Nondestructive Characterization of Fiber Couplers by a Local Perturbation Method

Carlos Alegria, F. Ghiringhelli, R. Feced, and M. N. Zervas

***Abstract*—A technique for the nondestructive characterization of fiber couplers is demonstrated. A CO_2 laser beam is scanned along the coupler length inducing a local perturbation to the coupler eigenmodes. Information about the power evolution and the coupling-constant variation along the coupler length can be obtained by applying an asymmetric and symmetric perturbation, respectively. Experimental results of the characterization of a half- and a full-cycle fiber coupler using this technique are presented.**

***Index Terms*—Optical fiber couplers, optical fiber devices, optical fiber filters, optical fibers.**

I. Introduction

COUPLERS are components of extreme importance in optical communication systems. They are used to split the power of an optical channel [1] or combine/split the power of different channels, corresponding to different wavelengths [2] (wavelength-division-multiplexing (WDM) splitters/combiners). Recently, fiber and integrated-optic couplers have been combined with reflective Bragg gratings to provide add/drop multiplexers for WDM systems [3]. These devices depend critically on the exact position of the grating within the coupler waist. In particular, the grating effective reflection point should coincide with the coupler-waist position where the power is equally split between each individual waveguide (50%–50% points). Several methods for probing different parameters of directional couplers have been reported in the literature. Bourbin *et al.* [4] reported a method for characterizing couplers in planar waveguides by inducing a small loss only in one of the coupled waveguides. The differential loss is induced by scanning a small mercury drop along the waveguide length. The other waveguide is covered with a resist film to avoid contact with the mercury. Gnewuch *et al.* [5] reported a method of measuring the beat-length of uniform couplers in buried planar waveguides by inducing a local perturbation in one of the waveguides by heating it with an incident 980-nm laser diode. To facilitate the 980-nm radiation absorption by the transparent waveguides, a 1-μm-thick layer of black ink was spin coated onto the surface of the waveguides.

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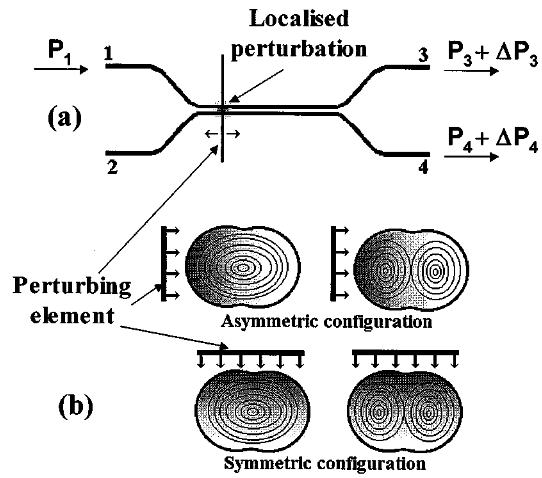

Fig. 1. (a) Principle of operation of the coupler characterization technique. (b) Schematic of the coupler-waist perturbation using an asymmetric (top) or symmetric (bottom) configuration.

In this letter, we describe a new method for nondestructive characterization of fiber couplers that does not involve any post-fabrication manipulation of the couplers. The method consists of scanning a localized perturbation along the coupler waist. Radiation of a CO_2 laser (or another heat source) is used to heat the coupler locally and perturb the lowest even and odd eigenmodes. Firstly, by applying an asymmetric perturbation between the two lowest order eigenmodes, the complex power evolution along the entire coupling region can be measured. Secondly, by applying a symmetric perturbation between the two lowest order coupler eigenmodes, information about the uniformity of the coupler waist and shape of the tapered regions can be obtained.

II. Principle of Operation

The principle of operation of the proposed technique is illustrated in Fig. 1. Light of the appropriate wavelength is launched in ports (#1 or #2) and detected at the output ports (#3 and #4). The characterization method consists of inducing a local perturbation along the coupling region and monitoring the change in power at the output ports [Fig. 1(a)]. The perturbing element induces a temperature gradient across the coupler waist [represented by the shaded area in Fig. 1(b)] that can be asymmetric or symmetric with respect to the power distribution of the even and odd eigenmodes of the coupler. Each configuration provides information about different coupler parameters.

In an unperturbed coupler, the even and the odd eigenmodes propagate along the coupler length with propagation constants

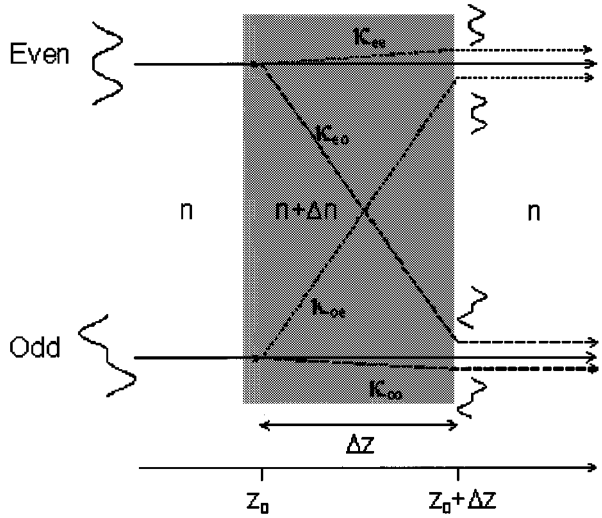

Fig. 2. Schematic of even and odd eigenmode self-coupling (κ_{ee}, κ_{oo}) and crosscoupling (κ_{eo}, κ_{oe}) induced by the external perturbation Δn, represented by the shaded area.

