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A comparison of temperature sensing characteristics of SMS structures using step and graded index multimode fibers

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ABSTRACT

A comparative study of the temperature sensitivities of the single-multi-single mode (SMS) fiber structures employing step-index and graded-index multimode fibers (MMFs), for two different doping concentrations of GeO_2 in MMF core, is carried out. The temperature sensitivity for graded-index MMF is found to be much larger (approx. 45–285 times) for the entire range of wavelength operation (0.7–1.6 μm). A physical explanation of the observed behavior is also presented. The study should be useful in designing various fiber optic multimode interference based devices with high or low temperature sensitivities.

1. Introduction

Fiber optic devices based on the modal interference among guided modes of a MMF, spliced in between two single mode fibers (SMFs), have attracted enormous research attention in the recent past, due to their low cost, ease of fabrication, and the freedom they offer in tailoring the output spectrum. These, so called SMS fiber structures have been extensively used for various applications such as sensors [1–3], optical beam shaper [4], optical switches, directional couplers [5], band pass/stop filters [6,7], and fiber lenses [8] etc. Some of these devices, such as temperature sensors, require high temperature sensitivity while others require zero or low temperature sensitivity. The transmission characteristics of SMS fiber structures are basically decided by the spectral variation of propagation constant differences of various guided modes of the MMF used. This in turn is decided by the refractive index profile, dopant concentration and other fiber parameters of the MMF. For example in a recent paper we have shown that such structures can be made temperature insensitive by properly adjusting the concentrations of P_2O_5 and GeO_2 in the core region of the MMF [9]. A systematic study of the effect of MMF parameters such as refractive index profile on the temperature sensitivity of such structures is however not yet reported. In this paper we theoretically obtained and compared the temperature sensitivities of various SMS fiber structures consisting of step and graded index MMFs with different GeO_2 doping concentrations in their cores for wavelength range of 0.7–1.6 μm. It is observed that the temperature sensitivity is always much higher (approx. 45–285 times) in the case of graded index multimode fibers.

2. Theoretical analysis

We consider a SMS fiber structure consisting of a step/graded index MMF of length, L, axially spliced at both the ends to identical step index SMFs as shown in Fig. 1. At the first splice light is launched into the MMF section through the lead-in SMF. Generally, the spot size of the fundamental mode of the MMF is different than that of the SMF. This leads to the excitation of a number of guided modes in the MMF, at the input splice, which propagate with their respective propagation constants along the length of the MMF developing a certain phase difference among them. At the second splice these modes along with their respective phases are coupled back to the fundamental mode of the SMF leading to a periodic transmission spectrum, with the period governed by the accumulated phase difference among the MMF modes. If at the first splice the MMF is axially aligned with the SMF, only the axially symmetric modes (LP_{0m}) of the MMF will be excited, whereas a transverse misalignment will lead to the excitation of modes other than axially symmetric modes also.

In our analysis, we assume that fibers are axially aligned at both the splices. Considering $\Psi \equiv \Psi_S(r)$ as the normalized fundamental mode field of the SMF, the field within the MMF can be expressed as $\Psi_M = \sum_m a_m \psi_m$, where a_m and ψ_m are the field amplitude at the lead-in splice and the normalized axially symmetric field of the

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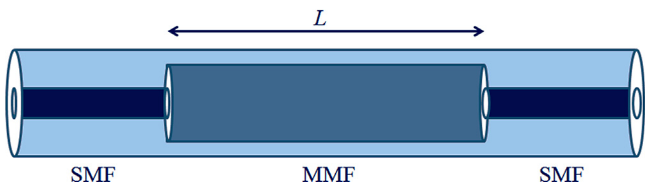

Fig. 1. Schematic diagram of a SMS structure.

mth mode of the MMF, respectively. The field amplitudes a_m are basically determined by the modal overlap between the fundamental mode of the SMF and the concerned mth mode of the MMF, i.e.,

$$a_m = 2\pi \int_0^\infty \Psi_S \psi_m r dr \tag{1}$$

As mentioned earlier different guided modes, will develop a certain phase difference as they propagate along the MMF length. At the lead-out splice these fields are then coupled back to fundamental mode of the SMF, and the power in the lead-out fiber can be written as [2]

$$P_{SM} = \left| a_1^2 + a_2^2 e^{i(\beta_1-\beta_2)L} + a_3^2 e^{i(\beta_1-\beta_3)L} + \cdots \right|^2 \tag{2}$$

where, β_m is the propagation constant of the mth mode.

Using well known Gaussian approximation, modal field of the SMF can be written as [10]

$$\Psi_S(r) = \sqrt{\frac{2}{\pi}} \frac{1}{w_S} e^{\frac{-r^2}{w_S^2}} \tag{3}$$

here, w_S is the Gaussian spot size of the mode, which can be approximated as

$$\frac{w_S}{a_S} = \left[0.65 + \frac{1.619}{V_S^{3/2}} + \frac{2.879}{V_S^6}\right]; 0.8 \le V_s \le 2.5, \tag{4}$$

here, a_S and V_S represent the core radius and the V-number of the SMF, respectively.

