All-optical fiber switching based on cross-phase modulation in high-nonlinear photonic crystal fiber Sagnac loop mirror

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We designed a novel and low switching-power all-optical fiber switch. The highly nonlinear photonic crystal fiber (PCF) and the bidirectionally pumped Er^{3+} doped fiber amplifier are inserted into the Sagnac loop mirror simultaneously. Therefore, the symmetry of the loop is broken, and the switching function is realized for the phase shift of the reversely propagating signal. The theoretical analysis shows that the switching power is inversely proportional to the product of the amplifier gain and the PCF nonlinear coefficient. In the experiment, 40 mW switching power and 15.9 dB switching extinction are obtained, furthermore, the transmission of signal light is cosine proportional to the peak power of the pump pulse. The experimental result agrees well with that from theory.

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All-optical fiber switching has excited the interests of most researchers in past years[1−17], because it is the key passive device to solve "electronic bottle-neck" and to realize all-optical network. For example, the standard conventional fibers or some high-nonlinear special fibers[1,10] (such as Yb^{3+}-doped fiber[1]) are used in some fiber functional device, such as Bragg grating[1−4], long period grating[5−8], laser resonant cavity[9], interferometer[11,12], coupler[13] and so forth, when the laser propagates in above fiber functional device, the all-optical switching can be realized based on the nonlinear effect, such as self-phase modulation (SPM), cross-phase modulation (XPM), optical-brooming effect, four-wave mixing (FWM) and so on. Most research demonstrated that high switching threshold, low switching extinction and low switching speed are three primary obstacles to block the development and applications of all-optical switching.

The appearance of photonic crystal fiber (PCF) provides possibility to solve these three obstacles for its flexibly designed structure and its particular properties[14−18]. Most researchers realized optical switching by using PCF, e.g. the operation of a 2R regenerative optical switching based on dispersion shift in high-nonlinear PCF was reported by Petropoulos *et al.*[19] in 2001; an all-optical switching based on cross-phase modulation in microstructure fiber has also be reported by Sharping *et al*[12] in 2002; an optical switching could be realized based on the PCF infiltrated with liquid crystals in 2003[20]. Recently, Zheltikova proposed an all-optical fiber switch based on Kerr effect of bandgap PCF[21] and Salgueiro designed an all-optical fiber switching by using dual-core PCF coupler[13].

In this paper, all-optical fiber switch based on XPM by inserting the high-nonlinear PCF (HN-PCF) and bidirectionally pumped Er-doped fiber amplifier (BP-EDFA) into the Sagnac loop mirror were proposed and demonstrated simutaneously. The theoretical analysis shows that the switching power is inversely proportional to the product of BP-EDFA gain and HN-PCF nonlinear coefficient. Therefore, in order to decrease the switching-power we can improve the gain of BP-EDFA and the nonlinear coefficient of the HN-PCF. We got almost 40-mW switching power and almost 15.9-dB switching extinction in the experiment, furthermore, the transmission of the signal light is cosine proportional to the peak power of the pump pulse. All the results of experiment are in good agreement with those by theory.

The experimental setup is shown in Fig. 1, the fiber Bragg gratings (FBG1 and FBG2) are two identical Bragg gratings fabricated in photosensitive fiber using phase-mask-writing technique by ourselves, whose central wavelength and reflection are 1547.5 nm and 100%, respectively. C1 and C2 are 1×2 and 2×2 3-dB coupler, respectively. CI1, CI2 are two circulators. Broadband source (BBS) is in C band and the pump source's central wavelength is 1552.5 nm and its power is tunable, respectively. The length of single-mode fiber (SMF) is 20 m and HN-PCF is 20 m, the mode area and zero-dispersion wavelength are 2.5 μm^2 and almost 1550 nm, respectively. BP-EDFA is Er-doped fiber amplifier pumped by two 980-nm laser diode in bidirectional, whose bidirectional gains are almost identical and are 20 dB.

