30-Gbaud PM-16-QAM transmission over E-, S-, C- and L-band with hybrid Raman amplifier

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Abstract: We demonstrate 50km, 30-Gbaud PM-16QAM transmission with a hybrid distributed-discrete Raman amplifier over 25.8THz bandwidth. E-band distributed Raman amplification shows 0.7dB averaged Q^2-penalty, versus 1.9dB and 0.9dB due to S-band and C+L-band discrete Raman amplification.

1. Introduction

With the continuing growth of data demand, emerging technologies such as space-division multiplexing (SDM) and multiband transmission (MBT) can be key solutions for future optical communication systems [1, 2]. While SDM offers unlimited capacity growth, it potentially requires full scale upgrade of the established optical fibre network. In contrast, MBT, while limited in overall bandwidth to that of the installed standard single mode fibre (SSMF), requires system upgrade only at the node and operator level. An essential requirement for MBT systems is a new set of optical amplifiers capable of signal amplification in spectral windows other than the C-band [3]. Novel amplifiers based on rare-earth materials such as bismuth are promising candidates with recent experimental demonstrations showing amplification in the O-, E- and S-bands [4, 5]. A new class of high power, semiconductor optical amplifiers (SOAs) with polarization diversity have also shown an amplification bandwidth of ~100 nm [6]. In addition, the discrete Raman amplifier (DRA) forms a class of spectrally flexible solutions, with a recent demonstration achieving an ultra-wideband (UWB) amplification of 210 nm covering the E-, S-, C- and L-band [7].

Previous experimental demonstrations of data transmission using DRAs have shown degradation in performance in the E-band, partially due to transceiver limitations, but mainly due to higher E-band fibre loss and inline amplifier noise figure (NF) [7]. Hence, in this paper, to reduce the transmission penalties on the shorter wavelength channels, we investigate a novel hybrid combination of distributed-discrete Raman amplifier (DDRA) based on a split-combine approach of spectral bands enabling signal amplification from 1410-1605 nm. This design of hybrid DDRA was chosen to minimize the performance penalty (Q^2 penalty) of the shorter wavelength signals, improving the overall transmission performance of the UWB signals. Our experimental results with the DDRA show a negative effective NF for 1410-1457 nm signals and a maximum NF of 7.5 dB for 1470-1605 nm. The measured average gain is 14 dB over the entire bandwidth. The developed amplifier is tested over a 50 km SSMF using a 30 GBaud PM-16QAM signal coupled with 146x100 GHz WDM channels. Our transmission results show an averaged Q^2 penalty of 0.7 dB for E-band (1410-1457 nm) with a maximum penalty of 1.2 dB at 1410 nm, 1.9 dB for S-band (1470-1520 nm) with a maximum penalty of 2.5 dB at 1470 nm, and 0.9 dB for C+L-band (1530-1565 nm, 1570-1605 nm) with a maximum penalty of 1.2 dB at 1580 nm.

2. Hybrid Raman amplifier setup and characterization

The experimental setup of the hybrid DDRA is illustrated in Fig. 1(a). The amplifier was characterized with a 147-line WDM grid of 143x100 GHz amplified spontaneous emission (ASE) dummy channels from 1470-1605 nm. The 1470-1520 nm dummy channels were generated using an in-house supercontinuum source and a commercial waveshaper for shaping and flattening, followed by a thulium doped fibre amplifier (TDFA). Guard bands of +/-2 nm were placed in the vicinity of 1485 and 1508 nm to prevent an overlap of the pumps with the S-band dummy channels. The C- and L-band dummy channels from 1530-1605 nm were generated using two C- and L-band EDFAs and two waveshapers. Due to the absence of a commercial waveshaper and ASE source in E-band, we were limited to the use of independent laser diodes at 1411, 1431, 1451 nm and a PM-16QAM signal at 1457 nm to encompass the target bandwidth. The sub-bands were combined via a WDM coupler before propagation through 50 km of SSMF. Three pump diodes at 1325, 1345 and 1365 nm with pump powers of 439, 153 and 318 mW were used to amplify the E- and lower S-band dummy channels in a backward (BW) distributed configuration. The pumps and the signals were coupled using a high power WDM coupler with the pass band from 1260-1370 nm and the reflection band from 1390-1620 nm. The residual counter-propagating pumps were prevented from entering the transmitter using an identical WDM coupler whose 1260-1370 nm arm was connected to a beam dump. Following the high power WDM, the forward propagating signals were split into two groups using a filtered-WDM (FWDM). The first group, covering from 1410-1457 nm, bypassed the DRA (upper path in Fig. 1(a)). The second group, covering from 1470-1605 nm, were amplified using a dual stage DRA (lower path in Fig. 1(a)) with 8 pumps at wavelengths and powers of 1365 nm (495 mW), 1385 nm (212 mW), 1405 nm (170 mW), 1425 nm (294 mW), 1445 nm (312 mW), 1465 nm (198 mW), 1485 nm (110 mW) and 1508 nm (136 mW) respectively) [7]. A 7.5km inverse dispersion fibre (IDF) was used as a Raman gain medium in each of two stages, with the first stage providing S-band amplification and the second stage providing C- and L-band amplification. The pump powers were adjusted to compensate for the combined SSMF and the WDM losses.

