Raman-Generated Pump and Its Use for Parametric Amplification and Phase Conjugation

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Abstract *We demonstrate the use of high gain Raman amplification for generating a high power pump for use within a fibre optical parametric amplifier and an optical phase conjugator showing potential for application across the entire low loss fibre transmission window.*

Introduction

Fibre optical parametric amplifiers (FOPA) have potential to enable transmission bandwidth expansion beyond the C and L bands, thus breaching current capacity limits[1] due to their ability to provide ultra-wide gain[2] and in principle to operate at arbitrary wavelengths[3]. However, practically realisable FOPAs typically require an EDFA to generate a parametric pump (PP) of sufficient power (≥1W) and quality, having narrow linewidth and low noise. Significant FOPA research progress[4] has therefore been restricted to the EDFA band and around it. A number of methods have previously been reported to avoid this EDFA restriction such as the use of: high-power wavelength conversion; semiconductor optical amplification; and Ytterbium doped fibre amplification. However, for various reasons (noise figure, ubiquity, etc.) these approaches have not provided a practical substitute for the EDFA. It is surprising therefore that, to the best of our knowledge, non-resonant Raman gain has not been explored for FOPA PP generation. Replacing the EDFA with a high-power Raman amplifier[5] would grant the FOPA the flexibility to operate anywhere in the low loss window of modern fibres (1310–1625nm). This wavelength flexibility will also be required for optical phase conjugation (OPC) applications outside of the EDFA band in future optical communications.

This paper explores the suitability of Raman-generated PP for broadband FOPA and OPC flexible operation outside of the EDFA band. Previous works on Raman sources providing a sufficient power of >1W are either not narrow linewidth[6] or are not wavelength flexible arrangements[7] and none of them describe the generated wave in terms of its applicability for FOPAs. In contrast, we generate a 1.5W pump using a high-power Raman amplifier reproducible anywhere in the low loss window and characterise this pump in the FOPA context. Furthermore, for the first time to the best of our knowledge, we employ a Raman-generated PP in the FOPA to obtain a gain up to 24.9dB and over >35 nm. In addition, we perform EDFA-free Raman-assisted OPC (RA-OPC) with internal conversion efficiency (CE) >0dB over a 60nm range. In contrast to previous works on the RA-OPC demonstrating an improvement of the nonlinear crosstalk[8] and the CE[9], we focus on the Raman amplification of a low input power PP seed (10mW) to achieve a broadband OPC requiring high PP power. The proof of concept employment of the Raman-generated PP in the FOPA and the OPC is performed within the C and L bands, but it is extendable beyond this range.

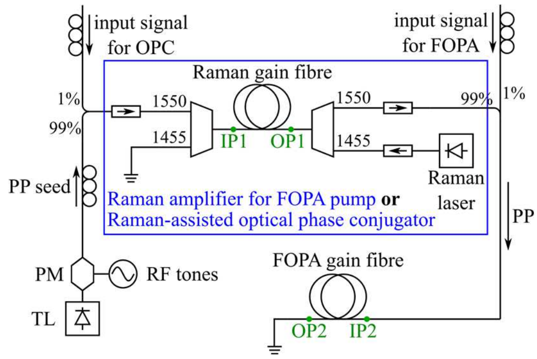

Fig. 1: Experimental setup of FOPA employing a Raman-generated pump and RA-OPC employing low power parametric pump (PP) seed.

Experimental setup

The experimental setup is shown in Fig. 1. A PP seed was provided by a single-polarisation continuous wave 100kHz linewidth tuneable laser (TL) with a maximum power of 40mW. The PP seed was first phase-modulated (dithered) with three RF tones to mitigate stimulated Brillouin scattering (SBS) and coupled into a Raman gain fibre for amplification to obtain a high-power PP. The Raman gain fibre, a 6.5km long dispersion shifted fibre with zero dispersion wavelength (ZDW) ~1543nm, was backward pumped by a Raman fibre laser operating at 1455nm with a maximum power of ~5W. The PP was then coupled with a signal probe derived from a TL and guided into a separate FOPA gain fibre for signal probe parametric amplification. The FOPA gain fibre was a 500m long highly nonlinear fibre (HNLF) with $\gamma \sim 8.2W^{-1}km^{-1}$ and ZDW ~1565nm.

