Quantum Electronics **46** (6) 543–544 (2016)

LETTERS

DOI: 10.1070/QEL16118

On the possibility of using metamaterials in a ring laser gyroscope

V.G. Veselago, E.M. Dianov, V.N. Kuryatov, G.B. Malykin, O.D. Volpian

Abstract. **An approach is proposed that ensures a theoretically unlimited improvement in the sensitivity of ring laser gyroscopes (RLGs) to rotation. Basic to this approach is the filling of the optical path in an RLG (outside its gain element) with two different optical media: a conventional optical medium with a refractive index $n > 1$ and a so-called metamaterial with $n < 0$. We consider effects that limit the real sensitivity of the proposed approach.**

Keywords: *ring laser gyroscope, metamaterial, sensitivity.*

The emergence of the term ‘negative refraction’ in the scientific vocabulary made researchers look with a fresh eye at the phenomena and devices that are described by formulas containing the refractive index n. If n is negative, the meaning and properties of the corresponding formulas or phenomena may change radically [1, 2].

This statement is completely valid in describing the properties of the ring laser gyroscope (RLG) [3]. Basic to this device is a ring laser generating two electromagnetic waves which travel around a closed loop in opposite directions and interfere at the input of a photodetector. As a result, an ac voltage is generated across the photodetector load with a frequency equal to the difference between the frequencies of the two waves, $\Delta\nu$. The frequency difference $\Delta\nu$ is zero if the device is immobile in an inertial frame of reference, but if the RLG rotates at angular frequency Ω, $\Delta\nu$ differs from zero:

$$\Delta\nu = \frac{4S\Omega}{\lambda_0 L}, \tag{1}$$

where S is the loop area of the gyro; L is its perimeter; and λ_0 is the laser wavelength in vacuum. Formula (1) implies that both beams in the gyro propagate in vacuum. The question that arises in this context is how this formula should be modified if both beams in the gyro propagate through a transparent material having a refractive index n. Strange as it is, there is no general agreement regarding this issue in the literature. In particular, Malykin [3] presents several modified versions of formula (1) obtained by different researchers. He shows that, in the case under consideration, the relation

$$\Delta\nu = \frac{4S\Omega}{n\lambda_0 L} \tag{2}$$

is valid, which is supported by direct experiments [4]. A natural question that now arises is how relation (2) should be modified if the optical path in a gyro is only partially filled with a dielectric whose refractive index differs from unity, e.g. if a part (of length l) of the optical path (of total length L) is filled with a dielectric and the rest (of length $L - l$) is filled with vacuum. According to Malykin [3], $\Delta\nu$ is then given by

$$\Delta\nu = \frac{4S\Omega}{[ln + (L - l)]\lambda_0}. \tag{3}$$

A very interesting implication of relation (3) is a sharp increase in $\Delta\nu$ if n is negative but less than $(L - l)/l$ in magnitude. Since the sensitivity of gyros is proportional to $\Delta\nu$, it increases with an increase in the magnitude of the negative refractive index n. This means that the use of metamaterials with negative n may considerably improve the sensitivity of gyros. Clearly, this is due to the effective decrease in the length of an optical channel when negative-n elements are incorporated into it.

This phenomenon can also have a significant effect on parameters of a conventional Fabry–Perot cavity. Indeed, if such a cavity of length d is completely filled with a medium having a refractive index n, its resonance frequencies are

$$\Delta\nu = \frac{cm}{2nd}, \tag{4}$$

where c is the speed of light in vacuum; $m = N + 1, N + 2, N + 3, \ldots$; $N = d/\lambda_0$; and the frequency spacing is

$$\Delta\nu = \frac{c}{2nd}. \tag{5}$$

If a part (of length l) of the cavity is filled with a medium having a refractive index n_1 and the rest (of length $d - l$) is filled with a medium having a refractive index n, the eigenfrequency spacing is

---

V.G. Veselago Moscow Institute of Physics and Technology (State University), Institutskii per. 9, 141700 Dolgoprudnyi, Moscow region, Russia;
E.M. Dianov Fiber Optics Research Center, Russian Academy of Sciences, ul. Vavilova 38, 119333 Moscow, Russia;
V.N. Kuryatov JSC M.F. Stel’makh Polyus Research Institute, ul. Vvedenskogo 3/1, 117342 Moscow, Russia;
G.B. Malykin Institute of Applied Physics (Federal Research Centre), Russian Academy of Sciences, ul. Ul’yanova 46, 603950 Nizhnii Novgorod, Russia;
O.D. Volpian Fotron-Auto Scientific Manufacture Enterprise, ul. Vvedenskogo 3, 117342 Moscow, Russia; e-mail: o.d.volpian@mail.ru

Received 29 April 2016
Kvantovaya Elektronika **46** (6) 543–544 (2016)
Translated by O.M. Tsarev

$$\Delta\nu = \frac{c}{2[n(d-l)+n_1 l]}. \qquad (6)$$

It follows from relation (6) that incorporating materials with opposite signs of n and n_1 into a cavity paves the way to the ability to decimate its eigenfrequency spectrum, which is of obvious practical importance. Clearly, this statement is only valid if the interface between regions differing in refractive index is matched, i.e. if neighbouring portions of the optical channel have identical impedances.

