Broad-Band Tunable Wavelength Conversion Using Raman-Assisted Parametric Four-Wave Mixing in Highly Nonlinear Fibers With Double-Pass Geometry

Ming Tang, Yandong Gong, and Ping Shum

***Abstract*—Efficient wavelength conversion using distributed Raman gain and the Raman-assisted parametric four-wave mixing in 1 km of highly nonlinear fibers (HNLFs) is demonstrated in this letter. We present the theoretical analysis of the Raman-assisted parametric process and investigate the mechanism of wavelength conversion between parametric Stokes and anti-Stokes light. The system is implemented in a double-pass Raman amplifier where a tunable optical bandpass filter and a wide-band reflector are used to form a laser oscillation in the normal dispersion region of HNLF. The lasing light acts as the parametric pump to enable the wide-band wavelength conversion about the pump wavelength. Conversion efficiency greater than 0 dB over 50 nm is obtained and the converted idler wavelength can be adjusted more than 10 nm continuously by tuning the tunable optical filter. Hence, an arbitrary new wavelength can be converted within the tunable range of optical filter with high efficiency.**

***Index Terms*—All-optical wavelength converter, four-wave mixing (FWM), stimulated Raman scattering (SRS).**

I. Introduction

ALL-OPTICAL wavelength conversion is a key technology for improving the flexibility and increasing the capacity of optical fiber networks [1]. Among various schemes, the use of parametric four-wave mixing (FWM) attracted considerable attention in wavelength-division-multiplexing (WDM) lightwave systems. Broad-band wavelength converters based on the dual-pump parametric amplification have been proposed with negligible polarization-dependent gain (PDG) [2]. In order to employ the wide range amplification property of stimulated Raman scattering (SRS), a Raman-assisted parametric converter has been reported [3]. However, such devices cannot obtain an arbitrary new converted wavelength in wide-band wavelength range while keeping the polarization independence. In this letter, we propose and implement a highly efficient wavelength converter utilizing the interaction between the parametric-FWM and the SRS in highly nonlinear fibers (HNLFs). A double-pass Raman amplifier is used to form a fiber Raman oscillator in which a tunable optical bandpass filter (TOBPF) and a wide-band Faraday rotator mirror (FRM) are used to generate a lasing light in the normal dispersion region of HNLF to seed the Raman-parametric wavelength conversion. We achieve the wavelength conversion with an efficiency larger than 0 dB over 50 nm. Arbitrary new wavelength in the tunable range of filter can be obtained.

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II. Technical Concepts

At first, we recall some theoretical results of the interactions between FWM and SRS for a better understanding of our experiments. SRS is characterized by a down-conversion of a pump photon into a low-frequency Stokes photon through excitation of a vibrational mode of the transmission medium [4]. An up-conversion process that generates an upshifted anti-Stokes wave is also possible through the parametric FWM. The anti-Stokes is located symmetrically to the Stokes wave around the parametric pump wavelength. This FWM-influenced Raman scattering is highly dependent on the dispersion of the pump wavelength. On one hand, significant Raman gain improvements can be obtained for the Stokes and anti-Stokes if the Raman pump wavelength is in the anomalous dispersion region [5], [6]. The Raman pump acts as a parametric pump in this case and the Raman gain variation is associated with chromatic dispersion. The cancellation of linear phase-mismatch and nonlinear self-phase modulation results in the phase matching [4]–[6]. Although this phenomenon is quite useful to improve the Raman amplification efficiency significantly on the Stokes sideband, the depleted parametric pump power cannot feed an efficient wavelength conversion between Stokes and anti-Stokes. On the other hand, if the pump wavelength is located in the normal dispersion region, the parametric suppression of the seeded Stokes exponential amplification takes place and the anti-Stokes idler generation and amplification occur even phase matching condition is not perfectly satisfied. In this case, a sequence of data transmitted by the Stokes light is transferred to the anti-Stokes light. Similarly, the seeded anti-Stokes light containing data sequence can transfer the energy downshifted to the Stokes idler due to the Raman effects and Raman-assisted FWM [3]. This way, efficient wavelength conversion between Stokes and anti-Stokes light can be achieved around the pump wavelength. The modulation-instability-induced amplitude noise associated with the wavelength conversion is avoided since the parametric pump light is located inside the normal dispersion regime. A flat dispersion slope is necessary to maintain the nearly phase-matching condition.

