Experimental Demonstration of 50-Gb/s/λ O-band CWDM Direct-Detection Transmission over 100-km SMF

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Abstract: We demonstrate the first single-sideband 50-Gb/s/λ coarse WDM direct-detection transmission in the O-band. It is shown that the Kramers-Kronig-detection assisted single-sideband transmission exhibits significant OSNR sensitivity improvements over double-sideband transmission, enabling up to 100-km reach.

1. Introduction

The O-band is an attractive alternative optical window to the C-band and has already been used extensively in both data center and metro/access networks [1,2]. However, its use has been primarily restricted to short-reach links, due to the higher loss of single-mode fibers (SMFs) and the lack of a suitable amplification technology. The recent emergence of bismuth-doped fiber amplifiers (BDFAs) [3,4] has the potential to disrupt this position. Silica-glass host based BDFAs are more cost-efficient and offer a broader gain bandwidth compared to the fluoride-glass host based praseodymium-doped fiber amplifiers [4]. While offering a lower noise figure and a higher gain, BDFAs also exhibit significantly better linearity than semiconductor optical amplifiers [5,6]. A few transmission experiments have already been demonstrated [4-6], showing the potential of BDFAs for reach extension.

When extending the reach, the chromatic dispersion (CD), which has long been neglected in O-band systems, will emerge as another crucial factor that may limit the transmission performance [7,8]. Even though the CD of SMFs in the O-band is relatively low (the average CD value ranges from around -5.1 to 3.8 ps/ns/km over the 100-nm bandwidth according to the ITU G.652 standard), its cumulative effects will still introduce severe power fading in double-sideband direct-detection (DD) transmission, and thus degrade the performance. This may prove a critical issue if pushing the currently deployed short-reach 50-Gb/s/λ O-band coarse wavelength-division multiplexed (CWDM) systems to longer-reach scenarios, e.g., in inter-data center interconnects.

In this paper, we present to the best of our knowledge, the first comparative investigation on the performance of dispersion-sensitive double-sideband and dispersion-tolerant single-sideband transmission in a 4×50-Gb/s/λ O-band CWDM system. A pair of BDFAs were used as the booster- and pre-amplifier, respectively. In this length-resolved study, we demonstrate that Kramers-Kronig (KK) detection assisted single-sideband quadrature phase shift keying (QPSK) transmission exhibits significantly better optical signal-to-noise ratio (OSNR) sensitivity than double-sideband Nyquist on-off keying (OOK). As a result, up to 100-km reach was achieved, which constitutes the longest O-band CWDM transmission at 50-Gb/s/λ to date.

2. Experimental Setup

Fig. 1(a) shows the experimental setup of the BDFA-amplified O-band CWDM DD system. Four CW lasers operating at 1330.6, 1343.1, 1351.1, and 1360.0 nm were adopted as the optical carrier and fed to external Mach-Zehnder modulators (MZM). One dual-drive and one single-drive MZM were available for our experiments. For the double-sideband transmission, both MZMs were modulated with 50-Gb/s Nyquist OOK signals, whereas for the single-sideband transmission, the DD-MZM was modulated with 50-Gb/s QPSK half-cycle Nyquist subcarrier modulation (SCM) signals and the single-drive MZM was driven by 50-Gb/s OOK signals, as shown in Fig. 1(b). In the single-sideband QPSK transmission, the MZMs for odd and even channels were swapped, and only the performance of the QPSK signals was evaluated. The outputs of the MZMs were then amplified by the booster BDFA1 before launching them into the 75-/100-km length of SMF. The launch power to the SMF was around 13.5 dBm in both OOK and QPSK cases. After SMF transmission, a variable optical attenuator (VOA1) was used to adjust the input power to BDFA2, so as to vary the OSNR at the receiver. Another VOA (VOA2) was used to fix the optical power to the photodetector (PD) to be around -10 dBm for all OSNR cases and all channels. An optical bandpass filter (OBPF) with a bandwidth of 1.2 nm was used to select each WDM channel for performance evaluation. The gain profiles of the BDFAs, measured at an input power of -6 dBm and 20 dBm for the booster- and pre-amplifier, respectively, are given in Fig. 1(c).