β_e and β_o. The total phase difference between the propagating eigenmodes

$$\Delta\phi_{eo}(z_0) = \int_0^{z_0} \Delta\beta(z)\, dz = \int_0^{z_0} (\beta_e - \beta_o)\, dz$$

gives the evolution of power along the coupler length. The field amplitudes at each of the coupler ports are given by the sum and the difference between the even and odd eigenmodes, i.e., $A_1 = (A_e + A_o)/\sqrt{2}$ and $A_2 = (A_e - A_o)/\sqrt{2}$. At the positions along the coupler length where this phase difference reaches a multiple of $\pi/2$, the power is equally distributed between the individual waveguides. On the other hand, when $\Delta\phi_{eo}(z_0)$ is a multiple of π, all the power is concentrated primarily into one of the individual waveguides. When the coupler is perturbed by a local change in the refractive index, light is scattered and the coupler eigenmodes exchange power along the perturbed region Δz as illustrated in Fig. 2. The local power exchange between the eigenmodes due to the local perturbation, at a given position along the coupler waist, is described by the coupled mode equations for two copropagating modes using the self-coupling coefficients κ_{ee} and κ_{oo} and the crosscoupling coefficients κ_{eo} and κ_{oe}, namely

$$\frac{dA_e}{dz} = -i\kappa_{ee}A_e - i\kappa_{eo}A_o e^{i\Delta\beta z} \quad (1a)$$

$$\frac{dA_o}{dz} = -i\kappa_{oo}A_o - i\kappa_{oe}A_e e^{-i\Delta\beta z}. \quad (1b)$$

The coupling coefficients are proportional to the overlap integral between the refractive index change distribution due to the heat gradient and the coupler eigenmodes. In a symmetric configuration (illustrated in Fig. 1(b)-bottom)], the crosscoupling coefficients are zero ($\kappa_{eo} = \kappa_{oe} = 0$) and the self-coupling coefficients are in general nonzero ($\kappa_{ee} \neq \kappa_{oo} \neq 0$). In the asymmetric configuration (illustrated in Fig. 1(b)-top), both the crosscoupling and self-coupling coefficients are in general nonzero ($\kappa_{eo} = \kappa_{oe} \neq 0$ and $\kappa_{ee} \neq \kappa_{oo} \neq 0$, respectively). For slightly detuned couplers $\int_0^{L_C} \Delta\beta\, dz = n\pi + \Delta\phi_L$, where

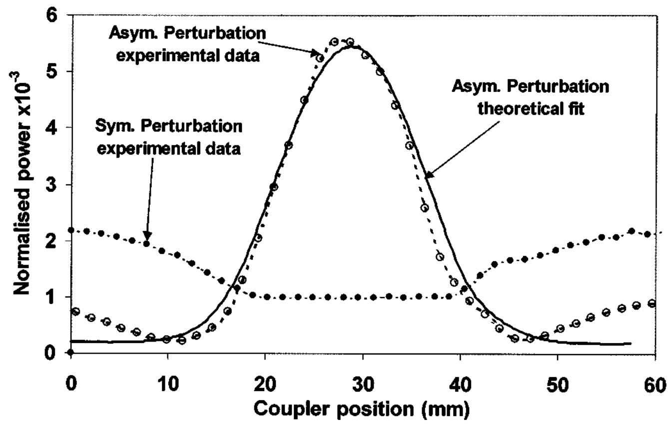

Fig. 3. Characterization of a half-cycle coupler using a local perturbation in both an asymmetric and symmetric configuration. The asymmetric perturbation was fitted using the symmetric perturbation data.

$\Delta\phi_L \ll 1$ is the coupler phase detuning from the exact resonance condition. Simplified expressions for the power change at the null-power coupler output port can be obtained by solving (1) for both the asymmetric and symmetric perturbation configurations [6], namely

$$\Delta P_{\text{asym}}(L, z_0) \approx (\Delta\phi/2)^2 + (|\kappa_{eo}|\Delta z)^2 \sin^2(\phi(z_0) - \Delta\phi/2) \quad (2)$$

$$\Delta P_{\text{sym}}(L, z_0) \approx (\Delta\phi/2)^2 + 1/2\Delta\phi_L(\kappa_{ee} - \kappa_{oo})\Delta z. \quad (3)$$