Similarly, we have for a ring cavity

$$\Delta\nu = \frac{c}{n(d-l)+n_1 l}. \qquad (7)$$

Single-mode metamaterial optical fibres that employ a plasmon mechanism of electromagnetic radiation transport have already been demonstrated [5, 6]. The light-guiding core of such fibres has the form of an ordered structure of dielectric elements whose dimensions are far less than optical wavelengths and has a negative effective refractive index. Such fibres have so far been fabricated only for the far- and mid-IR spectral regions, but obviously their analogues for the visible and near-IR regions will emerge in the near future. This will allow fibre RLGs with high sensitivity to rotation to be created.

Consider briefly the effects that limit the real sensitivity of the proposed approach. First, these are natural laser frequency fluctuations [7, 8]. Technical laser frequency fluctuations typically exceed the natural ones, but they can be suppressed in a variety of ways, which is a purely technical problem. The natural laser frequency fluctuations are rather difficult to suppress. This can be achieved e.g. using an internal absorbing cell [9], but in the case of RLGs this technique leads to undesirable competition between the counterpropagating waves [10]. The increase in the frequency difference between the counterpropagating waves due to the decrease of the denominator in (3), (6) and (7) will be accompanied by an exactly identical increase in laser frequency fluctuations, both natural and technical. Moreover, it follows from relation (7) that the presence of a metamaterial in a cavity leads, as mentioned above, to longitudinal mode 'decimation' in the RLG and, hence, to a reduction in the effective ring cavity length. At the same time, as shown by Gelikonov and Malykin [9] a decrease in cavity length leads to a decrease in mode volume, which in turn leads to an increase in natural laser frequency fluctuations. The fact that the structure of metamaterials contains a large number of dielectric elements whose size is far smaller than optical wavelengths leads to considerable light scattering [11], which may cause lock-in of the counterpropagating waves in the RLG. At the same time, the use of metamaterials in the form of 3D all-dielectric gradient structures produced by magnetron sputtering [12] seems to be capable of eliminating this effect.

Acknowledgements. The main points of this paper were presented on 26 May 2015 in the seminar at the Fiber Optics Research Center, Russian Academy of Sciences (RAS), and on 23 June 2015 in the seminar at the Nonlinear Dynamics and Optics Division, Institute of Applied Physics, RAS. We are grateful to A.S. Biryukov and A.D. Pryamikov for useful discussions of our results.

This work was supported by the RF Ministry of Education and Science (State Research Task No. 0035-2014-0018) and in part by the RF President's Grants Council through the Support to the Leading Scientific Schools of the Russian Federation Programme (Grant No. NSh-2001.2014.2.2).

References

1. Veselago V.G. *Usp. Fiz. Nauk*, **92**, 517 (1967).
2. Veselago V., Braginsky L., Shklover V., Hafner C. *J. Comput. Theor. Nanosci.*, **3**, 1 (2006).
3. Malykin G.B. *Usp. Fiz. Nauk*, **184**, 775 (2006).
4. Privalov V.E., Filatov Yu.V. *Kvantovaya Elektron.*, **4**, 1418 (1977) [*Sov. J. Quantum Electron.*, **7**, 802 (1977)].
5. Kuhlmey B.T., Tuniz A., Argyros A., Fleming S. *Europ. Conf. Opt. Commun. (ECOC)* (France, Cannes, 2014) We.3.7.1, pp 1–3.
6. Pratap D., Ramakrishna S.A., Pollock J., Iyer A.K. *Opt. Express*, **23**, 9074 (2015).
7. Bershtein I.L., Andronova I.A., Zaitsev Yu.I. *Izv. Vyssh. Uchebn. Zaved., Radiofiz.*, **10**, 59 (1967).
8. Zaitsev Yu.I., Stepanov D.P. *Pis'ma Zh. Eksp. Teor. Fiz.*, **6**, 733 (1967).
9. Gelikonov V.M., Malykin G.B. *Kvantovaya Elektron.*, **10**, 145 (1983) [*Sov. J. Quantum Electron.*, **13**, 85 (1983)].
10. Andronova I.A., Bershtein I.L., Markelov N.A. *Kvantovaya Elektron.*, **2** (2), 294 (1975) [*Sov. J. Quantum Electron.*, **5** (2), 166 (1975)].
11. Malykin G.B. *Opt. Spektrosk.*, **120**, 113 (2016).
12. Shvartsburg A.B., Obod Yu.A., Volpian O.D. *Prog. Opt.*, **60**, 489 (2015).