The dispersion-shifted HNLF used in our work for optical signal processing owns quite large Raman gain coefficient ($g_R = 5.9\ \mathrm{W}^{-1}\cdot\mathrm{km}^{-1}$) and nonlinear coefficient ($\gamma = 10\ \mathrm{W}^{-1}\cdot\mathrm{km}^{-1}$).The zero-dispersion wavelength (ZDW) of the HNLF is at 1559 nm with a dispersion slope

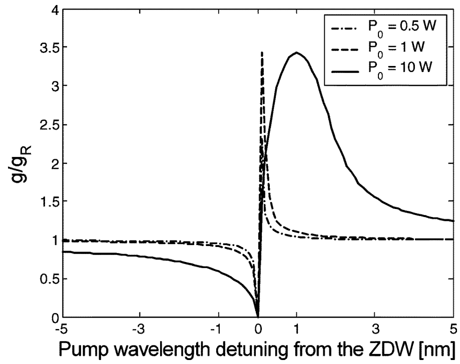

Fig. 1. Normalized gain coefficient g/g_R versus pump wavelength at Stokes shift of 13.2 THz.

0.02 $ps/nm^2/km$ and a cut-off wavelength below 1200 nm. The typical loss is less than 0.75 dB/km from 1550 to 1650 nm. In order to achieve the frequency conversion, the selection of pumping wavelength is important. Due to the interaction between parametric-FWM and SRS, the mixed Raman gain coefficient experienced by the Stokes light can be given as $g = 2\gamma\Re\left[\sqrt{K(2q-K)}\right]$ [6]. $K = -\Delta k/(2\gamma P_0)$ is the ratio between linear phase mismatch ($\Delta k = \beta_2\Omega^2$) and the nonlinearity-induced mismatch $2\gamma P_0$. Here, β_2 is the dispersion at the pump wavelength, Ω is the angular frequency shift between pump and Stokes light, and P_0 is the peak power of pump. $q = 1 - f - f\tilde{h}_R(-\Omega)$, where $\tilde{h}_R(\Omega)$ is the Fourier transform of the complex Raman susceptibility and $f \cong 0.18$ measures the fractional contribution of Raman effect. $\Re$ represents the real part of the formula. This equation reveals the relationship between parametric-Raman gain and fiber dispersion. The peak gain coefficient for a Stokes frequency shift, $\Omega/(2\pi) = 13.2$ THz, of HNLF versus pump wavelength is shown in Fig. 1 with different pump power. Note that we normalize the gain coefficient g to the standard peak value g_R. A significantly enhanced Raman gain exists when the pump wavelength is in the anomalous-dispersion region. However, the Raman gain is suppressed by FWM when the pump wavelength is less than ZDW.

It is clear that the efficient suppression of Raman gain can be achieved with a large pump power ($P_0 = 10$ W). In order to employ the FWM-Raman-induced wavelength conversion at the frequency range $\Omega/(2\pi) = 13.2$ THz, we must use quite high power pump laser. However, the phase matching is also relevant to the Stokes shift $\Omega_s/(2\pi)$. If Ω_s is not too large, the required pump power can be low to feed efficient conversion. Thus, we calculated and plotted the Raman gain suppression as a function of pumping wavelength and Stokes shifts in Fig. 2 when pump power is 100 mW. The suppression factor is defined as the ratio between the parametric-Raman gain coefficient and the normal Raman gain at the same Stokes shift. The smaller the suppression factor, the stronger the suppression effect. It is verified that significant Raman gain suppressions can be obtained when the Stokes shifts is less than 3 THz (25 nm). Thus, 50-nm bandwidth for the efficient conversion between Stokes and anti-Stokes waves is obtained.

