Seven-Ring-Core Erbium-Doped Fiber for OAM-MDM Amplification

Qi Jiang, Xiaobo Xue, Fufei Pang, Liang Zhang, Mengshi Zhu, Heiming Wei, Cheng Du, Wei Li, and Tingyun Wang

***Abstract*—Orbital angular momentum (OAM) mode division multiplexing (MDM) amplification in a seven-ring-core erbium-doped fiber (7-RC-EDF) has been experimentally demonstrated, in which the 1st–4th order OAM modes within each core of the 7-RC-EDF can be supported. By combining the OAM modes with the pump laser into the 7-RC-EDF, 112 OAM modes are predicted to be amplified in the C-band with a net gain of more than 22.36 dB with the differential modal gain (DMG) of less than 1.7 dB. The optical signal-to-noise ratio (OSNR) can be higher than 30 dB. As a proof of concept, signals with three wavelengths were individually converted into the 2nd–4th higher order OAM modes, respectively, and then injected together into one ring core of the 7-RC-EDF. The amplification with a net gain of more than 27.7 dB and OSNR of more than 22 dB was achieved. The proposed wavelength division multiplexing (WDM) combined with the OAM-MDM technique verified its potential applications in large-capacity OAM-MDM optical fiber communication systems.**

***Index Terms*—Orbital angular momentum mode, seven-ring-core erbium-doped fiber, mode division multiplexing.**

I. Introduction

DUE to the nonlinear effects of optical fiber, traditional single-mode fiber-based communication technologies are facing great challenges in boosting the transmission capacity [1], [2]. Compared to traditional wavelength division multiplexing (WDM) and time division multiplexing (TDM) technologies, mode and space division multiplexing (MDM/SDM) based on few-mode fibers (FMF)/multi-core few-mode fiber (MC-FMF) provide additional dimensions of multiplexing for optical fiber communications to break through the single-mode fiber limitation [3], [4], [5]. The orbital angular momentum (OAM) modes carrying different topological charges are orthogonal to each other and the number of topological charges could be infinitely large, which is of widespread interest in MDM/SDM communications [6], [7], [8]. The OAM modes present ring-shape intensity, therefore, ring-core fibers were paid great attention for the OAM mode division multiplexed optical fiber communications in recent years. Thanks to the ring-core structure of these ring-core fibers, OAM modes can be transmitted stably with high order radially modes being effectively suppressed, avoiding the complexity of digital signal processing (DSP) with multiple inputs and multiple outputs (MIMO) [6], [9], [10], [11]. Currently, fibers with single ring-core have been demonstrated to support the transmission from the 1st- to 4th-order OAM [12]. To further expand the transmission capacity of a single-core fiber, 56 OAM modes in a seven-ring-core fiber were proposed and achieved [13], [14]. However, the transmission distance was mainly determined by the transmission loss. A compatible multi-core OAM-mode fiber amplifier with good performance is desirable to overcome this issue.

The OAM mode amplifiers based on erbium-doped fibers have attracted widespread interest since it is compatible with optical fiber communication systems and can achieve excellent gain performance [15], [16]. The first OAM mode amplifier based on air-hole erbium-doped fiber was achieved [17]. This OAM modes amplifier enabled stable transmission and amplification of the $\pm 1^{st}$ order OAM modes. Then, the researchers demonstrated excellent performance in data carrying and amplifying based on the $|l| = 1$ order OAM mode amplifier using a ring-core erbium-doped fiber [18]. X. Zhang et al. designed and fabricated a double-layer erbium-doped ring-core fiber and achieved the amplification of 14 OAM modes [19]. To match the high spatial density of OAM-based optical fiber communication, T. Wen et al. successfully demonstrated the amplification of 4 orders of OAM modes per ring core at a single wavelength in a seven-ring core erbium-doped fiber (7-RC-EDF) [20]. However, these OAM mode amplification researches mainly focused on single or multiple OAM mode amplification by using a single wavelength without considering the implementation of wavelength multiplexing.

