An all-fiber device for generating radially and other polarized light beams

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Abstract

Radially polarized beams are beams for which the electric vector is radially distributed along the beam axis. Such beams are interesting for applications in which a total symmetry of the electric field is required. In this paper we propose an all-fiber method allowing the generation of radially, azimuthally, and hybrid polarized light beams in a rapid and simple way.

1. Introduction

From both theoretical and experimental works, it is known that the polarization state is particularly important in near-field optical confinement [1–4]. More precisely, it has been shown that the polarization will strongly influence the width of the peak confinement. Therefore, in the framework of immaterial tip use, the knowledge and the choice of the polarization is compulsory. These comments can be generalized to any large aperture imaging systems, such as solid immersion systems [5] although, in that case, the effect of polarization on the focal spot is not so significant.

It turns out that the radial polarization of the incident beam, because of total symmetry, will enhance the E_z component of the field (versus E_x and E_y) after beam focusing. Since the component E_z of the field is responsible for the confinement, the diameter of the central spot will decrease consequently. Note that radial polarization has been also proposed for large numerical aperture systems (see [6]).

For more than 30 years, various methods have been developed in order to generate such radially polarized fields. Those methods are based on interferometric systems [7,8], on computer generated holograms [9], or polarization converters using liquid crystals [10]. Annular transverse radially or azimuthally polarized modes have been selected in passive resonant cavities [11] and in laser cavities [12–16]. Such peculiar beams have also been reconstructed by interferometry inside the cavity [17]. Despite the efficiency of such techniques (in terms of polarization purity and energy efficiency)

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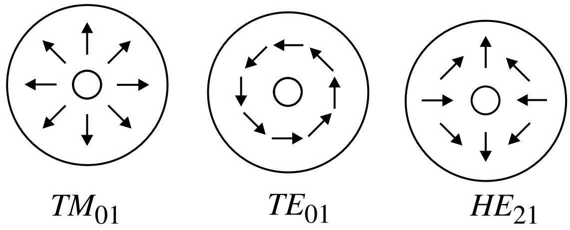

Fig. 1. Schematic representation in intensity and polarization of the three annular modes TM_{01} radially polarized, TE_{01} azimuthally polarized and HE_{21} with hybrid polarization.

they are generally rather heavy and tricky (mainly due to problems of stability).

We propose here a simple and cheap technique allowing the generation of radially polarized beams. Its principle is based on mode selection inside an optical fiber rather than inside a laser cavity. It is well known that a multi-mode optical fiber (step index fiber) accepts several annular modes including TM_{01} mode with radial polarization, TE_{01} mode with azimuthal polarization and HE_{21} mode with an hybrid polarization state (combination of radial and azimuthal polarization) (see Fig. 1). HE_{21} is named as hybrid mode. In the case of weak guiding those three modes have the same cutoff parameters which are smaller than the cutoff parameters of the other modes (except the fundamental mode HE_{11}) [18,19]. Far from cutoff, they can combine and lead to degenerated linearly polarized LP_{11} modes with a two-lobe structure in intensity.

2. Experiments

The problem to solve deals with the way of selectively exciting the purely radial mode, i.e. TM_{01}. The technique which is presented and described here is easy to carry out. It uses a precise control and monitoring (in shift and tilt) of the injection of a linearly polarized light beam (at the wavelength $\lambda = 632.8$ nm) in a multi-mode fiber. For the three annular modes, the cutoff diameter is 4.2 μm for a fiber with an index difference $\Delta n = 0.0045$ between core and cladding. The diameter reaches 6.7 μm for the next mode EH_{11} in the cutoff classification. Since the core diameters of the multi-mode fibers used here are 5 and 6 μm for approximately the same Δn, only the fundamental and the three annular modes will be transmitted, the other modes being filtered. We note that for those fiber widths, the selected modes propagate far from cutoff.

The light injection is performed by means of a mono-mode fiber the exit face of which is set in the vicinity of the entrance face of the multi-mode fiber. First of all, the three annular modes exhibit similar intensity profiles, they only differ from the polarization state. Therefore, the shift and the tilt between the two fibers will be defined according to the polarization direction of the incident beam. Moreover, the field distributions of the three modes show axial symmetry, for they follow the cylindrical symmetry of the fiber. Consequently, we can expect that a system which is able to select such annular modes has to keep the axial symmetry given by optical fibers as much as possible. A priori, tilt between fibers has to be weak or null. In this work, only shift will be used for filtering the unwanted modes in the multi-mode fiber.

The setup is shown in Fig. 2. The source is a He–Ne 10 mW laser. An objective allows the light injection in the first mono-mode piece of fiber. The multi-mode fiber is set in such a way that the cleaved extremity be as closed as possible to the extremity of the first fiber. The two faces must be as flat and clean as possible which implies that the cleaning procedure must be carried out very carefully. An index matching liquid can be used to reduce parasitic reflections and to cancel the possible cleavage defects.

The mono-mode fiber length is about 1 m. It is equipped with a polarization controller allowing the choice of the direction of the linearly polarized field. The multi-mode fiber is shorter (less than 1 m). It is mounted on an optical bench and, by means of precision actuators it can be shifted and tilted versus the mono-mode fiber position at will. The proposed setup allows the positioning and the setting of the two fibers in a simple, precise and reproducible manner. By using a binocular, the two-fiber alignment can be better than 5 min arc.

When the two fiber axis are superposed only the fundamental mode can be visualized. When the two fibers are shifted in the direction of the

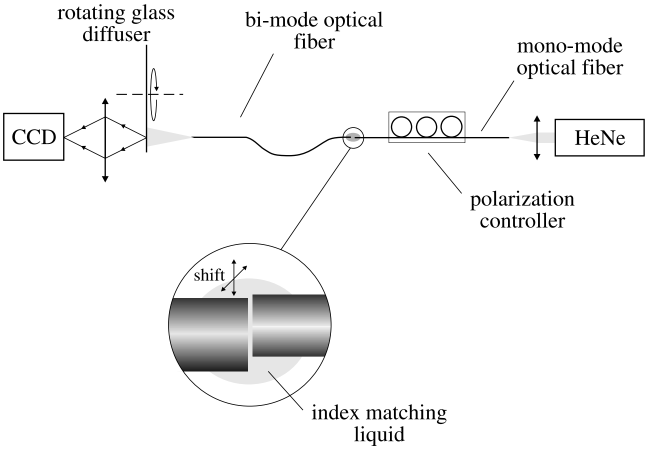

Fig. 2. Experimental setup. By performing the proper light injection in the bi-mode fiber (shorter than 1 m) by means of the mono-mode fiber (length of 1 m), either radially, azimuthally or hybrid polarization beam can be created at the output of the system.

incident beam, the TM_{01} mode is selected. When the shifting is performed along the perpendicular direction, the TE_{01} mode is selected instead. Although the rotation of the incident field direction would not affect the filtering behavior of the system, because of symmetry, we have observed in our case that the HE_{21} mode is obtained whatever the shifting between the two fibers, by rotating the polarization of the incident beam or the holder of the second fiber of 90°. The residual dissymmetry is probably due to a <5 min arc residual tilt or some birefringence effects due to the fiber clipping on the translation stage. The maximum value for the shift is about 7 μm. The precise setting can be achieved in a few minutes only.

Two types of multi-mode fibers characterized by cutoff wavelengths (for the fundamental mode) of 820 and 980 nm have been used. In the two cases, the characteristics of the fibers are far from the cutoff parameters of the annular modes. Moreover, the possible effect of the fiber length has been considered (50 and 100 cm). Whatever the chosen configuration for the multi-mode fiber, the results are similar.

From several experiments in various conditions we can assert that the modal selection is strictly due to the injection of light in the multi-mode fiber. According to its cutoff characteristics, the multi-mode fiber (which must be free from mechanical stresses) generate the expected mode from the field distribution on its entrance face. Because of short fiber lengths, some more complex effects described for instance by coupled mode theory can be neglected.

3. Results

The field intensity distribution of the radially polarized beam in the multi-mode fiber exit plane is shown in Fig. 3. To comfortably observe the field behavior, the out-coming light beam is projected onto a rotating glass diffuser, in order to break down the light speckle. Pictures have been recorded by means of a CCD camera. The field distributions shown in Fig. 4 have been recorded

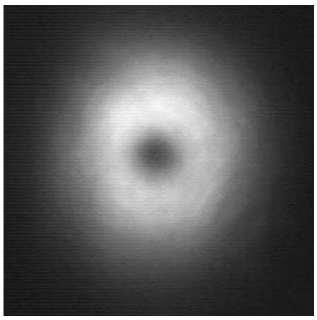

Fig. 3. Annular radially polarized TM_{01} mode.

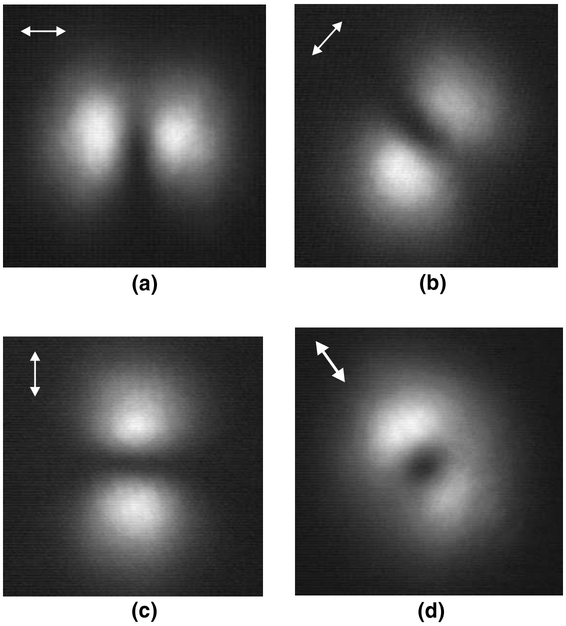

Fig. 4. Intensity distributions after crossing a polarizer whose axis is oriented along the arrows. (d) The two-lobe structure is spoiled by residual annular shaped light due to the partial cancellation of the fundamental mode in the bi-mode fiber.

by setting a polarizer between the fiber and the diffuser. The polarizer directions are indicated by arrows on the pictures.

