Four-Wave Mixing Bandwidth Enlargement Using Phase-Matching Control by Gain-Transparent Stimulated Brillouin Scattering

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Abstract—**We demonstrate an optical approach to control four-wave mixing (FWM) conversion bandwidth based on gain-transparent stimulated Brillouin scattering (SBS) in fiber. By introducing self-compensation of optical gain/loss with frequency-locked SBS pump and Stokes waves, the FWM phase matching condition can be flexibly controlled through SBS induced refractive index change without affecting the signal power. The conversion efficiency has been enhanced by up to 9.3 dB for an idler outside the original conversion bandwidth. The 3-dB bandwidth is enlarged from 11.04 nm to 15.62 nm, resulting in 41% increase from its original value. Our technique can be adopted to other applications of parametric processes where phase matching is not automatically satisfied.**

Keywords-Four-wave mixing; stimulated Brillouin scattering; optical wavelength conversion; optical phase matching

I. INTRODUCTION

A significant number of optical processing and routing approaches rely on fiber nonlinearities, among which four-wave mixing (FWM) offers the benefits of transparency to modulation format, bit rate, and protocol. FWM has found applications in wavelength conversion and multicast, tunable delay, logic operation, regeneration, ultrafast switching, format conversion, parametric amplification and oscillation [1-3]. Despite the many applications, FWM has the downside of limited operation bandwidth since the phase matching condition can hardly be satisfied for interplaying fields that are spectrally far apart. In this paper, we demonstrate experimentally the use of gain-transparent stimulated Brillouin scattering (SBS) to control purely the phase difference among the fields, offering a degree of freedom to suppress or enlarge the FWM conversion bandwidth without changing the input FWM pump or signal powers. SBS has been actively used to realize slow light in fibers [4, 5]. In 2008, by applying SBS slow light to a FWM pump, Mateo et al. demonstrated optical control of FWM phase-matching condition [6]. However, in the experiment, both the real and imaginary parts of the SBS gain coefficient were inevitably modified. While the imaginary part influences the phase-matching condition simply through SBS induced refractive index change, the real part complicates the situation by introducing a nonlinear phase term and by increasing the idler power through amplification of the FWM pump. In practice, it is crucial to have full control of the phase-matching condition without disturbing other parameters of the FWM process. This was merely examined by simulation in [6] where the real part of the SBS gain has been intentionally removed. Even so, only a negligible improvement of less than 1 dB was predicted in the conversion efficiency. The SBS effect was insignificant because the simulation study was confined to an operating range within the original 3-dB conversion bandwidth, where the phase velocities of the interplaying fields are already nearly matched.

In this paper, we experimentally demonstrate the control of FWM phase-matching condition entirely through gain-transparent SBS induced index change. Consequently, optical powers of the signal and the FWM pump are not affected. We have observed a pronounced enhancement of 9.3 dB in the conversion efficiency associated with a 41% enlargement in the 3-dB bandwidth.

II. THEORY

The principle of our scheme is illustrated in Fig. 1. Here, ν_B is the Brillouin frequency shift, f_{RF} is the frequency spacing between SBS pump and signal, and between signal and SBS Stokes wave, $g_b(\delta)$ is the complex Brillouin gain coefficient with δ being the normalized frequency detuning from the Brillouin resonance. The signal and the FWM pump

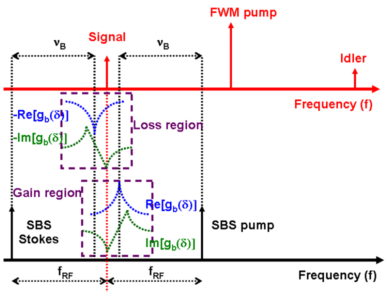

Fig. 1. Principle of FWM bandwidth enlargement using gain-transparent SBS. ν_B: Brillouin frequency shift; f_{RF}: frequency spacing between SBS pump and signal, and between signal and SBS Stokes wave; $g_b(\delta)$: complex Brillouin gain coefficient with δ being the normalized frequency detuning.

