Integrated Optical Ring Resonator of The Quantum Gyro with Quasicoherent Source of Radiation

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Abstract

An integrated optical ring passive resonator (IORPR) has been developed and studied. IORPR utilizes optical channel waveguides formed on a K-8A glass substrate by the method of ion diffusion exchange in the potassium nitrate melt. The resonator waveguide structure contains a ring waveguide and two Y-shaped splitters. The symmetrical arms of the splitters are coupled with the ring waveguide, while their homogenous arms – with an external quasicoherent semiconductor laser and photodiode. Coupling between external devices and channel waveguides was implemented by means of end joints and coupling prisms. Experiments have been performed by measurement of the sharpness and transfer function of the ring resonator, which illustrates its resonant properties. The ultimate sensitivity of the quantum gyroscope has been estimated and ways for its improvement have been envisaged. According to the result it is shown that quasicoherent laser diode like ILPN can be used with IORPR.

Key words: integrated optical ring passive resonator; waveguide; laser diode; photodiode; sharpness.

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1.Introduction

As the result of our study it is proposed to use a wide range spectrum quasicoherent source of radiation for a quantum gyroscope. It has been successfully combined with an integrated-optical ring passive resonator of the original topology. The scheme of the quantum gyroscope with an interference output of the optical signal is described in detail in [1-5]. The mathematical basis of the operation of a wide range quasicoherent source with the IORPR, which has a channel ring single mode waveguides, has already been analysed. This problem is quite actual as standard semiconductor heterojunction lasers do not provide necessary sharpness (optimal sensibility of the sensor).

We used here the same approach that we applied in reports [5,8] for studying the noncoherent optical gyroscope that is shown on the Fig.1a schematically. This is the integrated optical ring passive resonator which is constructed on the basis of single mode channel waveguides. Assume that this resonator is excited by a quasicoherent wide range source of light through waveguide connectors DC1 and DC2, which are symmetrical branches of Y-coupler. The homogeneous waiveguide of Y-coupler is connected to the source either by a short fiber or directly. As a source the semiconductor laser diode could be used, because it is the typical wide range source both in the frequency and auto-adjustment modes.

In case of a relatively small wide range, when the width of spectrum line $\Delta\lambda$ is about $\sim 10^{-3}$ nm (in frequency scale $\Delta\nu \sim 5$ MHz, that represents an approximate limit for

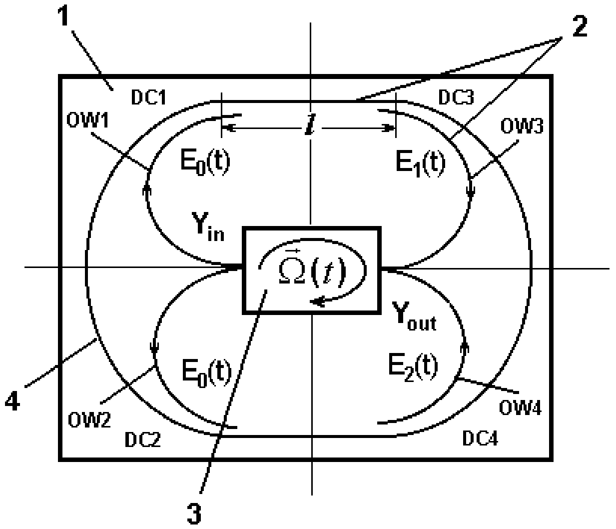


Fig. 1. Waveguide topology of the integrated-optical ring passive resonator. 1 – substrate; 2 – waveguide; 3 – window; 4 – ring waveguide; OW – optical waveguide; DC – coupler direction; Y_{in} Y_{out} – entrance, exit.

