# Low penalty, dual stage, broadband discrete Raman amplifier for high capacity WDM metro networks

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**Abstract:** We present a broadband (>70nm), dual stage, discrete Raman amplifier built with small and standard core fibre with ~19.5dB net gain. We transmit 120Gb/s DP-QPSK signals over 3040km with 38 amplifications for a preFEC BER<3.8x10$^{-3}$.

**OCIS codes:** (190.5650) Raman effect; (140.3550) Lasers, Raman; (250.4480) Optical amplifiers.

## 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 ~40 nm. 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].

Raman amplifiers can in principle have fully configurable gain spectra determined by the Raman gain spectra of multiple pump lasers and scale to more than 100 nm total bandwidth [2]. However, achieving a flat gain spectrum can be costly as it requires pumping at many wavelengths [3]. The majority of Raman amplifiers uses distributed amplification, where the transmission fibre itself is used for amplification, which improves the optical signal to noise ratio (OSNR) thereby extending transmission reach [1]. However, this method requires high optical pump powers to be launched into the transmission fibre, which can be disadvantageous for operational reasons, such as laser safety. An alternative is discrete Raman amplification, which uses a separate fibre as the gain medium. In choosing the right fibre type the effective area is an important factor because while a smaller core results in higher gain, it can also lead to increased nonlinear transmission penalties. Most reported discrete Raman amplifiers use dispersion compensating fibre (DCF) as the gain medium, which offer simultaneous compensation of loss and dispersion [4]. Other types of Raman gain fibre: highly nonlinear fibre (HNLF), dispersion shifted fibre (DSF) and inverse dispersion fibre (IDF) have also been investigated [5]. Apart from nonlinearity, the challenges of using these fibres include 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 of 10-15 dB, depending on the tolerable penalty per amplification [1]. As the DRS induced MPI noise tends to increase with the fibre length, it was found that using multiple gain stages with an optical isolator in between them reduces this effect and results in better overall performance [6].

In this paper we experimentally investigate the performance of a >70 nm, 19.5 dB net gain with <2.5 dB gain flatness dual stage amplifier built with IDF and SMF. The first stage consists of 10 km of IDF and provides 14.5 dB gain, while a 10 km SMF second stage was designed to extend the gain by 5 dB with minimum additional nonlinear penalty due to its larger core area. To test the amplifier in long distance transmission, we measured the signal quality (Q$^2$) of amplified 120 Gb/s DP-QPSK modulated signals in a recirculating loop, where we reach a distance of 38x80 = 3040 km for a maximum pre-FEC BER of 3.8x10$^{-3}$ (Q$^2$ = 8.5 dB).

## 2. Amplifier design

The discrete Raman amplifier design, gain, noise figure and the pump powers used are shown in Fig 1. It is made of two independent amplification stages, each backward pumped with 14xx semiconductor lasers. The first stage, consisting of 10 km IDF (0.23 dB/km attenuation, -44 ps/nm-km dispersion and 31 μm$^2$ effective area at 1550nm), generated an average gain of 14.5 dB across >70 nm from 1530 nm to 1600 nm. We chose IDF for the first stage because of its improved balance between the gain efficiency and nonlinear penalties, having a core area greater than DCF it generates less nonlinear penalty while optimally utilizing our available pumping power. As shown in Fig. 1d, the first stage had a noise figure (NF) between 7 dB and 5.5 dB, decreasing with wavelength. An additional 10 km of SMF extended the gain and output power, giving a total net gain of 19.5 dB with <2.5 dB gain ripple and a small increase in the NF of <0.3 dB.
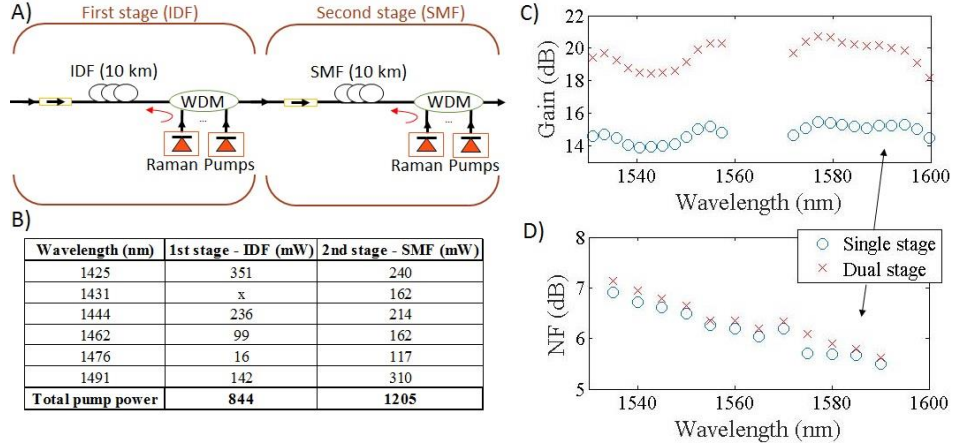
Fig. 1. a) Amplifier design, b) pump powers used, c) gain and d) noise figure.