copropagate in an optical fiber and generate an idler wavelength. At the same time, the SBS pump and Stokes waves are directed to the same fiber from the opposite end. Optical gain and loss are introduced on the signal by the counter-propagating SBS pump and Stokes waves, respectively. It is worth mentioning that simultaneous gain and loss on a single optical carrier has previously been used to realize an RF photonic phase shifter [7]. The real parts of SBS gain and loss ($\mathrm{Re}[g_b(\delta)]$ and $-\mathrm{Re}[g_b(\delta)]$) cancel each other, while the imaginary parts ($\mathrm{Im}[g_b(\delta)]$ and $-\mathrm{Im}[g_b(\delta)]$) add together to strengthen SBS induced index change. The phase mismatch in FWM under SBS can be approximated by [6]:

$$\kappa = \Delta k + 2\gamma \overline{P}_{FWM} - 2\,\mathrm{Im}[g_b(\delta)]\overline{P}_{SBS} \qquad (1)$$

where Δk is the linear phase mismatch, γ is the nonlinear coefficient of the fiber, $\overline{P}_{FWM}$ and $\overline{P}_{SBS}$ are average powers of the FWM and SBS pumps, respectively. The last term in Eq. (1) represents the SBS induced phase mismatch and can be adjusted by tuning the frequency spacing f_{RF}. Hence, the phase-matching condition can be controlled without affecting the power of the signal. When the scheme is applied to an idler wavelength beyond the original 3-dB conversion bandwidth, one can expect a significant power enhancement through minimizing the phase mismatch. Thus, enlargement of the conversion bandwidth can be achieved.

III. Experiment

Our experimental setup is shown in Fig. 2. The output of a laser 1 at 1549.84 nm is split into two branches. The upper branch is amplified by an erbium-doped fiber amplifier (EDFA) to – 6.48 dBm and serves as the signal. The lower branch is modulated by an electro-optic intensity modulator (EOM) biased to suppress the optical carrier and driven at a frequency f_{RF}. The carrier suppression ratio is over 23 dB. The two sidebands act as the SBS pump and Stokes waves after amplification by an EDFA. A FWM pump is provided from another tunable laser 2. The pump is amplified to 16.48 dBm by an EDFA. It is then combined with the signal through a 3 dB coupler. The signal together with the FWM pump are directed to a 1 km highly nonlinear fiber (HNLF) where FWM takes place in the presence of the counter-propagating SBS pump and Stokes waves. The HNLF has a nonlinear coefficient of 11/(W·km), a dispersion coefficient of –0.4 ps/(nm·km) and a dispersion slope of 5.7×10^{-3} ps/(nm^2·km) at ~1550 nm. It has no zero-dispersion wavelength over the range of 1510 to 1620 nm. The Brillouin frequency shift and gain bandwidth of the

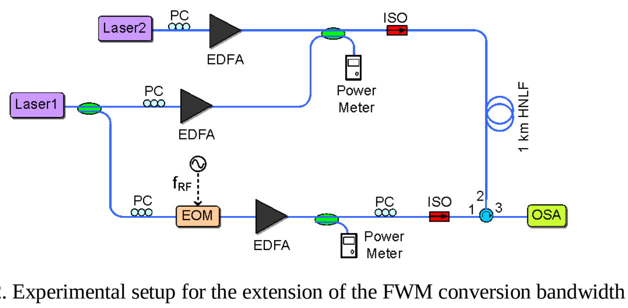

Fig. 2. Experimental setup for the extension of the FWM conversion bandwidth by SBS. TL: tunable laser; EOM: electro-optic intensity modulator; EDFA: erbium-doped fiber amplifier; PC: polarization controller; BPF: band pass filter; HNLF: highly nonlinear fiber; ISO: isolator; OSA: optical spectrum analyzer.

HNLF are measured to be 9.698 GHz and 50 MHz, respectively. During the experiment, all the operation wavelengths are in the normal dispersion region. By optimizing the driving frequency f_{RF}, the conversion efficiency (CE) can be maximized for different FWM pump wavelengths through minimizing the phase mismatch. Therefore, the FWM conversion bandwidth can be enlarged.

IV. Results and Discussion

We first investigate the performance of this technique in controlling phase matching when the FWM pump wavelength is fixed at 1546.94 nm. Fig. 3 (a1) shows the FWM spectrum when the SBS pump and Stokes waves are turned off. By optimizing the polarization state of the FWM pump, we obtain a CE of –17.68 dB. Next, the SBS pump and Stokes waves are turned on with a power of 16 dBm. A maximum CE of –15.35 dB is achieved at a driving frequency f_{RF} =9.717 GHz while a minimum CE of –30.24 dB is obtained at f_{RF} =9.667 GHz. The two corresponding FWM spectra are depicted in Fig. 3 (a2) and (a3), respectively. Comparing Fig. 3 (a2) with 3 (a1), the limited enhancement of 2.33 dB in the CE is explained by the fact that the idler wavelength is within the original 3-dB FWM conversion bandwidth. Thus, the initial FWM process is already quasi-phase-matched. It is also verified from another perspective that the matching condition can be totally destroyed by SBS induced phase mismatch, as shown in Fig. 3 (a3). The frequency response of the CE is shown in Fig. 3 (b). Each RF driving frequency results in a different SBS induced phase term, thus allowing precise control of the CE. As the driving frequency is varied, the signal power is monitored with an optical spectrum analyzer (OSA). The result is also plotted in Fig. 3 (b). The power variation is within 1.4 dB, confirming nearly gain-transparent operation. The slight variation may originate from non-perfect Lorentzian lineshape of the Brillouin gain, resulting in non-ideal compensation of SBS gain and loss [7]. To further investigate the effect of the power of SBS pump and Stokes waves, we measure the CE at different power levels and depict the results in Fig. 3 (c). The

