Characterization of Polarization Sensitive, High Efficiency Dielectric Gratings for Formation Flight Interferometry

Ke-Xun Sun, Patrick Lu, and Robert L. Byer

Ginzton Laboratory N-119, Stanford University, Stanford, CA94305-4088, USA

Jerald A. Britten, Hoang T. Nguyen, James D. Nissen, Cindy C. Larson, Michael D. Aasen, Thomas C. Carlson, and Curly R. Hoaglan

Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

kxsun@stanford.edu

Abstract. Reflective diffraction gratings enable novel optical configurations that simplify and improve laser interferometers. We have proposed an all-reflective grating interferometer that can be used in LISA type interferometers for space gravitational wave detection [1]. One configuration requires a highly polarization sensitive grating. We report on characterizations of a grating made atop high reflective dielectric layers. Using a direct measurement method, the diffraction efficiency at the Littrow angle for s-polarization is measured as 97.3% and for p-polarization 4.2%, leading to a s/p polarization diffraction ratio of 23.2. The depolarization from s- to p-polarization is measured to be $\sim 1.7\times10^{-4}$, and from p- to s-polarization 1.8×10^{-4}. We derived a transfer matrix based on these measurements. Furthermore, we have developed a more accurate method for diffraction efficiency measurement using a grating cavity. These measurements are encouraging steps taken towards the requirements of an ideal grating interferometer.

1. Introduction

Grating interferometers have been proposed for ground-based gravitational wave detectors such as Laser Interferometer Gravitational Observatory (LIGO) [1]. Grating interferometers may also benefit Laser Interferometer Space Antenna (LISA) by both simplifying optical configurations and enhancing instrument performance [2].

LISA [3] and other formation flights for fundamental physics must make connected distance measurements from the gravitational reference sensor (GRS) center to the GRS housing and to other spacecrafts. In the Modular GRS (MGRS) design [2], we proposed using a double-sided reflective grating at the connecting points, so that both the GRS internal interferometry and external inter-spacecraft interferometry can be independently optimized. For the external interferometry, a highly polarization-sensitive, high-efficiency grating will be needed. Ideally, the diffraction efficiency should be near unity in the high efficiency polarization, but near zero in the low efficiency polarization. In addition, the depolarization, or the cross coupling of the two polarizations, should be as low as possible.

Such a grating can be difficult to find if we are limited to conventional metal gratings. However, the exciting development of multilayer dielectric (MLD) gratings provides a promising solution [4]. In this paper, we report on characterizations of two high-efficiency dielectric gratings designed and fabricated at Lawrence Livermore National Laboratory. Using a direct measurement method, the diffraction efficiency of one grating at the Littrow angle for s-polarization is measured to be 97.3% and for p-polarization 4.2%, leading to a s/p polarization diffraction ratio of 23.2. The depolarization from s- to p- was measured to be ~1.7×10^{-4}, and from p- to s- 1.8×10^{-4}. Further improvement of the grating characteristics are needed. However, these characteristics are already very promising for an initial build of the grating interferometer described in [2].

We further report measurement results using a grating cavity for a more accurate determination of diffraction efficiency and thermal wavefront distortion measurements made to characterize grating power handling.

2. Reflective Interferometry Using a Polarization Sensitive Grating

We first review the grating interferometer design [2] for the external laser interferometry for formation flight represented by LISA. Figure 1 shows the grating interferometer configuration. The grating is designed to be highly polarization sensitive. As shown in the example in Figure 1, the external laser beam (green-colored in drawing) with the majority of its polarization lying in the plane of incidence (p-polarization), will specularly reflect into the zeroth order and be transmitted to the remote spacecraft. The small portion of the beam that is in the orthogonal, or s-, polarization will diffract onto the detector, forming the local oscillator. The incoming beam from the remote spacecraft is polarized orthogonal to the outgoing beam. By proper design, the incoming beam is mostly diffracted onto the detector to mix with the local oscillator to produce the interference signal for the science measurement. In the grating-based MGRS, the external laser light does not illuminate the proof mass. Therefore, the power and wavelength of the external laser beam can be selected to optimize the measurement precision to the remote spacecraft. For example, for LISA a green laser beam would improve the sensitivity. For DECIGO (Deci-hertz Gravitational wave Observatory) and BBO (Big Bang Observer) the extreme sensitivity requirements could be met by using shorter wavelengths such as the 532 nm, 355 nm or 266 nm, all harmonics of the Nd:YAG laser at 1064 nm. This configuration essentially has the basic functions of external interferometry required by LISA, but has a significantly simplified structure. Also, we have shown that by proper selection of the grating period, the incoming and outgoing beams can have an angular separation equal to the "look ahead angle" [2].

