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Raman-amplified pump and its use for parametric amplification and phase conjugation

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ABSTRACT

We experimentally demonstrate the use of a discrete Raman amplifier for generating a high power, narrow linewidth pump for use within a fiber optical parametric amplifier (FOPA). We demonstrate the suitability of the Raman-amplified pump for parametric amplification by characterizing its optical signal to noise ratio and relative intensity noise (RIN). The amplified pump is subsequently employed within a FOPA obtaining net gain of up to 24.9 dB and a gain of > 11 dB over 35 nm. The approach described here offers the key advantage over traditional EDFA-based pump generation of wavelength tuneability outside the EDFA bands. In principle this allows to place the parametric pump at any wavelength within the low fiber attenuation window. Here we additionally demonstrate Raman-assisted optical phase conjugation to provide positive conversion efficiency over 60 nm whilst employing the phase-conjugating pump power of < 10 mW not requiring an amplification by EDFA. We consider this technique to show a significant promise for broadband optical phase conjugation and wavelength conversion as well as the prospect for implementation of these important phenomena outside of the EDFA bands.

1. Introduction

Fiber optical parametric amplifiers (FOPAs) have the potential to enable transmission bandwidth expansion beyond the C and L bands and thus to breach current capacity limits [1] owing to a FOPA's ability to provide ultra-wide gain and, in principle, to operate at arbitrary wavelengths [2]. In addition, FOPA can offer unique features of phase-sensitive [3], widely tunable [4] or instantaneous [5] amplification. However, the current state of the art FOPAs require an EDFA to generate a pump of sufficient power (≥1 W) and quality, having narrow linewidth and low noise. Significant FOPA research progress [6] has therefore been restricted to the EDFA band and around it. Although a pump situated within the EDFA gain window can provide FOPA gain spreading well beyond the C band [4,7], the ability to generate a pump for FOPAs in other spectral regions is vital to make the most of the FOPA wavelength flexibility. It is particularly beneficial to enable a flexible FOPA operation anywhere between 1310 and 1625 nm where attenuation of modern fibers (i.e. ITU-T G.652.D) can be < 0.4 dB thus allowing this ~44 THz wide range for signal transmission. Besides amplification, FOPA can substantially improve transmission capacity via its implementation for optical phase conjugation (OPC) and wavelength conversion. OPC enables compensation for nonlinear impairments occurring along the link [8], while wavelength conversion can be used to employ vacant bands for signal transmission [9]. The improved pump wavelength tuneability is necessary for OPC implementation outside of C and L bands in future optical communications and is beneficial for wavelength conversion flexibility.

Up to now the following approaches have been employed to generate a pump for FOPA outside the EDFA range: amplification by semiconductor optical amplifiers (SOAs) [10] or Ytterbium doped fiber amplifiers (YDFAs) [11] and high power wavelength conversion from the C and L bands [12]. However, these approaches present major limitations, namely: SOAs provide insufficient power for broadband FOPA performance, YDFA restricts FOPA to wavelength range (around 975–1150 nm [13]) inappropriate for signal transmission due to high attenuation in silica fibers, and wavelength conversion is still reliant on EDFAs and so does not offer a full wavelength flexibility whilst introducing an energy efficiency penalty.

It is surprising therefore that, to the best of our knowledge, virtually wavelength unrestricted Raman gain [14] has not been explored for FOPA pump amplification except in context of Raman-assisted FOPA (RA-FOPA) [15–17]. However, RA-FOPA still requires external

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amplification of the FOPA pump (e.g. by EDFA) for parametric gain to be more significant than Raman gain [17] and thus to enable advantages of parametric amplification. In contrast, we propose to employ a high-gain high output power discrete Raman amplifier [18] to enable pump amplification for FOPA and related applications at virtually any wavelength. Raman sources potentially suitable for pumping FOPA with sufficient power (> 1 W) and narrow linewidth (few GHz) [19,20] are not characterized typically in terms of qualities important for FOPA pumping, such as optical signal-to-noise ratio (OSNR) and relative intensity noise (RIN). Other Raman sources have been found to provide inadequate OSNR [21], insufficient power [22] or too wide a linewidth [23,24].

