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Mode coupling in glass optical fibers and liquid-core optical fibers by three methods

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ABSTRACT

We test Slemon and Wells's function and recently reported Hurand et al.'s (*Appl. Opt.*, 50, 492–499, 2011) function for calculation of coupling characteristics in step-index optical fibers against experimental measurements and against calculations by a related method that is based on the power flow equation. Compared are the coupling length L_c (which is the fiber length where the equilibrium mode distribution is achieved) and length z_s (where steady-state distribution is achieved) in three step index glass optical fibers as well as a liquid core optical fiber. The two functions, while simpler to apply being just algebraic formulas, are less accurate over a wide range of numerical apertures. It is also shown that fibers with same coupling coefficient can have much different coupling characteristics.

1. Introduction

Mode coupling in step index (SI) optical fibers is the transfer of power between neighboring modes. It strongly affects transmission characteristics of the fiber by altering the input (angular) power distribution progressively along the fiber length [1–8]. Mode coupling is caused by fiber impurities and inhomogeneities introduced during the fiber manufacturing process. Examples of such imperfections are microscopic bends, diameter variations, irregularity of the core-cladding boundary, and refractive index distribution fluctuations.

Due to mode coupling, the optical power distribution at the output end of the fiber depends not only on the launch conditions but also on fiber length and properties. For example, light launched with a specific angle θ_0 relative to the fiber axis (along a cone) can be focused behind the output fiber-end into a sharply defined ring image – but only for short fibers. Mode coupling causes the boundary (edges) of such a ring to become blurred or fuzzy for longer fibers because the narrow angular power distribution of the launch widens. The extent of this fussiness increases with fiber length and the ring-pattern in the image evolves gradually into a disk. "Coupling length" L_c marks the fiber length at which the distribution of the highest order guiding modes shifts its mid-point to zero degrees (from the initial value of θ_0 at the input fiber end).

An equilibrium mode distribution (EMD) is said to exist beyond the coupling length L_c of the fiber. It is characterized by the absence of rings regardless of launch conditions (i.e. angle of launch). The resulting disk pattern is still not uniform throughout and light distribution across it continues to vary with launch conditions. Nevertheless, EMD indicates a substantially complete mode coupling. It is of critical importance when measuring characteristics of multimode optical fibers (linear attenuation, bandwidth, etc). Measurement of these characteristics is considered meaningful only if performed at or beyond the EMD condition when it is possible to assign to a fiber a unique value of loss per unit length [2].

At fiber length z_s ($z_s > L_c$), all individual disk patterns corresponding to different launch angles take the same light-distribution across the fiber core. The "steady-state distribution" (SSD) is then said to have been achieved as the output light distribution becomes independent of launch conditions. SSD indicates the full completion of the mode coupling process (the coupling process continues but with no further apparent effects).

To experimentally determine the fiber length L_c (where the EMD is achieved), pulse broadening measurements can be performed for different fiber lengths z while trying to identify that specific length $z=L_c$ beyond which the bandwidth becomes proportional to $1/z^{1/2}$ – instead of $1/z$ up to that length z [3,6]. An alternative method of determining L_c is to identify that specific fiber length $z=L_c$ after which the output angular power

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distribution extends over the entire fiber core (takes the disk pattern in the far field image) regardless of the incidence angle. Actually, L_c marks the length at which this happens with the highest guided input modes; the lower ones achieve the same at lengths that are shorter than L_c.

In this paper, the coupling length L_c for achieving EMD and the length z_s at which the SSD is achieved are calculated using previously reported functions [8–10] and also by solving the power flow equation [10]. The two methods are compared to experimental findings. This is done for three glass optical fibers and for a liquid-core optical fiber (which is a multimode waveguide with a liquid core that is contained by a hollow glass or capillary tube serving as fiber cladding).

2. Calculation of the coupling length L_c and length z_s for achieving SSD

In order to determine the coupling length L_c and length z_s for achieving the SSD, we solve Gloge's power flow equation [10]:

$$\frac{\partial P(\theta, z)}{\partial z} = -\alpha(\theta)P(\theta, z) + \frac{D}{\theta}\frac{\partial}{\partial\theta}\left(\theta\frac{\partial P(\theta, z)}{\partial\theta}\right) \tag{1}$$

where $P(\theta,z)$ is the angular power distribution, z is distance from the input end of the fiber, θ is the propagation angle with respect to the core axis, D is the coupling coefficient assumed constant [10–12] and $\alpha(\theta)$ is the modal attenuation. The boundary conditions are $P(\theta_c,z)=0$, where θ_c is the critical angle of the fiber, and $D(\partial P/\partial\theta)=0$ at $\theta=0$. Condition $P(\theta_c,z)=0$ implies that modes with infinitely high loss do not carry power. Condition $D(\partial P/\partial\Theta)=0$ at $\theta=0$ indicates that the coupling is limited to the modes propagating with $\theta>0$. Except near cutoff, the attenuation remains uniform $\alpha(\theta)=\alpha_0$ throughout the region of guided modes $0\le\theta\le\theta_c$ [13] (it appears in the solution as the multiplication factor $\exp(-\alpha_0 z)$ that also does not depend on θ), and may be omitted from the equation when only relative modal power distribution is of interest. Therefore, Eq. (1) reduces to [14]:

