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Complex method for measuring losses and amplification in active and passive ring laser cavities

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Abstract. **A complex method for measuring the parameters of laser resonators is considered. A combination of two fundamental methods for measuring the *Q* factors of resonators, namely, a method based on analysis of the transmission spectra of multiple-beam interferometers and a method for measuring the radiation decay in high-quality resonators, in one measuring device allowed us not only to extend in fact indefinitely the range of parameters being measured but also to obtain a new method for measuring the gain in the active medium in the resonator.**

Keywords: *laser resonators, mirrors, measurement of losses, gain measurement in an active medium.*

1. Introduction

Laser mirrors are one of the main elements of laser gyroscopes. Good mirrors for laser resonators should have high reflectivity, low scattering, long-term resistance to the UV radiation of a discharge, temperature variations, and to the interaction with a He – Ne plasma. Scattering from mirrors comprising a part of total losses, and especially backward scattering resulting in coupling of counterpropagating waves in the resonator, should be reduced to minimum. The scattering from mirrors depends mainly on the quality of the mirror substrate, and the measurement of the roughness of the mirror substrate of the order of several angstrem is a complicated metrological problem. The total losses related to mirrors affect the limiting accuracy of laser gyroscopes [1, 2] and determine their reliability. When losses are small, low gains can be used and, therefore, discharge currents are weak, so that the sputtering of cathodes is reduced and the action of the plasma on the resonator mirrors decreases. The reflectivity of modern mirrors can be as high as 99.995 %, which means that the total losses related to scattering, transmission, and absorption in dielectric layers do not exceed 0.005 %. The measurement of such low losses is a complicated problem.

In laser gyroscopic sensors, ring monoblock resonators are used. The requirements to the quality of such resonators are very high. Methods for control and alignment of the resonators are especially important in the manufacturing ring lasers with monoblock resonators. Such lasers are compact and not very sensitive to vibrations and shocks. As a rule, these lasers cannot be disassembled and do not require alignment, so that it is very important to control the parameters of the resonator at different stages of their manufacturing. The basic parameters of the resonator are the quality of the mirror alignment, the resonator sphericity, the mode selection coefficient, the total intracavity losses, the backward scattering coefficient, and the gain of an active medium. The problems of measuring the parameters of mirror substrates, multilayer dielectric coatings, active mixture, and resonators have been considered in papers [3 – 12]. In this paper, we will describe a new complex method for measuring the parameters of ring laser resonators, mirrors, and the active medium.

This method is based on the extension of the range of measurements of intracavity losses by combining two fundamental methods: analysis of the transmission spectrum of the resonator and measuring the radiation decay in the resonator using one compact device. To align the resonator and to control the diffraction losses of the transverse modes of the resonator, one should be able to measure comparatively large intracavity losses in the range from 0.1 to 5 %. For this aim, the transmission spectra are used. To control the quality of resonator mirrors for gyroscopic sensors, the highly sensitive methods and equipment are required for measuring the reflectivity $R > 0.99995$ (i.e., losses less than 0.005 %). By measuring the decay time, we can solve this problem. In addition, the sensitivity of the transmission spectrum method can be increased by using the so-called time lens, which expands the transmitted pulse in time. The complex method allows also measuring the gains of active media.

2. Formulation of the problem and basic equations

Consider a ring laser resonator with four mirrors and two active media. Fig. 1 shows the scheme of the resonator for measuring the reflectivity of mirrors, the gain of the active mixture, and the total intracavity losses for different transverse modes, etc.

Radiation at the frequency ω with the electric-field amplitude E_{00} is coupled through one mirror into the resonator and is coupled out of the resonator with the amplitude E_{20} through another mirror. Taking into account phase variations upon multiple round trips of radiation in

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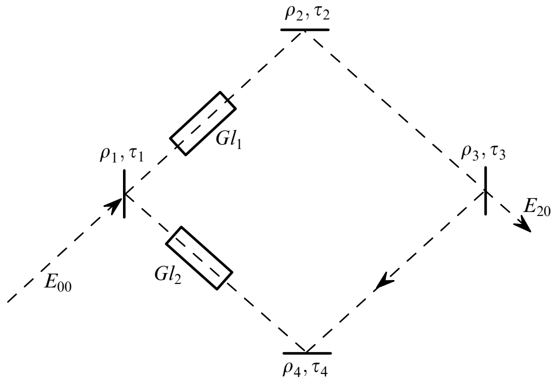

