U-band Raman Gain Tailoring and RIN Transfer Suppression using a Shaped, Broadband Incoherent Pump

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Abstract *Using a wavelength selective switch, we shape the high-power amplified spontaneous emission of an EDFA to obtain a finely controlled, incoherent Raman pump. This pump is used to obtain U-band Raman gain with suppressed RIN transfer and controllable gain spectrum. ©2023 The Author(s)*

Introduction

Fibre-based Raman amplification is a versatile technology that is generally able to offer gain throughout the entire transmission window of its gain fibre, provided suitable pumps can be sourced. Indeed, with the Raman response of a silica fibre typically extending across a bandwidth of ~20nm under excitation from a single-wavelength pump [1,2], the adoption of multi-wavelength pumping and meticulous control of pump powers is required to realise a Raman amplifier with broadband (>30nm) gain (see [2] where a gain bandwidth of 80nm was demonstrated in a 4-pump amplifier).

It is generally desirable to use low-quality pumps (nanometre-linewidth diode lasers) in Raman amplification, not only due to cost considerations, but also to avoid the pump undergoing spurious stimulated Brillouin scattering. Given the fast response time of the Raman effect, transfer of relative intensity noise (RIN) from the pump to the amplified signals can severely detriment performance. With high quality pumps dismissed as above, RIN transfer is reduced by allowing the pump and signals to 'walk past' each other, either due to fibre dispersion or counter-propagation. This effect essentially allows RIN transfer to be averaged out, to an extent that depends on factors including fibre length and chromatic dispersion. Of course, higher speed pump power fluctuations will be averaged out more rapidly than slower ones and this leads to an interesting conclusion: the broader the bandwidth of pump that is used to obtain Raman gain, the lower the total RIN transfer from the pump to the signal [3,4]. This fact was exploited in [5] where a 10nm bandwidth pump was used to reduce RIN by 3.9dB relative to a narrowband semiconductor laser pump.

Recently, we demonstrated a U-band Raman amplifier [6] in both discrete and distributed configurations. There, we made use of the ASE of a high-power (2-5W) C-band EDFA to obtain a broadband incoherent pump source, delivering ripple-free gain over a 23nm 3-dB bandwidth. The spectral shape of the incoherent pump was determined naturally by the gain profile of the EDFA itself (as well as the injected seed ASE) and, as such, was not necessarily ideal, with a substantial amount of its total power centred around a peak in power at 1543nm.

In this work, we combine a wavelength selective switch (WSS) with C-band EDFA sourced high-power ASE to create a broadband (4THz, 30nm), incoherent pump with controllable spectral shape. Not only does this enable the extension of the 3-dB U-band gain bandwidth from 23nm in [6] to 34nm, but it also enables us to demonstrate the possibility for ripple-free gain tailoring through precision pump spectrum control. We use the system to measure the extent of RIN transfer for pumps with bandwidths ranging from 0.8nm (0.1THz) to 23nm (2.9THz).

Experimental Setup

Fig. 1 provides a schematic of the experimental setup used in this study. The pump is derived from the ASE of a high power (2W) EDFA. This output power was far beyond the specified power handling of the WSS used for spectral shaping and so the WSS was instead used to shape an ASE seed appropriately to obtain the desired output spectrum from the final EDFA stage. A low power EDFA was used to compensate for the loss of the WSS before the final, 2W EDFA. Once the pump had been synthesised, it was multiplexed with a test signal using a 3-port C/L multiplexer. The pump and (polarisation scrambled) signal were then launched into the gain medium (25km of spooled Corning SMF28-

