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# Two-channel method for measuring losses in a ring optical resonator at a wavelength of 632.8 nm

V.V. Azarova, A.S. Bessonov, A.L. Bondarev, A.P. Makeev, E.A. Petrukhin

***Abstract.*** **A two-channel method is proposed for measuring losses in an optical ring resonator (RR), in which eigenmodes (counter-propagating waves) are excited by means of a Zeeman ring He–Ne laser with a wavelength of 632.8 nm. The measured frequency splitting of the laser counterpropgating waves is used to determine the absolute value of losses in an exemplary RR. The value of losses in the measured RR is determined by comparing the resonance width of the output radiation intensity with the resonance width of the radiation intensity for an exemplary resonator. The algorithm of intensity resonance processing takes into account the distortions caused by the dynamic effect, which allows a significant increase in the accuracy (up to 1%–2%) and sensitivity of the proposed method. The measured losses in the RR with a perimeter of 28 cm constitute 80–5000 ppm.**

***Keywords:*** *ring optical resonator, ring He–Ne laser with a wavelength of 632.8 nm, laser gyroscope, radiation intensity resonances at the RR output, eigenmode losses in the RR.*

## 1. Introduction

Laser gyroscopes (LGs) on the basis of ring He–Ne lasers with a wavelength of $\lambda = 632.8$ nm are widely used in solving many navigation problems, for measuring angular displacements, and also in geodesy and geophysics [1–4]. Ring resonator (RR) mirrors in LGs possess small losses associated with absorption and scattering of radiation on the irregularities of a multilayer interference coating. The total losses in the RR used in the modern LGs vary, depending on the LG type, in the range of 100–3000 ppm. The measurements of these losses involve two basic methods. The first one, a so-called 'ring-down spectroscopy' method [5], is based on measuring the intensity decay time of radiation coming out of the resonator. The second method is based on measuring the intensity resonance width of this radiation [6].

When measuring the decay time losses in a RR, an eigenmode is excited by means of an external probing laser, and then an optical shutter blocks external radiation. Herewith, an exponential decrease is observed in the intensity $I(t)$ of the emission coming out of the cavity:

$$I(t) = I_0 \exp\left(-\frac{t}{\tau}\right), \tag{1}$$

where $\tau = L/(c\delta)$; $L$ is the resonator perimeter; $\delta$ are the RR losses; and $c$ is the speed of light. Having measured the value of $\tau$ by means of the time dependence of the intensity $I(t)$, we can determine the amount of losses in the RR. Since the right-hand side of (1) contains the absolute values of time and length, no additional calibration in determining the absolute value of the RR losses is required.

The second method for measuring losses in the RR is based on the analysis of its transmission spectrum. If the frequency $\nu$ of the probe laser's generation is varied quasi-statically, the spectrum of radiation emerging from the RR represents a Lorentz line:

$$I(\nu) = I_0\left[1 + \frac{(\nu - \nu_0)^2}{\Delta\nu_{1/2}^2}\right]^{-1}, \tag{2}$$

where $\nu_0$ is the eigenmode frequency in the RR; and $\Delta\nu_{1/2} = \delta c/(2\pi L)$ is the line width at half maximum. Thus, the losses can be calculated using the formula

$$\delta = \Delta\nu_{1/2}\frac{2\pi L}{c}. \tag{3}$$

The second method requires a calibration associated with determination of a distance between the adjacent longitudinal modes in the RR. To this end, a sawtooth voltage is applied to a piezoelectric transducer (PZT) of the RR, and thus not only the resonance width, but also the distance between the adjacent resonances are measured. In the case of linear scanning of the probe laser's frequency, the intermodal spacing $c/L$ and the resonance width $\Delta\nu_{1/2}$ are converted into the corresponding time intervals $T$ and $\Delta t$, so that relation (3) can be presented in the form:

$$\delta = 2\pi\frac{\Delta t}{T}. \tag{4}$$

Both methods for measuring losses in the RR have certain limitations related to their magnitude. In particular, the decay time is reduced when the RR losses increase, and also certain engineering difficulties arise in recording the optical pulses with a duration of less than 100 ns. Some problems emerge when the second method is used to measure small losses; in this case, due to the dynamic effect [7], the shape of the resonance curve is markedly different from the Lorentz shape.

