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Observation of the Sagnac effect in a ring resonant interferometer with a low-coherence light source

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Abstract. A fibre-optic resonant ring interferometer with a low-coherent light source was investigated experimentally. The feasibility of measuring the parameters of ring cavities characterised by very narrow lines (of the order of tens of kilohertz) was demonstrated by using a broad-band light source and a retroreflecting Doppler mirror. The Sagnac effect was first observed in a ring resonant interferometer with a low-coherence light source. Modulation and compensation of the phase nonrecriprocity in a low-coherence resonant interferometer with the aid of an optical frequency shifter located outside a sensing fibre loop were observed experimentally.

1. Introduction

One of the promising ways of improving the characteristics of optical angular velocity sensors involves going over from systems based on the classical Sagnac interferometer to resonant systems in which the sensing loop consists of a ring cavity [1]. Since in resonant interferometers the counterpropagating waves travel repeatedly around the sensitive loop, accumulating a nonreciprocal phase delay, the resonant interferometers with the same loop dimensions may be many times more sensitive than the usual Sagnac interferometers. This leads to extensive opportunities for miniaturising optical rotation sensors and for construction of 'single-crystal' integrated optical gyroscopes.

However, despite their potential advantages, the resonant systems cannot so far compete with the nonresonant fibre-optic Sagnac interferometers. This is because of a number of disadvantages inherent in the traditional methods for measuring the phase nonreciprocity in ring cavities, which are based on the use of monochromatic light sources. The most serious of these disadvantages are a transient nonreciprocal 'pedestal' associated with the interference of the backscattered light, a high sensitivity of the interferometer to the temperature instability of the optical length of the cavity, and the need for tight locking of the source frequency to the operating resonance of the ring cavity arising from this, as well as the need to use light sources with very narrow lines (10 kHz – 1 MHz), which prevent the miniaturisation and simplification of the rotation sensors. All these disadvantages are linked fundamentally to the use of monochromatic light and so far it has not been possible to overcome them within the framework of the traditional 'high-coherence' approach.

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2. Resonant ring interferometer based on low-coherence light

In a previous study [4], we proposed a new method for measuring the phase nonreciprocity in ring cavities, based on the use of nonmonochromatic light sources. This method may be used in measuring the angular velocity and also very small Doppler shifts of the light frequency [5]. By virtue of the short coherence length of the source, the interferometers described previously [4] do not suffer from the disadvantages characteristic of systems based on high-coherence light. This communication describes an experimental observation of the Sagnac effect in a fibre-optic resonant cavity with a low-coherence light source.

The basic setup of the low-coherence resonant interferometer is presented in Fig. 1. The interferometer consists of a low-coherence light source (1), a 3-dB fibre coupler (2), a ring cavity (3) closed by couplers (4) and (5), a retroreflecting mirror (6), and a photodetector (7). It is postulated that the width of the radiation source spectrum exceeds greatly the mode spacing of the cavity (or, which amounts to the same thing, the coherence length of the source is much shorter than the perimeter of the sensing loop).

The interferometer operates as follows. The light from the source (1) passes through the coupler (4) into the ring

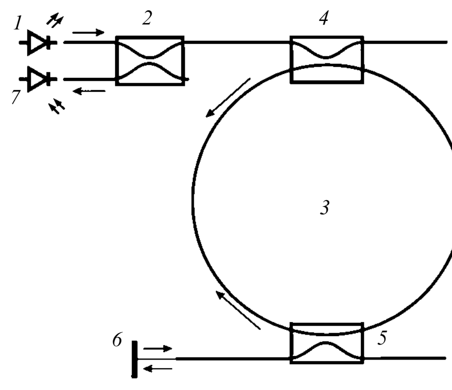

Figure 1. Basic setup of a resonant ring interferometer with a low-coherence light source: (1) light source; (2) fibre coupler; (3) ring cavity; (4, 5) weakly coupled fibre couplers; (6) retroreflecting mirror; (7) photodetector.

cavity (3), travels round it clockwise, proceeds round the coupler (5) to the retroreflecting mirror (6), and after reflection from this mirror, it returns to the cavity, travels round it anticlockwise, and reaches the photodetector (7). Since the cavity transmits only its resonant lines, the spectrum of the light incident on the retroreflecting mirror consists of a set of narrow lines selected by the cavity from the broad spectrum of the source. The central frequencies of these lines are equal to the resonance frequencies of the ring cavity for light propagating clockwise.

