Experimental Demonstration of Amplifying 14 Orbital Angular Momentum Modes in Ring-Core Erbium-Doped Fiber with High Modal Gain

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Abstract *We propose and experimentally demonstrate an orbital angular momentum (OAM) fiber amplifier supporting 14 OAM modes based on a fabricated ring-core erbium-doped fiber with a core pump configuration acquiring a high modal gain up to 30.32 dB at 1550 nm.*

Introduction

Space division multiplexing (SDM) utilizing light beams carrying orbital angular momentum (OAM) as a promising approach to increase the per-fiber capacity has attracted much attention[1], [2]. OAM beams are featured by a helical phase front of exp($il\theta$), where l is the topological charge and θ represents the azimuthal angle. Compared with traditional multimode fibers (MMFs), ring-core fibers (RCFs) with an annual refractive index profile have been proven to be a preferable design for stable propagation of OAM modes in fibers since being first demonstrated in 2009[3]. Meanwhile, RCFs could suppress unwanted radially higher-order modes which is conducive to reducing the complexity of multiple-input multiple-output (MIMO) digital signal processing (DSP) traditionally used to mitigate the mode crosstalk[4], [5].

Another crucial key building block to realize long-haul large-capacity fiber transmission networks based on OAM-division multiplexing is high-performance inline OAM fiber amplifiers. Since the OAM modes supported in RCFs have a high degree of mode field overlap, ring-core erbium-doped fibers (RC-EDFs) have a natural advantage for achieving large and balanced modal gain of different OAM modes[6]. Amplification of two OAM modes with topological charge $|l|$ = 1 has been demonstrated in an air-hole EDF[7] with gain up to 15.6 dB and RC-EDF[8] employed in data-carrying OAM-division multiplexing and wavelength-division multiplexing system. However, the mode number and gain is not large enough to meet the rapid development of OAM communication system. In this scenario, a laudable goal in OAM communication would be to implement an OAM fiber amplifier supporting higher-order modes with high modal gain.

In this paper, we propose a RC-EDF with a tailored ring-doped profile and implement an OAM fiber amplifier based on the designed RC-EDF. The fabricated RC-EDF supports 14 OAM modes (topological charge |l| = 0, 1, 2, 3). A core pump configuration is employed in the OAM fiber amplifier with a high modal gain up to 30.32 dB at the wavelength of1550 nm.

Modeling of the RCF and amplification in RC-EDF

Assuming the RC-EDF as a two-level system, the expressions of number of metastable particles and power transmission equation in an EDF system are followed as Eq. (1) and Eq. (2), respectively[9]:

$$n_2(r,\varphi,z) = N_t(r,\varphi,z)\frac{\sum_k \frac{\sigma_{k,a}\tau}{hv_k} i_k(r,\varphi)P_k(z)}{\sum_k \frac{(\sigma_{k,a}+\sigma_{k,e})\tau}{hv_k} i_k(r,\varphi)P_k(z)+1}. \quad (1)$$

$$\begin{aligned}\frac{dP_k}{dz} &= u_k\sigma_{k,e}[P_k(z)+2h\Delta v_k]\int_0^{2\pi}\int_0^a i_k(r,\varphi)n_2(r,\varphi,z)rdrd\varphi \\ &\quad -u_k\sigma_{k,a}P_k(z)\int_0^{2\pi}\int_0^a i_k(r,\varphi)n_1(r,\varphi,z)rdrd\varphi - u_k\alpha P_k(z).\end{aligned} \quad (2)$$

Where r, φ, z are the radius, azimuthal angle and longitudinal position. k represents the k-th beam transmitted in the optical fibers comprising all modes corresponding to pumps, signals, and amplified spontaneous emission (ASE) noise, and its optical frequency, bandwidth, normalized modal intensity, and power are denoted as v_k, Δv_k, i_k and P_k. $\sigma_{k,a}$ and $\sigma_{k,e}$ denote the stimulated absorption and emission cross section, respectively, $u_k = \pm 1$ indicates a mode traveling in the forward (+) or backward (-) direction. n_1, n_2 and N_t are the erbium ion densities of the ground state, the metastable state, and the total erbium ion density. h is the Planck constant, α is the background loss, and τ is the lifetime of the erbium ions at metastable level. By solving the equations (1) -(2) through the Runge-Kutta 4th-

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order calculation, the gain for OAM modes supported by the RC-EDF can be assessed.

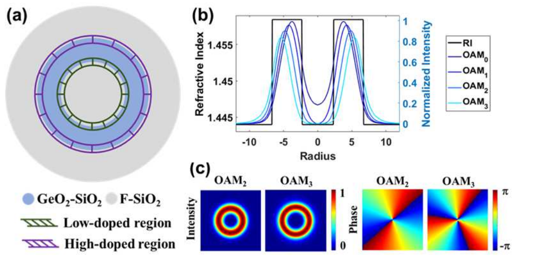

Fig.1: (a) The schematic cross-section of designed RC-EDF; (b) the refractive index profile of designed RC-EDF and normalized modal intensities of OAM_0, OAM_1, OAM_2 and OAM_3; (c) intensity and the phase distributions of OAM_2 and OAM_3.

