European Conference on Optical Communication (ECOC) 2022 © Optica Publishing Group 2022

Demonstration of up to 480-km BDFA-based WDM Direct-detection Transmission in the O-band

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Abstract *We report on experiments of 3×50-Gb/s O-band WDM direct-detection transmission using a BDFA-based optical recirculating loop. Record-long transmission distances up to 480 km are achieved at the SD-FEC limit in experiments with two different channel spacings. ©2022 The Author(s)*

Introduction

Use of the O-band (1260-1360 nm) is already well established for short-reach wavelength-division multiplexed (WDM) direct-detection (DD) systems [1, 2]. Extending the reach of O-band systems to greater distances has the potential to simplify optical interconnects by eliminating the requirement for use of different wavelength bands for intra- and inter-datacenter links and the associated optical-electrical-optical conversions. Reach extension of the O-band transmission will also be desired in future multi-band amplified systems, which offer a sustainable and cost-effective solution to the challenge of boosting the capacity of single-mode fibres (SMFs) by making a fuller use of the existing fibre infrastructure [3].

The key to extending the possible transmission reach of such systems lies in the realization of efficient optical amplifiers in this spectral region. Candidate technologies currently include semiconductor optical amplifiers (SOAs), praseodymium-doped fibre amplifiers, Raman amplifiers, and the more recently emerging bismuth-doped fibre amplifiers (BDFAs) [4-6]. While SOAs represent the most mature solution, they are generally considered unsuitable for in-line multi-span amplification due to their relatively high nonlinearity, the introduction of patterning effects and inferior noise performance relative to fibre-based devices. The longest transmission distance reported in an SOA-based O-band system was 200 km with a span length of 50 km and a data rate of 4×10 Gb/s [7]. Compared to SOAs, the recently emerged BDFAs have been demonstrated to offer higher gain, lower noise figure (NF), lower nonlinearity and the potential to cover wide bandwidths extending from the O- to the E-bands [8-11].

In this work, we exploit these features of the BDFA to demonstrate O-band WDM transmission of 3×50-Gb/s signals in an optical recirculating loop, which constitutes the first demonstration of using BDFAs for potential transmission over appreciable multi-span distances. We experimented with two different channel spacings, namely 6 nm and 1.2 nm. Both Nyquist on-off keying (OOK) and Kramers-Kronig (KK) detection-assisted single-sideband (SSB) quadrature phase-shift keying (QPSK) formats are considered. DD transmission up to 360-km for the 6-nm spacing case and up to 480-km for the 1.2-nm spacing case are achieved at the soft-decision forward error correction (SD-FEC) limit of 2.4×10^{-2}. These results represent the longest reach (and the highest rate-reach product) ever reported in the O-band and highlight the feasibility of using BDFAs to significantly extend the reach of O-band systems.

Experimental Setup

Fig. 1 shows the experimental setup of the BDFA-based optical recirculating loop system. Three continuous wave (CW) lasers were adopted as the optical carriers, and odd and even channels were modulated by two separate Mach-Zehnder modulators (MZMs) for signal decorrelation. In this work, we considered two channel spacings of around 6 nm (1 THz) and 1.2 nm (200 GHz), which we will be referring to as coarse (CWDM) and dense spacing (DWDM), respectively. Specifically, the adopted wavelengths were 1330.9 nm, 1336.9 nm, and 1343.0 nm in the CWDM case, whereas 1340.7 nm, 1341.9 nm, and 1343.1 nm were used in the DWDM case. Note that the wavelength choice was limited by the few sources available to us and the gain profile of the BDFA [5]. The outputs of the two MZMs were combined using a 3-dB coupler and then amplified by a BDFA (Tx BDFA). The powers of the three channels were adjusted to be the same at the output of the Tx BDFA.

