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Modal power decomposition of light propagating through multimode optical fiber

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ABSTRACT

The structure of the light field propagating through multimode fibers is of great interest for creating fiber sensors and other applications. Here, using only one linear polarized component of spatial-intensity profiles in near- and far-field regions of a beam emitted from the fiber, we propose a method for the modal power decomposition. As a simple example, modal power decomposition has been done for optical fibers with a step-like index profile. Experiments have been carried out for the fiber with $V=54$. The method can be used for fibers with any known refractive index profile, core diameter, indices of the core and cladding.

1. Introduction

Multimode fibers have many advantages in optical communication systems in comparison with a few mode fibers. Multimode fibers can transmit a lot of information and parallel data transfer is possible due to a number of modes propagating through the fibers. Examples of multimode fiber usage include dispersive multiplexing [1], spatial mode multiplexing [2], quantum information processing [3,4], and magnetic field sensors [5–7]. Modal power decomposition for multimode optical fibers is important for the development of multimode communication systems. Many sophisticated techniques have been developed to study the structure and propagation characteristics of laser beams through optical fibers [8–14].

The computer-generated holographic filters were used for the complete modal decomposition of optical fields for arbitrary mode contents propagating through a single-mode fiber with a waveguide parameter $V_{max} = 5$ with the approximation of weakly guided modes [8]. The amplitude filter had low diffraction efficiency which was less than 10% in the central diffraction order. The phase diffraction filters were used for modal decomposition for multimode optical fibers with step-like refractive index profile ($V_{max} = 15$) [10]. The element allowed it to use only ~ 80% of the light intensity. The drawback of these techniques is low transmission signals. The cost of filters is very high. Moreover, one filter can only be used for a fiber with definite parameters.

The first experiment was carried out by Shapira et al. [11]. A modal analysis technique was proposed using the field distribution in a near- and far-field region. This method requires the information not only about intensity but about polarization distribution as well. The method proposed in Ref. [12] was developed for a real-time mode decomposition technique for a few mode fibers based on analyzing field distribution at the fiber output.

In this paper we present a new experimental method of modal power decomposition for multimode optical fibers. The main advantage of the method is that the polarization distribution is not required to carry out the modal power decomposition. The method was demonstrated for optical fibers with a step-like index profile. The proposed method can be applied for fibers with different values of waveguide parameter V. Only one linearly polarized component of the output field in the object and the Fourier planes is required. The linearly polarized field is retrieved by Gerchberg–Saxton algorithm [15] from intensity measurement.

To the best of our knowledge, this is the first demonstration of modal decomposition carried out through only one linearly polarized component of the output intensity. It will reduce the cost and the complexity of the modal decomposition system.

2. Theoretical description of coherent polarized light wave propagation through a multimode fiber with a step-like index profile

Let us consider propagation of polarized light in an axial symmetric optical fiber with the following refractive index profile:

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$$n^2(R) = n_{co}^2[1 - 2\Delta f(R)],$$

where

$$\Delta = \frac{1}{2}\left(1 - \frac{n_{cl}^2}{n_{co}^2}\right),$$

and in the approximation of weakly directing waveguide

$$\Delta \approx \frac{n_{co} - n_{cl}}{n_{co}},$$

function $f(R)$ is as follows:

$$f(R) = 0, \quad R = r/\rho < 1,$$
$$f(R) = 1, \quad R = r/\rho > 1,$$

and

$$n(r) = n_{co}, \quad r/\rho < 1,$$
$$n(r) = n_{cl}, \quad r/\rho > 1.$$

Here $r = |\mathbf{r}|$, $(x, y) = \mathbf{r}$ are the transverse coordinates, ρ is the radius of the fiber core, n_{co} and n_{cl} are the refractive indices of the core and the cladding, respectively. In the approximation of weakly guiding fibers, the requirements of symmetry allow us to write down four polarization modes for fiber length z, any orbital angular momentum m $(m > 0)$ and radial quantum number N in the following form [16,17]:

$$\begin{aligned}
\mathbf{e}_{m,N}^{(1)}(r, \varphi) &= [\cos(m\varphi)\mathbf{e}_x - \sin(m\varphi)\mathbf{e}_y]\cdot F_{m,N}(r),\\
\mathbf{e}_{m,N}^{(2)}(r, \varphi) &= [\cos(m\varphi)\mathbf{e}_x + \sin(m\varphi)\mathbf{e}_y]\cdot F_{m,N}(r),\\
\mathbf{e}_{m,N}^{(3)}(r, \varphi) &= [\sin(m\varphi)\mathbf{e}_x + \cos(m\varphi)\mathbf{e}_y]\cdot F_{m,N}(r),\\
\mathbf{e}_{m,N}^{(4)}(r, \varphi) &= [\sin(m\varphi)\mathbf{e}_x - \cos(m\varphi)\mathbf{e}_y]\cdot F_{m,N}(r).
\end{aligned} \tag{1}$$

