400GBASE-LR4 Transmission Over Field-Deployed Fibre Link Supported by Bismuth-Doped Fibre Amplifier

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Abstract *We demonstrated a transmission of 4x53 GBd PAM4 signals using a bismuth-doped fibre amplifier for the first time. Transmission reach was successfully expanded by amplifying 4 CWDM signals from 1271 to 1331 nm.*

Introduction

For data centres and service provider networks, 400 Gigabit Ethernet (GbE) specification for 10 km has been approved by IEEE 802.3bs in December 2017, in which the interface was defined as 400GBASE-LR8[1]. In 400GBASE-LR8, eight wavelength channels were multiplexed on local area network wavelength-division multiplexing (LAN-WDM) grid. The typical wavelengths range is from 1273 to 1309 nm. Each wavelength channel was modulated with 26 GBd 4-level pulse-amplitude modulation (PAM4) format. Although the regulation provides the transmission distance up to 10 km, the transmission experiments carried out over 35 km[2]. The transmission distance can be expanded by using bismuth-doped fibre amplifiers (BDFAs)[3], which are viewed as one of the key technologies that will extend the transmission reach and provide a boost in the O-band's capacity. In October 2020, a new 400 GbE specification up to 10 km was announced by multi-source agreement (MSA)[4], which is based on 100 Gb/s per wavelength on coarse WDM (CWDM) grid from 1271 to 1331 nm in typical. The transceiver modules based on quad small form factor pluggable double density (QSFP-DD) have been already released from various vendors, which are currently cost effective compared to 400GBASE-LR8 modules because the number of required optical components is small. However, to achieve 100 Gb/s per wavelength, the symbol rate was increased to 53 GBd. Therefore, chromatic dispersion would be one of the major objections to expand the transmission reach. In addition, an ultra-wide gain bandwidth is required to support 4 CWDM channels.

In this paper, we conducted a performance evaluation of a BDFA for a transmission of 400 Gb/s. For the evaluation, a test bed was set up with an installed fibre cable. This is the first demonstration to show the feasibility of the BDFA for the 400GBASE-LR4 signals in the range from 1271 to 1331 nm.

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Experimental setup

We used a 400GbE tester and a 400GBASE-LR4 transceiver based on the QSFP-DD form factor, as shown in Fig. 1. The 400GbE tester generated eight electrical signals at 26.6 GBd and multiplexed each two electrical lanes to modulate optical channels with 53.2-GBd 4-PAM signals. The optical signal was encoded with KP4 FEC. The average transmitted optical powers for 1271, 1291, 1311 and 1331 nm were $+2.5$, $+1.3$, $+1.8$ and $+1.9$ dBm, respectively. The CWDM optical signals were launched to a field deployed fibre cable[5]. The cable accommodated 200 fibres in total, in which 10 fibre units were contained. Each fibre unit bundled five rollable 4-fibre ribbons. The cable length was 1 km, which is relatively short but installed across circumstances including aerial and conduit areas. The input and output ends of the fibres were concatenated resulting a variety of transmission distances. The fibres used here were conformed to ITU-T G.657.A1 standardisation, which is compliant with G.652.D in all bands 1260-1625 nm; however the minimum bend radii of G.657.A1 is smaller than that of G.652.D for access networks. The measured attenuation and chromatic dispersion of the concatenated fibre cable was plotted in Fig. 2. The attenuation was measured over 50 km and normalised by distance in logarithmic scale. The dispersion was measured with an optical time-domain reflectometer, which emits optical pulses at four wavelengths of 1310/1450/1550/1625 nm.

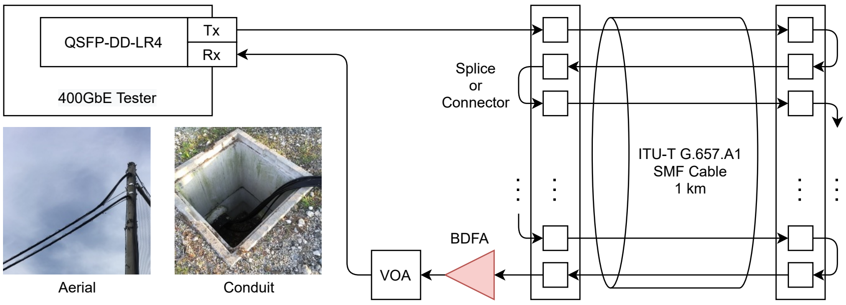

Fig. 1: Experimental setup.