Figure 1. Scheme of the active resonator.

the resonator, the output electric field is described by the expression

$$E_{20}\exp(-i\omega t) = E_{00}K_{mnq}\exp(-i\omega t)[1-\rho\exp(Gl_1+i\delta)]^{-1}, \quad (1)$$

where

$$K_{mnq} = C_{mnq}\tau_1\rho_2\tau_3\exp(Gl_1); \quad (2)$$

C_{mnq} is the mode-matching coefficient, which characterises the efficiency of the propagation of the TEM$_{mnq}$ mode in the resonator; τ_1 and τ_3 are the amplitude transmission coefficients for the input and output mirrors, respectively; $\rho=\rho_1\rho_2\rho_3\rho_4$ is the total amplitude reflectivity of the mirrors; G is the gain per unit of the active medium length for a given mode; $\delta=\omega l/c+\varphi$ is the optical phase shift appearing after the round trip of radiation in the resonator taking into account the transverse structure of the field (φ); and $l=l_1+l_2$ is the total length of the active medium.

A photodetector detects the intensity I_t of the transmitted light. The ratio of the transmitted light intensity to the incident light intensity I_i is described by the expression

$$\frac{I_t}{I_i} = A\left\{1+\frac{4\sqrt{R}}{\left[1-\sqrt{R}\exp(Gl)\right]^2}\sin^2\frac{\delta}{2}\exp(Gl)\right\}^{-1}, \quad (3)$$

where

$$A = C_{mnq}^2\frac{T_1T_3R_2\exp(2Gl_1)}{\left[1-\sqrt{R}\exp(Gl)\right]^2}; \quad (4)$$

$$T_1=\tau_1^2;\ \ T_3=\tau_3^2;\ \ R_2=\rho_2^2;\ \ R=\rho^2.$$

By scanning a probe laser frequency or the perimeter of the resonator under study by applying a saw-tooth voltage to a piezoelectric transducer of one of the mirrors, we can observe periodical transmission peaks of the resonator. For resonators with highly reflecting mirrors, taking into account that $R_i\simeq 1$, we can calculate, after simple transformations, the full width of the transmission peak at half-maximum, using the following conditions:

$$\frac{I_t}{I_i}=\frac{A}{2}, \quad (5)$$

$$\frac{\delta}{2}=m\pi\pm\frac{\varepsilon}{2}, \quad (6)$$

$$\frac{4\sqrt{R}\exp(Gl)}{\left[1-\sqrt{R}\exp(Gl)\right]^2}\left(\frac{\varepsilon}{2}\right)^2=1, \quad (7)$$

where ε is a small variation of the phase. By assuming that $R^{1/4}\simeq 1$ and $G\leqslant 0.1$, we obtain

$$\varepsilon=\frac{\sigma}{2}-Gl, \quad (8)$$

where $\sigma=1-R$ are the total resonator losses, which include scattering, absorption, and transmission losses, as well as diffraction losses in the resonator.

The finesse F of a multiple-beam interferometer is defined as the ratio of its free spectral range $\Delta\nu_0$ to the width $\Delta\nu$ of the resonator line

$$F=\frac{\Delta\nu_0}{\Delta\nu}=\frac{\pi}{\varepsilon}=\frac{2\pi}{\sigma-2Gl}. \quad (9)$$

If a mirror mounted on the piezoelectric transducer moves linearly in time, then

$$F=\frac{T}{\Delta t}, \quad (10)$$

where T and Δt are the time interval between the transmission peaks at one mode and the peak width. From (9) and (10), we find

$$\sigma-2Gl=2\pi\frac{\Delta t}{T}. \quad (11)$$

For a 'cold' resonator, when $G=0$ or $l=0$, we have

$$\sigma_c=2\pi\frac{\Delta t_c}{T}. \quad (12)$$

Knowing the resonator losses, we can measure the gain K for each active medium separately. Taking into account that the lasing threshold is achieved when the gain equals the losses per round trip of radiation in the resonator ($\sigma=K$), we obtain

$$K=\sigma_c-2\pi\frac{\Delta t}{T}\ \text{ or }\ \sigma_{\text{eff}}=\sigma_c-K. \quad (13)$$