This paper extends the work presented in [25] and examines suitability of Raman gain for pump amplification in FOPA and OPC (or wavelength conversion) to greatly improve their wavelength flexibility. In Section 2, we propose to use a discrete Raman amplifier to amplify pump for FOPA. We generate a 1.5 W pump using a high gain Raman amplifier and characterize this pump in the FOPA context, particularly, in terms of linewidth, OSNR and RIN. We then employ a Raman-amplified pump in a FOPA arrangement and obtain a gain up to 24.9 dB and an > 11 dB gain over > 35 nm bandwidth. In Section 3, the OPC case is treated in a separate experiment where mitigation of stimulated Brillouin scattering (SBS) via pump broadening is restricted to avoid distortion of phase-conjugates [26]. We amplify an OPC pump from 10 mW up to 470 mW within Raman-assisted OPC (RA-OPC). We demonstrate a positive internal conversion efficiency over > 60 nm range in EDFA-free RA-OPC similarly to the prominent works on EDFA-reliant OPC and wavelength converters addressing limitations on SBS mitigation [27,28]. Whereas RA-OPC has previously been demonstrated to improve nonlinear crosstalk [29] and conversion efficiency [30,31], here we focus on Raman amplification of low input power pump to enable implementation of broadband OPC and wavelength conversion in spectral bands lacking a suitable pump amplifier. Although proof-of-concept experiments on FOPA and OPC presented here are performed within the C and L bands due to restrictions of readily available equipment, we verify that provided with commercially available light sources and re-optimized fiber profiles these experiments are extendable to any wavelength range between 1310 and 1625 nm and beyond.

2. Raman-amplified pump and its use for parametric amplification

2.1. Experimental setup

Fig. 1 shows an experimental setup for Raman amplification of a FOPA pump, characterization of the Raman-amplified FOPA pump and its employment in FOPA. A continuous-wave single-polarization FOPA pump was sourced from a 100 kHz linewidth laser tunable across the C band with maximum power of 40 mW. Then, the FOPA pump was phase-modulated (dithered) with a combination of three tones of 100, 320 and 980 MHz to mitigate SBS [32] and guided to a high gain Raman amplifier. The Raman amplifier employed a 6.5 km long dispersion shifted fiber with zero dispersion wavelength (ZDW) of ~ 1542 nm and was backward pumped by a commercial Raman fiber laser operating at 1455 nm with a maximum pump power of 5 W and 3 dB linewidth < 2 nm. The backward pumping scheme was chosen to reduce the Raman pump noise transfer to the amplified FOPA pump [33].

Gain of FOPA employing Raman-amplified pump was measured using a continuous probe sourced from a 100 kHz linewidth laser tunable across the C band. The probe and the Raman-amplified FOPA pump were coupled via a 1% coupler and guided into a separate FOPA gain fiber (Fig. 1). The FOPA gain fiber was a 500 m long highly nonlinear fiber (HNLF) with ZDW of ~1565 nm and nonlinearity of ~8.2 $W^{-1}km^{-1}$.

Calibrated bidirectional 1% couplers were placed at the ends of gain fibers (points IP1, OP1, IP2 and OP2 at Fig. 1) to non-intrusively characterize the Raman amplifier and the FOPA employing Raman-amplified pump via measurements of optical spectra, powers and relative intensity noise. Optical spectra were measured using one of two spectrum analyzers with resolution bandwidths of 150 MHz or 0.1 nm (the factual 3 dB bandwidth was 8.6 GHz) respectively.

2.2. Results and discussion

The FOPA pump power after Raman amplification (at OP1) and on-off Raman gain were measured at 1550 nm as the input FOPA pump power was maximized and reached 9.3 mW (9.7 dBm) at IP1 and the Raman pump power was adjusted (Fig. 2 (a)). An output FOPA pump power of 1.5 W (31.7 dBm) and on-off Raman gain of 24 dB were achieved when the Raman pump power was maximized and reached 3.8 W at its input to the Raman gain fiber (OP1). Essentially the same output FOPA pump power of ~1.5 W (31.7 ± 0.1 dBm) was observed for the same Raman pumping level as the FOPA pump wavelength was swept across a 15 nm range (inset Fig. 2(a)). An output power of 1.5 W for an input of 3.8 W implies a satisfactory optical conversion efficiency within the Raman gain fiber of 40%. The total electrical power consumption of the Raman amplifier was < 70 W similarly to that of commercially available high-power EDFAs able to generate 1.5 W.

