Polarization Sagnac interferometer with a reflective grating beam splitter

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All-reflective interferometric gravitational-wave detector configurations with a diffraction grating as a power beam splitter have been proposed to reduce thermal lensing. We demonstrate the use of a diffraction grating as a polarization beam splitter in a zero-area polarization Sagnac interferometer. © 2000 Optical Society of America

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Thermal effects that are due to absorption in the transmissive optical elements limit the power circulation in laser-interferometric gravitational-wave detectors.[1–3] The use of diffraction gratings as beam splitters in all-reflective interferometer topologies has been proposed for future detector configurations to reduce thermal effects,[4,5] which would allow the detector to handle higher circulating power.

Common-path Sagnac-type interferometers with zero dc response are under investigation for use in future detectors.[6,7] A zero-area Sagnac interferometer in an all-reflective configuration with a diffraction grating as a power beam splitter has been demonstrated.[8] The grating split the incident light into the 0 and the −1 diffraction orders. After counterpropagating though the interferometer loop, the reflected light and the diffracted light interfered on the same grating. A dark fringe was formed at the asymmetric port, and a bright fringe was formed at the symmetric port. In this configuration, however, any deviation from the ideal 50% diffraction efficiency leads to a reduction of the interferometer fringe contrast. Furthermore, even with an ideal 50% diffraction efficiency, the fringe contrast of the interferometer is reduced by the differences between the shapes of the diffracted beam (which becomes elliptical) and the reflected beam (which remains circular).

Recently, a polarization Sagnac interferometer with a transmissive beam splitter was proposed[9] and demonstrated.[10] The polarization of the circulating light can be adjusted such that all the light exits the interferometer at the symmetric port of the polarizing beam splitter so that very high fringe contrast (greater than 0.999) is possible even for an imperfect beam splitter.

We report the realization of a polarization Sagnac interferometer with a reflective grating as a polarizing beam splitter. The replicated holographic sinusoidal diffraction grating had a period of 0.55 μm and a groove depth of 0.194 μm and was aluminum coated. For a given wavelength, the diffraction efficiency of such a grating depends on the polarization of the incident light. Figure 1 shows the percentage of the incident optical power from a 1064-nm Nd:YAG laser that was measured in the specular order and in the first order of the grating as a function of the polarization state of the incident light. The diffraction efficiency for s-polarized light at this wavelength was measured to be 86.8%, with 1.5% of the incident light reflected into the specular order. The losses for s-polarized light therefore were 11.7% for this grating. For p-polarized light the diffraction efficiency was measured to be 1.4%, whereas 97.7% of the incident light was found to be reflected into the specular order, giving a grating loss of 0.9% for p-polarized light. By adjustment of the polarization state of the incident light, the beam-splitting ratio, i.e., the power difference in the two output ports of the beam splitter, can be continuously adjusted.

We used the diffraction grating to replace the transmissive polarizing beam splitter of the zero-area polarization Sagnac interferometer with 2-m delay lines in the arms, as described and analyzed in detail previously.[9,10] A schematic diagram of the interferometer setup with a grating as a polarizing beam splitter is shown in Fig. 2(b) in comparison with the transmissive setup in Fig. 2(a). The diffracted order of the grating was used to couple s-polarized light into the interferometer loop, and the specular order was used to couple p-polarized light into the interferometer circulating in the opposite direction. A half-wave plate in the loop changed the polarization of

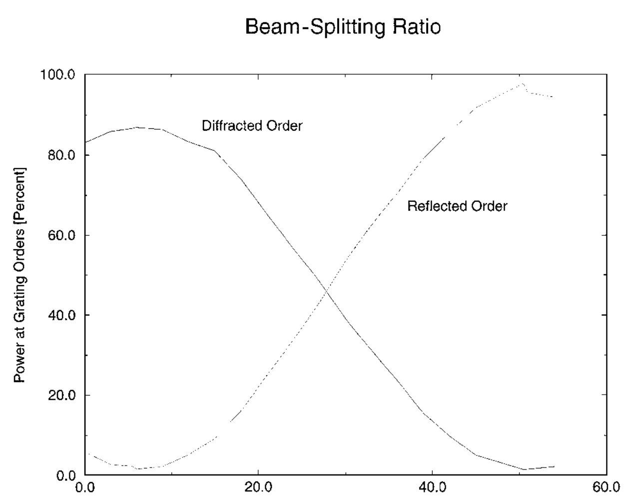

Fig. 1. Measured beam-splitting ratio of the diffraction grating as a function of polarization, in percent of incident light power. By adjustment of the polarization of the light the beam-splitting ratio can be optimized.

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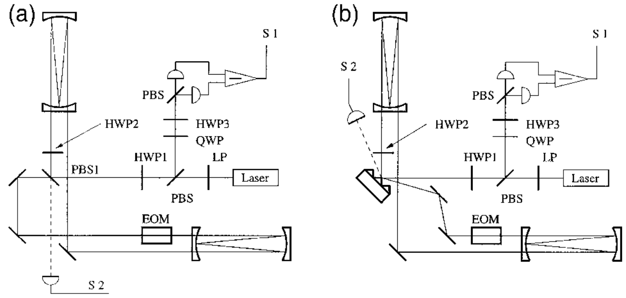

