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Automation of set-ups for the measurement of refractive index profile and attenuation in planar waveguides

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The paper presents the structure of a computer-controlled set-up for the measurement of refractive index distribution using the measurement of synchronous angles and the IWKB method. Also, a method for measuring planar waveguide attenuation has been presented. In this method, the decoupling of light from the waveguide is carried out by means of immersion liquid. It ensures stability of the coupling with the waveguide being measured and, furthermore, it enables full automation of the measurement process, as well as its application in the elaboration of measurement results.

1. Introduction

The distribution of refractive index and its attenuation constitute basic parameters in the production technology of planar waveguides and strip waveguides. The knowledge of these quantities allows us to carry out work on the selection of optimum diffusion parameters in order to produce waveguides of the expected properties. Since the problem is of considerable importance and the determination of these quantities is very laborious, the authors have constructed computer-controlled measurement set-ups. The profile of the refractive index was measured by means of the inverse WKB method [1]–[4]. The algorithm of this method was first proposed by WHITE and HEIDRICH [1].

2. Set-up for the measurement of refractive index profile of the planar waveguide

The structure of the set-up is presented in Fig. 1. The planar waveguide under investigation is excited using a standard method with the application of a prism coupler. In the place of a generally applied output prism coupler, the authors applied a multimode waveguide fibre of high numerical aperture (NA = 0.36), which transmits the output signal from the waveguide to the detector system. A laser diode (LD) of wavelength $\lambda = 670$ nm was used as light source; the diode was fed with a rectangular signal from the generator system (M). The planar waveguide was

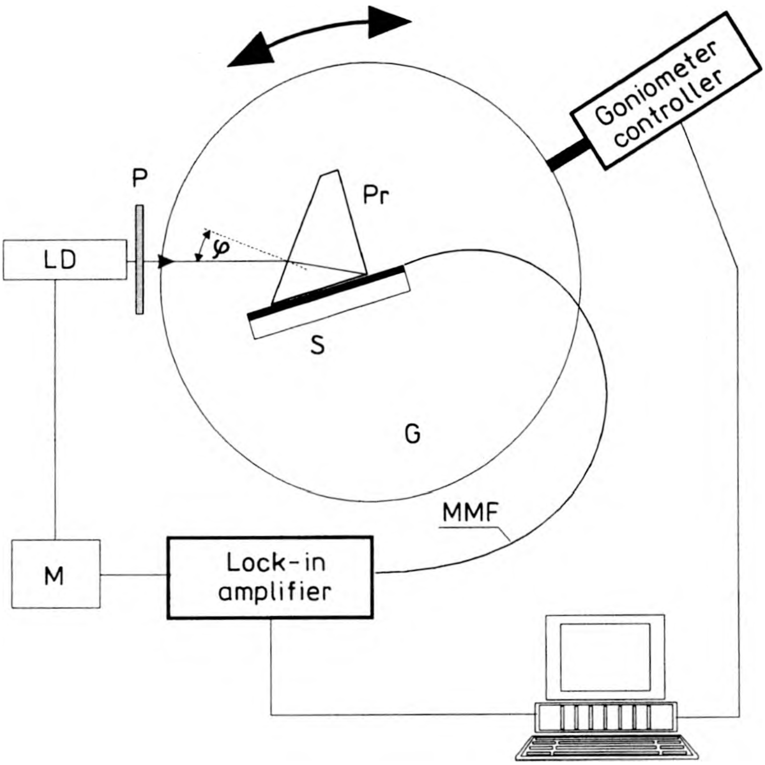

Fig. 1. Scheme of the measurement system of the synchronous angles of planar waveguides. S — substrate plate with planar waveguide, Pr — prism, P — polarizer, LD — laser diode, G — goniometric table, MMF — multimode waveguide fibre, M — generator.

placed on the goniometric table whose rotation was enforced by a step motor controlled by a computer. In the measurement process, the level of output power from the waveguide was being recorded as a function of rotation angle φ. The measurement system applied allows the recording of rotation angle of the goniometric table with the accuracy of 1.8″. In the detection system, the authors applied a lock-in nanovoltmeter, whose output signal was passed onto the input of the measurement card placed in the computer. The computer has an overall control of the measurement process: it controls the positioning of the goniometer's head and controls the acquisition of the signal from the detector. An exemplary mode spectrum which has been recorded in the measurement system described here is presented in Fig. 2.