In this work, optical fiber amplification for OAM-MDM by using a 7-RC-EDF combining with the WDM technique has been demonstrated. The amplifications of the 1st–4th order OAM modes were firstly characterized for each core of the 7-RC-EDF in the C-band with a net gain of more than 22.36 dB with the differential modal gain (DMG) of less than 1.7 dB. The optical signal-to-noise ratio (OSNR) can be higher than 30 dB

Manuscript received 5 June 2023; revised 13 July 2023; accepted 16 July 2023. Date of publication 24 July 2023; date of current version 31 July 2023. This work was supported in part by the National Key Research and Development Program of China under Grant 2018YFB1801800 and in part by the National Natural Science Foundation of China under Grant 61635006 and 61975113. *(Corresponding author: Fufei Pang.)*

Qi Jiang, Xiaobo Xue, Fufei Pang, Liang Zhang, Mengshi Zhu, Heiming Wei, and Tingyun Wang are with the Key Laboratory of Specialty Fiber Optics and Optical Access Networks, Joint International Research Laboratory of Specialty Fiber Optics and Advanced Communication, Shanghai University, Shanghai 200444, China (e-mail: qijiang0617@shu.edu.cn; moki1997@163.com; ffpang@shu.edu.cn; liangzhang@shu.edu.cn; zhmsh@shu.edu.cn; hmwei@shu.edu.cn; tywang@shu.edu.cn).

Cheng Du and Wei Li are with the Fiberhome Telecommunication Technologies Co. Ltd., Wuhan 430074, China (e-mail: ducheng@fiberhome.com; liweii@fiberhome.com).

Digital Object Identifier 10.1109/JPHOT.2023.3297594

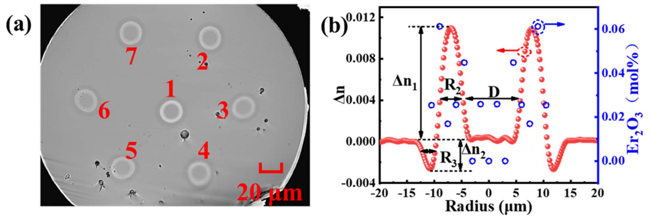

Fig. 1. Features of 7-RC-EDF. (a) Cross-sectional observation of the 7-RC-EDF under a microscope; (b) refractive index and Er_2O_3 molar percentage profile of the 7-RC-EDF.

by adjusting the signal power. Theoretically, 112 OAM modes could be supported and amplified, considering the polarization and topological charges of the OAM. Then, a WDM-based OAM multiplexing was constructed by generating three wavelengths of OAM modes corresponding to the 2nd-4th orders and injecting into one ring core together. In results, the 3-WDM OAM modes were amplified with a gain of more than 27.7 dB and an OSNR of more than 22 dB.

II. Characteristics of 7-RC-EDF

The process of the fabrication of 7-RC-EDF is as follows: 1) each RC-EDF preform were first fabricated by using the modified chemical vapor deposition (MCVD) method; 2) the pure silica preform were drilled according to the design of the fiber core distribution in the 7-RC-EDF; 3) 7 core preforms were inserted into the drilled preforms; 4) the preform was drawn into 7-RC-EDFs.The cross-section of the 7-RC-EDF was observed by a microscope as shown in Fig. 1(a). The cladding diameter of the fabricated 7-RC-EDF is 245 μm, the core-to-core distance is approximately 70 μm, the core-to-cladding distance is 52.5 μm, the inner ring diameter (D) is around 11 μm, and the width (R_2) of ring core is approximately 4.5 μm. The refractive index profile and the molar percentage distribution of Er_2O_3 along the ring-core were measured by using a near-field method and electron probe micro analysis separately, as shown in Fig. 1(b). The inner core and cladding have essentially the same refractive index. The refractive index difference (Δn_1) between the ring core and the cladding is 0.011. The cladding-trench with refractive index difference (Δn_2) is -0.0022, which results in less inter-core crosstalk. The width of the trench (R_3) is 3 μm. Such a large refractive index difference enables the ring core to support up to the 4th order OAM modes. Erbium ions were doped in the high refractive index ring core, which accomplished OAM mode amplification with a high degree of overlap between the erbium ions and the mode field of the OAM mode.

Based on the ring-core fiber parameters, the OAM mode group supported by the fiber in the C-band and their effective refractive index were analyzed by using the finite element method. As shown in Fig. 2, the ring core can support the 1st–4th order OAM modes in the wavelength range 1525–1570 nm. The refractive index difference between the mode group is greater than 10^{-3}, which ensures the effective separation of OAM mode groups of different orders.

