Research Article | Vol. 26, No. 6 | 19 Mar 2018 | OPTICS EXPRESS 7091
Optics EXPRESS

Low transmission penalty dual-stage broadband discrete Raman amplifier

LUKASZ KRZCZANOWICZ,* MD ASIF IQBAL, IAN PHILLIPS, MINGMING TAN, PAVEL SKVORTCOV, PAUL HARPER, AND WLADEK FORYSIAK

Aston Institute of Photonic Technologies, Aston University, Birmingham, B4 7ET, UK
**l.krzczanowicz@aston.ac.uk*

Abstract: We present a broadband (>70nm), dual stage, discrete Raman amplifier designed with small and standard core fibres to maximize gain and minimize nonlinearity. The amplifier provides ~19.5dB net gain, 22.5dBm saturation output power and a noise figure of <7.2dB. 120Gb/s DP-QPSK transmission over 38x80km at a pre-FEC BER $<3.8\text{x}10^{-3}$ is demonstrated.

Published by The Optical Society under the terms of the Creative Commons Attribution 4.0 License. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

OCIS codes: (060.1660) Coherent communications; (060.2320) Fiber optics amplifiers and oscillators; (190.5650) Raman effect; (140.3550) Lasers, Raman; (250.4480) Optical amplifiers.

References and links

1. M. N. Islam, "Raman amplifiers for telecommunications," IEEE J. Sel. Top. Quantum Electron. **8**(3), 548–559 (2002).
2. N. Gryspolakis, L. R. Chen, and T. Zambelis, "Performance of two-stage discrete fiber Raman amplifiers with and without all-optical gain clamping," Appl. Opt. **44**(1), 83–90 (2005).
3. D. Hamoir, J. Boniort, L. Gasca, and D. Bayart, "Optimized, two-stage architecture for Raman amplifiers," in Optical Amplifiers and Their Applications, A. Mecozzi, M. Shimizu, and J. Zyskind, eds., Vol. **44** of OSA Trends in Optics and Photonics (Optical Society of America, 2000), paper OMD8.
4. S. Namiki and Y. Emori, "Ultrabroad-band Raman amplifiers pumped and gain-equalized by wavelength-division-multiplexed high-power laser diodes," IEEE J. Sel. Top. Quantum Electron. **7**(1), 3–16 (2001).
5. Y. Emori and S. Namiki, "100nm bandwidth flat gain Raman amplifiers pumped and gain-equalized by 12-wavelength-channel WDM high power laser diodes," in Optical Fiber Communication Conference and the International Conference on Integrated Optics and Optical Fiber Communication, OSA Technical Digest Series (Optical Society of America, 1999), paper PD19.
6. L. E. Nelson, X. Zhou, B. Zhu, M. F. Yan, P. W. Wisk, and P. D. Magill, "All-Raman-Amplified, 73 nm Seamless Band Transmission of 9 Tb/s Over 6000 km of Fiber," IEEE Photonics Technol. Lett. **26**(3), 242–245 (2014).
7. M. A. Iqbal, L. Krzczanowicz, P. Skvortcov, A. El-Taher, I. D. Philips, W. Forysiak, J. D. Ania-Castañón, and P. Harper, "Performance characterization of high gain, high output power and low noise cascaded broadband discrete Raman amplifiers," in *Proceedings of 19th International Conference on Transparent Optical Networks (ICTON)* (2017), pp. 1–4.
8. S. A. E. Lewis, S. V. Chernikov, and J. R. Taylor, "Characterization of double Rayleigh scatter noise in Raman amplifiers," IEEE Photonics Technol. Lett. **12**(5), 528–530 (2000).
9. M. E. McCarthy, N. M. Suibhne, S. T. Le, P. Harper, and A. D. Ellis, "High spectral efficiency transmission emulation for non-linear transmission performance estimation for high order modulation formats," in *Proceedings of The European Conference on Optical Communication (ECOC)* (2014), pp. 1–3.
10. I. Phillips, M. Tan, M. F. Stephens, M. McCarthy, E. Giacoumidis, S. Sygletos, P. Rosa, S. Fabbri, S. T. Le, T. Kanesan, S. K. Turitsyn, N. J. Doran, P. Harper, and A. D. Ellis, "Exceeding the Nonlinear-Shannon Limit using Raman Laser Based Amplification and Optical Phase Conjugation," in Optical Fiber Communication Conference, OSA Technical Digest (online) (Optical Society of America, 2014), paper M3C.1.
11. L. Grüner-Nielsen, S. N. Knudsen, B. Edvold, T. Veng, D. Magnussen, C. Larsen, and H. Damsgaard, "Dispersion Compensating Fibers," Opt. Fiber Technol. **6**(2), 164–180 (2000).
12. G. Khanna, T. Rahman, E. De Man, E. Riccardi, A. Pagano, A. C. Piat, S. Calabro, B. Spinnler, D. Rafique, U. Feiste, and H. De Waardt, "Single-Carrier 400G 64QAM and 128QAM DWDM Field Trial Transmission Over Metro Legacy Links," IEEE Photonics Technol. Lett. **29**(2), 189–192 (2017).
13. P. J. Winzer, "High-Spectral-Efficiency Optical Modulation Formats," J. Lightwave Technol. **30**(24), 3824–3835 (2012).
14. J. Renaudier, A. Meseguer, A. Ghazisaeidi, P. Tran, R. Müller, R. Brenot, A. Verdier, F. Blache, K. Mekhazni, B. Duval, H. Debregeas, M. Achouche, A. Boutin, F. Morin, L. Letteron, N. Fontaine, Y. Frignac, and G.