2.1. Calculation of β_m and ψ_m

(i) For graded index MMF
The spot size of the SMF is generally very small as compared to the MMF core diameter, and hence only the first few modes of the MMF are excited at the input splice. These modes are typically tightly confined within the MMF core region and hence the refractive index distribution of the graded index MMF can be approximated by an infinitely extended parabolic distribution. Under this approximation the propagation constant of the mth symmetric mode and the field distribution of the graded index MMF are given by [2,11]

$$\beta_m = k_0 n_0 \left[1 - \frac{2(2m-1)\alpha_m}{k_0^2 n_0^2}\right]^{1/2} \tag{5}$$

here, m=1, 2, 3… and $\alpha_m = (k_0 n_0 / a_M)\sqrt{2\Delta_M} = V_M / a_M^2$, with V_M being the V-number of the graded index MMF defined through, $V_M = k_0 a_M \sqrt{n_0^2 - n_{cl}^2}$. The normalized field distributions are

$$\psi_m(r) = \sqrt{\frac{2}{\pi}} \frac{1}{w_M} L_{m-1}\left(\frac{2r^2}{w_M^2}\right) e^{(-r^2/w_M^2)} \tag{6}$$

here, $L_m(r)$is the Laguerre polynomial of degree m, and w_M is the Gaussian spot size of the fundamental mode given by

$$w_M = \left[\frac{2a_M}{k_0 n_0 \sqrt{2\Delta_M}}\right]^{1/2} = a_M \sqrt{\frac{2}{V_M}} \tag{7}$$

(ii) For step index MMF
The modal field patterns for various modes of a step index fiber are also well known [11]. The modal field for mth symmetric mode can be written as

$$\psi_m = \begin{cases} \frac{A}{J_0(U_m)} J_0\left(\frac{U_m r}{a_M}\right); & r < a_M \\ \frac{A}{K_0(W_m)} K_0\left(\frac{W_m r}{a_M}\right); & r > a_M \end{cases} \tag{8}$$

here $U_m = a_M (k_0^2 n_0^2 - \beta_m^2)^{1/2}$;$W_m = a_M (\beta_m^2 - k_0^2 n_{cl}^2)^{1/2}$
The corresponding propagation constants are calculated numerically by solving the following Eigen value equation

$$U_m \frac{J_1(U_m)}{J_0(U_m)} = W_m \frac{K_1(W_m)}{K_0(W_m)} \tag{9}$$

Using the propagation constants and the modal field distributions in Eqs. (1) and (2), the power in the lead-out SMF and hence the transmission spectrum for SMS structures consisting of various step and graded index (parabolic-core) MMFs can be calculated.

3. Results and discussion

In our calculations the SMF core region is considered to be made of 3.1 mol% GeO_2 in SiO_2 host. The MMFs core regions are considered to be doped with 7.0 mol% of GeO_2 and 13.5 mol% of GeO_2 in SiO_2 for both step as well as parabolic core profiles. The cladding region for both the SMFs and MMFs is considered to be made of fused SiO_2. The diameters of SMF and MMF are taken as 4 μm and 62.5 μm respectively. The wavelength dependent refractive indices of various regions are obtained by using the Sellmeier relation [12].

In Fig. 2, we plot the variation of the spot size (w_S) of the fundamental mode of the SMF obtained using Eq. (4), as a function of wavelength. The spot size is much smaller than the core radius of the MMF in the entire wavelength range. This justifies the infinitely extended parabolic core approximation (see Section 2.1) used for obtaining the fields and propagation constants of the graded index MMF.

The temperature dependence of the refractive index of ith region has been obtained by using the relation $n_i = n_{0i} + (dn_{0i}/dT)(T - T_0)$, where n_{0i} represents the refractive indices at room temperature T_0. The thermo-optic coefficient dn/dT for fused SiO_2 and 15 mol% GeO_2 doped SiO_2 are known to be $1.06 \times 10^{-5}/^\circ C$ and $1.24 \times 10^{-5}/^\circ C$ respectively [2]. Assuming a linear dependence of the

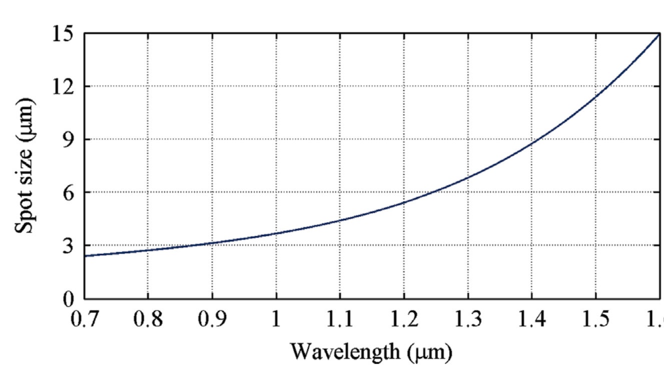

Fig. 2. Variation of spot size of SMF with wavelength.