The light returned by the retroreflecting mirror must pass through the cavity anticlockwise. In this direction, the cavity transmits only on the resonant counterpropagation lines. If there is a phase nonreciprocity in the cavity, the resonance frequencies for the counterpropagating directions are not equal and the cavity transmission lines for light travelling anticlockwise are frequency-shifted relative to the lines of the radiation arriving in the cavity from the retroreflecting mirror. This reduces the total optical power incident on the photodetector. The same thing happens if there is a Doppler light-frequency shift on reflection from the retroreflecting mirror.

In the presence of the cavity nonreciprocity and the Doppler effect in reflection from the retroreflecting mirror, the optical power reaching the photodetector is given by

$$P_{\text{out}} = \frac{1}{4}\int T^{-}(\omega)T^{+}(\omega)P_0(\omega)\,\mathrm{d}\omega \,, \tag{1}$$

$$T^{\pm}(\omega) = T\left(\omega^{\pm} \pm \frac{\phi_{\text{s}}}{2}\frac{c}{nL}\right)$$

$$= \left[1 + \left(\frac{2F}{\pi}\right)^2 \sin^2\left(\frac{\omega^{\pm}Ln}{2c} \pm \frac{\phi_{\text{s}}}{4}\right)\right]^{-1}, \quad \omega^{-} = \omega^{+} + \Delta\omega \,, \tag{2}$$

where $T^{\pm}(\omega)$ are the transmission coefficients of the ring cavity in the counterpropagating directions; $P_0(\omega)$ is the power spectrum of the light source; F is the cavity finesse; ϕ_{s} is the Sagnac nonreciprocal phase difference for the counterpropagating waves per round trip through the cavity; $\Delta\omega$ is the Doppler frequency shift on reflection from the retroreflecting mirror; L is the cavity perimeter; n is the refractive index.

If the spectral width of the source spectrum accommodates very many resonances of the ring cavity but at the same time ϕ_{s}, $\Delta\omega$ may be regarded as independent of the frequency ω, the expression for the output power of the interferometer assumes the simple form [4]

$$P_{\text{out}}(\phi) = \frac{\pi}{16}\,\frac{P_0}{1 + (2F/\pi)^2\sin^2(\phi/2)} \,, \tag{3}$$

where

$$F = \frac{\pi\sqrt{R}\exp(-\delta L/4)}{1 - R\exp(-\delta L/2)} \,; \tag{4}$$

R is the fraction of the noncoupled power in the couplers (4) and (5) (the 'reflection coefficient'); δ is the decrement of the power losses in the ring cavity; P_0 is the total power of the light source;

$$\phi = \phi_{\text{s}} + \Delta\omega\frac{Ln}{c} \tag{5}$$

is the total phase nonreciprocity consisting of the phase nonreciprocity proper ϕ_{s} and the effective Doppler nonreciprocity due to the frequency shift on reflection from the mirror (6). The form of the relationship $P_{\text{out}}(\phi)$ is similar to that of the transmission spectrum of the ring cavity $T(\omega)$ [formula (2)], but instead of the total phase $\varphi = \omega Ln/c$ the phase nonreciprocity ϕ occurs in expression (3). It is important that the interferometer output power is independent of the optical length of the cavity nL provided that one disregards the changes in the scaling factor for ϕ_{s} and $\Delta\omega$. This ensures a high temperature stability of the interferometer and eliminates the need to match the cavity length to the source frequency.

Since the Doppler and Sagnac nonreciprocities act on the interferometer in exactly the same way, in measuring the Sagnac nonreciprocity by the modulation method it is possible to achieve signal modulation and compensation by the frequency shift on reflection from the retroreflecting mirror. The important factor is that in this case the modulator and compensator may be placed between the coupler (5) and the retroreflecting mirror, i.e. outside the sensing loop. In this arrangement, the parasitic nonreciprocities of the modulator and compensator do not influence the interferometer operation.

The interferometer may be modulated also with the aid of a mutual phase modulator located asymmetrically relative to the input coupler (4) and operating at a frequency equal to the free spectral range of the ring cavity [5]. Since this modulation method is used widely in fibre-optic Sagnac interferometers [6], suitable modulators have been thoroughly developed and have good characteristics.

