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Fiber-guided modes conversion using superposed helical gratings

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ABSTRACT

Optical fibers can support various modal forms, including vector modes, linear polarization (LP) modes, and orbital angular momentum (OAM) modes, etc. The modal correlation among these modes is investigated via Jones matrix, associated with polarization and helical phase corresponding to spin angular momentum (SAM) and OAM of light, respectively. We can generate different modal forms by adopting superposed helical gratings (SHGs) with opposite helix orientations. Detailed analysis and discussion on mode conversion is given as for mode coupling in optical fibers with both low and high contrast index, respectively. Our study may deepen the understanding for various fiber-guided modes and mode conversion among them via fiber gratings.

1. Introduction

The light field has some inherent properties, such as its intensity, wavelength, polarization, and phase. The latter two have attracted a rapidly growing interest in recent years, due to their unique features. The polarization has become extremely diversiform with exploiting arbitrary states of polarization [1,2], not just presents in the well-known vector fields with abundant vectorial polarization, such as cylindrically symmetric beams [3]. It can yield the optical chirality and spin, and manifests intrinsic spin angular momentum (SAM) of field [4]. As for the phase, its gradient of light beams brings about optical vortices producing orbital angular momentum (OAM) [4–6]. These features of light field or beam have been opening novel applications in various realms, such as electron acceleration [7], optical trapping [8,9], laser machining [10], three-Dimensional focus engineering [11], mode-division multiplexing (MDM) [12,13] and unidirectional excitation of surface and waveguide modes [14] in optics communications, and quantum optics and information [15], etc. Optical modes carrying OAM is characterized by the term of exp($il\phi$)with l being the topological charge number [5]. In optical fibers, modes carrying both SAM and OAM can be attributed to the combination of two vector modes [16] that are supplied with vector Helmholtz equation [17].

Optical modes in common weakly guiding fibers (WGFs) exhibit in the form of linear polarization (LP) modes due to the effect of mode degeneracy [18]. However, in the high-contrast-index fibers that have high refractive index difference between fiber core and cladding, LP modes would split into the vector mode components [17,18], because of not equal effective index. The vector modes are the true eigenmodes of optical fibers, and the even and odd ones with a $\pi/2$ phase shift can combine into orbital angular momentum (OAM) modes. Conversely, two OAM modes with the same signs of SAM and OAM can combine into HE vector modes, whereas those with the opposite signs form EH modes [19]. Therefore, both vector and OAM modes can be respectively regarded as complete mode bases to combine fiber modes in different forms. The correlation of these modal forms is investigated via the methods of Jones matrix in detail in the beginning of this article. Apart from three kinds of common fiber modes discussed above, we find that the WGFs also support other modal forms, such as OAM modes with linear polarization, and the modes with the states of circularly polarized lobes (CL) or hybrid polarization (HP).

Furthermore, based on the coupling principle of helical gratings (HGs) [20], we propose the superposed helical gratings (SHGs) to generate fiber-guided modes in different modal forms. This method of mode conversion is analogous to generation high order modes using tilted fiber gratings [21,22]. Here we supervise the angular momentum states in the process of mode coupling between different modal forms through the SHGs. We believe that our investigation on mode correlation and conversion in this article provides a clear perspective on the understanding of the relationship among different modal forms, and it may make sense to exploit the angular momentum of these modes with application to optical trapping, mode manipulation, and optics communications, etc.

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2. Mode decomposition via Jones matrix

In this section, we discuss the OAM mode components of fiber eigenmodes and manifest them via Jones matrix, and reveal the mode correlation between different fiber-guided modal forms. First of all, the electric field of eigenmodes need to be expressed in Cartesian coordinate system. The transformation relation between this coordinate system and the polar coordinate system is as follows:

$$\begin{bmatrix} e_x \\ e_y \end{bmatrix} = \begin{bmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{bmatrix} \cdot \begin{bmatrix} e_r \\ e_\phi \end{bmatrix} \tag{1}$$