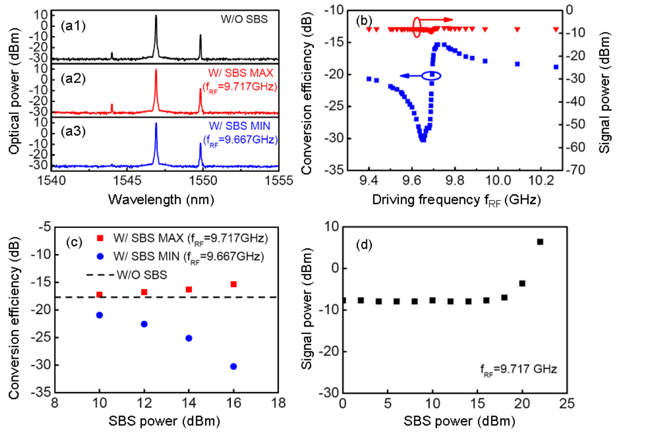

Fig. 3. Experimental results of phase matching control by gain-transparent SBS at a FWM pump wavelength of 1546.94 nm. (a1)–(a3) Measured FWM spectra without SBS (W/O SBS), with gain-transparent SBS for maximum conversion efficiency (W/ SBS MAX) and with gain-transparent SBS for minimum conversion efficiency (W/ SBS MIN); (b) conversion efficiency and signal power as a function of the RF driving frequency f_{RF}; (c) maximum and minimum conversion efficiency versus the powers of SBS pump and Stokes waves; (d) the signal power versus the powers of SBS pump and Stokes waves.

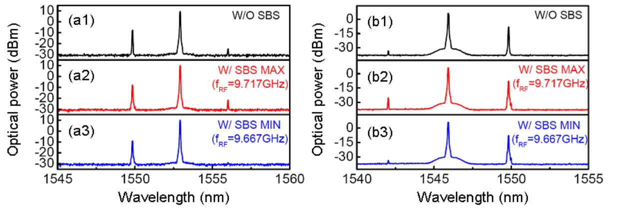

Fig. 4. Measured FWM spectra without SBS (W/O SBS), with gain-transparent SBS for maximum conversion efficiency (W/ SBS MAX) and with gain-transparent SBS for minimum conversion efficiency (W/ SBS MIN) at a FWM pump wavelengths of (a) 1552.94 nm and (b) 1549.94 nm.

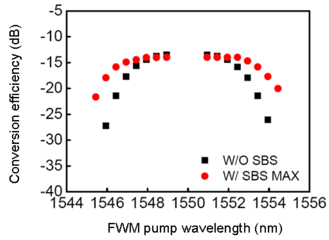

Fig. 5. Conversion efficiency versus the FWM pump wavelength without and with gain-transparent SBS in achieving maximum CE.

black dashed line indicates the CE (–17.68 dB) without SBS corresponding to the case in Fig. 3 (a1). For all the SBS power levels, the maximum and minimum CE are achieved at f_{RF} =9.717 GHz and f_{RF} =9.667 GHz, respectively. As the SBS power increases, the maximum CE increases from –17.21 to –15.35 dB; while the minimum CE decreases from –20.93 to –30.24 dB. It is also observed that the enhancement in CE is much weaker than the degradation in CE. This is due to the aforementioned quasi-phase matching condition at the particular idler wavelength. We also measure the variation of the signal power versus the power of SBS pump and Stokes waves, as shown in the Fig. 3 (d). During the measurement, the driving frequency is fixed at 9.717 GHz. For SBS power ranging from 0 to 16 dBm, the signal power remains almost constant with a maximum fluctuation of around 0.24 dB. Above 16 dBm, the signal power starts to increase rapidly. The observation can possibly be explained by saturation of energy transfer from the signal to the SBS Stokes wave. Consequently, SBS loss of the signal is not sufficient to cancel the increasing SBS gain. In order to maintain a constant signal power, we limit the power of the SBS pump and Stokes waves to be 16 dBm in our following experiments.