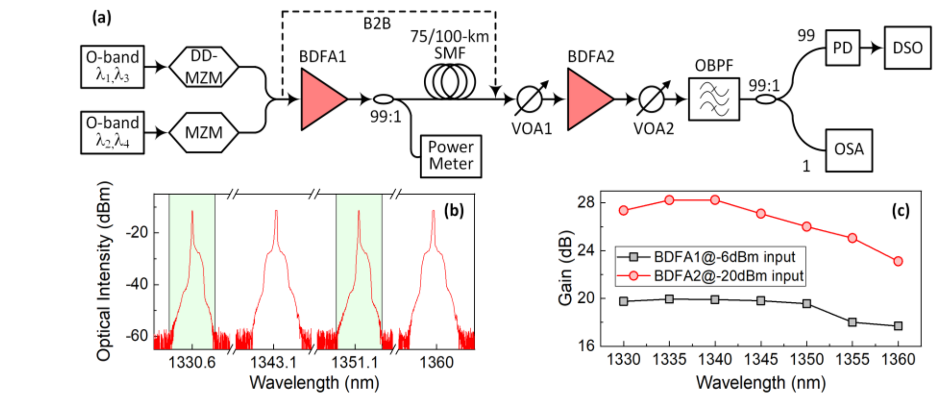

Fig. 1. (a) Experimental setup of the BDFA-amplified O-band CWDM DD system, (b) optical spectra of the WDM signals at the input of BDFA1 in the single-sideband transmission case, and (c) gain profiles of the two BDFAs.

In the offline processing of the experiments, the roll-off factor of the Nyquist filtering for both OOK and QPSK was 0.1. The same T/2-spaced decision feedback equalizer with 17 feedforward and 7 feedback taps was applied in both cases for signal equalization. For the single-sideband QPSK transmission, the captured signals at the digital storage oscilloscope (DSO) were first up-sampled 6 times before the KK algorithm [9] was used for the recovery of the I and Q components. CD compensation was then performed for the recovered complex signals. The remaining processing [8] was nearly identical in the two cases to ensure a fair comparison.

3. Experimental Results

We first investigated the back-to-back (B2B) performance of the system, which excluded the booster BDFA1 and the SMF, as indicated by the dashed line in Fig. 1(a). The results of bit error rate (BER) versus OSNR at 0.1-nm resolution bandwidth for all four channels are shown in Figs. 2(a-d). Note that the measurements of the signal power in the calculation of the OSNR included both the optical carrier and sideband signal. It is seen that in both the OOK and the QPSK cases, the four WDM channels exhibited similar BER performance. Furthermore, the double-sideband OOK required ~3-dB less OSNR to achieve BERs lower than the hard-decision forward error correction (HD-FEC, 3.8×10-3) limit, when compared to the single-sideband QPSK.

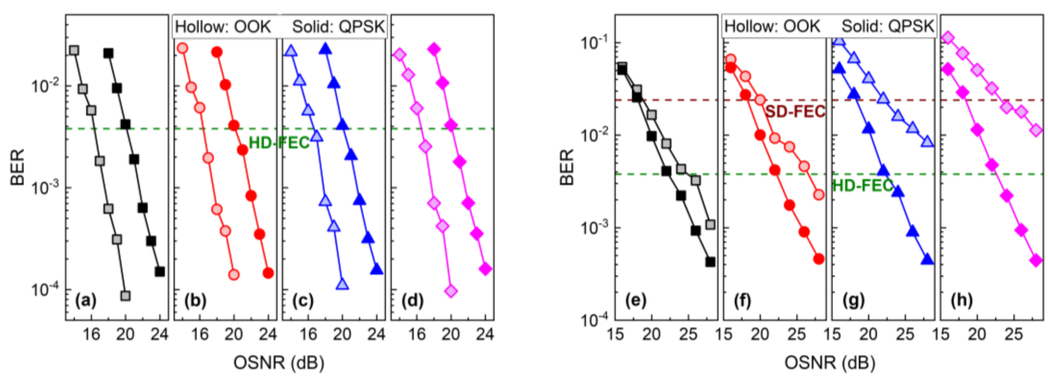

Fig. 2. BER versus OSNR of the B2B link for (a) 1330.6-nm, (b) 1343.1-nm, (c) 1351.1-nm, and (d) 1360.0-nm channel; and BER versus OSNR after transmission in 75-km length of SMF for (e) 1330.6-nm, (f) 1343.1-nm, (g) 1351.1-nm, and (h) 1360.0-nm channel.

We further examined the system performance after transmission in the 75-km length of SMF, and the corresponding results are presented in Figs. 2(e-h). In contrast to the B2B case, the OOK transmission showed worse BER performance than QPSK transmission on all four channels. Furthermore, the performance of the OOK signals degraded with an increase in wavelength (i.e., increase in CD in this work) to an extent that only a BER below the soft-decision FEC (SD-FEC, 2.4×10-2) limit, but still above the HD-FEC limit, could be achieved for the two longest wavelengths (i.e., 1351.1 and 1360.0 nm), as shown in Figs. 2(g-h). In comparison, the QPSK transmission maintained similar BER performance at all channels and was able to achieve BERs well below the HD-FEC limit.