The light launched by BBS is filtered by FBG1 to generate continuous signal whose central wavelength is 1547.5 nm, and the 1552.5 nm pump pulse is launched by pump. The two beams are coupled into one SMF by C1 and incident into C2, the spectra of incident signal light and pump pulse are shown in Fig. 2. The incident light is divided into two parts by C2, one part propagates clockwise, and the other propagates anticlockwise. Because the signal light and the pump pulse are located at two sides of zero-dispersion wavelength symmetrically,

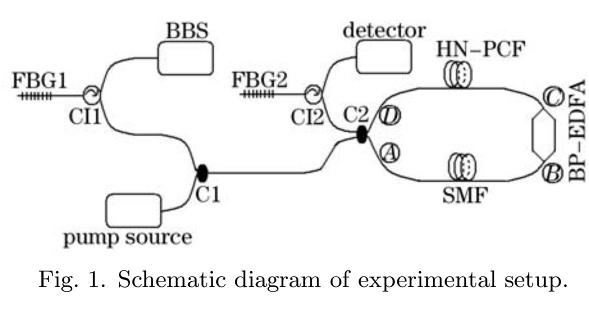

Fig. 1. Schematic diagram of experimental setup.

whose group velocities are equal, the walk-off effect between the signal light and the pump pulse can be neglected. The symmetry of the Sagnac loop mirror is broken by inserting the HN-PCF and BP-EDFA into the loop, the nonlinear phase shifts of the signal beams inversely propagating caused by SPM and XPM are unequal, therefore, some signal power will be transmitted out and be filtered by FBG2. Finally we can detect the signal pulse by oscillograph, power meter and optical spectrum analyzer in detector.

At first, we assume the pump pulse and signal light located at two sides of zero-dispersion wavelength symmetrically, so the walk-off effect between signal light and pump pulse can be neglected for their equal group velocity. Secondly, we assume the attenuation coefficient $\alpha = 0$, namely, having neglected the loss of HN-PCF and the fusion loss of HN-PCF and SMF for their mode area not matching. Finally we assume that the power of continuous signal light P_{S} is far less than the peak power of pump pulse P_{P}, namely, $P_{\mathrm{S}} \ll P_{\mathrm{P}}$, therefore, the nonlinear phase shift caused by SPM is far less than that caused by XPM. It can be seen from Fig. 1 that the incident signal light and pump pulse are divided into two parts symmetrically by C2, in this paper, we not only consider the variety of signal phase and its power, but also consider the power variation of pump pulse.

Suppose the phase of signal light is zero when it is incident into the C2, there is no phase shift for the part propagating anticlockwise but there is $\pi/2$ phase-shift for the part propagating clockwise in Fig. 1 according the transfer matrix of coupler. Therefore, the signal optical field in A and D can be expressed as

$$A_{\mathrm{AC}} = \sqrt{0.5}\sqrt{P_{\mathrm{S}}}, \quad A_{\mathrm{C}} = i\sqrt{0.5}\sqrt{P_{\mathrm{S}}}, \tag{1}$$

where A_{C} and A_{AC} are the optical-field amplitudes of clockwise and anticlockwise signals, respectively. The two signals return to C2 after propagating inversely in the Sagnac loop mirror and the optical-field amplitudes become

$$A'_{\mathrm{AC}} = \sqrt{0.5GP_{\mathrm{S}}}\exp\left(i\phi^{\mathrm{L}}_{\mathrm{AC}} + i\phi^{\mathrm{NL}}_{\mathrm{AC}}\right), \tag{2}$$

$$A'_{\mathrm{C}} = i\sqrt{0.5GP_{\mathrm{S}}}\exp\left(i\phi^{\mathrm{L}}_{\mathrm{C}} + i\phi^{\mathrm{NL}}_{\mathrm{C}}\right), \tag{3}$$

where G is the gain of the BP-EDFA, $\phi^{\mathrm{L}}_{\mathrm{C}}$, $\phi^{\mathrm{L}}_{\mathrm{AC}}$ are the linear phase shifts of the clockwise and anticlockwise signals after the two parts of signal return to C2, respectively, and $\phi^{\mathrm{NL}}_{\mathrm{C}}$, $\phi^{\mathrm{NL}}_{\mathrm{AC}}$ are the nonlinear phase shifts of the signal clockwise propagating and the signal anticlockwise propagating after the two parts of signal return to C2, respectively. According the transfer matrix of fiber coupler, the amplitudes of transmitted optical field and reflected optical field can be expressed as

$$\begin{pmatrix} A_{\mathrm{t}} \\ A_{\mathrm{r}} \end{pmatrix} = \begin{pmatrix} \sqrt{0.5} & i\sqrt{0.5} \\ i\sqrt{0.5} & \sqrt{0.5} \end{pmatrix} \begin{pmatrix} A'_{\mathrm{AC}} \\ A'_{\mathrm{C}} \end{pmatrix}, \tag{4}$$