quasicoherent application of laser diodes) and high Q-value of the IORPR, there is an opportunity of implementing a gyro on the frequency principles of operation, when output value has the different frequency F_d as a function of the measured angle speed $\Omega(t)$. For very wide range laser diodes like ILPN 207A with $\Delta\lambda = 0.2$ nm etc., there is another mode of operation of the gyroscope though less preferable. In this mode the information about angle velocity is contained in the change of the output intensity just as it occurs in a phase sensitive fiber gyroscope. Below we shall give a detailed view of this situation, considering that $\Delta\lambda$ is great, i.e. the sources are noncoherent, as it is the closest approach to up-to-date practice. First we shall assume that the optical waves come to the inputs of directional couplers DC1 and DC2, and the electric filed strains are identical and equal $E_0(t)$, where t is the current time. Let us also assume that the coupling coefficients have the same values as in DC3 and DC4 couplers, which are included in the IORPR, and equal K_c. So the start values of electric-field intensities, which are led into the closed ring waveguides in clockwise (CW) and contreclockwise (CCW) directions, equal $\sqrt{K_c E_0(t)}$. The waves that are directed into the RPR through the closed ring waveguide, are removed by the directional couplers DC3 and DC4, respectively (they select a little part of energy) and directed into the optical receiver, which is a photomixed device (phodotector). The photoreceiver is installed on the end-butt of the input branch of the second Y-coupler, which has the waveguide branches with the distant ends in DC3 and DC4 and with the ring channel waveguide. The contour energy is selected during each passing of the waves through the couplers DC3, DC4, including the first passing just after injection of those waves into the sensitive contour of the IORPR and all further recirculations. If the ring waveguides are made as reciprocal, i.e. lengths of the optical ways in CW and CCW directions are almost the same, it's important not to exceed the wavelength of the coherent laser source, which is estimated as $l_k = \lambda^2/\Delta\lambda$; with $\Delta\lambda = 10nm$ and $\lambda_0 = 0.85\mu m$ we have $l_k = 72\mu m$.

2. Theoretical analysis

Let us calculate the electric field density in the input branch of Y-coupler that is connected with the photodetector. The field is generated by the optical waves that circulate in the CW direction. The field density equals:

$$
\begin{aligned}
E_1(t)&=K_c\exp(-\alpha l+i\beta l)\times\\
&\times\sum_{m=0}^{\infty}E_0(t-m\tau-\tau')\cdot(1-K_c)^{2m}\times\\
&\times\exp[(-\alpha L+i\beta L)m]\ ,
\end{aligned}
\tag{1}
$$

where: α is the amplitude coefficient of attenuation of the optical wave in the channel waveguides, expressed in cm^{-1}; β is the propagation constant of the optical mode recirculating in the closed channel waveguide; l is the length of the waveguide between DC1 and DC3 as well as between DC2 and DC4; counted from the average points of couples; τ is the time of one ring passing of the optical wave in the closed ring waveguide: $\tau=Ln/c$, where L is the perimeter of the sensitive contour, n is the refractive index; $c=3\cdot10^{8}m/c$ is the velocity of light in vacuum; τ' is the time of waves propagation delay in the waveguides with length l_i; m is the number of circulations.

A similar formula could be drawn for the field, which is generated by the wave circulating in the closed ring waveguide in CCW direction. Let us denote that this field equals $E_2(t)$. The total field, coming to the photoreceiver, equals:

$$
\begin{aligned}
E(t)&=E_1(t)+E_2(t)=\\
&=2K_c\exp(-\alpha l+i\beta l)\times\\
&\times\sum_{m=0}^{\infty}E_0(t-m\tau-\tau')\cdot(1-K_c)^{2m}\times\\
&\times\exp[(-\alpha L+i\beta L)m]
\end{aligned}
\tag{2}
$$

The average value of this field intensity is:

$$
\begin{aligned}
\langle I(t)\rangle&=\left\langle|E(t)|^2\right\rangle=4K_c^2\exp(-2\alpha l)\times\\
&\times\sum_{m,r=0}^{\infty}\left\langle E_0^*(t-m\tau-\tau')\cdot E_0(t-r\tau-\tau')\right\rangle\times\\
&\times(1-K_c)^{2(m+r)}\times\\
&\times\exp[(-\alpha-i\beta)mL+(-\alpha+i\beta)rL],
\end{aligned}
\tag{3}
$$

where the ensemble average, is marked with the brackets $<...>$ since $E(t)$ is a random process. For ergodic processes, such as laser radiation, the ensemble average coincides with time average, i.e. the time measurement T_m. In the formula

$$\left\langle E_0^*(t-m\tau-\tau')\cdot E_0(t-r\tau-\tau')\right\rangle$$

the correlation function $G(t,\tau,\tau')$ is under the double sum, which for the stationary fields depends on the difference between the arguments $t-m\tau-\tau'$ and $t-r\tau-\tau'$, so that

$$\left\langle E_0^*(t-m\tau-\tau')\cdot E_0(t-r\tau-\tau')\right\rangle=G[(m-r)\tau].$$

