GENERATION OF OAM AND COMPARATIVE ANALYSIS OF GENERATION METHODS RELATED TO POLARIZATION DEPENDENCY

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ABSTRACT

Optical fibers can carry various modal forms, including vector modes, linear polarization (LP) modes, orbital angular momentum (OAM) modes, and so on. We have investigated the structure of OAMs in optical fiber. We have simulated OAM modes, made a comparative analysis followed by a rigorous critique of the methods of shaping the orbital angular momentum beams related to polarization dependency. This analysis and criticism were made for the techniques using optical solids (cylindrical lenses, spiral phase plate, ...) and those generating the OAM in a fiber or fiber grating in helical form. The results showed that our method used to simulate OAM and those used for shaping in optical solids are considerably limited by polarization and hence applications of OAMs. On the other hand, the methods using a fiber or fiber grating in helical form leave a wide range of maneuver related to the polarization thus a greater application.

Keywords: *OAM modes, optical solids, polarization dependency.*

1. INTRODUCTION

Since the light beam is an electromagnetic wave with a corpuscular and wave character [1], it has inherent properties such as its wavelength, phase, polarization, and moment (angular orbital momentum, linear momentum, angular momentum of spin ...). In the last centuries, it has been noticed that a circularly polarized beam of light carries an angular momentum of spin (SAM) estimated at $\pm\hbar$ by photon [2]. In 1992, Allen et al. have discovered by their work that a spiral-phase vortex beam evolving with an azimuth phase dependency in $exp(jl\varphi)$, carries the orbital angular momentum (OAM) [3] of $\pm l\hbar$ per photon. In the expression $exp(jl\varphi)$, l is an integer called topological charge and corresponding to the number of rotations of the phase per wavelength, and φ the azimuth angle.

The OAM beams with its interesting properties are useful in the fields of free space optical communications [4], fiber optic communication systems [5] …etc.

Based on a proposed generation method and on the results of some OAM shaping research, we noted a particular feature related to polarization passing from generation through optical solids (cylindrical lenses, spiral phase plate, ...) to generation in an optical fiber or helical fiber grating. We believe that our study of the state of polarization before and after OAM beam shaping in this article provides a clear perspective on the dependency of polarization that would limit OAM-related applications in micromanipulations, telecommunication, and many other areas.

2. OAM BEAMS IN AN ADAPTED FIBER

Having a helical phase front, the Poynting vector, which indicates the direction of the energy flow, has an azimuthal component producing an angular orbital moment parallel to the axis of the beam [6], these beams have a phase singularity or an "optical vortex" (ie a zero in the center), as shown in Figure 1.b.

Although high order Bessel beams [7] and Mathieu beams [8] have been implemented, the most commonly used orbital angular momentum beams are Laguerre-Gauss beams (LG_{pl}), with p the radial order and l the azimuth order. Also as lasers naturally emit a cylindrical LG_{pl} mode [9], the most common way to obtain this type of beam is to modify a Gaussian beam, whose profile is detailed and illustrated in Figure 1 (a).

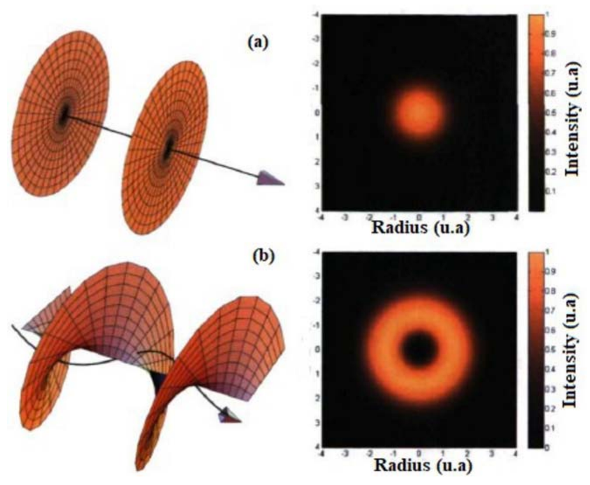

Figure 1: *(a) Representation of the phase front and transverse intensity distribution for a Gaussian beam. (b) Representation of the phase and the transverse intensity distribution for a beam with angular momentum l = 1.*

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Vector modes are the true eigen modes of optical fibers. The eigen modes "even" and "odd" being out of phase by $\pi/2$ can be combined into OAM modes. And similarly two OAM modes with the same signs of SAM and OAM recombine in vector modes HE, while those of opposite signs in vector modes EH [10].

