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Research Article

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Modeling of Fiber for Orbital Angular Momentum Modes Propagation

Mariano C. Mahissi*, Michel Dossou, Kokou M. Assogba, Antoine Vianou

Computer Science and Information Technology Department, Polytechnic of Abomey-Calavi, University of Abomey-Calavi, Benin

Abstract The use of OAM (Orbital Angular Momentum) states of light for multiplexing the channels in communication systems has become of great interest, both for free space telecommunications, and those using fiber optics. The ever-increasing need for digital data transfer is driving the development of new technologies to increase network capacity, especially with regard to fiber optic networks. The present study made it possible to model an ACF fiber (Air-Core Fiber) accepting OAM modes with the aim of transmitting information on these modes. This consists of considerably increasing the number of channels and therefore increasing the optical transmission capacity. Thus we have proposed an air core ring fiber (ACF) model with the ability to transmit OAM beams.

Keywords OAM, fiber modeling, transmission capacity, ACF

Introduction

The electromagnetic wave (EM) can be decomposed into two distinct parts [1]: the spin angular momentum that corresponds to the polarization of the wave, and the orbital angular momentum (OAM) that is associated with the electric field spatial distribution. Thus, an EM wave carrying OAM is characterized by an azimuthal dependence of its phase denoted $e^{-jl\theta}$ with $l$an integer called topological charge and corresponding to the number of rotations of the phase per wavelength, and $\theta$the azimuth angle. In addition, the phase distribution implies a discontinuity on the axis of the beam, thus creating a vortex.

While the polarization has only two states, at each relative integer l is associated an OAM mode. There is therefore, in theory, an infinite number of modes$l$, all orthogonal to each other and independent of the polarization. This orthogonality is then likely to be exploited as a new diversity for telecommunications, since there are emission systems capable of generating these modes of OAM. The "vortex" fiber allows the transmission of data using the states of angular orbital moment (OAM) of the light [2]. We will first present and simulate light beams with orbital angular momentum, and in a second time model a fiber that accepts orbital angular momentum modes.

Properties of laser beams with angular momentum

The beams with an orbital angular momentum are characterized by an azimuth phase of the type $e^{-jl\theta}$ where l is a non-zero integer corresponding to the topological charge and$\theta$is the azimuthal angle [3-4]. Indeed, having a helical phase front, the Poynting vector, which indicates the direction of the energy flow, has an azimuth component producing an orbital angular momentum parallel to the axis of the beam [5]. This family of beams is said to possess a phase singularity or an "optical vortex" (i.e. a zero in the fiber core center).

Characterization of an OAM fiber and the geometry of the targeted ACF

The number of modes in the optical fibers takes into account all degenerations. The number of channels carrying the information is the current number of states used to carry the information. So far, OAM fibers support a limited number of channels. For example, the original vortex fiber [6] supports four information channels. IPGIF (inverse parabolic index gradient fiber) supports one more OAM mode and eight information channels [7]. And the air-core fiber (hollow core fiber) of Gregg et al. [8] is multimode, but supports only twelve information channels.

The purpose of this work is to model an OAM fiber that supports a larger number of channels. We also want to use as many information channel states as possible, that is, all OAM modes should be usable as information channels. It has already been demonstrated that, to support OAM modes, the fiber must present:

- good effective index separation between vector modes (the true eigenmodes of the fiber), to minimize modal coupling and avoid degeneracy into LP modes;
- a fiber profile that matches the doughnut shaped OAM fields [9].

To obtain good mode separation, we must have a high contrast in refractive indices of the fiber materials; in this way we violate the weakly guiding approximation under which LP modes are formulated. In particular, there must be great separation between the effective indices of $HE_{(l+1,m)}$ and $EH_{(l-1,m)}$modes, otherwise those modes would couple into $LP_{(l,m)}$modes, and we may lose the OAM states during propagation. Design of polarization-maintaining fibers suggests that an effective index separation on the order of 10^{-4}between the modes in a group will preclude LP mode formation [9]. This is an order of magnitude greater separation than typically found in conventional fibers. However, this number should be seen as a rule ofthumb; this is not a hard limit. In [10], they transmitted OAM modes over a 2m fiber with an effective index separation around $0.6 * 10^{-4}$.