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It is no accident that LG developers prefer to measure 'small' RR losses in terms of the decay time of radiation and 'large' losses in terms of the RR transmittance curve [8, 9]. For the RR with a perimeter $L = 28$ cm, the boundary of 'smallness' can be estimated as 500 ppm.

Even if we may agree with the conclusion regarding the limitations in measuring the losses in the decay time terms, the statement about the limitations in the case of measurements in terms of the intensity resonance width seems doubtful. First of all, it should be noted that these limitations are stipulated by the use of calibration of the parameter $T$ relative to the distance between adjacent longitudinal modes in the RR. In engineering implementation of this calibration method, the scanning time of the oscillation frequency of the probe laser commonly does not exceed 100 ms. Such a short time leads to distortions in the shape and intensity of resonances and introduces significant errors in determination of the amount of losses in the RR.

In order to reduce these errors and distortions, it is necessary to significantly decrease the frequency scanning speed of the probe laser, to use a different method of absolute calibration, and also to make allowance for the dynamic effect in determination of the amount of losses in the RR. In this work, a method for measuring the resonator losses in the range of tens to several thousand ppm is described and implemented.

## 2. Measurement technique and scheme of the setup

The losses in the RR are measured in two stages. At the first stage, the losses in an exemplary RR are measured. Then, by comparing the transmittance resonance widths in the measured and exemplary RRs, the losses in the measured resonator are determined. Since an additional measurement channel is used for calibration of the absolute value of losses, we call this technique a two-channel measurement. Below we describe the measurement procedure in more detail.

### 2.1. Measurement of losses in the exemplary RR

A schematic diagram for measuring the losses in an exemplary RR is shown in Fig. 1. As a probe laser, we used a Zeeman He–Ne ring laser ($\lambda$ = 632.8 nm) [10] operating in the regime of beats of the counterpropagating waves. The beat frequency of the counterpropagating waves constituted 150 kHz; the single-mode lasing power was 50 μW. One of the exemplary RR mirrors was mounted on a piezoelectric transducer (PZT), which allowed the eigenmode of the resonator to be scanned near the lasing frequency. Eigenmodes in the exemplary RR were excited in opposite directions, so that two time-shifted intensity resonances of the counterpropagating waves emerging from the exemplary RR were observed in the course of frequency scanning (Fig. 2). Due to the fact that the time shift is proportional to the beat frequency of the counterpropagating waves, the resonance width can be measured in hertz, and the value of losses can be determined using relations (2) and (3).

In recording the intensity of resonances, a sawtooth voltage with a frequency of 5–30 Hz was applied to the PZT of the exemplary RR perimeter. The voltage amplitude was varied in the range of 1–10 V. The PZT transmission ratio was about 80 V $\lambda^{-1}$ (when retuning the resonator's perimeter on $\lambda$).

An important feature of the optical scheme we use is that some part of radiation of counterpropagating waves, emerging from the exemplary RR, comes back to the probe laser. This undesirable feedback results in significant distortions of the intensity resonance shapes. In order to avoid this, we use an optical isolator (OI) with an intensity isolator factor of 40 dB. To limit ourselves to a single OI, we mounted it in such a way that radiation of the two counterpropagating waves of the laser, directed towards each other at a slight angle of about 3°, passed through that OI.

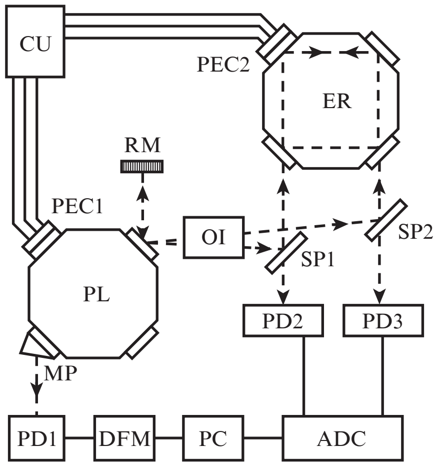


**Figure 1.** Scheme for measuring losses in the exemplary ring resonator: (PL) probe laser; (MP) mixing prism; (ER) exemplary resonator; (CU) control unit; (RM) return mirror; (OI) optical isolator; (SP1,2) semitransparent plates; (PD1,2,3) photodetectors; (PZT1,2) piezoelectric transducers; (DFM) digital frequency meter; (PC) personal computer; (ADC) analogue-to-digital converter.