The schematic cross-section of designed RC-EDF with double layers erbium doping is shown in Fig.1(a). The inner and outer radii of the ring core are 2.3 μm and 6.7 μm, respectively. The cladding radius is fixed at 62.5 μm. The core-to-cladding refractive index difference is Δn = 1% with a pure silica cladding. The step-index RCF designed effectively guides up to 3-order OAM mode groups (MGs) with a single-radial-order over the whole C band. Since the intensity distributions of degenerate modes in the same group are almost identical, we only take one mode of each group into consider. Fig.1(b) shows the refractive index profile (RIP) and normalized modal intensities of the OAM modes. One can see that the high-order and low-order OAM modes supported in the RC-EDF have obvious differences in the radial intensity distributions. Since the differential modal gain (DMG) depends strongly on the overlap between signal modes, pump modes and the rare earth dopant distribution, the diversity in mode field distribution of different MGs should be considered in order to reduce the DMG. We adopt different concentrations of erbium doping on the inside and outside of the ring area. The inner and outer radii of the low-doped region with the doping concentration being 1.3×10^{25} m^{-3} are 2.2 μm and 4.2 μm, which are 5.2 μm and 7.2 μm for high-doped region with the doping concentration being 1.5×10^{25} m^{-3}, respectively. Fig.1(c) indicates the normalized modal intensity and phase distribution of OAM_2 and OAM_3. One can clearly see the doughnut intensity profiles due to the phase singularity at the beam center.

Performance evaluation of OAM fiber amplifier assisted by RC-EDF supporting 14 OAM modes

The measured RIP and erbium-doping profile of the fabricated RC-EDF are shown in Fig.2(a). There are some distortions of the fabricated-RCF RIP compared with the design in Fig.1(b), which may result from the diffusion of doped elements during fiber drawing. The four red solid circles are the measured erbium ion doping concentration in four radial positions, and the red dashed line is the interpolation curve obtained by fitting the doping concentration of four test points for simulation. The simulated normalized modal intensity and phase distribution of OAM_2 and OAM_3 at 1550 nm are shown in Fig.2(b). The distortion of intensity and phase singularities of OAM_2 and OAM_3 are due to ellipticity of the ring core introduced by the drawing process. Fig.2(c)-(f) present the simulated gain of guided OAM modes based on the interpolation curve of erbium-doping profile in Fig.2(a). The simulations are under the following conditions: (1) The RC-EDF-assisted OAM fiber amplifier is assumed to be fundamentally pumped into fiber core at the 980 nm, (2) only one degenerated mode in each OAM MGs is considered, (3) the noise and modal coupling are ignored and the RC-EDF is assumed to be lossless, (4) the RC-EDF length is 5 m, (5) the pump and signal power are 550 mW and -25 dBm, respectively, (6) the signal wavelength is 1550 nm. The gain is simulated by scanning one of the parameters including EDF length, pump power, signal power and wavelength with the others fixed as above. One can see that the smaller signal power benefits larger gain and the growth rate of gain becomes smaller with the increase of pump power. The gain nadir is located at ~1535 nm with the minimum gain of 20.85 dB for the guided OAM modes over the whole C band.

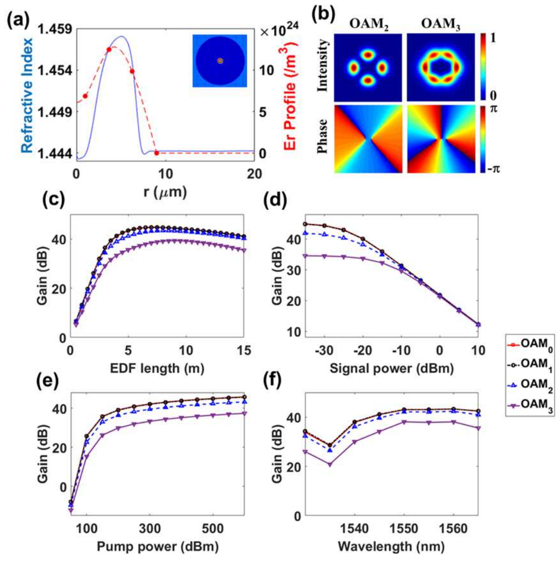

Fig.2: (a) The measured RIP and erbium-doping profile of the fabricated RC-EDF; (b) intensity and phase distribution of OAM_2 and OAM_3; simulated modal gain versus (c) EDF length, (d) signal power, (e) pump power and (f) wavelength.