The performance difference shown in Figs. 2(e-h) results from the fact that the double-sideband OOK is vulnerable to CD effects and will suffer from severe power fading. Fig. 3(a) shows the normalized electrical spectra of the detected OOK signals at the 1330.6-nm and 1351.1-nm channels. It is clear that severe power fading was experienced at both wavelengths after 75-km transmission. A spectral null occurred at ~17 GHz at the more dispersive 1351.1-nm channel. In contrast, the single-sideband QPSK transmission did not suffer from the power fading issue, and the signals of the two channels exhibited comparable electrical spectra. Note that the roll-off of the spectra shown in Fig. 3(b) is indicative of the limited bandwidth of the transceiver rather than the CD. The impact of CD was eliminated by dispersion compensation after the recovery of the complex signal via KK detection.

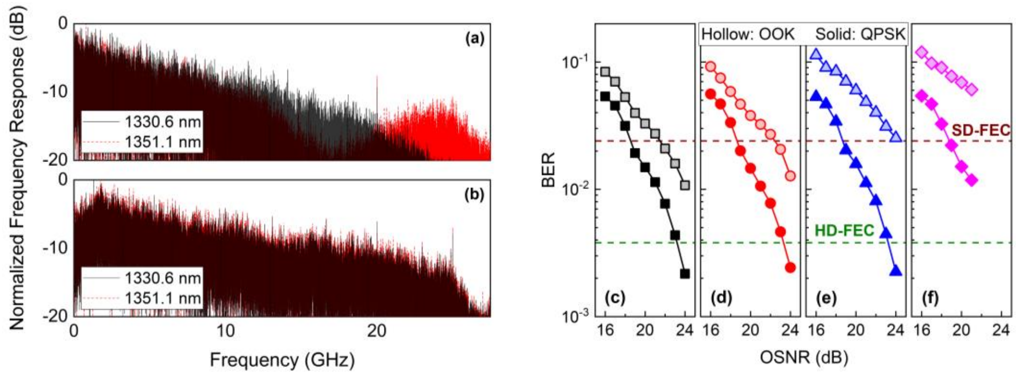

Fig. 3. Normalized electrical spectra of the detected signals at the 1330.6-nm and 1351.1-nm channels after 75-km transmission: (a) double-sideband OOK, and (b) single-sideband QPSK; and BER versus OSNR after transmission in 100-km length of SMF for (c) 1330.6-nm, (d) 1343.1-nm, (e) 1351.1-nm, and (f) 1360.0-nm channel.

Finally, we further extended the transmission reach of the system to 100 km, and the corresponding BER comparison is shown in Figs. 3(c-f). For the OOK transmission, the BERs of all channels were above the HD-FEC limit, and only the two shorter-wavelength channels (i.e., 1330.6 and 1343.1 nm) were able to achieve BERs lower than the SD-FEC. In comparison, significant OSNR sensitivity improvement was obtained when transmitting the single-sideband QPSK signals, for which the first three channels exhibited BERs below both FEC limits. While having comparable BER performance as the other three channels at small values of the OSNR, the performance of the signal at 1360.0 nm was compromised by the lower gain of the BDFAs at this wavelength (see Fig. 1(c)). Nevertheless, BERs well below the SD-FEC limit were achieved even at this wavelength.

4. Conclusions

In this paper, we present the first comparative study of the performance of double-sideband and single-sideband transmission in a 4×50-Gb/s/λ O-band CWDM system. While the fiber propagation loss was compensated for using BDFA-based optical amplification, CD emerged as the dominant factor limiting the system performance. As a result, single-sideband transmission exhibited markedly improved performance relative to Nyquist OOK, in terms of OSNR sensitivity. By using KK detection-assisted single-sideband QPSK, up to 100-km transmission distance was achieved, which to the best of our knowledge, represents the longest 50-Gb/s/λ O-band CWDM demonstration to date. Our results provide useful insights and show a viable route towards future longer-reach high-speed O-band CWDM systems.

This work was supported by the UK's EPSRC under the Airguide Photonics Programme grant (EP/P030181/1) and the PHOS project (EP/S002871/1). The data for this work is accessible at https://doi.org/10.5258/SOTON/D1842.

5. References

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