#317997 https://doi.org/10.1364/OE.26.007091
Journal © 2018 Received 19 Dec 2017; revised 14 Feb 2018; accepted 15 Feb 2018; published 8 Mar 2018

Research Article | Vol. 26, No. 6 | 19 Mar 2018 | OPTICS EXPRESS 7092
Optics EXPRESS

Charlet, "First 100-nm Continuous-Band WDM Transmission System with 115Tb/s Transport over 100km Using Novel Ultra-Wideband Semiconductor Optical Amplifiers," in *43rd European Conference on Optical Communication (ECOC)* (2017).
15. S. Koenig, R. Bonk, H. Schmuck, W. Poehlmann, T. Pfeiffer, C. Koos, W. Freude, and J. Leuthold, "Amplification of advanced modulation formats with a semiconductor optical amplifier cascade," Opt. Express **22**(15), 17854–17871 (2014).

1. Introduction

One convenient way of increasing network capacity is to enhance the optical transmission bandwidth around the presently used spectrum. Most installed fibre links are currently dominated by C band erbium doped fibre amplifiers (EDFAs), whose gain bandwidth is limited to ~40nm. It is possible to combine EDFAs operating in different bands to extend the transmission bandwidth, but this technique generates a "bandwidth gap" and introduces excess losses due to band splitters. This can be easily avoided by using Raman amplification to provide seamless broad bandwidth gain [1]. Dual stage Raman amplifiers have been investigated over a decade ago, both theoretically [2] and experimentally [3], but the design used a single pump wavelength, thus limiting the bandwidth to <20nm. The main focus of these papers was the tradeoff between gain efficiency and noise performance using CW unmodulated signals, thus neglecting important nonlinear crosstalk effects. With the increased interest in broadband enabling technologies that has emerged recently, here we re-consider dual stage Raman amplification, capable of providing high gain (~20dB) and output power (>22dBm) over a broad bandwidth (>100nm).