The maximum interferometer sensitivity is attained in modulation measurements at the modulation amplitudes ϕ^*_{m} corresponding to the maximum of the derivative $(\mathrm{d}P_{\text{out}}/\mathrm{d}\phi)_{\phi\text{m}}$. For $F \gg 1$ and low-frequency 'quasi-steady-state' modulation at a frequency much lower than the width of the cavity resonance line, the optimal modulation amplitude is

$$\phi^*_{\text{m}} \approx \frac{\pi}{F\sqrt{3}} \,. \tag{6}$$

In Doppler modulation, this corresponds to the following frequency shift on reflection from the retroreflecting mirror:

$$\Delta\nu^* = \frac{\phi^*_{\text{m}}}{2\pi}\frac{c}{nL} = \frac{1}{2\sqrt{3}F}\frac{c}{nL} = \frac{1}{2\sqrt{3}F}\nu_{12} \,, \tag{7}$$

where $\nu_{12} = c/nL$ is the mode spacing of the ring cavity. Under these conditions, the output signal of the interferometer, i.e. the signal at the first harmonic of the modulation frequency, is

$$P_1 \approx 0.04P_0\frac{4\pi\nu_0 aLn}{c^2}\Omega \,, \tag{8}$$

where ν_0 is the central light-source frequency; a is the radius of the sensitive loop (it is postulated that this loop is in the form of a coil); Ω is the angular rate of rotation of the interferometer (in radians per second).

On modulation at a frequency equal to half the mode spacing of the cavity, the useful signal is approximately half the signal described by expression (8). This can be explained by the fact that in such modulation the nonreciprocal phase modulation is acquired only by the counterpropagating waves passing a number of times through the cavity.

The noise at the interferometer output (for a 1 Hz transmission band of the output device) is

$$\delta P_{\text{out}} = \frac{1}{4}\left\{\left(\frac{\pi h\nu_0 P_0}{F}\right)^{1/2} + P_0(2\pi)^{-1/4}\frac{[G(2\pi f_{\text{m}} nL/c]^{1/2}}{(\Delta\nu_0)^{1/2}}\right\}, \quad (9)$$

where

$$G(\varphi) = \frac{1}{2\pi}\int_{-\pi}^{\pi}\left\{\left[1+\left(\frac{2F}{\pi}\right)^2\sin^2\frac{\varphi'}{2}\right]\times\left[1+\left(\frac{2F}{\pi}\right)^2\sin^2\frac{\varphi-\varphi'}{2}\right]\right\}^{-2}\mathrm{d}\varphi' \; ; \quad (10)$$

f_{m} is the modulation frequency; $\Delta\nu_0$ is the width of the light-source spectrum. The first term in expression (9) corresponds to shot noise, whereas the second corresponds to a beat noise of the spectral components of the radiation at the photodetector [7, 8]. As a consequence of the inhomogeneity of the radiation spectrum at the interferometer output, the dependence of the spectral components of the beat noise on the modulation frequency f_{m} becomes strongly inhomogeneous. This dependence is determined by the function $G(\phi)$, which is very close in profile to the Airy resonance function (2) (Fig. 2).

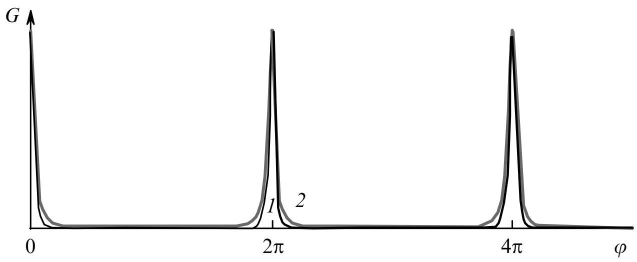

Figure 2. The function $G(\varphi)$ (1) and the Airy function (2) for $F = 30$.

The function $G(\varphi)$ is periodic with the period 2π. It has very sharp maxima at $\varphi_l^{\max} = 2\pi l$, where l is an integer [the maxima with $l \neq 0$ correspond to beats between resonance lines with frequencies which are multiples of the mode spacing of the cavity $\nu_{12} = c/(nL)$], and broad minima separated from the maxima by π. The presence of a minimum in the function $G(\varphi)$ at $\varphi = \pi$ promotes suppression of the spectral components of the beat noise in modulation at the frequency $f_{\text{m}} = c/2Ln = 1/2\nu_{12}$. It can be shown that, in the course of modulation at the frequency $f_{\text{m}} = 1/2\nu_{12}$, the beat noise of the spectral components is approximately a factor F^2 smaller than in the case of low-frequency 'quasi-steady-state' modulation at a frequency much smaller than the width of a ring-cavity resonance.