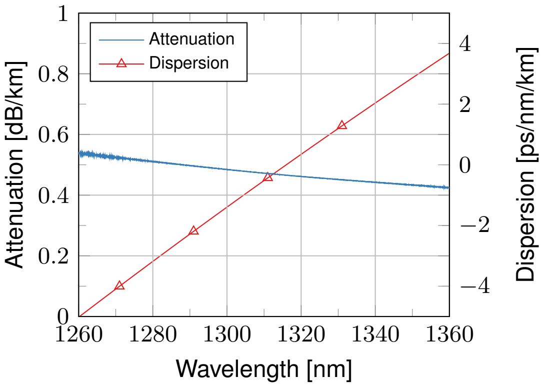

Fig. 2: Attenuation and chromatic dispersion of an installed fibre cable.

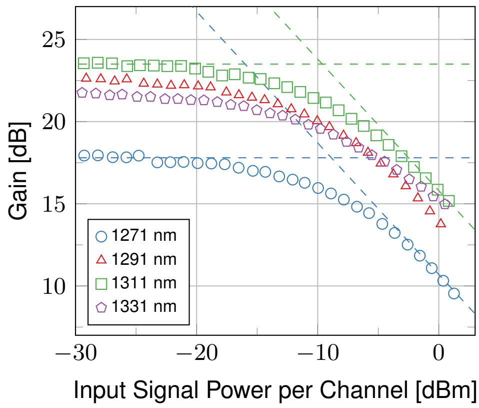

Fig. 3: Gain vs. input signal power per channel.

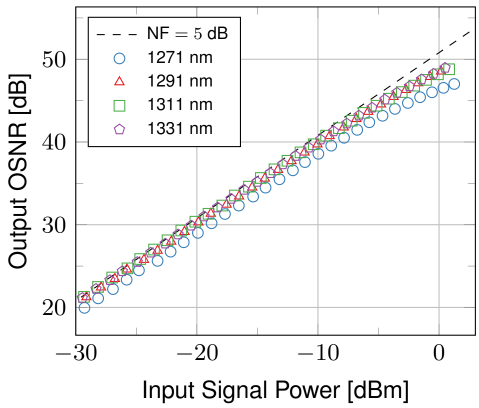

Fig. 4: Output OSNR vs. input signal power.

From the measured points, chromatic dispersion was estimated using a polynomial fitting. According to this estimation, the zero dispersion point was calculated at 1320 nm. The quality of the shortest wavelength channel at 1271 nm can be predicted as the worst case for the highest transmission loss and the largest dispersion in the CWDM channels of 400GBASE-LR4. The signal output from the cable was fed into a BDFA. The BDFA was driven by two pump lasers at a constant current. The amplified optical signal from the BDFA was suppressed by a variable optical attenuator for optimising the optical signal power at the reception.

BDFA characterisation

The gain and NF of the BDFA were characterised by attenuating the CWDM signals from the transmitter. Fig. 3 shows the gain at each wavelength for different input signal power per channel. The maximum gain was observed at 1311 nm and its small signal gain reached 23.5 dB. In the region of the small signal gain, the minimum gain was observed at 1271 nm and the difference from the maximum gain was 5.7 dB. This gain difference was almost kept for the higher input power. The gain of 1331 nm exceeded that of 1291 nm at the input power of -6 dBm and it was approaching to the gain of 1311 nm for higher input power. The BDFA showed an ultra-wide 6-dB gain bandwidth over 60 nm. Fig. 4 shows output optical signal-to-noise ratio (OSNR) for different input signal powers per channel. The output OSNR was starting to be saturated around the input power of -7 dBm or higher. Except for 1271 nm, all of channels were close together in entire of the measurement points. The dashed line indicates an ideal OSNR assuming the NF of 5 dB, which was estimated from input signal power and the shot noise level at 1310 nm. The NF values were estimated as 5.0 to 6.7 dB for the small signal gain.

Transmission trials

Fig. 5 shows the received power over distances up to 25 km. The symbol error rate (SER) was 2.4×10^{-7} in a back-to-back configuration. It was

Tab. 1: Symbol error rate for each electric lane over distances.

