

Polarization-based balanced heterodyne detection method in a Sagnac interferometer for precision phase measurement

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Received March 21, 1997

We describe a balanced heterodyne detection method for a Sagnac interferometer that uses a polarization-dependent beam splitter. The signal and the local oscillator are orthogonally polarized components of a single laser beam, permitting the detection of the signal by subtraction of two photocurrents produced in appropriate polarization projections. Using this scheme, we experimentally demonstrate a phase measurement with a sensitivity of 9×10^{-10} rad/ $\sqrt{\text{Hz}}$. The measurement is robust in the presence of laser frequency noise, as a result of preserving the common-path nature of the Sagnac interferometer, and of laser-amplitude noise, as a result of balanced detection. © 1997 Optical Society of America

PACS numbers: 04.80.Nn, 07.60.Ly, 42.25.Hz, 42.62.-b.

The Sagnac interferometer was proposed¹ and experimentally investigated^{2,3} as a candidate for laser interferometric gravitational-wave detection. The common-path nature of the Sagnac interferometer makes it insensitive to low-frequency mirror-displacement noise and thus reduces the demands on the length control and the seismic-isolation systems. Furthermore, in a common-path interferometer one can use low-temporal-coherence illumination to reduce the noise caused by parasitic paths introduced by scattered light. A key question is how one introduces a local oscillator to linearize the signal at the dark port of the interferometer while maintaining the common-path character of the Sagnac topology. A passive biasing scheme for a Sagnac fiber gyroscope was proposed⁴ but is not appropriate for gravitational-wave detection applications. Adoption of an external modulation scheme^{5,6} such as that developed for Michelson interferometers would eliminate the common-path advantage of the Sagnac design; frontal modulation also requires phase modulators that are capable of operation at high optical powers.⁷ In this Letter we report a novel signal-extraction scheme based on polarization control that preserves the common-path character of the Sagnac interferometer and allows balanced heterodyne detection with rf modulation in the dark port of the interferometer.⁸

In the method described here the Sagnac interferometer contains a polarization-dependent beam splitter and two orthogonally polarized fields. In the *s* polarization a high-power input is divided into two equal counterpropagating waves in the usual fashion for a Sagnac interferometer. In the *p* polarization the beam splitter has low reflectance, so that a small fraction of the incident laser beam propagates through the Sagnac loop without interference effects and can serve as a local oscillator for the signal beam. In this scheme one can use the polarization-sensitive transmission properties of this Sagnac interferometer to pro-

duce a dark fringe for the signal component and an optimum transmission for the local-oscillator component. Furthermore, such a scheme allows one to achieve balanced heterodyne detection by mixing the local oscillator and the signal on a properly oriented polarizer at the dark port while preserving a single common path for both signal and local oscillator. Consequently, the interferometer does not require any additional control of the local-oscillator phase and is insensitive to laser frequency noise.

The power transmission through a Sagnac interferometer with a stationary loop is given by

$$T_{\text{sagnac}}^{(i)} = [T^{(i)} - R^{(i)}]^2, \quad (1)$$

where $T^{(i)}$ and $R^{(i)}$ are power reflectivity and transmissivity of the beam splitter, respectively, and the superscript *i* indicates *s* or *p* polarization. For an oblique incidence angle, $T^{(i)}$ and $R^{(i)}$ are in general polarization dependent. To achieve the maximum signal-to-noise ratio, we choose the reflectivity for the signal component in the *s* polarization to be 50%, i.e., $R^{(s)} = T^{(s)} = 0.5$, so that $T_{\text{sagnac}}^{(s)} = 0$. The *s* polarization is then nonzero only in the presence of a dynamic signal, as given in Eq. 2 of Ref. 3. In contrast, the beam splitter should have zero reflectivity for the *p* polarization, i.e., $R^{(p)} = 0$, so that $T_{\text{sagnac}}^{(p)} = 1$ for reduction of the power loss of the local oscillator. The two polarization components are then superposed both in phase and out of phase at the two ports of a properly oriented polarizing beam splitter following the dark port of the interferometer. Detection of the outputs produces two photocurrents containing out-of-phase signals, which are then electronically subtracted to give the signal.

Figure 1 illustrates the experimental setup and the polarization states at several points in the system. The Sagnac interferometer was illuminated with a 725-mW diode-pumped Nd:YAG laser (Lightwave Electronics 123). An electro-optic phase modulator (PM1)

