Phase-conjugate fiber-optic gyro

Pochi Yeh, Ian McMichael, and Monte Khoshnevisan

Rockwell International Science Center, 1049 Camino Dos Rios, Thousand Oaks, California 91360.
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Several types of phase-conjugate gyro are proposed in the literature.[1–4] In this Letter, we describe a new type of fiber-optic gyro that uses the phase-reversal property of polarization-preserving phase conjugation. Although the insensitivity of phase-conjugate gyros to reciprocal phase shifts and their sensitivity to nonreciprocal phase shifts such as the Faraday effect have been reported,[3,4] to date no one has demonstrated rotation sensing. In this Letter, we report the first demonstration of rotation sensing with a phase-conjugate gyro.

Polarization scrambling is a well-known source of signal fading and noise in fiber-optic gyros. Polarization-preserving fibers and couplers must be used to decouple the two states of polarization and hence improve the sensitivity.[5] In the phase-conjugate fiber-optic gyro, a polarization-preserving phase conjugator is used to restore the severely scrambled waves to their original state of polarization.[6–8] This eliminates the signal fading and noise due to polarization scrambling without the need for polarization-preserving fiber.

Referring to Fig. 1, we consider a phase-conjugate Michelson interferometer[9] in which a fiber loop is inserted in the arm that contains the phase-conjugate reflector ϕ^*. We now examine the phase shift of light as it propagates along the fiber. From point A to point B, the light experiences a phase shift of

$$\phi_1 = kL - \frac{2\pi RL\Omega}{\lambda c}, \tag{1}$$

where $k = (2\pi n)/\lambda$ is the wave number and L is the length of fiber, R is the radius of the fiber coil, Ω is the rotation rate, λ is the wavelength, and c is the velocity of light. The second term in Eq. (1) is due to rotation. In the return trip, the phase shift is

$$\phi_2 = kL + \frac{2\pi RL\Omega}{\lambda c}, \tag{2}$$

where we notice that the term due to rotation is reversed because of the change in propagation direction relative to the rotation. If there were no phase conjugation, the total round-trip phase shift due to regular mirror reflection would be $2kL$. However, because of the phase reversal on phase-conjugate reflection, the round-trip phase shift becomes

$$\phi = \frac{4\pi RL\Omega}{\lambda c}. \tag{3}$$

This phase shift can be measured by using the interference with the reference beam from the other arm. Notice that as a result of the phase reversal on reflection, the reciprocal phase shift kL is canceled on completion of a round trip. The net phase shift left is due to anything nonreciprocal such as rotation.

This net phase shift is proportional to the rotation rate and can be used for rotation sensing. In addition, if the phase-conjugate reflector is polarization-preserving,[6–8] it will produce a true time-reversed version of the incident wave and will undo all the reciprocal changes (e.g., polarization scrambling, modal aberration, temperature fluctuation) when the light completes the round trip in the fiber. Since the polarization scrambling and modal aberration of multimode fibers can be corrected by polarization-preserving phase conjugation, multimode fibers can replace the polarization-preserving single-mode fiber in this new type of gyro.

Figure 2 shows a schematic diagram of the experimental setup used to demonstrate the phase-conjugate fiber-optic gyro. Since this experiment does not use a polarization-preserving phase-conjugate mirror, it does not demonstrate the correction of polarization scrambling. However, the experiment does measure the phase shift described by Eq. (3). A highly reflective beam splitter $BS1$ isolates the argon laser from retroreflections of its output. The light reflected by $BS2$ is focused by lens $L1$ (60-cm focal length) into a crystal of barium titanate to provide the pumping waves for degenerate four-wave mixing (DFWM). The light transmitted by $BS2$ is split into two arms of a Michelson interferometer by $BS5$. One arm of the interferometer contains a 10-cm radius coil of ~7 m of optical fiber. Since the phase-conjugate mirror in this experiment is not polarization-preserving, we use single-mode polarization-preserving optical fiber. Light exiting the fiber provides the probe wave for DFWM. The c-axis of the barium titanate crystal is parallel to the long faces of the crystal and points in the direction of beam splitter $BS3$. The pumping waves from mirrors $M2$ and $M3$ have powers of 18 and 3 mW, respectively, and their angle of incidence is ~45°. The probe wave, exiting from the end of the fiber loop, makes a small angle (<10°) with the pumping wave from mirror $M2$ and has a power of 0.7 mW. Under these conditions we obtain a phase-conjugate reflectivity of 50% and a response time of 0.1 s. The reference arm of the interferometer is terminated by a mirror $M4$ mounted on a piezoelectric transducer so that the operating point of the interferometer can be set at quadrature. Light from both arms combines to form complementary fringe patterns at detectors $D3$ and $D4$. Detectors $D1$ and $D2$ measure the powers in the recombining waves.