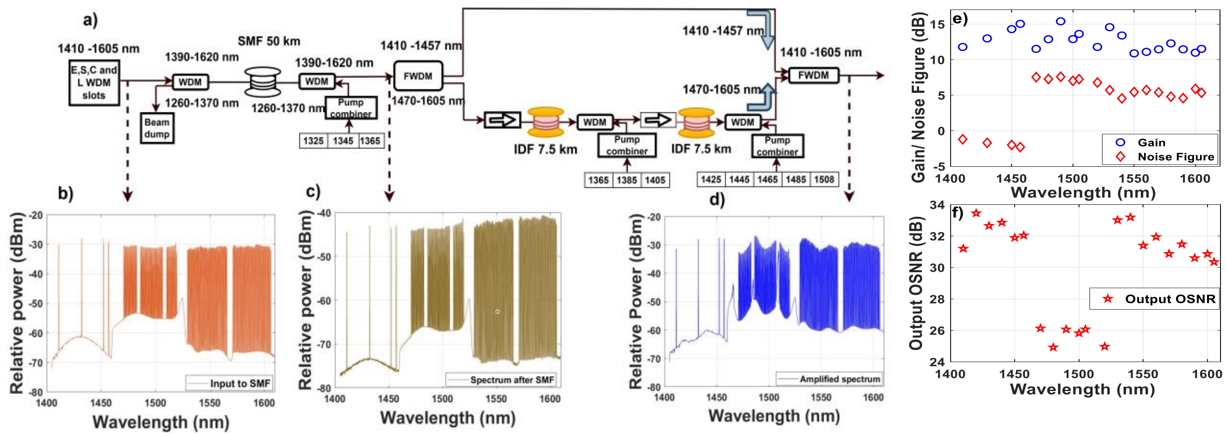

Fig. 1. Ultrawideband hybrid distributed-discrete Raman amplifier: a) schematic; b) input spectrum to WDM and SSMF; c) output spectrum after SSMF and WDM; d) amplified output spectrum; e) amplifier net-gain and noise figure; f) amplified output OSNR.

The spectral characteristics and the performance of the amplifier are shown in Fig. 1(b-f). An overall average gain of ~14 dB was obtained across the entire 195 nm (25.8THz) bandwidth. Higher gain was required in the E- and S-band due to the higher intrinsic fibre loss and inter-channel stimulated Raman scattering (ISRS) from the E- and S-band signals to the C- and L-band signals. The localized effective NF in the E-band was below 0 dB due to distributed amplification, whereas the highest NF was 7.5 dB at 1470 and 1490 nm in the S-band region. An average NF of 5.5 dB was obtained for the C- and L-band signals (1530-1605 nm). The output OSNR measured after the amplifier using a 30 GBaud PM-16QAM signal, swept at an interval of 10 nm was > 30 dB for all the E-, C- and L-band signals, whereas for the S-band it was <27 dB. The large reduction in output OSNR of S-band in comparison to the other bands is due to the different sources and amplifier used in generating the channelized ASE and the high NF of the DDRA in the S-band region.

3. Transmission setup, results and discussion

The experimental setup for the coherent transmission is illustrated in Fig. 2(a). A 30 GBaud PM-16QAM signal was generated using a 120 GSa/s digital to analog converter (DAC) and a $LiNbO_3$ DP-IQ modulator. The modulated signal was then amplified using a corresponding transmitter (Tx) amplifier (BDFA, TDFA, C-EDFA and L-EDFA) and coupled with the remaining WDM channels using a 70/30 coupler. The total input power to the SSMF was ~17.6 dBm with a power per channel of ~-4 dBm. All channels were then passed through the 50 km SSMF and DDRA to compensate the combined WDM and SSMF loss. After amplification with the DDRA, the signals passed through a 99/1 tap whose 1% arm was used to measure the output OSNR and the remaining 99% signal power was passed through an optical band-pass filter (OBPF) for separation of the modulated signal. The modulated signal was then amplified using a corresponding receiver (Rx) amplifier (BDFA, TDFA, C-EDFA and L-EDFA), to optimize power at the detection stage. The coherent receiver used a 36 GHz bandwidth, 80 GSa/s real time oscilloscope and was followed by offline DSP for data recovery. The recorded symbols together with the transmitted symbols were then used to calculate the Q^2 factor from the bit error rate (BER) [8].