Subsequently, the optical signal was launched into an optical recirculating loop which was controlled by two acousto-optic modulators (AOMs), both of which exhibited an insertion loss of around 1 dB. A 60-km length of SMF was adopted in the loop, which had a loss of ~19 dB, a zero-dispersion wavelength of ~1316 nm and a

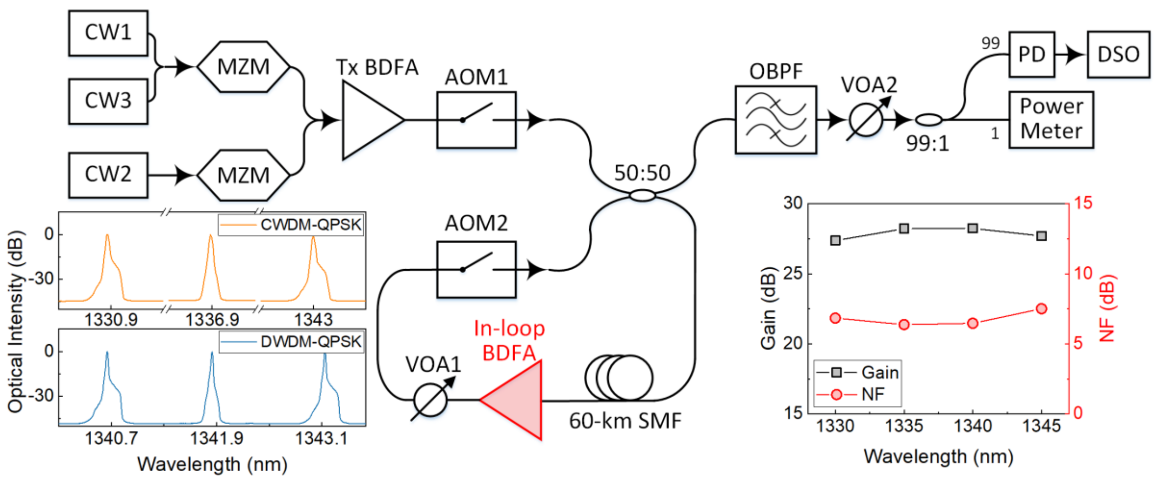

Fig. 1: Setup of the BDFA-based WDM recirculating loop system. Insets: optical spectra of the CWDM QPSK transmission and the DWDM QPSK transmission (left) and gain and NF performance of the in-loop BDFA at -20 dBm input (right).

dispersion slope of ~0.083 ps/nm^2/km. A second BDFA was used for in-loop amplification. The input power to the in-loop BDFA was maintained at around -9 dBm in both CWDM and DWDM cases. The noise performance of the in-loop BDFA was comparable at the wavelengths of interest, whereas the gain at 1330.9 nm was slightly lower, as indicated in the inset of Fig. 1. Detailed gain and noise characterizations were reported in [5, 8]. A variable optical attenuator (VOA1) was utilized to balance the gain and loss in the loop. At the DD receiver, an optical band-pass filter (OBPF) with a bandwidth of 1.2 nm was used to select the desired WDM channel. Another VOA (VOA2) was placed in front of the photodetector (PD) to fix the received optical power to -3 dBm in all cases. Finally, the detected signal at the PD was captured by a digital storage oscilloscope (DSO) for offline digital signal processing.

In the experiments, we adopted either Nyquist OOK or SSB QPSK as the DD format for the CWDM and DWDM transmission, and the data rate per channel in all cases was 50 Gb/s. For the Nyquist OOK, square-root-raised-cosine filtering with a roll-off factor of 0.1 was used for Nyquist shaping, and a T/2-spaced recursive least squares algorithm-based decision feedback equalizer was used for adaptive equalization. For the SSB QPSK, half-cycle subcarrier modulation with KK detection was used [12, 13]. The same adaptive equalization as in the Nyquist OOK transmission case was adopted, and the chromatic dispersion (CD) was additionally compensated for digitally after recovery of the complex signal. As only one dual-drive and one single-drive MZM were available when conducting the experiments, we swapped the modulators between odd and even channels, and only signals generated by the dual-drive MZM (either for OOK or QPSK) were evaluated to ensure a fair comparison. The optical spectra in the case of SSB QPSK for the CWDM and DWDM transmission are shown in the inset of Fig. 1.

