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QoT Evaluation of Optical Line System Transmission with Bismuth-Doped Fiber Amplifiers in the E-Band

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Abstract: We numerically investigate E-band quality of the transmission using an experimentally characterized bismuth-doped fiber amplifier, demonstrating its impact on deployed C+L systems.

1. Introduction

The growing traffic demand of optical networks, mainly led by imminent 5G deployment, data center interconnection and continuous IP traffic increases are stimulating the development of novel approaches to increase their capacity [1]. Band-division multiplexing (BDM) exploits a wide spectral region of the already deployed fiber infrastructure (i.e., based on a single mode fiber) and is one of the most attractive practical solutions to cope with these growing capacity demands. Data transmission should be possible at least from the L- to E-bands, where fiber loss is smaller than 0.30 dB/km for a standard single-mode fiber (SSMF). BDM solutions based on Erbium-doped fiber amplifiers (EDFA) are commercially available for C+L-band systems, however, the use of EDFAs is not possible for other transmission bands. Therefore, to further extend network capability using additional transmission bands (e.g., the S-, E-, and O-bands) novel types of optical amplifiers are required. Due to their exceptional spectral flexibility and good performance, bismuth-doped fibers are a promising solution for the realization of broadband optical amplifiers [2–4]. However, only limited effort has been spent to evaluate experimentally or numerically the capability of bismuth-doped fiber amplifiers (BDFAs) for data transmission [5, 6]. In this work, we numerically evaluate the Quality of Transmission (QoT) of an optical system when a BDFA (characterized experimentally in the S- and E-bands) is deployed to extend the transmission bandwidth beyond the existing C+L-band transmission system.

2. QoT Estimator

We use the GNPy open-source project [7] to perform lightpath QoT estimation, which is computed using the generalized signal-to-noise ratio (GSNR). This GSNR calculation considers both the amplified spontaneous emission (ASE) and the nonlinear interference (NLI) disturbances arising from the amplifiers and the optical fiber propagation, respectively. The NLI disturbance is computed using the generalized Gaussian-noise (GGN) model, which includes the NLI interaction with the stimulated Raman scattering (SRS). In the multi-band scenario, SRS is the dominant effect, causing a power transfer from the higher to lower frequency channels [8].

3. Bismuth-doped fiber amplifier

The experimental setup of the BDFA is presented in Figure 1(a). The amplifier consists of two 14xx nm isolators, a pair of thin-film-filter wavelength-division multiplexers (TFF-WDMs), a 320 m long Bi-doped fiber, a 1320 nm pump diode, and a 1320 nm isolator. The active media of the amplifier is a germanosilicate Bi-doped fiber fabricated in Dianov Fiber Optics Research Center, Russia [2]. The modified chemical vapor deposition (MCVD)-solution doping technique was used, resulting in the following fiber core composition: 95 mol% SiO_2, 5 mol% GeO_2, and < 0.01 mol% of bismuth. The 9 μm fiber core and 125 μm fiber cladding make it fully compatible with SMF-28 fiber. The numerical aperture of the bismuth-doped fiber is 0.14, and the cutoff wavelength is around 1.2 μm. Due to the low concentration of Bi-related active centers, the optimal length of Bi-doped fibers in optical amplifiers usually exceeds 100 m. The TFF-WDMs, used to couple the signal and pump radiation, have an extremely flat transmission (in the 1300–1362 nm range) and reflection (in the 1370–1565 nm range) bands, with an internal optical loss of about 0.1 dB. This low loss enables a uniform coupling of the wideband radiation into the Bi-doped fiber. One 1320 nm pump diode is used for the forward pumping. The second TFF-WDM can be used in combination with existing or additional pumping diodes for either backward of bi-directional pumping schemes. The forward pumping scheme has been chosen because it allows the smallest noise figure (NF) to be achieved in comparison to other pumping schemes with the same level of total pumping powers [4].

Figure 1 also depicts the spectral dependencies of gain and NF for different pump and input signal powers. The analysis of Fig. 1 shows that the BDFA gain increases with the forward pump power, until reaching a saturation level that depends on the input signal power. The NF shows the opposite behavior, i.e., decreases with the pump power until reaching the saturation level. Moreover, the gain spectrum flattens as the input signal power increases. However the maximum achievable gain is highly impaired in this case. The small signal gain of the BDFA can be extracted from the measured gain spectrum at -20 dBm input signal power. Fig. 1 shows that, in this case, a maximum signal gain of 30.5 dB is achieved at 209.6 THz, with a corresponding NF of 5.5 dB. On the other hand, the smallest achieved NF was about 4.8 dB at 206.8 THz, with a corresponding gain of 27 dB.