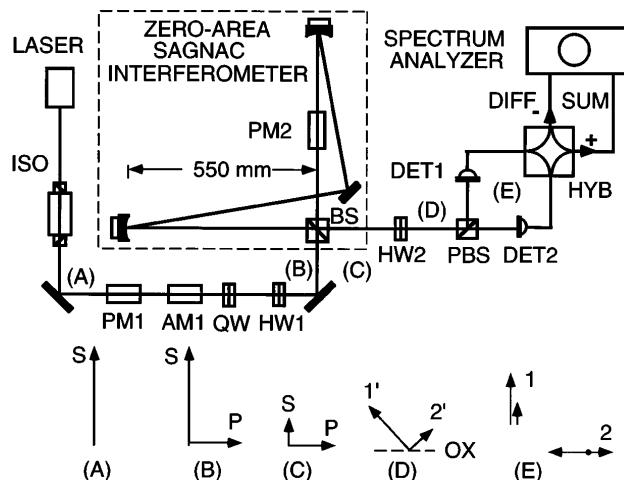


Fig. 1. Experimental setup and the polarization states at each location. The light source is a 725-mW Nd:YAG laser. ISO, Faraday isolator; BS, beam splitter; PBS, polarizing beam splitter; OX, transmission polarization axis of the polarizing beam splitter. DET1, DET2, detectors for polarization projections 1 and 2; HYB, rf hybrid junction. Polarization states at locations (A)–(E) are shown below the experimental setup.

and an electro-optic amplitude modulator produced frequency and amplitude modulations of the input laser beam, which are used for testing the robustness of the detection method. A small *p*-polarized component could be generated by rotation of the laser; however, for convenience a combination of a quarter-wave plate (QW) and a half-wave plate (HW1) was used to compensate for the polarization change in the optics chain and produce a small *p*-polarized component that functioned as the local oscillator, whose power was adjustable by rotation of HW1. An asymmetrically placed electro-optic phase modulator (PM2) provided phase modulation to the *s*-polarized component in the interferometer loop that simulated a displacement signal such as that from a gravitational wave. The counterclockwise and clockwise optical path lengths from PM2 to the interferometer beam splitter were 330 and 1979 mm, respectively, and hence the sideband output response to PM2 modulation was maximum at 90.9 MHz.³ The beam splitter was 50% transmissive for the *s* polarization and 99% transmissive for the *p* polarization. Therefore the *s*-polarized component experiences a complete cancellation, producing a dark fringe at the output, except for a small uncancelled part that is due to wave-front distortion in the interferometer. The leakage of the *s*-polarized component was 0.9 mW, giving a contrast ratio of $C = 0.9975$. The transmission for the *p* polarization was determined by use of Eq. (1) to be $T_{\text{sagnac}}^{(p)} = [T^{(p)} - R^{(p)}]^2 = (0.99 - 0.01)^2 \approx 0.96$. For the convenience of placing both detectors in the tabletop plane, a half-wave plate (HW2) with its optical axis oriented 22.5° from vertical plane (*s*-polarization plane) was used after the output port to rotate the *s* polarization 45° clockwise and the *p* polarization 135° counterclockwise. Then a polarizing beam splitter projected the two polarizations onto the two detectors, whose photocurrents were recombined with a rf

hybrid junction. The difference and the summation signals were monitored by a rf spectrum analyzer.

Figure 2 shows a typical spectrum of the difference current for an interferometric phase-sensitivity measurement centered at 90.9 MHz. The rf spectrum was taken when the local-oscillator power was adjusted to be 5 mW on each detector. The total-noise (shot noise plus electronic noise) floor was 10 dB above the electronic-noise floor, representing a shot-noise-limited phase measurement to within 1 dB for frequencies from ~1 to 100 MHz. A calibration signal of 90.9 MHz was applied to PM2. The spectral density of the noise floor was determined to be $9 \times 10^{-10} \text{ rad}/\sqrt{\text{Hz}}$.

In Fig. 3 we demonstrate the robustness of the signal-extraction scheme against laser frequency noise by comparing the phase measurements performed when the simulated frequency noise was off and on. Figure 3(a) shows a phase-sensitivity measurement similar to that in Fig. 2, except that the local-oscillator power was raised to give a 12-dB separation between the total-noise and the electronic-noise floors. This reconfirmed that our measurement was performed at the maximum phase sensitivity. Figure 3(b) shows the same measurement with frequency modulation applied to the input laser. The frequency modulation consists of three components: a fast laser frequency modulation, which we obtained by applying an 8-kHz sinusoidal voltage to a piezoelectric transducer bonded to the laser crystal to produce a frequency excursion of 130 MHz; a frequency modulation with excursion of 99 kHz at 90 MHz introduced into the laser beam through PM1, such that the modulation depth was 42 dB greater than the calibration signal produced by PM2; and a 2.5-GHz laser frequency shift that was thermally scanned at a rate of 0.1 Hz. It is striking that the extraction of the calibration signal was not affected, and there was no significant change (<0.3 dB variation) in the noise floor of the phase measurement in the presence of these multiple laser-frequency modulations.