The experimental setup of OAM fiber amplifier assisted by fabricated RC-EDF is illustrated in Fig.3. OAM modes with different topological charge are generated by a spatial light modulator (SLM) loading different phase patterns. A half-wave plate (HWP) and a polarizer are combined to control the polarization of input signal beam, in order to ensure the highest modulation efficiency. A 980 nm pump laser is coupled from free space into the fiber by a dichroic mirror (DM). Another DM is used at the amplifier output to separate amplified OAM modes and the residual pump beam. The RC-EDF as the gain medium is 5 meters long and the output end is angle-cleaved to suppress unwanted parasitic lasing. Two free-space isolators (ISO) are adopted to reduce the potential for Fresnel reflections. The variable optical attenuator (VOA) is used to adjust input signal power and two collimators are used to couple light into free space or fiber.

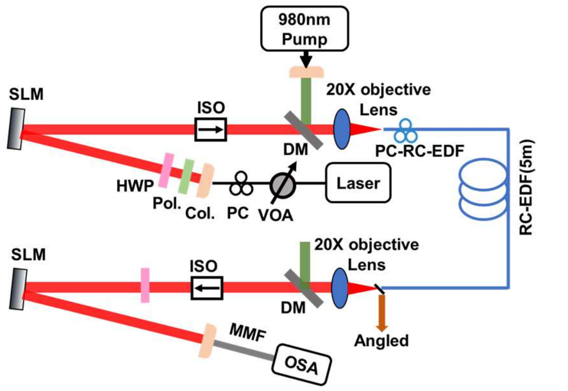

Fig. 3: The experimental setup of the OAM amplifier. SLM: spatial light modulator; HWP: half-wave plate; Pol.: polarizer; Col.: collimator; PC: polarization controller; VOA: variable optical attenuator; ISO: isolator; DM: dichroic mirror; RC-EDF: ring-core erbium-doped fiber; PC-RC-EDF: polarization controller on RC-EDF; MMF: multimode fiber; OSA: optical spectrum analyzer.

We first measure the intensity and demodulation profiles of typical OAM modes (OAM_2 and OAM_3) by a CCD as shown in Fig. 4(a). Then we measure the gain of different OAM modes to evaluate the performance of the OAM fiber amplifier. Fig.4(b) illustrated the measured gain of OAM_3 as a function of wavelength. The gains are larger than 22.94 dB from 1540 to 1560 nm with input signal power equaling -25 dBm. Fig.4(c) presents the measured modal gain for OAM modes versus pump power with fiber length, signal power and wavelength fixed at 5 m, -25 dBm and 1550 nm, respectively. One can clearly see that the gain can be increased with the pump power increasing, while the gain increases slightly when the pump power is larger than 300 mW due to the population inversion of erbium ion reaching saturation. For simplicity, we choose one OAM mode in each mode group, i.e. OAM_0, OAM_1, OAM_2 and OAM_3. Additionally, Fig.4(d) depicts the measured gain of OAM modes as a function of signal power at a fixed pump power equaling 700 mW with fiber length and wavelength launched at 5 m and 1550 nm, respectively. It can be observed that the modal gain decreases with the increase of signal power which is up to 30.32 dB with signal power launched at -25 dBm. In addition, the mode gains of all 4 OAM modes from 4 MGs (|l| = 0, 1, 2, 3) are larger than 25 dB with signal power lower than -20 dBm.

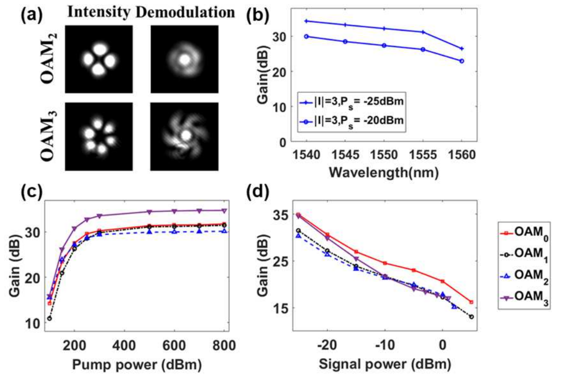

Fig.4: (a) the intensity profiles and demodulation of OAM_2 and OAM_3; The measured modal gain for OAM modes versus (b) wavelength, (c) pump power and (d) signal power.

Conclusion

We have proposed and demonstrated an OAM fiber amplifier supporting 14 OAM modes (topological charge |l| = 0, 1, 2, 3) based on a RC-EDF. With a core pump configuration, the high modal gains up to 30.32 dB of 4 typical OAM modes from 4 different MGs are achieved at the wavelength of 1550 nm. The gains of OAM_3 from 1540nm to 1560 nm are larger than 22.94 dB with input signal power equaling -25 dBm. The obtained results indicate successful implementation of the RC-EDF-assisted OAM fiber amplifier for 14 OAM modes with favorable performance.

Acknowledgements

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