Characterization of Ten-Mode EDFA Using Swept Wavelength Interferometer and Digital Holography

Yetian Huang [1,2], Hanzi Huang [1,2], Yan Wu [2], Haoshuo Chen [1,*], Jianxiang Wen [2], Lauren Dallachiesa [1], Nicolas K. Fontaine [1], Cheng Guo [1], Mikael Mazur [1], René-Jean Essiambre [1], Yingxiong Song [2], Tingyun Wang [2], and Roland Ryf [1]

[1] *Nokia Bell Labs, 600 Mountain Ave, Murray Hill, NJ 07974, USA*
[2] *Key Laboratory of Specialty Fiber Optics and Optical Access Networks, Shanghai University, 200444 Shanghai, China*
[*] *haoshuo.chen@nokia-bell-labs.com*

Abstract: We characterize the spatially and spectrally resolved gain profiles of a ten-mode EDFA over C+L band via Rayleigh backscattering measured by a coherent swept wavelength interferometer. Wavelength-dependent mode-dependent gain is characterized employing digital holography.

1. Introduction

Mode division multiplexing (MDM) leverages the intrinsic spatial modes of a fiber to concurrently transmit multiple independent data channels [1,2]. This capability offers a substantial increase in transmission capacity, potentially addressing the anticipated future capacity challenges. While MDM presents immense potential, its success hinges on the development of a key component, namely a few-mode erbium-doped fiber amplifier (FM-EDFA), capable of supporting and amplifying diverse spatial modes simultaneously. A critical metric for a FM-EDFA is the mode-dependent gain (MDG) to ensure an even gain distribution across different modes [3]. In addition, when the C-band (1530-1565 nm) becomes depleted in the future, the L-band (1565-1625 nm) may emerge as the primary candidate to expand the available spectral window due to well-established L-band EDFA technology. The amplification mechanisms exhibit distinct characteristics when operated in the C- and L-band wavelength ranges. The L-band EDFA generally necessitates a longer length of erbium-doped fiber (EDF) to achieve the same gain compared with its C-band counterpart, owing to the wavelengths being located farther from the peak emission band of Er^{3+} ions, resulting in lower pump conversion efficiency [4]. Within the scope of L-band few-mode amplification, realizing the key objectives of optimizing MDG and L-band gain demands a thorough exploration of the combination of pump power, signal power, and EDF length, influenced by specific erbium distribution and concentration. Therefore, characterizing the gain for each mode of an FM-EDFA across varying EDF lengths and signal wavelength is essential for iterative design optimization.

The conventional approach for gain characterization, such as the cut-back method, is both destructive and time-consuming, especially when seeking a high-spatial-resolution gain profile. In contrast, the use of a swept wavelength interferometer (SWI) to measure Rayleigh backscattering offers a non-destructive means to derive both spatially and spectrally resolved gain profiles in a single sweep [5,6]. Combing with the mode dependent information providing by digital holography [7] can offer a comprehensive gain characterization over length, spatial mode and wavelength. Notably, it only needs one mode multiplexer (MUX), enhancing the accuracy of MDG measurement by reducing the mode dependent loss (MDL) from second MUX in the cut back scheme.

In this work, we characterize spatially and spectrally resolved gain profiles for each mode group of a ten-mode EDFA over the C+L band using coherent swept wavelength interferometer. We employ digital holography to evaluate MDG variation under different pump configurations for amplifying a low differential mode group delay 10-mode graded-index (GI) FMF supporting LP_{01}, $LP_{11a/b}$, $LP_{21a/b}$, LP_{02}, $LP_{31a/b}$ and $LP_{12a/b}$ modes [8].

2. Spatially and Spectrally Resolved Gain Characterization With SWI

Figure 1(a) illustrates the setup of the SWI used for FM-EDFA characterization. The sweep range of the SWI is from 1525 to 1620 nm at a rate of 200 nm/s. The Rayleigh backscattered light from the FM-EDFA is directed to the input port of a polarization-diversity coherent receiver. Within this receiver, the backscattered light interferes with a reference light, generating an interferogram that captures both amplitude and phase information across sweep range. Fig. 1(b) presents the schematic of the amplification subsystem under test, comprising a mode switch, a multi-plane light conversion (MPLC)-based mode MUX, 1480-nm pump lasers, pump/signal wavelength division multiplexing (WDM) couplers, and a 11.8-m FM-EDF. The swept light of SWI is sent to port 1 of circulator and transmitted to the input of this amplification subsystem through port 2 with an input power of -3.5 dBm. The FMF at the output of MUX is spliced to a 11.8-m FM-EDF, and subsequently spliced to a coreless fiber to reduce back reflection at the end facet. The pump lasers (A, B, C) with ~24 dBm output power are combined into the MUX through WDM couplers, following the sequence of LP_{01}, LP_{11a}, and LP_{21a} modes as the number of pumps