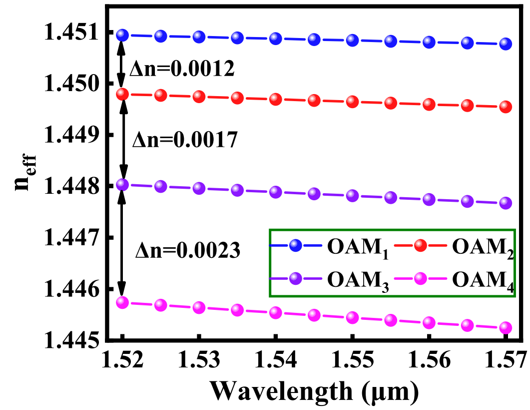

Fig. 2. Effective refractive index variation with wavelength for different OAM mode groups of the ring-core erbium-doped fiber.

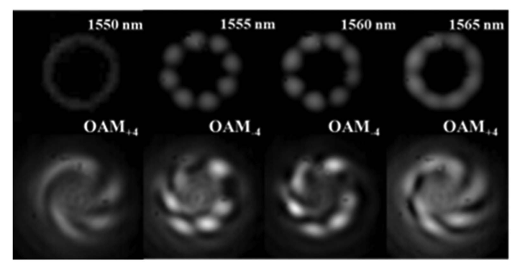

Fig. 3. $\pm 4^{th}$-order OAM mode output and its interference at different wavelengths.

The mode field distribution and corresponding inference pattern were observed by using an infrared camera separately. The $\pm 4^{th}$ order OAM beams were generated at typical wavelengths of 1550 nm, 1555 nm, 1560 nm, and 1565 nm in the C band and injected into one core of the 7-RC-EDF. As shown in Fig. 3, the output OAM modes presented circular distribution and four interferometric spiral patterns as interfering with spherical Gaussian light. Therefore, the 7-RC-EDF was experimentally demonstrated to be able to support the OAM modes up to a topological charge of 4 in the C-band.

Based on the cut-back method, the absorption of the erbium-doped ring-core was further evaluated. A white light source (AQ4305) was injected into one of the ring cores in 7-RC-EDF, and a high-refractive index matching liquid was used near the end to remove the cladding mode. As shown in Fig. 4, the absorption of the fiber at 648.40 nm, 798.00 nm, 975.10 nm, and 1529.50 nm was 5.87 dB/m, 2.40 dB/m, 4.15 dB/m, and 10.96 dB/m, respectively. The absorption peaks were caused mainly by the typically excited state absorption of the erbium ion corresponding to energy levels $^4I_{7/2}$, $^4I_{9/2}$,$^4I_{11/2}$ and $^4I_{13/2}$.

III. Amplification Characteristics of 7-RC-EDF

A. OAM Modes Amplification

Based on the 7-RC-EDF, the setup for OAM modes amplification was constructed as shown in Fig. 5. It consisted of OAM mode signal light generation, OAM mode amplification section,

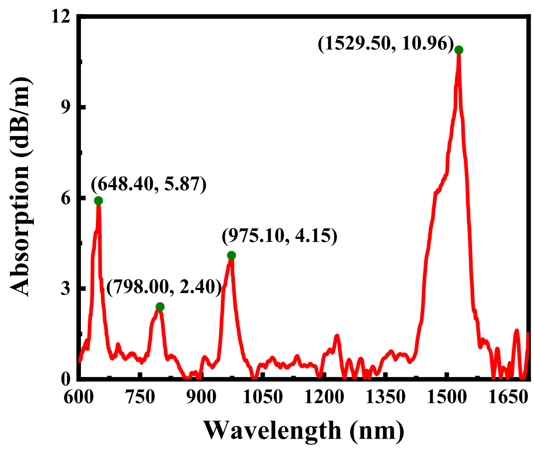

Fig. 4. Absorption spectrum of erbium-doped ring-core.