The FOPA pump quality was investigated at 1566 nm, the wavelength in proximity of the FOPA gain fiber ZDW and therefore close to an optimal FOPA pump wavelength [7]. The FOPA pump was not distorted by Raman amplification above the level of −40 dB as shown by optical power spectra taken at the input and the output of the Raman gain fiber with resolution of 150 MHz (Fig. 2(b)). The FOPA pump linewidth of 3.7 GHz measured at 3 dB level (Fig. 2(b)) therefore was not affected by Raman amplification and was defined by dithering only. Dithering is known to cause signal degradation [34], but it is inevitable in state-of-the-art FOPAs [35]. OSNR of the Raman-amplified FOPA pump defined by the Raman amplified spontaneous emission (ASE) noise was 50 dB as shown by the optical power spectrum taken at the Raman gain fiber output with resolution of 0.1 nm (Fig. 2(b)). A RIN of the Raman-amplified FOPA pump was measured to be up to −130 dB/

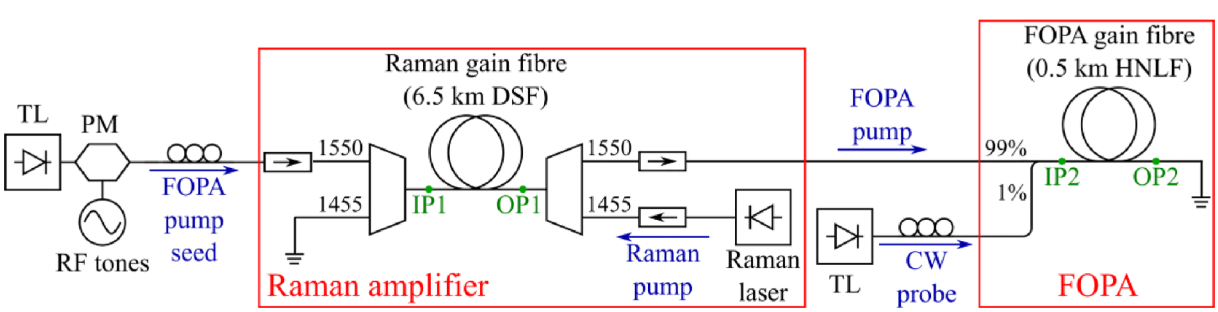

Fig. 1. Experimental setup for Raman-amplified pump characterization and its employment in FOPA. TL – tunable laser, PM – phase modulator, RF – radio frequency, CW – continuous wave.

