High-Capacity 400Gb/s Real-Time Transmission over SCUBA110 Fibers for DCI/Metro/Long-haul Networks

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Abstract: We demonstrate real-time transmission 23.2 Tb/s (58x400Gb/s) DWDM signals over 1507km of G.654E SCUBA110 fiber using 400ZR+ pluggable coherent transceiver modules, additionally, 26Tb/s (65x400Gb/s) is transmitted over 200km SCUBA110 fiber link using 400ZR pluggable modules.

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1. Introduction

Internet traffic continues to increase explosively due to the rapid growth of cloud computing, Internet of Things (IoT), and social media services in the data center interconnects (DCI), metro/long haul networks. To cope with this trend, data center operators, cloud providers, and traditional network carriers, all are boosting the bandwidth of their networks, meanwhile, they are constantly seeking to lower networking cost. Last few years, high-speed pluggable transceivers have brought cost efficiencies and overall economic benefits for operators to scale their networks. The 400ZR/ZR+ specification [1-2] is another effort to define an interoperable 400G coherent interface to further reduce cost. New advanced fibers such as large-area ultra-low-loss (ULL) fiber, that improves the transmission performance for high data rate and high spectral efficiency (SE), have also allowed the operators to increase the capacity and reduce network cost by optimizing fiber cabling infrastructures that provide better capacity upgrade pathways and add sufficient system margins. Large-area ULL fiber G.654.D has been widely deployed in undersea cable systems, and ITU-T has specifically standardized large-area fiber G.654.E [3] for terrestrial applications. Recently, several transmission experiments and field trials have been reported on G.654.E fibers with high data rates for terrestrial applications [4-7]. For example, experiments have been realized to transport of 20.8 Tb/s over 1200km of G.654.E fibers using 400Gb/s 64Gbaud CFP2-DCO interfaces and hybrid Raman/EDFA amplification [4]. 500Gb/s single-carrier signals transmission over 1234.2km field-installed G.654.E fiber link was reported using EDFAs with forward and backward Raman amplification [5]. In addition, real-time transmissions of 16Tb/s (80x200Gb/s) over 1020km of G.654.E fibers have been demonstrated with long repeaters span length of 170km [6]. Twelve 800 Gb/s channels transmission over 1122km G.654.E fiber was also demonstrated using EDFA/Raman amplification and 90.5Gbaud 64QAM with probabilistic constellation shaping (PCS) [7].

In this paper, we report the real-time transmissions of 23.2Tbs (58x400Gb/s) capacity over 1507km fiber using lost cost 400ZR+ pluggable modules [2] and only EDFA amplification. This is achieved by employing advanced OFS TeraWave® SCUBA110 fiber (fully G.654.E compliant cutoff-shifted fiber) with average loss of 0.152dB/km. In addition, real-time transmission of 26 Tb/s over 200km amplified link with SCUBA110 fiber is demonstrated using 400ZR pluggable modules. This is obtained by transmitting sixty-five 400ZR channels with 75GHz frequency grid in full C-band (1528.77-1567.13nm), and it has average Q^2-margin of 1.6dB. This reach is much longer than that targeted by 400ZR standard interoperability agreement (IA) [1] thanks to large-area ULL of SCUBA110 fiber.

2. SCUBA110 Fiber

TeraWave® SCUBA110 fiber is one type of OFS SCUBA series fibers [8-9], that is designed to meet both undersea G.654.D and terrestrial G.654.E standard. It is a silica-core fiber which results in lower overall attenuation and lower nonlinear refractive index, which is benefit the tolerance towards nonlinear effects. The larger A_{eff} (compared to G.652 fiber) also results in an increase in the dispersion of SCUBA110 fiber, which further improves tolerance towards nonlinear effects. The key optical fiber parameters of the fiber that used in this transmission experiment are shown in Table. 1. Also, the refractive index profile of the SCUBA-110 is a so-called trench design, which ensures that the macro-bend performance is no worse than a standard effective area G.652 fiber despite the larger effective area. The micro-bend performance is excellent also at longer wavelengths (L-band) due to the trench design [9]. As shown in the Table 1, the attenuation is much lower than typical Germania-doped fiber, and cutoff wavelength is much lower than that in typical G.654.E fiber, which is excellent for DCI, metro/long haul network applications.

Table 1: Key fiber parameters (average at 1550nm)

Attenuation (dB/km)	0.1520
Effective area (μm^2)	107.7
Dispersion (ps/(nm.km))	21.81
Dispersion slope (ps/nm^2.km))	0.06
Cutoff wavelength (nm)	1317