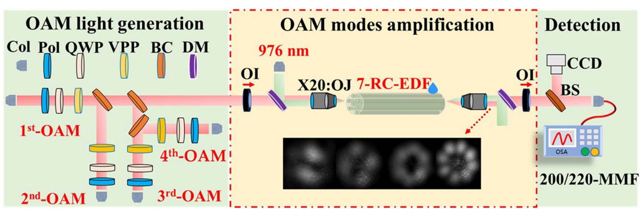

Fig. 5. Schematic diagram of the seven-ring-core erbium-doped fiber OAM mode amplification detection system device; Col., collimator; Pol., polarizer; QWP., quarter wave plate; VPP., vortex phase plate; BC., beam combiner; BS., Beam splitter; OI., isolator; OBJ., objective lens; 7-RC-EDF., ring-core erbium-doped fiber; DM., dichroic mirror; MMF., multimode fiber; OSA., optical spectrum analyzer.

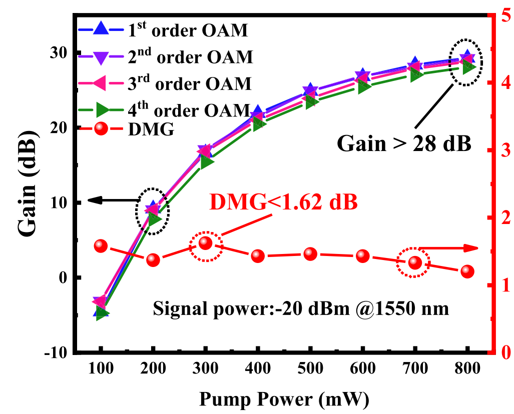

Fig. 6. Measured modal gains and DMG of OAM modes ($|l|$ = 1, 2, 3, 4) versus pump power.

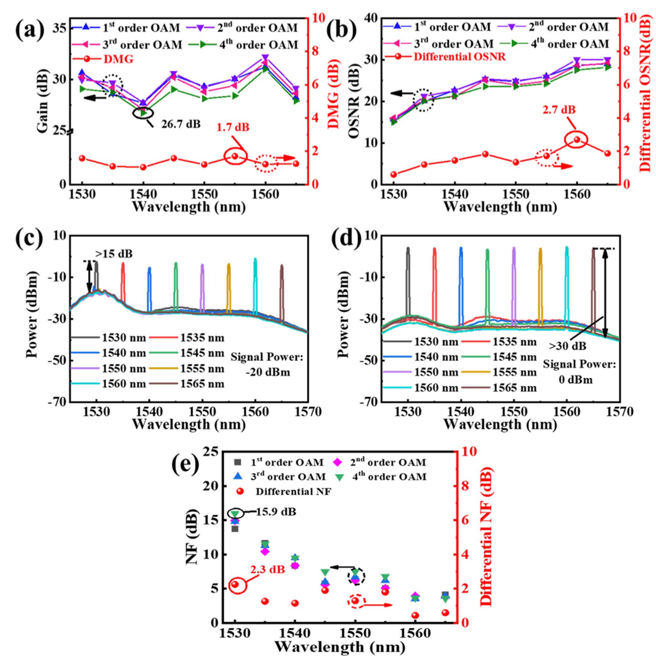

Fig. 7. Modal gain, OSNR and NF characteristics of the OAM amplifier of the C- band. (a) Measured modes gain and DMG of the amplifier. (b) Measured OSNR and differential OSNR of the amplifier. (c) Measured amplified spectra across C-band for the 4th order OAM mode at an optical power of −20 dBm. (d) Measured amplified spectra across C-band for the 4th order OAM mode at an optical power of 0 dBm. (e) Measured NF and differential NF of the amplifier.

and detection section. The 1st–4th order OAM modes were generated by using different order vortex phase plates (VPP) and combined by using beam combiners (BC). The signal light was adjusted into a circular polarization state by using a polarizer (Pol) and a quarter waveplate (QWP). The circularly polarized light was converted to the corresponding order of OAM mode as passing through the VPP. The OAM mode amplification section consisted of a 3.5 m 7-RC-EDF, an optical isolator (OI), a dichroic mirror (DM), a 20x objective lens, and a 976 nm pump laser. The DM was used to combine the 976 nm pump laser and OAM mode signals at the optical input and to separate them at the output. The objective lens was used to inject the 976 nm pump laser and the OAM mode light into the 7-RC-EDF. In the detection section, the infrared camera was used for observing the OAM mode field output, and the optical spectrum analyzer (OSA) was used for analyzing the amplified spectrum. It is important to note that the output end face of the 7-RC-EDF was cleaved at approximately 8° to avoid parasitic laser generation.