The detection limit of the rotation, determined from the equality of the signal (8) and the noise (9), is as follows for $F \gg 1$ in the case of low-frequency modulation at $f_{\text{m}} \ll c/2Ln$:

$$\Omega_{\min} \approx \frac{c^2}{2nLa\nu_0}\left[\left(\frac{\pi h\nu_0}{P_0 F}\right)^{1/2} + \frac{(2/\pi)^{1/4}}{(\Delta\nu_0)^{1/2}}\right]. \quad (11)$$

In the case of modulation at the frequency $f_{\text{m}} = c/2Ln$, we have

$$\Omega_{\min} \approx \frac{c^2}{4nLa\nu_0}\left[\left(\frac{\pi h\nu_0}{P_0 F}\right)^{1/2} + F^{-2}\frac{(2/\pi)^{1/4}}{(\Delta\nu_0)^{1/2}}\right]. \quad (12)$$

We shall now compare the maximum sensitivities of ring interferometers of three types: a ring-cavity interferometer with a low-coherence source ($\Omega_{\min}^{\text{LCRI}}$), a Sagnac interferometer ($\Omega_{\min}^{\text{S}}$), and a ring-cavity interferometer with a monochromatic source ($\Omega_{\min}^{\text{mono}}$). In the case of the ring-cavity interferometer with a low-coherence source and the Sagnac interferometer [9] with the same light source and the same geometrical parameters of the sensing loop, we obtain (for low-frequency modulation in the resonant interferometer)

$$\frac{\Omega_{\min}^{\text{LCRI}}}{\Omega_{\min}^{\text{S}}} \approx 2.5\left(\frac{\pi}{2F}\right)^{1/2}\frac{1+\pi^{-1/2}(2/\pi)^{1/4}[P_0/(h\nu_0\Delta\nu_0)]^{1/2}}{1+0.5(2/\pi)^{-1/4}[P_0/(h\nu_0\Delta\nu_0)]^{1/2}} \sim \left(\frac{1}{F}\right)^{1/2}. \quad (13)$$

The multiplier $(1/F)^{1/2}$ represents the resonance gain in sensitivity attainable in the resonant interferometer with a low-coherence source. If the resonant interferometer is modulated with the aid of an asymmetrically placed mutual phase modulator at the frequency $f_{\text{m}} = c/2Ln$, relationship (13) changes still further in favour of the resonant interferometer by virtue of suppression in the latter of the beat noise of the spectral components.

When the detection limits of the rotation of the ring-cavity interferometer with a low-coherence source and the ring-cavity interferometer with a monochromatic source and low-frequency modulation are compared, we obtain

$$\frac{\Omega_{\min}^{\text{LCRI}}}{\Omega_{\min}^{\text{mono}}} = 2\left(\frac{2F}{\pi}\right)^{1/2}\left[1+\left(\frac{2}{\pi^3}\right)^{1/4}\left(\frac{P_0}{h\nu_0\Delta\nu_0}\right)^{1/2}\right]. \quad (14)$$

It follows from expression (14) that the interferometer with a low-coherence source is inferior to the interferometer with a monochromatic source as regards the maximum sensitivity. This can be explained by the fact that, as a consequence of the frequency-selective properties of the cavity, only $1/F$ of the power of the broad-band light enters it, whereas monochromatic light, of frequency close to the resonance frequency of the ring cavity, is almost fully transmitted by this cavity. Moreover, because the absence of instabilities associated with backscattering and with the temperature-induced variations in the optical length of the cavity, the resonant interferometer with a low-coherence source should exhibit a much better long-term stability than the resonant interferometer with a monochromatic source.

The influence of backscattering in the interferometer with a low-coherence source is expected to be smaller by at least the factor l_{coh}/nL than in the interferometer with a high-coherence source (l_{coh} is the coherence length of the low-coherence source). This is associated with the fact that, in the interferometer with a low-coherence source, the signal waves interfere solely with the waves arising as a consequence of backscattering over a short section of the cavity of length l_{coh}/n, whereas in the interferometer with a high-coherence source the signal waves interfere with the waves formed by backscattering over the entire length of the cavity.