As the source of radiation has very little time coherence, $G[(m-r)\tau]$ differs from zero only for coincided numbers of circulations $(m=r)$. Mathematically it should be written as follows: $I_0\delta_{mr}=G[(m-r)\tau]$, where δ_{mr} is the Kroneker's symbol $I_0=\left\langle|E_0|^2\right\rangle$.

Taking into account the last equation, (3), it results:

$$
\begin{aligned}
\langle I(t)\rangle&=4K_c^2\exp(-2\alpha l)\cdot I_0\times\\
&\times\sum_{m=0}^{\infty}(1-K_c)^{4m}\cdot\exp(-2\alpha Lm)=\\
&=\left(4K_c^2\exp(-2\alpha l)\cdot I_0\right)/\\
&/\left(1-(1-K_c)^4\cdot\exp(-2\alpha L)\right)=\\
&=4K_c^2\exp(-2\alpha l)\times\\
&\times\frac{I_0}{1-(1-K_c)^4\cdot\exp(-2\alpha L)}
\end{aligned}
\tag{4}
$$

The factor $\exp(-2\alpha l)$ in equation (4) has a secondary meaning. So, considering the topology of IORPR, the length l of straight-line portion of waveguides is small (less then 1 cm) and one can actually suppose that $\exp(-2\alpha l)\sim1$ or include this factor into I_0 and take this fact into account for numeric estimations. That is why the equation (4) can be simplified to the ultimate form:

$$\langle I(t)\rangle=\left(4K_c^2I_0\right)/(1-p),$$

where

$$p=1-(1-K_c)^4\cdot\exp(-2\alpha L).$$

Let us underline that this formula is made for IORPR in its static state. however, if the ring resonator rotates around the sensibility axis, which is perpendicular to the surface of the resonator, the expression for average intensity of the electric field will be changed. Assume that the rotation takes place with an angle speed $\Omega(t)$. For circulating waves the Sagnac's phase shift equals $\varphi_c = 4\pi S\Omega(t)/c\lambda$, where S is the area enclosed into the ring waveguide of the IORPR. As before, we can write the formula for electric field intensities $E_1(t)$ and $E_2(t)$ in the rotating resonator. With changed indexes it equals:

$$\begin{aligned} E_1'(t) &= K_c \exp(-\alpha l + i\beta l + i\varphi_c') \times \\ &\times \sum_{m=0}^{\infty} E_0(t - m\tau - \tau') \times \\ &\times \left[(1 - K_c)^2 \exp(-\alpha L + i\beta L + i\varphi_c')\right]^m \end{aligned} \tag{6}$$

$$\begin{aligned} E_2'(t) &= K_c \exp(-\alpha l + i\beta l - i\varphi_c') \times \\ &\times \sum_{m=0}^{\infty} E_0(t - m\tau - \tau') \times \\ &\times \left[(1 - K_c)^2 \exp(-\alpha L + i\beta L - i\varphi_c')\right]^m \end{aligned} \tag{7}$$

In equations (6-7) we included the factors $\exp(i\varphi_c')$ making phase shift that is inducted by Sagnac's effect, in the waves propagation in straight-line portions of the channel waveguides with the length l in CW- and CCW- directions. According to our estimations φ_c' is a small value, therefore we shall suppose that $\exp(i\varphi_c') = \exp(-i\varphi_c') = 1$. Let us find the optical intensity collected on the photodetector:

$$\begin{aligned} \langle I'(t) \rangle &= \left\langle |E_1'(t)| + |E_2'(t)|^2 \right\rangle = \\ &= 2K_c^2 I_0 \sum_{m=0}^{\infty} \left[(1 - K_c)^4 \exp(-2\alpha l)\right] \times \\ &\times (1 + \cos(2\varphi_c m)) \end{aligned} \tag{8}$$