The positioning of synchronous angles with respect to the excited modes is determined numerically from the recorded mode spectrum. Based on the parameters of the excitation prism (refractive index and refracting angle) as well as on synchronous angles, the respective values of effective refractive indices $N_{\mathrm{eff}}^{(i)}$ were determined. For the determination of a refractive profile of the waveguide, the IWKB method has been applied; the method allows us to determine the positioning of turning points $x_t^{(i)}$ based on the known quantities of the set $N_{\mathrm{eff}}^{(i)}$. Sets of the points

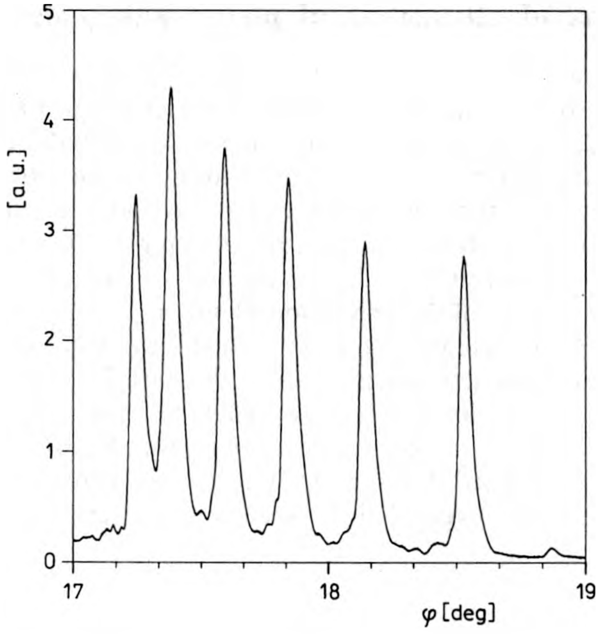

Fig. 2. Exemplary mode spectrum recorded in the measurement system presented in Fig. 1.

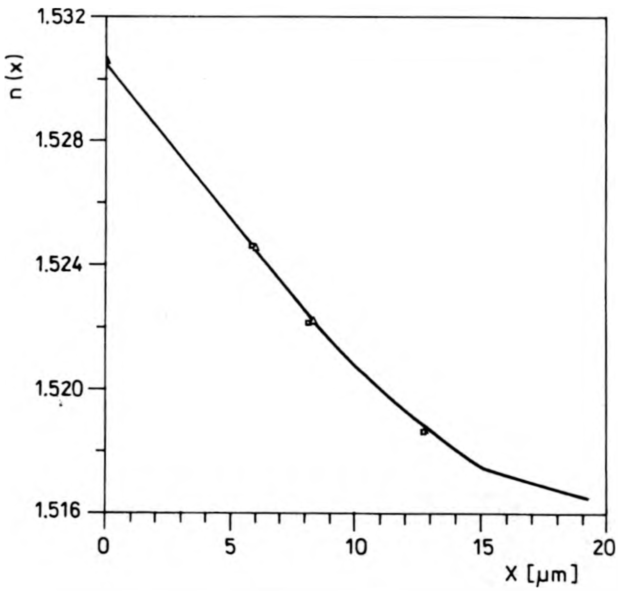

Fig. 3. Refraction profile determined on the basis of spectrum from Fig. 2.

$N_{eff}^{(i)}$ and $x_t^{(i)}$ constitute the approximation of the refractive profile of a given waveguide (Fig. 3).

3. Set-up for the measurement of attenuation of planar waveguides

The method of attenuation measurement is presented in Fig. 4. The planar waveguide is excited from the light source using an input prism coupler (prism PR) whose coupling is constant during the measurement. The output coupling is realized by a cuvette filled with liquid having suitable high refractive index, in which the waveguide is immersed. By changing the immersion depth of the waveguide in the liquid, the length of light propagation path in the waveguide changes. Due to mismatched propagation conditions along the border waveguide – immersion liquid ($n_i > n_w$, where: n_i – refractive index of the immersion liquid, n_w – effective refractive index of the waveguide), the guided light is emitted out from the waveguide. The phenomenon takes place immediately below the surface of the immersion liquid. The power of light decoupled from the waveguide is measured by a photodetector placed on the way of the output beam. The output beam leaves the cuvette passing through its cylinder-shaped transparent wall whose centre of curvature lies at the point where the propagated light is emitted out from the waveguide.

