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New method for calculating the coupling coefficient in graded index optical fibers

Svetislav Savović [a,b], Alexandar Djordjevich [b,*]

[a] University of Kragujevac, Faculty of Science, R. Domanovića 12, Kragujevac, Serbia
[b] City University of Hong Kong, 83 Tat Chee Avenue, Kowloon, Hong Kong, China

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ABSTRACT

A simple method is proposed for determining the mode coupling coefficient D in graded index multimode optical fibers. It only requires observation of the output modal power distribution $P(m, z)$ for one fiber length z as the Gaussian launching modal power distribution changes, with the Gaussian input light distribution centered along the graded index optical fiber axis ($\theta_0 = 0$) without radial offset ($r_0 = 0$). A similar method we previously proposed for calculating the coupling coefficient D in a step-index multimode optical fibers where the output angular power distributions $P(\theta, z)$ for one fiber length z with the Gaussian input light distribution launched centrally along the step-index optical fiber axis ($\theta_0 = 0$) is needed to be known.

1. Introduction

Transmission characteristics of multimode step-index (SI) and graded-index (GI) optical fibers depend strongly upon the differential mode-attenuation [1–4] and rate of mode coupling [2,3,5–7]. The latter represents power transfer between neighboring modes caused by fiber impurities and inhomogeneities introduced during the fiber manufacturing process (such as microscopic bends, irregularity of the core-cladding boundary and refractive index distribution fluctuations) [6]. Modal dispersion in GI optical fibers is reduced by the graded-index distribution of the core and by mode coupling which leads to a square-root dependence of the bandwidth on the fiber length instead of the linear dependence expected in the absence of mode coupling [7,8]. Because of the influence of mode coupling and modal attenuation on fiber transmission, it is necessary to have effective and accurate methods for calculating the rate of these processes in GI optical fibers.

Output power distribution in the near and far fields of GI optical fibers has been studied extensively. Time-independent power flow equation is employed to calculate modal power transients along the GI optical fibers [8]. Time-dependent power flow equation is employed to calculate frequency response and bandwidth in GI optical fibers [9,10]. Arrue et al. [11] used ray tracing method and also experimentally investigated mode coupling to predict output-field patterns in GI plastic optical fibers (POFs). Garito et al. [12] experimentally investigated influence of mode coupling on pulse broadening in GI POFs. Inoue et al. [13] have investigated experimentally and by solving the coupled power equation the influence of microscopic heterogeneities on mode coupling and bandwidth in GI POFs.

The rate of mode coupling in GI optical fibers, which is the power transfer between modes, has been described by the constant "coupling coefficient" D [14]. A more general form of the power flow equation has been used in which this coefficient depended on the principal mode number [8]. The method of determining the mode dependent coupling coefficient in GI optical fibers proposed by Kitayama et al. [8] required that the steady-state power distribution and total loss in a steady-state be known.

An alternative method is presented in this paper. The coupling coefficient D is obtained from just one output modal power distribution. This distribution is for the Gaussian light beam distribution launched centrally along the fiber axis ($\theta_0 = 0$) without radial offset ($r_0 = 0$), at selected distance z from the input fiber end. The variance of the launch modal power distribution has to be known, which is usually the case. Should it not be known, variances of the output modal power distributions at two fiber lengths $z > 0$ have to be known. The condition of the launching the beam without radial offset ($r_0 = 0$) is crucial, since in the case of radial offset $r_0 > 0$ (although $\theta_0 = 0°$), excitation of modes with $m > 0$ occurs, which results in an initial distribution $P(m, z = 0)$ which is in the ring form (disk form of a launch beam distribution $P(m, z = 0)$ is

* Corresponding author at: City University of Hong Kong, 83 Tat Chee Avenue, Kowloon, Hong Kong, China.
E-mail addresses: savovic@kg.ac.rs (S. Savović), mealex@cityu.edu.hk (A. Djordjevich).

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a crucial condition of the proposed method). Of course, a finite radial dimension of the launch beam spot size is common, but it can be easily reduced to be of order of a few micrometers [15].

2. Time-independent power flow equation for GI optical fiber

The index profile of GI optical fibers may be expressed as:

$$n(r,\lambda)=\begin{cases} n_1(\lambda)\left[1-2\Delta(\lambda)\left(\frac{r}{a}\right)^g\right]^{1/2} & (0\leqslant r\leqslant a)\\ n_1(\lambda)(1-2\Delta(\lambda))^{1/2}=n_2(\lambda) & (r>a)\end{cases} \tag{1}$$

where g is the core index exponent, a is the core radius, n_1 is the maximum index of the core, n_2 is the index of the cladding and $\Delta\cong[n_1(\lambda)-n_2(\lambda)]/n_1(\lambda)$ is the relative index difference. The optimum value of the core index exponent g to obtain maximum bandwidth depends on the wavelength λ (in free-space) of the source [11,16].

Time-independent power flow equation for GI optical fiber is [8,17]:

$$\frac{\partial P(m,z)}{\partial z}=-\alpha(m)P(m,z)+\frac{1}{m}\frac{\partial}{\partial m}\left(md(m)\frac{\partial P(m,z)}{\partial m}\right) \tag{2}$$

where $P(m, z)$ is the power in the m-the principal mode (modal group), z is coordinate along the fiber axis from the input fiber end, $\alpha(m)$ is the attenuation of the mode m, $d(m)$ is the coupling coefficient of the mode m. The maximum principal mode number M, can be obtained as [8,10]:

$$M(\lambda)=\sqrt{\frac{g\Delta(\lambda)}{g+2}}akn_1(\lambda) \tag{3}$$

where $k=2\pi/\lambda$. The boundary conditions for the power flow described by Eq. (2) are: $P(m, z) = 0$, for $m > M$ and $d(m)\frac{\partial P(m,z)}{\partial m}\Big|_{m=0}=0$ for $m = 0$. The first condition implies that modes with infinitely high loss do not transmit power. The second one indicates that the coupling is limited to the modes $m > 0$.