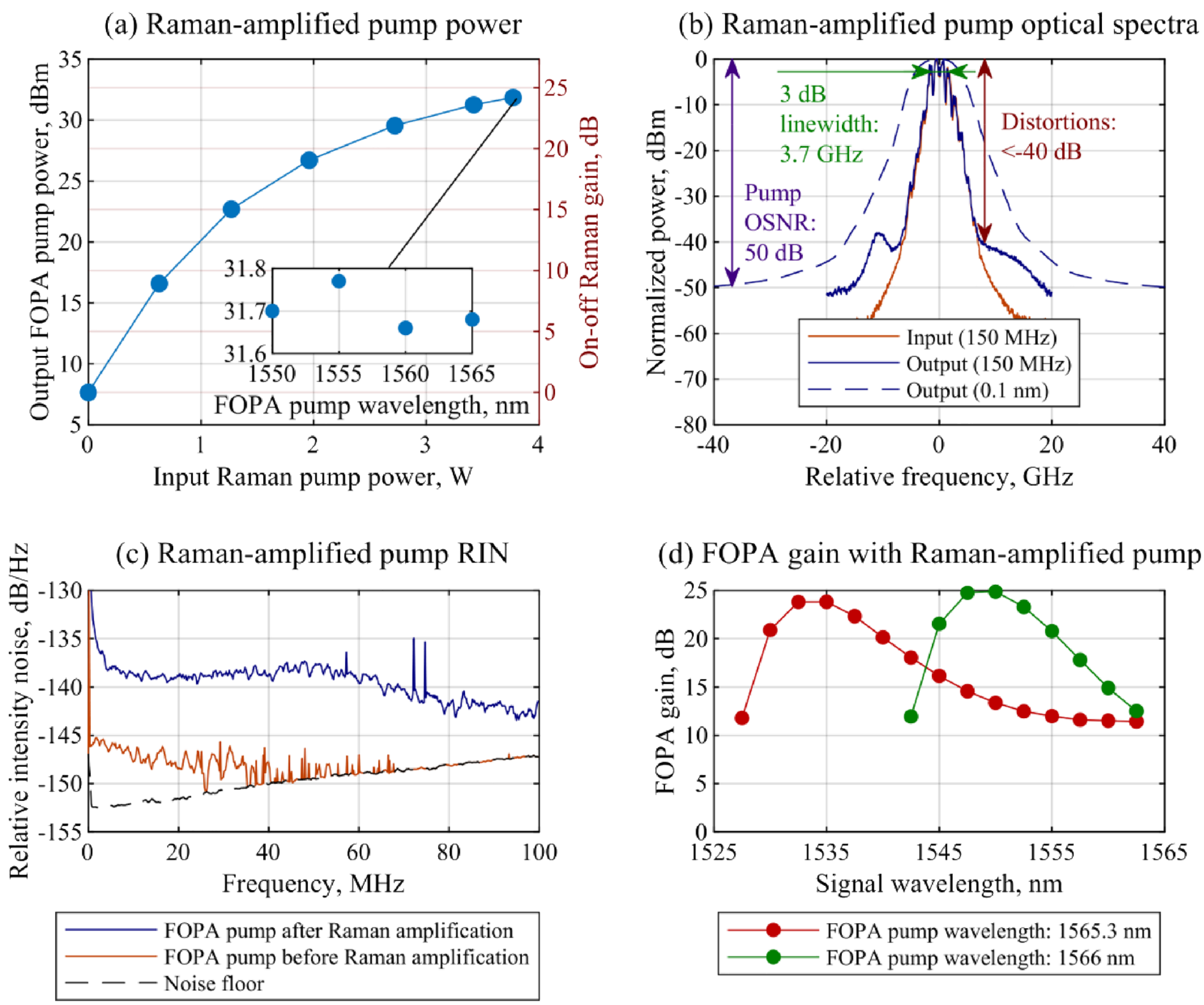

Fig. 2. Experimental characterization of the Raman-amplified FOPA pump. (a) Output power (at OP1) and on-off gain at 1550 nm versus input Raman pump power (at OP1). FOPA pump output power (at OP1) versus its wavelength for the maximum input Raman pump power of 3.8 W is shown inset. (b) Normalized for visual aid optical spectra of the FOPA pump (at 1566 nm) measured at the input of the Raman gain fiber (orange curve) and the output of the Raman gain fiber (blue curves) with resolution bandwidth of 150 MHz (solid curves) and 0.1 nm (broken curve). (c) RIN of the FOPA pump at 1566 nm measured before and after Raman amplification. (d) Experimental gain spectra of FOPA employing Raman-amplified pump at wavelengths of 1566 nm and 1565.3 nm.

Hz at frequencies under 4 MHz and was in the range of -140 ± 3 dB/Hz above 4 MHz [36] (Fig. 2(c)). The RIN spikes at ~75 MHz were attributed to the FOPA pump dithering. Employment of a pump with such OSNR and RIN in FOPA is likely to introduce a small penalty on the noise figure [37,38]. An improvement of the Raman-amplified pump quality and consequently the FOPA noise figure is possible by employing in the Raman amplifier a second-order pumping [39], two-stage design [40], or a different gain fiber [41].

The FOPA pump power at the input of the FOPA gain fiber was 1 W (30.1 dBm) due to 1.6 dB power loss between OP1 and IP2 (Fig. 1). Depending on the FOPA pump wavelength, the FOPA gain was reaching a peak of 24.9 dB or spanning over an EDFA equivalent 35 nm bandwidth with a minimum of 11.4 dB (Fig. 2(d)). This result demonstrates that FOPA employing Raman-amplified pump is capable of providing a broadband high gain. Moreover, a Raman-amplified pump can be employed in any state-of-the-art FOPA design to enable its implementation in different spectral bands.