Here $\mathbf{e}_x$, $\mathbf{e}_y$ are the eigenvectors, $x = r\cdot\cos\varphi$, $y = r\cdot\sin\varphi$. Radial distribution function $F_{m,N}(R)$ holds as follows:

$$F_{m,N}(R) = \frac{J_m(U_N R)}{J_m(U_N)}, \quad R = r/\rho < 1,$$
$$F_{m,N}(R) = \frac{K_m(W_N R)}{K_m(W_N)}, \quad R = r/\rho > 1,$$

where J_m and K_m are Bessel and modified Bessel functions, accordingly, quantities U_N and W_N for each value m are determined from the eigenvalue equation:

$$U_N \frac{J_{m+1}(U_N)}{J_m(U_N)} = W_N \frac{K_{m+1}(W_N)}{K_m(W_N)}, \tag{2}$$

where $V^2 = W_N^2 + U_N^2$, $V = \rho k(n_{co}^2 - n_{cl}^2)^{1/2}$, $k = 2\pi/\lambda$, λ is the wavelength of light in the air. In the scalar approach all modes propagate with velocity determined by propagation constant $\beta_{m,N}$:

$$\beta_{m,N} = \frac{V}{\rho(2\Delta)^{1/2}}\left\{1 - 2\Delta\frac{U_N^2}{V^2}\right\}^{1/2}.$$

The influence of the polarization state of each of the four modes on its propagation velocity is taken into account by the introduction of polarization corrections $\beta_{m,N}^{(j)}$ to propagation constants $\beta_{m,N}$. Following the results obtained in Ref. [17], we have the following expressions for the polarization corrections to the propagation constants in case of a fiber with a step-like refractive index profile:

$$\delta\beta_{0,N}^{(1)} = \delta\beta_{0,N}^{(3)} = \delta\beta_{0,N}^{(2)} = \delta\beta_{0,N}^{(4)} = -\frac{(2\Delta)^{3/2}}{2\rho}\frac{W_N U_N^2}{V^3}\frac{K_0(W_N)}{K_1(W_N)},$$
$$\delta\beta_{1,N}^{(1)} = \delta\beta_{1,N}^{(3)} = -\frac{(2\Delta)^{3/2}}{2\rho}\frac{W_N U_N^2}{V^3}\frac{K_1(W_N)}{K_0(W_N)},$$
$$\delta\beta_{1,N}^{(2)} = -\frac{(2\Delta)^{3/2}}{\rho}\frac{W_N U_N^2}{V^3}\frac{K_1(W_N)}{K_2(W_N)},$$
$$\delta\beta_{1,N}^{(4)} = 0,$$
$$\delta\beta_{m,N}^{(1)} = \delta\beta_{m,N}^{(3)} = -\frac{(2\Delta)^{3/2}}{2\rho}\frac{W_N U_N^2}{V^3}\frac{K_m(W_N)}{K_{m-1}(W_N)},$$
$$\delta\beta_{m,N}^{(2)} = \delta\beta_{m,N}^{(4)} = -\frac{(2\Delta)^{3/2}}{2\rho}\frac{W_N U_N^2}{V^3}\frac{K_m(W_N)}{K_{m+1}(W_N)}.$$

As $\delta\beta_{m,N}^{(1)} = \delta\beta_{m,N}^{(3)}$ for all values of m and $\delta\beta_{m,N}^{(2)} = \delta\beta_{m,N}^{(4)}$ for all values of $m \neq 1$, any linear combinations of modes $\mathbf{e}_{m,N}^{(1)}$ and $\mathbf{e}_{m,N}^{(3)}$ for all values of m and any linear combinations of modes $\mathbf{e}_{m,N}^{(2)}$ and $\mathbf{e}_{m,N}^{(4)}$ in case of $m \neq 1$ will also be eigenmodes. It is easy to show that combinations of modes $\mathbf{e}_{m,N}^{(1)} \pm i\mathbf{e}_{m,N}^{(3)}$ and $\mathbf{e}_{m,N}^{(2)} \pm i\mathbf{e}_{m,N}^{(4)}$ represent the modes with homogeneous circular polarization $\mathbf{e}_x + i\sigma\mathbf{e}_y$ in the fiber section. Here $\sigma = +1$ for light with the right circular polarization and $\sigma = -1$ for light with the left circular polarization. These new modes are as follows:

