POWER TRANSFER BETWEEN SINGLE-MODE AND MULTIMODE OPTICAL FIBERS

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ABSTRACT

Based on a coupled-mode theory, the power transfer between two parallel single-mode and multimode optical fibers is investigated. Numerical calculations show that power coupling among the guided modes can be very complicated. The theoretical results provide an important guidance for the design of directional couplers composed of such fibers.

INTRODUCTION

It is well known that when the optical fiber cores are brought close enough to each other, wave coupling and thus the transfer of optical power between the fibers can occur due to the interaction of the extended evanescent optical fields just outside of the cores. By making use of this physical phenomenon, various optical-fiber directional couplers have been fabricated (1). One application of the directional coupler in optical-fiber local-area networks (LAN's) is as the Drop/Insert (D/I) device of a node (2) where the receiver picks up a small fraction of the optical energy carried on the fiber bus and the transmitter injects the lightwave signal onto the bus. It is desirable that the power from the local transmitter can be tightly coupled into the bus, while most of the power on the fiber bus can propagate through the node without being taken away. It has been proposed (3) that utilizing a single-mode pigtail fiber for the local transmitter along with the multimode fiber bus may achieve such performance. This design calls for the consideration of a directional coupler composed of a single-mode fiber and a multimode fiber.

In this paper we present the results of a theoretical investigation of directional coupling effect between a single-mode (SM) and a multimode (MM) optical fiber, based on a coupled-mode theory (4).

COUPLED-MODE ANALYSIS

For simplicity, we consider two infinitely long and parallel cores embedded in a background cladding as shown in Figure 1. The refractive indices of the cladding, the SM core, and the MM core are denoted as n_c, n_s, and n_m, respectively. The radii of the SM core and the MM core and the distance between the centers of the cores are a_s, a_m, and D, respectively.

We adopt the coupled-mode equations derived in Reference (4). For the present system of two parallel lossless fibers, the set of coupled-mode equations is of the form

$$\frac{dA_0(z)}{dz} + i\beta_0 A_0(z) = -i\sum_{k=1}^{N} c_{0k}A_k(z) \qquad \text{(1a)}$$

$$\frac{dA_k(z)}{dz} + i\beta_k A_k(z) = -ic_{k0}A_0(z), \qquad k=1,2,\ldots,N. \qquad \text{(1b)}$$

The z direction is taken to be parallel to the fiber axes. We assume that only the guided mode of the SM fiber and N guided modes of the MM fiber dominate the coupling process. In equations (1a) and (1b), the subscript 0 refers to the SM fiber and the subscript k refers to the MM fiber. The β's represent the modal propagation constants and the A(z)'s represent the modal coefficients on the z plane. The c_{0k}'s and c_{k0}'s are the coupling coefficients between the guided mode in the SM fiber and those in the MM fiber. They are given by the following surface integrals

$$c_{0k} = \frac{\omega}{2}\int_{A_m}(n_m^2 - n_c^2)\,\bar{e}_0\cdot\bar{e}_k\,ds \qquad \text{(2a)}$$

$$c_{k0} = \frac{\omega}{2}\int_{A_s}(n_s^2 - n_c^2)\,\bar{e}_k\cdot\bar{e}_0\,ds \qquad \text{(2b)}$$

where ω is the wave frequency, A_s and A_m represent the cross sections of the SM and MM cores, respectively, and $\bar{e}$'s are the modal electric field vectors. All

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modes are assumed to travel in the +z direction.

NUMERICAL RESULTS AND DISCUSSION

In the following calculation, we assume that both the SM and MM fibers have step-index cores. The wavelength is taken to be 1.3 μm and the parameters of Figure 1 are $n_s = n_m = 1.458$, $n_c = 1.4551$, $a_s = 3.1645$ μm, $a_m = 25$ μm, and $D = a_s + a_m + 1$ μm. We use the linearly polarized modes (LP_{lm} modes) for the guided modes. The propagation constant β_0 of the guided (LP_{01}) mode of the SM fiber is found to be 7.035487 μm^{-1}. Seventeen guided modes (i.e., N = 17 in equation (1b)) with β_k's close to β_0 are then chosen for the coupled-mode analysis. These modes and their corresponding propagation constants are listed in TABLE I. Equations (1a) and (1-b) thus become a set of 18 equations and are solved numerically.

We consider two cases that correspond to power transfer from the SM fiber to the MM fiber and vice versa. The results for the first case are shown in Figure 2. The initial conditions are $A_0(0) = 1$ and $A_k(0) = 0$, for k = 1,2,...,N, on the z = 0 plane. Four of the 17 modes (LP_{04}, LP_{23}, LP_{42}, and LP_{71}) considered for the MM fiber appear to undergo most significant power variations, as indicated by the power-versus-distance curves in Figure 2. It is noticed that at a distance of 2 mm, almost all the power in the SM fiber has been transferred to the MM fiber.