III. Experimental Results and Discussions

We implement the wavelength conversion in a double-pass Raman amplifier as depicted in Fig. 3. The TOBPF with

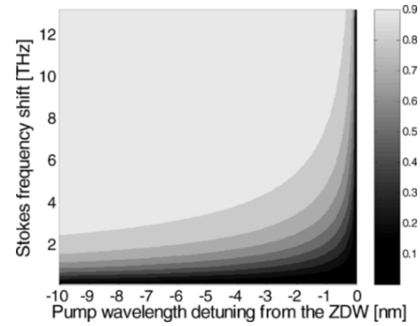

Fig. 2. Contour map of Raman gain suppression effects when pump is 0.1 W.

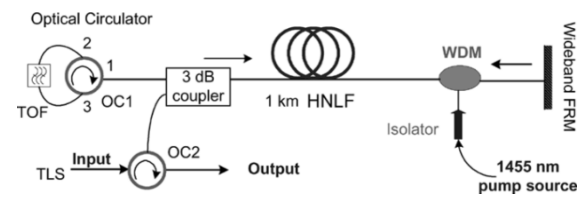

Fig. 3. Experimental setup.

3-dB bandwidth of 0.65 nm can be tuned in the C-band (1530–1565 nm). The HNLF is pumped by a 1455-nm Raman fiber laser (RFL) through the WDM and the peak Raman gain coefficient of HNLF occurs at 1554 nm. By using the optical circulator 1 (OC1), the wide-band FRM and the TOBPF are able to form a laser which acts as the parametric pump light for efficient wavelength conversion. The signal from the tunable laser source is injected through the optical circulator 2 (OC2) to be a control light and its linewidth is set as 50 MHz to suppress the stimulated Brillouin scattering (SBS). The converted idler wave is monitored at the output of the circulator. Note that the FRM optimized for 1556 nm is able to eliminate the PDG and achieve a polarization-independent conversion. The lasing light (parametric pump) in the HNLF is measured to be 21 dBm when the RFLs power is 450 mW. The converted idler waves located inside the Raman gain spectrum of the RFL can be amplified by the double-pass amplifier to obtain a further efficiency enhancement [7].

Fig. 4 shows an example of the spectrum at the output of our system when the input signal is -8 dBm at 1543 [Fig. 4(a)] and 1567 nm [Fig. 4(b)]. The parametric pump wavelength is 1555 nm by adjusting the filter central wavelength. It is shown that highly efficient wavelength conversion is realized between Stokes and anti-Stokes light around the pump wavelength. To verify the feasibility of wavelength conversion, we implemented time domain experiments. The input signal is externally modulated using a $LiNbO_3$ Mach–Zehnder modulator with 2.5-Gb/s nonreturn-to-zero, $2^{31} - 1$ pseudorandom bit stream. The converted idler is filtered by a 0.4-nm fiber Bragg grating-based bandpass filter and detected by a 7-GHz bandwidth photodetector. The eye diagrams of the 1543-nm input signal and the corresponding idler output from OC2 are shown in Fig. 4(c). The measured Q factors of the input signal and converted wave are 9.2 and 7.3, respectively. The results show that the present scheme is applicable for the converted signal transmission with a forward-error correction technique. From the eye diagram, the higher noise appears when "1" is transmitted and this performance degradation is most probably due to the relative-intensity-noise fluctuation in the double-pass cavity.

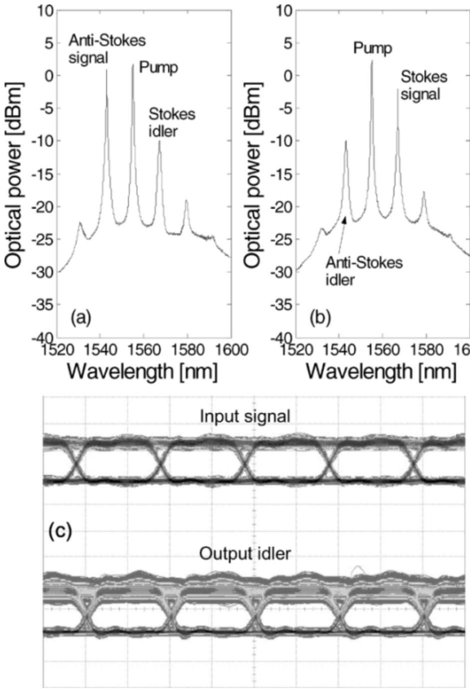

Fig. 4. Example of converted waves at the output with a control signal at (a) 1543 and (b) 1567 nm. Resolution is 0.2 nm. (c) Eye diagrams of 1543-nm input signal and its idler output.