$$\begin{aligned}
\mathbf{e}_{+,m,N}^{(+)}(r, \varphi) &= \mathbf{e}_{m,N}^{(1)}(r, \varphi) + i\mathbf{e}_{m,N}^{(3)}(r, \varphi) = (\mathbf{e}_x + i\mathbf{e}_y)e^{im\varphi}F_{m,N}(r),\\
\mathbf{e}_{-,m,N}^{(-)}(r, \varphi) &= \mathbf{e}_{m,N}^{(1)}(r, \varphi) - i\mathbf{e}_{m,N}^{(3)}(r, \varphi) = (\mathbf{e}_x - i\mathbf{e}_y)e^{-im\varphi}F_{m,N}(r),\\
\mathbf{e}_{+,m,N}^{(-)}(r, \varphi) &= \mathbf{e}_{m,N}^{(2)}(r, \varphi) + i\mathbf{e}_{m,N}^{(4)}(r, \varphi) = (\mathbf{e}_x - i\mathbf{e}_y)e^{im\varphi}F_{m,N}(r),\\
\mathbf{e}_{-,m,N}^{(+)}(r, \varphi) &= \mathbf{e}_{m,N}^{(2)}(r, \varphi) - i\mathbf{e}_{m,N}^{(4)}(r, \varphi) = (\mathbf{e}_x + i\mathbf{e}_y)e^{-im\varphi}F_{m,N}(r).
\end{aligned} \tag{3}$$

Thus, if polarized radiation with the right or left circular polarization is incident on the input of the fiber, the modes with $m = 0$ and $m > 1$ will retain the state of polarization.

Polarized light with arbitrary state of polarization of light can be presented as superposition of light with the left and right circular polarization. To describe the propagation of linearly polarized light or light with the arbitrary state of polarization through the fiber, it is possible to consider propagation through the fiber of light as superposition of mode equations (3) at the fiber input. Let us consider a case when we illuminate a multimode optical fiber input end with right circular polarized light ($\sigma = +1$). According to the results obtained in Ref. [17]

$$\mathbf{E}^{+}(r, \varphi, z = 0) = (\mathbf{e}_x + i\mathbf{e}_y)\sum_m\sum_N C_{\pm,m,N}e^{\pm im\varphi}F_{m,N}(r). \tag{4}$$

Here coefficients $C_{+,m,N}$ and $C_{-,m,N}$ determine the contribution of modes $\mathbf{e}_{+,m,N}^{(+)}$ and $\mathbf{e}_{-,m,N}^{(+)}$ (Eqs. (3)) at the fiber input. Each mode has a different propagation constant in the fiber. All modes retain their polarization except modes with $m = 1$. Therefore, we have the following distribution of the amplitude of light field $\mathbf{E}^{+}(r, \varphi, z)$ at the fiber output of length $z = z_0$:

$$\begin{aligned}
\mathbf{E}^{+}&(r, \varphi, z_0)\\
&= \frac{(\mathbf{e}_x + i\mathbf{e}_y)}{\sqrt{2}}\Big[\sum_{m\neq 1}\sum_N C_{-,m,N}e^{-im\varphi}F_{m,N}(r)e^{iz_0(\beta_{m,N}+\delta\beta_{m,N}^{(2)})}\\
&+ \sum_m\sum_N C_{+,m,N}e^{+im\varphi}F_{m,N}(r)e^{iz_0(\beta_{m,N}+\delta\beta_{m,N}^{(1)})}\\
&+ \sum_N C_{-,1,N}e^{-i\varphi}F_{1,N}(r)e^{iz_0\beta_{1,N}}(e^{i2z_0\delta\beta_{1,N}^{(2)}} + 1)\Big]\\
&+ \frac{(\mathbf{e}_x - i\mathbf{e}_y)}{\sqrt{2}}\left[e^{+i\varphi}\sum_N C_{-,1,N}F_{1,N}(r)e^{iz_0\beta_{1,N}}(e^{i2z_0\delta\beta_{1,N}^{(2)}} - 1)\right].
\end{aligned} \tag{5}$$

Let us project light field $\mathbf{E}^{+}(r, \varphi, z)$ at direction x at the fiber output of length $z = z_0$: