Erbium-Doped Fiber Amplifier for OAM Modes Using an Annular-Core Photonic Lantern

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Abstract: We experimentally demonstrated an erbium-doped fiber amplifier for OAM modes using an annular-core photonic lantern. The small signal gain for OAM modes with |L|=1 and 2 are obtained to be 22.1dB and 16.7dB.

OCIS codes: (230.2285) Fiber devices and optical amplifiers; (050.4865) Optical vortices.

1. Introduction

Vortex beams carrying orbit angular momentum (OAM) associated with helical phase fronts [1] have been intensely investigated in the past few decades. In microscopy, vortex beam can enhance the resolution of images by orders of magnitude for a variety of object structures [2,3]. They can also be used to optimized the size of dark focal spot in stimulated emission depletion (STED) microscopy [4]. For material processing, high-order OAM beam can achieve clearer and smoother processed surfaces [5]. Recently, amplifiers for OAM modes have received significant interests. Erbium-doped fiber amplifier (EDFA) for OAM modes has been theoretically studied in [6] and an EDFA for the $\mathrm{OAM}_{|L|=1}$ mode using phase plate based mode multiplexers has recently been experimentally validated [7]. However, phase plate based mode multiplexers are not ideal for this application as they exhibit appreciable coupling loss between free space and the amplifier fiber.

In this work, we demonstrated an EDFA for OAM modes using an annular-core photonic lantern [8]. Since the photonic lantern is a low-loss all-fiber device, it can effectively reduce coupling losses and allow scaling to large number of OAM modes. In our experiment, both the first- and second-order OAM modes are amplified with small-signal gains of up to 22.1dB and 16.7dB, respectively. The amplified OAM mode intensity profiles are captured by a CCD camera. We also swept the signal wavelength through the C-band, the results indicate that our scheme works well for the entire C-band.

2. Experimental setup and results

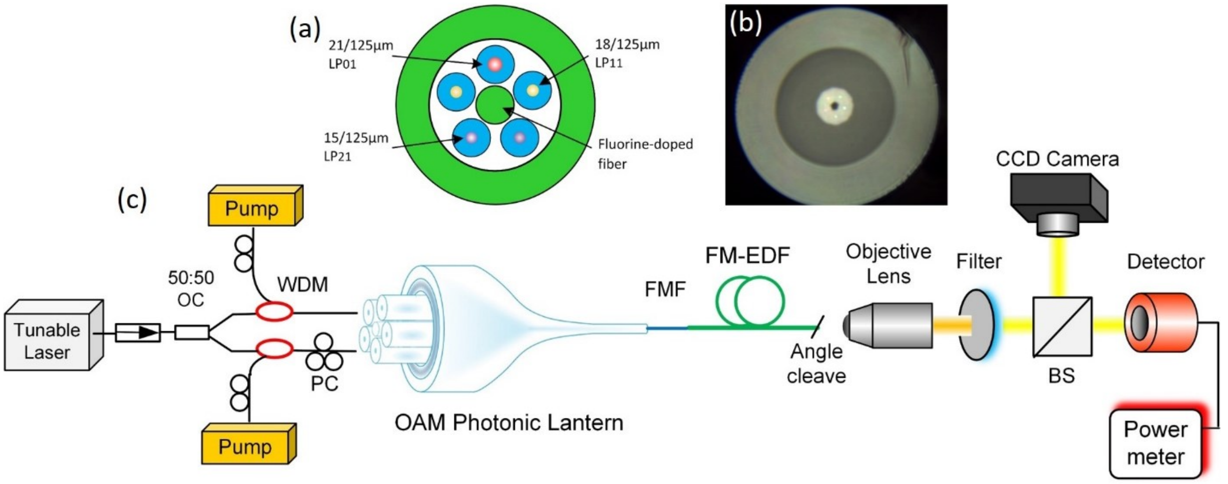

Fig. 1. (a) Schematic cross section of the annular-core PL; (b) cross section microscope image of fabricated annular core PL; and (c) experimental setup of the OAM EDFA based on the annular-core PL. OC: optical coupler; PC: polarization controller; BS: beam splitter.