In Figure 3 we present the results for the second case. The initial conditions now are $A_0(0) = 0$ and $A_k(0) = 1$, for k = 1 ,2,...,N. Note that the total power in this case is actually 17 times of that in the first case. Again, the same four modes show significant power variations and it is observed that the first maximum power in the SM fiber takes place at z = 1.5 mm, corresponding to a peak power of 2.8, or 16.5% of the total power. It is interesting to see that due to the perturbation or the presence of the SM fiber, power transfer between the guided modes of the MM fiber, which are in fact orthogonal to one another, can occur, resulting in $A_k(z) > 1$ for some modes at certain locations.

Our results demonstrate that the power coupling between SM and MM fibers can in fact be very complicated. As far as the design of a directional coupler is concerned, Figures 2 and 3 may provide an important guidance. The theoretical curves reveal that the power transfer from the SM fiber to the MM fiber increases uniformly along the propagation direction away from z = 0, whereas that in the reverse direction shows a "threshold" type of behavior. More specifically, there is a distance before significant power transfer to the SM fiber can take place. Based on this observation, if we choose a coupling length of 1 mm, for example, 82% of the power initially in the SM fiber can be transferred to the MM fiber, while only 2% (0.4 versus 17) of that in the MM fiber is taken away and moved to the SM fiber. This fulfills the requirements of the application as the D/I device in the nodes of local networks mentioned in the Introduction.

CONCLUSION

In this paper we have calculated the power transfer between a single-mode optical fiber and a multimode optical fiber, based on a coupled-mode analysis. The results show that the power transfer among different modes can be very complicated and the theoretical curves obtained can be useful for the design of directional couplers composed of two different fibers, as needed in a local area network. More realistic coupler structures involving graded-index MM optical fibers and curved guides are currently under investigation.

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TABLE I

LP Modes for the Multimode Fiber

k	LP_{lm}	$\beta_k(\mu m^{-1})$
1	LP_{01}	7.046282
2	LP_{02}	7.043941
3	LP_{03}	7.039806
4	LP_{04}	7.034212
5	LP_{11}	7.045435
6	LP_{12}	7.042180
7	LP_{13}	7.037221
8	LP_{21}	7.044325
9	LP_{22}	7.040168
10	LP_{23}	7.034497
11	LP_{11}	7.042970
12	LP_{12}	7.037327
13	LP_{41}	7.041380
14	LP_{42}	7.035485
15	LP_{51}	7.039565
16	LP_{61}	7.037534
17	LP_{71}	7.035295

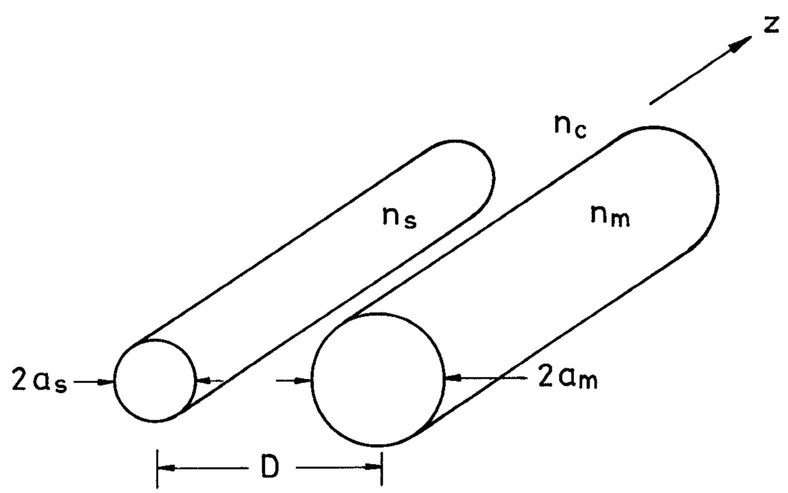

Fig. 1. Sketch of a system of two parallel single-mode and multimode fibers.