It is clear that the integrated-optical gyroscope with the wide range source operates as a combination of usual fiber phase gyroscopes. In this gyroscope the Sagnac's phase shifts accumulates and the amplitude of the partial waves that take part in forming the output signal, falls and decreases at every next recirculation in $1/\left((1 - K_c)^4 \exp(-2\alpha l)\right)$. The equation (8) could be added up. As a result we have got the final formula for $\langle I'(t) \rangle$, suitable for computing;

$$\begin{aligned} &\langle I'(t) \rangle = 2K_c^2 I_0 \times \\ &\times \left[\frac{1}{1 - p} + \frac{1 - p\cos 2\varphi_c}{1 + p^2 - 2p\cos 2\varphi_c}\right] \end{aligned} \tag{9}$$

Let us give a short analysis of this equation. If $\Omega(t) = 0$, function $\cos 2\varphi_c = 1$, therefore $\langle I'(t) \rangle = 4K_c^2 I_0 / (1 - p)$ coincides with the equation (5) for a permanent ring resonator, as we has obtained before. The first member of equation in square brackets does not depend on $\Omega(t)$; it is the constant factor of the output signal. The second term in square brackets carries useful information about angle speed. If $\Omega(t) = 0$ and $\varphi_c = 0$ it reaches the maximum value and equals $1/(1 - p)$. In case $2\varphi_c = \pi$, it reaches the maximum $1/(1 + p)$; this term is a periodical function of the Sagnac's phase. The ratio of the maximum value of this term to the minimum value equals $(1 + p)/(1 - p)$. If we turn back to the equation (5) we shall see that parameter p is the function of two other parameters: coupling coefficient K_c and integral attenuation for one passing of an optical wave in IORPR $\exp(-2\alpha L)$. In order to obtain the large value of the ratio $(1 + p)/(1 - p)$ we obviously need $p \to 1$. The integral attenuation $\exp(-2\alpha L)$ must be small and coupling coefficient K_c must be chosen as small as possible. It gives the answer to what value of the coupling coefficient K_c should be present in the directional couplers.

Making K_c smaller we decrease the registered optical intensity as it follows from (9). We consider that the value of K_c must be chosen as large as the minimum intensity of the output characteristic was:

$$\langle I'(t) \rangle = f(\varphi_c) 4K_c^2 I_0 / (1 - p^2) \geq I_{th} \tag{10}$$

where I_{th} – is the threshold intensity. A similar equation may be written for powers

$$4K_c^2 P_0 / \left(1 - p^2\right) \geq P_{th} \qquad (11)$$

An unknown value of K_c is defined from the solution of the transcendental equation

$$4K_c = \sqrt{\left(1 - K_c^2\right) P_{th} / P_0} = \\ = \sqrt{\left[1 - \left(1 - K_c\right)^8 \exp\left(-4\alpha L\right)\right] P_{th} / P_0} \qquad (12)$$

Let us give a numerical example. $L = 11.17 cm$ for the experimental pattern designed by us [9] with the scheme in Fig 1a. While attenuation in the channel waveguide is $\sim 0.4\, dB/cm$ ($\alpha = 0.046\, cm^{-1}$), the exponent $\exp(-4\alpha L)$ equals ~ 0.128. Further consideration shows that the source of the radiation has nominal power $10\, mW$ and the losses for input of the radiation in channel waveguide are $20\, dB$. On the average we shall obtain the value of power in input DC1 that equals $P_0 = 10^{-4}\, W$, i.e. few microwatt. Therefore $P_{th} / P_0 = 10^{-2}$. So we obtain $K_c = 0.048$, that is just a bit less than $\sim 5\%$.

