Polarization Sagnac interferometer with postmodulation for gravitational-wave detection

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We describe a polarization Sagnac interferometer with an in-loop half-wave plate that allows signal detection at the reciprocal port of the beam splitter while maintaining the ability to detect the signal at a dark fringe. Postmodulation and balanced heterodyne detection are used to recover the signal. This topology is simple to control because of its common-path characteristics and its collinear signal and local oscillator. The robustness of this scheme to amplitude and frequency fluctuations of the laser is demonstrated. Intraloop birefringence in this interferometer acts as a loss, reducing the power on the detector. The magnitude of this loss is discussed and experimentally verified. © 1999 Optical Society of America

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Sagnac interferometers[1,2] have been proposed[3] and are being experimentally investigated[4,5] for use in gravitational-wave detectors. An attractive aspect of the Sagnac interferometer is that both interfering beams sample the same optical path with the same elements, so distortions of the optics have a minimal effect on the sensitivity of the differential signal.

In previously proposed Sagnac configurations, placing the photodetector at the asymmetric port of the beam splitter, where interference is destructive, avoided photodetector saturation. At the asymmetric port one beam is reflected twice from the beam splitter while the other is transmitted twice; the contrast of the resulting interference, and hence the interferometer sensitivity, is limited by the ability of the beam splitter to split the amplitude of the beam equally.

Here we present a polarization Sagnac interferometer that allows detection of the interference minimum on the symmetric port of the beam splitter.[6] The interferometer topology includes a signal-extraction scheme that uses a common-path local oscillator for balanced heterodyne detection. Unlike in many signal-extraction schemes, in the scheme described here the modulator that is used to generate the heterodyne frequency sidebands can be placed at an interference minimum away from the high circulating power, which minimizes the thermal loading of the modulator crystal.

By controlling the polarization state of the light as it circulates in the interferometer, one can make the polarization of the signal orthogonal to that of the background light[7] so that polarization ellipsometry techniques can be used for signal detection. This scheme has been used in fiber gyroscopes[8] and is extended here to detection on the dark fringe of the interference. Balanced heterodyne detection provides greater than 32 dB of amplitude noise reduction,[9,10] and the common paths of the interfering beams prevent input frequency fluctuations from being converted to amplitude noise. The result is an interferometer that is insensitive to both laser frequency and amplitude noise.

Here we demonstrate the robustness of the polarization Sagnac interferometer to amplitude and frequency noise of the laser and to static birefringence in the loop of the interferometer. We also report some of the practical advantages offered by this topology. The sensitivity of the polarization Sagnac interferometer is similar to that of previously investigated topologies and therefore is not investigated.

The optical layout of the polarization Sagnac interferometer is shown in Fig. 1. This interferometer topology offers many practical advantages over conventional Sagnac or Michelson topologies. Because the signal light and carrier light are orthogonal polarization components of a single beam, the carrier can be used as a local oscillator without the need for active control of its phase or alignment with the signal beam. Suppression of scattered light is provided by a spatial filter placed in the path of the collinear input and output beams. The spatial filter provides maximum interference contrast by ensuring spatial mode overlap at the detector.

The behavior of the instrument can be understood by use of Jones calculus to trace the polarization state of the light through the interferometer. Assuming that

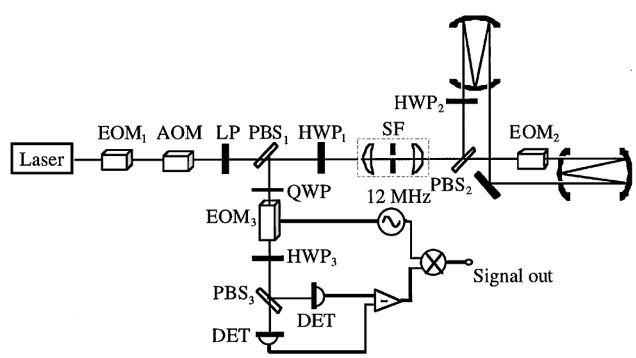

Fig. 1. Optical layout of the polarization Sagnac interferometer: LP, linear polarizer; AOM, acousto-optic modulator; PBS_1-PBS_3, polarizing beam splitters; HWP_1-HWP_3, half-wave plates; QWP, quarter-wave plate; SF, spatial filter; EOM_1-EOM_3, electro-optic modulators; DET's, photodetectors. Each arm contains a 75-bounce 2-m-long delay line. PBS_1 is slightly tilted to leak 0.3% of the cross polarization. Not shown is the resonant ring cavity[11] immediately after the laser, which is used as a spatial and temporal mode cleaner. EOM_2 is used to introduce modulation that simulates a gravitational-wave signal and would not be present in a gravitational-wave detector.