The gain of the 1st–4th order OAM modes at different wavelengths was measured comprehensively by using the same one of side cores. The gains of the 1st–4th order OAM modes were shown in Fig. 6 with increasing the pump power. The gain increased gradually with increasing pump power and then tended to saturate. The net gains at 1550 nm for the 1st–4th order OAM mode were more than 28 dB at a pump power of 800 mW. The gains present similar features to traditional single mode EDFA. The reason for saturation is that the erbium ion number of the inversion level trend to saturate with pump power increasing, and so does the gain. The DMG of the 1st–4th OAM modes is less than 1.62 dB as the pump light is varied.

Then the gain characteristics of different OAM modes in the C-band and their spectral characteristics were measured as shown in Fig. 7. Typical wavelengths equally spaced were chosen in the C-band. All the wavelengths for the 1st–4th order modes were amplified with high gain (>26.7 dB) when the signal power was −20 dBm under the pump power of 800 mW. The 1st–4th order OAM modes have similar gain characteristics in the full C-band and the DMG is less than 1.7 dB as shown in

Fig. 7(a). This is mainly due to the fact that the ring-core erbium-doped fibers enable the 1st–4th order OAM modes to have similar mode field distributions. The different OAM modes have similar overlap factors with erbium ions and pumped light, resulting in small DMG. The variations at different wavelengths for the same OAM mode were due to the different absorption and emission cross-sections of the 7-RC-EDF at different wavelengths. The OSNR is also an issue to be considered as the accumulation of multi-cascade amplification noise over long transmission distances. OSNR is defined as the ratio of the optical output power of the amplified OAM signal to the ASE optical power [1]. The OSNR of the measured output spectra is calculated to be more than 15 dB for OAM modes of the 1st–4th order at a signal optical power of −20 dBm. The low optical signal-to-noise ratio at 1530 nm is due to the strong spontaneous emission of the erbium-doped fiber at 1530 nm. From the experimental results, it can be seen that the 1st–4th order OAM modes also have similar optical signal-to-noise ratios, with the largest difference of the OSNR being 2.7 dB. The OSNR can be improved to 30 dB by increasing the signal optical power across C-band at an incident optical power of 0 dBm, as shown in Fig. 7(d). The increase in signal light results in faster consumption of sub-stable erbium ions and therefore weaker spontaneous radiation, ultimately resulting in an improved OSNR. The noise characteristics can also be optimized in the future by optimizing the distribution of pump and erbium ions. Finally, we measured the noise figure (NF) of the amplifier. Within the C-band, the NF at different wavelengths ranged from 3.5 dB to 15.9 dB. The NF difference for the 1st–4th order OAM modes is found as less than 2.3 dB, as shown in Fig. 7(e). The highest NF at 1530 nm is 15.9 dB, due to the heavy amplified spontaneous emission of erbium doped fibers at 1530 nm.

To further investigate the gain performance of different erbium-doped ring-cores, 7 cores were examined amplifying individually. The OAM mode gains of the seven cores gradually increased with pump power and then saturated at an incident power of −20 dBm for the 4th-order OAM mode at 1550 nm, as shown in Fig. 8(a). At a pump power of 800 mW, the gains of all seven cores were greater than 24.5 dB. The side core No.5 obtained a maximum gain of 28.35 dB while core No.1 obtained a minimum gain of 24.52 dB. The gains of the 4th-order OAM mode of the C band at a pump power of 800 mW were shown in Fig. 8(b). All seven cores have an effective net gain of more than 22.36 dB across the C-band. The minimum intra-core DMG of the 4th order OAM is 3.83 dB at 1550 nm wavelength, as shown in Fig. 8(b). By injecting the optical power into one fiber core, the crosstalk was measured by the output power of another adjacent fiber core, which is less than −20 dB.