3. Experiment

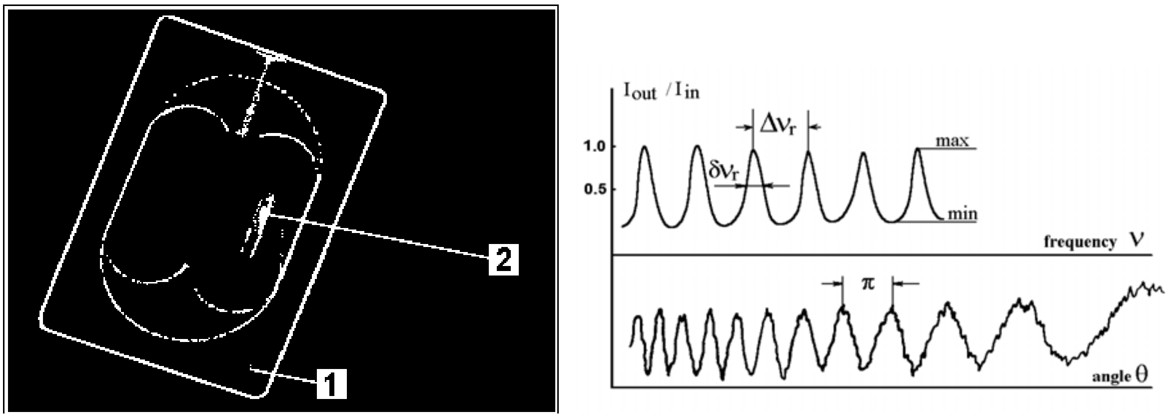
A ring passive resonator has been developed and studied. The IORPR optical channel waveguides were formed on a K8-A glass substrate by the method of ion diffusion exchange K$^+$ on ion Na$^+$ in a potassium nitrate melt. The resonator waveguide structure contains a ring waveguide and two Y-shaped splitters, the symmetrical arms of which are coupled with the waveguide, and their homogeneous arms are coupled with an external heterojunction laser and photodetector. Coupling between external devices and channel waveguides was implemented by means of a coupling prism and end joints (Fig.1).

The diffusion ion exchange time was selected to be approximately 40-45 minutes followed with results permitting to obtain buried single mode waveguides ($\lambda_0 = 0.85\, \mu m$) with an effective refractive index ($n = 1.5157$) for TM_{00} mode.

The ring waveguides and channel waveguides of Y-branches conjugated with them, had the width of approximately $\sim 6\, \mu m$. Integral losses for one passage through the resonator loop were equal to $4.4\, dB$ ($L = 11.17 cm$) [5, 9].

The excitation of the IORPR was generated by external semiconductor heterojunction lasers of ILPN type, where $\lambda_0 = 0.85\, \mu m$, bandwidth $\Delta\lambda \sim 0.1\, nm$. It was shown how IORPR operate as a filter, radiated modes and as a sensitive element of the integrated optical gyroscope.

Experiments have been performed on measurements of the sharpness and the transfer function of the ring resonator, which illustrates its resonant properties. (Fig.2).



a)

b)

Fig.2. Photo of the track light waves visible with the help of talc (a) and resonant characteristics of the IORPR (b): 1 – substrate; 2 – coupling prism prepared with TF-5 glass.

For measurement of the IORPR transfer response of optical signal intensity at output I_{out} as a function of electromagnetic wave phase delay $\theta = \omega nL/c$, the wave was propagated in a single direction through the closed contour of the RPR, which has been excited. Phase delay variation was obtained by means of heating action of the substrate and changing optical track $[nL]$ of the ring waveguide. For this purpose the substrate was placed on the free cooling part, which had been previously heated up to the temperature $\sim 60°C$. The distance between the resonant peaks of the amplitude–frequency characteristic (Fig.2) is in agreement with phase delay and it is caused by the temperature change to $\sim 0.1°C$. The experimentally measured values are identical with calculations on the assumption that $K_c = 0.1$ and $\alpha \approx 0.4\, dB/cm$; $F \approx 4$ [9].

Microphotos of channel waveguides are shown in Fig. 3, which were obtained by means of the phase–contrast method for two channel quality waveguides: (a) sharpness is $F = 0.7\ldots1.0$; (b) sharpness is $F = 4.0\ldots4.5$ (magnification is $\sim 10^4$). One can see parts of nonuniform etching, rough edges and curvature of the channel waveguide's shape.

4. Discussion

An attempt was made to give a mathematical substantiation of the operating of a quantum gyroscope with a wide-range source of radiation. We studied this optical phenomenon in integrated optical ring waveguide structures and elements. The integrated optical ring passive resonator is one of the principle devices used for measurement of characteristics of physical fields [4-6,11,12].

We completed the analysis of the equation (9). Let us add that the numerical estimation of coupling coefficients K_c can differ from the one we have for different approaches, depending on the criteria we use. We have used the criterion of minimum power registered by a photodetector. However, regardless of anything, the equation (9) must be the basis.

