Intracavity Laser Spectroscopy of Waveguide Structures

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Abstract. A new technique of intracavity waveguide spectroscopy for investigating planar waveguide was proposed. It's based on recording and processing angular spectrum of a light beam reflected from a prism coupler in case of exciting a guided mode in thin-film structure by the intracavity radiation of low-gain laser using a parallelepiped coupling prism in which the intracavity radiation enters the input faces of the prism at the Brewster angles and undergoes double internal reflection in the prism. It was demonstrated that the excitation of guided modes can be performed at the weak coupling. It was shown that the proposed technique can be used for measuring the optical parameters of low-loss planar waveguides.

Introduction

Waveguide spectroscopy of thin films [1] is a powerful tool for investigation of the optical properties of thin-film structures, so the elaboration of new and precise methods of measuring the optical parameters is a foreground task of waveguide spectroscopy. The real and imaginary part of the mode propagation constant $h = h' + ih''$ is the optical parameter of the most interest for an investigator [2]. In the waveguide method of testing thin-films used at the present time in many cases are the prism-coupling techniques [3] in which the measuring the intensity angular distribution of the light reflected from a prism coupler when exiting a guided mode are employed. If a light beam falls on the prism coupler, goes through the prism side and undergoes a total internal reflection from the prism base, a part of light energy can tunnel through a thin air gap into the waveguide. But several conditions should be met for the waveguide excitation to occur. At first, the refraction index of the prism material has to be higher than the effective refractive index of the relating guided mode. Secondly, the phase velocity of the surface electromagnetic wave should be equal to the propagation velocity of the guided mode. Third, the gap width should be small enough (smaller than half of a wavelength) to allow the light energy to "leak" into the waveguide. The thinner the air gap the more light energy passes through it. As a result so-called black *m*-lines are observed in the reflected light. The angular position of an *m*-line minimum relates to the angle of excitation of the guided mode what allows one to determine the effective refractive index of the guided mode. The angular distribution of the reflected light intensity in case of guided mode excitation is determined by the optical properties of the waveguide and, more specifically, by the imaginary part h'' of the mode propagation constant. But the accuracy of the determination is influenced by the vicinity of the coupling prism that makes it difficult to account for, when investigating the low-loss waveguides whose imaginary part of the complex propagation constant $\mathrm{Im}(h / k_0) < 10^{-5}$ (k_0 is the wave number). To reduce the influence of the coupling prism the gap between the prism and the waveguide should be wide enough what in turn excludes recording with the sufficient distribution contrast of the light reflected from the coupling prism. In order to overcome the described above problem a new technique of intracavity waveguide excitation was proposed [4]. The intensity of intracavity radiation of low gain laser is very sensitive to low intracavity losses. If the cavity gain doesn't overcome its losses there will be no lasing and changing of light absorption of intracavity elements can change considerably the laser output power. [5]. For this reason the intracavity laser spectroscopy can be used as a sensitive technique for measuring ultra-small optical losses. There are two main obstacles that don't allow to put a conventional coupling prism into laser cavity without losing the lasing. The first one is that any rotation of the prism will cause the cavity misalignment. The second one is that the Fresnel losses on the prism faces can overcome the laser gain. To solve the first problem, the coupling prism was made in the form of a parallelepiped with opposite faces parallel to each other. When placing the prism in the cavity of a He-Ne laser, the intracavity radiation undergous double internal reflection keeping the angles of incidence and transmittance unchanged. To reduce the Fresnel reflection losses the coupling prism was made so that the light reflecting from the prism base was incoming in the prism entrance faces at the angles close to the Brewster ones.

