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Intensity profile stabilities of high order vectorial modes of optical fibers

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ABSTRACT

It is known that the high order vectorial modes of ideally circular optical fibers possess cylindrical symmetries in electric field distributions as well as intensity distributions. Unfortunately, the cylindrical symmetries may be disturbed by slight deformation of the fiber core in reality. In the present work we propose a method to evaluate the symmetries of intensity profiles of the high order vectorial modes of optical fibers. We firstly perform the numerical simulations of the intensity profiles of four vectorial modes within the LP_{11} mode group of the different fibers assuming the fiber core is deformed to be elliptical. Using the proposed method the symmetries and the stabilities of the intensity profiles of the modes are further deduced. It has been demonstrated that the symmetries of the modes are more sensitive to the deformation of the fiber core for fibers with smaller normalized frequencies. Furthermore, it is also concluded that for fibers with identical normalized frequencies the determined symmetries and stabilities of the modes appear to be different for different fiber configurations.

1. Introduction

Recently high order mode fibers have found various applications in dispersion compensations, high-power lasers and all-fiber mode converters [1–6]. For these applications of high order mode fibers it is necessary to identify the individual transverse mode to precisely characterize the dispersion properties. On the other hand, optical fibers can be used to generate light beams with cylindrically symmetric electric field distributions, e.g., radially and azimuthally polarized beams [7–12]. A radially or azimuthally polarized beam may explore new applications in optical data storage, high resolution microscopy, particle trapping and acceleration, to name just a few [13–18]. It has been numerically verified by us that in terms of electric fields the TM_{01} and TE_{01} vectorical modes of an ideally circular fiber have 99.99% similarities with radially and azimuthally polarized beams in free space, respectively.

Unfortunately, the refractive-index profile of the fiber is never exactly as same as the designed refractive-index profile because of the limitation of the fiber manufacturing technique and the suffering disturbances in usage. The imperfections of an optical fiber can be various, e.g., irregular fiber core along the propagation, non-circular geometric shape of the fiber core within the fiber cross section and stress induced by the nonuniformity of the material. It is normally very hard to characterize these imperfections of the fibers. In particular if the fiber is assumed to have an elliptical core within the cross

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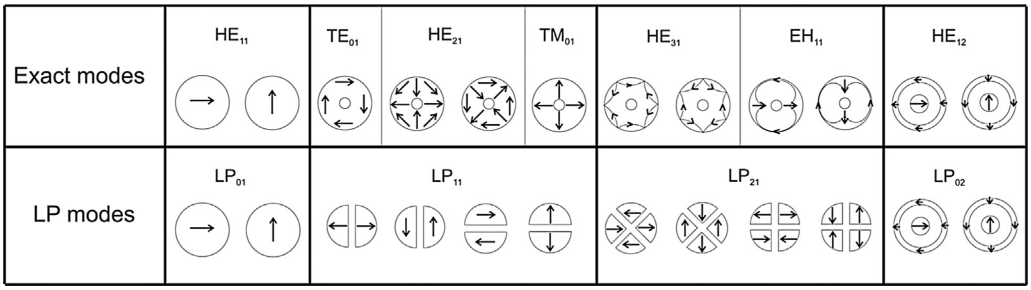

Fig. 1. Modes of an ideally circular step-index fiber. The arrows respresent the electric fields. The first row represents exact vector solutions of Maxwell's equations. The second row represents LP modes which can be obtained by solving scalar Maxwell's equations under weakly-guiding condition.

section, the problem is much simplified. In this context the symmetries and the stabilities of the TM_{01} and TE_{01} fiber modes with respect to the fiber ellipticity are import for us to judge the availability of the fiber for producing the radially and azimuthally polarized light beams.

Some theoretical and experimental work on the optical properties of high order modes of weakly-guiding optical fibers and special fibers related to ellipticity of the fiber has been published. Fadeyeva has proposed the topological deformation coefficient for descripting the vortex behaviours in perturbed low-mode weakly-guiding fibers [19]. It is found out, that even small fiber cross-section deformations can cause a large vortex field structural change. Alexeyev investigated the further properties of the vortical fields in an elliptic weakly-guiding optical fiber [20]. The eigenfunctions and the spectrums of polarization corrections to the scalar propagation constant in the case of relatively large and small values of a fiber ellipticity were obtained. Herstrøm has investigated the cutoff wavelengths as a function of ellipticity for quite a number of high order modes in a special elliptical optical fibers in simulations and measurements [21]. Ma has identified the intensity deformations of the high order modes and the mode splittings in group delay of the initially degenerate HE_{21} modes of a dispersion-tailored fiber with slight ellipticity in measurements [22], as predicted by Snyder [23]. The ellipticity of the fiber was further determined by fitting the simulation results of group-index differences of high order modes to the measurement results obtained using two types of interferometry [24]. Vengsarkar presented high order cutoff values of the normalized frequencies for step-index fibers of varying ellipticities in theory [25]. He discussed the effect of ellipticity and refractive-index profile on the differential propagation constant related to the LP_{01} and LP_{11} modes. Liang has completed the comprehensive analysis of the characteristics of HE_{11} and HE_{21} modes of an elliptical multilayer–core fiber in theory and experiments [26]. Nevertheless, to the best knowledge of us, the symmetries of the high order vectorial modes in electric field or optical intensity have not been quantitatively studied. A full analysis of the mode intensity profile stabilities has not been implemented when the fiber core is deformed to be elliptical.

In the paper we focus our work on the intensity profile stabilities of high order vectorial modes of optical fibers. Transverse modes of step-index fibers as well as radially and azimuthally polarized beams are introduced in Section 2. In Section 3 the ε parameter is for the first time proposed to quantitatively evaluate the symmetries of the intensity distributions of the TE_{01}, TM_{01}, and HE_{21} vectorial modes of step-index fibers. In Section 4 the variations of ε are studied for the modes of the fibers with different normalized frequencies when the fiber core is deformed to be elliptical. The ε variations are also demonstrated for fibers with similar normalized frequencies but different inherent parameters. Conclusions are drawn in Section 5.

2. Optical fiber modes and cylindrically symmetric light beams

Step-index fibers have the simplest refractive-index profile. Fig. 1 shows the lowest 12 vectorial modes and the corresponding scalar modes (linearly-polarized, LP, modes) of an ideally circular step-index fiber. The true vectorial eigenmodes are displayed in the first row. Each eigenmode has a unique propagation constant except of the even and odd modes of the hybrid modes (HE and EH) which have different polarization patterns and are always degenerate in a perfectly circular fiber. The modes shown in the second row are LP modes derived by using a scalar approximation. LP modes represent approximate solutions of Maxwell's equations valid for small core-cladding refractive-index steps. In the weakly-guiding regime the propagation constants of the LP modes in a perfectly circular fiber depend only on the mode intensity pattern and are independent of the polarization.

When transverse fiber modes are discussed, the normalized frequency V is well known as

$$V = \frac{2\pi a}{\lambda}\sqrt{n_{co}{}^2 - n_{cl}{}^2} \tag{1}$$

Here a is the radius of the fiber core, λ is the wavelength of the light, n_{co} is the refractive index of the core and n_{cl} is the refractive index of the cladding. V depends on the inherent parameters of the fiber as well as the wavelength. It is well known that for conventional step-index fibers the normalized parameter V exclusively determines the dispersion properties of the optical fibers, i.e., fibers with identical Vs must possess identical dispersion properties no matter how large a, n_{co}, n_{cl} and λ are.