The net gain characteristics of the 7-RC-OAM-EDFA depended on the input OAM mode optical power, as shown in Fig. 8(c). Here, the 4th order OAM mode was injected and the pump power was fixed at 800 mW. When the incident power was small, the amplifier worked in the linear amplification region, the gain tended to be constant, and the net gain of the small signal was greater than 24.48 dB. With the increase of the incident signal light power, the gain presented a decreasing trend. This difference in the amplification performance between different

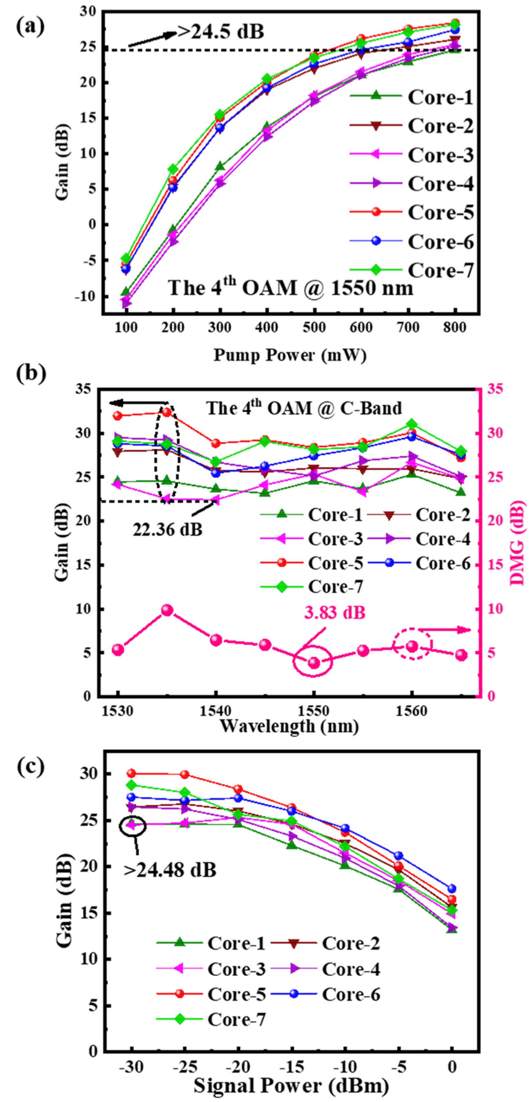

Fig. 8. Amplification characteristics of the 4th order OAM modes in different fiber cores. (a) The measured modal gain versus the pump power. (b) The measured modal gain spectrum of C-band. (c) The measured modal gain versus the input signal power of the 4th order OAM mode.

cores mainly results from the slightly inconsistent in profiles of ring core and dopants, which can also be observed from the cross-sectional micrograph in Fig. 1(a). In addition, the fiber cores of the 7-RC-EDF may be not ideally circular symmetric while exhibiting ellipticity during the practical fiber fabrication, which would affect the purity of the mode propagating and hence interactions between OAM signal, pump lights and erbium ions, leading to the differences in the OAM mode amplification performance of different fiber cores.

Overall, the 7-RC-OAM-EDFA has been experimentally verified to be able to amplify four orders of OAM modes per core. The OAM modes of the same core have almost the same amplification performance because they have similar mode field distribution. Based on the above experimental results, the 7-RC-OAM-EDF theoretically can be extended for amplifying a total

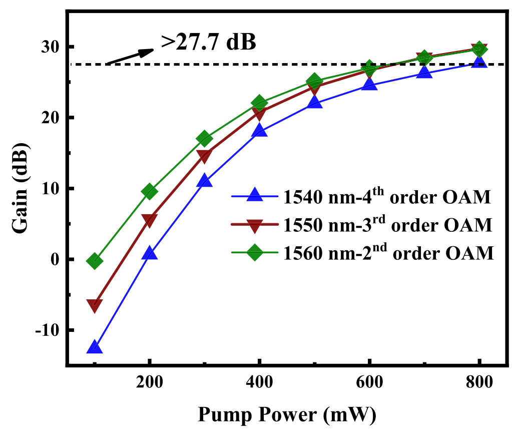

Fig. 9. 3-Wavelength-OAM-MDM amplification gains versus pump power.

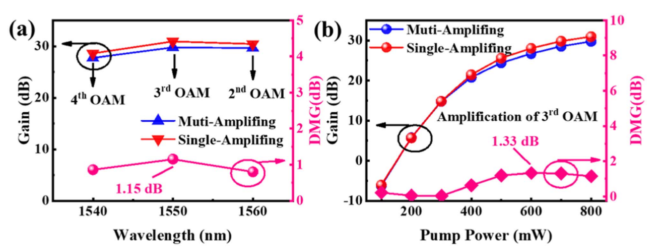

Fig. 10. Difference of modal gain between multiplexing and single (a) Modal gain variation versus wavelength and modes. (b) The modal gain versus pump power.

of 112 OAM modes with 16 OAM modes per core if considering the polarization and topological charges of the OAM [11].