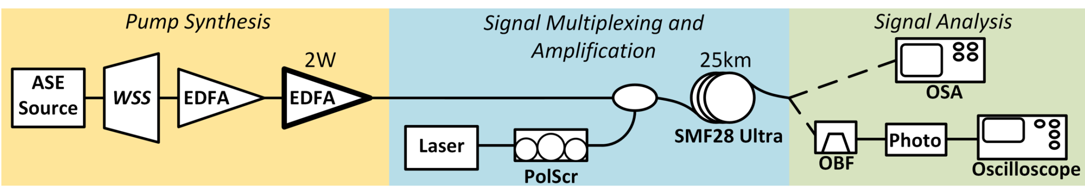

Fig. 1: Experimental setup

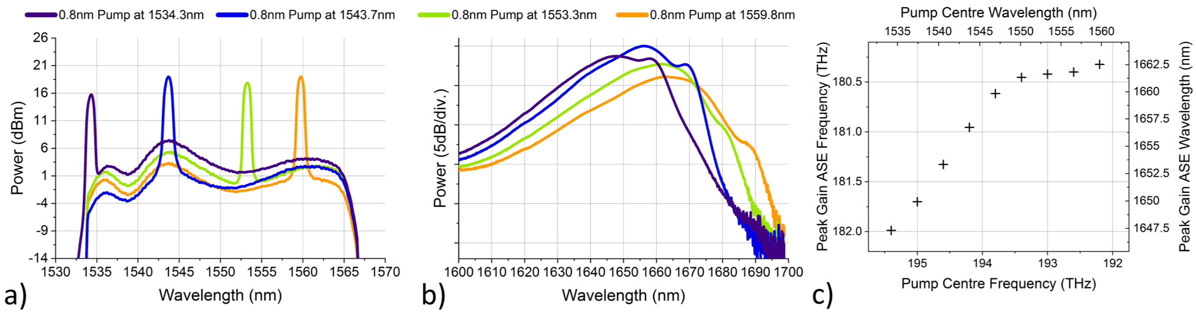

Fig. 2: a) Pump spectra b) Corresponding gain spectra c) Peak gain ASE frequency vs pump frequency.

Ultra). Since an objective of this study was to test the benefit of using a shaped, broadband source to suppress RIN transfer, we opted for a co-propagating pumping configuration, which is known to encourage RIN transfer compared to counter-propagating pumping. In a discrete Raman amplifier, forward pumping can offer improved (ASE derived) noise figure, owing to higher pump powers at the beginning of the fibre. Returning to the setup, once the pump and signal exited the fibre, the output was analysed either directly using an optical spectrum analyser (protected by a fixed attenuation) or using an oscilloscope, after passing an optical bandpass filter (to reject residual pump light) and photodetection.

Results

Gain Tunability

In the first study, the broadband pump was shaped via the WSS into a narrow, and flat-topped 100GHz band, the central wavelength of which was swept from 1534.3nm to 1559.8nm in 3.2nm steps, to explore the potential gain tuning range. Fig. 2-a shows a selection of the pump spectra trialled, whilst Fig. 2-b shows the resulting ASE observed in the gain band. This ASE will be used as an estimator of the gain spectrum of the amplifier, as a probe laser was not available that could cover the entire gain bandwidth. As can be seen, the longer the pump centre wavelength, the longer the peak gain ASE wavelength. This relationship is shown in Fig. 2-c, where the Gain Centre (defined as the frequency with peak ASE power) is traced as it varies with pump frequency and wavelength (note that the frequency axes are inverted). Between 193.5 (1549.3nm) and 195.5THz (1533.5nm) the points possess a gradient of ~0.9 (close to the expected value of 1) and an estimated Raman shift of 13.27THz (determined through linear fitting). Beyond this, further changes in pump frequency/wavelength result in little change in the gain centre. We believe these discrepancies are mainly due to the increased loss at longer (shorter) wavelengths (frequencies) due to infrared absorption in the silica fibre. As such, we expect more typical behaviour when the technique is applied to amplification at shorter wavelengths.

Gain Tailoring

In this study, a number of pump profiles were chosen to demonstrate the possibility of the approach to offer tailored gain spectra. The first case considered was that of a flat (and untilted) pump spectrum. The grey lines in Fig. 3-a and -b show the pump and the resultant ASE spectrum, respectively. Next, two flat, but tilted pump spectra were trialled, one with positive tilt (orange line) and one with negative tilt (blue line). In both cases, the difference in power between the two extreme wavelength edges was 7dB. As can be expected, the positively tilted spectrum (with its highest pump power at the long wavelength edge) provided an ASE spectrum that is relatively red shifted compared to the negative tilt case.

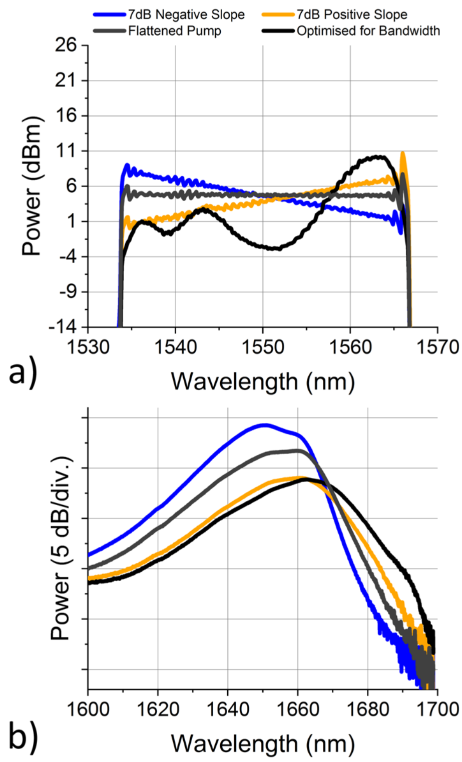

Fig. 3: a) A range of tested pump spectra b) their corresponding gain ASE spectra.