Apart from the system examined above [4], other systems may be put forward for ring-cavity interferometers with low-coherence sources, in particular a very simple system in which the ring cavity is closed by a single coupler (Fig. 3). This system was in fact used in our experiments. In the simplest version of the system, when the ring cavity operates in reflection, the entire light reflected from it reaches a photodetector.

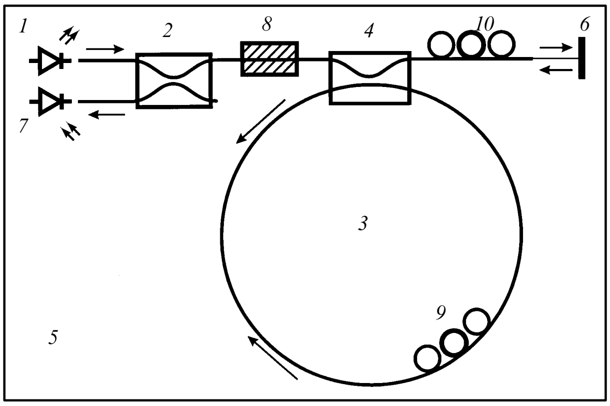

Figure 3. Schematic diagram of a resonant ring interferometer with a low-coherence light source: (1) light source; (2) fibre coupler; (3) ring cavity; (4) weakly coupled fibre coupler; (5) rotatable stage; (6) retroreflecting mirror; (7) photodetector; (8) polariser; (9, 10) components for polarisation control.

Since the cavity has a reflection coefficient close to unity at all frequencies apart from the resonance, most of the light from a broad-band source is reflected from it. This light carries no information about the phase nonreciprocity and merely creates a strong interfering background against which it is necessary to observe a weak interference signal.

This background can be eliminated with the aid of a polariser (8) and polarisation-controllers (9) and (10) (Fig. 3). In the round trip through the cavity, the wave polarisation is rotated by $\pm 90^\circ$ in the component (9) (the opposite signs correspond to opposite directions of the trip). The Jones matrix of the ring cavity in Fig. 3 then assumes the form

$$\hat{\boldsymbol{T}}^{\pm} = R^{1/2}\left\{1 - \left[1 - R^{1/2}\exp(\mathrm{i}\varphi^{\pm})\right]\frac{R^{1/2}(1-R)\exp(\mathrm{i}\varphi^{\pm})}{1+R\exp(\mathrm{i}2\varphi^{\pm})}\right\} \times \begin{vmatrix} 1 & 0 \\ 0 & 1 \end{vmatrix} + \frac{R^{1/2}(1-R)\exp(\mathrm{i}\varphi^{\pm})}{1+R\exp(\mathrm{i}2\varphi^{\pm})}\begin{vmatrix} 1 & \mp 1 \\ \pm 1 & 1 \end{vmatrix}, \quad (15)$$

where φ is the phase shift of an optical wave during a round trip through the cavity. The first term in expression (15) represents the background with an admixture of the useful signal, whereas the second term represents the useful signal. If the distance from the coupler (4) to the retroreflecting mirror (6) is made equivalent to a quarter-wave plate rotated by 45° relative to the polarisation plane of the polariser (8) with the aid of the component (10), the wave corresponding to the first term in expression (15) is fully absorbed by the polariser (8). The output power of the interferometer is then given by

$$P_{\mathrm{out}}(\phi) = \frac{\pi}{16F}\frac{P_0}{1+(2F/\pi)^2\sin^2\phi}, \quad (16)$$

where

$$F = \frac{\pi\sqrt{R}\exp(-\delta L/2)}{1-R\exp(-\delta L)}. \quad (17)$$

Compared with the system in Fig. 1, the effective cavity length is now doubled because the polarisation is restored after two round trips through the cavity. If the intrinsic losses in the cavity are small, then the finesse of the latter remains the same as in the system in Fig. 1: the doubling of the losses owing to exclusion of the waves travelling an even number of times round the cavity is compensated by the absence of leakage of the power generated by the second coupler (5). Doubling of the effective cavity length reduces the rotation detection limit by the factor $\sqrt{2}$, compared with that given by formula (12).

