Amplification of high-order azimuthal mode based on a ring-core Yb-doped fiber*

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In order to increase the number of amplified azimuthal modes in Yb-doped fiber (YDF), a multiple azimuthal modes amplifier based on a ring-core Yb-doped fiber (RC-YDF) was proposed and demonstrated. A home-made RC-YDF which can support 6 azimuthal mode groups was employed to amplify the signal mode at 1 064 nm, using a core pump scheme. The amplification characteristics of 5 high-order azimuthal linear polarization (HA-LP) mode groups (LP_{11}, LP_{21}, LP_{31}, LP_{41}, LP_{51}) were studied comprehensively. A more than 8 dB gain is obtained for each signal mode with 5 dBm input power, and the associated differential modal gain between all modes is less than 1 dB. The intensity profiles of all modes are stable and well preserved during the process of amplification.

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Structured light[1,2], including cylindrical vector beams (CVBs), orbital angular momentum (OAM) mode and linear polarization (LP) mode, is widely used in many fields, such as super-resolution imaging[3], material processing[4], ultrahigh-density data storage[5,6], and optical communication[7], etc. Most of these modes have two independent degrees of freedom corresponding to the radial and azimuthal indices. The azimuthal freedom of the mode avoids the limitation of radial freedom due to the size of most optical systems, in principle, the azimuthal modes are unlimited, and it captured more interests. As a subset, high-order azimuthal linear polarization (HA-LP) mode is relatively popular, which can not only be used to generate OAM mode, but also find applications in quantum communication[8], nonlinear optics[9], manipulation of particle[10,11] and other fields. HA-LP modes are usually generated by spatial devices, such as spatial light modulator (SLM). However, the power of HA-LP mode generated by these methods is relatively low due to the limitation of low conversion efficiency or power damage threshold of spatial device. In order to meet the needs of the application, it is necessary to amplify the HA-LP mode. The amplification based on fiber amplifier is potential because of the characteristics of high efficiency and flexibility. On the other hand, HA-LP modes can also be obtained by all-fiber devices, for example, HA-LP mode can be generated in the all-fiber laser[12,13]. Using a fiber which can support the amplification of desired HA-LP mode as gain fiber to realize direct oscillation of the desired HA-LP mode is an effective way to improve the performance of lasers[14]. Based on above reason, amplification of HA-LP mode based on fiber is necessary. High-order azimuthal modes operating at 1.0 μm are necessary for many practical applications, such as nonlinear optics[15,16] and manipulation of particle[17]. Driven by these applications, amplification of HA-LP mode based on Yb-doped fiber (YDF) has attracted great interest because YDF has broad-gain bandwidth and excellent power conversion efficiency in the band of 1.0 μm[18].

KIM et al[19] demonstrated the amplification of the LP_{11} mode by employing a double-clad polarization maintaining large-mode-area YDF. Recently, LIN et al[20] implemented a few-mode fiber amplifier based on commercially available few-mode large mode area Yb-doped fiber, which realized the amplification of LP_{11} and LP_{21} modes. There is a relatively large difference between intensity distributions of different HA-LP modes in the step-index fiber, although it can achieve good amplification performance of several HA-LP modes by designing a complex Yb-ions distribution, which will extremely complicate the manufacturing

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process. Fortunately, there is a good overlap between ring-type pump mode and high-order azimuthal mode in the ring core fiber[21], which is an ideal candidate for the amplification of several high-order azimuthal modes. FANG et al[22] firstly proposed the adaptive modal gain of the LP mode in the fiber laser system based on a ring-core Yb-doped fiber (RC-YDF), and realized the output of 2-order CVBs with high purity. In 2022, this group proposed a random fiber laser based on RC-YDF which can realize direct oscillation of the LP_{11} mode[23]. However, the azimuthal orders in these reports are less than 3. It is urgent to develop a method that can realize amplification of more HA-LP modes in the 1.0 μm band with good performance.

In this paper, in order to realize the amplification of more HA-LP modes, an RC-YDF fiber which can support 6 HA-LP mode groups at 1 064 nm was fabricated, a 976 nm pump source was adopted, and an optical amplifier based on the RC-YDF was built. The amplification characteristics of the 5 HA-LP modes are comprehensively analyzed. Experimental results show that the gain is more than 8 dB when the input power of each mode is 5 dBm, and differential modal gain between all modes is less than 1 dB. It is expected to achieve higher gain and higher power beam by further improving the pump power and signal power.

