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Abstract: An analytical study of higher-order modes in step-index fibers has been conducted with the aim of justifying the circular asymmetry experimentally observed in the intensity of higher-order Bessel-like modes.

1. Introduction

Fiber Bessel-like modes are attracting increasing interest due to their many applications, such as amplification [1], four-wave mixing [2], and soliton self-frequency shift [3]. In a previous work [4], the excitation of higher-order Bessel-like modes in a large-core fiber has been studied, highlighting the presence of an unexpected azimuthal asymmetry in the mode intensity. This phenomenon, denoted *bowtie effect*, has been ascribed to the different boundary conditions experienced by the electric field azimuthal and radial components at the core/cladding interface [4]. Nevertheless, the nature of this shape "defect," also observed in [5], has not been completely defined. Imperfections in experiments have been excluded from its possible causes by showing that also numerical results present a bowtie shape. In this work, a mathematical understanding of the bowtie effect and its connection to the experimental results are provided.

2. Background

When solving Maxwell's equations for an ideal step-index fiber in cylindrical coordinates (r, ϕ, z), it is common to find the full-vectorial solution by first writing the electric field $\mathbf{E} = (E_r, E_\phi, E_z)$ and magnetic field $\mathbf{H} = (H_r, H_\phi, H_z)$ as functions of the longitudinal components E_z and H_z, and then use separation of variables to describe these components and obtain the characteristic equation [6]. In particular, assuming that $\Psi = \Psi(r, \phi, z, t)$ represents either E_z or H_z, for a given mode it is possible to write $\Psi = R_\nu(r)\Phi(\nu\phi)\exp[i(\omega t - \beta z)]$, where $R_\nu(r)$ is the Bessel function J_ν, inside the core, and the modified Bessel function K_ν, in the cladding ($\nu \in \mathbb{Z}$ being the function order), ω is the angular frequency of the electromagnetic wave, and β is the mode propagation constant. Due to geometrical reasons, the function $\Phi(\nu\phi)$ has to meet the periodicity condition in $[0, 2\pi]$. As basis function, either $\cos(\nu\phi)$ or $e^{i\nu\phi}$ can be chosen. An arbitrary initial phase is omitted for simplicity and without losing generality.

Although sinusoidal or complex exponential functions are mathematically equivalent, the two options yield two different sets of hybrid modes, here denoted cosine-choice modes (CCMs) and exponential-choice modes (ECMs), respectively. For instance, in ECMs, a change in ϕ corresponds to a mere phase change in the whole field. In other words, ECMs are invariant (to within a phase factor) under rotation about the z-axis, and hence they all have perfectly circular intensity. Furthermore, the orthogonal field of such modes is always circularly polarized and opposite values of ν imply opposite rotation directions. Two identical, but counterrotating, ECMs can be added together to obtain a CCM. CCMs are always locally linearly polarized (i.e. the resulting orthogonal electric field oscillates without changing direction, although this direction is not the same everywhere) and for them the circular symmetry is not an intrinsic property. It is important to highlight that CCMs should not be confused with the conventional linearly polarized (LP) modes, for which, instead, the polarization direction is the same over the entire fiber cross section.

3. The bowtie effect

When $|\nu| = 1$, the asymmetry of $HE_{\nu,X}$ CCMs manifests itself as a bowtie-shaped intensity. Not even the $HE_{1,1}$ CCM is perfectly circular, although its angular variation is very small and difficult to perceive. The bowtie effect is more evident when X is sufficiently large. Here, as an example, an ideal fiber with normalized frequency of about 45.9 is considered. The corresponding $HE_{1,15}$ ECM and CCM are depicted in Figs. 1a and 1b, respectively. In these polar representations, the orientation of ϕ is counterclockwise and its origin is the right half of the horizontal axis (not
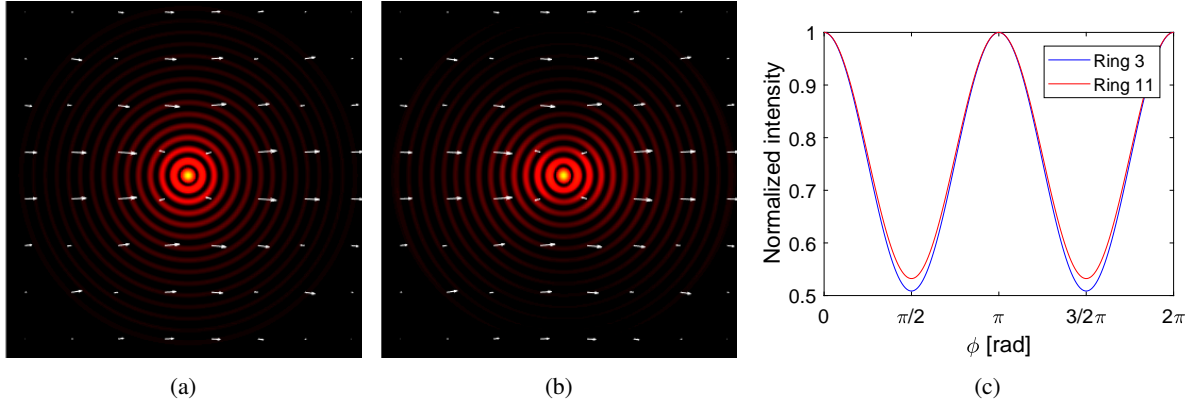
Fig. 1: Bowtie effect on $HE_{1,15}$. (a) ECM and (b) CCM representations of intensity and transverse electric field vectors. (c) Intensity variation of the CCM along the crest of the 3rd and the 11th rings.

shown) passing through the center of the mode. The field vectors represent the real part of the transverse electric field, plotted for $\omega t - \beta z = 0$ and identical in the two figures. However, as t or z evolves, the ECM field rotates as a whole, and hence its time-averaged intensity must be circular. The CCM, instead, maintains its orientation. Figure 1c represents the $HE_{1,15}$ CCM intensity against ϕ along two arbitrarily chosen rings, the 3rd and the 11th (counted starting from the innermost one), normalized with respect to their maximum. In Figs. 1a and 1b, it is clear that the horizontal component of the electric field is predominant, although the arrows are not perfectly aligned. This explains why, experimentally, the bowtie effect is achievable, as confirmed in [4]. In fact, when exciting a $HE_{1,X}$ mode with a linearly polarized source, only the component of the mode along the polarization direction of the input is excited, obtaining a field very close to that of a CCM. Consequently, the azimuthal asymmetry takes place and, in order to recover the circular shape of the "full" mode, a circularly polarized input is needed.

4. Conclusion

Higher-order modes do not have azimuthal symmetry if a sinusoidal function is chosen as basis for the angular dependence of the longitudinal field component. In $HE_{1,X}$ modes, this choice leads to an almost linear polarization, enabling the asymmetry to be reproduced also experimentally by exciting such modes with a linearly polarized input.

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