The hybrid modes (HE_{mn}/EH_{mn}) can be transferred as

$$HE_{mn}/EH_{mn} = \sqrt{\frac{2}{1+\eta^2}} \cdot F_{mn}(r) \cdot \begin{bmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{bmatrix} \cdot \begin{bmatrix} \cos m\phi \\ \eta \sin m\phi \end{bmatrix} \tag{2}$$

and the radially and azimuthally polarized modes (TM_{0n} and TE_{0n}) [23],

$$TM_{0n} = F_{0n}(r) \cdot \begin{bmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 0 \end{bmatrix} \tag{3}$$

$$TE_{0n} = F_{0n}(r) \cdot \begin{bmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 1 \end{bmatrix} \tag{4}$$

where η indicates the proportion of azimuthal to radial field components for HE_{mn}/EH_{mn} modes. It takes negative sign for HE_{mn} modes, and positive sign for EH_{mn} modes. $F_{mn}(r)$ and $F_{0n}(r)$ correspond to the radial-dependent distribution of electric fields of these modes. Using the decomposition relations,

$$\begin{bmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{bmatrix} = \frac{1}{2} e^{i\phi} \begin{bmatrix} 1 & i \\ -i & 1 \end{bmatrix} + \frac{1}{2} e^{-i\phi} \begin{bmatrix} 1 & -i \\ i & 1 \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} \cos m\phi \\ \mp \sin m\phi \end{bmatrix} = \frac{1}{2} e^{im\phi} \begin{bmatrix} 1 \\ \pm i \end{bmatrix} + \frac{1}{2} e^{-im\phi} \begin{bmatrix} 1 \\ \mp i \end{bmatrix} \tag{6}$$

The Jones vectors of fiber eigenmodes can be written as:

$$HE_{mn} = \frac{1}{2} F_{mn}(r) \left\{ e^{i(m-1)\phi} \begin{bmatrix} 1 \\ i \end{bmatrix} + e^{-i(m-1)\phi} \begin{bmatrix} 1 \\ -i \end{bmatrix} \right\} \tag{7}$$

$$EH_{mn} = \frac{1}{2} F_{mn}(r) \left\{ e^{i(m+1)\phi} \begin{bmatrix} 1 \\ -i \end{bmatrix} + e^{-i(m+1)\phi} \begin{bmatrix} 1 \\ i \end{bmatrix} \right\} \tag{8}$$

$$TM_{0n} = \frac{1}{2} F_{0n}(r) \left\{ e^{i\phi} \begin{bmatrix} 1 \\ -i \end{bmatrix} + e^{-i\phi} \begin{bmatrix} 1 \\ i \end{bmatrix} \right\} \tag{9}$$

$$TE_{0n} = \frac{1}{2} i F_{0n}(r) \left\{ e^{i\phi} \begin{bmatrix} 1 \\ -i \end{bmatrix} - e^{-i\phi} \begin{bmatrix} 1 \\ i \end{bmatrix} \right\} \tag{10}$$

Assuming that HE_{mn}/EH_{mn} modes expressed above correspond to even modes, the corresponding odd modes with a $\pi/2$ angular offset can be given by

$$HE^o_{mn} = \frac{1}{2} i F_{mn}(r) \left\{ e^{-i(m-1)\phi} \begin{bmatrix} 1 \\ -i \end{bmatrix} - e^{i(m-1)\phi} \begin{bmatrix} 1 \\ i \end{bmatrix} \right\} \tag{11}$$

$$EH^o_{mn} = \frac{1}{2} i F_{mn}(r) \left\{ e^{-i(m+1)\phi} \begin{bmatrix} 1 \\ i \end{bmatrix} - e^{i(m+1)\phi} \begin{bmatrix} 1 \\ -i \end{bmatrix} \right\} \tag{12}$$

One can see that HE_{mn} modes comprises two OAM modes with the same sign of SAM and OAM that is spin-orbit aligned, whereas EH_{mn} modes comprises two OAM modes with the opposite sign of these angular momentum states that is spin-orbit dis-aligned [19]. It is obvious that OAM modes can be obtained by combination of even and odd vector modes with a $\pi/2$ phase shift, i. e.,

$$OAM^{\pm 1}_{\pm m,n} = HE^e_{m+1,n} \pm i \cdot HE^o_{m+1,n} = F_{mn}(r) \cdot e^{\pm im\phi} \begin{bmatrix} 1 \\ \pm i \end{bmatrix} \tag{13}$$

Table. 1
Mode combination with OAM mode bases.