B. WDM-OAM-MDM Amplification

Previous researches have focused on testing 7-RC-OAM-EDFA through a single wavelength and single mode. In actual optical fiber communication systems and future multi-dimensional multiplexing optical fiber communication systems, it is desirable to use different orders of OAM modes as a new multiplexing dimension. It means that OAM-based optical fiber communication should be compatible with previous WDM and other techniques to achieve a significant increase in the capacity of optical fiber communication. A simple approach was used to further investigate the performance of simultaneous amplification of multiple OAM modes assisting with the WDM technique.

A WDM-OAM-MDM amplification setup was constructed by using three wavelengths corresponding to three different higher-order OAM modes. The multiplexed three modes were amplified with high gain just like the individual incident. The gain of 3-Wavelength-OAM-MDM varied with pump power as shown in Fig. 9. The gain of all three OAM modes increased with increasing the pump power and tended to saturate. The gains of the 2nd–4th order OAM modes were 29.62 dB, 29.74 dB, and 27.70 dB, respectively at a pump power of 800 mW for multiplexed amplification, while these gains for separate amplification were 30.42 dB, 30.89 dB, and 28.56 dB, respectively, as shown in Fig. 10(a). The gain of each OAM mode for multiplexed amplification was decreased by 1 dB, because the

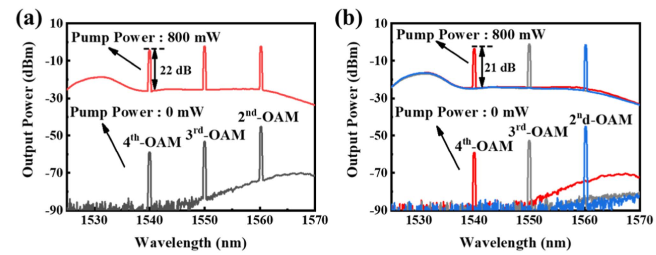

Fig. 11. Amplification spectrum. (a) WDM -OAM-MDM amplification. (b) Single amplification of different OAM modes at different wavelength.

increase in total input optical power for multiplexing led to accelerated consumption of erbium ions in the sub-stable state, as a result of decreasing in gain. Subsequently we also compared the variation of gain performance with pumping for the 3rd order OAM mode under multiplexing and single amplification. The maximum DMG between multiplexing and single OAM was 1.33 dB when pump power was 600 mW, as shown in Fig. 10(b).

In addition, the minimum OSNR was about 21 dB for the separate amplification, while the minimum OSNR was 22 dB for multiplexing amplification, as shown in Fig. 11. The OSNR was increased by 1 dB for the multiplexing amplification due to the increase of the total input optical power, which increased the consumption of erbium ions and reduced the noise caused by the spontaneous emission transition of erbium ions. Therefore, in future WDM-OAM-MDM communication systems, multi-wavelength multiplexing would reduce the gain to a certain degree while improving the OSNR, which is beneficial for the application of OAM-mode erbium-doped fiber amplifiers in the long-distance transmission.

IV. Conclusion

The amplification characteristics by using 7-RC-EDF have been investigated comprehensively for OAM-MDM. The optical gains of the 1st–4th order OAM modes in the seven cores were measured individually in the C band. Net gain of more than 22.36 dB with a DMG of less than 1.7 dB and OSNR higher than 30 dB were observed. A 3-WDM setup was constructed to test OAM-based multiplexing amplification. The impacts of the multiplexing on the gain, DMG, and OSNR have been experimentally investigated. The results would provide preliminary support for the development of EDFA in OAM-MDM transmission systems. The performance of the OAM-mode amplification technique based on 7-RC-EDFs could be further investigated by optimizing the pump modes. It is expected to find potential applications in the OAM-based multiplexing large-capacity long-distance optical communication systems.