Although the experiment has been performed in the C band, it is extendable beyond this range if suitable components, especially pump lasers and the FOPA gain fiber, are procured. Both Raman laser and seed laser suitable for this experiment are commercially available with a selection of emission wavelengths between 1100 nm and 1700 nm thus allowing to produce a pump for FOPA anywhere within this range. In turn, the main characteristic of the FOPA gain fiber, its ZDW, can be designed to be any value from ~ 1300 to ~ 1650 nm by engineering the fundamental mode waveguide dispersion [42]. In addition, ZDW below 1300 nm can be obtained in fibers guiding higher-order-modes [43]. Note, a high nonlinearity of the FOPA gain fiber is desirable but not necessary, because high FOPA gain can be obtained in fibers with low nonlinearity [44]. Overall, given the present availability of critical components, a similar experiment can be readily performed anywhere within the appealing for optical communications range 1310–1625 nm as well as beyond this range.

The first to the best of our knowledge FOPA employing Raman-amplified pump has been demonstrated and proved to be viable. It has been envisaged that this design can be employed to implement FOPA at any wavelength in range 1310–1625 nm and beyond. The Raman amplifier has provided an output power of 1.5 W sufficient for broadband FOPA and has allowed for the FOPA pump wavelength tuneability across > 15 nm range, typical for high-power EDFA. An energy efficiency of this Raman amplifier has matched that of EDFA. The FOPA pump has not been broadened by Raman amplification, but optimization of the Raman amplifier in terms of RIN and OSNR would be required to avoid penalties on the FOPA noise figure.

3. Broadband EDFA-free Raman-assisted optical phase conjugation /wavelength conversion

In this section we demonstrate broadband OPC which pump is amplified solely by virtually wavelength unrestricted Raman gain. This allows to eliminate operation wavelength constraints imposed by (Erbium) doped fiber amplifiers typically employed for OPC pump amplification. Importantly, all results and discussion on OPC are also applicable to wavelength conversion.

The OPC is treated separately from FOPA because it is incompatible with pump broadening [26] (e.g. dithering) implemented in FOPA to mitigate SBS. Therefore, a Raman gain fiber with a higher SBS threshold was employed in this section to increase the allowed OPC pump power and consequently to improve conversion bandwidth [2]. In addition, the OPC was performed concurrently with the OPC pump amplification in a single Raman gain fiber making this arrangement a RA-OPC to improve the conversion efficiency [31].

3.1. Experimental setup

Fig. 3 shows an experimental setup to amplify an OPC pump by Raman gain and to perform EDFA-free RA–OPC. A continuous-wave single-polarization OPC pump was sourced from a 100 kHz linewidth tunable laser (TL) with a maximum power of 40 mW. The OPC pump was passed through a phase modulator (PM) and guided to a Raman amplifier. A polarized continuous wave probe for the RA-OPC characterization was sourced from a 100 kHz linewidth laser tunable across C or L band and coupled with the OPC pump before the Raman amplifier using 1% coupler. The Raman amplifier employed a 500 m long HNLF with ZDW of ~1565 nm and nonlinearity of ~8.2 $W^{-1}km^{-1}$, which was backward pumped by a commercial Raman fiber laser operating at 1455 nm with a maximum pump power of 5 W and 3 dB linewidth < 2 nm. The backward pumping scheme was chosen to reduce the Raman pump noise transfer to the amplified OPC pump and the phase conjugated wave [33]. The OPC pump power reaching the input of the Raman gain fiber (IP1) was 9.3 mW (9.7 dBm).

Although SBS mitigation [35] by phase-modulation (dithering) of the OPC pump distorts generated phase-conjugates [26], some dithering can be tolerated if digital signal processing is employed to compensate for the induced distortion [45]. Therefore, two dithering scenarios were explored in this work: (a) phase modulation of the OPC pump was turned off; (b) the OPC pump was phase modulated with a 100 MHz tone.