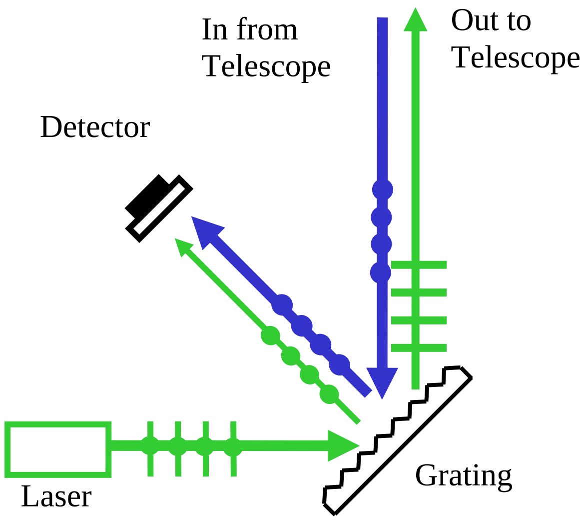

Figure 1: Optical configuration for laser interferometer using a polarization sensitive grating.

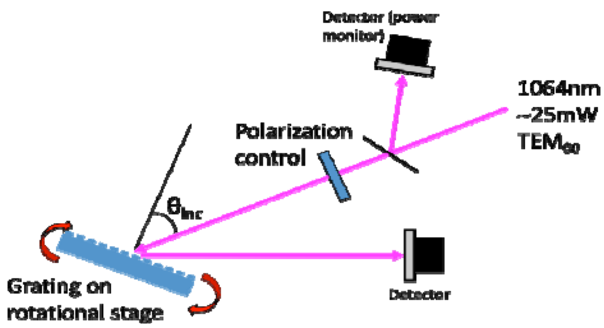

Figure 2: Experimental setup for measuring angle dependent polarization diffraction ratio.

3. Incident angle dependence of diffraction efficiency for each polarization

The design of a grating enjoys freedom to achieve the desired diffraction characteristics. The diffraction angles are determined by the grating period. The diffraction efficiency depends on the details of the grating shape, depth and design of the underlying stack [5], as does the polarization selectivity. The verification of strong polarization dependence of diffraction efficiency is a first step towards the polarization grating interferometer proposed in [2]. If verified, we can adjust the grating period and other parameters to tune the grating diffraction angle according to the requirement of the interferometer.

Our first measurements were therefore made to confirm the feasibility of using a grating to separate s- and p-polarized light. An all-dielectric diffraction grating consisting of a SiO_2/HfO_2 multilayer stack coated on a 100 mm diameter BK7 substrate at the University of Rochester Laboratory for Laser Energetics, with a 1740 line/mm grating patterned and etched into the top 575 nm-thick SiO_2 capping layer at LLNL, was used for this experiment.

The experimental setup is illustrated in Figure 2. A monochromatic 1064 nm, 25 mW laser beam from an NPRO laser was directed through a mode cleaner and a half-wave plate. The latter allowed for polarization rotation. This laser beam was directed at the grating mounted on a rotational stage. A detector was placed so that it captured light diffracting off the grating. Measurements were taken for a range of incident angles and results are plotted in Figure 3.

Figure 3(a) shows the -1 order diffraction efficiency for s-polarized light. The maximum efficiency of 97.3% was located near the Littrow angle 67.8°. Moreover the diffraction efficiency was maintained above 90% over a large angular range, from 61° to 77°. The large angular range of high efficiency diffraction makes a variety of interferometer arrangements possible. Figure 3(b) shows the -1 order diffraction efficiency for p-polarized light. The maximum diffraction efficiency was only ~4.2%, also located at the Littrow angle. The majority of the p-polarized light was specularly reflected into the zeroth order. Figure 3 (c) shows the ratio between s- and p- polarization diffraction efficiencies. The lowest ratio of ~23.2 was located at 67.8°, the Littrow angle, with higher ratios around both sides.

