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Invited Papers

Invited Paper: Optical fibers for the transmission of orbital angular momentum modes

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ABSTRACT

Orbital angular momentum (OAM) of light is a promising means for exploiting the spatial dimension of light to increase the capacity of optical fiber links. We summarize how OAM enables efficient mode multiplexing for optical communications, with emphasis on the design of OAM fibers.

1. Introduction

1.1. The orbital angular momentum of light

Light is an electromagnetic radiation that can carry momentum, just like matter does. There is angular momentum associated with spin, as well as angular momentum associated with the spatial distribution of light. The latter is known as orbital angular momentum (OAM). The high dimensionality of orbital angular momentum gives rise to an interest in the telecommunications industry to exploit this property of light for multiplexing of data signals.

The linear momentum of light is known as radiation pressure [1], and has a value of $k_0\hbar$ per photon, where $k_0 = 2\pi/\lambda$ is the wavenumber, and $\hbar$ is the reduced Plank constant. The angular momentum of light can be related to the spin of the photons, with a value of $\hbar$. It is then known as spin angular momentum (SAM), and it is associated with the circular polarization of the light [2]. The OAM has a value of $\ell\hbar$, where ℓ is an integer known as the topological charge. While SAM is characterized by the rotation of the polarization vectors, OAM is characterized by the rotation of the phase front of the light beam. In other words, it is the beam of light itself that rotates around its propagation axis. The phase of an OAM beam has the form $\exp(j\ell\phi)$, where j is the imaginary unit, ℓ is the topological charge, and ϕ is the azimuthal coordinate. This rotation implies than the light beam with OAM carries no energy (but still has a momentum) in its center, since the phase at this point is undefined. For this reason, OAM beams are often called *vortex beams*. Under the paraxial approximation, SAM and OAM can be considered as uncoupled; i.e., the polarization and the orbital angular momentum of a light beam are independent of each other [3].

1.2. OAM in optical communications

Space division multiplexing (SDM) increases the capacity of optical fiber links [4–6]. The spatial dimension can be exploited to multiply capacity, while keeping the already used time, wavelength, quadrature, and polarization dimensions. SDM can be implemented using multicore fibers, or multimode (few mode) fibers. In multicore fibers, each fiber core carries a different channel, and those separate channels can themselves be multiplexed in wavelength, polarization, and quadrature. Supermodes are formed from coupled multicore fiber. In multimode fibers, the channels are carried by different modes. It is even possible to design fibers with multiple cores carrying multiple modes. With multimode fibers, SDM can be performed using LP (scalar) modes or OAM modes. Fig. 1 summarizes the different ways to implement SDM. Like LP modes, OAM has the potential to be exploited in hybrid multimode, multicore fibers. In this paper we focus on exploitation of OAM modes.

There are many ways of multiplexing modes in optical fibers. LP modes are a good approximation of the modes of weakly guiding fibers, and are relatively easy to generate. Some LP few-mode fibers

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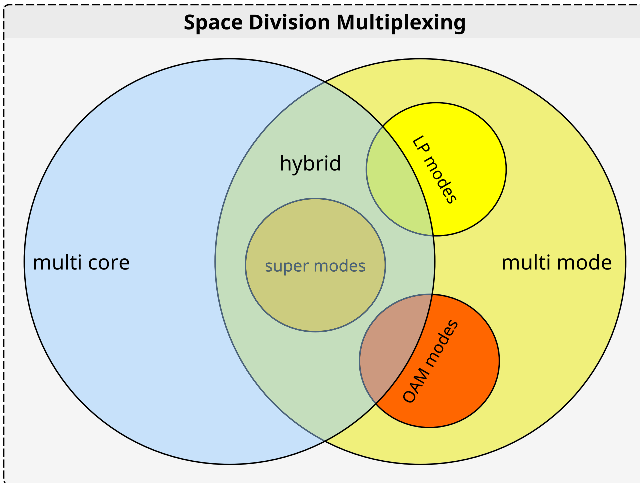

Fig. 1. Different ways of implementing space division multiplexing (SDM).

were designed with high intermodal coupling, to reduce the required length of the digital equalizers, but require heavy multi-input, multi-output (MIMO) processing to be recovered after transmission [7,8]. Non-degenerate LP modes ($LP_{0,1}$ and $LP_{0,2}$) were shown to be recoverable with standard complexity MIMO when using a specialized multiplexer to avoid modal crosstalk; degenerate modes, however, still required higher MIMO complexity [9].

Supermodes are arbitrary sets of modes that are orthogonal to each other. Short fibers supporting supermodes can be exploited in photonic lanterns [10] as multiplexers and demultiplexers (rather than fibers for propagation) with a quasi perfect efficiency. When supermodes are used for transmission, as with LP modes, they require heavy MIMO processing for data recovery. OAM is another modal basis that can be used for SDM [11–13]. OAM modes have distinct propagation constants; therefore, they couple less than LP modes do, lessening the need for MIMO processing. Furthermore, the circular symmetry of OAM modes make their coupling to fibers more efficient, compared to LP modes which have a square symmetry [14]. However, OAM modes require special fibers to allow transmission over long distances.