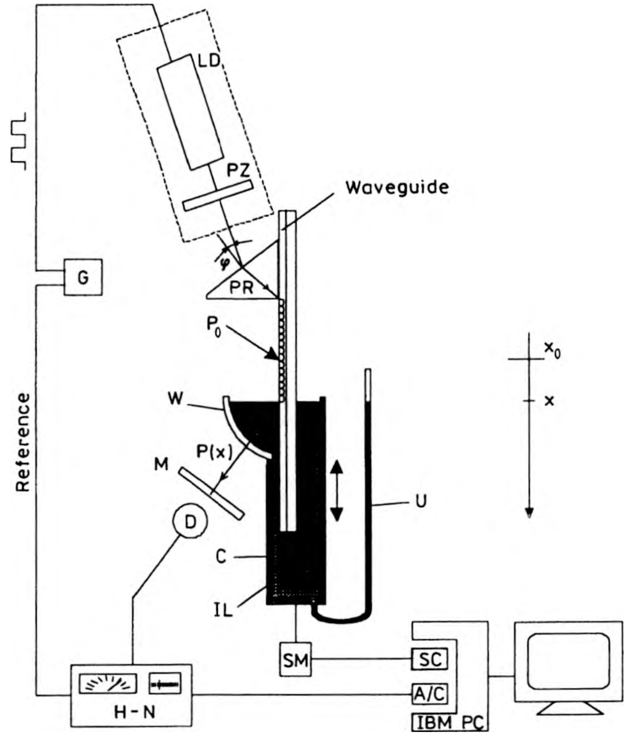

Fig. 4. Structure of a measurement set-up for the measurement of attenuation. L – laser diode, PZ – polarizer, M – ground glass, U – compensation pipe, C – cuvette, IL – immersion liquid, W – cylinder-shaped window, G – generator, H-N – lock-in nanovoltmeter, SM – step motor, SC – card of the step motor, A/C – card of the a/c transformers.

A laser diode ($\lambda = 670$ nm, beam divergence <0.5 mrad) was used as light source; it was modulated with the rectangular signal from the generator. The polarizer allows us to set the required polarization of light introduced to the waveguide. Due to the possibility of rotating the laser with respect to the input coupler, the waveguide modes are excited selectively. Light source, polarizer and the system prism – waveguide are stiffly connected with one another, which ensures invariable level of power introduced to the waveguide during the measurements.

After leaving the cuvette, the light emitted from the waveguide falls on the detector connected stiffly with the cuvette. A photodiode of large light-sensitive area (1 cm^2) is used as a detector. The signal from the photodiode is amplified by a lock-in nanovoltmeter and matched to the standard level accepted by the laboratory measurement card. Both the control of the system and the acquisition of measurement results and their processing are carried out using a computer and the dedicated software. Due to the fact that the measurement signal may be subject to systematic error resulting from the recorded background (dissipated light) and systematic error caused by the electronic system of the lock-in nanovoltmeter, the power recorded by