In this experiment, we use an annular-core PL to efficiently generate OAM modes in a low-loss fashion. Fig. 1(a) shows the structure of the PL. It contains 5 single mode input fibers of dissimilar size inside a low refractive index capillary, and a pure fluorine-doped central fiber. During adiabatic tapering, each input fundamental mode can evolve into a specific LP mode at the output [9]. The cross-sectional image at output is shown in fig. 1(b), depicting a ring core with a thickness of 8μm and the cladding diameter is 115μm. The OAM mode can be expressed as a superposition of two degenerate LP modes. When two degenerate modes launch into the PL together with a π/2 phase difference, the output would be an OAM beam. The experimental setup of our OAM EDFA is shown above in fig. 1(c). The signal laser was launched from a tunable laser with an optical power of 0.2mW at 1550nm. After splitting into two channels by a 3dB optical coupler, each channel was combined with the pump of 967nm by a WDM coupler. The output of two WDMs can be selected to connect either LP$_{11a,b}$ or LP$_{21a,b}$ port of the OAM PL to generate OAM$_{|L|=1}$ and OAM$_{|L|=2}$ modes. The output of the PL was spliced with a 1m long intermediate 6-LP mode few-mode fiber (FMF), and further spliced with a 5m long erbium-doped FMF (ED-FMF). The gain fiber has a core and cladding diameter of 13/163μm, which may support over 6 LP modes at the signal wavelength [10]. The amplified signal was focused by an objective lens, and a bandpass filter centered at 1550nm was employed to block the pump light.

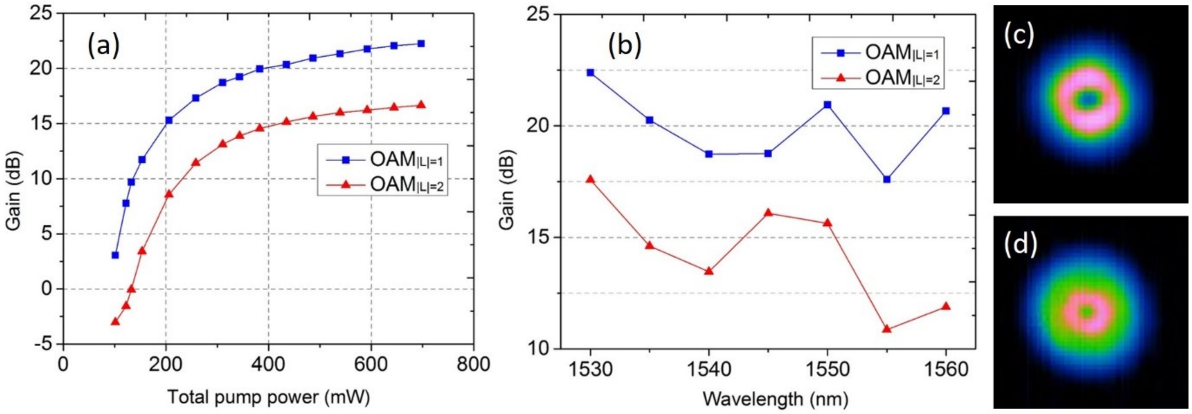

Fig. 2. (a) Small signal gain of OAM$_{|L|=1,2}$ vs total pump power (LP$_{11a+b}$ or LP$_{21a+b}$); (b) gain figure of OAM modes at different signal wavelength; and mode intensity profile of amplified (c) OAM$_{|L|=1}$ and (d) OAM$_{|L|=2}$ modes.

Fig. 2 (a) shows the gain figure of OAM$_{|L|=1,2}$ under different pump powers. When the total pump power at the input of the PL is 697mW, the small signal gain for OAM$_{|L|=1}$ and OAM$_{|L|=2}$ are 22.1dB and 16.7dB, respectively. The differential modal gain (DMG) is 5.4dB. The reason that the gain for OAM$_{|L|=2}$ is smaller than OAM$_{|L|=1}$ is mainly due to the loss of the PL for LP$_{21}$ modes are larger than LP$_{11}$ modes at both pump and signal wavelength. We used a CCD camera the capture the mode profiles of the two OAM modes after being amplified, the results are shown in fig. 2 (c) and (d). We can see that both of them has a doughnut shaped intensity profile, which indicates that they are vortex beams after being amplified; however, the patterns seems not perfectly symmetric. This is partly due to the gain equalization between two degenerate LP modes being imperfect. The main reason is there are mode crosstalk in the gain fiber, the original LP modes will couple to higher-order modes supported by the gain fiber and further being amplified. Finally, we fixed the total pump power to be 486mW and swept the signal wavelength from 1530nm-1560nm, the results are shown in fig.2 (b). We find the curve for both OAM$_{|L|=1}$ and OAM$_{|L|=2}$ are similar with the ASE spectrum of the gain media. The minimum DMG is achieved at 1545nm which is 2.68dB.

3. Conclusion

We have experimentally demonstrated an EDFA for OAM modes using an annular-core PL. The small-signal gains of the first- and second-order OAM modes are 22.1dB and 16.7dB, respectively. The mode intensity profiles are maintained after amplification. Our scheme works well for the entire C-band.

4. References

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