	(S_1,S_2)	(1,1)	(1,−1)	(1,0)	(0,1)
(S_3,S_4)		$HE^e_{m+1,n}$	$HE^o_{m+1,n}$	$OAM^{+1}_{+m,n}$	$OAM^{-1}_{-m,n}$
(1,1)	$EH^e_{m-1,n}$ ($m \geq 2$) TM_{0n} ($m = 1$)	$LP^{e,x}_{mn}$	$HP^{e,+1}_{mn}$		
(1,−1)	$EH^o_{m-1,n}$ ($m \geq 2$) TE_{0n} ($m = 1$)	$HP^{e,-1}_{mn}$	$LP^{o,x}_{mn}$		
(1,0)	$OAM^{-1}_{+m,n}$			$OAM^x_{+m,n}$	$CL^{e,-1}_{m,n}$
(0,1)	$OAM^{+1}_{-m,n}$			$CL^{e,+1}_{m,n}$	$OAM^x_{-m,n}$

$$OAM^{\mp 1}_{\pm m,n} = EH^e_{m-1,n} \pm i \cdot EH^o_{m-1,n} = F_{mn}(r) \cdot e^{\pm im\phi} \begin{bmatrix} 1 \\ \mp i \end{bmatrix} \tag{14}$$

for $m \geq 2$, and

$$OAM^{\pm 1}_{\mp 1,n} = TM_{0n} \pm i \cdot TE_{0n} = F_{0n}(r) \cdot e^{\mp i\phi} \begin{bmatrix} 1 \\ \pm i \end{bmatrix} \tag{15}$$

for $m = 1$.

In WGFs, it is well known that the mode pairs of $HE_{m+1,n}$ and $EH_{m-1,n}$ ($m \geq 2$) modes and mode group of HE_{21}, and TM_{01}, TE_{01} modes would degenerate into LP modes, due to the approximate effective index. Therefore, it is obvious that the mode degeneration may also occur among the corresponding OAM modes. When the four kinds of OAM modes are set as a group of complete bases, arbitrary fiber modes (AFMs) can be generated as

$$AFM = S_1 \cdot OAM^{+1}_{+m,n} + S_2 \cdot OAM^{-1}_{-m,n} + S_3 \cdot OAM^{-1}_{+m,n} + S_4 \cdot OAM^{+1}_{-m,n} \tag{16}$$

The usual mode combinations are listed in Table 1. As the expressions using Jones Matrix, the OAM modes with linear polarization in the x direction are

$$OAM^x_{\pm m,n} = 2F_{mn}(r) \cdot e^{\pm im\phi} \begin{bmatrix} 1 \\ 0 \end{bmatrix} \tag{17}$$

and even and odd LP modes in the x direction correspond to

$$LP^{e,x}_{mn} = F_{mn}(r) \cdot \cos m\phi \begin{bmatrix} 1 \\ 0 \end{bmatrix} \tag{18}$$

$$LP^{o,x}_{mn} = F_{mn}(r) \cdot \sin m\phi \begin{bmatrix} 1 \\ 0 \end{bmatrix} \tag{19}$$

In addition, there are other modal forms characterized by CL states

$$CL^{e,\pm 1}_{mn} = 2F_{mn}(r) \cdot \cos m\phi \begin{bmatrix} 1 \\ \pm i \end{bmatrix} \tag{20}$$

and HP states

$$HP^{e,\pm 1}_{mn} = F_{mn}(r) \cdot \cos m\theta \begin{bmatrix} 1 \\ \pm i \end{bmatrix} + i \cdot F_{mn}(r) \cdot \sin m\theta \begin{bmatrix} 1 \\ \mp i \end{bmatrix} \tag{21}$$

To intuitively visualize these combined modes based on vector modes with mode order being $m = n = 1$, we give the mode field distributions of linearly polarized OAM mode, conventional LP mode, CL and HP modes in Fig. 1. As for the odd, even and y-polarization

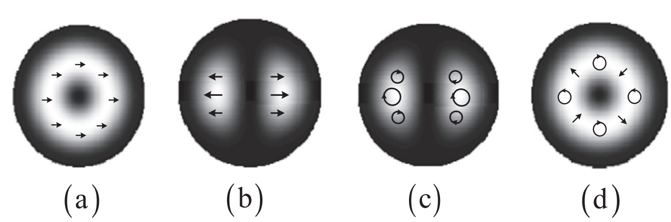

Fig. 1. Mode field distributions with polarization states, (a) $OAM^x_{\pm 1,1}$, (b)$LP^{e,x}_{11}$, (c) $CL^{e,+1}_{11}$, (d) $HP^{e,-1}_{11}$.