OAM modes exist both as free-space (laser) modes, and as guided fiber modes. In free-space, they often are modeled as Laguerre–Gaussian (LG) modes, since they have circular symmetry with a vortex in the center. $LG_p\ell$ modes are characterized by two parameters: p is a non-negative integer giving the number of concentric rings minus one ($p = m - 1$), and ℓ is an integer related to the thickness of the rings. In the case of an OAM beam, ℓ is also the topological charge, giving the number of phase fronts.

The interest of using OAM (and SDM in general) in telecommunications is to increase the capacity of the communication links. However, the system cost needs to be lower than the cost of an equivalent system made of parallel single-mode links; otherwise there is no gain. To achieve that goal, the whole transmission system, including transmitters, amplifiers, switches, and receivers, must support the SDM scheme. Many OAM system components are under investigation to develop a complete OAM communication system [15,13].

1.3. OAM modes in optical fibers

OAM modes exist in optical fibers, as they are formed from the fiber's underlying vector mode basis [16]. In cylindrical fibers, the electro-magnetic fields can be separated in radial-dependent and azimuthal-dependent parts:

$$\vec{E}(r,\phi,z,t) = \vec{e}(r)\begin{Bmatrix} f_\nu(\phi) \\ g_\nu(\phi) \\ f_\nu(\phi) \end{Bmatrix}\exp(j\beta z - j\omega t) \tag{1a}$$

$$\vec{H}(r,\phi,z,t) = \vec{h}(r)\begin{Bmatrix} g_\nu(\phi) \\ f_\nu(\phi) \\ g_\nu(\phi) \end{Bmatrix}\exp(j\beta z - j\omega t) \tag{1b}$$

where

$$f_\nu(\phi) = \begin{cases} \cos(\nu\phi) & \text{even modes} \\ \sin(\nu\phi) & \text{odd modes} \end{cases} \tag{2a}$$

$$g_\nu(\phi) = \begin{cases} -\sin(\nu\phi) & \text{even modes} \\ \cos(\nu\phi) & \text{odd modes} \end{cases} \tag{2b}$$

The difference between *even* and *odd* modes is a $\pi/2$ rotation of the fields around the propagation axis. The fields can be represented in complex coordinates, to include information about the phase. For instance, $j\vec{E}(r,\phi,z,t)$ is equivalent to $\vec{E}(r,\phi,z,t)$ with a $\pi/2$ phase shift. If we sum an even vector mode with an odd vector mode, with a $\pi/2$ phase shift between the two, the trigonometric $f_\nu(\phi)$ and $g_\nu(\phi)$ functions become complex exponentials (Euler formula) and the fields are now

$$\vec{E}(r,\phi,z,t) = \vec{e}(r)\begin{Bmatrix} \exp(j\sigma\phi)\exp(j\ell\phi) \\ -\exp(j\sigma\phi)\exp(j\ell\phi) \\ \exp(j\nu\phi) \end{Bmatrix}\exp(j\beta z - j\omega t) \tag{3a}$$

$$\vec{H}(r,\phi,z,t) = \vec{h}(r)\begin{Bmatrix} -\exp(j\sigma\phi)\exp(j\ell\phi) \\ \exp(j\sigma\phi)\exp(j\ell\phi) \\ -\exp(j\nu\phi) \end{Bmatrix}\exp(j\beta z - j\omega t) \tag{3b}$$

where $\sigma = \pm 1$ for right- or left-circular polarization (or 0 for linear polarization), ℓ is the topological charge, and $\nu = \ell + \sigma$ is the total angular momentum (spin plus orbital). The $\exp(j\ell\phi)$ term shows the resulting mode is an OAM mode, and $\exp(j\sigma\phi)$ shows that it has a circular polarization. This result carries many implications. First, it shows that OAM modes can exist in optical fibers as they are composed of vector eigenmodes with the following relation:

$$\mathrm{OAM}^{\pm}_{\pm\ell,m} = \mathrm{HE}^{\mathrm{even}}_{\ell+1,m} \pm j\mathrm{HE}^{\mathrm{odd}}_{\ell+1,m} \tag{4a}$$

$$\mathrm{OAM}^{\mp}_{\pm\ell,m} = \mathrm{EH}^{\mathrm{even}}_{\ell-1,m} \pm j\mathrm{EH}^{\mathrm{odd}}_{\ell-1,m} \tag{4b}$$

Second, it implies that OAM modes in optical fibers have a circular polarization; the polarization state of the OAM mode is denoted by the superscript in (4b). Therefore, SAM and OAM are not independent in optical fibers, as is the case in free-space. The circular polarization direction will be aligned or anti-aligned with the orbital angular momentum, see Fig. 2, depending on whether the constituting eigenmodes are HE or EH [17]. Third, since OAM modes are made of a combination of vector modes having the same propagation constant, β, OAM modes do not suffer from intra-modal dispersion caused by walk-off between constituting eigenmodes [18].

The notation we use for OAM modes is similar to the notation used for LP modes. OAM modes with topological charge ℓ are made from $HE_{\ell+1,m}$ or $EH_{\ell-1,m}$ eigenmodes, just like $LP_{\ell,m}$ modes are made of $HE_{\ell+1,m}$ *and* $EH_{\ell-1,m}$ eigenmodes:

$$\mathrm{LP}_{\ell,m} = \mathrm{HE}_{\ell+1,m} \pm \mathrm{EH}_{\ell-1,m} \tag{5}$$

However, since the propagation constants in EH and HE modes are different, LP modes suffer from intra-modal dispersion caused by mode walk-off.