3.2. Results and discussion

An employable Raman gain was limited by SBS of the OPC pump. Therefore, Raman gain was adjusted by tuning the Raman pump power (Fig. 4(a)) whilst monitoring presence of SBS via RIN measurements of the output OPC pump [46]. The highest Raman gain not inducing SBS of the OPC pump was employed for each dithering scenario. In the no-dithering scenario Raman pump power of 3 W allowed for on-off gain of 15.4 dB and amplified the OPC pump up to 230 mW (23.6 dBm) without inducing SBS. In the 100 MHz dithering scenario the highest available input Raman pump power (at OP1) of 3.9 W was has allowed for on-off gain of 18.5 dB and output OPC pump power of 470 mW (26.7 dBm) without inducing SBS.

Fig. 4(b) shows experimental optical spectra at the input (IP1) and the output (OP1) of the Raman gain fiber and demonstrates an example phase-conjugation of a −20 dBm probe (‘signal’) at 1550 nm in the no dithering scenario with 15.4 dB Raman gain. Although an input OPC pump power was only 9.3 mW (9.7 mW), a high conversion efficiency of 1.9 dB (measured as shown at Fig. 4(b)) was achieved because of Raman amplification of the OPC pump, signal and phase-conjugate itself. The OPC pump OSNR was 64.1 dB at the end of the Raman gain fiber implying negligible noise transfer from the OPC pump to the phase conjugate [37]. The phase-conjugate OSNR was 30.9 dB (Fig. 4(b)) and it scaled as shown in Eq. (1) with input signal power P_s, conversion efficiency G_i and Raman ASE power P_{ASE} corresponding to the phase-conjugate wavelength. Therefore, OSNR of the phase conjugate could be improved significantly by increasing input signal power.

$$\text{Phase conjugate OSNR} = P_s + G_i - P_{ASE} \quad (1)$$

Conversion efficiency was measured in a range of ‘signal’ probe wavelengths 1530–1600 nm for two dithering scenarios with corresponding Raman gains of 15.4 dB and 18.5 dB (Fig. 5(a)). In the no dithering scenario conversion efficiency has reached a peak of 2.5 dB and has been positive across a range of 25 nm. For comparison, a positive conversion efficiency range is typically limited to ~30 nm in prominent works on broadband OPC addressing limitations on pump dithering [27,28]. Therefore, this work demonstrates that a comparable performance can be achieved without implementation of EDFA. In addition, a positive conversion efficiency over a superior range of 60 nm has been achieved in this work with an employment of 100 MHz dithering (in principle, compensable by digital signal processing). The 100 MHz dithering scenario also features conversion efficiency up to 10.2 dB and at least −3 dB across all measurement range of 70 nm and beyond it.

The broad wavelength range of phase conjugation in this experiment is attributed to the high parametric pump power (up to 470 mW) achieved in the HNLF. A high conversion efficiency (> 0 dB) is delivered by Raman amplification of both signals and their phase conjugates. Although single Raman pump gain bandwidth does not exceed 35 nm, the Raman gain band location immediately aside of the OPC pump essentially doubles the bandwidth of Raman gain contribution towards conversion efficiency. Indeed, location of the Raman ASE noise at Fig. 5(c) demonstrates that Raman gain mostly exists in the range 1530–1565 nm where conversion efficiency is improved by Raman amplification of the signals. On the other hand, conversion efficiency of signals in the range 1565–1600 nm is boosted by Raman amplification of their phase conjugates produced in the 1530–1565 nm range.

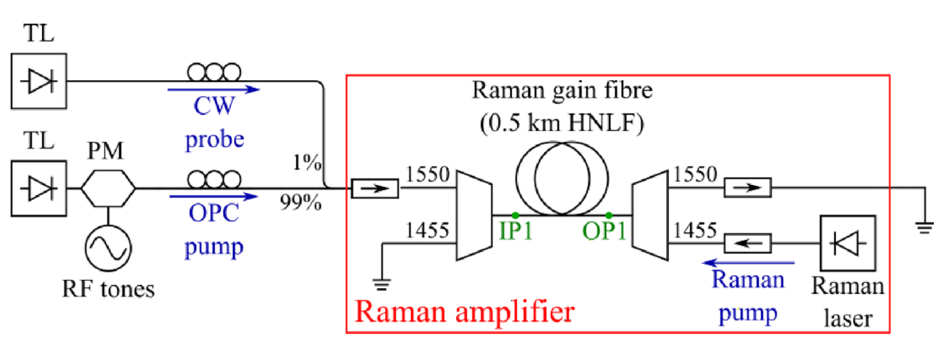

Fig. 3. Experimental setup of broadband EDFA-free RA-OPC.

