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Generation of Spiral Interference Fringes with Few Mode Optical Fibers

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Abstract

We demonstrate a method to generate spiral interference fringes with a few-mode optical fiber. These are generated from the interference of donut shaped vector vortex modes of few mode fiber with a Gaussian plane wave. These spiral fringes are the consequence of helical wave fronts of the donut shaped vector vortex modes, originating from the skew ray propagation of electromagnetic radiation within the fiber core.

Keywords: *Spiral fringes; helical wave fronts; few mode fiber.*

I. INTRODUCTION

It has been experimentally verified that light carries orbital angular momentum (OAM) alongside spin angular momentum (SAM) where in the SAM is attributed to the polarization of light and OAM to the wave front. The OAM is the cause for light beams to have helical wave fronts where each point at any cross section of the beam is at different phase. When joined, the points with same phase, forming a phase front of the beam, it looks as a helix. These optical helices are also referred as optical vortices, often found in Laguerre- Gaussian (LG) laser modes which are the solutions for paraxial wave equation in cylindrical coordinate system. The LG modes is one such laser mode with annular intensity cross section, carries OAM and hence helical wave front. These beams will have optical null region at the center as a result of their helical wave fronts. The modes carrying OAM are finding applications in optical tweezers for holding micro particles of size few microns. This has drawn the interest of research community towards the generation and manipulation of such light fields with non-uniform spatial polarization with helical wave fronts. This field is growing very fast and attracting the attention due to the unique properties of such beams which are finding applications in laser machining, lithography and also in various biomedical fields. Methods of generating these fields majorly classified as active and passive. Active method can also be referred as an intra-cavity method, as dichroic mirrors and q-plates are inserted into the laser cavity to produce required spatial optical field, where as in passive methods, the fundamental laser output is modified using optical elements like spiral phase plates (SPP), diffractive optical elements, computer generated holograms (CGH) and optical fibers etc., to generate annular shaped beams, also in general known as cylindrical vector beams (CVB). Another method of generating such beams is nanophotonic based, which is fast

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developing and can replace bulk optical materials such as lenses and wave plates. By tailoring the geometry of plasmonic nanostructured arrays or metasurfaces, one can modify the phase accumulated by light when it propagates through such structures and can generate beams with OAM.

On comparison with all aforementioned methods to generate CVBs, fiber based generation of such beams is an easy and cost-effective method where in the true waveguide modes of optical fiber are excited with an offset launching of linearly polarized Gaussian beam. The CVBs of optical fiber i.e., radially polarized TM_{01}, azimuthally polarized TE_{01} and hybridly polarized $HE_{21}^{o,e}$are seemingly similar in intensity cross section but vary in their spatial polarization. All these beams possess an optical null region at the center which is a significance of phase singularity and hence can form spiral fringes when interfered with reference Gaussian beam used to excite them. Here, we present a fiber based method to generate spiral fringes by exciting the CVBs in optical fiber and forming interferograms with reference beam.

II. EXPERIMENTAL DETAILS

An unpolarized Gaussian beam from a 5mW He-Ne laser is first polarized by passing through a vertical polarizer, which then passes through a half-wave plate (HWP) to change the orientation of state of polarization (SOP). Light emerging from the HWP is focused on to cleaved end ofa few-mode optical fiber of length 24.6 cm held using a 3-axis micro translational stage that enables the offset light launching with respect to axis of fiber. The optical fiber has core radius 1.8 m and 0.2 NA which when operated at a 632.8 nm wavelength, the V parameter calculated to be 3.57. This indicate the fiber can support a total of six wave-guide modes i.e., two-fold degenerate fundamental LP_{01} and four-fold degenerate first order LP_{11}. Output of the fiber is then collimated on to a charge coupled device (CCD) camera to scan tip of the fiber and image the spatial pattern of the beam. An analyzer can be inserted in front of CCD to examine the polarization content of the beam. An interferometer is constructed using two beam splitters (BS1 & BS2) and two mirrors (M1 & M2) in parallel with optical fiber, to guide the reference Gaussian beam in free space. The CVB generated in optical fiber and the reference Gaussian beam are interfered coaxially to form spiral fringes. The experimental setup is shown in Fig.1.

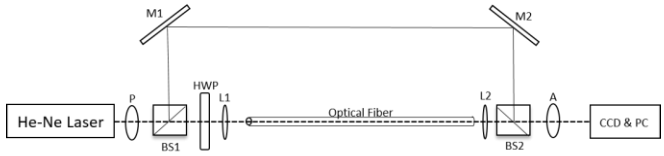

Fig.1 Experimental setup. P: polarizer, BS1 and BS2: Beam splitters, HWP: Half-Wave Plate, L1 and L2: Lens, M1 and M2: Mirrors, A: Analyzer, CCD: Charge coupled device, PC: Personal computer.

III. GENERATION OF VECTOR MODES

As discussed in the previous chapter, LP_{11} modes are four-fold degenerate and their selective combinations will result in vector modes. These vector modes can be generated by precisely controlling the coupling conditions of fiber with respect to incident light. Various modes can be excited by launching tilted and/or offset Gaussian beam into the optical fiber. By launching skew and offset rays into the fiber core, one can realize four possible vector modes i.e., TE_{01}, TM_{01} and $HE_{21}^{o,e}$ at the fiber output.

