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Measurement of Complex Coupling Coefficients of Directional Coupling by Thermo-Optic Modulation

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Introduction

Directional coupling between two parallel single-mode optical waveguides is the functional principle underlying numerous integrated optical devices, such as modulators [1], filters [2] and sensors [3, 4]. As the coupling efficiency depends critically on the synchronism of wave propagation and on the field overlap of the two guides, tight tolerances apply in waveguide fabrication, and a precise determination of the coupling parameters is essential.

Here we address the problem of measuring the coupling coefficient C which characterizes the coupling between the two guides which form a symmetric coupler. In a lossless coupler optical power is transferred completely back and forth between the guides, oscillating with a spatial periodicity $\Lambda = 2\pi/C$. When the guides are lossy, the oscillation is attenuated. Using an alternative description the oscillation and attenuation may be understood by as a "beating" phenomenon between the symmetric and antisymmetric 'supermode' ($m = 1, 2$) of the structure. These modes propagate independently of each other with complex propagation constants $\Gamma_m = \beta_m + j\alpha_m$. Their superposition varies according to the complex difference $C = \Gamma_2 - \Gamma_1 = \Delta\beta + j\Delta\alpha$, where $\Delta\beta = \beta_2 - \beta_1$ and $\Delta\alpha = \alpha_2 - \alpha_1$. This means a spatial periodicity $\Lambda = 2\pi/\Delta\beta$ and an attenuation of the beat amplitude proportional to $\exp(-\Delta\alpha z)$. In this paper we measure the difference C by scanning a small thermo-optic perturbation along the coupler and observing the induced periodic variation of the output power. In the earlier interpretation this C is the coupling constant between the two guides.

This thermo-optic method has recently been demonstrated for the measurement of the beat length Λ between two modes of orthogonal polarization [5]. It works equally well between the supermodes of a directional coupler, and its generalization to include the loss difference is straightforward. Compared to alternative techniques [6, 7, 8, 9] of measuring Λ, the thermo-optic method is advantageous because it does not require access to the evanescent field above the coupler. Therefore it permits application also to buried guides.

Theory

We consider the general case of a lossy symmetric directional coupler. It supports two guided waves ('supermodes') with complex propagation constants Γ_m, local amplitudes $A_m(z) = A_m(0)\exp(j\Gamma_m z)$, and vectorial field distributions $\mathbf{F}_m(x, y)$. In the absence of a perturbation they propagate independently along the coupler. Their total electrical field is the superposition $\mathbf{E}(x, y, z) = \sum_m A_m(0)\mathbf{F}_m(x, y)\exp(j\Gamma_m z)$. At a position z along the coupler the modal powers are $P_m(z) = |A_m(z)|^2 = |A_m(0)|^2\exp(-2\alpha_m z)$, assuming that the $\mathbf{F}_m$ are normalized to $\int \mathbf{F}_m^* \mathbf{F}_n dx\,dy = \delta_{mn}$.

When a dielectric perturbation $\Delta\epsilon(x,y,z)$ is introduced by heating of a spot at $z = z_0$ on the coupler, the modal propagation constants Γ_m are modified by small amounts κ_{mm} and the supermodes become coupled by local coupling coefficients κ_{mn} which may be shown for $m, n = 1, 2$ to be

$$\kappa_{mn}(z) = \frac{k_0^2}{2\beta_m} \int\int \mathbf{F}_m^*(x,y)\Delta\epsilon(x,y,z)\mathbf{F}_n(x,y)dxdy \tag{1}$$

with k_0 as the free space wavenumber. As a consequence the modal amplitudes are modified from their original values A_m to new values A_m° in the region beyond z_0. These new amplitudes can be found by integrating the coupled mode equations

$$\begin{aligned} dA_m(z)/dz &= j\sum \kappa_{mn}(z)\exp[j(\Gamma_m - \Gamma_n)z]\, A_n(z) & (2)\\ A_m^\circ(z_0^+) &= A_m(z_0^+) + j\sum K_{mn}\, A_n(z_0) & (3)\\ \text{where}\quad K_{mn} &= \int \kappa_{mn}(z - z_0)\, \exp[j(\Gamma_n - \Gamma_m)(z - z_o)]\, dz & (4) \end{aligned}$$