Raman amplifiers can in principle have a fully configurable gain profile determined by the Raman gain spectra produced by multiple pump lasers and can scale to more than 100nm total bandwidth [4]. However, achieving a flat gain spectrum can be costly as it requires pumping at many wavelengths [5]. The majority of deployed Raman amplifiers employ distributed amplification, where the transmission fibre itself is used as the gain medium. This improves the optical signal to noise ratio (OSNR) and thus directly increases the achievable transmission distance [1]. However, it requires low loss between the terminal equipment and the transmission fibre, and high optical pump powers to be launched into the transmission fibre, which can be disadvantageous due to laser safety. An alternative approach which overcomes these limitations at the expense of no improvement in OSNR is to use discrete Raman amplification, where a separate fibre (which can be collocated with the Raman pumps) is used as the gain medium. In this case, choosing a suitable fibre is an important factor because while a smaller core area results in higher gain, it can also lead to greater nonlinear transmission penalties.

Most reported discrete Raman amplifiers use dispersion compensating fibre (DCF) as the gain medium [6]. Other types of Raman gain fibre: highly nonlinear fibre (HNLF), dispersion shifted fibre (DSF) and inverse dispersion fibre (IDF) have also been investigated [7]. Apart from the impact of Kerr nonlinearity on the amplified signals, the challenges of using these fibres include deleterious effects due to double Rayleigh scattering (DRS) and induced multipath interference (MPI). In particular, DRS significantly deteriorates the OSNR performance and sets an upper limit to the maximum gain of the amplifier which is typically of order 10-15dB, depending on the application [1]. As the DRS-induced MPI noise tends to increase with the fibre length, it has been found that using multiple gain stages each preceded with an optical isolator reduces this effect and results in better overall performance [8].

In this paper we experimentally investigate the performance of a >70nm, 19.5dB net gain with <2.5dB gain flatness dual stage discrete Raman amplifier built with two different fibre types (IDF and SMF), which is a novel approach to reduce the nonlinear penalties introduced by the booster stage. The first stage consists of 10km of IDF and provides 14.5dB gain, while a 10km SMF second stage extends the gain by 5dB with minimum additional nonlinear penalty due to its larger core area. Adding the second stage increased the saturation output power by almost 3dB, up to 22.5dBm. To test the amplifier in long distance transmission, the signal quality (Q^2) of amplified 120Gb/s DP-QPSK modulated signals was measured in a recirculating loop, where a distance of 38x80km (3040km) was reached for a maximum pre-FEC BER of $3.8\text{x}10^{-3}$ (Q^2 = 8.5dB).

2. Amplifier design

The discrete Raman amplifier design is shown in Fig. 1. It comprises two independent stages, each backward pumped with 14xx semiconductor lasers. Since the Raman gain process is polarization sensitive, the pumps are cross-polarized using polarization beam combiners (PBCs) and two pump diodes per wavelength, after which they were combined with a cascade of WDM combiners, so as to maximize the pump power of the lowest wavelength pumps.

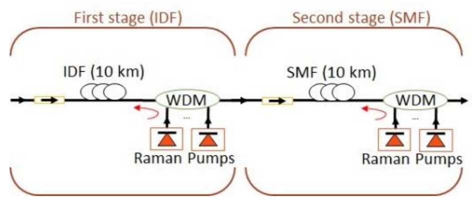

Fig. 1. Amplifier design: two backward pumped stages each preceded by isolators, consisting of 10km IDF and 10km SMF. Pump powers of [351, 0, 236, 99, 16, 142] mW and [240, 162, 214, 162, 117, 310] mW at wavelengths of [1425, 1431, 1444, 1462, 1476, 1491] nm were used in the IDF and SMF, respectively.

We selected a classic two stage amplifier design, where the first stage acts as a relatively high gain pre-amplifier and the second stage acts as a lower gain booster amplifier. The design aimed to maximize the first stage gain, where the input power level and therefore the nonlinear crosstalk is low. In the second stage, where the optical channel power is relatively high, we aimed to minimize nonlinear crosstalk, with a lower gain, but increased saturated output power. For the first stage, we used 10km of IDF (0.23dB/km loss, −44ps/nm.km dispersion at 1550nm) which has a slightly larger core area (A_{eff} = 31µm^2) compared with DCF (often used in discrete Raman amplifiers), to give a good balance between gain efficiency and nonlinear crosstalk. IDF also has a lower loss in the 1425-1500nm region than DCF allowing the Raman pumps to propagate further in the fibre, giving a similar gain (for equivalent power), but reduced noise figure [7]. For the second stage we used 10km of SMF (0.2dB/km loss, 16.7ps/nm.km dispersion at 1550nm), with a larger A_{eff} of 80µm^2 to minimize nonlinear crosstalk.