Experimental Results

We first investigated the performance of the CWDM transmission, and the results are shown in Figs. 2 and 3. For the OOK transmission (Fig. 2), the bit-error rate (BER) performance of the CWDM channels degraded with an increase in wavelength, since the longer-wavelength channels experienced a more severe impact of CD. This indicates that although CD in the O-band is relatively low, it may still represent the limiting factor in longer-reach transmission [12, 13]. A theoretical analysis suggests that even at the 1330.9-nm channel (assuming CD=1.2 ps/nm/km), a 3-dB bandwidth of <20-GHz will be available after 100-km transmission [13].

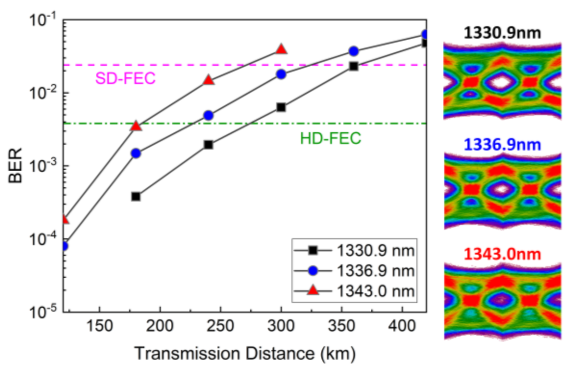

Fig. 2: BER versus transmission distance for the 50-Gb/s/λ O-band CWDM transmission using Nyquist OOK. Insets: the eye diagrams of the 240-km OOK transmission.

This is also evidenced by the gradually degraded quality of the recovered eye diagrams of the three channels captured at 240-km transmission, as presented in the insets of Fig. 2.

As a result, for the longest wavelength channel of 1343.0 nm, the reach was limited to 180 km in order to keep the BER below the hard-decision FEC (HD-FEC) limit of 3.8×10^{-3}. When the SD-FEC limit was considered, the achievable reaches for the three wavelengths were 240 km, 300 km, and 360 km, respectively.

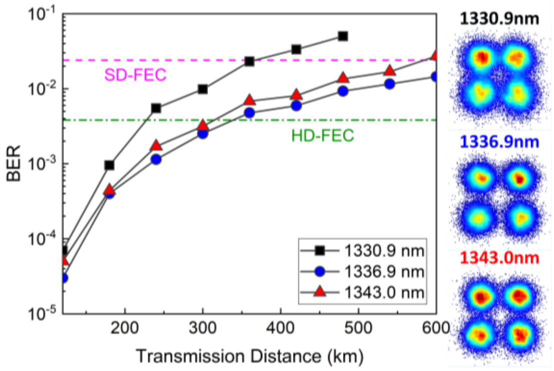

Fig. 3: BER versus transmission distance for the 50-Gb/s/λ O-band CWDM transmission using SSB QPSK. Insets: the constellation diagrams of the 360-km QPSK transmission.

To combat the CD and hence further extend the achievable reach, we also investigated use of the SSB QPSK format for the CWDM transmission, and the results are depicted in Fig. 3. Since the in-loop BDFA did not incorporate a gain-equalizing filter, the three wavelengths experienced slightly different gain in the loop, resulting in slightly varying performance. Consequently, the central channel of 1336.9 nm achieved the lowest BERs and could be transmitted up to 600 km while exhibiting a BER lower than the SD-FEC limit. The worst BER performance was experienced at 1330.9 nm due to the lower gain of the in-loop BDFA at this wavelength [5, 8]. Nevertheless, a transmission distance up to 360-km was still achievable at the SD-FEC limit. The constellation diagrams of the recovered QPSK signals after 360-km transmission are illustrated in the insets of Fig. 3.

We next experimented with the 50-Gb/s Nyquist OOK and SSB QPSK signals in a 3-channel DWDM configuration, and the results are shown in Figs. 4(a) and 4(b), respectively. In both cases, all three DWDM channels exhibited a similar BER performance, thanks to the uniform gain of the in-loop BDFA across this relatively narrow spectral window as well as the uniform CD degradation (for OOK transmission). Specifically, for the OOK transmission, the achievable reach was around 180 km (at the HD-FEC limit) or 240 km (at the SD-FEC limit).