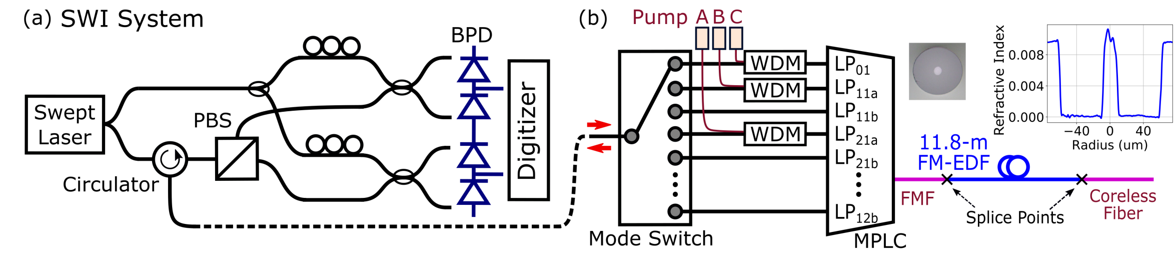

Fig. 1: Experimental setup with (a) an SWI and (b) amplification subsystem under test. (PBS: polarization beam splitter, BPD: balanced photodetector)

increases from 1 to 3. The fiber cross section and refractive index profile of this ten-mode EDF are also shown in Fig. 1(b), and more details of the EDF design can be found in [9].

Figure 2(a) presents the spatially resolved gain profiles spanning the C+L band under various pump configurations. The curve representing the scenario without any pump serves as a reference for calibration purposes. Additionally, the splice point between the 10-mode GI-FMF and EDF, as well as the end of the FM-EDF, are pointed out for clarity. When the pumps are on, an ASE-induced noise floor can be observed and constrains the dynamic range of the measurement. The obscured gain profile within this ASE noise at the EDF's onset can be estimated using a linear fit of the ascending slope extended to the splice point [6], as depicted by three dashed lines in Fig. 2(a). Fig. 2(b) and (c) illustrate the spectrally resolved gain at different lengths of EDF for the first mode group, revealing a trend of the gain spectrum tilting towards longer wavelengths as the EDF length increases. Additionally, the gain spectra for different mode groups at various EDF lengths are measured using 3 pumps, as shown in Fig. 2(d-f). At the end of EDF (L=11.8 m), the observed gain ranges from 3 to 8 dB within the 1580 to 1622 nm span, which can be attributed to the insufficient pump power near the end of the FM-EDF. Fig. 2(g) illustrates the distribution of accumulated gain across a range of wavelengths and EDF lengths, employing 3 pumps, which is measured by injecting the signal into the first mode group at the MUX. Gain spectrum tilt towards L-band starts to appear after 5.5-m EDF, indicating a dropping population inversion rate [10]. Spatially and spectrally resolved gain characterization offers a non-destructive solution to determine an optimum EDF length for amplifying different wavelength bands. The optimum EDF lengths for C and L-band amplification are around 3.8 m and 7.2 m, respectively, under current input signal power and pump conditions.