3. Experiment

The resonant ring interferometer with a low-coherence light source (Fig. 3) was investigated experimentally. A detailed schematic illustration of the experimental setup is presented in Fig. 4. A superluminescent diode (1) with a central wavelength of 0.83 μm and an output power of about 100 μW served as the light source in the interferometer constructed on the basis of an all-fibre Sagnac interferometer.

A cavity loop (3), 500 m long, was made from an isotropic single-mode fibre wound on a drum of 10 cm radius and was closed by a polished fibre coupler (4) with a splitting coefficient of 1:10. For this splitting coefficient, the cavity finesse was determined by the intrinsic losses in the ring, which amounted to about 2.2 dB km^{-1}. In the regime without elimination of the light reflected from the cavity and with the polariser (8) 'open', the maximum finesse of the loop was 4 whereas in the regime with elimination of the light reflected from the cavity (by a 'closed' polariser) it was 1.8, so that in the latter case the interferometer worked nearly in a single-pass regime.

A retroreflecting mirror (6) was attached to a dynamic loudspeaker (11) used as the Doppler phase-nonreciprocity modulator. The interferometer was mounted on a rotatable stage (14), which could be rotated in both directions at an angular velocity of 600° h^{-1}.

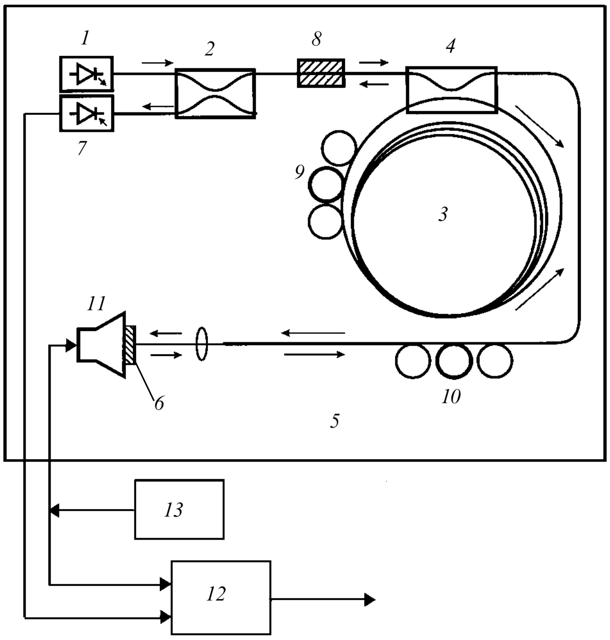

Figure 4. Schematic diagram of the experimental setup: (1) super-luminescent diode; (2) fibre coupler; (3) ring cavity; (4) weakly coupled fibre coupler; (5) rotatable stage; (6) retroreflecting mirror; (7) photo-diode; (8) polariser; (9, 10) components for polarisation control; (11) loudspeaker; (12) lock-in detector; (13) modulating voltage generator.

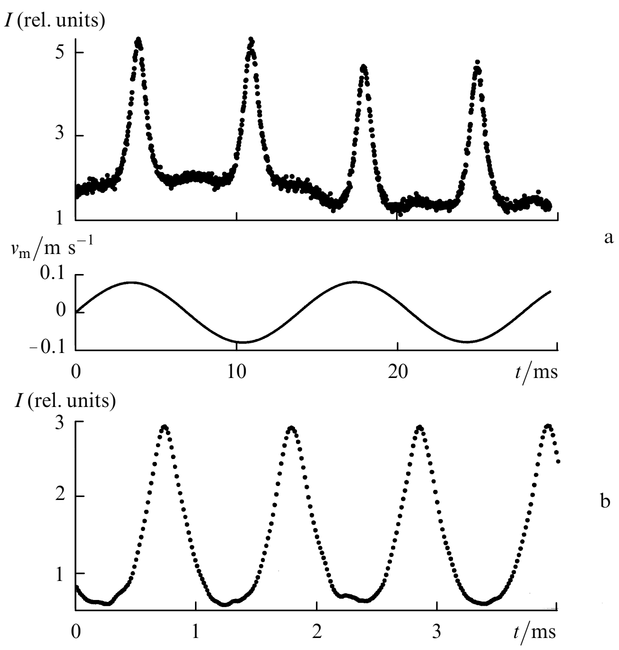

Figure 5. Oscillograms of the photodetector signal for Doppler modulation of the phase nonreciprocity in a ring cavity without filtering (upper curve, photocurrent; lower curve, velocity of the retroreflecting mirror) (a) and with filtering (b) of the light reflected from the ring cavity at the modulation frequency of 72 Hz (a) and 475 Hz (b) and for the cavity finesse of 3.5 (a) and 1.8 (b); modulation amplitude, π rad.