The modified amplitudes propagate through the remaining distance $(L - z_0)$, and at the end of the guide, $z = L$, we have $A_m(L) = [A_m(0) + j\sum K_{mn}A_n(0)\exp[j(\Gamma_n - \Gamma_m)z_0]]$. The corresponding power $P_{m,L}^\circ$ in mode m is obtained as

$$P_{m,L}^\circ(z_0) \;=\; |A_m^\circ(L)|^2 \;=\; P_m(L) + 2\,K_{mn}\sqrt{P_mP_n}\,\exp(-\Delta\alpha\, z_0)\,\cos(\Delta\beta\, z_o + \phi_{mn}) \tag{5}$$

This equation shows the periodicity $\Delta\beta$ of the variation of the output power $P_m(L)$ when the position z_0 of the perturbation is scanned along the coupler. It also shows the attenuation with $\Delta\alpha$ of the oscillation amplitude. Therefore, a measurement of $P_{m,L}^o(z_0)$ yields the complex coupling coefficient C.

Experiments and Results

We start with the measurement of real coupling coefficients in nonabsorbing directional couplers. The symmetrical coupler supporting two modes comprised a single-ended input, the parallel coupling section, and a tapered section at the output, Fig. 1. The couplers were fabricated in soda-lime glass slides by thermal $K^+ - Na^+$–exchange. A thin black layer deposited on top of the waveguides was heated by local illumination inducing thermo-optic perturbation using thermo-optic and elasto-optic effects. In order to prevent absorption a transparent Teflon layer was deposited prior to the spin-coated absorbing film. Light from a 980 nm laser diode was coupled into a single mode fibre and directed onto the absorbing film, Fig. 1. The distance between fibre tip and the sample was $h \approx 20\,\mu m$, yielding a spot size of $\approx 9\mu m$ on the sample surface. The coupler modes were excited at 0.6328 μm via the input waveguide. At the output, light emerging from one branch of the coupler was TM-polarized and detected. By applying lock-in detection with a chopping frequency of $f_0 \approx 350\,Hz$ and having $\approx 8\,mW$ optical power at the fibre tip a relative modulation depth of $\approx 3 \cdot 10^{-4}$ was measured. For the measurement of the coupling coefficient the fibre was scanned along the waveguide and the lock-in reading was simultaneously monitored. Fig. 2 shows a typical measurement. With regard to Eq.(5), by fitting a sinusoid to the data, a relative error in the coupling coefficient below $\delta C/C = 1.6\,\%$ has been obtained. Finally, in Fig. 3 coupling coefficients corresponding to directional couplers with different edge-to-edge gap, d, in the original mask are shown. The plot shows to the first order an exponential dependence of the coupling coefficient on d, which is consistent with theory.

For the measurement of complex coupling coefficients of absorbing directional couplers we chose a compound structure comprising a dielectric waveguide in glass and a gold film covering the waveguide over a well defined length, Fig. 4. The dielectric waveguides were fabricated in Pyrex by thermal $K^+ - Na^+$–exchange. Subsequently, various goldfilms with varying thicknesses between $d = (20...50)$

nm were deposited and the coupler performance was measured dependent upon the superstrate index above the gold. Unlike the case of the directional coupler in glass we used the gold film itself as an inherent absorber. Again the absorber was illuminated using a laser diode, but now operating at 780 nm, via a single mode fibre whereby a thermo-optic perturbation was induced. The modes of the compound structure were excited at 0.6328 μm via the single mode input waveguide. At the output of the compound structure, the remaining fractions of the mode powers couple into the single mode of the output waveguide which is p-polarized and detected. In order to keep the perturbation region relatively small despite having a comparetively high thermal conductivity of gold we chose a modulation frequency of the perturbation source of $f_0 = 11$ kHz. For the measurement an index liquid was put onto the gold film. The fibre tip was then immersed into the index liquid and brought into close proximity to the gold film, $h \approx 50$ μm. The fibre was scanned along the whole length of the compound structure and the detected signal monitored simultaneously. For having ≈ 2 mW at the fibre tip a relative modulation depth of $\approx 1 \cdot 10^{-3}$ has been determined. Fig. 5 shows a modulation signal which is nearly point symmetric to the center of the coupling structure. By subtracting the modulation signals at points equally spaced to the center and subsequent normalization, an increase with increasing distance to the center is noticable which can be explained by the perturbation source becoming increasingly disaligned. Taking this into account, the mirror symmetry of the peaks is analogous to both cases of maximum modulation depth, [5], having either two modes excited and one mode at the output, or vice versa. Between the peaks coupling from the remaining less absorptive mode to the higher absorptive mode can not be seen at the output due to the excessive waveguide length for the higher absorptive mode. Note that part of the z-independent modulation signal between the peaks is therefore related to cross-coupling ! In Fig. 6 both the real and imaginary coupling coefficient can be determined. The real coupling coefficient has been determined with a relative error of 4 %.