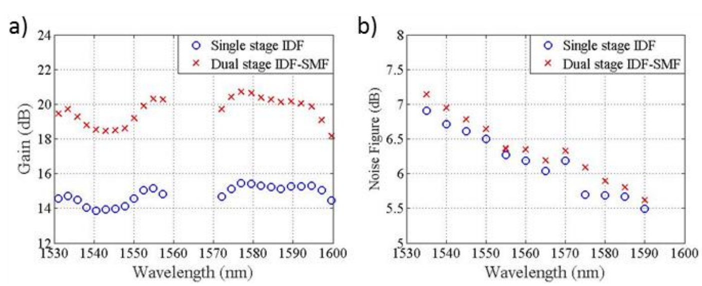

Fig. 2. Amplifier gain (a) for single and dual stage amplifier and the corresponding noise figure (b) vs wavelength.

Figure 2 shows the gain and noise figure of the single stage IDF pre-amplifier, and the dual stage IDF + SMF amplifier. The first stage has an average gain of 14.5dB across >70nm at 1530nm to 1600nm, with a noise figure (NF) of 7-5.5dB, decreasing with wavelength. The second stage extends the gain and output power, giving a total net gain of 19.5dB with <2.5dB gain ripple and a small increase in the NF of <0.3dB. Figure 3 shows saturated output power curves for both the first stage IDF pre-amplifier, and the dual stage amplifier. The saturated output power for the dual stage amplifier was 22.5dBm, ~3dB greater than that of the first stage pre-amplifier.

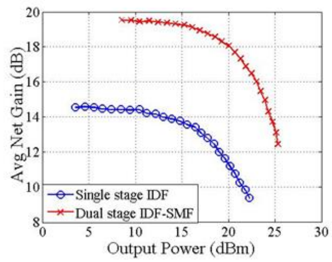

Fig. 3. Average net gain vs output power showing ~3dB saturated output power improvement up to 22.5dBm.

To estimate the nonlinear transmission penalties introduced by each amplifier stage, we first matched the simulated gain across the bandwidth with the experimental measurements using the standard average power numerical model described in [7]. The net gain simulated in both stages presents a very close match with the experimental measurements, as shown in Fig. 4(a), with only a +/-2% difference in simulated and measured pump powers. Using these parameters we calculated the nonlinear phase shift (NPS) [7] of each stage as shown in Fig. 4(b). Here, it can be seen that the second stage produces greater NPS as a result of higher path average signal powers propagating along the fibre when compared with the first stage. Figure 4 also shows results of simulations of a dual stage amplifier with a 6km IDF second stage and pump powers modified to match the previously achieved 5dB second stage gain, predicting ~3x increase in NPS by such a stage, due to smaller effective area and higher nonlinear coefficient of the IDF.

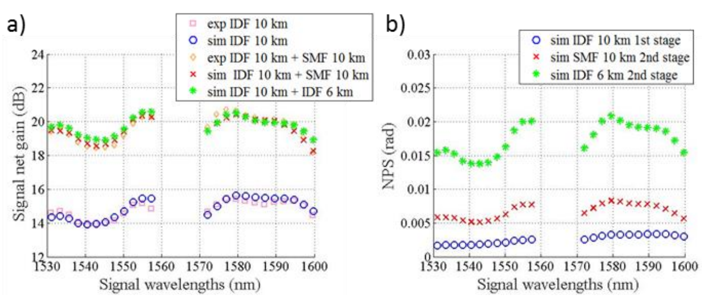

Fig. 4. Simulations for single and dual stage Raman amplifiers built with different fibres: a) comparison of simulated and measured gain profiles versus wavelength b) simulated NPS versus wavelength.