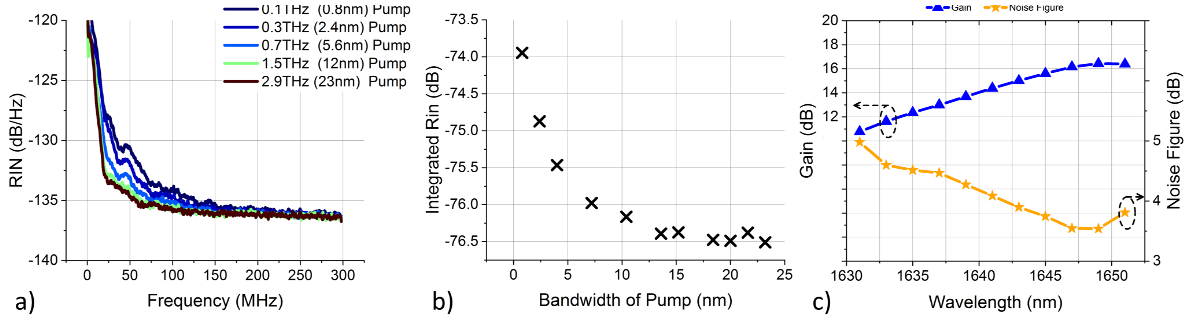

Fig. 4: a) RIN curves for various pump bandwidths b) Integrated RIN vs pump bandwidth c) Optical Noise Figure and Gain

The peak power of the ASE spectrum is ~6dB lower than for the negatively tilted case, and we believe that the onset of infrared absorption at these longer wavelengths, the lower total pump power (visible in Fig. 3-a) and pump-pump intraband Raman amplification contribute to this effect. Finally, a simple optimisation algorithm (an iterative proportional error feedback loop) to flatten the gain in order to offer the broadest gain bandwidth possible was tested (black line in Fig.3). Tab. 1 summarises the bandwidth of each tested pump scenario. The results show the sensitivity of the gain ASE to pump profile and the opportunity to improve gain bandwidth through appropriate pump selection. Although the performance of the bandwidth optimisation process was marred by the infrared absorption at longer wavelengths (as discussed earlier), it did discover a pump solution offering the widest bandwidth of the scenarios studied, albeit with compromised gain as the gain at the shorter wavelengths was effectively reduced to match the gain available at longer wavelengths. We believe that pumping at shorter wavelengths to move the gain band away from the infrared absorption edge of silica, would enable gain bandwidth broadening with no gain compromise.

Scenario	3-dB Bandwidth (nm)
7dB Neg. Slope	28.21
7dB Pos. Slope	30.91
Flattened Pump	33.12
Optimised Bandwidth	34.22

Tab. 1: Bandwidth of different scenarios

Noise Performance

One of the main motivations for adopting a broadband incoherent pump was to reduce RIN transfer. For this measurement, a photodiode and an oscilloscope were used to capture the intensity of an amplified test signal and the data was processed to obtain the RIN [7]. RIN was recorded for a range of pumps with rectangular spectra and a variety of widths. Fig. 4-a provides a selection of these plots spanning the pump bandwidth measurement range of 0.8nm to 23nm, centred at 1545.3nm. It is clear that the RIN overall is reduced with increasing pump bandwidth, especially between 25 and 150MHz. To better visualise this improvement, the RIN was integrated for each measurement between frequencies of 25 and 150MHz and the results plotted in Fig. 4-b against pump bandwidth. A 2.5dB reduction in total RIN transfer can be seen when the pump bandwidth is increased from 0.8nm to 20nm. Further increases beyond this value do not seem to offer further benefit, which is understandable if we recall that a single-wavelength pump results in ~20nm of gain.

Finally, we measured gain and noise figure (NF) measurement (using an OSA), the latter being performed to provide confidence that a Raman amplifier constructed with such a broadband pump does not exhibit excessive NF. Fig. 4-c provides plots of net gain (blue triangles) and NF (orange stars) across a wavelength range of 1631 to 1651nm (restricted by equipment availability) for the 'Flattened Pump' case shown in Fig. 3-a. Near the peak gain between 1643 and 1651nm, the NF lies below 4dB, reaching a minimum of 3.5dB at the peak gain wavelength.

Conclusions

We demonstrated a technique for the fine control of a broadband, incoherent pump source for Raman amplification. We studied the sensitivity of the ASE spectrum to the gain spectrum and showed that gain bandwidth can be increased through pump shaping. We confirmed that increasing pump bandwidth is a valuable strategy for reducing RIN transfer and showed that benefits can be had up to 2.5THz (~20nm C-band) pump bandwidths. Finally, we verified that using such a broad bandwidth pump does not compromise NF, with an NF of 3.5dB, coincident with the highest gain. Although our data suggest that RIN transfer shows little reduction beyond pump bandwidths of 20nm, we expect gain tailoring to continue to improve.

Acknowledgements

This work is supported by the EPSRC under the Laser Technologies for Future Manufacturing (EP/P027644/1) Platform Grant and Airguide Photonics (EP/P030181/1).

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