DIAGNOSTIC METHODS FOR PLANAR OPTICAL WAVEGUIDES

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Abstract

Basic diagnostic methods for examining planar optical waveguides, namely the mode spectroscopy for determining the propagation constants of waveguide modes and two methods for measurement of attenuation coefficient of a waveguide or loss in some waveguide components, are presented. A promising advanced method — optical coherence-domain reflectometry — is briefly mentioned.

Keywords:
Integrated Optics, Optical Waveguides

1. Introduction

Integrated optoelectronics is of still increasing importance in conjunction with the rapid development of optical communications, sensors, and special optical measurements. Specific nature of optical guided-wave structures requires correspondingly specific approach not only in their fabrication technology but also in their design and measurement. Various diagnostic methods for optical guided-wave devices were developed in the authors' laboratory within last years in connection with the research of passive and "dynamic" devices like couplers, polarizers, electrooptic modulators and switches, *etc.*.

2. Mode spectroscopy

Mode spectroscopy [1] is the basic experimental method which makes possible to find out the existence of guided modes in a planar waveguide (a layer with constant refractive index n_f or index profile $n(x)$ on a substrate with the refractive index n_s; $n_s < n_f, n(x)$) and to measure their characteristics — effective indices N (or propagation constants $\beta = 2\pi N/\lambda$). Usually, it is based on the prism coupling of a collimated laser beam into the guided wave in the arrangement shown in Fig. 1, where the prism of refractive index n_p ($n_p > n_f, n(0)$) is pressed against the surface of the waveguide. A guided mode is excited, if the condition

$$N = n(0)\sin\theta = \cos\varepsilon_p \sin\alpha + \sin\varepsilon_p \sqrt{n_p^2 - \sin^2\alpha}$$

is fulfilled; thus, its effective index N can be determined from the measurement of the angle of incidence α. For this, the waveguide with the coupling prism must be located on a rotational table (goniometer). The excitation can be proved, *e.g.*, by coupling the guided light out by another prism as shown in Fig. 1.

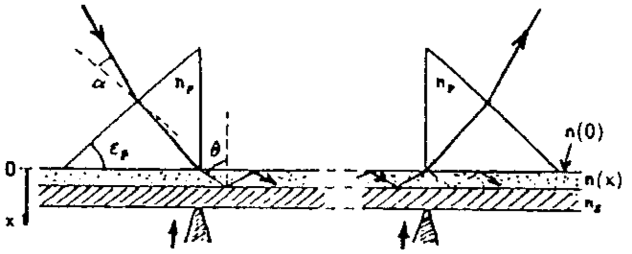

Fig. 1
Principle of prism coupling for mode spectroscopy

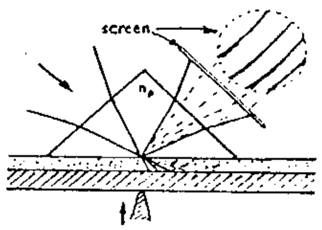

Fig. 2
Dark mode spectroscopy

In an alternative arrangement with a single symmetrical prism (Fig. 2), a wide angle light beam is used which is focused onto the base of the prism to excite all existing guided modes simultaneously. Then, the light guided away by waveguide modes is missing in the totally reflected output cone, which results in dark lines on the screen. Thus, the entire mode spectrum of the waveguide can be observed directly. This so called "dark mode spectroscopy" also yields the effective indices provided that the screen is calibrated.

The knowledge of effective indices of at least two-mode waveguide allows to evaluate the parameters of the waveguiding layer, *i.e.*, its thickness and refractive index n_f [2].

For multimode waveguides (with at least several guided modes) with monotonnically decreasing refractive index into the depth it is possible to use the mode spectrum to determine the refractive index profile of the waveguide. Figure 3 shows the example of a 10-mode waveguide prepared in a lithium niobate substrate by proton exchange in adipic acid (collaboration with the Institute of Chemical Technology in Prague). The algorithm for evaluation was adapted from [3].

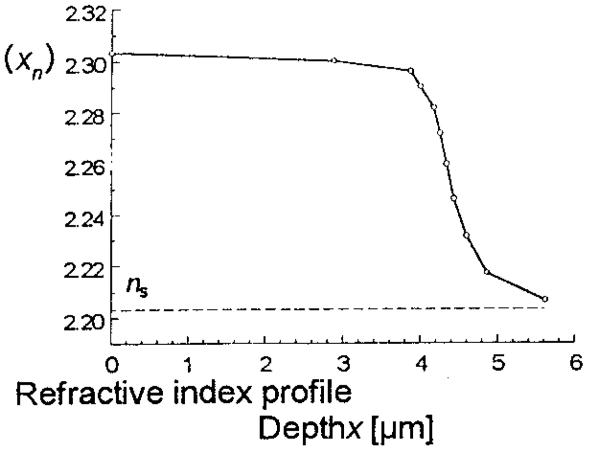

Fig. 3
Refractive index profile evaluated from mode spectroscopy

It should be noted that the mode spectroscopy fails for extremely multimode waveguides since the effective indices of individual modes are so close to each other that they are experimentally undistinguishable. In this case, a similar method of guided beam tracking [4] may be used instead for determining the refractive-index profile.