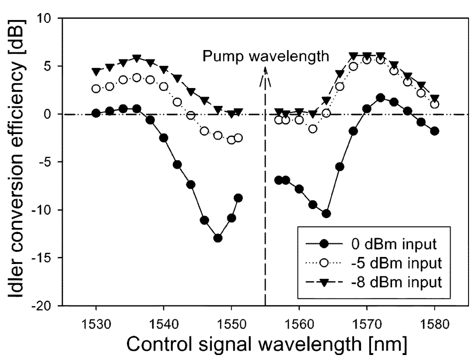

Fig. 5. Idler conversion efficiency measured with different signal power levels. Pump wavelength is 1555 nm.

The wavelength conversion efficiency over a wide bandwidth is measured (idler power at the output of the HNLF/signal power at the input of HNLF) by monitoring the output with an optical spectrum analyzer and the results are plotted in Fig. 5 at different input signal power levels. As can be seen from Fig. 5, we obtain a conversion efficiency greater than 0 dB for over 50-nm signal bandwidth (1530–1580 nm) with an input signal power of -8 dBm. When the signal shifts toward the pump from the 1580 nm, the linear phase mismatch reduces such that a strong FWM-Raman gain of idler wave occurs. However, with further shift, the FWM is perfectly phase-matched because of the flat dispersion slope. Cascaded FWM happens through the beat between pump and idler wave, hence, the conversion efficiency at the idler wave deceases. A maximum efficiency can be observed in Fig. 5. If the input signal power increases, the control signal itself will act as an FWM pump and generate its sideband since the phase matching can be nearly satisfied due to the flat dispersion slope. The wavelength conversion efficiency decreases accordingly as observed in Fig. 5.

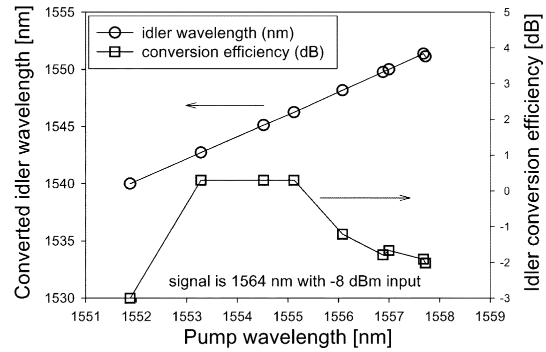

Fig. 6. Tunable idler wavelength (left axis) and conversion efficiency (right axis) as a function of pump wavelength.

Besides wide wavelength operation ranges, our wavelength converter can also provide an arbitrary new wavelength when the phase-mismatch is not serious. Although the wavelength conversion with wide pump tuning range has been reported previously [8], the parametric pump wavelength in our system can be adjusted simply by tuning the TOBPF and the distributed Raman gain in the double-pass system is beneficial to the Raman-assisted FWM. Actually, from Fig. 2, efficient Stokes Raman gain suppression can be obtained to support the wavelength conversion when pump wavelength is adjusted in normal dispersion region. For a given input control signal, the pump wavelength can be tuned continuously using the TOBPF, thus, the frequency shift between pump light and control signal can be tailored. Hence, the wavelength of converted wave can be adjusted continuously with Raman-assisted FWM. When the input control signal is -8 dBm at 1564 nm, by tuning the TOBPF to keep the pump wavelength inside the normal dispersion region, we obtained the idler wavelength and its conversion efficiency versus the pump wavelength, as plotted in Fig. 6. When the pump wavelength shifts from 1558 to 1552 nm, an idler from 1540 to 1552 nm can be adjusted continuously with a conversion efficiency larger than -3 dB. The flat dispersion slope enables the efficient wavelength conversion within the tunable range of TOBPF.

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