Conclusions

In conclusion, we extended the theoretical description of the beatlength measurement technique based upon induced modal coupling to absorbing modes and applied the thermo-optical modulation technique to the measurement of the beatlength in nonabsorbing and absorbing directional couplers. The technique has been demonstrated for integrated optical directional couplers in glass and for a directional coupler comprising a dielectric waveguide in glass and a gold film covering the waveguide.

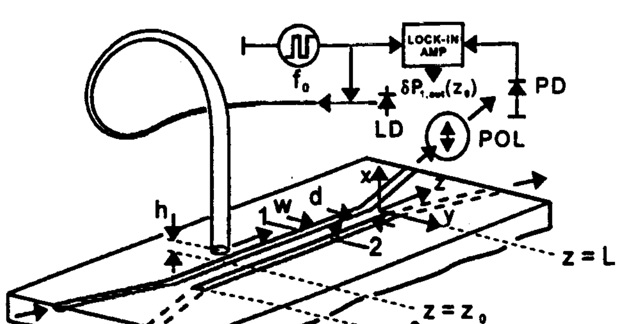

Fig. 1 : Experimental setup for the measurement of the coupling coefficient of directional couplers; waveguide width *w*, edge-to-edge waveguide gap *d*, distance between fibre tip and surface of sample *h*, laser diode LD, photodiode PD, linear polarisor POL.

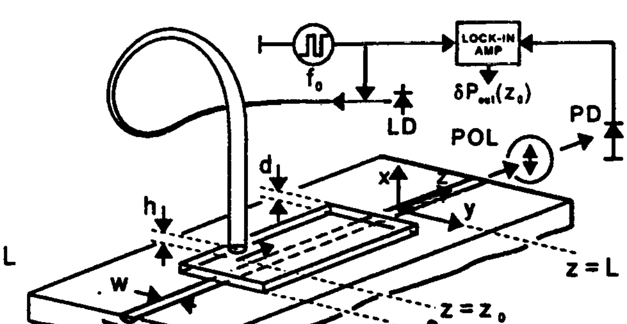

Fig. 4 : Experimental setup for the measurement of complex coupling coefficients of surface plasmon coupled dielectric waveguide modes; all abbreviations as in Fig. 1 but gold layer thickness *d*.

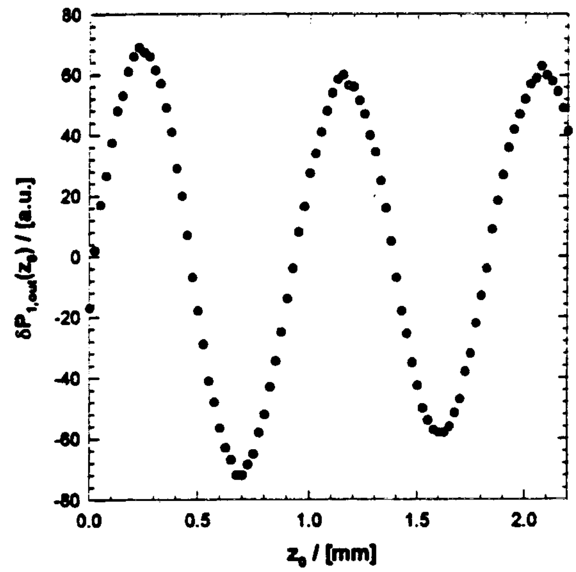

Fig. 2 : Measurement of the coupling coefficient for directional coupler with waveguide width w = (2.3 +/- 0.2)μm and gap d = (2.3 +/- 0.2)μm.