3. Measurement of waveguide attenuation

3.1 Scattered light tracking

The attenuation coefficient of a planar or channel waveguide is perhaps the most significant parameter for evaluating its usefulness for applications in optical circuits. Here we describe a computerized system for quick determination of optical waveguide losses. The system is based on the measurement of intensity of the light scattered from the guided mode perpendicularly to the waveguide surface as a function of the propagation length [5]. In our system, a streak of the excited mode in the waveguide is imaged onto a CCD camera. A schematic arrangement of the measuring setup is shown in Fig. 4.

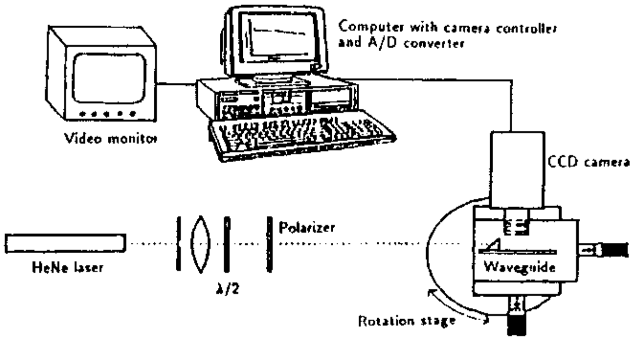

Fig. 4
Waveguide loss measurement setup

Light from a HeNe laser passes through a lens onto a prism–waveguide coupler mounted on a rotation stage. A polarizer and a half-wave plate allow to adjust the polarization (TE or TM) as well as the incident power. A CCD camera (Tesla PTK 256.1) with a $f = 50$ mm objective lens is used to register light scattered from a (selectively excited) mode. The camera is interfaced by video system controller TM 991 to a PC computer. The intensity variation along the streak of a guided mode is read-out and stored in the computer as a data file. Then, a commercial program for data processing is used to find the least mean square fitting these data to a decreasing exponential function, and, if necessary, for other operations like smoothing, filtering out unwanted features, *etc.* The exponent then coresponds to the attenuation coefficient of the measured waveguide. Typical results of measurement of two planar waveguides are presented in Fig. 5.

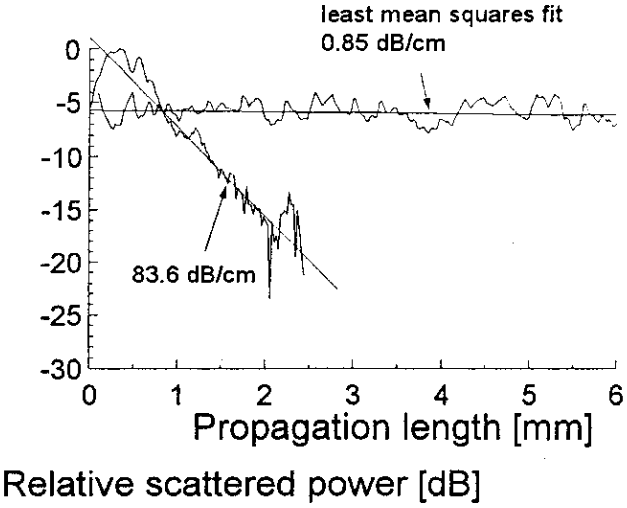

Fig. 5
Attenuation measurement output

It shows the power scattered from the TE_0 mode *vs* the propagation distance for two different waveguide structures composed of $Si/SiO_2/Si_3N_4$ (collaboration with the Institute of Chemical Technology in Prague, too). The attenuation coefficients were found to be 0.85 dB/cm and 83.7 dB/cm for these waveguides. Thus, the possibility of optical waveguide loss measuring over a large range from less than 1 dB/cm to very high values as high as 100 dB/cm is demonstrated.

3.2 Interferometric method

It was shown [6, 7] that the attenuation in single-mode channel waveguide structures can be measured utilizing Fabry-Perot resonances due to internal reflections of guided light from the waveguide endfaces. The method is especially suited for high-index semiconductor waveguides where nearly perfect endfaces can be simply cleaved, but it can also be applied to $LiNbO_3$ waveguides with endfaces carefully polished. Let us consider the waveguide shown in Fig. 6.