Table 1: Index constraints for air-core annular fiber

Layer	Material	Refractive index	Molar concentration
I	Air	1	-
II	$SiO_2 + GeO_2$	1.444 – 1.474	Up to 20%
III	$SiO_2 + P_2O_5 + F$	1.437 – 1.444	Up to1.5%
IV	SiO_2	1.44	-

The contrast of the refractive index is limited by the constraints of the material and the manufacturing process. To achieve maximum contrast, a hollow air core was suggested [11], since the air has an index of about 1, which is far from that of the doped silica. In this modeling, the modes are crossed inside the doped ring core, not inside the core in air. This is different from PCF (Photonic crystal fiber) fibers, which are also called air-core fiber, where light passes through the air, guided by a photonic bandgap [12].

The fiber modeled in [10] supports a large number of vector modes, but only a few of them are quite separate (in terms of effective index) to be able to transmit OAM modes. Thus only three OAM modes, supporting twelve channels carrying the information, can actually be used. On the other hand, we want to model a fiber that supports fewer vector modes, but where all these vector modes can be used as a basis for OAM modes. All modes must have an effective index that lies between the refractive index of the cladding and the maximum refractive index of the fiber core. A fiber with fewer vector modes allows them to be more separated (in terms of effective index), as the possible effective index space is exploited by all supported modes. This is accomplished by carefully adjusting the width of the doped region in the fiber to limit the total number of supported vector modes. We include an outer layer of materials with a refractive index lower than that of the sheath, a trench, in order to increase the contrast of the refractive indices, and to limit the number of higher order modes.

Figure 1 shows the targeted design. We call this design air-core annular fiber (ACF), as the center of the fiber is air, but the fiber really is an annular (or ring-core) fiber, since this is the second layer that is guiding the modes. In this design, $n_1$is the air refractive index, and n_4 is the silica refractive index. $n_2, n_3, r_1, r_2$and $r_3$are parameters to be determined. We target a fiber with 125 µm cladding diameter, for compatibility with standard fiber connectors. The indices for n_2, and n_3 are limited by the constraints of the material. Table 1 gives approximately the possible index intervals at 1550nm, without facing construction problems.

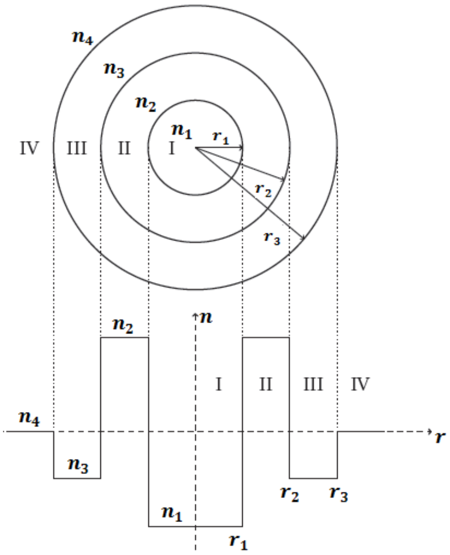

Figure 1: Air-core annular fiber geometry

Find the right profile of a fiber is a complex optimization problem. In general, a high index contrast will allow a high effective index of separation. However, a significant number of modes will decrease the effective separation index, since several modes will be packaged in the same possible effective index range. Therefore, the number of supported modes needs to be controlled by the thickness of the second layer. To achieve our modeling goal, a compromise must be made between the number of modes supported and the effective separation index.

There are many ways to investigate the effective separation index. The simplest optimization is to maximize the minimum separation of effective index. However, for a given fiber, there may be a pair of modes that are closer than the other pair, and that model of fiber would be rejected, even if all other modes are well separated. Another possible optimization would be to maximize the mean of the minimum separation of effective index of each mode. But it is possible that this optimization promotes modeling with some very well separated modes, and other very close modes

Table 2: Parameters of designed air-core annular fiber

	Radius (µm)	$SiO_2 + GeO_2$**Molar concentration(%)**	**Refractive Index (At 1550 nm)**
Layer 1	9.2	-	1.000
Layer 2	11.6	22.5	1.480
Layer 3	15.6	1.1	1.439
Cladding	62.5	-	1.444

The transfer matrix method [13] allows the fast and accurate calculation of the effective index of each mode. While using fixed indices for each layer should be sufficient to compute the effective index of each mode, we use rather the index-dependent wavelength calculated from the Sellmeier equation [14]. This allows us to obtain effective indices as a function of the wavelength, and to estimate other modal parameters, such as group index and dispersion.