## 3. Broadband transmission setup and operating procedure

The experimental transmission setup is shown in Fig. 2. For convenience, the transmitter consisted of C and L band EDFAs, whose ASE was shaped with the use of wavelength selective switches (WSS) to generate 24 channels with 300 GHz spacing (12 in each band) from 195.8 THz (1531.12 nm) to 192.5 THz (1557.36 nm) in C band and 190.7 THz (1572.06 nm) to 187.4 THz in L band (1599.75 nm). It has been previously shown that using channelized ASE is suitable for emulating nonlinear transmission performance in QPSK systems [7]. These were combined with a 100 kHz linewidth tunable laser through a 50/50 coupler, which was used as a "channel under test" while the corresponding ASE channel was switched off during the measurement. A 120 Gbit/s DP-QPSK signal was generated using an IQ modulator and a polarization multiplexer (PolMux). The generated transmission spectrum was amplified with a pair of C and L band EDFAs before launch into a recirculating loop through an acousto-optic modulator (AOM).

The loop itself consisted of a 59 km SMF transmission span (12.5 dB loss) for measurements using the single stage Raman amplifier and a 80 km SMF span (17 dB loss) in the case of the dual stage amplifier. The amplifier was followed by a C/L band splitter. The C band part of the 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. This was followed by C and L band EDFAs to compensate for the additional loop losses (~14 dB) generated by GFFs, couplers and 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 100 kHz linewidth local oscillator and captured using an 80 GSa/s, 36 GHz 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) [8].
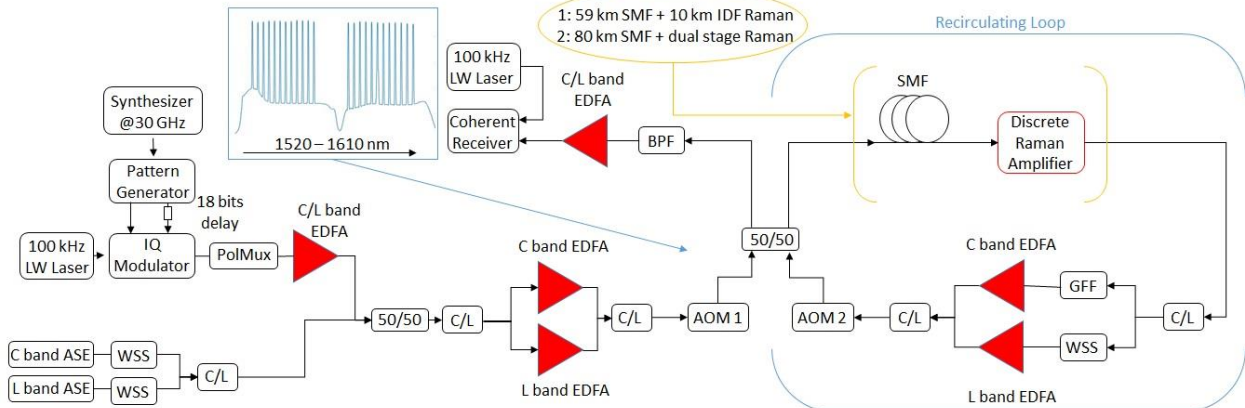


Fig. 2. Broadband transmission setup.

## 4. Transmission results and discussion

Fig. 3a. shows the $Q^2$ vs distance for the middle channel of both bands (1545.32 nm and 1584.53 nm) for the single stage Raman amplifier compensating for the 59 km SMF transmission span and Fig. 3b. shows the dual stage Raman amplifier compensating for the 80 km SMF span in the recirculating loop. We assumed a $Q^2$ threshold of 8.5 dB

(BER $3.8\times10^{-3}$) for forward error correction (FEC). As anticipated, due to increased span loss, the 80 km configuration compensated by the dual stage amplifier has a shorter overall reach when compared to the 59 km configuration compensated by a single stage amplifier. In both cases the transmission in L band showed higher $Q^2$ than in the C band due to the NF tilt. Fig 3c. shows $Q^2$ for selected channels at a distance of 3040 km with the use of the dual stage Raman amplifier, the distance achieved throughout the C and L band. We were not able to test the channels above 1590 nm (or in the gap between C and L bands) because of equipment limitations, but the NF trend suggests 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 inset of Fig. 3c.) is due to the different devices used for gain flattening of each band.

