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"Modal Spectroscopy" of multimode optical waveguides.

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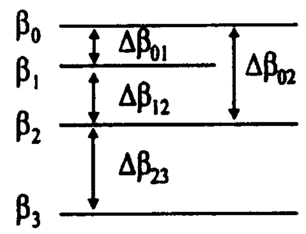
In many integrated-optical devices operation is based on distributed coupling between two guided modes. Examples are directional couplers, travelling wave modulators and polarisation converters. In fabricating such devices it is a fundamental task to measure the propagation characteristics of these modes accurately enough for phase matching.

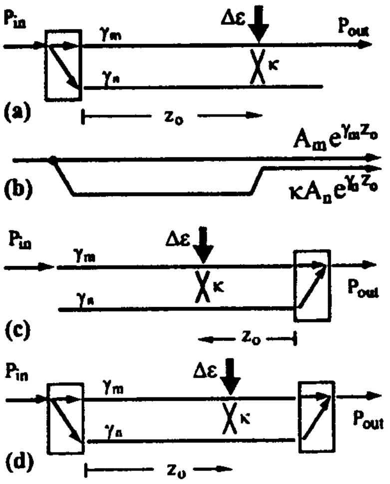
We describe a family of techniques for measuring the differences $\Delta\gamma_{mn} = \Delta\alpha_{mn} + j\ \Delta\beta_{mn}$ of the complex propagation constants γ_m, γ_n of two modes (m,n) in a waveguide supporting $M \geq 2$ modes. The imaginary part of this difference, $\Delta\beta_{mn} = \beta_m - \beta_n$, may be understood as the modal 'birefringence' of the guide. It is directly related to the 'beat length' $\Lambda_{mn} = 2\pi/\Delta\beta_{mn}$ of the two modes which, in turn, is typically equal to the period of the electrode pattern in a mode converter. Likewise, the real part $\Delta\alpha_{mn} = \alpha_m - \alpha_n$ is the difference of the attenuation constants of the two modes. As all techniques considered below yield only *differences* $\Delta\beta_{mn}$, the experimental situation is comparable to that in spectroscopy where measured line frequencies correspond to differences in energy levels, and line widths are determined by the broadening of *both* contributing levels.



All such techniques are interferometric. In the basic arrangement (a), monochromatic light is fed by some beam-splitting element into the two modes (m,n) of the guide which are to be compared. At some position z_o along the guide a sharply localized perturbation $\Delta\varepsilon$ is applied to the dielectric structure of the guide. It couples a small fraction κ of the amplitude of one mode into the other mode and vice versa. The detected power P_{out} results from superposition of the two waves A_m and κA_n at the output (b) and, therefore, varies sinusoidally with z_o.

$$P_{out}(z_o) = \left|A_m e^{\gamma_m z_o} + \kappa A_n e^{\gamma_n z_o}\right|^2 = \bar{P} + \tilde{P} e^{-\Delta\alpha_{mn} z_o} \cos(\Delta\beta_{mn} z_o)$$

When the perturbation is scanned along the guide, the period of the function $P_{out}(z_o)$ is directly the beat length $\Lambda_{mn} = 2\pi/\Delta\beta_{mn}$ of the two excited modes. The decay of the amplitude of the modulation gives the differential attenuation $\Delta\alpha_{mn}$ of the modes.



We report on the application of this technique to a wide variety of waveguides, ranging from optical fibers to single-mode and multi-moded guides in $LiNbO_3$:Ti, to leaky guides in $LiNbO_3$:Ti, to ion-exchanged directional couplers in glass, and to dielectric waveguide coupled surface plasmons on thin metallic films. The modulation techniques employed comprised electro-, magneto-, elasto-, and thermo-optic effects. This permits non-contacting, high-accuracy measurements of the birefringence and of its uniformity along the guide. Depending on the device under test, various modifications of the basic scheme (a) are of interest. Arrangement (c), which is the inverse of (a), is advantageous whenever it is possible to excite a single mode. Arrangement (d) represents a directional coupler with non-coupling sections at the input and output. Here, the perturbation produces a total of 6 interfering output beams, and a judicious choice of input and output connections is necessary to obtain a measurable signal.

The technique proved to be particularly useful in the construction of electro-optic modulators for microwave frequencies, in which a travelling electric wave must be phase-matched to two guided optical waves, and in the construction of position-sensitive fluorescence sensors, in which the beating phenomenon between two guided modes serves to localize a fluorescing object.