Over 90-km 400GBASE-LR8 Repeatered Transmission with Bismuth-doped Fibre Amplifiers

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Abstract *Simple single-stage bismuth-doped fibre amplifiers extend the transmission reach of an emerging 400G transceivers' capability. The 8 LAN-WDM signals are continuously delivered over 90-km deployed cable without frame loss for more than 7 days. ©2022 The Author(s)*

Introduction

Aiming at short reach applications, 400 Gigabit Ethernet (GbE) and beyond 400 Gigabit Ethernet (GbE) specifications have been announced[1]–[3]. With these new specifications, transmission reach extension has been attractively studied using a bismuth-doped fibre amplifier (BDFA)[4],[5]. Interestingly, the BDFA showed a relatively wide gain spectrum compared to the C-band typical erbium-doped fibre amplifier (EDFA)[6],[7]. In[5], by employing alternate-mark-inversion, transmission reach could be extended up to 60 km with only a BDFA as pre-amplifier. In[4], 400GBASE-LR8 signals were transmitted over 40 km with a BDFA introduced as pre-amplifier. By using another BDFA as a booster, the transmission reach was successfully extended up to 55 km.

In this work, we developed simple single-stage BDFAs to further extend the transmission reach. We established two kinds of repeatered transmission links with equal and unequal spans for 400GBASE-LR8 signals over 90 km. The stable transmission was valid over a week. To the best of our knowledge, the multi-span repeatered transmission with BDFAs was demonstrated for the first time.

Experimental setup

The setup for transmission is shown in Fig. 1. 16 lanes of electric signals were generated by a 400GbE tester (Anritsu/MT1040A) and drove a QSFP-DD-LR8 module, generating an optical signal that consisted of 8 wavelength channels on the LAN-WDM grid, resulting in the net data rate of 400Gb/s. The typical wavelengths were 1273.55 nm, 1277.89 nm, 1282,26 nm, 1286.67 nm, 1295.56 nm, 1300.06 nm, 1304.59 nm and 1309.14 nm. The total output power was +10 dBm. The power per channel was pre-emphasised by a reconfigurable optical filter consisting of a pair of LAN-WDM multiplexers and variable optical attenuators (VOAs). The VOA values were determined by minimising the total symbol error rate (SER) of aggregated optical signals. A BDFA was used as a booster to compensate for the loss of the pre-emphasis filter. The optical signal was transmitted through three spans and then back to the tester. A fourth BDFA was setup as a pre-amplifier. The signal was split by an optical fibre coupler; one path went to optical spectrum analyser (OSA) to monitor the spectrum and the optical signal-to-noise ratio (OSNR). The other path was connected to the receiver via VOA. Since the damage threshold for each lane was specified at 6.3 dBm, the VOA values were carefully chosen. Here, the total input power to the receiver was kept at +10 dBm in total. This setup could maintain the received power per lane below the damage threshold level.

All BDFAs were based on a simple backward pumping setup[4]. Two laser diodes (LDs) at 1195 nm were used to pump 200 m of BDF in the backward direction. The two pump LDs were polarisation multiplexed to suppress polarisation-dependent gain. The total pump power was set at $<\sim$500 mW, similar to a conventional C-band

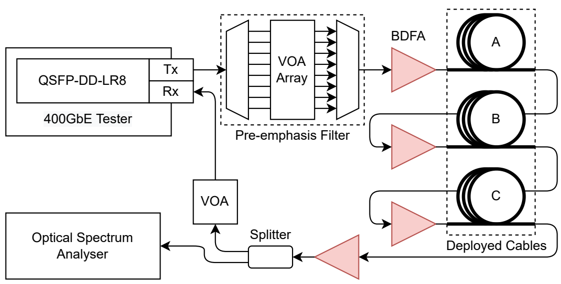

Fig. 1: Experimental setup

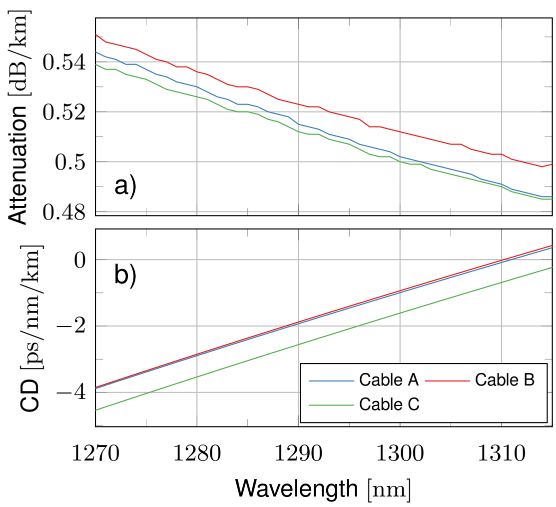

Fig. 2: Cable characterisation; a) fibre attenuation and b) chromatic dispersion for cables

erbium-doped fibre amplifier (EDFA). The four BDFAs were packed into two 1U chassis (two BDFAs per 1U chassis) to fit a 19-inch rack system. The BDFAs were tested with the commercially available packages for long term measurement.