Fig. 2. Schematic of (b), the all-refractive and (a), the transmissive zero-area polarization Sagnac interferometers with delay lines in the arms. A half-wave plate (HWP1) is used to adjust the polarization state of the input light at the symmetric port. The transmissive polarizing beam splitter (PBS1) is replaced with a grating that splits the polarization components. The diffracted order couples s-polarized light into the interferometer loop, and the specular order couples p-polarized light into the interferometer circulating in the opposite direction. A half-wave plate within the interferometer loop (HWP2) changes the polarization of the circulating light. The fringes of the interference are formed by the polarization components that are leaving the interferometer at the symmetric port. S1 is the signal at the symmetric port, and S2 is the signal at the asymmetric (dark) port. A phase modulator (EOM) was used to measure the interferometer's frequency response. LP's, linear polarizers; PBS's, transmissive polarizing beam splitters; QWP's, quarter-wave plates; HWP3, half-wave plate that sets the polarization angle of the output for balanced detection.

the circulating light so that the diffracted light returns to the grating in the p-polarization and is thus reflected into the symmetric output port. The reflected light returns to the grating in the s-polarized and is thus diffracted into the symmetric output port also.

The spatial profile of the diffracted beam is different from that of the incident beam. Assume that a radially symmetric Gaussian beam with beam radius w_0 illuminates a reflection grating in a plane perpendicular to the grating grooves. Let w_x be the radius of the beam projected onto the p plane, i.e., parallel to the grating lines, and let w_y be the radius of the beam projected onto the s plane, i.e., perpendicular to the grating lines. A circular beam would thus be described by $w_0 = w_x = w_y$. If the light is diffracted, the radius of the beam perpendicular to the grating lines (w_y) depends on the angle of incidence and diffraction. w_y increases for a diffraction angle ϕ_d smaller then the angle of incidence, whereas it decreases for a diffraction angle larger the angle of incidence. The result is an elliptical beam profile. For any reflection grating, the beam-shaping effect can be described by $w_y = w_0(\cos\phi_d/\cos\phi_i)$. The maxima in the ellipticity are at diffraction angles $\phi_d = 0°$ and $\phi_d = \pm 90°$. For a Littrow configuration with $\phi_d = \phi_i$, the beam radii do not change ($w_y = w_x = w_0$). However, the grating cannot be used in the Littrow configuration, as the diffracted order represents one output port of the beam splitter, so the induced beam ellipticity must be addressed in the design of an all-reflective interferometer.

In our configuration the interference fringes were formed by two polarization components that interfered at the symmetric port of the beam splitter. It is important to note that, owing to the nature of the polarization Sagnac interferometer, both components were reflected once and diffracted once. The beam-shaping effect described above affected both components identically and therefore produced no degradation in the interference quality. We measured the fringe contrast by chopping the light and detecting the power levels in the polarization states representing the bright and the dark fringes at the interferometer's symmetric port with a lock-in amplifier. A very high contrast of $\bar{v} = 0.9987 \pm 0.0016$ was found. Approximately 2% of the circulating light was measured at the asymmetric port of the beam splitter, owing to the beam splitter's extinction of approximately 0.98, which does not affect the fringe contrast but reduces the maximum throughput, as do any scatter or other losses in the optical system.

The frequency response of a Sagnac interferometer[6] is proportional to $\sin^2(\pi\tau_s f)$, where τ_s is the light-storage time, as was demonstrated for the zero-area polarization Sagnac interferometer with a transmissive beam splitter.[10] To measure the frequency response of the interferometer we placed a phase modulator at one end of the loop to produce a periodic differential phase shift for the counterpropagating beams. The frequency response of the interferometer with a grating as a polarizing beam splitter, shown in Fig. 3, had the same $\sin^2(\pi\tau_s f)$ behavior as was found for the interferometer with a transmissive polarizing beam splitter.[10]

In summary, we have experimentally demonstrated a polarization Sagnac interferometer with a reflection grating as a polarizing beam splitter. In a high-power interferometer such as a gravitational-wave detector, the half-wave plate can be replaced with a reflective device, such as a periscope or a reflective thin-film retarder, so that one can operate the interferometer in an all-reflective topology to reduce optical distortion caused by substrate heating. The effect of the

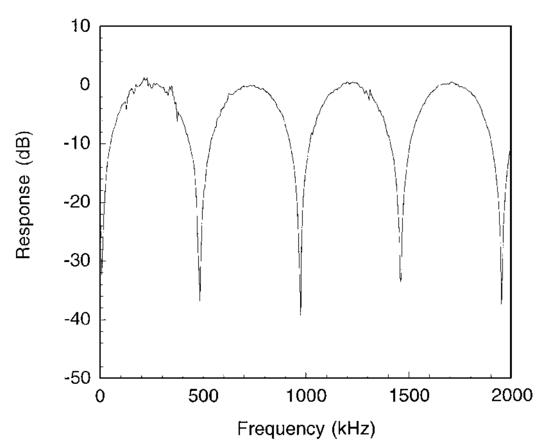

Fig. 3. Frequency response of the tabletop all-reflective polarization Sagnac interferometer with delay lines in the arms, measured by use of a phase modulator in the loop. For a long-baseline interferometer the peak response would be in the frequency band of interest for a gravitational-wave receiver.

ellipticity of the diffracted beam on the fringe contrast was eliminated by use of the symmetric port of the beam splitter, resulting in a high fringe contrast of $\bar{v} = 0.9987$. A phase modulator was used to measure the interferometer's frequency response, which was found to be consistent with theoretical predictions. In future work the wave-front distortion that is due to absorption in the coatings of a grating in a high-power interferometric gravitational-wave detector should be investigated, as well as the problems related to the light that is scattered at a grating beam splitter and the design of gratings optimized for this application.

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