The four degeneracies in the fiber are shown in (Figure2) with the directions of the spin and the topological charge. We can summarize the relationship between the OAM vector modes by the relations (a), (b).

$$OAM^{\pm}_{\pm l,m} = HE^{even}_{l+1,m} \pm jHE^{odd}_{l+1,m} \qquad (a)$$

$$OAM^{\mp}_{\pm l,m} = EH^{even}_{l-1,m} \pm jEH^{odd}_{l-1,m} \qquad (b)$$

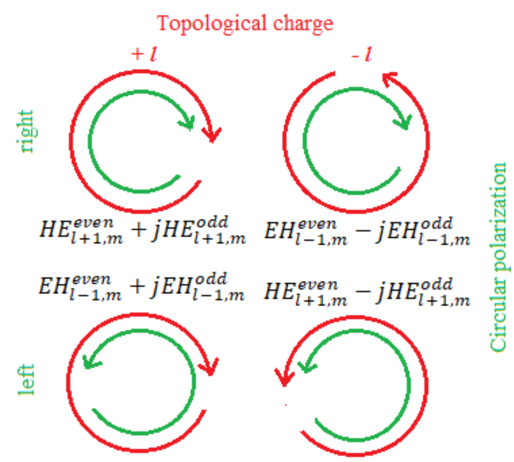

Figure 2: *The mode degeneracies.*

In theory, we could also have the OAM modes made from TM_{0m}, and TE_{0m} like this :

$$OAM^{\mp}_{\pm 1,m} = TE_{0,m} \pm jTM_{0,m} \qquad (c)$$

However, this mode is not stable and cannot propagate, because the propagation constants β of the modes $TM_{0,m}$ and $TE_{0,m}$ are different. So, this is called an unstable vortex [11].

3. SIMULATION AND OAM SHAPING TECHNIQUES

Various OAM beamforming techniques have been the subject of several research projects in this quarter of a century. In this part of this article, we have divided these different searches into two groups. For the shaping of the OAM beams, a first group prefers to generate through optical solids (spiral phase plate, cylindrical lenses ...), and a second group generates inside a fiber or helical fiber grating.

Belonging to the first group, we propose in this paper a beam generation technique carrying OAM. We used a CW laser (Continuous Wave laser) producing a coherent wave at 1550nm at the input a LTMG and the output connected to a Spacial Visualizer (see Figure 3 (a)). As shown in Figure 3 (b), we were able to generate the modes LG_{01} ; LG_{02} ; LG_{11} and LG_{12} all carrying topological charge l.

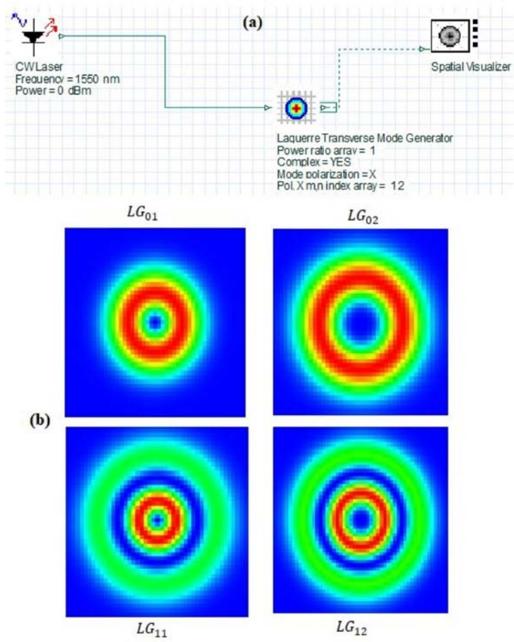

Figure 3: *(a) LG mode generation circuit. (b) result of formatting LG_{01}, LG_{02}, LG_{11}, LG_{12} modes through the laguerre transverse mode generator (LTMG).*

Among the large number of existing formatting methods, we have generation by spatial light modulators (SLM). Based on computer-controlled holographic patterns [12], SLMs can be tuned to excite OAMs by rearranging liquid crystal display (LCD) molecules.