We did not endeavour to construct apparatus with the optimal parameters, because the aim of the experiment was merely to demonstrate a new measurement method.

The cavity finesse was determined from an oscillogram of the interferometer output power, obtained for Doppler modulation of the phase nonreciprocity. The retroreflecting mirror (6), mounted on the loudspeaker (11), served as the modulator. The amplitude of the Doppler modulation of the reflected-light frequency was equal to half the mode spacing of the cavity. In conformity with relationship (16), the resonant curve of the ring cavity was observed on the screen of an oscilloscope (Fig. 5). This system made it possible to measure the finesse of cavities with very narrow resonances and did not require pulsed or narrow-band light sources or complex methods for the stabilisation and adjustment of the cavity. The finesse of a ring cavity with a resonance about 50 kHz wide was measured in our experiments and the spectral width of the light source was of the order of 10 THz.

The Sagnac effect was measured by the modulation method with the aid of a Doppler modulator, in the form of the retroreflecting mirror (6). The first harmonic of the modulation frequency, of amplitude proportional to the Sagnac phase nonreciprocity in the sensitive loop, was selected by a lock-in detector. The modulation frequency was 475 Hz. The measurements were performed without filtering the light reflected from the cavity ('open' polariser) and with filtering of the light reflected from the cavity ('closed' polariser). In the 'closed' polariser regime, the signal/noise ratio was approximately 15 times better. This can be seen from a comparison of the oscillograms in Fig. 5 obtained for the 'open' and 'closed' polariser cases, respectively. Furthermore, when the polariser was 'open', a 'pedestal' comparable with the signal was present. It was associated with parasitic transverse oscillations of a membrane, leading to scanning of the reflected beam. When the polariser was 'closed', this pedestal was diminished by an order of magnitude.

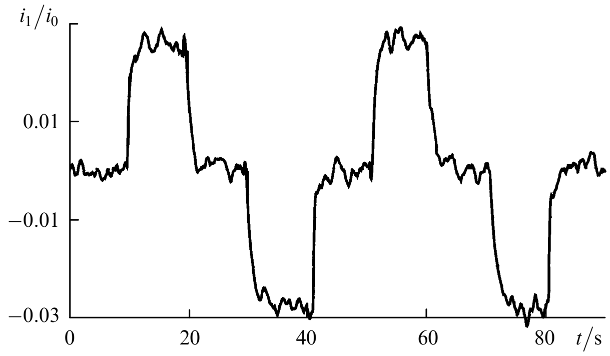

Figure 6. Signal from a ring resonant interferometer rotating at a rate of $\pm 600°\ h^{-1}$ for a time constant of the lock-in detector amounting to 0.3 s (i_1 is the amplitude of the first harmonic of the photocurrent; i_0 is the constant component of the photocurrent).

Fig. 6 presents a record of the rotation signal observed at an angular velocity of $600°\ h^{-1}$ in the system with the 'closed' polariser. The sensitivity of the interferometer was about $30°\ h^{-1}\ Hz^{-1/2}$ and was determined by the photodetector noise.

4. Conclusions

The possibility of measuring the angular velocity with the aid of a ring-cavity interferometer and a low-coherence light source was demonstrated in the present study both theoretically and experimentally. The parameters of a ring cavity with a small (200 kHz) mode spacing and a resonance 50 kHz wide in an optical system with a low-coherence light source (superluminescent diode) and a Doppler retroreflecting mirror were determined experimentally. The phase nonreciprocity in the low-coherence resonant ring interferometer was measured with the aid of a Doppler modulator placed outside the sensing loop.

The expected higher (compared with the resonant systems having high-coherence light sources) long-term stability, a sensitivity better than in the Sagnac interferometer, the possibility of placing modulators and compensators outside the sensitive loop, and the relative simplicity and low cost of the optical system, combined with the availability and the high degree of development of the components, may render the low-coherence resonant interferometer attractive for use in the next-generation optical angular-velocity sensors.

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