Continuous-Wave One-Pump Fiber Optical Parametric Amplifier with 270 nm Gain Bandwidth

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Abstract: *We report operation of a continuous-wave one-pump fibre OPA with net gain between 1447 nm and 1717 nm. We used a 114 m long step-index highly-nonlinear fibre, and 5 W of pump power.*

Introduction

Fibre optical parametric amplifiers (OPAs) have the potential for providing gain spectra that are several hundred nanometres wide, by using either one or two pumps[1]. To obtain a wide gain spectrum, it is necessary to use a fibre with a large nonlinearity coefficient γ, and/or high pump power P_0. To date the widest gain spectra for one-pump OPAs (1P-OPAs) in the telecommunication range have been obtained with step-index highly-nonlinear fibres (HNLFs), with $\gamma \approx 15$ W^{-1}km^{-1}, and pulsed pumps with peak powers as high as 80 W. In this manner, gain spectra as wide as 730 nm have been demonstrated[2]. However, because such OPAs operate in a pulsed mode, they are not suitable for telecommunication applications, such as the amplification of WDM spectra. Continuous-wave (CW) operation is required for such applications. To date the widest gain spectra obtained with CW 1P-OPAs correspond to: (i) over 150 nm with gain between 5 and 16 dB[3]; (ii) gain between 10 and 13 dB over about 100 nm[4].

Here we report a CW 1P-OPA with net gain over 270 nm, which to the best of our knowledge is the widest to date for this type of amplifier. The gain medium was a 114-m long step-index HNLF with γ = 15 W^{-1}km^{-1}, and the CW pump power was about 5 W.

Experiments

Fig.1 shows the experimental setup for 1-pump OPA. For the pump, a tunable laser (TL1) is first phase modulated (for SBS suppression) and amplified by a 10-W EDFA. It is then injected into the HNLF through a 99/1 coupler after the ASE of the EDFA is rejected using a 1-nm bandpass filter. The HNLF had the parameters: $\beta_3 = 7.5 \times 10^{-41}$ s^{3}m^{-1}, $\beta_4 = 2.8 \times 10^{-57}$ s^{4}m^{-1}, λ_0 = 1570 nm^5.

We first operated the OPA without any input signal. The output spectrum for pump wavelength λ_P= 1570.33 nm is shown in Fig.2. It corresponds to the ASE generated by the OPA itself. It is a good indication of where OPA gain is available. The fact

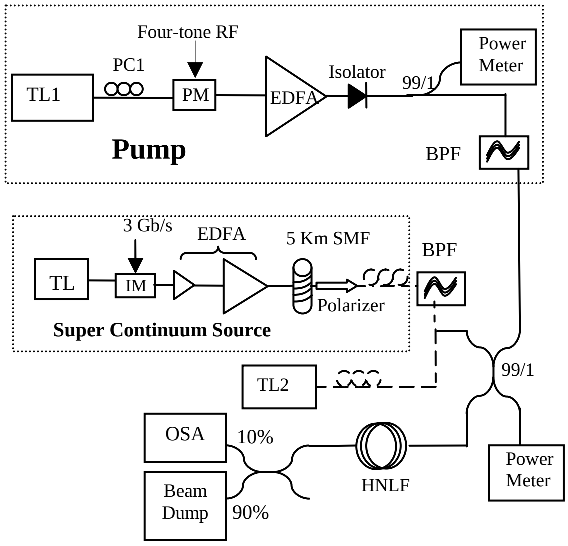

Fig. 1: Experimental Setup for one-pump OPA (A supercontiniuum source is used as signal for wavelengths beyond 1640nm.)

that the spectrum is wider on the Stokes side of the pump is attributed to the influence of stimulated Raman scattering (SRS). This spectrum indicates the presence of gain over a range of nearly 300 nm.

In order to measure the gain itself, we then injected a narrowband signal into the OPA. Because the gain spectrum is so wide, we had to use two different sources to cover most of it. We first injected a signal generated by another laser source (TL2) tunable in the [1440 nm-1640 nm] range. A polarization controller was used to align the signal state of polarization (SOP) with the pump. Pump and signal were injected into the HNLF through a 99/1 coupler. 90% of the HNLF output was diverted into a beam dump, while the remaining 10% was analyzed on an optical spectrum analyzer (OSA).