In (2), $\Delta\phi$ includes the additional phase detuning of the coupler due to the self-coupling perturbation coefficient difference, namely $\Delta\phi = \Delta\phi_L + (\kappa_{ee} - \kappa_{oo})\Delta z$ where Δz is the spatial extent of the perturbation. The parameter $\phi(z_0) = \int_0^{z_0} \Delta\beta(z)\, dz$ is the total phase difference between the even and odd eigenmodes of the coupler from the beginning of the coupler to the position z_0 where the coupler is currently perturbed. The power evolution along the coupler can be deduced by utilizing an asymmetric perturbation. The maxima of ΔP_{asym} in (2) can be used to determine the positions along the coupler where the power is equally split between the individual waveguides (50%–50% points) or equivalently, where $\int_0^{z_0} \Delta\beta(z)\, dz = \pi/2 + n\pi$ and the coupler eigenmodes are $\pi/2$ out of phase ($n = 0, 1 \cdots$ depending on the number of power-exchange cycles along the coupler). The power change ΔP_{sym} in the output port due to a symmetric perturbation of the coupler waist [see (3)] provides information about the variation in the difference of the self-coupling coefficients $(\kappa_{ee}(z) - \kappa_{oo}(z))$ along the coupler length. The profile obtained is also related to the coupling strength profile $K(z) = \Delta\beta(z)/2$ and was used to fit the experimental asymmetric perturbation data.

III. Experiments

We have demonstrated the proposed nondestructive technique experimentally by characterizing a half-cycle coupler (Fig. 3) and a full-cycle coupler (Fig. 4) using both the symmetric and asymmetric perturbation configurations. The couplers were fabricated using the traveling flame technique with a uniform waist length of $L = 30$ mm and a resonance wavelength around 1.55

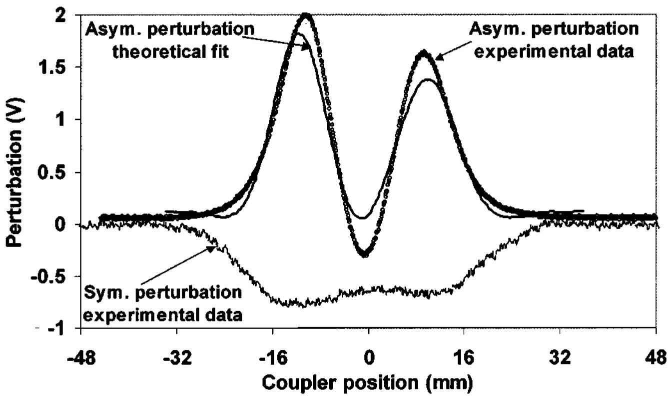

Fig. 4. Characterization of a full-cycle coupler using a local perturbation in both an asymmetric and symmetric configuration. The asymmetric perturbation was fitted using the symmetric perturbation data.

μm. The total length of the half- and full-cycle couplers, including the tapered regions, was 107 and 110 mm, respectively. The perturbation was obtained by scanning a CO_2 laser beam along the coupler length. The laser beam power was 100 mW and was modulated at a frequency of 500 Hz. The beam diameter was 1 mm. The fiber was rotated by 90° in order to switch between the asymmetric and symmetric perturbation configurations. Light from a DFB-LD at 1.55 μm was launched into port#1 and monitored at the low-power output port using a detector and a lock-in amplifier to pick up the modulated signal. The characterization of a half-cycle coupler $(\Delta\phi_{eo}(L) = \pi)$ is shown in Fig. 3. The change in the port power due to the symmetric perturbation was normalized to π and used as the coupling profile, $K(z) = \Delta\beta(z)/2$, to fit theoretically the asymmetric perturbation data. Although strictly speaking the symmetric perturbation results follow the coupler-waist outer diameter variation, they will match closely the coupling profile $K(z)$ of the measured coupler since this parameter is proportional to the coupler diameter [6]. The asymmetric perturbation, on the other hand, follows the power distribution along the coupler length and its maximum corresponds to the 50%–50% power point of the coupler $(\Delta\phi_{eo}(L) = 2\pi)$. Fig. 4 illustrates the characterization of a full-cycle coupler. The symmetric perturbation was normalized to 2π and used as the coupling profile to fit the asymmetric perturbation data. A nonuniform variation of the coupler-waist diameter is observed that is thought to be due to the coupler fabrication process. As expected, the asymmetric perturbation has two maxima at the points where the power is split equally between the two individual waveguides. The small difference in the peak heights can be due to small variations of the coupler-waist radius, a slight twist in the coupler waist or small misalignment of the CO_2 laser beam relative to the coupler waist. The asymmetric perturbation was fitted assuming a linear variation of 5% from end to end along the coupler waist of the crosscoupling coefficient κ_{eo}.

IV. Conclusion

We have demonstrated a novel nondestructive method for the characterization of fiber couplers. Valuable information about the evolution of power along the coupler and the shape of the tapered regions as well as the uniformity of the coupler waist can be obtained using this method. The method can be employed to optimize the performance of add/drop multiplexers based on the inscription of gratings in the waist of fused couplers by correctly identifying the positions along the coupler where the power is equally split between the two waveguides (50%–50% points). It can also be used as a tool for the identification of errors in the coupler fabrication process.

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