The fiber coil is rotated with the rest of the setup remaining fixed at various rotation rates [first clockwise (CW), then

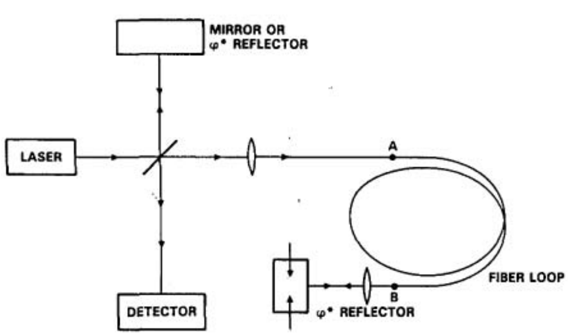

Fig. 1. Schematic drawing of the phase-conjugate fiber-optic gyro.

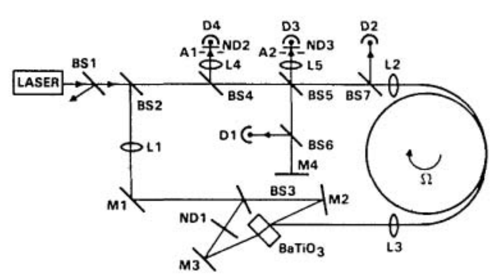

Fig. 2. Experimental setup of the phase-conjugate fiber-optic gyro.

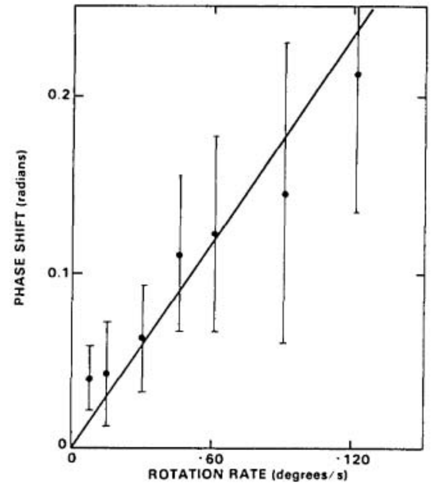

Fig. 3. Measured phase shift as a function of applied rotation rate.

counterclockwise (CCW), etc.] in a square wave fashion for 10 cycles with an amplitude of 120°. The measured powers from all detectors are used to calculate the average phase shift between rotation in the CW and CCW directions of rotation. Figure 3 shows a plot of the measured phase shift as a function of the rotation rate. The solid line indicates the expected rotation-induced Sagnac phase shift. The large uncertainty in the data is due to rapid (faster than the response time of the DFWM) phase changes that are produced by the twisting of the fiber when the fiber loop is rotated and that act as a source of noise.

In conclusion, we have proposed a new type of fiber-optic gyro that uses polarization-preserving optical phase conjugation, and we have presented the first demonstration of rotation sensing by a phase-conjugate gyro.