Belonging to the second group, a team generates OAMs by using a twisted photonic crystal fiber with the beam of light forced to follow a spiral path [13]. The left and right asymmetric chiral fiber grating (RCFG, LCFG) enabled the shaping of the OAM modes [14]. Based on the principle of coupling helical gratings (HG), superposed helical gratings (SHG) have enabled the conversion of fundamental modes into vector modes under different configurations of SHGs [15].

4. COMPARATIVE AND CRITICAL ANALYSIS

The LTMG in Figure 3 (a) is a component that attaches Laguerre-Gaussian (LG) transverse mode profiles to the input signal. It also converts single-mode signals into multimode signals. The LTMG attaches mode profiles to the input signal X and Y polarizations. A LG profile is attached to each polarization. As results for this simulation, an error message announcing an unsuitable input signal is displayed when we choose in the LTMG a polarized input signal Y. We obtain the LG modes when we parameterize the input signal on the X polarization. Then we draw from this experience that our method of shaping an OAM beam rigorously depends on the polarization of the input signal and this remains a handicap for OAM applications.

The results provided by the experiment of the reference [16] clearly show us that in order not to touch the polarization, it is necessary in this method that the molecules have the same direction as the orientation of the electric field. So the OAM shaping by the SLMs is rigorously related to the polarization and orientation of the LCD molecules.

Then of the two methods of generation of OAM, one faces practically the same problems of polarization causing the same consequences on the applications of OAM.

Always with the aim of generating OAM mode, the researchers had the ingenious idea to use fibers made in helical form as in the references [13, 14, 15, ...]. As for the previous case we have investigated the polarization situation of the input light beam, and to judge the stability that it can provide for the various applications mentioned above.

The CFG (Chiral Fiber Grating) manufactured at reference [14] shows in its experimental results a coupling efficiency of more than 99%. With the devices installed before the CFG (see Figure 3 ref [14]) to create all kinds of polarizations at the input of the latter, the helical phase at the output can be preserved. At the end of this experiment, no coupling was observed between the OAM modes of order -1 and +1, which allowed them to suggest that the vortex formed is solely determined by the helicity of the CFG. In addition, the polarization state of these excited OAM modes was the same as that of the input light.

Using superposed helical grating (SHG) denoted by $[-1,\Lambda)+\exp(i\Delta\varphi).[+1,\Lambda)$ with opposite helix orientations [15], the researchers were able to mathematically convert (see equations (35, 36, 37, 38, 40, 41)) and experimentally the fundamental modes HE_{11} and LP_{01} in vector modes HE_{21}^{even}, $CL_{11}^{even,+1}$, $CL_{11}^{odd,+1}$, TM_{01}, TE_{01}, $LP_{01}^{even,y}$, $LP_{01}^{odd,x,y}$ …etc.

Equations allowing the conversion of the fundamental modes, whatever the polarization of the fundamental mode of entry, there exists a conversion in vector mode according to the setting of the SHG. Unlike the technology using optical solids to analyze and criticize above, the latter proves in its experimental results that the polarization of the fundamental mode does not prevent a conversion to vector modes while knowing how to adjust the parameters of the SHG. So this these last two methods can offer a wide range of application of OAM compared to that using optical solids.

5. CONCLUSION

In this article, we give a rigorous comparative analysis of the methods of generation of orbital angular momentum beams, and we have shed light on how the polarization of a light beam can become limiting to the applications of OAM. And finally, following an objective discussion from our comparisons, we focused on the method of OAM generation using helical fibers as the most adequate method creating enough freedom on OAM applications.

6. ACKNOWLEDGMENTS

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