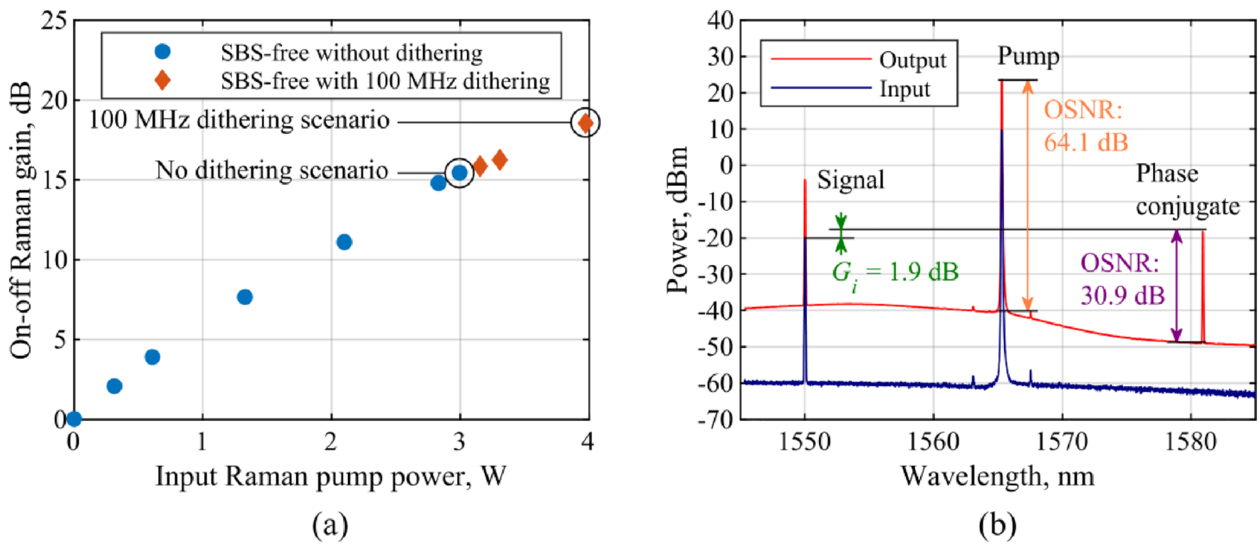

Fig. 4. (a) Experimentally measured on–off Raman gain of the OPC pump. Dithering requirements to keep SBS negligible as well as operation points for two explored scenarios are indicated. (b) Experimental optical spectra (resolution of 0.1 nm) at the input and output of the Raman gain fiber showing RA-OPC in the no dithering scenario.

Fig. 5(b) shows phase-conjugate OSNR for input signal power of 0 dBm. It was calculated by substituting into Eq. (1) an input signal power of 0 dBm, an experimentally measured conversion efficiency (Fig. 5(b)) and a Raman ASE noise power (Fig. 5(c)). The phase-conjugate OSNR was > 34 dB across all measurement range in both scenarios and reached > 50 dB across 15 nm/30 nm range range in scenarios with 15.4 dB/18.5 dB Raman gain respectively (Fig. 5(b)). The phase-conjugates of the signals < 1565 nm has ~10 dB higher OSNR than phase conjugates of signals > 1565 nm, because the former are produced at wavelengths > 1565 nm where Raman ASE noise power is low (Fig. 5(c)) and the latter are produced in the high ASE noise power range (1530–1565 nm).

The demonstrated RA-OPC allows for phase-conjugation/wavelength conversion of the whole C band with positive conversion efficiency and high OSNR. The employed input OPC pump power of < 10 mW does not require amplification by EDFA, so this experiment could be performed anywhere between 1310 nm and 1625 nm and beyond this range similarly to the FOPA employing Raman-amplified pump. Additionally, bandwidth and symmetry of the conversion efficiency spectrum can be further improved by optimization of wavelengths and powers of the Raman and the OPC pumps.