where A_{t} and A_{r} are the transmitted and reflected optical-field amplitudes, respectively. Therefore, the transmission of the Sagnac loop mirror can be got from Eqs. (2)–(4)

$$T = |A_{\mathrm{t}}|^2/P_{\mathrm{S}} = G\left[1 - \frac{1}{2}(1 + \cos\delta\phi)\right], \tag{5}$$

where P_{S} is the incident signal power, $\delta\phi$ is the signal phase-shift difference of the two parts propagating inversely and $\delta\phi = |(\phi^{\mathrm{L}}_{\mathrm{AC}} - \phi^{\mathrm{L}}_{\mathrm{C}}) + (\phi^{\mathrm{NL}}_{\mathrm{AC}} - \phi^{\mathrm{NL}}_{\mathrm{C}})|$. It can be seen that the transmission of the signal light is linearly proportional to the gain of the BP-EDFA and cosine proportional to the phase shift difference $\delta\phi$. The nonlinear phase shift is caused by SPM and XPM in the experiment, and it can be divided into three parts, one part is generated in HN-PCF, the second part generated in the SMF, and the third part generated in BP-EDFA. Suppose the interval of the pump pulse is not shorter than the time of it propagating a cycle in the Sagnac loop mirror and the walk-off effect can be neglected, the clockwise nonlinear phase shift can be expressed as

$$\delta\phi^{\mathrm{NL}}_{\mathrm{C}} = \delta\phi^{\mathrm{C}}_{\mathrm{EDFA}} + \frac{1}{2}\gamma_{\mathrm{P}}(P_{\mathrm{S}} + 2P_{\mathrm{P}} + 2GP_{\mathrm{S}})L_{\mathrm{PCF}} + \frac{1}{2}\gamma_{\mathrm{S}}[G(P_{\mathrm{S}} + 2P_{\mathrm{P}}) + 2P_{\mathrm{S}}]L_{\mathrm{SMF}}, \tag{6}$$

where γ_{P} and γ_{S} are the nonlinear coefficients of HN-PCF and SMF, respectively; L_{PCF} and L_{SMF} are the length of HN-PCF and SMF, respectively; P_{P} and P_{S} are the incident peak power of pump pulse and the incident power of continuous signal light, respectively; $\delta\phi^{\mathrm{C}}_{\mathrm{EDFA}}$ is the clockwise nonlinear phase shift in BP-EDFA. And the anticlockwise nonlinear phase shift can be expressed as

$$\delta\phi^{\mathrm{NL}}_{\mathrm{AC}} = \delta\phi^{\mathrm{AC}}_{\mathrm{EDFA}} + \frac{1}{2}\gamma_{\mathrm{S}}(P_{\mathrm{S}} + 2P_{\mathrm{P}} + 2GP_{\mathrm{S}})L_{\mathrm{SMF}} + \frac{1}{2}\gamma_{\mathrm{P}}[G(P_{\mathrm{S}} + 2P_{\mathrm{P}}) + 2P_{\mathrm{S}}]L_{\mathrm{PCF}}. \tag{7}$$

where $\delta\phi^{\mathrm{AC}}_{\mathrm{EDFA}}$ is the anticlockwise nonlinear phase shift in BP-EDFA.

When the attenuation is ignored, the power of anticlockwise signal and the peak power of the pump pulse at B is equal to those of clockwise signal and pump pulse at C, respectively. Furthermore, the gains of BP-EDFA are equal bidirectionally. Therefore, the nonlinear phase-shifts to the bidirectionally propagating signal are almost identical in BP-EDFA, namely, $\delta\phi^{\mathrm{C}}_{\mathrm{EDFA}} = \delta\phi^{\mathrm{AC}}_{\mathrm{EDFA}}$. Considering $L_{\mathrm{PCF}} = L_{\mathrm{SMF}}$, the nonlinear phase-shift difference can be expressed as

$$\delta\phi^{\mathrm{NL}} = |\delta\phi^{\mathrm{NL}}_{\mathrm{AC}} - \delta\phi^{\mathrm{NL}}_{\mathrm{C}}| = \frac{1}{2}(\gamma_{\mathrm{P}} - \gamma_{\mathrm{S}})(G - 1)(2P_{\mathrm{P}} - P_{\mathrm{S}})L, \tag{8}$$

while $\gamma_{\mathrm{P}} \gg \gamma_{\mathrm{S}}$, $G \gg 1$, and $P_{\mathrm{P}} \gg P_{\mathrm{S}}$, Eq. (8) can be