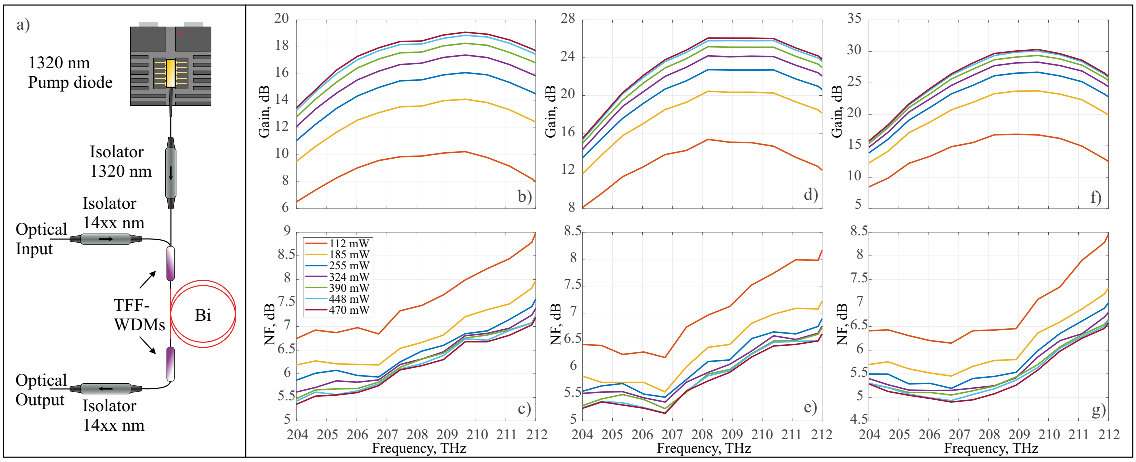

Fig. 1: a) schematic of BDFA; Dependencies of the measured gain (top) and noise figure (bottom) on frequency for different pump and b,c) 0 dBm; d,e) –10 dBm; f,g) –20 dBm input signal powers.

4. Results

We start by assessing which is the best spectral region for data transmission in E-band. To evaluate the QoT when using the BDFA, Fig. 2(a) shows the average, minimum and maximum GSNR dependence on the fiber length for a single span OLS when the transmission of 64 channels (64 Gbaud) in a 75 GHz WDM grid is assumed. Two frequency ranges are considered: the one leading to the best average NF (from 205.5 to 210.2 THz) and the one leading to the best average gain profile (from 207.0 to 211.7 THz). The average input power per channel is optimized using the local optimization global optimization (LOGO) technique [9]. Fig. 2(a) shows that, by using the spectral region leading to the smaller NF, the average GSNR may be enhanced by ~ 0.5 dB with respect to using the region corresponding to the highest gain. Moreover, the BDFA shows a better GSNR flatness in this case. Indeed, the GSNR variation (ΔGSNR) for each OLS distance ranges from 1.8 to 2.0 dB and from 3.3 to 4.0 dB for the smallest NF and higher gain frequency ranges, respectively. As the frequency range leading to the smaller NF showed the best performance, it will be the one considered henceforth.

In order to maximize the QoT, we have assessed if better performance could be achieved by changing the average gain of the BDFA, while changing the optimum launch power per channel accordingly. Fig. 2(b) presents the dependency of the average GSNR (in the E-band) on the BDFA gain offset (dB) considering a 40, 60 and 80 km OLS and data transmission in the E-band only and in a C+L+E-band scenario. The 0 dB offset corresponds to using the default launch power calculated using the LOGO approach and setting the average gain of the BDFA accordingly. Fig. 2(b) shows that, in both transmission scenarios, the LOGO algorithm approximately provides the optimum launch power. Moreover, Fig. 2(b) shows the QoT degradation in the E-band when the C+L system is active, compared with E-band only transmission. The GSNR degradation reaches the maximum of 0.8 dB for the 80 km span (optimum values). This small degradation suggests that E-band transmission using a BDFA is a promising solution to upgrade C+L systems in wideband scenarios, as the depletion by the SRS effect is small. Moreover, Fig. 2(c) presents the impact on C+L systems when the E-band is added, also shown for 3 span lengths (40, 60 and 80 km). The average GSNR on the top plot presents no significant changes when we add the E-band to the system. On the other hand, the C+L flatness levels decreases by adding E-band spectrum, as shown by the increase of the ΔGSNR on the bottom plot of Fig. 2(c), with the highest increase for 60 km length. Even increasing, the use of E-band do not significantly attenuate the C+L systems, as the change in flatness can be cover by system margins, ensuring the already deployed lightpaths will not be affected by this upgrade scenario.