As a conclusion we shall give another interpretation of the principle of the work of the integrated optical gyroscope with a wide-range source of radiation, using the concept of a frequency filter, which is the IORPR [1,2,4, 5,8,10].

As it is known from [1,4], the IORPR represents an interferometer Fabri-Perot and has all its properties. It has a large number of resonant frequencies f_m connected with the effective length of the resonator $L' = nL$ by the

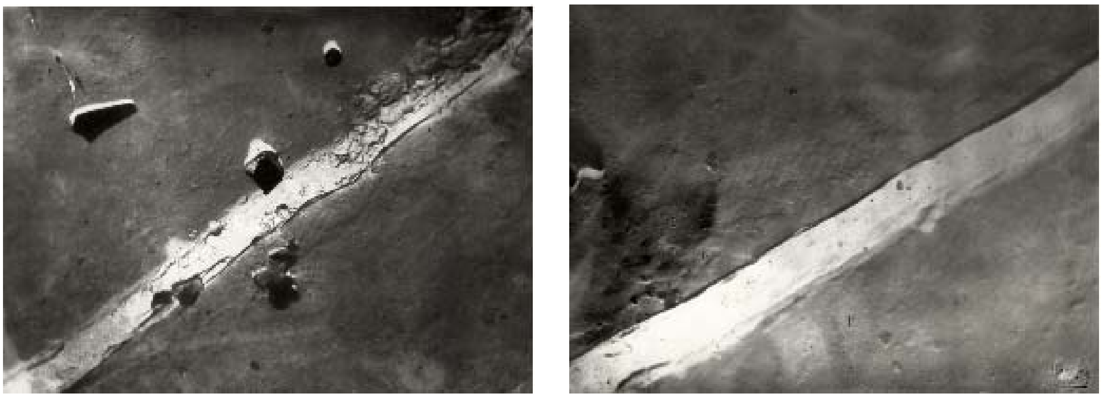

a) b)

Fig.3. Microphotos of channel waveguides, that were obtained by the phase-contrast method: (a) parts of nonuniform etching, roughness and curvature of the form of channel waveguide (magnification 10000^x, sharpness 0.7…1.0); (b) waveguide structure of better quality (magnification 10000^x, sharpness 4.0…4.5).

formula $m\lambda = L'$, where m – is the integer. In the permanent state ($\vec{\Omega}(t) = 0$) the ring resonator has identical resonant frequencies for CW and CWW directions coinciding with the above-mentioned natural permanent resonance. If the rotation takes place, the resonant frequencies will move to comparatively permanent states due to the Sagnac effect. The frequency of one of the IORPR contours increases in one direction, while the resonant frequency for the opposite direction decreases. Under the defined conditions this "break-up" of resonant frequencies, which is proportional to the angle speed $\vec{\Omega}(t)$, can be applied for registration of $\vec{\Omega}$.

IORPR can support the resonant frequencies ν_r and at the same time suppress the non-resonant frequencies. Its most important characteristic, as it is known, is the amplitude passing selected frequencies ν_r, that are passing with amplification, while the optical frequencies lying on both sides of ν_r are being suppressed. The wide-range IORPR is defined by the Q-value or sharpness parameter of the resonator.

If the source of excitation has a wide-range of radiation, then the IORPR will filter two waves with identical forms of resonance contour, which have different places of the source energy spectrum. In the scheme of topology shown in Fig.1 these waves are combined and mixed on the photodetector.

5. Conclusion

The principle trends, that shout be taken into consideration to improve the integrated-optical gyroscopes are:

- to increase power and efficiency of the laser source.

- to decrease the attenuation in the channel waveguides. The analysis shows that the losses in the channel waveguides by more than one order are larger compared to the data of this article and this can be done either by improving of ion-change technology K^+ in glass or by using other technologies, for example, thermal oxidation of silicon.

- to decrease the sensibility threshold of photodetectors by using low noise electronic circuits of optical signal processing. The logic of reasoning is practically the same as that on previous pages.

- to fulfil valuations of the limit sensibility of the integrated optical quantum gyroscope and consider the possibilities of increasing this [3,5,7].

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