In order to support amplification of several HA-LP modes, a home-made RC-YDF is used as the active fiber. The optical fiber was fabricated by using a modified chemical vapor deposition (MCVD) and an all-gas-phase high-temperature evaporation deposition process. Fig.1(a) shows the microscopy image of the RC-YDF. The RC-YDF consists of 4 parts, the central layer, ring core with Yb doping, trench layer and the cladding layer, and their outer radii are about 7.5 μm, 13.1 μm, 17.4 μm and 62.5 μm, respectively. The refractive index profile of RC-YDF at 1 064 nm is shown in Fig.1(b). Compared with the cladding, the refractive index differences of the central layer, ring core and trench layer are about 0, 0.004 4 and −0.000 4, respectively. The ring core with Yb doping has a high refractive index, which realizes the ring eigenmodes and annular Yb-doped layer in the RC-YDF, and they have high overlap. The trench layer with low refractive index is used to increase the modal confinement and reduce the bending loss. The modal characteristics of the RC-YDF were theoretically analyzed by full-vector finite element method, and the result shows that the fiber can support 6 azimuthal mode groups (LP_{01}, LP_{11}, LP_{21}, LP_{31}, LP_{41}, LP_{51}) at 1 064 nm. Fig.2 shows the electric filed distributions of the 6 modes in the RC-YDF.

The absorption coefficient of the RC-YDF was measured by the cutback method. The measured absorption coefficient is about 130 dB/m at 976 nm, and the absorption coefficients of LP_{11}, LP_{21}, LP_{31}, LP_{41} and LP_{51} modes are about 1.289 dB/m, 1.329 dB/m, 1.307 dB/m, 1.293 dB/m and 1.339 dB/m at 1 064 nm, respectively.

The modal gain of RC-YDF was studied theoretically. In this simulation, amplifier was considered as a two-level system, and the amplified spontaneous emission (ASE), coupling loss and transmission loss of pump light and signal light are neglected. Assume the pump mode is LP_{01} mode at 976 nm and with forward propagation, the signal wavelength is 1 064 nm, the input power is 4 mW, and the length of the RC-YDF is 1 m. The simulated modal gains of 5 HA-LP modes were calculated under different pump powers, as shown in Fig.3.

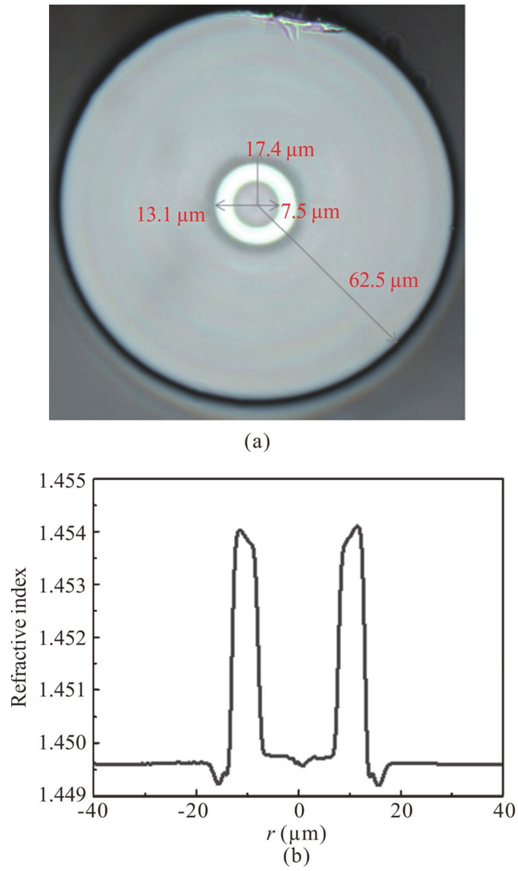


Fig.1 (a) Microscopy image of the RC-YDF; (b) Refractive index profile of the RC-YDF