Wavelength	Lane	20 km	25 km
1271 nm	0	4.9×10^{-7}	2.4×10^{-5}
	1	2.5×10^{-5}	2.0×10^{-4}
1291 nm	2	3.4×10^{-8}	6.2×10^{-7}
	3	3.2×10^{-7}	1.6×10^{-5}
1311 nm	4	2.5×10^{-6}	1.5×10^{-6}
	5	2.6×10^{-6}	1.3×10^{-5}
1331 nm	6	2.1×10^{-6}	5.0×10^{-4}
	7	6.6×10^{-5}	1.6×10^{-3}

increased rapidly after 5 km. The threshold of the symbol error count is 15 for KP4 FEC. The specification of 400GBASE-LR4 supports transmission distance at least 10 km. The frame loss was not observed up to 15 km according to the specification. The symbol error count exceeded the threshold when the transmission distance over 20 km and the 400GbE link was down. The received optical power was attenuated by 9.6 dB at the distance of 20 km. By adding the BDFA before the signal reception, the symbol error rate was improved and no frame loss was confirmed over 20 km for 60 minutes. Fig. 6 summarises the transmission performance over distances up to 25 km in terms of the probability of corrected codewords. The symbol error count was improved by introducing the BDFA. The distribution of the symbol error count after 20 km with BDFA was improved compared to that after 15 km without BDFA. The error count did not exceed the threshold of the symbol error count after 25 km; however, the probability of the higher error count was increased and resulted in the number of burst errors. Therefore, the throughput was significantly deteriorated and 400GbE link was down over 25 km. Fig. 7 shows the output power level after the BDFA. The power difference was enhanced from 1.2 to 6.8 dB by amplification. The minimum power was observed at 1271 nm; however, the minimum SER was observed at 1331 nm, as shown in Table 1. The OSNR was degraded by BDFA; however, it was over 35 dB. Consequently, the performance degradation was mainly caused by considerable dispersion for such a high symbol rate over 50 GBd. In fact, the dispersion values were expected from Fig. 2 as -84 and $+26$ ps/nm at 1271 and 1331 nm, respectively.

Conclusion

We have demonstrated a 400GBASE-LR4 transmission over an installed fibre cable. The transmission reach was successfully extended up to 20 km without frame loss by using a bismuth-doped fibre amplifier (BDFA) as a pre-amplifier at the signal reception. This is the first field demonstration to show the BDFA can support the CWDM signals across 60 nm in O-band.

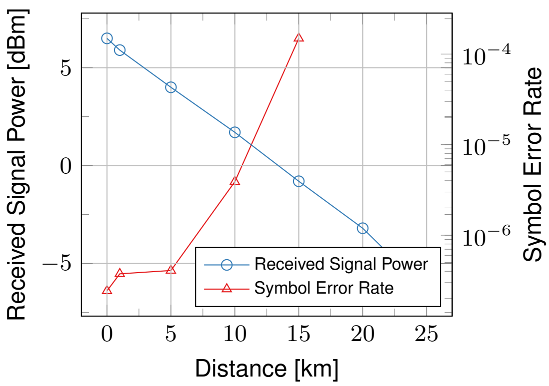

Fig. 5: Received signal power and symbol error rate for different distances.

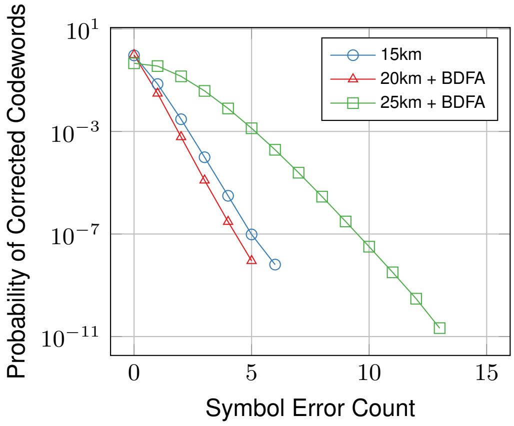

Fig. 6: Probability of corrected codewords for symbol error count.

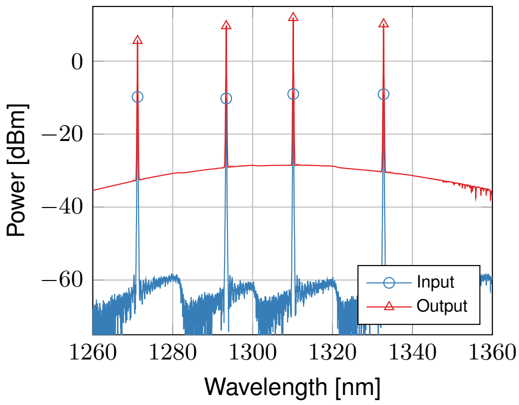

Fig. 7: Amplified spectrum after 25 km.

Acknowledgements

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