For demonstration of RA-OPC, two scenarios were explored: a) no dithering (to avoid distortion of the generated phase-conjugates) and b) one-tone dithering (compensatable via digital signal processing[10]). The PP seed and a signal probe were coupled into the Raman gain fibre for OPC along with Raman amplification of the PP, signal probe and the phase-conjugate. The Raman gain fibre was the HNLF removed from the FOPA.

Optical spectra and powers were non-intrusively measured at the inputs and outputs of gain fibres (points IP1, OP1, IP2 and OP2 at Fig. 1). The PP seed power was maximised achieving 9.3mW at IP1. The highest achievable Raman pump power at OP1 was 3.8W.

The employed PP seed source and the Raman laser are commercially available with a selection of emission wavelengths anywhere in the fibre low-loss window, so if suitable fibres and components are sourced the experiment could be performed anywhere in this range.

FOPA employing a Raman-generated pump

The PP output power and on-off gain were measured as the Raman pump power was adjusted (Fig. 2). The highest on-off gain of 24dB and an output PP power of 1.5W suitable for broadband FOPA applications were achieved. The same power was observed across a 15nm wide range of PP wavelengths allowing for the PP wavelength tuneability (Fig. 2). The generated PP was analysed at the wavelength of 1566nm which is close to the FOPA gain fibre ZDW. Optical spectra of the PP with resolution of 150MHz show that the PP is not distorted by amplification above the level of -40dB (Fig. 3). The PP 3dB linewidth of 3.7GHz was therefore defined by the dithering known to cause signal degradation[11], but inevitable in state-of-the-art FOPAs. The power ratio between the PP and the Raman amplified spontaneous emission (ASE) noise within 0.1nm bandwidth was 50dB (Fig. 3). Fig. 4 shows that the Raman-generated PP RIN was increased by ~10dB/Hz compared to the PP seed RIN and was around ~-140dB/Hz. Such PP OSNR and RIN will likely introduce a small penalty on the FOPA noise figure[12,13], so a further optimisation of the Raman-generated PP quality may be required in future work.

The 1.5W PP output power using a 5W Raman pump implies optical power efficiency of 30%. The electrical power consumption of the Raman pump was <70W – this is similar to that of a high-power EDFA able to generate 1.5W.

The PP power at IP2 was 1W due to 1.6dB power loss between OP1 and IP2. Depending on the PP wavelength, the FOPA gain was reaching a peak of 24.9dB or spanning over an EDFA equivalent 35nm bandwidth with a minimum of

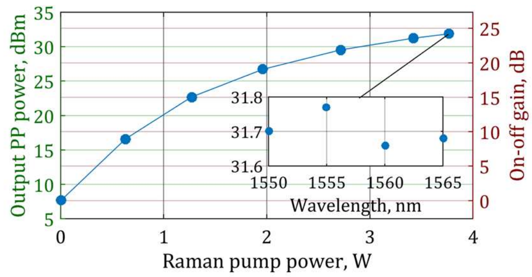

Fig. 2: The PP power at OP1 and on-off gain versus Raman pump power at OP1. The maximum output PP power [dBm] versus wavelength is shown inset.

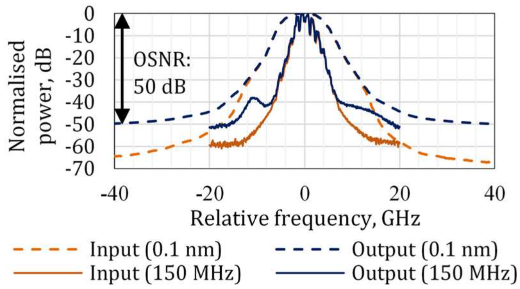

Fig. 3: Normalised to aid visual comparison optical spectra of the PP at the input and output of the Raman gain fibre with resolution of 150 MHz and 0.1 nm.

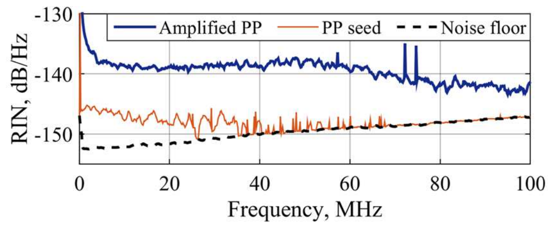

Fig. 4: RIN of the PP seed and the Raman-generated PP for FOPA.