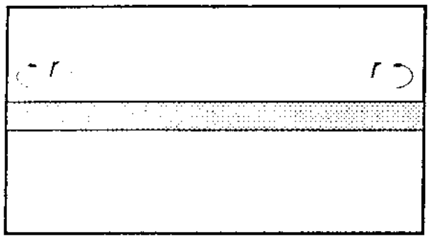

Fig. 6
Section of a channel waveguide as Fabry–Perot resonator

If coherent light is coupled into the waveguide, it is partly reflected at the waveguide-air interface. For weakly guiding waveguides like $Ti{:}LiNbO_3$ ones, the reflection coefficient can be well approximated by the (plane-wave) Fresnel coefficient, where N is the effecive refractive index of the mode. The endfaces act as mirrors of a Fabry-Perot resonator. The output power from the waveguide can be expressed in the well-known form:

$$P_{out} = \frac{(1-r^2)^2 \exp(-2\alpha L)}{\left|1-r^2 \exp(2ikNL)\exp(-2\alpha L)\right|^2} P_{in} ,$$

where L is the waveguide length and α is the attenuation coefficient of the waveguide. Changing the round-trip optical path $2kNL$ of the waveguide in a suitable way, the output power changes from the maximum $P_{out}^{\max}$ to the minimum $P_{out}^{\min}$. A simple algebra gives then the attenuation coefficient b (in dB/cm)

$$b = \frac{10}{L}\left|\log\frac{P_{out}^{\max}-P_{out}^{\min}}{P_{out}^{\max}+P_{out}^{\min}} - 2\log\frac{N-1}{N+1}\right| .$$

The optical path can be changed by changing the optical wavelength, temperature, or the efective index N. We use the latter two ways. In Fig. 7, a change of the output power from the $Ti{:}LiNbO_3$ electrooptic phase modulator is plotted as a function of the applied voltage. From the ratio of the minima and maxima, the attenuation coefficient of 0.6 dB/cm was found. (Moreover, the period of changes gives the value of the "half-wave voltage" $U_\pi = 4.4V$ of the modulator.) The method gives the upper estimate of the waveguide loss, since the endface imperfections, nonparallelity, *etc.* are considered as waveguide losses, too. Nevertheless, the method is well suited for the measurement of low-loss waveguides with attenuation coefficient typically around or below 1 dB/cm. In this sense, the method is just complementary to that discussed in subsection 3.1.

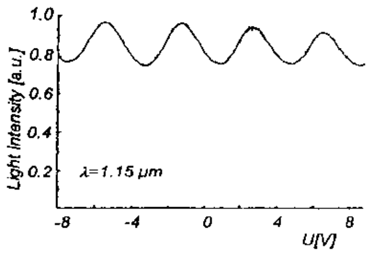

Fig. 7
Channel-waveguide Fabry–Perot resonator output

4. Optical coherence-domain reflectometry (OCDR)

Reflectometric methods like optical time-domain reflectometry (OTDR) are well-known and extensively used for the measurement of fibres and fibre-optic systems [8]. Recently, the method was modified also for the measurement of short integrated-optic waveguides and devices [9]. Instead of using ultrashort (femtosecond) light pulses to achieve high spatial resolution, a broadband light from *e.g.* a LED source is launched into the device under test, and the back-reflected signal is superposed with a reference signal reflected from a movable mirror. Because of a very short coherence length of the broadband source, the interference is obtained only if the measuring and reference arms are of equal lengths. One or both paths are periodically phase-modulated to increase the sensitivity of the method by the application of lock-in detection. Extremely large sensitivity of 146 dB was recently achieved [10]. In the optical setup of the method being now built in the authors' laboratory [11], the applicability of specially made integrated-optic serrodyne phase modulators are tested. The waveguide loss and U_π value of one of them were given in the preceding paragraph as an example of interferometric measurements of losses.

5. Conclusions

Some of the most important methods of characterisation of integrated-optic planar and channel waveguides that have been or are being built in the authors' laboratory were briefly reviewed. The oldest one, mode spectroscopy, is an indispensable tool for refractive index profile (or thickness) measurement of planar waveguides, although attempts to apply it for channel waveguides were also made [12]. For attenuation measurement on planar waveguides, fast and simple method of scattered light tracking using CCD camera is especially well suited as a diagnostic tool for technological development of waveguides because of its high "dynamic range". For low-loss channel waveguides, especially semiconductor ones, the interferometric method is most widely used. A relatively new method of coherence-domain reflectometry is suitable for channel waveguides and devices and has a wide range of applications: detection and localization of defects (imperfections) in the waveguides, attenuation measurement, group refractive index and dispersion measurements, measurement of reflectivity of waveguide facets with antireflection or reflection coatings, *etc.*

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Jiří Janta was born in Ostrava in 1933. He graduated in 1957 from Military Technical Academy in Brno, Faculty of Communications. After some practice in microvawes he joined in 1963 Physical Institute and later on the Institute of Radio Engineering and Electronics, Czechoslovak Academy of Sciences, where he worked in the applied research of the dielectric and optical properties of ferrolectric and electrooptic materials. He received PhD. degree in experimental physics from Physical Institute in 1968. Sincethe end of the 70s his research interests are in the area of planar waveguide optics, waveguide components and related measuring methods.

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