Fig.3 depicts several gain spectra recorded for different signal SOPs. The pump wavelength is λ_P = 1570.33 nm. The star curve corresponds to signal SOP optimized to maximize gain near 1520 nm; then the maximum gain was similar on both sides of the pump. The negative gain values below

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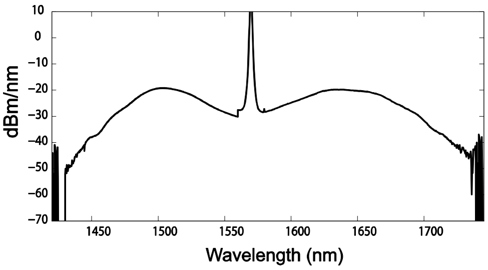

Fig. 2: ASE spectrum generated by the OPA. It indicates presence of gain over a region of about 300 nm.

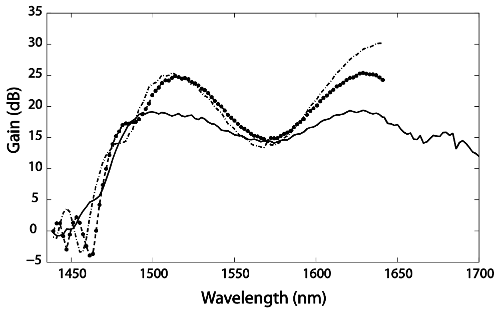

Fig. 3: Gain spectra for different signal SOPs.

1460 nm are attributed to the real part of the Raman susceptibility. The dot-dashed line is for signal SOP optimized to maximize gain near 1640 nm. It is seen that in this case the maximum gain is lower on the anti-Stokes side. It is attributed to Raman interaction on the Stokes side and to the fact that SOP evolution depends on the wavelength[6]. The effect of the latter becomes evident for large spans (i.e. >100 nm). This emphasises the need for redone SOP optimization for very broadband 1P-OPAs when the maximum power is desired. One other noteworthy observation was that the gain on the Stokes side tends to be less sensitive to signal polarisation. The solid curve was obtained by optimizing signal SOP to suppress the negative gain values below 1460 nm, thereby extending the gain spectrum to 270nm.

To measure gain beyond 1640 nm, we made a supercontiniuum (SC) source, Fig.1. It consisted of a 5-km spool of SMF, into which we injected pulses with peak power of about 20W. The output spectrum was quite flat, and extended from 1550 nm to 1750 nm, Fig.4. Since the output light is unpolarised a polariser is used after the source in order to have polarised light. The SC was filtered with a 1-nm bandwith tuneable filter, and injected into the OPA. In this manner we were able to extend the gain measurement from 1640 to 1700 nm (limited by the filter); the result is shown in Fig. 3 as part of the

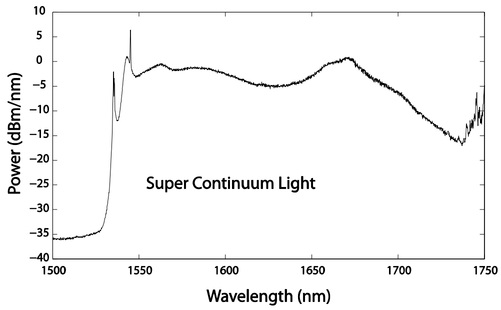

Fig. 4: Supercontiniuum source output. The power reaches 1 mW over 200 nm.

solid curve. It can be seen that there is still considerable gain at 1700 nm, and that according to the OPA ASE measurement, appreciable gain should still be available well beyond 1700 nm. Since we could not measure the gain itself in that region, we used a common symmetry argument to estimate the gain bandwidth by $\Delta\lambda = 1/(\frac{2}{\lambda_P} - \frac{1}{\lambda_1}) - \lambda_1$, where λ_1=1447 nm is the limit for the solid curve. This yields $\Delta\lambda$=270 nm.

Conclusion

We have demonstrated a CW 1P-OPA with net gain over 270 nm, which is a new record for CW fiber OPAs. We used a 114-m long step-index HNLF and about 5 W of pump power. The large bandwidth is attributed to the high pump power, and to the relatively small value of β_4 .Such an amplifier could find applications in the amplification of wideband high-speed WDM communication signals.

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