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Mode coupling in 340 μm GeO_2 doped core-silica clad optical fibers

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ABSTRACT

The state of mode coupling in 340 μm GeO_2 doped core-silica clad optical fibers is investigated in this article using the power flow equation. The coupling coefficient in this equation was first tuned such that the equation could correctly reconstruct previously reported measured output power distributions. It was found that the GeO_2 doped core-silica clad optical fiber showed stronger mode coupling than both, glass and popular plastic optical fibers. Consequently, the equilibrium as well as steady state mode distributions were achieved at shorter fiber lengths in GeO_2 doped core-silica clad optical fibers.

1. Introduction

Step-index (SI) multimode glass optical fibers have found their niche in a variety of applications involving laser beam delivery and sensing. For beam delivery, it is often desirable to use relatively large-core fibers (200–500 μm core radius) to transmit high-power laser pulses with high beam quality [1]. Applications may include the laser ignition of engines [2], medical diagnostics, or photocoagulation and other surgical treatments [3]. Large-core fibers may require lenses to focus the fiber output beam – for example for the spark to form in laser ignition. While conventional single-mode (SM) fibers with small cores might not need lenses, they would probably perform inadequately in such applications as the maximum power they can transmit would likely not suffice. Moreover, the SM fibers' low misalignment-tolerance at input couplers may be problematic in practical systems and diffraction and lens aberration may limit the focused spot sizes (to several micrometers), making the de-magnification of the fiber output difficult [1]. Similar considerations are of interest in laser-induced breakdown spectroscopy, as well as in laser drilling, cutting, and welding applications. Such applications benefit from the large-core optical-fibers' capacity to deliver high-power light pulses with high spatial beam quality. Thus for example, the smallest spot of the focused laser beam may be used in surgery for cutting and vaporizing tissue while a defocused spot may be of interest for coagulation. In contrast to telecommunications, these applications typically require pulse delivery over relatively short distances (1–15 m); this function may be similar to that of a fiber optic patch cord.

Transmission performance of multimode optical fibers is strongly affected by mode coupling. Such coupling represents the transfer of power between neighboring modes. It perturbs the angular power distribution of the launched light. The effect is cumulative and therefore more intensely manifested with distance along the fiber from the input end [1,4–8]. It is caused by fiber imperfections including in terms of its geometric shape and material homogeneity (for example bends, diameter and shape variations of the core-cladding boundary, or fluctuations of the refractive index).

While the angular power distribution expectedly depends on conditions of the launch, mode coupling makes it dependent also on fiber length and properties. A conical launch at a fixed angle θ_0 to fiber axis can, behind the output end of a short fiber, be focused into a sharply defined image of a ring (with diameter corresponding to θ_0). In longer fibers, however, mode coupling perturbs such image. The boundary of the ring blurs in longer fibers because the angular power distribution, narrow at launch, widens gradually with the fiber length. This blurring intensifies with fiber length and the image of a ring mutates gradually into a disk as the angular power distribution shifts its mid-point from the launch value of θ_0 to zero degrees. At the "coupling length" L_c, the distribution even of the highest order guiding mode has shifted its mid-point to zero degrees.

Beyond the coupling length L_c is an "equilibrium mode distribution" (EMD) when all individual ring patterns corresponding to different launch angles are imaged as disks. Mode coupling is then largely complete for most practical purposes because the variation in the launch angle produces only a slight variability in the light intensity across the said disk in the image. Coupling is fully complete at fiber length z_s ($z_s > L_c$) when even such variability in light distribution across the image phases out and the same disk-image results whatever the launch conditions. This represents a "steady-state distribution"

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(SSD) as the output distribution is independent of the launch. Further mode coupling produces no apparent effects.

In this paper, we study mode coupling and output beam quality of 340 µm GeO_2 doped core-silica clad fibers. The Gloge's power flow equation for diffusion of modal power is used to determine mode coupling coefficient by reference to measured data reported in literature. This enabled us to calculate the coupling length L_c for achieving the EMD and the length z_s at which the SSD is achieved, and then compare these characteristic lengths to those for glass as well as plastic optical fibers.

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 [9]:

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

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 [9–11] 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 $0 \le \theta \le \theta_c$ [11] (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 [12]:

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

The solution of Eq. (2) for the steady-state power distribution is given by [11]:

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

where J_0 is the Bessel function of the first kind and zero order and $\gamma_0[m^{-1}]=2.405^2 D/\theta_c^2$ 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 fiber length where steady-state distribution is achieved can be obtained from the empirical relationship proposed by Hurand et al. [1]:

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

where n_{core} is the refractive index of the core and NA is numerical aperture of the fiber. Hurand et al. have determined the coupling coefficient D in (4) by our previously reported method [13].