The experimental setup

In order to observe the intracavity reflection spectra in dependence on the angle of incidence on the coupling prism face the experimental set-up described below was assembled (Fig. 1). The Brewster coupling prism 1 (n = 1.65708) with a low-loss planar waveguide 2 on a glass substrate 3 was placed in the laser cavity consisting of two spherical mirrors: high reflector 4 and output coupler 5. The air gap 6 width was controlled by means of the adjustable pressure 7. The Brewster prism coupler was placed between the output coupler 5 and the He-Ne tube 8 of the laser. Precise angular positioning of the prism coupler was provided by the motorized rotational stage 9. The intensity of the laser beam was recorded by the photodetector 10. The laser radiation from the high reflector was recorded by a quadrant (segmented) photodiode 11 (with a summing and differential amplifier) on a kinematic mount. The set-up was aligned to get the maximum lasing. Changing the angular position of the coupling prism causes the lasing system misalignment and angular shift of the laser beam. To keep the laser pointing stability the kinematic mount of the output coupler was placed on a motorized translation stage 12. The system was automated as follows. Before the measuring process the laser pointing the center of the quadrant photodiode was ensured. Every angular step of the prism coupler leads to an angular shift of the laser beam which was recorded by the quadrant photodiode. The motorized translation stage moved the output coupler in the direction perpendicular to the optical axis of the laser and only when the initial angular position of the beam was restored the intensity of laser beam was recorded by the photodetector. The angular step of the optical stage rotation $\Delta\gamma = 1.13 \cdot 10^{-4}$ degree. The reflection angle γ of intracavity radiation from the input-output face of the prism was tested by a goniometer with angular error equal to 5" (not shown here).

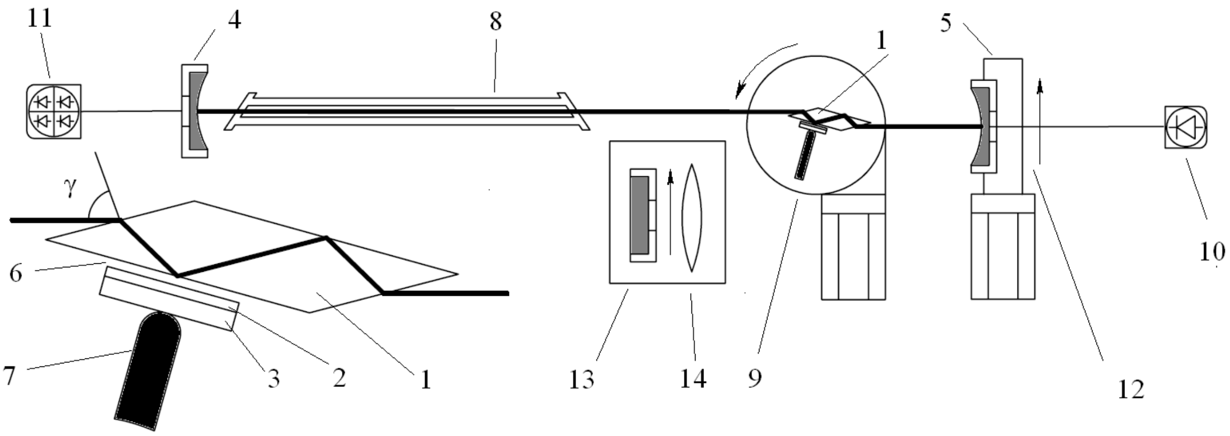

Fig 1. Schematic diagram of the experimental Set-up.

In order to be able to compare the experimental data obtained by the intracavity technique with those obtained by the “extracavity” method, the experimental set-up was arranged so that a flat output coupler 13 on a kinematic mount with a focusing lens 14 could be placed between the He-Ne laser tube and the prism coupler.

Discussions

As a test waveguide sample a low-loss ion-exchanged waveguide supporting five guided modes at $\lambda = 632.8$ nm was used [6]. The coupling prism was made so that its base angle allowed the laser beam, on the one hand, to be reflected at the Brewster angle and, on the other hand, to fall on the prism base at the angles of excitation of the guided modes. Optical parameters of this waveguide was measured by the independent method [7] and for the intracavity recorded modes were $h''/k_0 \sim 10^{-5}$. The gap between the waveguide and the coupling prism was selected by the adjustable pressure in order to reach the best intensity contrast. The recorded intracavity angular reflection spectra of intracavity radiation is plotted in Fig. 2.