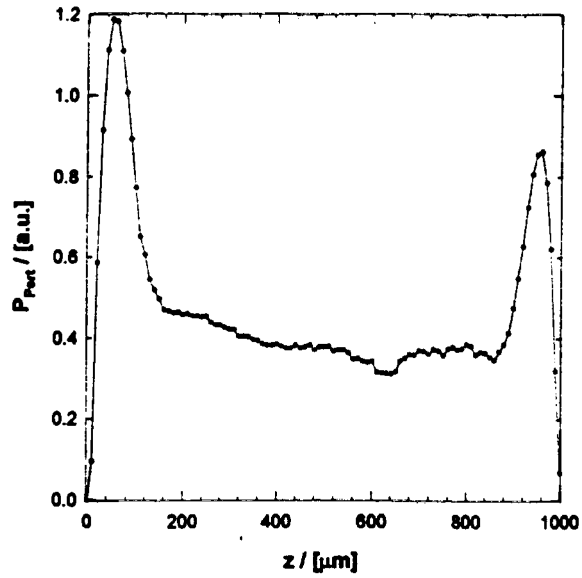

Fig. 5 : Modulation signal measured for waveguide covered by gold layer of thickness d = 33 nm; superstrate index n_0 = 1.390.

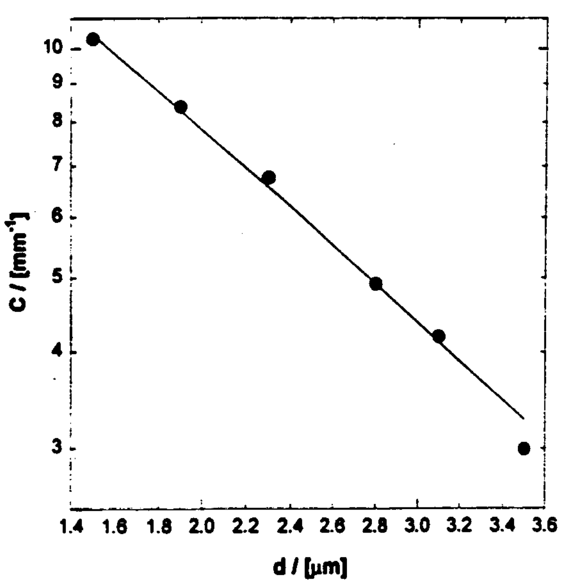

Fig. 3 : Log-linear plot of the coupling coefficient C versus waveguide gap d, waveguide width w = (2.3 +/- 0.2) μm.

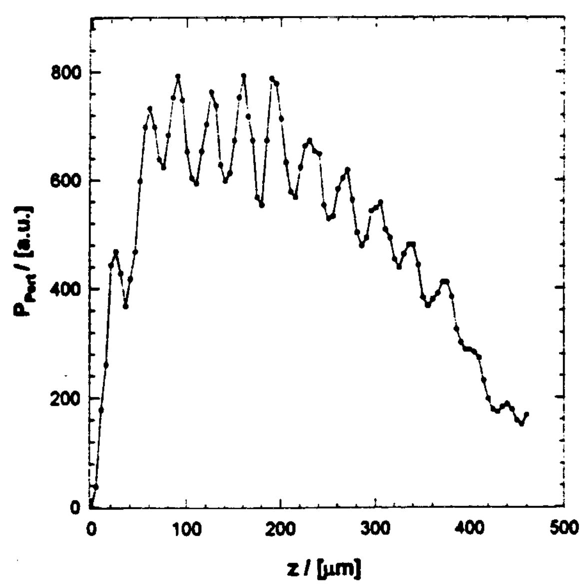

Fig. 6 : Modulation signal measured for waveguide covered by gold layer thickness d = 20 nm; superstrate index n_0 = 1.395.

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