Design and Characterization of a Plastic Optical Fiber Active Coupler

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***Abstract*—In this letter, we report on the first active coupler developed with the plastic optical fiber technology. The device constructed combines the characteristics of the most important devices arising from this technology, which are switches and couplers. The solution adopted is based on the structure of a passive contact coupler and on the switching properties of a nonquiral nematic liquid crystal. The device designed yields an experimental coupling of 4.5 dB with excess losses under 2.5 dB if the device acts as a coupler; and a dynamic range of 3 dB and switching times of 2 ms if the device acts as a switch.**

***Index Terms*— Liquid crystal, optical fiber coupler, optical switch, plastic optical fiber, POF.**

I. Introduction

FIBER OPTICS have drawn a great amount of research effort during the last two decades due to their optimum transmission characteristics. Plastic optical fibers (POF's) serve to reduce fiber optics costs, and their applications are rapidly growing [1] despite their attenuation drawback. Due to their ease of connection and high numerical aperture the use of POF is increasing in local area networks (LAN), home networks and other short distance applications [2].

The development of new devices, together with the improvement of the existing ones, constitutes an intensive field of research. Couplers and switches are two of the most important devices in POF technology. In this letter, we report on a POF active coupler, a new device combining the characteristics of couplers and switches. The coupling characteristics are obtained by the well-known physical positioning of the contact coupler [3], while its performance as a switch arises from the use of a liquid crystal (LC). As far as we know the device described is the first POF active coupler using LC's.

We begin by describing the physical structure of our POF active coupler, and the results of the simulations. Then we show the parameters measured for our active coupler. Finally, the main conclusions of the present work are summarized.

II. Description of the POF Active Coupler and Simulations

The physical structure of the POF active coupler resembles that of the contact coupler, where the matching oil has been substituted by a thin layer of LC. Fig. 1 shows that structure in detail. The coupler is composed of two polished fibers separated by a layer of LC. In order to correctly polarize the LC, a thin metal layer is deposited on the polished fiber cores.

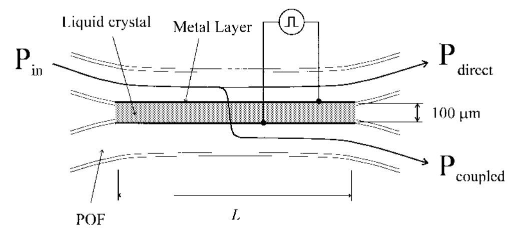

Fig. 1. Physical structure of the active coupler.

The fiber used for the coupler was Eska Premier GH-4001 (Mitsubishi Rayon Company Ltd.) which has a 980-μm diameter polymethylmethacrylate (PMMA) core and a fluorinated polymer cladding. The refractive indexes of the core and cladding are $n_{co} = 1.492$ and $n_{cl} = 1.402$. The LC used for the device was a nonquiral ZLI-1695 (Merck Ltd.), which exhibits a nematic phase between 253 K and 353 K. The ordinary and extraordinary refractive indexes are $n_o = 1.4717$ and $n_e = 1.5342$, respectively, which yield a positive optical anisotropy of $\Delta n = 0.0625$ at room temperature. A thin gold layer was deposited on the polished POF cores using a sputter coater (BACTEC SCD004).

The first step toward the design of the device was the characterization of the coupling structure. To obtain theoretical results, a simplified simulation model, consisting of two parallel polished fibers put together, was used. This model presents two geometrical parameters: the coupling length (L) and the separation between the axes of the fibers (d). The theoretical model is based on ray tracing theory and includes meridional and skew rays, as well as a diversity of light sources (Lambertian and Gaussian), the basis of the calculations being the ray invariants [4] and symmetry relations. The results show a great convergence as the number of rays is increased; in fact, the results for 10 000 rays are within 5% from those obtained for 2.83 million rays (which is approximately the number of modes propagating through the POF; for red light, $\lambda = 660$ nm and $N = V^2/2 = 1/2[2\pi a/\lambda(n_{co}^2 - n_{cl}^2)^{1/2}]^2 \cong 2.83 \cdot 10^6$, where a is the radius of the core of the fiber). Simulations also show that variations on the input power distributions do not alter the results significantly. Fig. 2 shows the coupling ($C(\text{dB}) = 10\log(P_c/P_{\text{out}})$, where P_c stands for the coupled power and P_{out} for the total output power) as a function of the geometrical parameters of the coupler (L, d) for a

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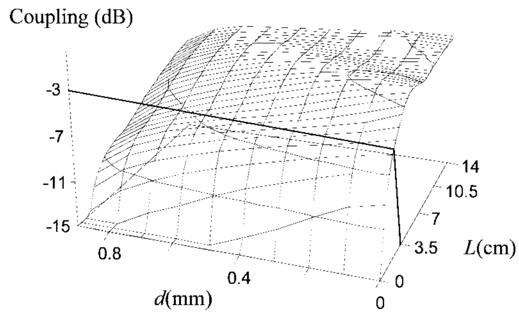

Fig. 2. Results of the simulations for the coupling structure as a function of the coupling length and the separation between fiber axes.

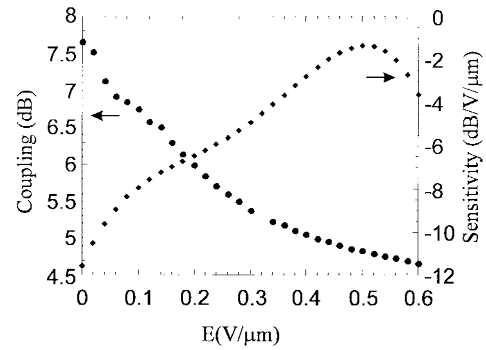

Fig. 3. Coupling and sensitivity of the constructed active coupler. Coupling length 3 cm, separation between fiber axes 0 cm and LC layer thickness 100 μm.