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a differential phase shift $\Delta\phi$ is accumulated owing to time-dependent or nonreciprocal elements between the counterpropagating beams, the field that is exiting the interferometer through the symmetric port is described[6] by

$$\mathbf{E}_{\text{out}} = \left[P_2{}^t W(\theta) P_2{}^r \exp\left(+i\,\frac{\Delta\phi}{2}\right) + P_2{}^r W(-\theta) P_2{}^t \exp\left(-i\,\frac{\Delta\phi}{2}\right)\right]\mathbf{E}_{\text{in}}\,, \quad (1)$$

where P is the Jones matrix representing PBS_2 and W is the Jones matrix representing HWP_2. The superscript t represents transmission and r represents reflection from the polarizing beam splitter. For an ideal beam splitter, a half-wave plate rotated to 45° relative to the beam splitter, and a unity-magnitude input field that is linearly polarized at 45° with respect to the beam splitter, Eq. (1) reduces to

$$E_{\text{out}} = \frac{1}{\sqrt{2}}\begin{bmatrix} \exp\left(+i\,\frac{\Delta\phi}{2}\right) \\ \exp\left(-i\,\frac{\Delta\phi}{2}\right)\end{bmatrix}, \quad (2)$$

where the polarization axes of the polarizing beam splitter define the axes for the Jones vectors and the matrix elements. The effect of a differential signal is to alter the polarization state of the output. For small signals ($\Delta\phi < \pi/2$) the output is elliptically polarized, with the minor axis of the ellipse representing the signal field (destructive interference) and the major axis representing the carrier (constructive interference). To detect the signal we use a leaky polarizing beam splitter (PBS_1) to pick off most of the signal polarization and a small fraction of the carrier as a local oscillator. A quarter-wave plate (QWP_1) is used to remove the static phase difference between the signal and carrier polarization. A polarization-dependent phase modulator (EOM_3) preferentially modulates the local-oscillator polarization to generate sidebands at the heterodyne frequency. The two polarization components are then superimposed both in and out of phase at the two ports of a properly oriented beam splitter. Detection of the outputs produces two photocurrents that contain out-of-phase signals, which we then subtract electronically to obtain the signal.

To demonstrate the immunity of the interferometer signal to frequency noise of the input field we illuminated the polarization Sagnac interferometer with a 300-mW diode-pumped Nd:YAG laser (Lightwave Electronics Model 122). A swept-frequency phase modulation with a depth of 2.5 rad was imposed on the input light by electro-optic modulator EOM_1 (see Fig. 1). A 300-kHz differential signal was imposed on the light by phase modulator EOM_2, with a modulation depth of 32 mrad placed immediately after beam splitter PBS_2 at the point of maximum asymmetry in the interferometer. Here the modulator's interaction with each of the counterpropagating beams occurs with a relative delay of one loop transit time, giving a peak frequency response at 275 kHz. We recorded traces of the interferometer output with both signals off to obtain a baseline and with both signals on. The average increase in the noise floor over the measurement bandwidth was attributed to the broadband phase modulation. The value of this noise was calibrated against the response of the interferometer to the 300-kHz signal. It was found that the conversion of frequency noise to amplitude noise by the interferometer from dc to four times the peak frequency was less than −35 dB (see Fig. 2).

Suppression of amplitude noise by balanced detection was demonstrated with a 1.125-MHz amplitude modulation that was imposed on the input field by an acousto-optic modulator. We chose this frequency to coincide with a null of the interferometer's frequency response so that a swept-frequency differential signal could also be imposed on the light without affecting the noise floor at the amplitude modulation frequency. With balanced detection the signal was observed, but the amplitude noise spike was suppressed owing to the electronic noise of the measurement. When one detector was blocked, the unbalanced output signal was reduced and the amplitude modulation noise spike was observed, as shown in Fig. 3.