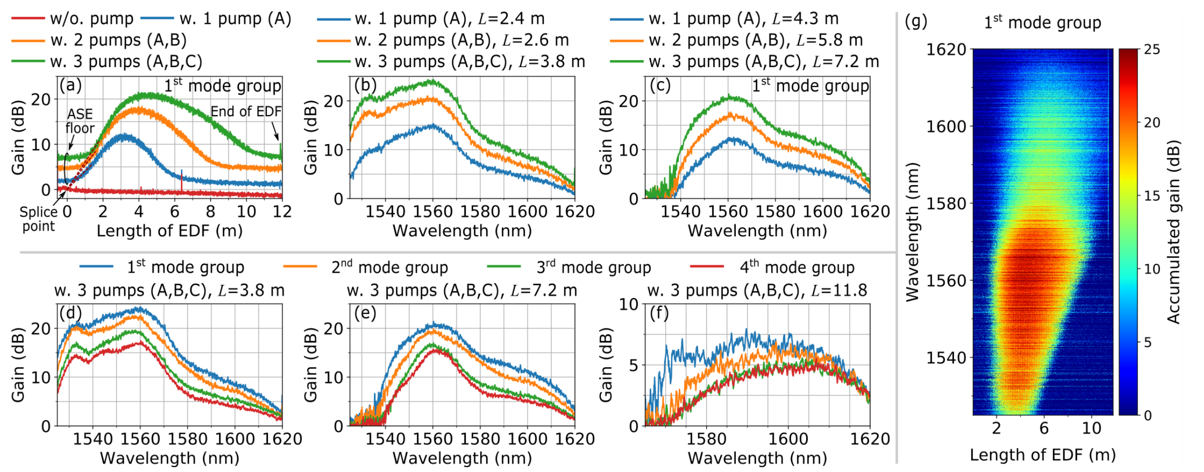

Fig. 2: (a) Spatially resolved gain profiles under different pump configurations, (b,c) gain spectra with different length of EDF for the first mode group, (d-f) gain spectra of different mode groups at various EDF lengths using 3 pumps, and (g) accumulated gain of the first mode group versus wavelength and EDF length using 3 pumps.

3. MDG Characterization with Digital Holography

Figure 3(a) depicts the experimental setup for MDG characterization of the FM-EDF amplifier utilizing digital holography. An L-band tunable laser with a 10-kHz linewidth splits its output into two pathways. One serves as the signal arm, and the other acts as the reference. A 1×2 switch is applied as a polarization switch with a pair of polarization controllers (PCs). After that, the light is sent to a 1×10 switch, whose output is connected to the input of the first ten modes of the MUX with -21-dBm input power. The output GI-FMF from MUX is spliced with a 11.8-m FM-EDF, and subsequently spliced to a 1-m GI-FMF. This GI-FMF output is angle-cleaved to eliminate facet reflection. The pump light's injection resembles the procedure used in the SWI experiment. An isolator (ISO) is placed after each WDM coupler to prevent backward reflections. A 4f imaging system is used with lenses with focal lengths of 4.5 mm and 150 mm in the signal arm. A dichroic mirror (DM) is used to filter the unabsorbed pump light, and an attenuator is used to prevent the saturation of the charge-coupled device (CCD) camera. The switches and camera cooperate using a synchronous clock and record one CCD frame of each spatial mode launched approximately every 3 ms, improving the measurement stability and strengthening the channel stationary. A free-space PBS is used to split both polarizations for simultaneous detection. A beam splitter (BS) then combines the signal with the flat-phase coherent reference beam. The resulting mode images with interference fringes are recorded by the CCD camera and processed offline to calculate the complex-valued mode transfer matrix.

Figure 3(b) illustrates the power transfer matrices of the MUX for individual modes (left) and summed mode groups (right) measured at the output of the MPLC with a 1622-nm laser. The measured MDL and crosstalk level of the MPLC are 6.4 dB and -6.8 dB respectively. After splicing to the FM-EDF with pumps off, MDL and crosstalk increase slightly to 6.7 dB and -2.8 dB, respectively, which indicates low mode profile mismatch between the GI-FMF and the FM-EDF. Upon activation of all three pumps, the measured MDL witnesses a further increase to 8 dB, and the measured power transfer matrices are given in Fig. 3(c). The MDG of the FM-EDFA is calculated by subtracting the MDL of the MPLC from the measured MDL under amplification. Fig. 3(d) compares the MDGs versus signal wavelength under different pump configurations. The MDGs are around 2∼3 dB in the range of 1575 to 1620 nm under three pumps as the gain of the LP_{01} mode reaches 13 dB at 1610 nm, see Fig. 3(e). This low MDG can be further reduced by optimizing the doping profile of the EDF. The measured gain discrepancy between Fig. 3(e) and Fig. 2(f) is mainly due to the difference in input signal power, which is 18 dB higher in the SWI measurement in order to keep backscattered signal level above the backward ASE floor.