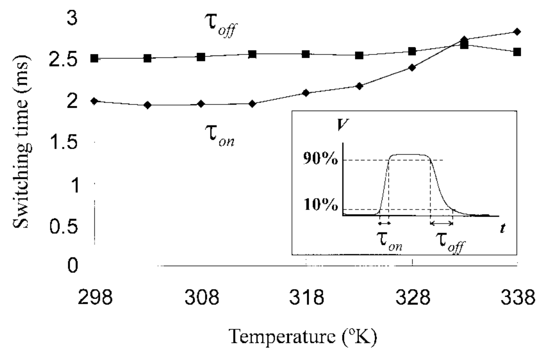

Fig. 4. Measured switching times corresponding to a layer of 10 μm of the ZLI-1695 LC.

uniform input power distribution. As L increases the coupling approaches 3 dB in an oscillatory way. For d close to 980 μm, the coupling exhibits a fast decay, not appreciated in Fig. 2, as the coupling section disappears. As marked on Fig. 2, an equal power splitting ratio can be obtained, for instance, with a separation between the fiber axes $d = 0$ and a coupling length $L = 3.5$ cm.

Once the dimensions of the coupling structure were theoretically determined ($C = -3$ dB; $d = 0$; $L = 3.5$ cm), the next step on the construction of the active coupler consisted in the insertion of the LC layer. By means of the sputtering technique, a thin layer of gold (around 5 nm) was deposited on the polished POF cores. The thickness of the metal layer must not exceed the skin depth ($\delta = 1/\sqrt{\pi\mu f\sigma} = 3.7$ nm $\lambda = 660$ nm), but the conductivity σ of the metal layer has to be high enough to allow the correct polarization of the LC. The LC layer was sandwiched between the two sections of the contact coupler and the thickness obtained for the layer was of the order of 100 μm.

III. Behavior Principles

The behavior of the device is based on the optical properties of LC's [5]–[7]. In the absence of an applied electric field the molecules of the LC are oriented along the polishing direction (fiber axis direction), yielding an average index of refraction for the LC close to the ordinary refractive index, which is lower than that of the core of the POF. Consequently, the reflection at the fiber-LC interface is high. As an increasing electric field is applied, the LC molecules are aligned in the direction of the applied field, due to the positive dielectric anisotropy of the LC. In this situation, the average refractive index of the LC $(\langle n_{LC}\rangle \cong (n_o + n_e)/2 = 1.503)$ is closer to that of the fiber core, which improves the transmissivity.

IV. Results and Discussion

The constructed device was then characterized. First of all, the fiber output powers of the coupler in terms of the applied control voltage was measured. The input fiber was illuminated with a 543.5-nm He–Ne laser, while the output fibers were connected to a dual-channel lightwave multimeter (HP-8153A) by two optical heads (HP-81 520A). The output power of the two fibers were simultaneously determined in terms of the applied control voltage.

Fig. 3 shows the results. The measurement procedure was repeated ten times, and the optical heads were switched before each repetition to eliminate the influence of the photodiode sensitivity. Fig. 3 shows the coupling $(C(\text{dB}))$ and the sensitivity $(S = dC/dE)$ of the active coupler, calculated from a fifth order polynomial approximation of the coupling.

The coupling increases with the electric field and reaches a maximum value of near 4.5 dB with the saturation electric field of the LC ($\cong 6 \cdot 10^5$ V/m). The increase is more rapid for low electric fields, as can be observed in the sensitivity curve. The coupling reaches 4.5 and 1.5 dB apart from the equally splitting ratio, for the ON state, with excess losses around 2.5 dB. The isolation is always over 30 dB, while the uniformity obtained is under 1 dB.

The active coupler also works as a switch if the applied field is conmuted from the ON to the OFF state and vice versa. The difference in coupling between the two states (dynamic range) is 3 dB.

A second characterization step consisted in measuring the switching time of the active coupler as a function of temperature. The switching time is determined by the behavior of the LC or, more specifically, by the relaxation of the Frederiks transition [8], [9]. As shown in Fig. 4, the LC works correctly for low frequencies (under 1 kHz depending upon the LC layer thickness). For temperatures ranging from 298 K to 323 K no relevant variation was observed, and, as shown in Fig. 4, the falltime shows a constant behavior while the rise time shows a slight decay. Out of the mentioned range, the LC undergoes phase transitions that make it unusable.

The results obtained for the switching time can be improved by using a ferroelectric LC instead of a nematic one. The behavior of the device can also be improved if the gold layer is replaced by an indium–tin–oxide (ITO) layer, either by reducing the LC layer thickness or by choosing or synthesizing an LC with more appropriate refractive indexes.

V. Conclusion

We have designed, analyzed, and characterized a POF active coupler for the first time. The device showed a coupling of 4.5 dB for electric fields around $6 \cdot 10^5$ V/m and switching times around 2 ms. A good uniformity between the output branches (under 1 dB) was also achieved, while the excess losses were kept under 2.5 dB and the isolation over 30 dB. The dynamic range obtained was of 3 dB.

Although we have demonstrated the behavior principles of an active coupler, the dynamic range and switching times obtained would have to be improved to meet the needs of practical systems. Some improvements on the fabricated device, such as the use of a ferroelectric LC or an ITO layer, have also been proposed.

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