By adopting the SSB QPSK format instead and compensating for the CD, these distances could be extended to around 300 km and 480 km, respectively, as shown in Fig. 4(b). This represents a maximum rate-reach product of 57.6 Tb/s-km (after accounting for the 20% redundancy of the SD-FEC).

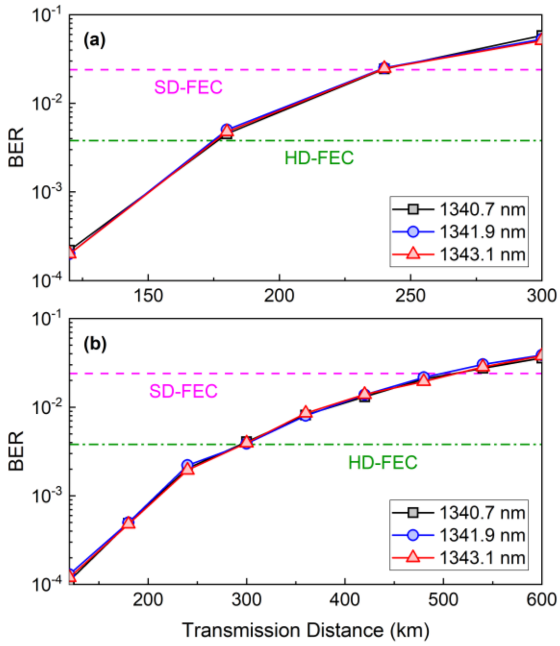

Fig. 4: BER versus transmission distance for the 50-Gb/s/λ O-band DWDM transmission using: (a) Nyquist OOK, and (b) SSB QPSK.

Furthermore, the nonlinearity of the SMF (e.g., four-wave mixing) appears not to have been a limiting factor in our DWDM transmission, as the adopted wavelengths are away from the zero-dispersion region and the BDFA exhibits low nonlinearity. However, a comparison between Figs. 3 and 4(b) reveals that the performance of the DWDM transmission was slightly worse than that achieved at the 1343.0-nm channel in the CWDM transmission. We provisionally attribute this minor penalty to the imperfect filtering provided by the 1.2-nm OBPF, which exhibits a full width at half maximum bandwidth of ~0.5 nm.

Conclusions

We demonstrated a record transmission distance and a record rate-reach product in an amplified WDM O-band system. Based on a BDFA-based recirculating loop, we transmitted 3×50-Gb/s signals over distances up to 480 km at the SD-FEC limit. Our results, although clearly still at an early stage, suggest that it should be possible to realize cost-effective high-capacity O-band transmission over appreciable distances through the existing fibre infrastructure.

Acknowledgements

This work was supported by the UK's EPSRC under the *Airguide Photonics*, *COALESCE*, and *PHOS* grants (EP/P030181/1, EP/P003990/1, EP/S002871/1). The data is accessible at https://doi.org/10.5258/SOTON/D2136.

References

[1] M. Sysak, J. Johnson, D. Lewis, and C. Cole, "CW-WDM MSA technical specifications," https://cw-wdm.org/?wpdmdl=2092, accessed on 08 April 2022.

[2] F.J. Effenberger, "PON standardisation status and future prospects," presented at *European Conference on Optical Communication*, Dublin, Ireland, paper M.2.F.1, 2019. DOI: 10.1049/cp.2019.0793

[3] N. Sambo, A. Ferrari, A. Napoli, N. Costa, J. Pedro, B. Sommerkorn-Krombholz, P. Castoldi, and V. Curri, "Provisioning in Multi-band Optical Networks," *Journal of Lightwave Technology*, vol. 38, no. 9, pp. 2598-2605, 2020. DOI: 10.1109/JLT.2020.2983227

[4] E.M. Dianov, "Amplification in extended transmission bands using bismuth-doped optical fibers," *Journal of Lightwave Technology*, vol. 31, no. 4, pp. 681-688, 2013. DOI: 10.1109/JLT.2012.2211569