To obtain a numerical solution of the power flow Eq. (2), we used the explicit finite-difference method (EFDM) [12]. We started the calculations with the following Gaussian launch-beam distribution:

$$P(\theta, z) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{(\theta-\theta_0)^2}{2\sigma^2}\right] \tag{5}$$

for $0 \le \theta \le \theta_c$, 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 state of mode coupling as well as a characteristic lengths L_c and z_s ($z_s > L_c$) by solving the power-flow equation.

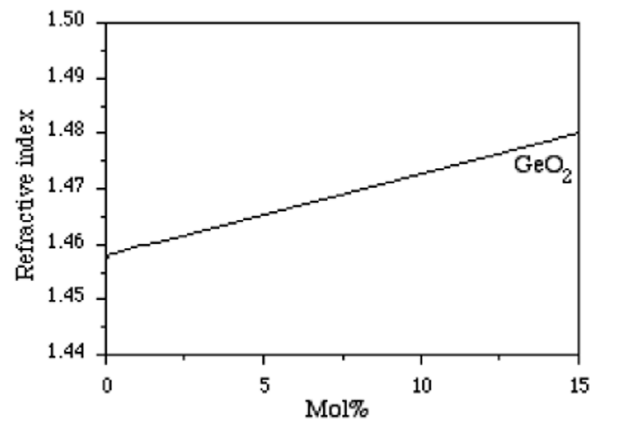

Fig. 1. Refractive index versus dopant concentration for silica doped with GeO_2, at λ=633 nm [14].

3. Results and discussion

We solved the power flow Eq. (2) to evaluate the lengths L_c and z_s for the GeO_2 doped-silica clad optical fiber that had been investigated experimentally by Fujii et al. [3]. Their fiber had NA=0.23, the inner critical angle θ_c=9° (θ_c=13° measured in air), core refractive index n_{core}=1.478, core diameter d_{core}=340 µm and cladding diameter d_{clad}=400 µm. Because the fiber manufacturer did not specify the concentration of GeO_2 dopants in the core of this fiber, we obtained it indirectly from the plot in Fig. 1 [14] showing how refractive index for silica varies with the GeO_2 dopant concentration (at wavelength of 633 nm). For n_{core}=1.478 in Fig. 1, it follows that the concentration of GeO_2 dopants is ≈14 mol%.

In their experiment, Fujii et al. focused a He-Ne laser beam to the input end of the fiber. The near-field power distribution of the fiber output they detected by a photomultiplier with a small pinhole in front of it that scanned across the receiving plane, Fig. 2.

We tuned the coupling coefficient D in the power flow equation such that it could correctly reconstruct the output power distributions in this fiber measured by Fujii et al. [3] and shown in Fig. 3. This required solving the power flow equation numerically for different coupling coefficients D. The value of $D=3.2\times10^{-4}$ rad^2/m was adopted as giving the best match between the calculated and measured (measured by Fujii et al.) output power distributions. In the calculations, we selected Gaussian launch beam distribution with $(\mathrm{FWHM})_0$=0.05°. Our solution of the power flow equation is presented in Fig. 4 showing the output power distribution for a 5 m long GeO_2 doped core-silica clad fiber and for five different input angles, θ_0=0, 4, 5, 6 and 7°. The output power distributions $P(x, z=5\text{ m}, L=4\text{ mm})$ shown in Fig. 4 are obtained from the output angular power distributions $P(\theta, z=5\text{ m}, L=4\text{ mm})$ using $x=L\cdot\mathrm{tg}\theta$, where L is receiving distance.

Fig. 5 shows the same data in normalized form and with the abscissa in terms of the output angles in degrees. It is evident from both Figs. (4 and 5) that the effects of coupling within the first 5 m of fiber length are stronger for the low-order modes: as their distribution maxima have already shifted towards the core center (x=0 mm or θ=0° in Figs. 4 and 5, respectively). Within the same length of 5 m, the coupling of highest-order modes (6° and 7°) was still insufficient to shift their distribution maxima to the fiber center (at x=0 mm, i.e. at θ=0°). It is not until the fiber's coupling length $z=L_c$=7 m that the

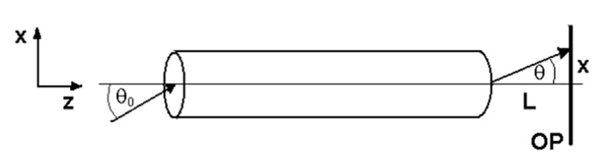

Fig. 2. Schematics of measuring power distributions in the near-field observation plane of the fiber output [3].