The collinearity of the input and output beams allows input and output mode selection by a reciprocal spatial filter. Because the same spatial filter is used to select both the input and the output modes, the overlap of the detected mode with the main interferometer mode is maximized. A pair of 10× microscope objectives and a 10-μm pinhole that formed a unity-gain telescope were used as a spatial filter outside the interferometer. The fringe contrast is defined by

$$FC = 10\log(P_{\text{dp}}/P_{\text{bp}})\,, \quad (3)$$

where P_{dp} is the power in the dark polarization and P_{bp} is the power in the bright polarization. Without the pinhole inserted to filter spatially the light, the fringe contrast was measured to be −11.1 dB, most likely limited by mode distortion caused by the many (300) reflections from the delay-line mirrors. Insertion of the pinhole improved the contrast to −31.0 dB, an improvement of almost 20 dB.

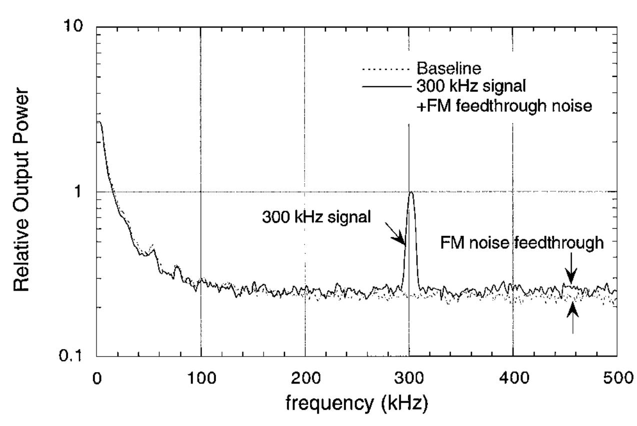

Fig. 2. Measurement of the frequency noise suppression of the polarization Sagnac interferometer. Output power levels are normalized to a 32-mrad amplitude-modulated calibration signal at 300 kHz. The difference between the two traces represents the conversion of the 2.5 rad of input frequency noise to amplitude noise on the detector.

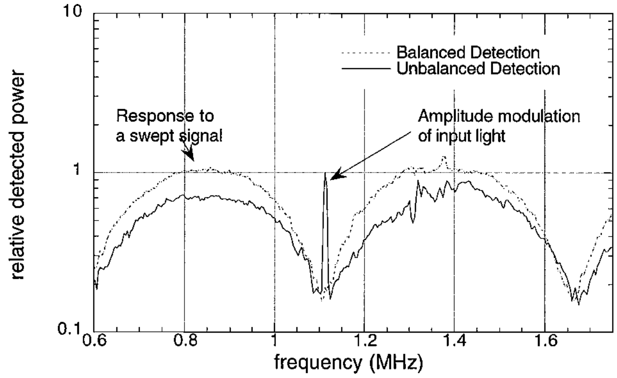

Fig. 3. Demonstration of the amplitude noise suppression owing to balanced detection. Both a differential swept-frequency signal, which traces out two peaks of the Sagnac interferometer response, and an amplitude modulation placed on the input field, which produces a spike at 1.125 MHz, are detected by a single detector (solid curve). By use of two balanced detectors (dotted curve) sensitivity to the amplitude modulation is eliminated.

In conclusion, we have experimentally confirmed several advantages of the polarization Sagnac interferometer for application to gravitational-wave interferometry. The alignment and control of the interferometer are simple, since both of the main interfering beams, as well as the local oscillator, travel a common path. Additionally, the interference contrast is maximized by the polarization scheme, which allows detection at the symmetric port of the beam splitter, where the spatial filter is used reciprocally and the beam-splitter ratio is not critical. The polarization Sagnac interferometer is not sensitive to the amplitude and frequency noise of the laser, which eases restrictions on laser design. Finally, the postmodulation scheme allows one to place the heterodyne sidebands on the local oscillator without subjecting the modulation crystal to high power in or before the interferometer. Interesting experiments, including the use of a broadband light source to reduce the coherence between scattered light and the main beam and the use of the unused beam-splitter port to support a second collinear interferometer based on the orthogonal polarization, remain to be done with the polarization Sagnac interferometer.

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