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

The solution of Eq. (2) for the steady-state power distribution is given by [12]:

$$P(\theta, z) = J_0\left(2.405\frac{\theta}{\theta_c}\right)\exp(-\gamma_0 z) \tag{3}$$

where J_0 is the Bessel function of the first kind and zero order and $\gamma_0[\mathrm{m}^{-1}]=2.405^2 D/\theta_c^2$ is the attenuation coefficient. We used this solution to test our numerical results for the case of the fiber length z_s at which the power distribution becomes independent of the launch conditions. This length, at which steady-state distribution is achieved, can be obtained using Hurand et al.'s equation [8]:

$$z_s \approx \frac{0.2}{D}\left(\frac{\mathrm{NA}}{n_1}\right)^2 \tag{4}$$

where n_1 is the refractive index of the core and NA is numerical aperture of the fiber.

Slemon and Wells [9] have shown that the coupling length L_c (at which an equilibrium mode distribution is achieved) is as follows:

$$L_c = \frac{(\mathrm{NA})^2}{D} \tag{5}$$

where NA is numerical aperture of the fiber and D is the coupling coefficient. Hurand et al. proposed function (4) on the basis of empirical examination of several steady state lengths Z_s, for different values of NA, n_1 and D. Similarly, Slemon and Wells proposed function (5) on the basis of empirical examination of several coupling lengths L_c, for different values of NA and D. Hurand et al. determined coupling coefficient D using our previously reported method [15] while Slemon and Wells determined coupling coefficient D using Gambling et al.'s method [11].

To obtain a numerical solution of the power flow Eq. (2), we used the explicit finite-difference method (EFDM) [14,16]. We started the calculations with the Gaussian launch-beam distribution in the following form:

$$P(\theta, z) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{(\theta-\theta_0)^2}{2\sigma^2}\right] \tag{6}$$

with $0\le\theta\le\theta_c$, where θ_0 is the mean value of the incidence angle distribution, and the full width at half-maximum is $\mathrm{FWHM}=2\sigma\sqrt{2\ln 2}\approx 2.355\sigma$ (σ is standard deviation). This distribution is suitable for both, LED and laser beams. One can obtain the characteristic lengths L_c and z_s ($z_s>L_c$) by solving the power-flow equation.

In our previous works we have shown that the lengths L_c and z_s depend on both, the numerical aperture of the fiber [16] and width of the launch beam distribution [17]. This contrasts Slemon and Wells's result (5) and Hurand et al.'s result (4) in which these lengths were independent of the width of the launch beam distribution. We will verify the accuracy of the proposed functions (5) and (4) by comparing the obtained results for L_c and z_s with the results obtained by solving the power flow equation.

3. Results and discussion

In order to test the Slemon and Wells's function (5) and Hurand et al.'s function (4), we solved the power flow equation to evaluate the lengths L_c and z_s for glass core optical fibers that had been investigated by Slemon and Wells [9] and Gambling et al. [11] and liquid core optical fiber investigated by Gambling et al. The two optical fibers used by Slemon and Wells are Valtec plastic coated glass fiber and Corning glass fiber. The Valtec plastic coated glass fiber has NA=0.3, the inner critical angle $\theta_c=11.9°$, refractive index of the core $n_1=1.46$ and coupling coefficient $D=2.0\times10^{-4}$ rad^2/m. The Corning glass fiber has NA=0.16, the inner critical angle $\theta_c=6.3°$, refractive index of the core $n_1=1.46$ and coupling coefficient $D=2.0\times10^{-4}$ rad^2/m. Both fibers were degraded by handling and age in the laboratory [9]. The two optical fibers used by Gambling et al. are lead glass core borosilicate cladding fiber and liquid-core fiber. The liquid core fiber comprised a liquid core of hexachlorobutadiene contained in a glass capillary of 100 μm bore. The lead glass core borosilicate cladding fiber has NA=0.63, the inner critical angle $\theta_c=22°$, refractive index of the core $n_1=1.65$ and coupling coefficient $D=4.0\times10^{-4}$ rad^2/m. The liquid core fiber has NA=0.46, the inner critical angle $\theta_c=17.3°$, refractive index of the core $n_1=1.552$ and coupling coefficient $D=3.0\times10^{-6}$ rad^2/m.

Our solution of the power flow equation is presented in Fig. 1 by showing the evolution of the normalized output power distribution with fiber length for glass core borosilicate cladding fiber. We show results for three different input angles $\theta_0=0°$, 5° and 10°. We selected Gaussian launch beam distribution with $(\mathrm{FWHM})_0=0.6°$ (the laser launch beam in the Gambling et al.'s experiment was with $(\mathrm{FWHM})_0=0.6°$) and 30°, by setting $\sigma_0=0.255°$ and $\sigma_0=12.739°$ in Eq. (6), respectively. We achieved stability of the finite-difference scheme with the step lengths of