Lastly, the dependency of the average GSNR per band on the number of spans, with 80 km each and varying from 80 to 640 km, is presented in Fig. 2(d) for the C+L and C+L+E-band transmission scenarios. For the C- and L-bands, we show that adding the E-band causes minimal QoT degradation. This result reinforces the viability of transmission over the E-band using a BDFA as a solution to upgrade C+L systems. As expected, the E-band

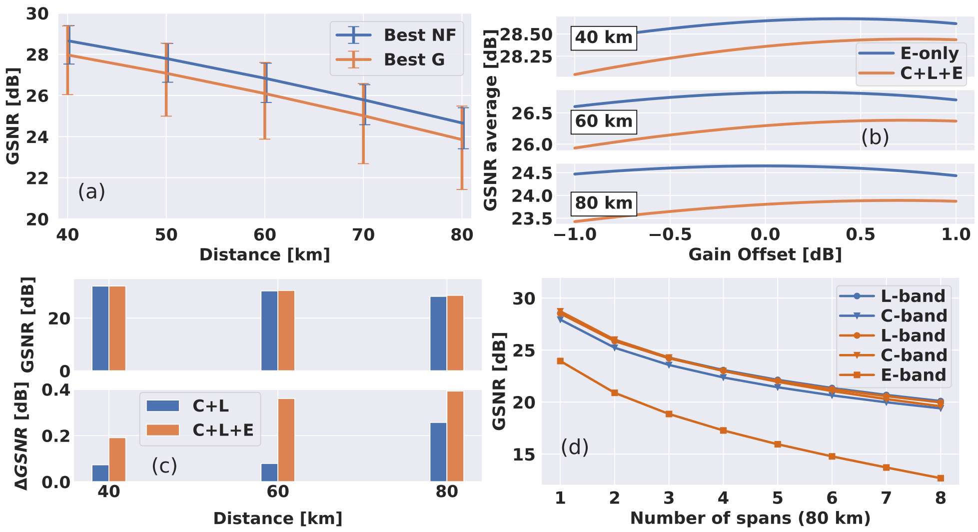

Fig. 2: (a) Average GSNR (bars show the minimum and maximum value) dependency on a single span OLS considering the frequency ranges leading to the smallest NF (blue line) and highest gain (orange line); (b) Average E-band GSNR dependency on BDFA gain offset in a single span OLS for 40, 60 and 80 km with E-band only and C+L+E-band transmission; (c) GSNR average (top) and ΔGSNR (bottom) versus distance for the C- and L-bands using only C+L and C+L+E transmission and (d) Average GSNR per band vs number of spans for C+L (blue lines) and C+L+E (orange lines) transmission.

GSNR presents the highest degradation, being limited to 12.7 dB at the end of the last span. Due to this effect, the E-band can be utilized to efficiently offload short reach traffic from the C- and L-band. Additionally, its use may be further enhanced by using flexible transceivers such as, e.g., ZR+ [10].

5. Conclusions

In this work, the GNPy was used to investigate the QoT in E-band considering both single- and multiple-span OLSs and employing an experimentally characterized BDFA. We show that the BDFA enables achieving quite good GSNR in E-band (≈ 24 dB for a single 80 km fiber span). Additionally, we show that the impact of the E-band on existing C+L-band systems is minimal, with maximum degradation of 0.8 dB for the E-band and small impact only on flatness of C+L systems. The E-band shows the worse QoT when compared to the C- and L-bands. Nevertheless, we show that GSNR exceeding 12 dB may be reached after transmission along 640 km (8×80 km fiber spans).

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