In order to estimate the energy coupling between the two fibers, we have calculated the overlap integrals between the single mode of a mono-mode planar waveguide (at $\lambda = 632.8$ nm) and the two modes of a bi-mode planar waveguide transversally shifted relatively to the first one. For a 4 μm shift, 16.3% of the incident energy is present in the higher mode whereas only 4.4% is transferred in the fundamental one. It appears that such a filtering process is not optimal since the cancellation of the fundamental mode is only partial. Experimentally, the fundamental mode residue can only be detected on the polarization purity. When the polarizer is oriented in the polarization direction of the incident beam, the spurious effect is significant (see Fig. 4(d)).

However, by increasing the mismatch between the two fibers (by simply increasing the shift) the fundamental mode can be greatly reduced ensuring a better polarization purity. Unfortunately, purity is accompanied by energy efficiency losses which can increase dramatically. As an example, the efficiency measured in the case of Fig. 3 is about 1% (few percents is, however, realistic). In the case of HE_{21} mode, a high purity can be achieved with about 10% efficiency. Note that weak efficiency is largely compensated by the simplicity and the stability of the device and that the use of pulsed laser sources can make it suitable for imaging applications.

4. Conclusion

We have shown that a linear polarized light beam can be easily converted into three quasi-perfectly rotationally polarized light beams by means of a very simple all-fiber device. Such a device is easy to realize and remarkably stable. However, two drawbacks have been pointed out: first, the residual fundamental mode spoils more or less the emerging field, second, the available intensity in the output of the multi-mode fiber is weak (often less than 1%). Therefore, a compromise has to be found between polarization purity and energy efficiency; it will depend on the type of application. As already mentioned, in applications where power is not compulsory, the method is very valuable. When high intensities are necessary, the use of a pulsed laser is a good solution. The non-linear effects induced in that case (self-phase modulation, white light continuum generation) are negligible for the short pieces of fiber used. Few solutions can be found to increase the efficiency of our setup. It has been noted first that in addition to the mismatch between the fibers, a slight twist of the end part of the multi-mode fiber permit the system rising more than 5% in efficiency for the TM_{01} mode selection. The fabrication of discontinuous phase elements onto the faces of the fibers, by focusing ion beam (FIB) etching for example, could also be a good alternative to improve the efficiency despite the complexity of the micromachinery. Finally, it seems to be the first time to our knowledge that a beam with hybrid polarization is created in a so simple way. Its particular polarization properties could be valuable in various imaging systems.

References

[1] T. Grosjean, D. Courjon, J. Microsc. 202 (2000) 273.
[2] D. Barchiesi, D. Van Labeke, in: D.W. Pohl, D. Courjon (Eds.), Near Field Optics, NATO ASI Series, Arc et Senans, France, vol. 242, Kluwer Academic Publishers, Dordrecht, 1993, p. 179.
[3] J.C. Weber, E. Bourillot, A. Dereux, J.P. Goudonnet, Y. Chen, C. Girard, Phys. Rev. Lett. 77 (27) (1996) 5332.
[4] O.J.F. Martin, C. Girard, Appl. Phys. Lett. 70 (6) (1997) 705.
[5] S.M. Mansfield, G.S. Kino, Appl. Phys. Lett. 57 (24) (1990) 2615.
[6] S. Quabis, R. Dorn, M. Eberler, O. Glöckl, G. Leuchs, Opt. Commun. 179 (2000) 1.
[7] S.C. Tidwell, D.H. Ford, W.D. Kimura, Appl. Opt. 29 (15) (1990) 2234.
[8] S.C. Tidwell, G.H. Kim, W.D. Kimura, Appl. Opt. 32 (27) (1993) 5222.
[9] E.G. Churin, J. Hosfeld, T. Tschudi, Opt. Commun. 99 (1,2) (1993) 13.
[10] M. Stalder, M. Schadt, Opt. Lett. 21 (23) (1996) 1948.
[11] J. Ammon, S. Quabis, G. Leuchs, Generation of a radially polarized doughnut-mode, Technical report, Lehrstuhl für Optik, 1996.
[12] Y. Mushiake, K. Matsumura, N. Nakajima, Proc. IEEE 60 (1972) 1107.
[13] D. Pohl, Appl. Phys. Lett. 20 (7) (1972) 266.
[14] J.J. Wynne, IEEE J. Quantum Electron. 10 (2) (1974) 125.
[15] M.E. Marhic, E. Garmire, Appl. Phys. Lett. 38 (10) (1981) 743.
[16] A.V. Nesterov, V.G. Niziev, V.P. Yakunin, J. Phys. D: Appl. Phys. 32 (1999) 2871.
[17] R. Oron, S. Blit, N. Davidson, A.A. Friesem, Z. Bomzon, E. Hasman, Appl. Phys. Lett. 77 (21) (2000) 3322.
[18] E. Snitzer, J. Opt. Soc. Am. 51 (5) (1961) 491.
[19] E. Snitzer, H. Osterberg, J. Opt. Soc. Am. 51 (5) (1961) 499.