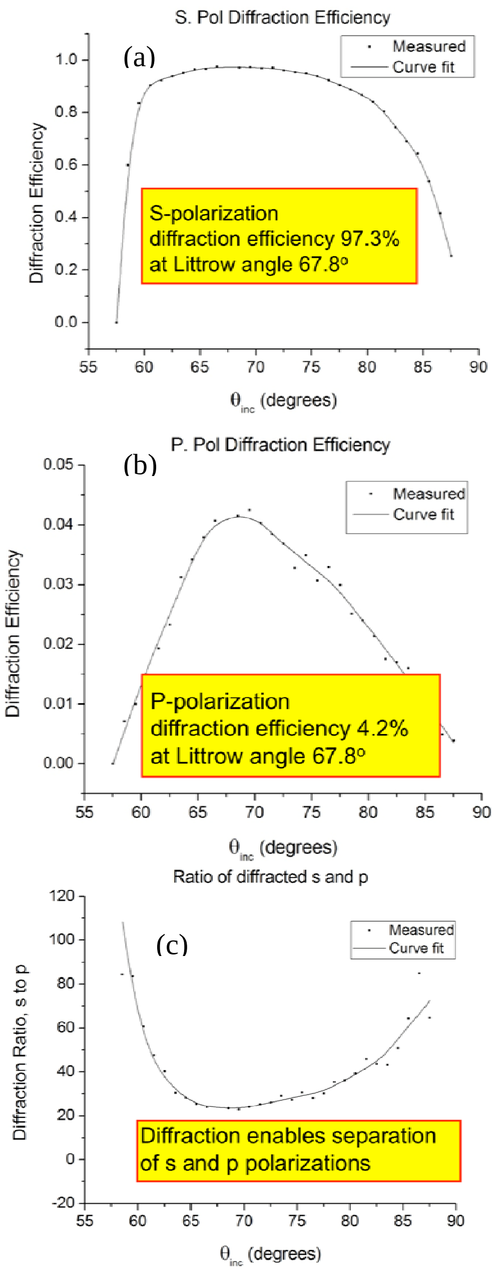

Figure 3: (a) Diffraction efficiency as a function of angle for s-polarized incident light. (b) Diffraction efficiency as a function of angle for p-polarized incident light. (c) Polarization-dependent diffraction efficiency ratio.

The grating diffracted significantly more for s-polarized light across all angles of incidence than that p-polarized light. This valuable property will help the implementation of the polarization grating interferometer.

4. Depolarization characterization

Ideally the grating should keep the polarization of incident light. Depolarization can cause undesirable mixing of the two polarizations, making noise enter the signal, and also resulting in loss of signal photons. Therefore, a grating with minimal depolarization is desired. Characterization of depolarization is necessary.

Figure 4 shows the experimental setup used to characterize the depolarization of the grating. These measurements were made near the Littrow angle. Light from an NPRO laser was diffracted off the grating into the -1 order and analyzed for s- and p- content, thereby determining the power transfer matrix of the grating diffraction. Most notably, only a very small amount of power from one polarization was diffracted into the other. Table 1 shows the measured data. Table 2 shows the calculated power transfer matrix.

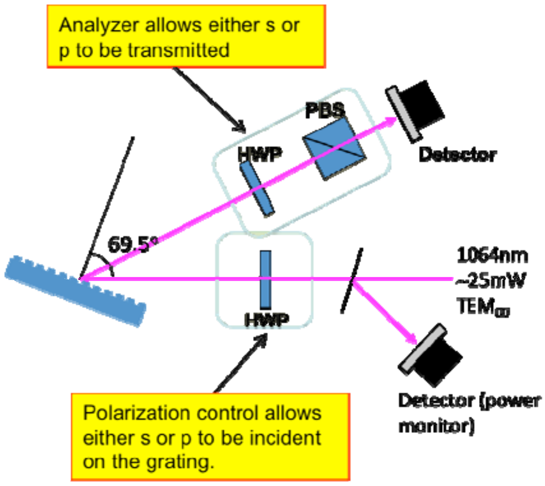

Figure 4: Experimental setup for depolarization measurements.

For s-polarized incident light, there was a transfer coefficient 1.67×10^{-4} for light diffracted into the p-polarization. For p-polarized light diffracting into s- the coefficient was 1.78×10^{-4}. These polarization extinction ratios rival those of transmissive polarizing beamsplitter cubes.