3. 58x400Gb/s Transmission over 1507km of SCUBA110 Fiber using 400ZR+

The straight-line transmisison experimental set-up is shown in schematic diagram Fig. 1. The transmitters consist of a measurement and a loading path. For the measurement path, three 400Gb/s channels using commercially available 400ZR+ pluggable transceiver modules are set to adjacent channels with 75 GHz spacing and then combined together. The spectral efficiency is 5.33 bits/s/Hz. The loading path is composed of a broadband ASE source and is notch-filtered by a 50GHz channelized wavelength selective switch (WSS) filter for a bandwidth window of ~250 GHz. 400ZR+ pluggable transceiver [2] is based on coherent technolgy utilising DP-16QAM modulation and uses open-FEC (O-FEC) which can correct a bit-error-ratio (BER) of ~ $1.89\text{x}10^{-2}$ (Q^2-factor =6.35dB) to BER lower than 10^{-15}. The combined signals are amplified and then sent to transmission fibre link, which consists of 13 SCUBA110 fiber spans with average span length of 112km. The average span loss is 17.6dB including splice and connectos losses, which are compensated by EDFAs. A dynamic gain equalizer (GDE) is used after 7th span to flatten the channels at receiver, and an additional EDFA with 51km SCUBA110 fiber spool is used as an additional span. After 1507km transmisison link, a 400Gb/s signal channel is selected by a demultiplexer (DeMux), and sent to 400ZR+ receiver. When assessing the system performance, the three 400ZR+ channels are loaded with equal launch powers with ASE channels, and we measure the middle channel among 3 consecutive 75GHz-spaced channels as they are translated across the C-band with wavelength ranging from 1529.94nm to 1564.07nm.

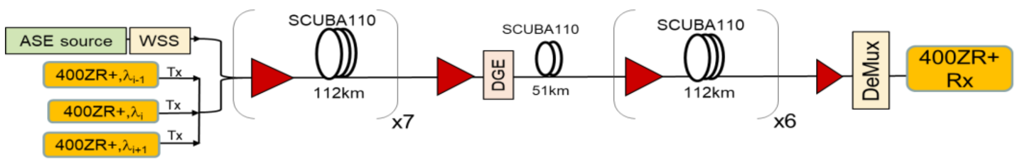

Fig. 1 Transmission experimental set up for 400ZR+ DWDM long-distance transmissions

To test the 400ZR+ transmission performance, we place the group of three 400 Gb/s channels and adjust the launch power of three channels together and measure the Q^2-margin of the middle channel. Fig.2 (a) shows Q^2- margin as a function of OSNR for 1531.12nm and 1554.52nm channels, the Q^2 margin is about 0.85~1dB after 1507 km transmission at optimal OSNR of 25.5~26 dB/0.1nm. The short wavelength channels suffer more transmission penalty. To test the transmission performance as a function of the wavelength channels, we determine the Q^2 margin from the measured real-time BER of the middle channel among three consecutive 75 GHz spaced channels. Fig. 2 (b) shows the measured Q^2-margin as a function wavelength channels along with the measured OSNR. The average Q^2- margin is 0.82dB with a variation of 0.79dB. The low Q^2-margin at wavelength around of 1536nm is due to relatively low OSNR. The average OSNR of 58 channels is 24.9 dB/0.1nm with a variation of 2dB. The received spectra recorded after 15th EDFA is also plotted in Fig.3 (c) with different measurement wavelengths showing equal power uniform loading of three 400Gb/s measurement channels. The signal channels are not completely flat at receiver due to only one DGE in 14 spans.

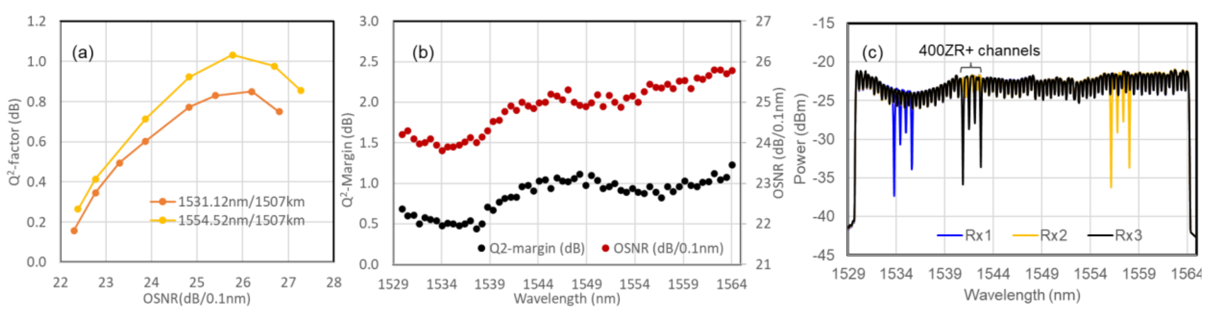

Fig. 2 (a) Q^2- margin as a function of OSNR for 1531.12nm and 1554.52nm channels after 1507km transmission, (b) Measured Q^2-margin and OSNR of all 58 400ZR+ channels, (c) Received spectra with different measurement channels