References

[1] R.-J. Essiambre and R. W. Tkach, "Capacity trends and limits of optical communication networks," *Proc. IEEE*, vol. 100, no. 5, pp. 1035–1055, May 2012.

[2] E. B. Desurvire, "Capacity demand and technology challenges for lightwave systems in the next two decades," *J. Lightw. Technol.*, vol. 24, no. 12, pp. 4697–4710, Dec. 2006.

[3] A. D. Ellis, J. Zhao, and D. Cotter, "Approaching the non-linear Shannon limit," *J. Lightw. Technol.*, vol. 28, no. 4, pp. 423–433, Feb. 2010.

[4] C. Castro et al., "15 × 200 Gbit/s 16-QAM SDM transmission over an integrated 7-core cladding-pumped repeatered multicore link in recirculating loop," *J. Lightw. Technol.*, vol. 36, no. 2, pp. 349–354, Jan. 2018.

[5] R. G. H. V. Uden et al., "Ultra-high-density spatial division multiplexing with a few-mode multicore fibre," *Nature Photon.*, vol. 8, no. 11, pp. 865–870, 2014.

[6] S. Ramachandran, P. Kristensen, and M. F. Yan, "Generation and propagation of radially polarized beams in optical fibers," *Opt. Lett.*, vol. 34, no. 16, pp. 2525–2527, 2009.

[7] Y. Shen et al., "Optical vortices 30 years on: OAM manipulation from topological charge to multiple singularities," *Light Sci. Appl.*, vol. 8, no. 1, pp. 1–29, 2019.

[8] J. Wang et al., "Terabit free-space data transmission employing orbital angular momentum multiplexing," *Nature Photon.*, vol. 6, no. 7, pp. 488–496, 2012.

[9] S. Ramachandran and P. Kristensen, "Optical vortices in fiber," *Nanophotonics*, vol. 2, no. 5-6, pp. 455–474, 2013.

[10] D. J. Richardson, J. M. Fini, and L. E. Nelson, "Space-division multiplexing in optical fibres," *Nature Photon.*, vol. 7, no. 5, pp. 354–362, 2013.

[11] S. Chen, S. Li, L. Fang, A. Wang, and J. Wang, "OAM mode multiplexing in weakly guiding ring-core fiber with simplified MIMO-DSP," *Opt. Exp.*, vol. 27, no. 26, pp. 38049–38060, 2019.

[12] J. Zhang et al., "Mode-division multiplexed transmission of wavelength-division multiplexing signals over a 100-km single-span orbital angular momentum fiber," *Photon. Res.*, vol. 8, no. 7, pp. 1236–1242, 2020.

[13] J. Zhang et al., "SDM transmission of orbital angular momentum mode channels over a multi-ring-core fibre," *Nanophotonics*, vol. 11, no. 4, pp. 873–884, 2021.

[14] J. Liu et al., "1-Pbps orbital angular momentum fibre-optic transmission," *Light Sci. Appl.*, vol. 11, no. 1, 2022, Art. no. 202.

[15] J. Ma, F. Xia, S. Chen, S. Li, and J. Wang, "Amplification of 18 OAM modes in a ring-core erbium-doped fiber with low differential modal gain," *Opt. Exp.*, vol. 27, no. 26, pp. 38087–38097, 2019.

[16] Q. Kang et al., "Amplification of 12 OAM modes in an air-core erbium doped fiber," *Opt. Exp.*, vol. 23, no. 22, pp. 28341–28348, 2015.

[17] Y. Jung et al., "Optical orbital angular momentum amplifier based on an air-hole erbium-doped fiber," *J. Lightw. Technol.*, vol. 35, no. 3, pp. 430–436, Feb. 2017.

[18] J. Liu et al., "Amplifying orbital angular momentum modes in ring-core erbium-doped fiber," *Research*, vol. 2020, no. 11, pp. 1–12, 2020.

[19] X. Zhang, J. Liu, S. Chen, W. Li, C. Du, and J. Wang, "Amplification of 14 orbital angular momentum modes in ring-core erbium-doped fiber with high modal gain," *Opt. Lett.*, vol. 46, no. 22, pp. 5647–5650, 2021.

[20] T. Wen et al., "112 orbital angular momentum modes amplification based on a 7RC-EDF with low differential mode gain," *Opt. Lett.*, vol. 48, no. 1, pp. 105–108, 2023.