Table 1: Measured depolarization data

Incident Pol.	Incident Power (mW)	Exiting Component	Exiting Component Power (mW)	Transfer Coeff.
S	23.4	S	22.3	0.955
	23.4	P	3.90×10^{-3}	1.67×10^{-4}
P	22.9	S	4.07×10^{-3}	1.78×10^{-4}
	23.6	P	0.893	0.038

Table 2: Calculated power transfer matrix

		Output: s	Output: p	Polarization Extinction Ratio
Input	S	0.955	1.67×10^{-4}	5729
	p	1.78×10^{-4}	0.038	213

5. Cavity measurements for precise determination of diffraction efficiency at Littrow angle

Precise grating diffraction efficiency characterization is required for the calibration of interferometers. However, directly measuring the diffraction efficiency at the exact Littrow angle requires a beamsplitter to sample the returning beam and extra calibration steps, potentially adding uncertainty. We have developed a highly precise method of measuring diffraction efficiency at the Littrow angle consisting of a linear Fabry-Perot cavity that uses the -1 diffracted order of the grating as one of the end reflectors. The efficiency of the grating is calculated from measurements of cavity finesse. Note that cavities in this configuration also have implications for displacement sensing.

This experiment characterized a 1740 line/mm MLD grating on a 200x100 mm BK7 substrate, similar to the one earlier described but optimized with respect to grating height and linewidth for maximal diffraction efficiency at the Littrow angle. Our experimental setup is illustrated in Figure 4 (a). As in the previous section, light was emitted by a 1064nm NPRO and passed through an F=50 mode cleaner. This beam was modulated at 12 MHz in an electro-optic modulator (EOM) to provide sidebands for Pound-Drever-Hall locking of the mode cleaner and also to create a frequency reference signal used to measure cavity spectral characteristics. A piezo-mounted mirror allowed for scanning of the cavity length, and a photodiode placed after the cavity monitored the transmitted power. The mirror motion was independently measured by a Michelson interferometer, which makes it possible to calibrate the PZT element movement. Figure 4b shows a photograph of the 20 cm x 10 cm grating measurement setup.

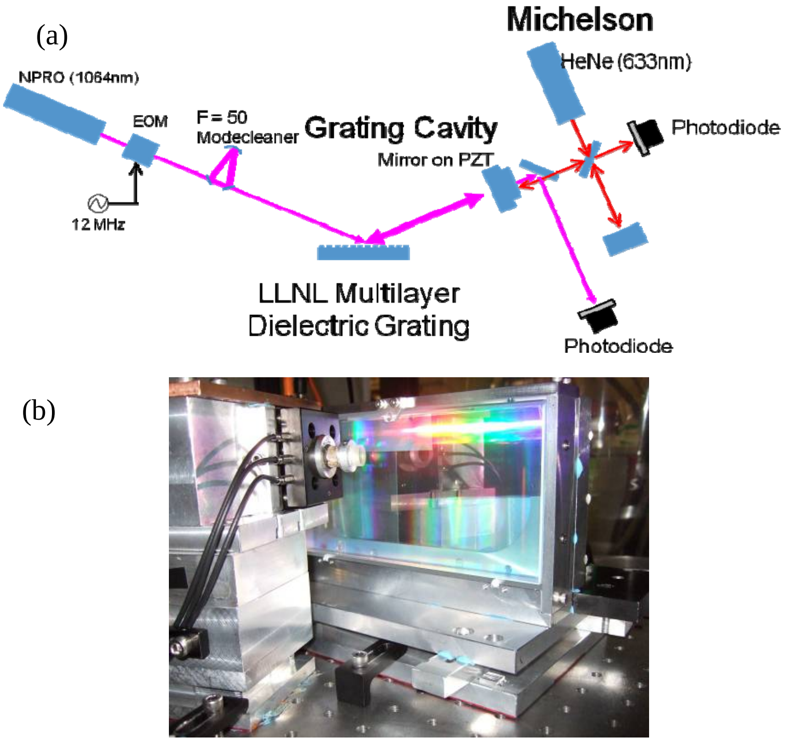

Figure 4: (a) Experimental setup for determination of grating efficiency at Littrow angle. (b) Photograph of the grating and Littrow cavity.