The final model is chosen because of the good balance between the number of modes supported and the separation of the effective indices, with a good tolerance to the imperfections introduced in the profile of the index during the manufacturing process.

Table 2 summarizes the chosen parameters. The indices are calculated from the molar concentration. The wavelength used for this model and in the calculations is 1550nm. To achieve the goal we overestimated the second layer $SiO_2 + GeO_2$concentration in the proposed model. This is maintained as the maximum possible concentration.

Figure 3 presents the effective index as a function of the wavelength, on the C band. We observe that 20 vector modes are supported by the proposed fiber at 1550nm. Then, 18 modes can serve as a basis for 10 OAM modes $(l = 0 \text{ à } 9)$.

Table 3 lists the effective indices, in addition to the minimum effective separation index for each supported mode at 1550nm. As we can see, all modes are separated by $1x10^{-4}$ or higher, the closest modes are $TE_{0,1}$ and $HE_{1,1}$. A special feature of this designed fiber is that the mode with the highest effective index is $TE_{0,1}$ and not $HE_{1,1}$.

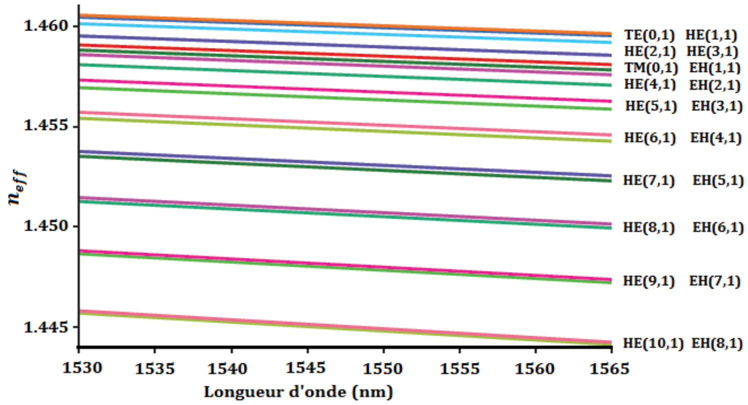

Figure 3: Effective indices as function of wavelength, for designed ACF. Fiber design parameters are given in Table 3.

Table 3: Effective indices and effective index separations, at 1550 nm, for designed ACF

Modes	n_{eff}	Δn_{eff}
$TE_{0,1}$	1.45990	$9.956x10^{-5}$
$HE_{1,1}$	1.45980	$9.956x10^{-5}$
$HE_{2,1}$	1.45947	$3.364x10^{-4}$
$HE_{3,1}$	1.45883	$4.595x10^{-4}$
$TM_{0,1}$	1.45838	$2.633x10^{-4}$
$EH_{1,1}$	1.45811	$2.382x10^{-4}$
$HE_{4,1}$	1.45787	$2.382x10^{-4}$
$EH_{2,1}$	1.45736	$5.139x10^{-4}$
$HE_{5,1}$	1.45657	$3.897x10^{-4}$
$EH_{3,1}$	1.45618	$3.897x10^{-4}$
$HE_{6,1}$	1.45491	$3.078\ x10^{-4}$
$EH_{4,1}$	1.45460	$3.078\ x10^{-4}$
$HE_{7,1}$	1.45289	$2.475\ x10^{-4}$
$EH_{5,1}$	1.45264	$2.475\ x10^{-4}$
$HE_{8,1}$	1.45052	$1.985\ x10^{-4}$
$EH_{6,1}$	1.45032	$1.985\ x10^{-4}$
$HE_{9,1}$	1.44778	$1.549\ x10^{-4}$
$EH_{7,1}$	1.44763	$1.549\ x10^{-4}$
$HE_{10,1}$	1.44469	$1.131\ x10^{-4}$
$EH_{8,1}$	1.44458	$1.131\ x10^{-4}$

Conclusion

In this work, we have designed an ACF fiber (Air-Core Fiber) accepting 10 OAM modes with the aim of being able to transmit information on these modes. We have suggested to increase the second layer molar concentration.

The future work will be focused on the spin orbit coupling between those OAM modes.

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