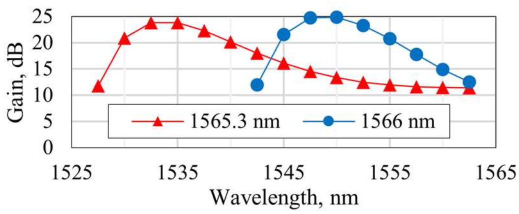

Fig. 5: Gain spectra of FOPA employing Raman-generated PP at wavelength of 1566 nm or 1565.3 nm.

11.4dB (Fig. 5). Overall, the FOPA employing a Raman-generated PP can provide a broader and higher gain than the employed Raman amplifier.

Low input PP power broadband RA-OPC

The PP wavelength was set to 1565.3nm as it allowed for a broad FOPA gain. Raman gain was adjusted by tuning the Raman pump power to find the highest SBS-free output PP power which was found to be 230mW/480mW without/with one-tone dithering. The RA-OPC internal (between IP1 and OP1) conversion efficiency (CE) was measured for these two cases in a range of signal wavelengths 1530–1600nm using input signal probe power of -20dBm at IP1. The measured

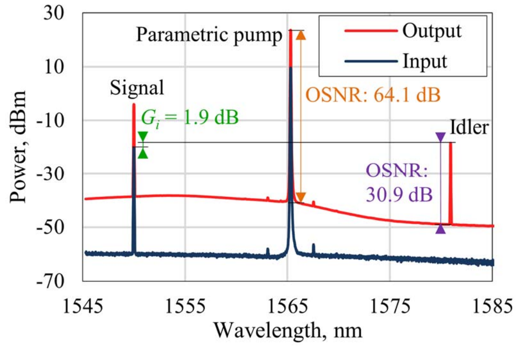

Fig. 6: Example optical spectra at the input and output of the RA-OPC showing measurements of the output PP OSNR, conversion efficiency and the idler OSNR.

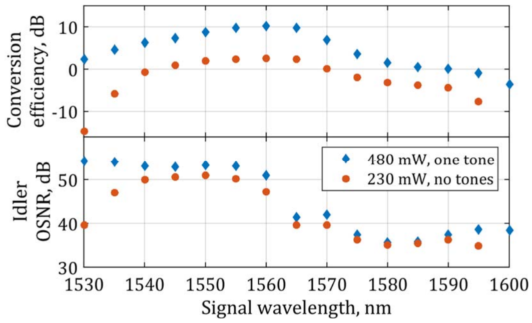

Fig. 7: Conversion efficiency and idler OSNR without and with one-tone dithering. Corresponding output PP powers were 230 mW and 480 mW.

output PP OSNR of 64.1dB (Fig. 6) has been shown to introduce no noise figure penalty[12].The idler OSNR was limited by Raman ASE, so it was only 30.9dB at Fig. 6 due to low input signal power. Fig. 7 shows measured CE and the idler OSNR calculated using Eq. (1) based on the input signal power P_s assumed to be 0dBm and measured CE G_i and Raman ASE noise power P_{ASE} at the idler wavelength.

$$OSNR_{idler} = P_s + G_i - P_{ASE}. \quad (1)$$

A positive CE was observed without/with one-tone dithering for signals in a 25nm/60nm range. The idler OSNR was >50dB within 15nm/30nm of this range. The demonstrated RA-OPC using a low power PP seed allows for a transparent RA-OPC of almost whole C band with high OSNR. A gain fibre optimal in terms of length, nonlinearity and ZDW is viewed to provide even broader positive CE range with an improved symmetry.

Conclusions

For the first time to the best of our knowledge, we have generated a 1.5W parametric pump using a Raman amplifier, examined its suitability for parametric amplification and employed it within a FOPA to obtain a peak gain of 24.9dB and a minimum gain of 11.4dB over 35nm. A Raman-generated pump linewidth of 3.7GHz, OSNR of 50dB and RIN around -140dB/Hz imply a small noise figure penalty and a need for further optimisation to achieve the best FOPA performance. Additionally, we have demonstrated a broadband EDFA-free RA-OPC suggesting an internal conversion efficiency >0dB over 60nm range. The demonstrated FOPA and RA-OPC use a low power pump seed amplified by a wavelength unrestricted Raman amplifier, so a pump for them can be generated anywhere in the low loss transmission window. This experiment is a step towards flexible FOPA and OPC operation outside of the EDFA band.

Acknowledgements

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