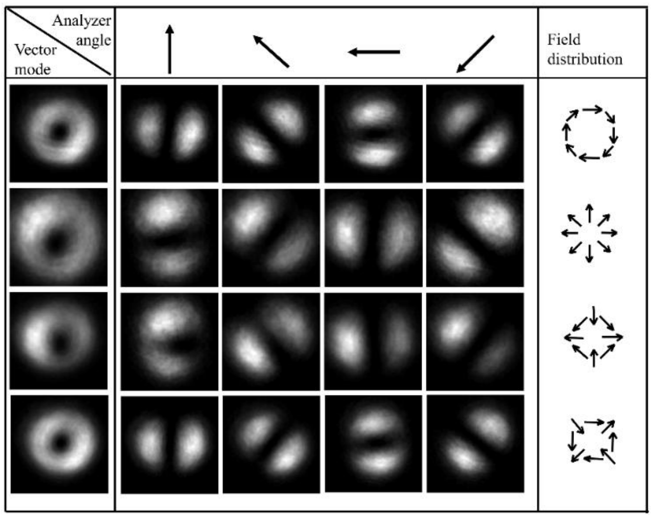

Fig. 2 Cylindrical vector beams excited for different coupling conditions

Figure 2 shows the experimentally generated vector modes and their behavior when passed through a rotating analyzer. As all the vector modes look alike in their intensity distribution, an analyzer is essential to distinguish them. By observing the rotation of two lobe pattern with respect to rotation of analyzer, the field distribution across the mode can be estimated. Though these vector modes have null intensity at the core region, due to the polarization inhomogeneity across the mode, the phase cannot be defined. But, the donut modes with homogenous polarization and dark core region have a phase vortex at their center and are often referred to as scalar vortex modes or simply vortex modes. These modes are equivalent to LG modes of radial order zero and azimuthal order one (LG_0^1). In fibers, these modes can be generated as linear combinations of vector modes i.e., TE_{01}±i(TM_{01}) or HE_{21}^{o}±i(HE_{21}^{e}).

IV. EXCITATION OF CVB AND FORMING SPIRAL FRINGES

Initially, the fiber tip is adjusted with an offset using the micro translational stage and a tilted Gaussian beam is launched with respect to axis of fiber. At a particular launching condition, intensity pattern in a ring shape is captured with CCD. The pattern is examined under rotating analyzer to know the polarization content of the generated beam. A null line separating the beam into two lobes is observed in the output when the beam passed through the analyzer. The null line is observed to be oriented at an angle 45^0 with analyzer axis in clockwise direction and rotating in same sense as that of analyzer axis which is significance of hybrid polarization due to in-phase combination of azimuthally polarized TE_{01} and radially polarized TM_{01} modes. The hybrid CVB and its spatial profile under rotating analyzer is shown in Fig. 3.

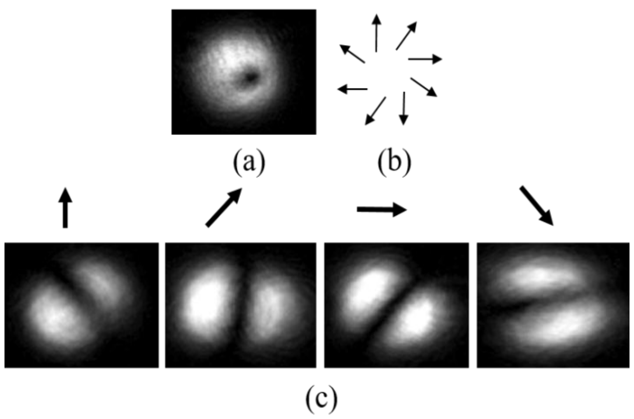

Fig.3 (a) hybrid CVB (b) field distribution (c) spatial patterns under rotating analyzer

The launching conditions were kept unaltered and the hybrid CVB is then used to generate spiral fringes. The reference Gaussian beam is directed towards the beam splitter placed after fiber output and adjusted for coaxial interference resulting in the formation of spiral fringes and it is observed to be a right-handed spiral. The hybrid CVB and its corresponding right-handed spiral fringes is shown in Fig. 4.

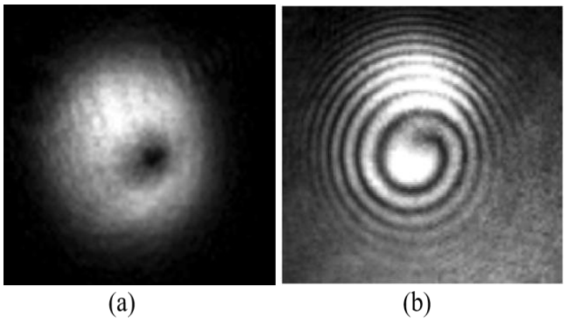

Fig.4 (a) Hybrid CVB (b) Right handed Spiral

V. CONCLUSION

In summary, we have successfully generated all the four zeroth order vector modes using a few mode optical fiber by controlling input state of polarization and coupling conditions. The hybrid CVB due to in-phase combination of TE_{01} and TM_{01} is selectively excited in the optical fiber and the formation of optical spiral or optical helix confirms the helical nature of the wave front generated from fiber. As the spiral is right handed and with single helicity, the topological charge of the generated CVB is +1. In addition to hybrid CVB, other CVBs generated in optical fiber can also form optical helices when interfered with plane wave front.

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