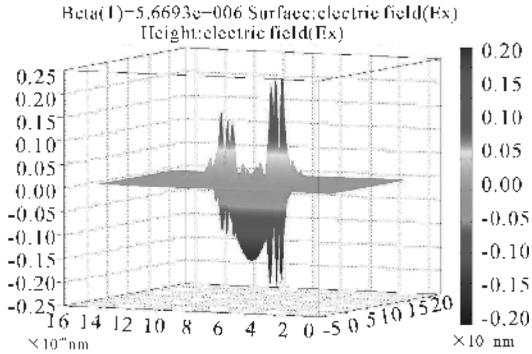

Fig.3 The three-dimensional view of electric field and propagation.

The effective refractive index n_{eff} can be expressed as $n_{eff} = \beta\lambda/2\pi$. When the wavelength λ is 1.55 μm, we obtain the effective refractive index n_{eff}= 1.401.

Numerical simulations validate the effects of this nano-material doped fiber in SBS slow light[8]: λ =1.55 μm , T_0= 900 ps, G ~15, L = 1600 m , A_{eff}= 10.01 μm^2, g_B = 2.2 × 10^{-11}, γ = 10.53 W^{-1} • km^{-1}, n_{eff}= 1.401,α = 0.524 dB/km, $\Gamma_B / 2\pi$ = 40 Hz, and the pump power P_p = 40 mW, T_0 is the pulse width of the input stokes pulse, L_W is the walk-off length, which is defined as

$$L_W = T_0 /(2 \times 10^{-12}\, ps/m) \quad . \tag{6}$$

$T = t - z/\upsilon_g = t - \beta z$ is a frame of reference moving with the pulse (so-called time delay frame).

Fig.4 shows the propagation of the Stokes wave in this system.

As shown in Fig.5, a typical slow light of the input pulse of 900 ps (FWHM) is obtained when the G is ~ 15, with ~ 738 ps of time delay. And the power at the peak of the pulse is amplified by $0.1634 \times 10^{-7}\omega$. So we can conclude that through this novel optical fiber doped with InP nano-material, a considerable slow light can be achieved.

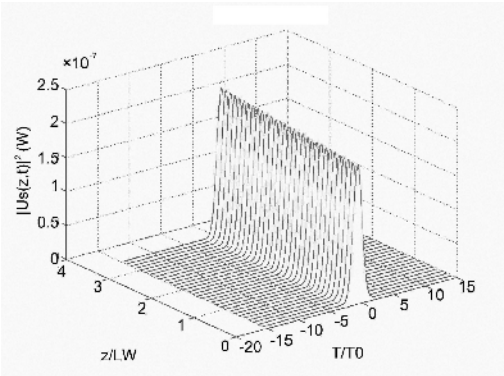

Fig.4 The propagation of the Stokes wave

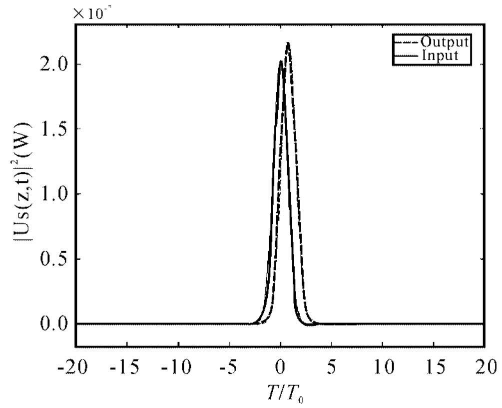

Fig.5 Stokes power vs. time delay of Stokes pulse.

For further research on this SBS slow light system involved nano-material doped fiber, we consider the time delay under different *G*. As can be seen in Fig.6, the time delay grows with increasing *G* linearly as theoretical prediction.

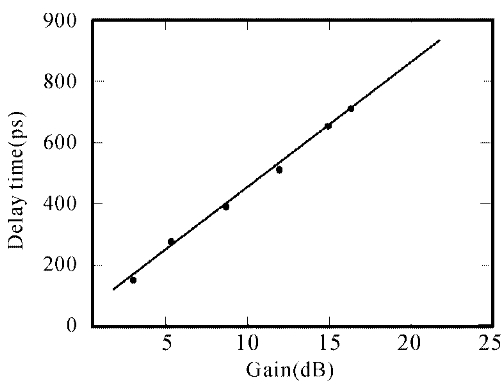

Fig.6 The pulse delay under increasing *G*

The small departure at some dots may be attributed to the inaccurate estimation of boundary conditions.

By changing the SBS gain, the delays are described from a pulse width to several pulse widths. Time delay of the optical pulse always goes with broadening because the linewidth of the Brillouin gain is relatively narrow (30-50 MHz).

However, in the system, the time delay of the pulse can not infinitely increase because of many factors in this slow light system. We can only increase the delay of pulse in the small-signal regime. But in the gain-saturated regime, the time delay decreases with gain and pulse advancement. The process of pulse delay is always accompanied with pulse broadening distortion, the gain saturation and spontaneous Brillouin scattering, and the achievable maximum time delay is limited .

In conclusion, a slow light can be obtained by this novel fiber. The time delay, which comes from its broader Brillouin bandwidth due to higher dopant concentration in the core, is still not ideal enough to apply in optical communications practically. Therefore, the further researches on the nanomaterial fiber should be done to improve the time delay of this slow light system. And it is still a preparation for continuous research on SBS slow light in high nonlinear optical fibers and provides a promising medium for slow light in the future optical communications.

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