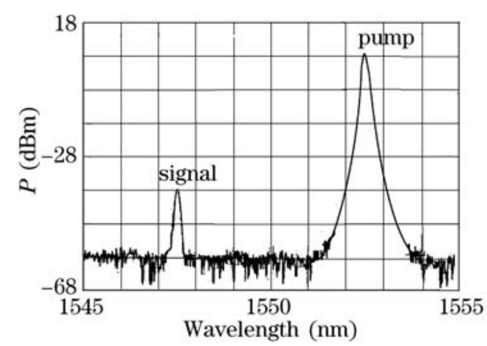

Fig. 2. Spectrum of incident signal light and pump pulse.

expressed concisely as

$$\delta\phi^{\mathrm{NL}} = G\gamma_{\mathrm{P}} P_{\mathrm{P}} L. \tag{9}$$

The difference of linear phase shift is zero because the optical distances of the two signal parts propagating inversely are equal, namely, $\phi_{\mathrm{AC}}^{\mathrm{L}} - \phi_{\mathrm{C}}^{\mathrm{L}} = 0$. Therefore, the phase-shift difference only lies on the nonlinear phase-shift difference. Namely, the phase-shift difference can be expressed as

$$\delta\phi = G\gamma_{\mathrm{P}} P_{\mathrm{P}} L. \tag{10}$$

According to Eqs. (5) and (10), we can get the relation of transmission and the peak power of pump pulse

$$T = |A_{\mathrm{t}}|^2/P_{\mathrm{S}} = G\left[1 - \frac{1}{2}(1 + \cos G\gamma_{\mathrm{P}} P_{\mathrm{P}} L)\right]. \tag{11}$$

Therefore the transmission is cosine proportional to the nonlinear phase shift, and will reach its maximum when the nonlinear shift is equal to odd times of π, namely,

$$\delta\phi = G\gamma_{\mathrm{P}} P_{\mathrm{P}} L = (2m-1)\pi, \tag{12}$$

where $m = 1, 2, 3, \cdots$. Therefore the switching power P_0 can be expressed as

$$P_0 = \pi/(G\gamma_{\mathrm{P}} L). \tag{13}$$

It can be seem obviously from Eq. (13) that the switching power decreased dramatically for the BP-EDFA and HN-PCF inserting into the Sagnac loop mirror. Moreover, the switching power is inversely proportional to the length of the HN-PCF. Because $\gamma_{\mathrm{P}} = n_2\omega/cA_{\mathrm{eff}}$, Eq. (13) can be rewritten as

$$P_0 = (\lambda A_{\mathrm{eff}})/(2n_2 G L), \tag{14}$$

where n_2 is the nonlinear refractive index constant, and $n_2 = 2.8 \times 10^{-20}$ m^2/W for pure silica; A_{eff} is the effective mode-field area of PCF. Considering $G = 100$, $L = 20$ m and $A_{\mathrm{eff}} = 2.5$ μm^2, the switching power is almost 34.6 mW for the 1547.5-nm signal light.

In experiment, the signal light almost could not be detected when the peak power of pump pulse P_{P} is low, e.g. $P_{\mathrm{P}} < -20$ dBm; but the transmitted signal power is rising gradually with the increasing of P_{P}. Figure 3 is the transmitted signal spectrum for $P_{\mathrm{P}} \approx 4.3$ dBm. These results from the nonlinear phase shift difference of the inversely propagating signal can be ignored in Sagnac loop mirror when there is no pump pulse or its peak power is very low, however, the nonlinear phase-shift difference will increase with the increase of P_{P} according to Eqs. (8) and (9), so the signal power will be transmitted gradually according to Eqs. (5) and (11).

Figures 4(a) and (b) are the incident pump pulse and the transmitted signal pulse for $P_{\mathrm{P}} \approx 15$ dBm and $f_{\mathrm{P}} \approx 1.50$ MHz, where f_{P} is the frequency of the pump pulse. It can be seen from Figs. 4(a) and (b) that the frequency of the transmitted signal pulse f_{S} lies on that of pump pulse, e.g. $f_{\mathrm{S}} = f_{\mathrm{P}} = 1.50$ MHz in the experiment. Furthermore, the full width at half maximum (FWHM) of transmitted signal pulse is less than that of pump pulse. For example, the FWHM of the transmitted signal pulse is 38.7 ns, but the FWHM of the pump pulse is 61.9 ns. This results from that the power of transmitted signal depends on the power of