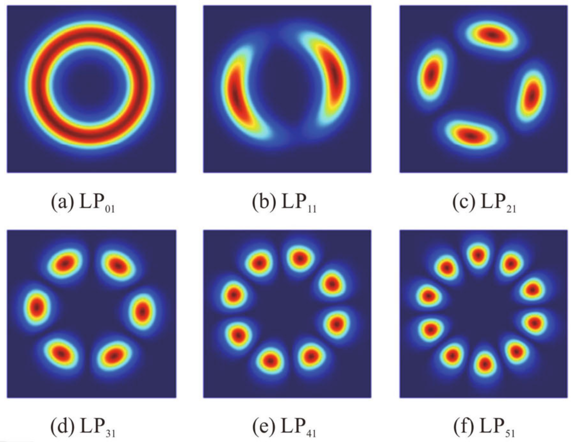


Fig.2 Electric field distributions of the six LP modes supported in the RC-YDF

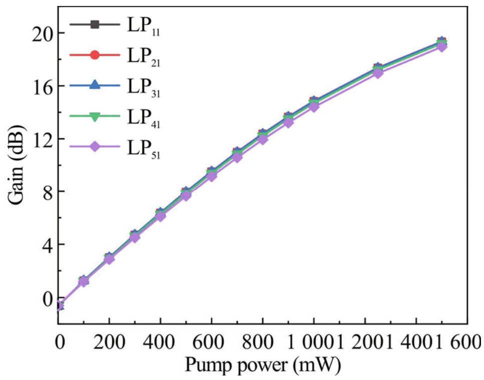


Fig.3 Simulated modal gains of different HA-LP modes as a function of the pump power

The simulated results indicate the RC-YDF can support the amplification of 5 HA-LP mode groups, and their gains are similar.

An experimental setup to amplify 5 HA-LP modes was constructed. The experimental system is shown in Fig.4. A Gaussian beam at 1 064 nm is generated by a tunable laser, 3 dB linewidth is about 0.032 nm, and it is injected onto a reflective SLM. HA-LP mode is generated by loading forked diffraction grating onto SLM, and through an isolator (ISO) to prevent reflected light and generation of parasitic laser. Then it is coaxial with a 976 nm single-mode pump beam which is generated by a power tunable laser (maximum output power is 1 400 mW) by a dichroic mirror (DM). The coaxial beams (signal and pump) are coupled into the RC-YDF by a 16× objective lens with numerical aperture (*NA*) of 0.25. The input end of the RC-YDF is flat-cleaved to reduce the coupling complexity of pump light and signal light. The pump power coupled into the fiber is difficult to measure because of the large absorption coefficient of the RC-YDF, and taking optical path loss of pump light due to collimator, DM and objective lens into consideration, so the pump power measured at the input end of the RC-YDF is used as effective power of pump light. The length of the used RC-YDF is about 80 cm. A polarization controller (PC) is used to adjust the polarization of the light propagating in the fiber to obtain the desired HA-LP mode with high purity. The amplified beam from the output end of the RC-YDF is collected by a 25× objective lens, and then residual pump light is filtered out by another DM. The output beam is divided into two branches by a beam splitter (BS). A few-mode fiber is used to couple one beam, and the spectra of different HA-LP modes are recorded by using optical spectrum analyzer (OSA) to connect few-mode fiber, which are used to calculate the gain of each HA-LP mode. The intensity profiles of signal are obtained by using an infrared charge-coupled device (CCD) to record another beam. A spatial light filter with a center wavelength of 1 064 nm is used to filter out the ASE, and obtain a relatively clear intensity profile of signal.

In order to verify the amplification characteristics of each HA-LP mode, an SLM is used to generate desired HA-LP modes, and the relatively positions between the RC-YDF and objective lens are adjusted by the six-axis adjuster. The signal and pump light are coupled into the fiber simultaneously, and ensure the coupling efficiency of pump light is maximized, using a spatial optical power meter (detector, S132C, THORLABS, display instrument, PM100D) to measure the signal power at the output end of the fiber without pump, and the signal power coupled into fiber was determined after considering the absorption loss of each mode at 1 064 nm. The signal with an input power of about −10 dBm was selected as the test sample, and the intensity profiles of all modes under different pump powers were captured by CCD, as shown in Fig.5.