The measurements of back-to-back (B2B) and 50km transmission performance are shown in Fig. 2(b-c). While a relatively level B2B performance is seen in the C- and L-bands, with an average Q^2 factor of ~17 dB, a roll-off in B2B performance of ~2dB, from long to short wavelengths, was seen in both the S-band (~17dB to ~15dB) and the E-band (~16dB to ~14dB). In the S-band, the roll-off is due mainly to NF variations of the Tx and Rx TDFA, while in the E-band, the roll-off is primarily due to the performance limitations of the C-band commercial components when operated over the E-band. The Q^2 factor measured after 50 km transmission and amplification with the DDRA follows a similar trend to the B2B. The Q^2 penalty (Q^2 factor difference between B2B and 50 km transmission) is highest for S-band signals, with an average value of 1.9 dB and a maximum penalty of 2.5 dB at 1470 nm, followed by C- and L-band with an average penalty of 0.9 dB and a maximum penalty of 1.2 dB at 1580 nm, and the E-band with an average penalty of 0.7 dB and a maximum penalty of 1.2 dB at 1410 nm. These variations can be well explained by the NF of the DDRA shown in Fig 1(e). The lower E-band penalty is due to the distributed amplification resulting in low effective NF, and therefore improved OSNR. In the S-band, the penalty is largely due to the high NF and low output OSNR (< 27 dB) of the signals. As mentioned previously, since the shorter wavelength channels are adversely affected by the use of standard C-band components, we studied the effects of polarization imbalance over different bands by measuring the difference in the Q^2 factor between X and Y polarization with the B2B setup. Fig. 2(d) shows these results: a high penalty of 1.6 dB at 1410 nm, decreased to ~0.6 dB at 1470 nm and a value below 0.5 dB over the 1500–1600 nm range. This polarization penalty indicates the transmission challenges towards the shorter wavelength channels in a UWB scenario with standard C-band components [9].

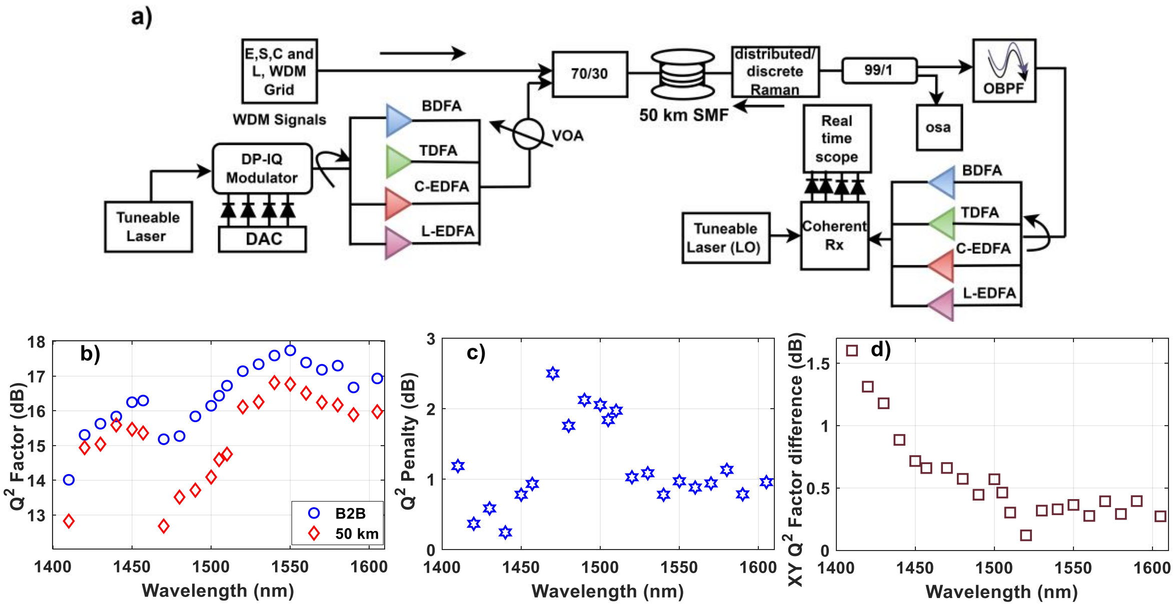

Fig. 2. 30 GBaud PM-16QAM transmission with 146 WDM signals: a) experimental setup; wavelength vs b) Q^2 factor between B2B and 50 km transmission; c) Q^2 penalty; d) B2B XY Q^2 factor difference

4. Conclusion

We experimentally demonstrated a hybrid DDRA capable of signal amplification from 1410-1605 nm, 25.8 THz bandwidth. The characterized amplifier has an average gain of 14 dB and maximum NF of 7.5 dB. The proposed DDRA was tested with 30 Gbaud PM-16QAM signals coupled with 146x100 GHz channelized ASE over 50 km SSMF. Our experimental results showed an averaged Q^2 penalty of 0.7 dB for E-band, followed by C- and L-band penalty of 0.9 dB, and a highest penalty for S-band of 1.9 dB. The experimental results clearly indicate the advantage of distributed amplification for the shorter wavelength channels in a UWB transmission system.

5. Acknowledgement

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6. References

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