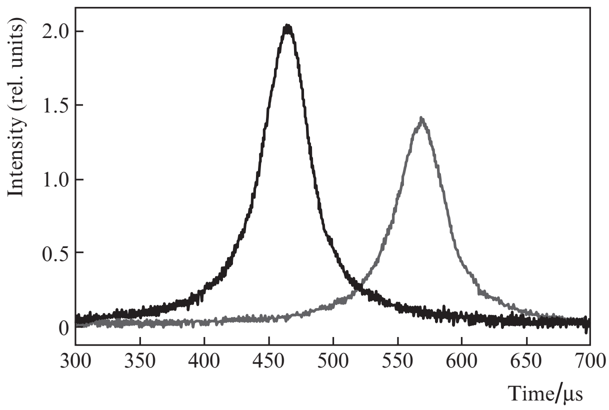


**Figure 2.** Time dependences of the intensity resonances of counterpropagating waves in the exemplary RR. The beat frequency of counterpropagating waves is 150 kHz; the exemplary resonator losses are 360 ± 3 ppm.

To record the intensity resonances, FD28KP silicon photodiodes with a photosensitive area having a diameter of about 1 mm were used. A photocurrent–voltage converter on a single LF411-CN operational amplifier served as an amplifier. The load resistance was 1.6 MΩ.

As housings for the exemplary RR, we used the pyroceramics housings of the LG sensors with no selection aperture. After placing the mirrors within optical contact, the housings were hermetically sealed to maintain the amount of losses unchanged in the exemplary RR for a long time. The change in losses during a year of observation did not exceed a few ppm. The losses in the exemplary RR we used in our experiments varied in the range of 250–360 ppm. The length of a four-mirror RR was 28 cm.

### 2.2. Measurement of losses in the RR by comparing the intensity resonance width with the resonance width of the exemplary RR

The use of a highly stable exemplary RR allows one to significantly simplify the measurements and to determine the absolute value of losses by comparing the widths of intensity resonances for two RRs. The scheme of the setup is shown in Fig. 3.

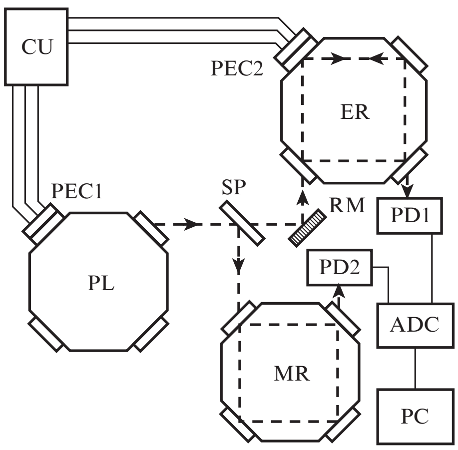


**Figure 3.** Scheme for measuring the ring resonator losses by comparing the intensity of two resonance widths in the RR:
(RM) rotating mirror; (MR) measured resonator; other designations are the same as in Fig. 1.

In this case, eigenmodes in the exemplary and measured RR are only excited in a single direction. Therefore, both lasers with ring and linear resonators can be used as probe lasers. Herewith, a sawtooth voltage should be applied to PZT1 of the probe laser. In this case, two intensity resonances are recorded and compared to each other, with the magnitude of losses in the exemplary RR being used as a calibration value.

Since the measured RR was not equipped with a piezoceramic transducer, in order to obtain a stable resonance intensity, a sawtooth voltage with an average value corresponding to the eigenfrequency of the measured RR was applied to PZT1 of the probe laser. Herewith, the PZT2 voltage in the exemplary RR was chosen such as to provide approximate coincidence of the frequency of its eigenmodes with the eigenfrequency in the measured RR. In other respects the loss measurement procedure was the same as in the case of measurements in the exemplary RR.