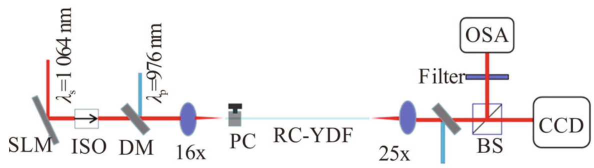


Fig.4 Experimental system of the amplifier

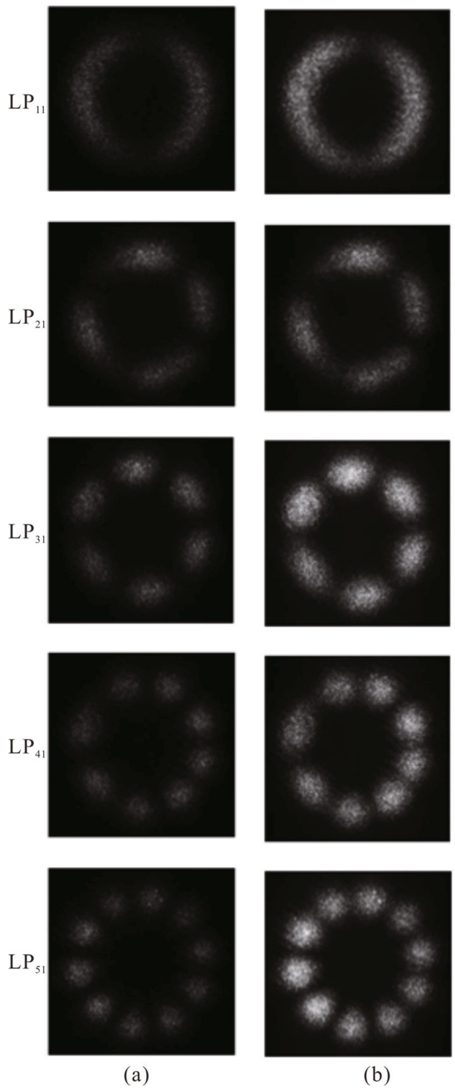


Fig.5 Intensity profiles of five HA-LP modes: (a) Pump power is 222 mW; (b) Pump power is 667 mW

Comparing the states of all modes under different pump powers, it can be seen that when the pump power increases from 222 mW to 667 mW, the intensity of each mode increases significantly, indicating that the mode is significantly amplified. And the intensity profiles of all HA-LP modes are well preserved during the amplification process, indicating that each mode is not distorted. The weak noise after amplification may be caused by ASE.

The change of the intensity profiles with pump power can directly reflect the amplification of the signal, but it is not enough to quantify the gain characteristics of each mode. In order to quantify the gain characteristics of each mode, three different signal powers (−10 dBm, 0 dBm and 5 dBm) were selected as test samples. In the experiment, the power of the pump was gradually increased from 0 mW to 1 037 mW, and the OSA (AQ6370, YOKOGAWA) was used to record the spectra of amplified modes.

Fig.6 shows the spectra of all HA-LP modes individually when pump power is 0 mW and 1 037 mW, respectively. It can be found that each HA-LP mode is significantly amplified with similar gain.

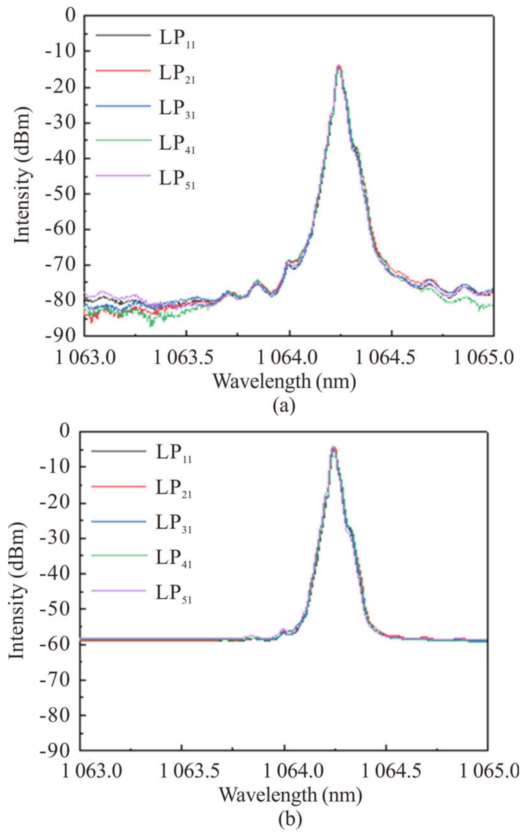
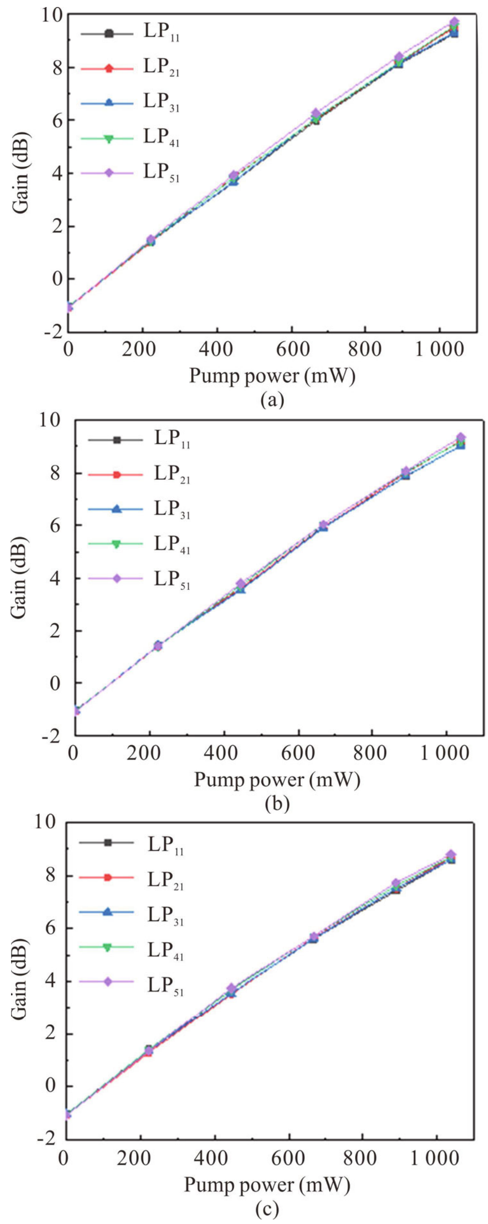