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 greatest and we anticipate using higher order modulation formats such as DP-64-QAM in the near future [9]. Recent improvements in SOAs [10] could offer comparably high bandwidth in metro networks and in data centre applications, but the nonlinear penalty due to repeated SOA passes is still an issue [11] while the proven cascadability of discrete Raman amplifiers could make them an attractive choice for such links.
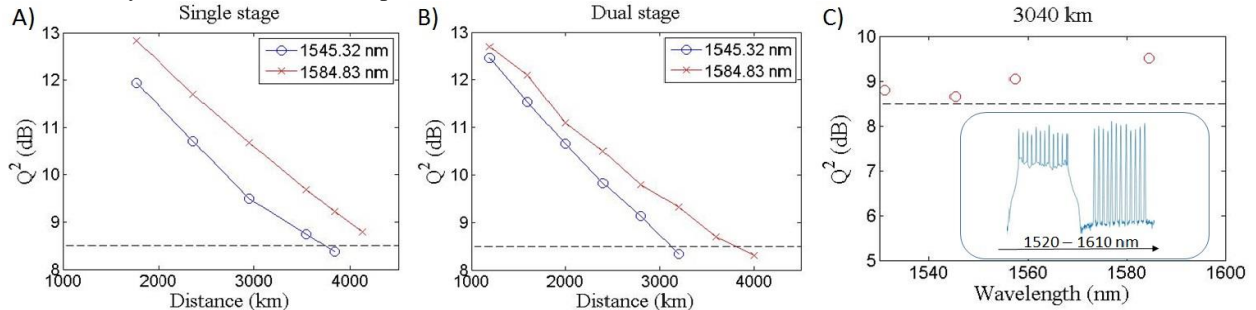


Fig. 3. Transmission results for: a) single stage discrete Raman vs distance, b) dual stage discrete Raman vs distance, c) dual stage discrete Raman for selected channels @3040 km and output spectrum in inset.

## 5. Conclusions

We have demonstrated a dual stage IDF/SMF design of discrete broadband Raman amplifier for use in a broadband WDM/metro network. The 5 dB extra amplification provided by second stage enabled us to extend the transmission span length from 59 to 80 km. A total gain of 19.5 dB and <2.5 dB gain flatness over 70 nm was achieved, and no gain equalizing elements inside the amplifier were used. The noise figure varied from 7.2 dB to 5.7 dB, decreasing with wavelength. The amplifier was tested in a recirculating loop, compensating for 38x80 km recirculation spans. Assuming an "error free" $Q^2$ threshold of 8.5 dB a distance of 3040 km was reached for broadband transmission of 120 Gb/s DP-QPSK signals.

## 6. Acknowledgements

## 7. References

[1] M. N. Islam, "Raman amplifiers for telecommunications," in *IEEE J. Sel. Topics Quantum Electron*., vol. 8, no. 3, pp. 548-559 (2002).
[2] S. Namiki and Y. Emori, "Ultrabroad-band Raman amplifiers pumped and gain-equalized by wavelength-division-multiplexing high-power laser diodes," in *IEEE J. Sel. Topics Quantum Electron*, vol. 7, no. 1, pp. 3-16 (2001).
[3] Y. Emori and S. Namiki, "100 nm bandwidth flat gain Raman amplifiers pumped and gain-equalized by 12-wavelength-channel WDM high power laser diodes," *OFC/IOOC Technical Digest. Optical Fiber Communication Conference,* San Diego, CA, USA, pp. PD19/1-PD19/3 (1999).
[4] L. E. Nelson *et al.,* "All-Raman-Amplified, 73 nm Seamless Band Transmission of 9 Tb/s Over 6000 km of Fiber," in *IEEE* Photon. Technol. Lett., vol. 26, no. 3, pp. 242-245 (2014).
[5] M. A. Iqbal *et al.*, "Performance characterization of high gain, high output power and low noise cascaded broadband discrete Raman amplifiers," *2017 19th International Conference on Transparent Optical Networks (ICTON)*, Girona, Spain, 2017, pp. 1-4 (2017).
[6] S. A. E. Lewis *et al.*, "Characterization of double Rayleigh scatter noise in Raman amplifiers," in *IEEE Photon. Technol. Lett.*, vol. 12, no. 5, pp. 528-530 (2000).
[7] M. E. McCarthy *et al.*, "High spectral efficiency transmission emulation for non-linear transmission performance estimation for high order modulation formats," *2014 The European Conference on Optical Communication (ECOC)*, Cannes, 2014, pp. 1-3 (2014).
[8] I. D. Phillips *et al.*, "Exceeding the nonlinear-Shannon limit using Raman laser based amplification and optical phase conjugation," *OFC 2014*, San Francisco, CA, 2014, pp. 1-3 (2014).
[9] G. Khanna *et al.*, "Single-Carrier 400G 64QAM and 128QAM DWDM Field Trial Transmission Over Metro Legacy Links," in *IEEE Photon. Technol. Lett.*, vol. 29, no. 2, pp. 189-192 (2017).
[10] J. Renaudier *et al.,* "First 100-nm Continuous-Band WDM Transmission System with 115Tb/s Transport over 100km Using Novel Ultra-Wideband Semiconductor Optical Amplifiers," *43rd European Conference on Optical Communication (ECOC)*, Gothenburg, Sweden (2017).
[11] S. Koenig *et al.*, *"Amplification of advanced modulation formats with a semiconductor optical amplifier cascade,"* Opt. Express 22, 17854-17871 (2014).