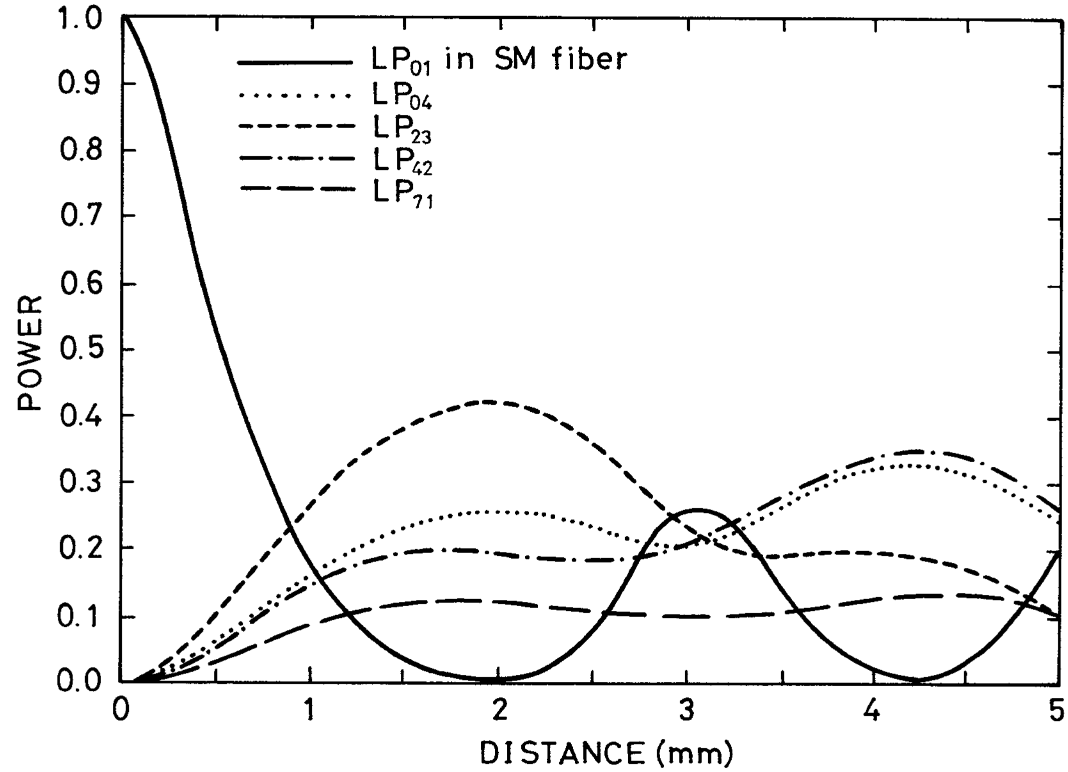

Fig. 2. Power variations versus distance of the fundamental mode in the SM fiber and four guided modes in the MM fiber. The power is initially confined in the SM fiber.

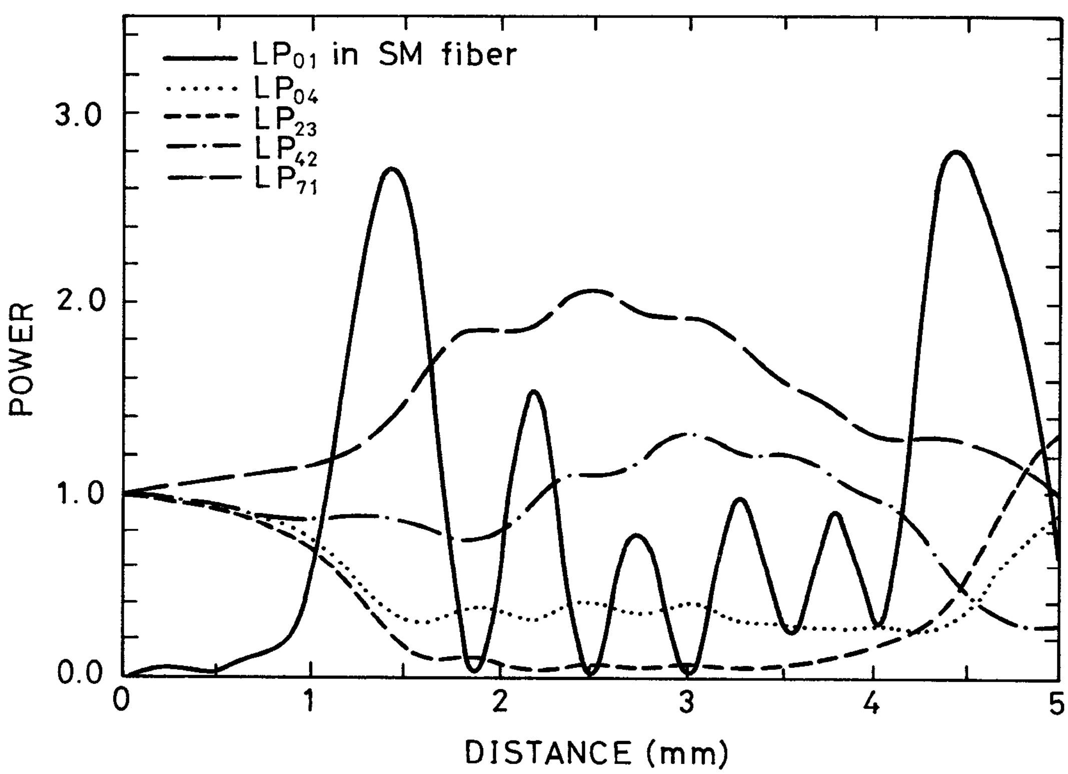

Fig. 3. Power variations versus distance of the fundamental mode in the SM fiber and four guided modes in the MM fiber. The power is initially uniformly distributed over 17 guided modes of the MM fiber.