Fig.6 Spectra of different HA-LP modes when input power is 5 dBm: (a) Pump power is 0 mW; (b) Pump power is 1 037 mW

The gain of each HA-LP mode was calculated. Figs.7(a), (b) and (c) show the relationship between the gain of each HA-LP mode and the pump power when the input signal power is −10 dBm, 0 dBm, and 5 dBm, respectively. It can be found that the gain of each mode increases as the pump power gradually increases from 0 mW to 1 037 mW. The gain of each HA-LP mode is higher than 8 dB. On the other hand, it can also be seen that each mode has similar gain, and the differential modal gain is less than 1 dB. These obtained results indicate that the gain of each HA-LP mode does not show a trend of saturation with the pump power increasing from 0 mW to 1 037 mW, which means that the gain of each HA-LP mode can be further improved by increasing the effective pump power. Fig.7(d) shows the gain of each mode at different input powers when the pump power is 1 037 mW. It can be found that when the input power of the signal light increases from −10 dBm to 5 dBm, the drop of gain is less than 1 dB. The gain does not decrease significantly, but the total signal output power is relatively up about 14 dB, which means that the output power of the amplifier is not saturated and can be boosted by increasing the power of signal light. There are some differences in the trend of the gain of each mode, which may be caused by fluctuations of the signal light



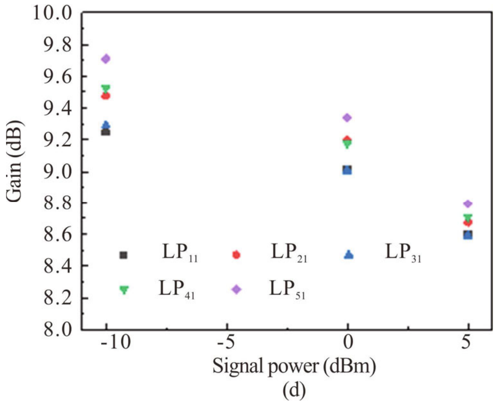


Fig.7 Gain curves of five HA-LP modes: (a) Input power is −10 dBm; (b) Input power is 0 dBm; (c) Input power is 5 dBm; (d) Pump power is 1 037 mW

source and OSA in the experiment. There are some differences between simulated and experimental results. Effective pump power in the experiment is less than that from simulation due to coupling loss of pump light.

In summary, a multiple azimuthal modes amplifier based on RC-YDF was demonstrated, which realizes the amplification of 5 HA-LP mode groups (LP_{11}, LP_{21}, LP_{31}, LP_{41}, LP_{51}) at 1 064 nm. Simulated and experimental results show that it is expected to achieve higher gain and higher power beam output in the future research by increasing the effective pump power and signal power. This amplifier also has potential application value in the high power field.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

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