Transmission link

The transmission spans consisted of three deployed cables manufactured by different vendors[6],[8]. The deployed cables accommodated 200 fibres within 12 mm diameter and met the ITU-T G.657.A1 specification. Sets of four fibres were partially bonded as ribbon. The fibre attenuations are shown in Fig. 2a. Cable B showed slightly higher attenuation of 0.09dB/km. Since each fibre cables included tens of splice points and connectors, the attenuation was relatively high for all cables. The chromatic dispersion (CD) coefficients are shown in Fig. 2b. The CD values were ranged from –3.4 ps/nm/km to –0.1 ps/nm/km. The cable C showed relatively small CD coefficients. The CD coefficients at the typical channel wavelengths were entirely negative. We tested on two transmission links. First, we configured a 91.5-km link with uniform span length of 30 km to characterise the transmission performance as an ideal case. Second, we made a 90-km link consists of the cables A, B and C with 40 km, 20 km and 30 km, respectively, to emulate practical conditions.

Transceiver characterisation

The transceiver performance was characterised by measuring SER a back-to-back configuration with and without the pre-amplifier BDFA. Fig. 3 shows two SER curves for the two configurations. When setup without pre-amplifier, the received

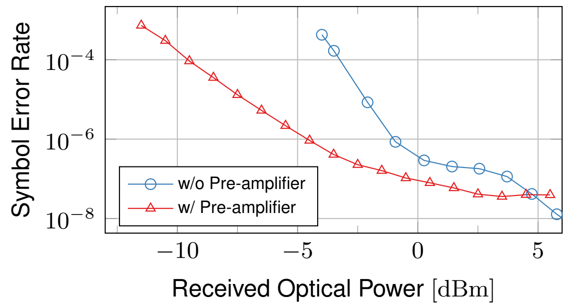

Fig. 3: Symbol error rate vs received optical power in back-to-back configuration

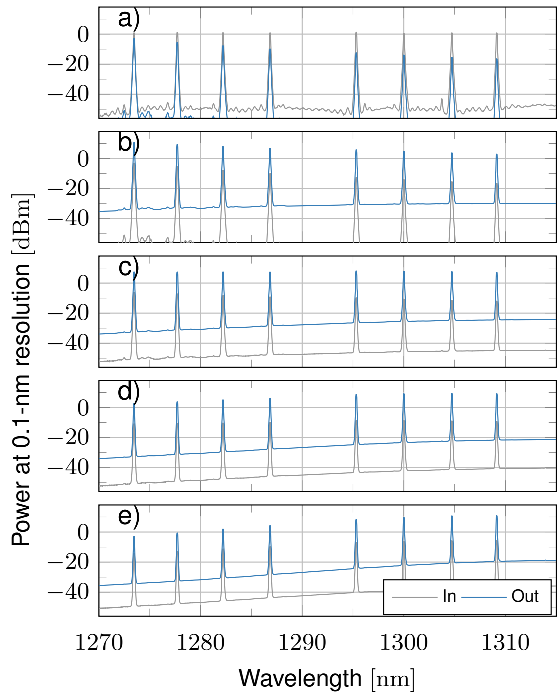

Fig. 4: Input/output spectra of a) pre-emphasis filter, b) first BDFA, c) second BDFA, d) third BDFA and e) fourth BDFA

optical power (ROP) was swept by a VOA. The ROP difference between the wavelength channels was within 2 dBm. However, this power difference was varied with the pre-amplifier. In case that the BDFA was used as a pre-amplifier, the ROP could be determined at the total optical power at the input of the BDFA. The BDFA was run in constant current mode during the measurement and varied the channel power. Although the BDFA induced a tilt of the signal power levels by ~6 dB according to the gain spectra, the ROP sensitivity could be improved by ~7 dB at the SER of 10^{-4}.