Figure 5 summarizes the cavity transmission while the piezo was scanned across a free spectral range of the cavity. We measured the finesse of a grid of points across the grating; in this example we present data gathered from the center point of the grating. In Figure 5(a), a full free spectral range of the cavity is shown, with both carrier and sideband peaks visible. The 12 MHz carrier-sideband and 24 MHz sideband-sideband beating components of the signal were digitally filtered out. Presenting the x-axis as the actuation distance is made possible by the Michelson interferometer, which allows for a mapping between scan time and distance traversed by the mirror. This calibration removes any nonlinearities in the piezo. In addition, by measuring the sideband spacing and using the known 12 MHz modulation frequency, it is straightforward to compute the free spectral range of the cavity and thus the cavity length. From these calculations, we arrived at a free spectral range (FSR) of 1.59 GHz, corresponding to a cavity length of 94.4 mm.

Figure 5(b) displays a zoomed view of one carrier peak and its sidebands. By performing a least squares fit on this plot to a model consisting of three summed Lorentzians, one can deduce the full-width-of-half-maximum (FWHM) of the central peak by comparing it to the sideband spacing. For this example, we have a FWHM of 1.97 MHz.

These two plots allow us to compute the finesse of the cavity formed between the grating and reference mirror to be 806. The reference mirror was independently characterized by taking two other mirrors and measuring the finesse of the cavities formed from each pairing of the mirrors in turn. The result was a reflectivity of 99.798%. With these two numbers, the diffraction efficiency of the grating is calculated to be 99.425%.

6. Grating power handling capability

As a test of the power handling capabilities of the dielectric grating, we illuminated a 1 mm patch of grating with 34W of 1064 nm light from a master oscillator power amplifier system. The illuminated spot was monitored with a Shack-Hartmann wavefront sensor, confirming that no significant wavefront distortions were present [6]. The power levels tested were significantly greater than the 2W required by LISA, indicating that similar gratings will be good candidates for BBO and DECIGO, which require ~100W of laser power.

7. Summary

A dielectric grating was measured for its efficiency across a range of incident angles for both polarizations, showing a polarization diffraction ratio of greater than 23.2 across all angles. We have also measured the depolarization of the grating, showing that less than 0.018% of incident light diffracts into the other polarization. In addition, a second grating was characterized for its diffraction efficiency at the Littrow angle. This was done using highly precise cavity measurements. Using this method, we have found grating diffraction efficiencies in excess of 99.4%, with five significant digits of precision. In light of these grating measurements, our proposed interferometer configuration shows future promise.

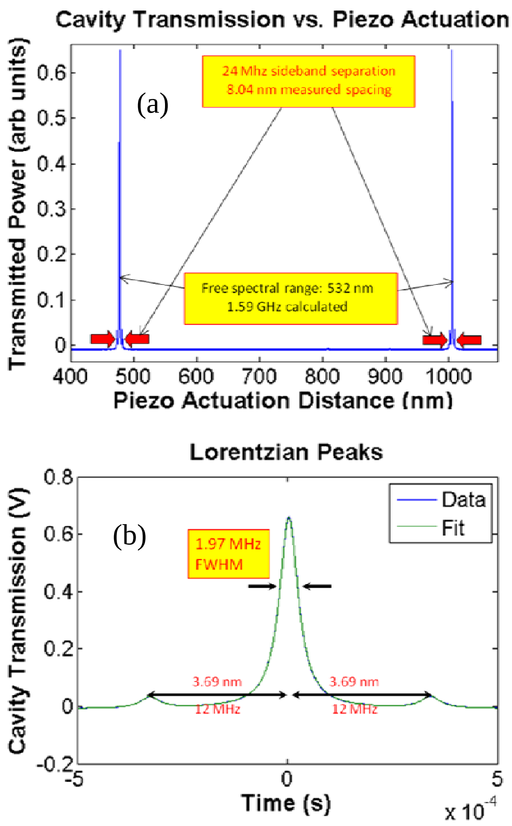

Figure 5: (a) Cavity transmission data during scan of cavity's length. (b) Zoomed view of the transmission peak that shows a cavity finesse of 806

Acknowledgements

This research is partially supported by NASA Beyond Einstein Science Foundation Grant NNX07AK65G "Modular Gravitational Reference Sensor for Space Gravitational Wave Detection", and by NSF grant for LIGO program.

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