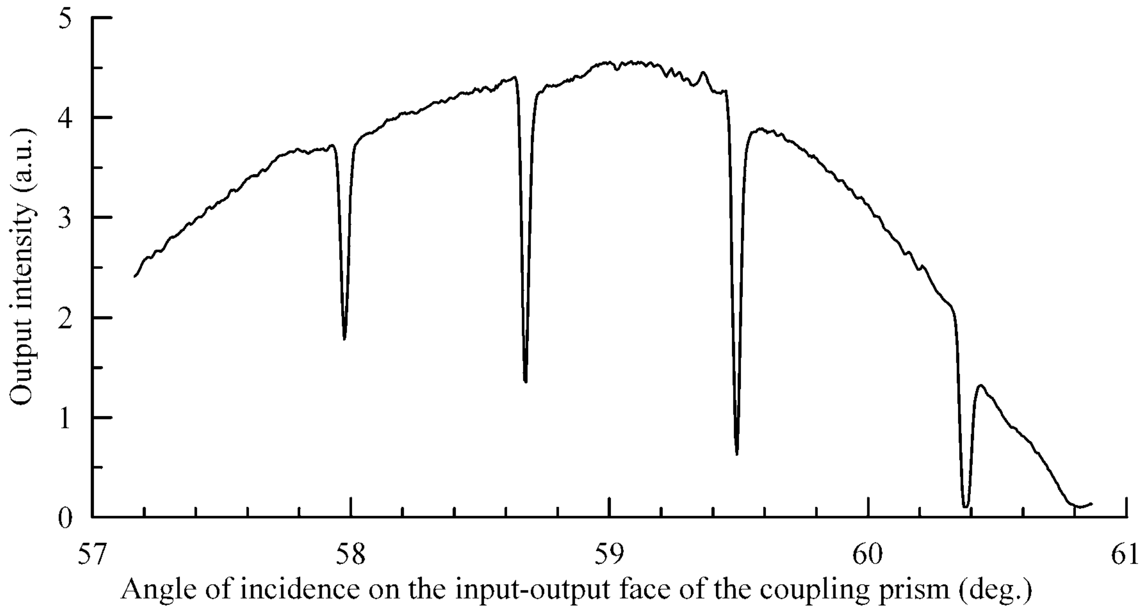

Fig. 1. The dependence of the output intensity of the cavity radiation on the angular position of the coupling prism

Table 1. Optical parameters of the test waveguide

Guided mode order	h'/k_0	h''/k_0 $\times 10^{-5}$
1	1.53359	3.7
2	1.52863	3.1
3	1.52384	1.5
4	1.51928	2.6

The measured data show that the proposed technique allows one to register reflection spectra in case of the weak coupling. The reflection spectra of “extarcavity” radiation had no resonance dips which were observed only at strong pressure of the test waveguide to the coupling prism. This fact confirms the advantage of the intracavtiy technique when registering low waveguide losses at weak coupling. In spite of difficulty of realization of the approach, this allowed us to improve the waveguide spectroscopy technique.

Summary

The analysis of the recorded light intensities reflected near the angles of the guided mode excitation shows that the technique of the intracavity waveguide spectroscopy provides far higher contrast of radiation intensity recording in comparison with the conventional waveguide techniques. High sensitivity of the method proposed allows one to measure small optical losses in the case of weak coupling of the prism and waveguide and to minimize the influence of the prism material on the measurement data. The main disadvantage of the given technique is a narrow angle of the excitation of the guided modes for the certain base angle of the prism. Further investigations of the units for intracavity spectroscopy of thin-film structures with certain optical parameters are required.

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