## 3. Computer processing of experimental data

Computer processing of experimental data represents an important component of the described method for measuring losses, which allows implementation of high accuracy and sensitivity of measurements. Having no opportunity to describe in detail all features of the data processing algorithm we have developed, let us only consider its basic fundamental points. A more detailed description of the algorithm can be found in [11, 12].

First and foremost, we should note that the algorithm is based on an *a priori* assumption of the Lorentzian shape of the intensity resonance in the case of an infinitely small speed of scanning of the generation frequency of a probe laser (or the eigenmode frequency in the RR). The resonance curves, inevitably possessing occasional distortions due to the action of noise and interference, have been isolated from the measurement signal and approximated by the Lorentz contour using mathematical regression, which allows us to smooth these curves, and, using one of the parameters of the found Lorentz function, to determine their width $\Delta t$ required for the loss calculation [see (2)–(4)]. The search for the approximation function is performed using the LabVIEW software which implements the Levenberg–Marquardt optimisation algorithm [12].

To reduce random errors, the measurements have been repeated many times. The resulting signal contains 30–40 resonance curves and is processed in a standard way [13], with finding the average value of $\Delta t$, evaluating its standard deviation and confidence interval at a confidence probability of 0.95.

The developed algorithm has allowed us, in further data processing, to take into account the impact of the effects resulting in a systematic distortion of the intensity resonance shape. These effects include the distortions introduced by photodetectors and electronic amplifiers, and also the distortions caused by the dynamic effect [7]. The consequence of these effects is the dependence of the losses calculated using the Lorenz function on the frequency scanning rate (or the scanning time $T$ between two longitudinal modes in the RR). To reduce systematic errors when using our algorithm, the scanning speed is controlled and the value of calculated losses is duly corrected. This correction is based on the functions of two types (see below), built in advance by modelling the processes in the RR and PD and leading to distortions of the resonance shapes. It is assumed that the dynamic effect in the RR is described using a special iterative procedure [11], while the photodetector corresponds to the first-order relaxation circuit [12].

## 4. Experimental results

The proposed method for loss determination was tested in a wide range of losses in a four-mirror RR with the perimeter of $L$ = 28 cm. The minimum value of the measured losses was 80 ppm, and the maximum value was 5000 ppm. The experiments employed two types of multilayer dielectric mirrors based on the pairs of $TiO_2$–$SiO_2$ and $Ta_2O_5$–$SiO_2$ layers, fabricated by the technique of ionic deposition onto a substrate from a crystalline glass-ceramic (Sitall CO-115M).

It should be noted that the main feature of the method of loss measurements by the resonance curve width is the tendency to the loss overestimation. This is due to the fact that both of the above-mentioned sources of distortions of the intensity resonance shape increase the resonance duration. With increasing scan time, the distortions are reduced and the measured value of losses approaches its actual value $\delta_0$. Figure 4 presents a typical dependence of the measured value of losses $\delta_{meas}$ in the RR on the scan time $T$. The actual value of losses was determined by extrapolation of the measured losses into the region of an infinite value of $T$ (or zero frequency scan rate). We conducted these measurements to determine the loss magnitude in the exemplary RR; then, we used this value to calibrate the measurements by means of the

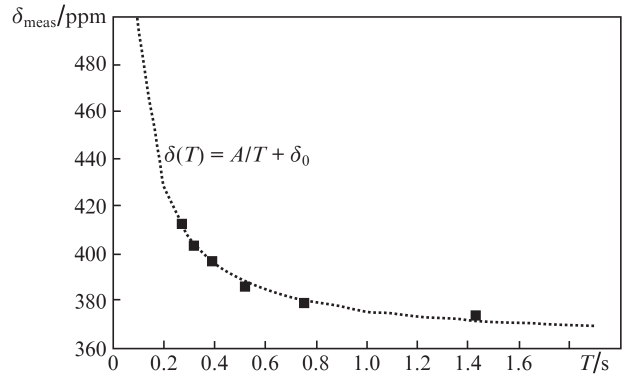


**Figure 4.** Measured losses in the RR vs. scan time $T$.

comparison technique. According to our estimates, the systematic error of the two-channel method of loss measurement does not exceed 1%–2% (relative value). Of course, this procedure can be used when measuring the losses by the method of comparison with the exemplary resonator. However, it should be taken into account that the measurement time for this dependence exceeds 30 min. This greatly restricts the applicability of this approach in solving a number of problems (for example, when adjusting the resonator), where only a few seconds are allocated for the measurement.