[5] N.K. Thipparapu, A.A. Umnikov, P. Barua, and J.K. Sahu, "Bi-doped fiber amplifier with a flat gain of 25 dB operating in the wavelength band 1320–1360 nm," *Optics Letters*, vol. 41, no. 7, pp. 1518-1521, 2016. DOI: 10.1364/OL.41.001518

[6] V. Mikhailov, J. Luo, D. Inniss, M. Yan, Y. Sun, G.S. Puc, R.S. Windeler, P.S. Westbrook, Y. Dulashko, and D.J. DiGiovanni, "Amplified transmission beyond C- and L-bands: doped fibre amplifiers for 1250-1450 nm range," presented at *European Conference on Optical Communication*, Brussels, Belgium, paper Mo1E-1, 2020. DOI: 10.1109/ECOC48923.2020.9333312

[7] J.P. Turkiewicz, M.T. Hill, G.D. Khoe, and H.de Waardt, "Cost-effective transmission concept for LAN/MAN/SAN applications," presented at *European Conference on Optical Communication*, Glasgow, United Kingdom, paper Th1.4.2, 2005. DOI: 10.1049/cp:20050730

[8] N. Taengnoi, K.R.H. Bottrill, Y. Hong, Y. Wang, N.K. Thipparapu, J.K. Sahu, P. Petropoulos, and D.J. Richardson, "Experimental characterization of an O-band bismuth-doped fiber amplifier," *Optics Express*, vol. 29, no. 10, pp. 15345-15355, 2021. DOI: 10.1364/OE.420995

[9] V. Mikhailov, M.A. Melkumov, D. Inniss, A.M. Khegai, K.E. Riumkin, S.V. Firstov, F.V. Afanasiev, M.F. Yan, Y. Sun, J. Luo, G.S. Puc, S.D. Shenk, R.S. Windeler, P.S. Westbrook, R.L. Lingle, E.M. Dianov, and D.J. DiGiovanni, "Simple broadband bismuth doped fiber amplifier (BDFA) to extend O-band transmission reach and capacity," presented at *Optical Fiber Communications Conference and Exhibition*, paper M1J.4, 2019. DOI: 10.1364/OFC.2019.M1J.4

[10] N. Taengnoi, K.R.H. Bottrill, Y. Hong, N.K. Thipparapu, C. Lacava, J.K. Sahu, D.J. Richardson, and P. Petropoulos, "4-Level alternate-mark-inversion for reach extension in the O-band spectral region," *Journal of Lightwave Technology*, vol. 39, no. 9, pp. 2847-2853, 2021. DOI: 10.1109/JLT.2021.3062446

[11] Y. Hong, K.R.H. Bottrill, N. Taengnoi, N.K. Thipparapu, Y. Wang, A.A. Umnikov, J.K. Sahu, D.J. Richardson, and P. Petropoulos, "Experimental demonstration of dual O+C-band WDM transmission over 50-km SSMF with direct detection," *Journal of Lightwave Technology*, vol. 38, no. 8, pp. 2278-2284, 2020. DOI: 10.1364/JLT.38.002278

[12] Y. Hong, K.R.H. Bottrill, N. Taengnoi, N.K. Thipparapu, Y. Wang, J.K. Sahu, D.J. Richardson, and P. Petropoulos, "First investigation on double- and single-sideband formats in BDFA-enabled O-band transmission," presented at *Conference on Lasers and Electro-Optics*, San Jose, United States, paper STh3L. 3, 2020. DOI: 10.1364/CLEO_SI.2020.STh3L.3

[13] Y. Hong, K.R.H. Bottrill, N. Taengnoi, N.K. Thipparapu, Y. Wang, J.K. Sahu, D.J. Richardson, and P. Petropoulos, "Numerical and experimental study on the impact of chromatic dispersion on O-band direct-detection transmission," *Applied Optics*, vol. 60, no. 15, pp. 4383-4390, 2021. DOI: 10.1364/AO.424962