We next tune the FWM pump wavelength to 1552.94 nm located at the long wavelength side of the signal, as shown in Fig. 4 (a1)–(a3). The corresponding CE are –17.68, –14.92 and –29.45 dB. Similar to the case of pump wavelength at 1546.94 nm (Fig. 3), limited enhancement of the CE is explained by original quasi-phase matching condition of the operating wavelengths. To obtain a large CE enhancement, the FWM pump wavelength is tuned to 1545.94 nm. The signal-pump spectral spacing is 1 nm larger than that shown in Fig. 3. The measured FWM spectra are depicted in Fig. 4 (b), where a lower reference level is used in the OSA to clearly show the change in CE. The measured CE without SBS is –27.12 dB, much lower than that in Fig. 3 (a1). The reason is the idler wavelength is out of the original 3-dB conversion bandwidth and thus the initial FWM process is far from quasi-phase-matched. When the SBS pump and Stokes waves are applied, the CE is enhanced to a maximum value of –17.91 dB at f_{RF} =9.717 GHz. A significant enhancement of 9.3 dB is obtained. Also, the CE can be suppressed to a minimum value of –30.38 dB at f_{RF} =9.667 GHz. The large enhancement of CE implies the feasibility of enlarging the 3-dB FWM conversion bandwidth by using this technique. Fig. 5 shows the experimental result of enlarging the bandwidth by gain-transparent SBS. The signal wavelength is fixed at 1549.84 nm while the FWM pump wavelength is tuned. The black squares plot the CE versus the pump wavelength without SBS. The original 3-dB conversion bandwidth is 11.04 nm and is twice that of 5.52 nm in the scale of sweeping the pump wavelength. Next, the SBS pump and Stokes waves are introduced with a total power of 16 dBm. For each FWM pump wavelength, the driving frequency f_{RF} is tuned to maximize the CE. The result is shown by the red circles in Fig. 5. It is clear that the CE enhancement is larger as the operation wavelength is further away from the central region covering the 3-dB conversion bandwidth. Near the central region, the FWM process is quasi-phase-matched even without SBS. Away from the region, the phase matching condition degrades significantly and thus CE enhancement through gain-transparent SBS phase control is of crucial importance. The maximum CE enhancement is 9.3 dB and occurs at a pump wavelength of 1545.94 nm. The 3-dB FWM conversion bandwidth with SBS is increased by 4.58 nm to 15.62 nm, corresponding to 41% enlargement. Experimental study on the control of FWM bandwidth for real data has been performed and the results will be presented.

V. Conclusion

In conclusion, we have experimentally demonstrated the dynamic control of FWM phase matching condition by gain-transparent SBS induced refractive index change. The technique presented here can be used to further increase/decrease the FWM conversion bandwidth. Although the control of phase-matching is evaluated in the context of conventional degenerate FWM, we believe its impact is significant in other applications where the precise control of optical phase velocity is necessary.

References

[1] L.-S. Yan, et al., "Simultaneous NRZ-to-RZ format conversion and one-to-six error-free channel multicasting using a single pump in a highly nonlinear fiber," Opt. Express, vol. 18, pp. 21404-21409, Sep. 2010.

[2] X. Fu, et al., "Bit-rate flexible demodulation of DPSK signals based on phase sensitive gain in cascaded four-wave mixing," IEEE Photon. Technol. Lett., vol. 24, no. 12, 994-996, Jun. 2012.

[3] X. Wu, et al., "Bit-rate-variable and order-switchable optical multiplexing of high-speed pseudorandom bit sequence using optical delays," Opt. Lett., vol. 35, no. 18, 3042-3044, Sep. 2010.

[4] Y. Okawachi, et al., "Tunable All-Optical Delays via Brillouin Slow Light in an Optical Fiber," Phys. Rev. Lett., vol. 94, 153902, April. 2005.

[5] K. Y. Song, M. G. Herráez, and L. Thévenaz, "Observation of pulse delaying and advancement in optical fibers using stimulated Brillouin scattering," Opt. Express., vol. 13, no. 1, pp. 82-88, Jan. 2005.

[6] E. Mateo, F. Yaman, and G. Li, "Control of four-wave mixing phase-matching condition using the Brillouin slow-light effect in fibers," Opt. Lett., Vol. 33, no. 5, pp. 488-390, Mar. 2008.

[7] A. Loayssa, and F. J. Lahoz, "Broad-Band RF Photonic Phase Shifter Based on Stimulated Brillouin Scattering and Single-Sideband Modulation," IEEE Photon. Technol. Lett., Vol. 18, no. 1, pp. 208-210 Jan. 2006.