When the mirror ceases to move at the transmission maximum for the mode being measured and radiation from a master oscillator is instantly switched off, the output radiation from the resonator decays exponentially:

$$\frac{I_t}{I_i}=A\exp\left(-\frac{t}{\tau}\right), \quad (14)$$

where

$$\tau=\frac{L}{c}(\sigma-2Gl)^{-1} \quad (15)$$

for the resonator with the active medium and

$$\tau=\frac{L}{c\sigma_c} \quad (16)$$

for cold or passive resonators. From (13), we obtain

$$\sigma_{\text{eff}} = \sigma_{\text{c}} - K = \frac{L}{c\tau}.$$

3. Principle of operation of the measuring device

The scheme of the complex method is shown in Fig. 2. Three operating regimes are possible. In regime 1, the transmission spectra of resonators under study are analysed. Regime 2 (the time-lens regime) supplements regime 1 and allows one to increase the pulse duration by a certain factor by decreasing the frequency scan range, thereby enhancing the sensitivity of the method. In regime 3, the radiation decay time is measured in the resonator after sharp periodic interruption of input radiation.

Regime 3 (the decay time measuring) is preferable for controlling high-quality resonators and measuring a very high reflectivity of mirrors because, according to expression (16), the decay time τ being measured increases with decreasing intracavity losses σ_{c}.

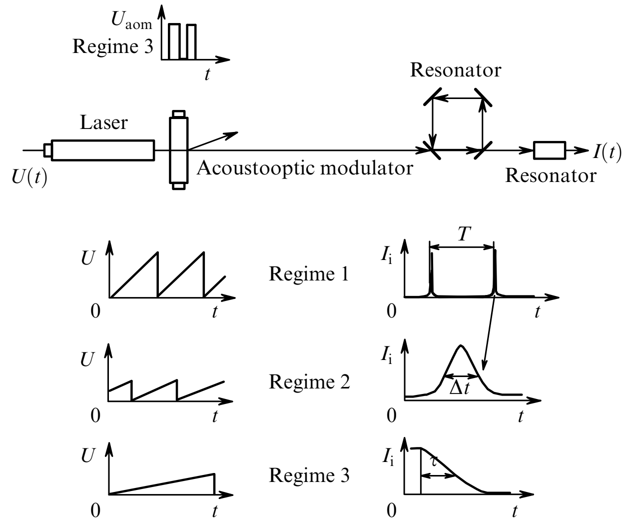

Figure 2. Principal scheme and possible operating regimes of the universal measuring setup: (1) regime of analysis of transmission spectra; (2) time-lens regime (measurement of a resonance peak); (3) regime of measuring the radiation decay time in the resonator.

By measuring the resonance peak and the decay time (the latter regime is optimal in this case), we can also determine the gain K of the active medium for each mode of the active resonator for the given pump current (13) if the intracavity losses σ_{c} for the given mode are preliminary measured by the methods described above.

4. Results of measurements and discussion

The measurements were performed with the help of a fast analog-to-digital converter built in a PC and analog detection equipment. Fig. 3 shows the results of measurements of intracavity losses and gains of the active medium for different pump currents. Also, the relative systematic errors of the methods are presented depending on the effective losses measured in the resonator.

One can see from Fig. 3 that, when intracavity losses change no more than by 0.02 %, the method of measuring the decay time is optimal because the systematic error of measurements is inversely proportional to the duration of the decay front being measured and decreases with increasing Q factor of the resonator. The Q factor of the active resonator was changed in the experiment by increasing the gain of the active medium by varying the pump current in one gas-discharge gap.

The principle of operation of the time lens is explained in Fig. 4. It consists in a change of the time scale upon measuring the width of a transmission peak, resulting in the enhancement of the sensitivity of the analysis of transmission spectra. Figs 5 and 6 show the oscillograms obtained by processing the results of measurements by the two methods.

The results of measurements of the duration of radiation decay fronts (at the 1/e level) in a cold resonator and in a resonator with an active medium below the lasing threshold are shown in Fig. 6. The radiation decay time in the cold resonator was 228 ns at the 1/e level, which corresponds to the pass band of the photodetector and is the lower limit of measurements of time intervals using our setup. The use of