3. Broadband transmission setup and operating procedure

The experimental transmission setup is shown in Fig. 5. The transmitter consisted of C- and L-band EDFAs, whose ASE was shaped using wavelength selective switches (WSSs) to generate 24 channels with 300GHz spacing (12 per band). It was previously shown that channelized ASE is suitable for emulating nonlinear transmission performance in QPSK systems [9], so these channels were combined with a 100kHz linewidth tunable laser via a 50/50 coupler, which was used as a “channel under test” while the corresponding ASE channel was disabled during measurement. A 120Gbit/s DP-QPSK signal was generated using an IQ modulator and a polarization multiplexer (PolMux). The whole spectrum was amplified with C- and L-band EDFAs before launch into a recirculating loop via an acousto-optic modulator (AOM).

The loop itself consisted of a 59km SMF transmission span (12.5dB loss) for measurements using the single stage Raman amplifier and an 80km SMF span (17dB loss) for the dual stage amplifier. The amplifier was followed by a C/L band splitter. The C-band spectrum was gain flattened by a gain flattening filter (GFF) whereas a WSS was used to flatten the L-band due to the lack of a broadband leveler. The levelers were followed by C- and L-band EDFAs to compensate for the additional loop losses (~14dB) due to GFFs, couplers and the AOM.

The receiver chain consisted of a tunable band pass filter (BPF) followed by an EDFA to provide constant power into a polarization diverse coherent receiver, where the signal was mixed with a 100kHz linewidth local oscillator and captured using an 80GSa/s, 36GHz real-time oscilloscope. The recorded data was then processed using offline Digital Signal Processing (DSP), where the Q^2 was derived from the bit error ratio (BER) [10].

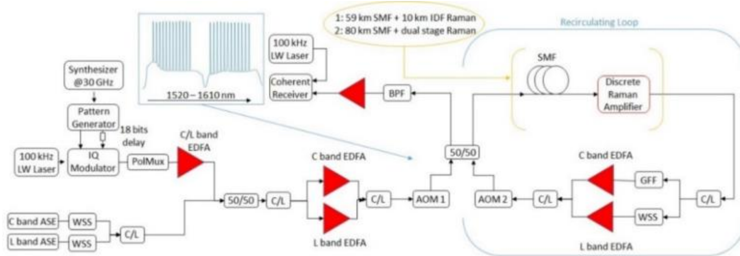

Fig. 5. Broadband transmission setup. Channels under test: 195.8THz (1531.12nm) to 192.5THz (1557.36nm) in C-band and 190.7THz (1572.06nm) to 187.4THz in L-band (1599.75nm), each at 300GHz spacing.

4. Transmission results

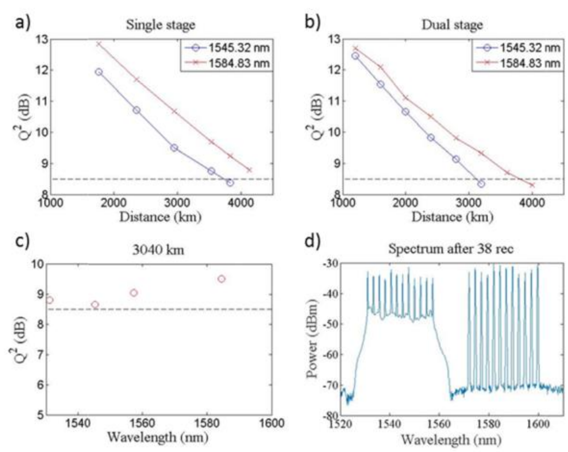

Fig. 6. Transmission results versus distance: a) single stage with 59km spans, b) dual stage with 80km spans, c) dual stage case for selected channels @3040km, d) spectrum at 3040km. Q^2 FEC threshold is 8.5dB (BER $3.8x10^{-3}$).