The use of corrections that take into account distortions of the intensity resonance allows a significant reduction of the measurement time with maintaining a high accuracy. Comparison of the measured ($\delta_{meas}$) and corrected ($\delta_{cor}$) losses with the actual value of $\delta_0$ (Fig. 5) shows that introduction of the correction procedures into the algorithm allows avoiding significant errors in the case of a small (1–2 s) measurement duration.

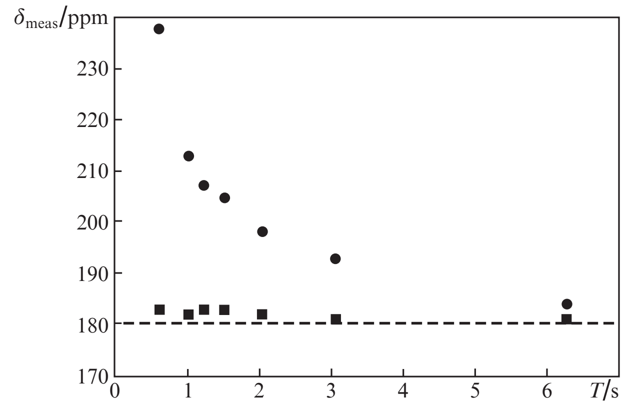


**Figure 5.** (●) Measured and (■) corrected losses vs. scan time $T$. The magnitude of actual losses in the measured RR is 180 ± 2 ppm (dashed line), the magnitude of losses in the exemplary RR is 265 ± 3 ppm.

To realise maximum capabilities of the described method, it is necessary to satisfy a number of conditions. They include the temperature stability in the laboratory room, the absence of significant acoustic disturbances (door slamming, etc.) and the sealing of the RR housings. Under these conditions, the standard deviation of losses for individual values did not exceed 2%–3% in the range of measured losses of 80–5000 ppm.

Special attention was paid to the filtering of the voltages applied to the PZT of the probe laser and exemplary RR. In our experiments, the typical width of intensity resonances, recalculated to the scanning voltage value, was 10 mV. Using a high-pass RC filter (with a cut-off frequency of about 1 Hz), connected to the PZT, allows reducing the ripple amplitude down to 1 mV.

Note that the correction algorithm has fundamental limitations. This is due to the fact that the Lorenz function approximation is efficient at relatively low distortions of the intensity resonance shape. Figure 6 shows the intensity resonance shapes that have been measured or calculated on the basis of a mathematical model of the dynamic effect. The coincidence between them is so good that we had to slightly shift vertically one of the resonances for better graphical representation. In this example, the introduced corrections allow us to avoid significant errors in determining the magnitude of losses.

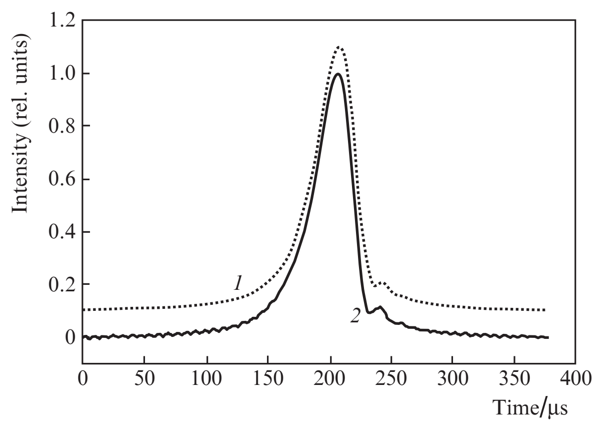


**Figure 6.** Shapes of (*1*) calculated and (*2*) measured intensity resonances; $\delta_{meas}$ = 180 ppm, $T$ = 1.025 s.

The distortions of the resonance shapes begin to grow with decreasing scan time. The resonances acquire an asymmetrical shape relative to the vertex; high-frequency oscillations typical of the dynamic effect appear on the right resonance wing. In the example above, the loss correction algorithm does not work when the scanning time $T$ is less than 0.5 s. In this case, the loss determination error exceeds 10%. This peculiarity of approximating the intensity resonances by the Lorentz function has been taken into account in operation of the measuring setup. If the scan time turns out less than the minimum allowable value, a recommendation for increasing the scan time appears on the computer screen.

