Fiber amplification of radially and azimuthally polarized laser light

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The results on amplifying either radially or azimuthally polarized light with a fiber amplifier are presented. Experimental results reveal that more than 85% polarization purity can be retained at the output even with 40dB amplification, and that efficient conversion of the amplified light to linear polarization can be obtained. © 2010 Optical Society of America

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Radially and azimuthally polarized laser light have unique properties and symmetries that are advantageous for high power lasers [1, 2]. For example, their cross section intensity distributions have doughnut shapes whose peak intensities are significantly lower than that of light with a Gaussian distribution, so non-linear and damage effects through fibers core are significantly reduced [3]. Accordingly, several laser resonator configurations have been developed to produce radially and azimuthally polarized light [3–10]. However, in all these the power of the output beam was relatively low, so that for some applications additional amplification is required [11, 12]. Thus far, amplification of either radially or azimuthally polarized laser light was demonstrated with bulk solid state laser amplifiers [2], but not with fiber amplifiers, probably because of deleterious effects of their birefringence and non-linearities. Here we present for the first time experimental results on amplifying radially and azimuthally polarized light with a large mode area fiber amplifier, where we obtained an amplification of 40dB with over 85% polarization purity. We also show that the amplified beam can be efficiently converted back into a linearly polarized near-Gaussian beam, confirming the modal structure and polarization purity of the radially and azimuthally polarized amplified beam.

The experimental arrangement for amplifying either radially or azimuthally polarized beam with a fiber amplifier is presented schematically in Fig. 1, along with an arrangement for converting the amplified radial or azimuthal light distribution to a Gaussian distribution. In this configuration a weak linearly polarized Gaussian beam of 40µW propagated through a space-variant retardation plate (SVR) to obtain either radially or azimuthally polarized light that served as the input [3–5]. The SVR was comprised of eight sectors each having λ/2 retardation in different orientations, where the direction of the slow axis of each retardation sector is denoted by an arrow as shown in Fig. 1. When the SVR was oriented at 0° with respect to the polarization of the input beam, it converted the linearly polarized light into radially polarized light, and when the SVR was oriented at 45° it converted the linearly polarized light to azimuthally polarized light. In both cases the spatial mode of the beam was converted into a $LG_{10}$ mode.

The radially or azimuthally polarized beam was then launched into a 10m long Ytterbium doped double clad fiber, with core diameter of 20µm and numerical aperture of 0.07, that served as the amplifier. Such a fiber amplifier can support the propagation of four modes, and in particular the $TE_{01}$ and $TM_{01}$ modes of the radial and azimuthal polarizations inside the fiber, which corresponds to the $LG_{10}$ mode in free space [13, 14]. The fiber amplifier was co-pumped with a 915nm diode laser.

![Fig. 1. Experimental configuration for amplifying radially and azimuthally polarized light with a fiber amplifier. Path A - space variant polarization measurement, path B - conversion arrangement to a linearly polarized light.](image-url)

We measured the amplified output power and found it to be 400mW, indicating that the amplification was 40dB. The polarization distributions of the input and amplified light beams were determined by measuring their intensity distributions after passing through three different sets of polarization elements, to obtain the four Stokes parameters [15]. Some representative results of three of the four Stokes parameters together with the resulting polarization state at each point in the beams, are shown in Fig. 2. Figures 2(a), (b) and (c) show the three Stokes parameters and the state of polarization for...
the calculated, input and output light distributions with radial polarization. Figures 2(d), (e) and (f) show the three Stokes parameters and the state of polarization for the calculated, input and output light distributions with azimuthal polarization. As evident, there is good agreement between the calculated results and the experimental results for the input and amplified beams.

Using the Stokes parameters, we calculated the polarization purity of the experimentally detected beams and found that for both the radially and azimuthally polarized input beams the polarization purity was over 95%, and for the corresponding amplified beams the polarization purity was over 85%. These results obviously indicate that polarization purity is essentially preserved. We found that the amplified radially and azimuthally polarized light beams were essentially stable for several hours in terms of polarization purity and intensity distributions. The experiments were conducted in usual laboratory environment, with minimal mechanical stresses on the fiber amplifier.

We also amplified a linear combination of radially and azimuthally polarized input light beam (generated when the SVR is oriented at 22.5°), and detected the Stokes parameters and the corresponding full state of polarization of the amplified beam. The results are presented in Fig. 3. Figure 3(a) shows the calculated results while Fig. 3(b) shows the experimental results. Here again there is good agreement between the calculated and experimental results. The corresponding polarization purity for the experimentally amplified output beam was calculated to be over 85%.

Finally, we converted the amplified radially polarized light beam into a linearly polarized light beam with Gaussian distribution by means of an additional SVR, and detected the far-field intensity distribution by means of a focusing lens and a CCD camera as shown in path B in Fig. 1. The results are presented in Fig. 4. It shows the experimental cross-sections of the amplified radially polarized light beam in the far-field, with and without conversion. Also shown are the actual far-field intensity distributions of the amplified radially polarized light without conversion (upper left inset) and that of the linearly polarized light with conversion (upper right inset). As evident, the far field intensity distribution of the radially polarized beam has the expected doughnut shape, reminiscent of the $LG_{10}^+$ mode distribution, and that of the converted linearly polarized beam has the expected Gaussian distribution. The conversion to a Gaussian or near Gaussian distribution with measured 85% polarization purity indicates that the amplified radially polarized light beam was indeed of high purity.

To conclude, we presented a novel configuration for amplifying radially and azimuthally polarized light, obtaining 40dB amplification while maintaining the polarization purity at over 85%. We also showed that the amplified radially polarized light beam can be efficiently converted to a linearly polarized light beam with near Gaussian distribution. All our experiments were done with relatively low power levels, where thermally induced stresses are not significant. At higher power levels these will have to be taken into account.

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Fig. 3. Calculated and experimental Stokes parameters and the state of polarization of amplified combination of radially and azimuthally polarized beam. (a) Calculated results; (b) experimental results.

Fig. 4. Experimental cross-sections of the far-field intensity distributions of the amplified radially polarized light beam with and without conversion to a linearly polarized near Gaussian beam. Solid (blue) curve - before conversion; dashed (red) curve - after conversion. Left inset depicts the far field intensity distribution before conversion and right inset the far field intensity distribution after conversion.

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