Except near cutoff, the attenuation remains uniform $\alpha(m) = \alpha_0$ throughout the region of guided modes $0\leq m\leq M$ (it appears in the solution as the multiplication factor $\exp(-\alpha_0 z)$ that also does not depend on m). Therefore, $\alpha(m)$ can be neglected when solving (2) for mode coupling, and this equation reduces to:

$$\frac{\partial P(m,z)}{\partial z}=\frac{1}{m}\frac{\partial}{\partial m}\left(md(m)\frac{\partial P(m,z)}{\partial m}\right) \tag{4}$$

It is assumed that mode coupling mainly occurs between neighboring modes due to the fact that coupling strength decreases sufficiently fast with the mode spacing. This assumption is commonly used in modeling a mode coupling process [3,12,14]. Assuming a constant mode coupling coefficient $d(m) = D$, time-independent power flow Eq. (4) can be written as:

$$\frac{\partial P(m,z)}{\partial z}=\frac{D}{m}\frac{\partial P(m,z)}{\partial m}+D\frac{\partial P^2(m,z)}{\partial m^2} \tag{5}$$

The first term of the right-hand side of Eq. (5) describes the drift of modal power distribution $P(m, z)$ towards $m = 0$, while the second term describes the change of the width of the launch modal power distribution with increasing the fiber length. When the narrow Gaussian input modal power distribution at the input end of the fiber is launched centrally along the fiber axis ($\theta_0 = 0$) without radial offset ($r_0 = 0$) (it is already centered at $m = 0$), with increasing distance from the input fiber end, the modal power distribution remains centered at $m = 0$, but its width increases, and Eq. (5) reduces to:

$$\frac{\partial P(m,z)}{\partial z}=D\frac{\partial P^2(m,z)}{\partial m^2} \tag{6}$$

If we think of $P(m, z)$ as a probability distribution, Eq. (6) is then seen as the special Fokker-Planck equation with constant diffusion coefficient D [18,19]. The solution of the Eq. (6) is [18,19]:

$$P(m,z)=\frac{1}{\sqrt{2\pi}\sigma_z}\exp\left(-\frac{m^2}{2\sigma_z^2}\right) \tag{7}$$

The variance σ_z^2 of the output modal power distribution (7) at the fiber length z, can be calculated as:

$$\sigma_z^2=\sigma_{z=0}^2+2Dz \tag{8}$$

where $\sigma_{z=0}^2$ is the variance of the launch modal power distribution. Coupling coefficient D from Eq. (8) is:

$$D=\frac{\sigma_z^2-\sigma_{z=0}^2}{2z} \tag{9}$$

In order to determine the coupling coefficient D, one needs to determine the variance σ_z^2 of the output modal power distribution $P(m, z)$ at an arbitrary length z along the fiber (the variance of the Gaussian launch modal power distribution $\sigma_{z=0}^2$ has to be known).

If the variance of the Gaussian launch beam distribution $\sigma_{z=0}^2$ is not known, coupling coefficient D can be determined using the following relation:

$$D=\frac{\sigma_{z_2}^2-\sigma_{z_1}^2}{2(z_2-z_1)} \tag{10}$$

where $\sigma_{z_1}^2$ and $\sigma_{z_2}^2$ are variances of the output modal power distribution $P(m, z_1)$ and $P(m, z_2)$ measured at the fiber lengths $z_1 > 0$ and $z_2 > 0$, respectively ($z_2 > z_1$). It is interesting to note that in our previous work [19] the same form of Eqs. (9) and (10) is proposed for calculating the coupling coefficient D in SI multimode optical fibers where the output angular power distributions $P(\theta, z)$ for one fiber length z with the known Gaussian form of the input light launched centrally along the fiber axis ($\theta_0 = 0$) is needed to be known.

3. Verification of the method

We applied our method to the GI glass optical fiber investigated in a previously reported work [14]. Fig. 1a shows the normalized modal power distributions at three fiber lengths $z = 0$ m, 1000 m and ∞ for light beam with Gaussian distribution launched centrally ($\theta_0 = 0°$) along the fiber axis without radial offset

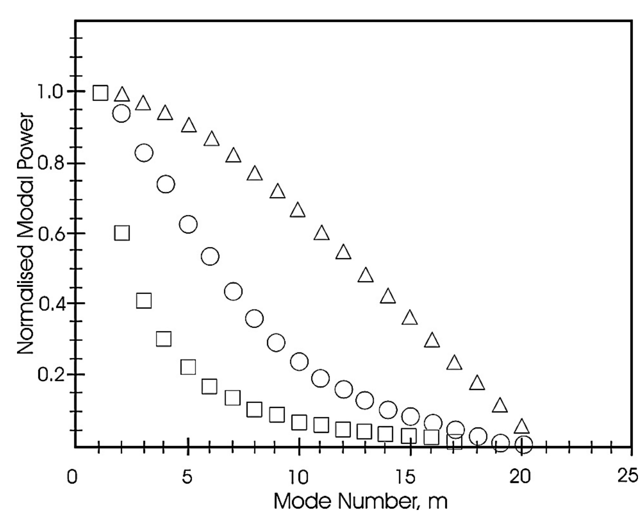

Fig. 1a. Normalized output modal power distribution $P(m, z)$ calculated by solving the time-independent power flow Eq. (2) at different fiber lengths $z = 0$ m (□), 1000 m (○) and ∞ (Δ) [14].