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Nonlinear effects in aspect ratio based far-field characterization of single-mode trapezoidal index fibers

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ABSTRACT

We investigate the effect of Kerr nonlinearity on the angle of beam divergence of single-mode trapezoidal index fibers from its linear and nonlinear values. From comparison of angle of beam divergence in presence and absence of Kerr nonlinearity, the nonlinear effect for each aspect ratio is observed to be more profound in lower values of normalized frequency. Moreover, the triangular index profile supersedes the other index profiles in respect of relative change of angle of beam divergence. It should give the system users and developers a much better control over far-field related calculations and can be widely used for experiments in presence of optical nonlinearity.

1. Introduction

Far-field intensity characterization is a familiar tool, used for characterizing optical sources and fibers. In recent literature it has generated considerable amount of interest for characterization of the square grooved-dielectric lens antenna [1], simulation and evolution in the free-space propagation of Schell-model beams [2], analysis of intensity distributions of a Gaussian beam after crossing a thin nonlinear nonlocal material [3] and more [4,5]. Properties and applications of optical nonlinearity on the other hand, have generated tremendous interest in supercontinuum generation [6], detection of coherent transmission systems [7] and self-focusing of soliton self-compression [8]. Specially, effects of the Kerr nonlinearity have been a primary focus throughout the last few years [9,10]. Hence, more attention is expected to be invited to seek the possible thoroughfare of deep involvement of optical nonlinearity and far-field characterization. Therefore, it, demands further investigation of their inter-relation and how nonlinearity affects far-field characterization of optical sources and fibers, with attention to the fibers having typical reflective index profiles of practical intentions.

It is well-known that a trapezoidal index single-mode fiber (TISMF) possesses both the merits of a step index fiber and a triangular index fiber [11]. While the former is rigid for monolithic distribution, the latter possesses dispersion shifting criterion which shifts the zero dispersion wavelength from 1.3 to 1.55 μm [11] where glass has the lowest loss window. Recently, following the Marcuse formalism [12], investigation of TISMF has generated notable amount of interest to propose similar formulation of spot size in terms of aspect ratio and normalized frequency [13]. Further, this formulation is extended to interpret situation in the context of maximization of nonlinear optical processes in TISMF [14] and to investigate the nonlinear effect on the propagation characteristics of TISMF in terms of aspect ratio based changes of spot size [15].

Very recently, study of the angle of beam divergence has been reported with relevant empirical relations in linear domain in terms of normalized frequency and aspect ratio of a TISMF [16]. While the study gives a proper idea of variation of the angle of beam

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divergence in linear domain, similar investigation of such variation in presence of optical nonlinearity is not available in literature to the best of our knowledge.

In this paper, in comparison to linear domain, we study how presence of Kerr nonlinearity affects the angle of beam divergence for TISMF and find the aspect ratio for which effects of nonlinearity is most prominent. Our analysis will be a ready reference for system users for easy computations and predictions of far-field characteristics in nonlinear domain.

2. Analysis

2.1. Preview

The refractive index distribution of a graded index fiber, under weakly guiding approximation [17,18], is given as,

$$n^2(\rho) = n_1^2[1 - \delta H(\rho)], \qquad R \le 1$$
$$n^2(\rho) = n_1^2[1 - \delta] = n_0^2, \qquad R > 1 \tag{1}$$

where $\rho = r/a$ and a are the normalized and fiber core radius, respectively. Further, r is the radial distance from the core axis, $\delta = \frac{n_1^2 - n_0^2}{n_0^2}$ is the relative index difference, and n_1 and n_0 are the axial and cladding refractive indices, respectively. The profile shape function, $H(\rho)$ is represented as

$$H(\rho) = \rho^g$$

where g is the profile exponent. Values of $g = \infty$, 2 and 1 respectively, correspond to step, parabolic and triangular index profiles. Further, for the trapezoidal index profile (TIP), the profile function, $H(\rho)$ is given as

$$H(\rho) = 0, \qquad 0 < \rho \le S$$
$$H(\rho) = \frac{\rho - S}{1 - S}, \qquad S < \rho < 1 \tag{2}$$

where S is the aspect ratio of the trapezoid, defined as the ratio of step width to core radius. The values of $S = 0$ and 1 correspond to triangular and step index profiles, respectively.

Under nonlinearity, the refractive index distribution [19], $n(\rho)$ in Eq. (1) is written as,

$$n^2(\rho) = n_L^2(\rho) + 2n_L(\rho)n_2 I \tag{3}$$

where $n_L(\rho)$ and n_2 are the linear refractive index and the nonlinear Kerr coefficient, respectively and I is the local power intensity, given by,

$$I = \frac{1}{2} n_0 c \varepsilon_0 \, |f(\rho)|^2 \tag{4}$$

where c and ε_0 correspond to the velocity of light and dielectric permittivity in free space, respectively, and $f(\rho)$ represents the modal field. Using Eq. (4), $n(\rho)$ can be written as,

$$n^2(\rho) = n_L^2(\rho) + \alpha \, |f(\rho)|^2 \tag{5}$$

where $\alpha = n_0^2 n_2 c \varepsilon_0$. Now, considering Kerr nonlinearity in the core, the modal field, $f(\rho)$ in the core is the solution of the nonlinear scalar wave equation given as [18],

$$\frac{1}{\rho}\frac{d}{d\rho}\left(\rho \frac{df(\rho)}{d\rho}\right) + V^2[q(\rho) - b + \gamma f^2(\rho)]f(\rho) = 0, \quad \rho < 1 \tag{6}$$

and $f(\rho)$ in the nonlinear cladding is, analytically, taken as [15],

$$f(\rho) = f(1)\frac{K_0(W\rho)}{K_0(W)}, \qquad \rho > 1 \tag{7}$$

with boundary conditions $f(0) = 1$ and $f'(0) = 0$. Hence Eqs. (6) and (7) represent two separate solutions in core and cladding where $f(1)$ is the solution of Eq. (6) at $\rho = 1$.

Here, V and W are the usual fiber parameters and $K_n(x)$ is the modified Bessel function of the n -th order. Here, $q(\rho) = \frac{n^2(\rho) - n_0^2}{n_1^2 - n_0^2}$ is the normalized linear index profile, $b = \frac{(\beta/k)^2 - n_0^2}{n_1^2 - n_0^2}$ is the normalized propagation constant and $\gamma = \frac{4n_2 P}{ca^2(n_1^2 - n_0^2)}$ is the normalized nonlinear coefficient where P is the total power flow in the fiber [18].

Now, analytically, one cannot reach the total solution of $f(\rho)$ from Eqs. (6) and (7) and, hence, has to take resort to approximate solutions in terms of simple Gaussian function. Such function provides readily available information of propagation characteristics easily as is elucidated below in case of far-field characterization in presence of Kerr optical nonlinearity.