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References

1. J.-C. Diels and I. C. McMichael, "Influence of Wave-Front-Conjugated Coupling on the Operation of a Laser Gyro." Opt. Lett. **6**, 219 (1981).
2. P. Yeh, J. Tracy, and M. Khoshnevisan, "Phase-Conjugate Ring Gyroscopes," Proc. Soc. Photo-Opt. Instrum. Eng. **412**, 240 (1983).
3. C. J. Bode, "Phase Conjugate Optics and Applications to Interferometry and to Laser Gyroscope," in *Experimental Gravitation and Measurement Theory*, P. Meystre and M. O. Scully, Eds (Plenum, New York, 1983), pp. 269–291.
4. B. Fischer and Shmuel Sternklar, "New Optical Gyroscope Based on the Ring Passive Phase Conjugator," Appl. Phys. Lett. **47**, 1 (1985).
5. W. K. Burns, R. P. Moeller, C. A. Villarruel, and M. Abebe, "Fiber Optic Gyroscopes with Polarization Holding Fiber," Opt. Lett. **8**, 540 (1983).
6. P. Yeh, "Scalar Phase Conjugation for Polarization Correction," Opt. Commun. **51**, 195 (1984).
7. I. McMichael and M. Khoshnevisan, "Scalar Phase Conjugation Using a Barium Titanate Crystal," in *Technical Digest, Conference on Lasers and Electro-Optics* (Optical Society of America, Washington, D.C., 1985), paper THN1.
8. I. McMichael, M. Khoshnevisan, and P. Yeh, "Polarization-Preserving Phase Conjugator," submitted to Opt. Lett.
9. M. D. Ewbank, M. Khoshnevisan, and P. Yeh, "Phase-Conjugate Interferometry," Proc. Soc. Photo-Opt. Instrum. Eng. **464**, 2 (1984).

Pulse broadening in graded-index optical fibers: correction

Goran Einarsson

University of Lund, Electrical Engineering Department, S-221 00 Lund, Sweden.
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Reference 1 includes an expression [Eq. (46)] for the intramodal rms dispersion of a graded-index optical fiber. The equation, often cited in textbooks and other literature, contains an error. The correct expression is

$$\sigma_{\text{INTRAMODAL}} = \frac{\sigma_\lambda}{\lambda}\left[(-\lambda^2 n_1'')^2 - 2\lambda^2 n_1''(N_1\Delta)\left(\frac{\alpha-2-\epsilon}{\alpha+2}\right) \times \left(\frac{2\alpha}{2\alpha+2}\right) + (N_1\Delta)^2\left(\frac{\alpha-2-\epsilon}{\alpha+2}\right)^2 \times \frac{4\alpha^2}{(\alpha+2)(3\alpha+2)}\right]^{1/2}.$$

The intramodal dispersion is the mean square average of $\lambda\tau_n'$ given by Eq. (45) of reference 1:

$$\sigma^2_{\text{INTRAMODAL}} = \frac{1}{N}\sum_{n=1}^{N}(\lambda\tau_n')^2.$$

The expression for $\lambda\tau_n'$ [Eq. (45)] can be written as

$$\lambda\tau_n' = -a + b\left(\frac{n}{N}\right)^\gamma,$$

where

$$a = \lambda^2 n_1'',$$

$$b = N_1\Delta\left(\frac{\alpha-2-\epsilon}{\alpha+2}\right)\left(\frac{2\alpha}{\alpha+2}\right),$$

$$\gamma = \frac{\alpha}{\alpha+2}.$$

Approximating the summation by integration yields

$$\sigma^2_{\text{INTRAMODAL}} = \frac{1}{N}\int_{n=0}^{N}\left[-a + b\left(\frac{n}{N}\right)^\gamma\right]^2 dn = a^2 - 2ab\,\frac{1}{\gamma+1} + b^2\,\frac{1}{2\gamma+1},$$

from which the correct expression for $\sigma_{\text{INTRAMODAL}}$ is obtained by substitution of a, b, and γ.

Reference

1. R. Olshansky and D. B. Keck, "Pulse Broadening in Graded-Index Optical Fibers," Appl. Opt. **15**, 483 (1976).

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