4. Summary

We have proposed, demonstrated and characterized the employment of a discrete high-gain Raman amplifier as the sole pump amplifier for FOPA. The FOPA pump obtained through Raman amplification had a power of 1.5 W, linewidth of 3.7 GHz, OSNR of 50 dB and RIN ≲–140 dB/Hz and thereby was suitable for employment in FOPA. For instance, we have employed the Raman-amplified pump in FOPA and achieved a peak gain of 24.9 dB or a minimum gain of 11.4 dB over 35 nm. Additionally, we have demonstrated an EDFA-free RA–OPC to provide a positive conversion efficiency over up to 60 nm, whereas the input phase conjugating pump power of < 10 mW is boosted by Raman

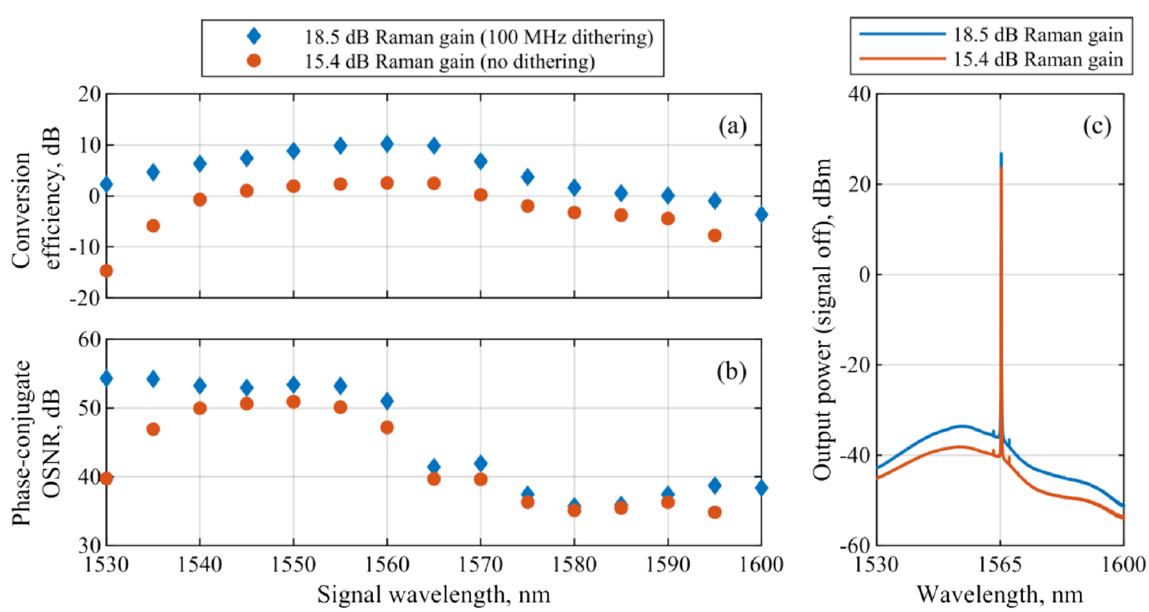

Fig. 5. Experimentally measured for two dithering scenarios and corresponding Raman pumping levels: (a) OPC conversion efficiency; (b) phase conjugate OSNR adjusted for input signal power of 0 dBm; and (c) output optical spectra (resolution of 0.1 nm) of Raman ASE noise and OPC pump.

gain. An amplification of pump for FOPA and related applications by a virtually wavelength unrestricted Raman gain can therefore enable parametric amplification, optical phase conjugation or wavelength conversion in any wavelength range where a suitable for parametric amplification fiber can be obtained.

CRediT authorship contribution statement

V. Gordienko: Conceptualization, Methodology, Investigation, Visualization, Writing - original draft, Writing - review & editing. **M.F.C. Stephens:** Resources, Supervision, Writing - original draft. **F.M. Ferreira:** Writing - original draft, Writing - review & editing. **N.J. Doran:** Supervision, Project administration, Funding acquisition, Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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