Transmission spectral evolution

Fig. 4 summarises the spectral evolution along the transmission link with the equal span length of 30 km. The transmission signal initially showed OSNRs >50 dB (Fig. 4a). The power per channel was flattened to ~1.3 dBm. However, the chan-

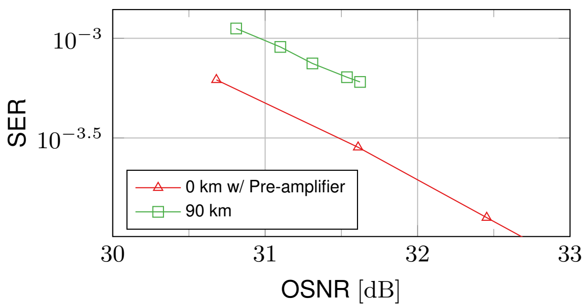

Fig. 5: OSNR penalty for 90 km transmission

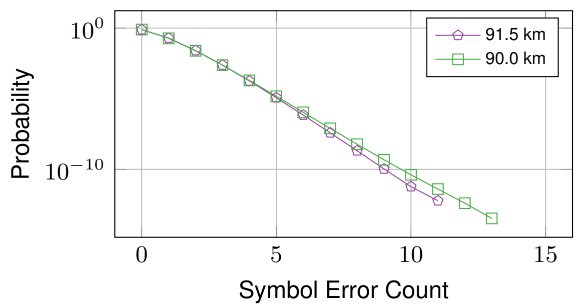

Fig. 6: Probability of corrected codewords for FEC symbol error count

nel power needed to be pre-emphasised to obtain a better SER after 90-km transmission since gain flattening filters were not implemented after the BDFAs. The BDFA and the transmission attenuation induce positive power tilt with increasing wavelength. Therefore, the pre-emphasis filter was set with a negative tilt to cancel the power tilt. In this experiment, we set a negative power tilt before inputting into the first BDFA. The power tilt was –13.5 dB from the shortest to the longest wavelength channel. A further power tilt was not possible due to OSNR degradation from substantial signal power suppression. After the first BDFA (booster amplifier), the output spectrum achieved a negative power tilt –7.7 dB, which means the BDFA induced +6 dB gain tilt across the eight wavelengths (Fig. 4b). The OSNR was degraded to 33.7-43.6 dB due to the addition of amplified spontaneous emission (ASE) noise, where the gain and the noise figure (NF) were 13.7-19.4 dB and 6.9-6.0 dB, respectively. For the second and third BDFAs (repeater amplifiers), the gain performance was similar to the first BDFA (Fig. 4c and d). After the second BDFA, the power levels were within 1 dB difference. The OSNRs of the input signal to the fourth BDFA (pre-amplifier) were in the range from 31.5 dB to 36.1 dB. The worst OSNR was observed at the longest wavelength. However, the OSNRs were flattened by 3 dB after the pre-amplifier. In the case of unequal span lengths, the longer span length would lead an extra OSNR degradation from the higher loss.

OSNR penalty for 90-km transmission

To characterise an OSNR penalty at 90 km, the SER as a function of OSNR was measured by inserting a VOA at the input of the fourth BDFA. In Fig. 5, the total SERs at 0 km and 90 km were plotted as circle and triangle. For 90-km transmission, the optical power could be swept up to 5 dB excluding the insertion loss of the VOA whilst the power tilt was maintained at –13.5 dB. The power budget for the last span was ~6 dB considering the insertion loss of the VOA. Over the swept OSNR range, the two curves are separated by ~1 dB. This 1-dB penalty could be considered that was mainly come from the accumulated CD and limited the transmission distance.

Long term measurement

We tested the 91.5-km transmission with equal spans for 24 hours and 90.0-km transmission with unequal spans for more than 7 days. The unequal case showed a higher SER than the equal case. The maximum SER was 4.51×10^{-4} in the unequal scenario. The probability of corrected codewords was observed up to the symbol error count of 13 (Fig. 6). It is noted that no frame error occurred for both cases and the maximum throughput was kept throughout.

Conclusions

We have demonstrated multi-span 400GBASE-LR8 transmission for the first time. We developed four single-stage backward pumped bismuth-doped fibre amplifiers (BDFAs). Nonetheless, the BDFAs worked not only as repeaters, but also fulfilled the roles of booster and pre-amplifier. Since the developed BDFA had an ultra-wide 6-dB gain window of 60 nm, the 90-km transmission line could be established without gain flattening filters after repeaters. The use of BDFAs kept the received OSNR higher than 30 dB. The transmission stability was validated for more than 7 days. In addition, we confirmed that the transmission link could be flexibly configured with unequal span lengths. Consequently, we showed that the BDFA could extend the O-band transmission reach of an emerging optical transceiver.

Acknowledgements

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