4. 26Tb/s Transmission over 200km of SCUBA110 Fiber Link with 400ZR

Fig. 3 shows a schematic of experimental set-up for 400ZR DWDM transmissions. Like that in Fig.1, three 400Gb/s channels using 400ZR pluggable coherent transceiver modules are used as the transmitters for measurement, and they are set to adjacent channels with 75 GHz spacing. The three 400ZR channels are combined with the broadband ASE source which is notch-filtered by a 50GHz channelized WSS filter. 400ZR pluggable transceiver module is targeted to provide low cost 400Gb/s Ethernet links for edge DCI applications with amplified DWDM link up to 80~120km distance [1]. It utilizes concatenated forward-error-correction (C-FEC), which has overhead ~ 14.8% and can correct a bit-error-ratio (BER) of ~ $1.08\text{x}10^{-2}$ (Q^2-factor =7.22dB) to lower than 10^{-15}. The combined DWDM channels are boosted by high power EDFA with output power of 26.8dBm, and then sent to the 200km SCUBA110 fiber link. The total loss of 200km span including splice and connectors is 31.1dB. A 2nd EDFA is used to amplify the DWDM signals before sending to the DeMux. The selected channel after DeMux is then sent back to 400ZR receiver. When assessing the system performance, the three 400ZR channels are loaded with equal launch powers with ASE channels, and we measure the middle channel among 3 consecutive 75GHz-spaced channels as they are translated across the C-band from 1528.77nm to 1567.13nm.

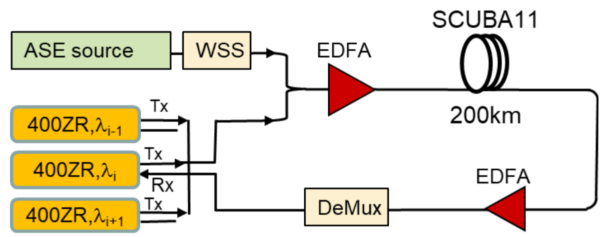

Fig.3. Experimental set-up for 400ZR DWDM 200km transmission

The accumulated CD in 200km SCUBA110 fiber link is from 4094ps/nm at 1528.77nm to 4579ps/nm at 1567.13nm, which are larger than the CD compensation (CDC) value of 2400ps/nm in 400ZR IA specification [1], therefore the 400ZR is operated in 'high power mode' [10] in this experiment, and maximum CDC value is set to be 4580ps/nm. As indicated in [10], the Q^2 value can be improved when operating in 'high power mode', that is mainly improved by the increase of internal bit-width of CDC, but the total power consumption is increased to 17.1W from 16.3W at 'low power mode'. Fig.4 (a) shows the measured Q^2 margin vs OSNR for two channels after 200km link, the short wavelength 1529.94nm channel shows large nonlinear transmission penalty and have Q^2 margin about 1.3dB, while the long wavelength channel 1552.52nm performs better and has Q^2 margin about 1.8dB at optimum launch power condition. The transmission performance as a function of the wavelength channels has also assessed by the Q^2 margin from the measured real-time BER of the middle channel among three consecutive 75 GHz spaced channels. Fig. 4 (b) shows the measured Q^2 and OSNR as a function wavelength channel. The average Q^2 margin ~ 1.6dB with a variation of 0.8dB, and the average OSNR across 65 channels is 29 dB/0.1nm. The received spectra are plotted in Fig.4 (c) with different measurement wavelengths showing equal power loading of three 400Gb/s measurement channels.

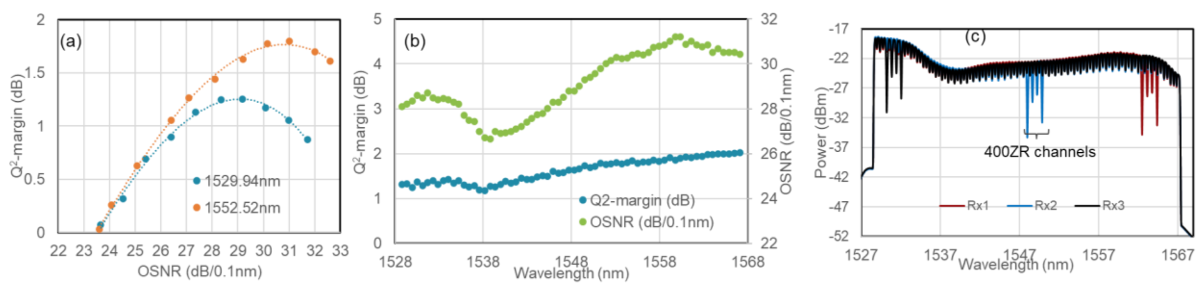

Fig. 4 (a) Measured Q^2 margin vs OSNR for two channels after 200km link, (b) Measured Q^2- margin and received OSNR of all 65 channels after 200km amplified span transmission, (c) Received spectra with different measurement channels

5. Summary

We have demonstrated real-time transmissions of 23.2Tbs (58x400Gb/s with 75 GHz frequency grid) capacity over 1507km fiber with average Q^2-margin of 0.82dB using 400ZR+ pluggable modules. This is achieved by employing SCUBA110 fiber with average loss of 0.152dB/km. With 400ZR modules, we successfully demonstrated the real-time transmission of 26 Tb/s over 200km of SCUBA110 fiber link with average Q^2 margin of 1.6dB, which gives sufficient system margin for practical deployable 200km amplified 400ZR link for large-scale DCI applications.

6. References

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