High sensitivity of the two-channel method, which, according to our estimates, constitutes about 0.1%, may be of interest for the LG developers. As an illustration, we represent the results of the loss measurements in the RR with a nonplanar contour. A characteristic feature of the mode spectrum in such a resonator is a slight difference in losses for the neighbouring modes with different polarisations. For typical total RR losses of 2000–3000 ppm, the difference between them can be up to several tens of ppm. Figure 7 shows the results of loss measurements for a 'comb' of modes with different polarisations of the four-mirror RR with a perimeter of 16 cm. The half-integer value of the mode index indicates that the frequency shift of the eigenmode is $c/2L$. A 'jump' in the loss

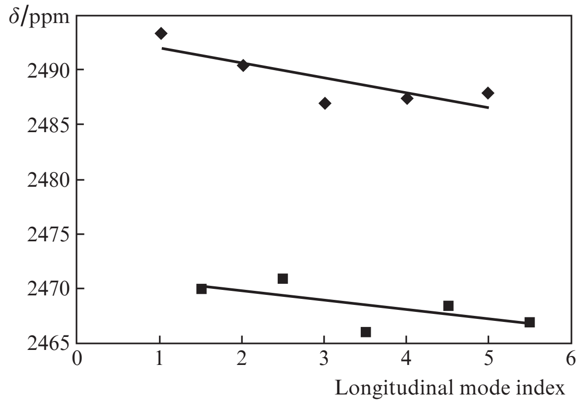


**Figure 7.** Losses in the nonplanar RR vs. index of differently polarised longitudinal modes.

magnitude in this case was about 20 ppm. The presence of a tilt in these dependences indicates a relationship between the diffraction losses in the resonator and the voltage applied to the PZT. This is explained by the fact that the PZT displacement is accompanied by a shift of the resonator's optical axis with respect to the selecting diaphragm mounted inside the monoblock RR housing. The main reason for this shift is a tilt of the piezoelectric mirror relative to the contact surface of the RR monoblock housing (the PZT 'tilt') to which a voltage is applied. The mirror tilt may constitute a few arcseconds. In the case of perfect alignment, when the optical resonator axis passes through the diaphragm centre, the dependence of diffraction losses on the PZT voltage is parabolic. If there is an initial mismatch, a linear component in this dependence appears.

It should be noted that high sensitivity of our setup has been demonstrated at relatively high losses in the RR. In this case, the deviations of the resonance shape from the Lorentzian one were virtually indiscernible, and the measurements were made at small scan times (less than 0.1 s). With decreasing measurable losses, the implementation of high sensitivity becomes difficult. In this case, the scan time should be increased inversely proportional to the magnitude of losses. In this regard, a slow temperature drift and atmospheric pressure in the room become major factors limiting the minimum value of the measurable losses and the method sensitivity.

We have not taken any special measures to reduce the effect of these disturbing factors, except that the measured monoblock RR have been sealed and 'kept' in a room during one to two hours before the measurements. The room temperature was not stabilised, and its drift, usually did not exceed 1–2 °C in the course of 5 h.

## 5. Conclusions

Our experiments have shown that the two-channel method allows a significant expansion of the scope of application of the intensity resonances for measuring losses in the ring resonators. It can be used to measure the RR losses in the range of tens to several thousand ppm. This avoids significant systematic errors inherent in the measurement method based on the intensity resonance width. In the case of the RR with a perimeter of $L = 28$ cm in the range of measured losses of 80–5000 ppm, the residual systematic error does not exceed 1%–2%. Herewith, the standard deviation of the single counts (rel. units) does not exceed 2%, while the sensitivity reaches 0.1%.

The measuring setup with such characteristics of accuracy can be used not only for controlling the metrological parameters of laser gyroscopes, but also for solving a wide range of engineering and technological problems arising in the LG development. These include the alignment quality control in the RR, improving the PZT design, and also solving the problems associated with decreasing the light absorption in the RR mirrors and reducing the impact of UV radiation of the gas discharge on the characteristics of mirrors.

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