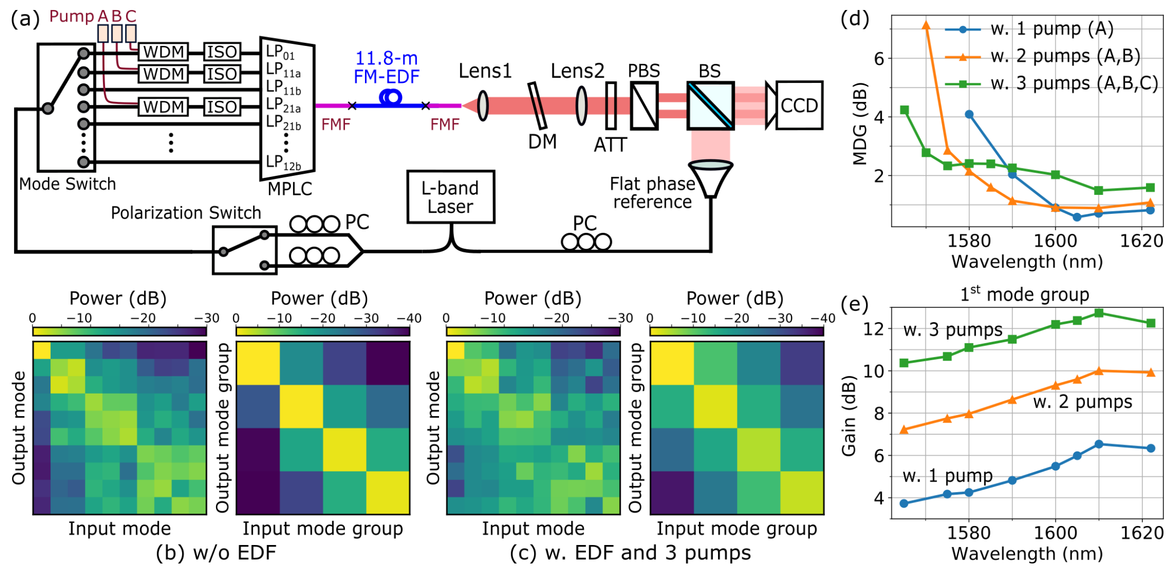

Fig. 3: (a) Experimental setup for characterizing the FM-EDFA using digital holography, measured mode and group-summed transfer matrices (b) before the FM-EDF and (c) after the FM-EDF with three pumps at 1622 nm, under different pump configurations: (d) calculated MDG results versus wavelength and (e) gain spectra of the first mode group.

4. Conclusion

The spatially and spectrally resolved gain of a ten-mode EDFA was characterized over C+L band for the first time using a swept wavelength interferometer. Using this non-destructive technique, the design of FM-EDFAs can be easily optimized and the optimum EDF lengths can be determined for different amplification bands. Moreover, we demonstrated an L-band ten-mode EDFA with a low MDG of 2 dB to support C+L band long-haul MDM transmission [8].

This work was supported by the National Key Research and Development Program of China (2020YFB1805800).

References

1. B. J. Puttnam *et al.*, "Space-division multiplexing for optical fiber communications", Optica 8, 2021.
2. R. Ryf *et al.*, "High-Spectral-Efficiency Mode-Multiplexed Transmission Over Graded-Index Multimode Fiber", Proc. ECOC, 2018, paper Th3B.1.
3. Masaki Wada *et al.*, "Differential Modal Gain Reduction of L-band 5-Mode EDFA Using EDF With Center Depressed Core Index", J. Lightw. Technol., 35(4), 762-767, 2017.
4. M. Vasilyev and S. Radic, "Optical amplifiers," in Springer Handbook of Optical Networks, paper 51-81, 2020.
5. Nicolas K. Fontaine *et al.*, "Multi-mode optical fiber amplifier supporting over 10 spatial modes", Proc. OFC 2016, paper Th5A.4.
6. Bin Huang *et al.*, "Spatially and Spectrally Resolved Gain Characterization of Space-Division Multiplexing Amplifiers With Coherent Swept-Wavelength Reflectometry", J. Lightw. Technol., 35(4), 741-747, 2017.
7. M. Mazur *et al.*, "Characterization of Long Multi-Mode Fiber Links using Digital Holography", Proc. OFC 2019, paper W4C.5.
8. R. Ryf *et al.*, "10-Mode mode-multiplexed transmission over 125-km single-span multimode fiber," Proc. ECOC 2015, paper PDP.3.3.
9. Y. Wu *et al.*, "Ten-Mode Erbium-Doped Fiber Amplifier with Extended Gain Bandwidth of 43 nm", Proc. CLEO 2023, paper SF2H.1.
10. B. Choi *et al.*, Journal of Quantum Electronics, 39(10), 1272-1280, 2003.