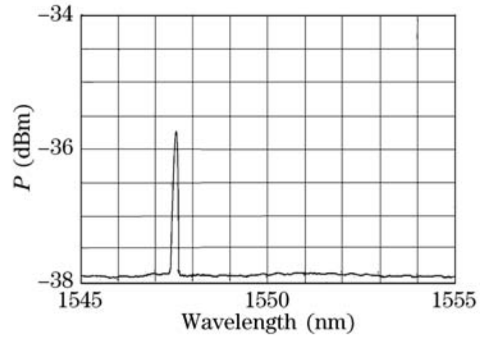

Fig. 3. Transmitted signal spectrum for $P_{\mathrm{P}} \approx 4.3$ dBm.

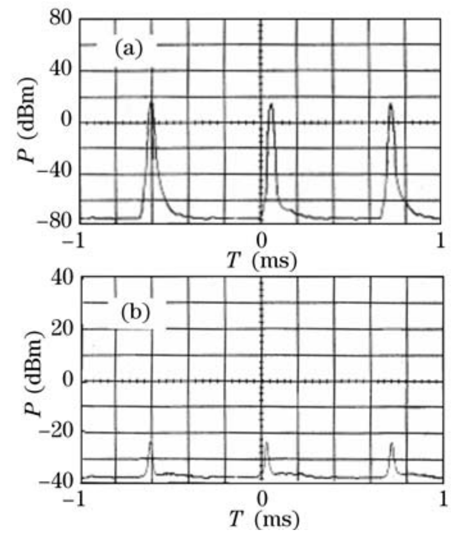

Fig. 4. (a) Incident pump pulse and (b) transmitted signal pulse.

pump pulse, only those higher power of the pump pulse may generate obvious nonlinear phase shift. In the experiment, the switching extinction reaches 15.9 dB when P_{P} is almost equal to 16 dBm.

Figure 5 shows the transmission of the signal pulse as a function of the peak power of the pump pulse. The solid curve is the theoretical results according to Eq. (11), the parameters selected by theory are consistent with those by experiment, namely, $G = 100$, $L = 20$ m, $n_2 = 2.8 \times 10^{-20}$ m^2/W, $A_{\mathrm{eff}} = 2.5$ μm^2 and $\lambda = 1547.5$ nm. The circle points are the experimental result. It can be seen from Fig. 5 that, the trend of the theoretical

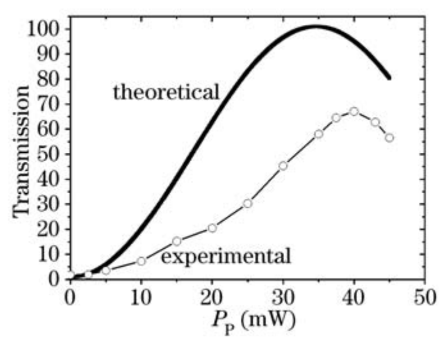

Fig. 5. Signal pulse transmission as a function of peak power of pump pulse.

result is in good agreement with the experimental result. However, the switching power by experiment is a little higher than that by theory, e.g., the switching power by experiment is almost 40 mW, but the switching power by theory according to Eq. (11) only is near to 34.6 mW. Moreover, the signal pulse transmission in experiment is less than that in theory, e.g., the peak transmission of signal pulse in experiment only is 67.04, which is a little less that in theory. All these result from the neglecting the propagation loss of HN-PCF and the fusion loss between HN-PCF and SMF in theoretical analysis, but in fact, the propagation loss of HN-PCF and the fusion loss by the mode area not matching usually attenuate the powers of pump pulse and signal light in experiment. On the one hand, the nonlinear phase shift is decreased for the attenuation of pump pulse power according to Eq. (9), therefore, the switching power by experiment is less than that by theory. On the other hand, the gain of the signal power after circumambulating in the Sagnac loop mirror is also decreased for the attenuation of the signal power, therefore, the transmission in experiment is less than that by theory.

In summary, the switching power of the all-optical switching can be decreased dramatically by inserting the HN-PCF and BP-EDFA into the Sagnac loop mirror. Furthermore, the walk-off effect can be ignored for the pump pulse and signal light locating at the two sides of zero-dispersion wavelength, respectively. In our experiment, the switching power almost is 40 mW and the switching extinction can reach 15.9 dB, moreover, the transmission of the signal pulse is cosine proportional to the peak power of the pump pulse, the result is in good agreement with that from theory.

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