Figure 4 demonstrates the robustness of the signal-extraction scheme against laser amplitude noise, resulting from the common mode rejection provided by balanced heterodyne detection. Figures 4(a) and 4(b)

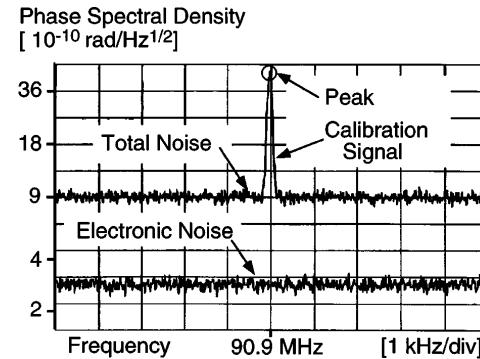


Fig. 2. Shot-noise-limited phase-sensitivity measurement at 90.9 MHz for the Sagnac interferometer. The calibration signal, the total-noise level (shot noise plus electronic noise), and the electronic-noise level are shown. The phase sensitivity is $9 \times 10^{-10} \text{ rad}/\sqrt{\text{Hz}}$.

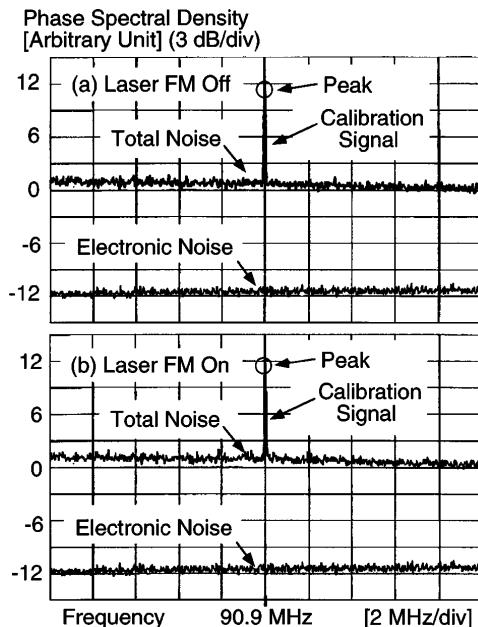


Fig. 3. Demonstration of the robustness of the detection system against laser frequency noise by comparison of phase measurements without (a) and with (b) laser frequency noise simulated by frequency modulation. No significant shift in the shot-noise-dominated noise floor was observed in response to frequency modulation applied to input laser beam.

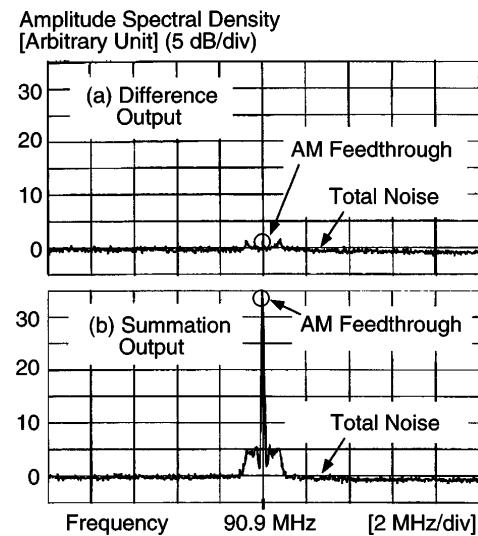


Fig. 4. Measurement of the system CMRR by comparison of difference (a) and summation (b) outputs from the hybrid junction. The signal peak that is due to laser amplitude modulation is 1 dB above the noise floor in (a) and 33 dB above the noise floor in (b), indicating a 32-dB CMRR of the balanced detection system to laser amplitude noise.

show the outputs from the difference and the summation ports of the hybrid junction, respectively, when

an amplitude modulation at 90.9 MHz was applied to the laser beam before it entered the interferometer. The summation-port output exhibited a signal 33 dB above the noise floor. In contrast, the difference-port output carried only amplitude modulation that was 1 dB above the noise floor. Therefore the balanced heterodyne detection system had a common-mode rejection ratio (CMRR) of 32 dB, or 1600 to 1. The signal in the difference port that was due to PM2 modulation was observed to be simultaneously maximized when the CMRR was maximized.

Important table-top experiments remain to be performed before we will be in a position to evaluate the use of a Sagnac interferometer for gravitation-wave detection. For example, we must incorporate delay lines to lower the frequency of the peak sensitivity. Frequency-response and mirror-alignment sensitivity studies must be performed and, in addition, a low-temporal-coherence fiber laser must be used for study of techniques for reducing the sensitivity of the interferometer to the parasitic paths that can result from scattered light.

In conclusion, we have experimentally demonstrated a polarization-based balanced heterodyne scheme that retains the common-path advantages of the Sagnac interferometer. Using this scheme, we have performed a shot-noise-limited phase measurement with noise spectral density of $9 \times 10^{-10} \text{ rad}/\sqrt{\text{Hz}}$ at the maximum response frequency of the Sagnac interferometer. We have demonstrated that precision phase measurement can be performed with a laser bearing a substantial amount of frequency and amplitude noise.

This research was supported by the National Science Foundation (NSF PHY 9212157 and 9630172). We thank M. Gifford of Lightwave Electronics for loaning us the laser.

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