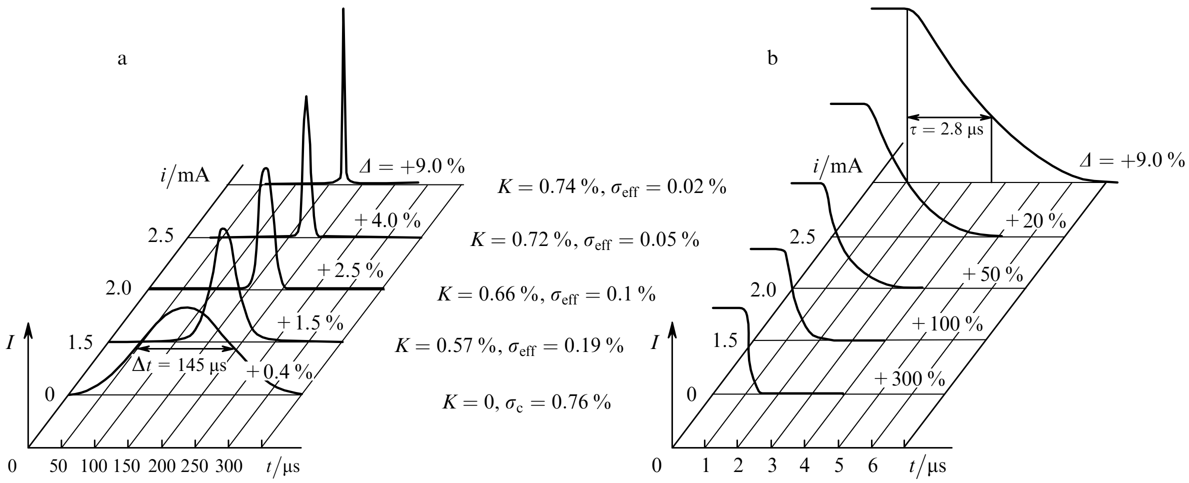

Figure 3. Total losses σ at mirrors and in the resonator and gains K of the active medium determined for different pump currents i by (a) analysing transmission spectra and (b) by measuring the radiation decay time in the resonator; Δ is the systematic error of the method.

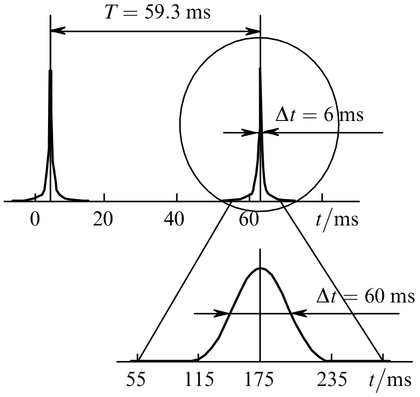

Figure 4. Principle of operation of the time lens.

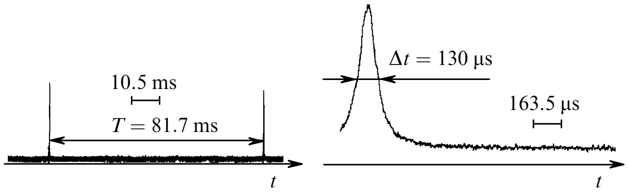

Figure 5. Transmission spectra of the resonator for different scan rates. The resonator losses are $\sigma = 0.5\,\%$, the sampling frequency is 1.25 MHz.

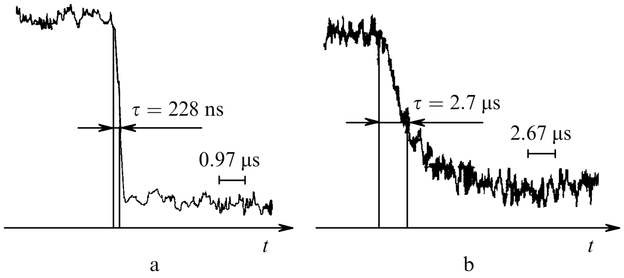

Figure 6. Oscillograms of the radiation decay front in (a) a cold resonator and (b) in a resonator with an active medium whose gain is close to the threshold value when losses are not compensated by the gain in the active resonator; $\sigma_{\text{eff}} = 0.02\,\%$.

PC with the fast ADC considerably simplified the measurements.

5. Conclusions

A setup combining analysis of the transmission spectrum with the measurements of the decay time can be very useful for control of various parameters of ring resonators for gyroscopic sensors and highly reflecting laser mirrors. The results of our experiments have shown that the range of measurements of the parameters of resonators and laser mirrors, as well as of intracavity losses can be extended in fact without restriction. The setup is universal and can be used for solving a variety of scientific and technological problems encountered in the building of lasers, laser gyroscopic sensors, and in manufacturing laser mirrors.

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