Figure 6(a) and 6(b) show the Q^2 vs distance for the central channel of each band for the single-stage and dual-stage Raman amplifiers compensating for the 59km and 80km SMF transmission spans, respectively. As expected, due to higher span loss, the 80km (dual-stage) configuration has a shorter overall reach compared to the 59km (single-stage) one. In both cases, the transmission in L band gave better performance (higher Q^2) than in the C band due to the NF tilt. Figure 6(c) shows Q^2 for selected channels at a distance of 3040km for the dual stage configuration, the distance achieved throughout the C and L band. It was not possible to test the channels above 1590nm (or in the gap between C and L bands) because of equipment

Optics EXPRESS

limitations, but the NF trend suggests for similar transceivers the Q^2 should be above the FEC threshold in that region. The difference in the noise floor between C and L band output spectra (shown in Fig. 6(d)) is due to the different devices used for gain flattening of each band.

5. Discussion

Selecting a suitable Raman gain fibre is one key task in designing a discrete Raman amplifier, but while the fibre type strongly influences the gain coefficients and nonlinear transmission penalties, it is the available pump powers and fibre lengths that determine the tradeoff between gain, output power and noise figure. Too short a length leads to pump power wastage and reduced gain, while too long a fibre will have under-pumped regions, leading to unnecessary signal losses and higher noise figure. The results described here include all the splicing losses due to the core area differences between dissimilar fibres (typically ~0.8dB, reducible to ~0.5dB with an intermediate fibre [11]) and all passive component losses (WDMs, isolators), both of which increase the total measured noise figure above that theoretically achievable. We note that the use of more powerful Raman pumps (600mW commercially available today) would also enable further increase in the saturated output power to levels comparable with the EDFAs deployed in today's WDM systems, an increasingly important consideration as networks migrate from 50GHz to flex-grid spacing and Nyquist shaped modulation.

While the long distance transmission demonstrated here confirms the low penalty due to intra-channel nonlinearity of these discrete Raman amplifiers, it is in short distance metro networks where capacity growth is currently the greatest and we anticipate using higher order modulation formats such as DP-64-QAM in the near future [12]. Those formats have relatively high OSNR requirements versus DP-QPSK [13], which would reduce the presented transmission reach, but the described discrete dual-stage Raman amplifier could still be usefully deployable. Recent improvements in semiconductor optical amplifiers (SOAs) [14] could offer comparably high bandwidth in future data centre applications, but the accumulated nonlinear penalty due to multiple SOA amplifications is still an issue [15] while the proven cascadability of discrete Raman amplifiers could also make them an attractive choice for such links.

6. Summary

We have demonstrated a dual stage IDF + SMF design of discrete broadband Raman amplifier for use in broadband DWDM networks. Using SMF in the second stage reduces the nonlinear penalties introduced by the booster stage of the amplifier, where the signal power is the highest. The design is self-contained, requiring no high-power Raman pump light in the transmission line which is advantageous compared with distributed Raman amplification. The 5dB extra gain provided by a second stage enabled the extension of the transmission span length from 59km to 80km. A total gain of 19.5dB with <2.5dB gain flatness over 70nm was achieved, with no gain equalizing elements inside the amplifier. The saturation output power of the amplifier was 22.5dBm. The noise figure varied from 7.2dB to 5.7dB, decreasing with wavelength. The amplifier was tested in a recirculating fibre loop, compensating for 38 spans of 80km. Based on an error free Q^2 FEC threshold of 8.5dB, a distance of 3040km was reached for broadband transmission of 120Gb/s DP-QPSK signals.

Funding

EPSRC project EP/M009092/1 (ToM3), FP7 ITN ICONE (No. 608099).

Acknowledgment

We acknowledge the industrial support from II-VI. The original data for this work is available at Aston Research Explorer (http://doi.org/10.17036/researchdata.aston.ac.uk.00000333).