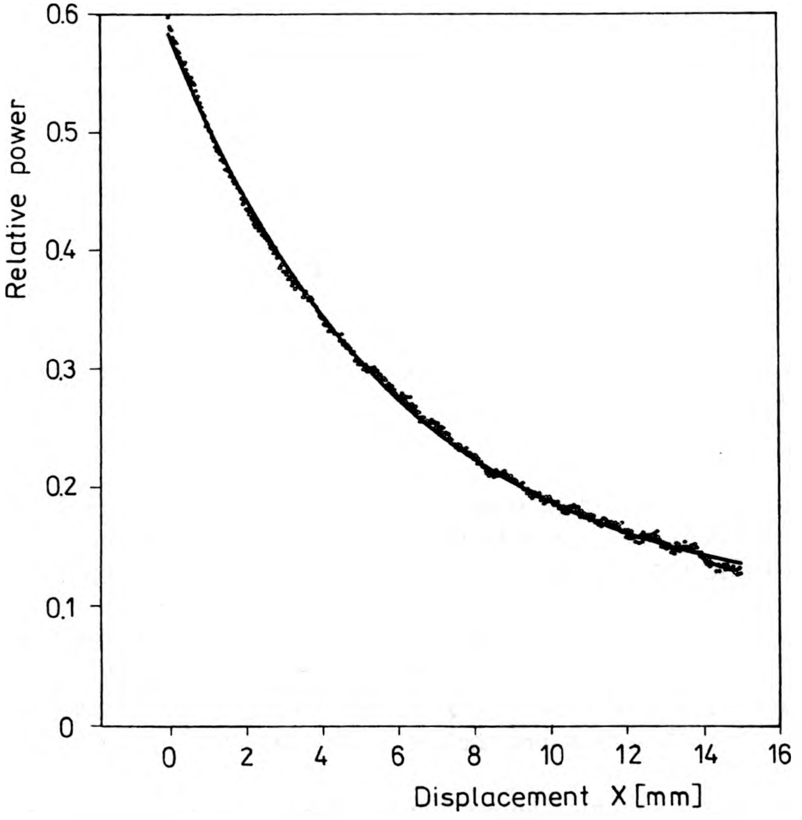

Fig. 5. Output power as a function of propagation path. ooo measured values, — curve matching measurement points.

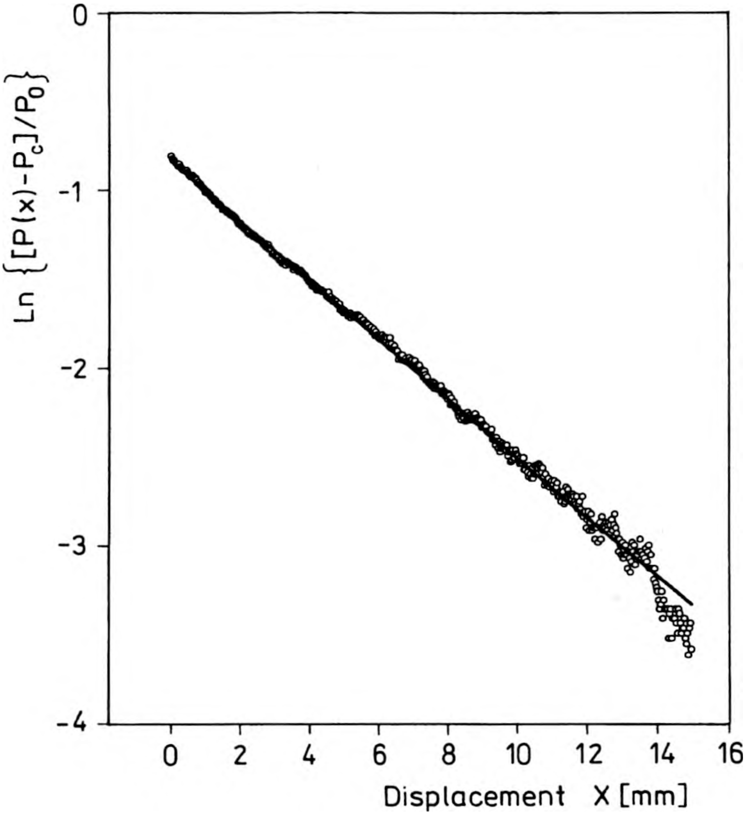

Fig. 6. Dependence of the function $\mathrm{Ln}[P(x)-P_c)/P_0]$ on the propagation path. ooo measured values, — approximation line.

the photodetector $P(x)$ depends on the change of the length of the propagation path x in the following way:

$$P(x) = P_0 \exp[-\alpha(x-x_0)]+P_c \tag{1}$$

where: P_0 – recorded power with maximum immersion, P_c – component taking into consideration the power of dissipated light and the systematic error caused by the electronic system of the detector, α – attenuation index [1/cm], x_0 – depth of maximum immersion.

The form of the above equation results from the fact that the function approximating the measurement results has three parameters. In order to determine the attenuation index α, the measurement results are approximated with the function (1) using the least squares method. Based on the above, the values of P_0, P_c and α are determined.

The measurement system presented allows fast and comfortable acquisition of a great number of measurement points. It increases the accuracy of the method and allows statistical processing of the results obtained.

Figure 5 presents the measured distribution of recorded relative power as a function of light propagation path in the waveguide under investigation. The approximation function (1) is placed in the same figure. The distribution in question contains 538 measurement points. Figure 6 presents the diagram of the dependence: $\mathrm{Ln}\{[P(x)-P_c]/P_0\}$ on the length of light propagation path which was obtained earlier. Measurement points were approximated with a straight line. A small dissipation of measurement points and a linear character of the dependence in Fig. 6 prove that the coupling at the output of the waveguide remains constant during the measurements, and, at the same time, confirms that the method applied was correct.

4. Summary

The paper presents the methods and set-up for measurement of refractive index profile of the planar waveguides. There is also presented a method and set-up for attenuation measurement.

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