Comparison of commercially available polarizing gratings for mid-infrared studies

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ABSTRACT

We present the results of lab comparison tests of performance for several commercially available grating polarizers sold for use at mid-infrared wavelengths. The tests were done using a polarized laser diode source (9.2 μm) and photoconductive HgCdTe single pixel detector. We describe some basic equations governing quantification of polarization performance, our instrumental test setup and our results. There is a great deal of difference in the contrast produced by polarizers from different companies. Availability of high-transmission, high-contrast polarizers for use at near and mid-infrared wavelengths will make it possible to routinely characterize polarization of astronomical sources, such as physical properties of dust grains and magnetic field lines around sources of interest.

Keywords: polarizer, grating, mid-infrared, instrumentation

1. INTRODUCTION

The availability of sophisticated techniques, including photolithography and holographic etching, has made it possible to routinely manufacture high-transmission polarizers for use in the mid (thermal) infrared. However, few of these gratings are consistently quantified for performance in terms of transmissivity, contrast, or extinction ratio, which are measures of ultimate importance to instrument builders and astronomers alike. Here we present results of laboratory tests of three comercially available polarizing gratings on ZnSe substrates, manufactured in similar ways.

In the first section, we describe some of the basic properties and equations governing performance/quantification of wire-grid polarizers. In section two we describe each of the gratings we tested based on what is available in the published literature from the manufacturers. In the third section, we describe our instrumental setup and methodology for testing both the contrast and extinction ratios of the gratings, and our tests regarding transmissivity using an FTIR. In the final section, we discuss our results and conclusions.

2. BASIC EQUATIONS DESCRIBING WIRE-GRID POLARIZERS

According to general polarization theory, there are four basic mechanisms through which an unpolarized light source can be polarized: dichroism (i.e. selective absorption), reflection, scattering and birefringence. Wire-grid polarizers fall into the first category, those performing polarization by introducing dichroism. This polarization occurs via the rejection of that component of the electric field which is parallel to the direction of the metal (wire) grid. For further detailed study, we direct the reader to any standard Optics text..[1,?]

In practice, the contrast of a polarizer in a linearly polarized beam can be easily characterized by measuring the maximum and minimum throughputs of the polarizer when the wire grid is aligned and crossed with respect to the beam. Let us define:

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k_1 = (maximum transmission with polarizer)/(output without polarizer)

and

k_2 = (minimum transmission with polarizer)/(output without polarizer)

then the contrast, C, becomes:

$$C = \frac{k_1}{k_2}.$$

The extinction ratio, for the purposes of this paper, is defined as 0.5 times the contrast, for the situation where two equivalent polarizers are tested in series using either a polarized or unpolarized light source. Occasionally one will also see defined a quantity called the degree of polarization, using the k_1 and k_2 above, as follows:

$$P = \frac{k_1 - k_2}{k_1 + k_2}.$$

When working with two polarizing gratings in series, the extinction ratio of the pair can be written as an equation containing two k_i for each polarizer. Then approximations are typically made to solve the system. This is the approach used in this paper and the extinction ratio for the pair of polarizers, a and b, in series is written:

$$E = \frac{max(ab)}{min(ab)} = \frac{k_1(a)k_1(b) + k_2(a)k_2(b)}{k_1(a)k_2(b) + k_2(b)k_1(a)}$$

In order to solve these equations, the numerator and denominator portions were treated seperately. Wherein, it was assumed that C > 100 for any individual polarizer, so that $k_1 >> k_2$ and the second term in the numerator portion of the equation can be neglected. Once solutions are obtained for $k_1(a)$ and $k_1(b)$, the final solution requires straightforward algebra, assuming one has measurements of all polarizers in the set in pairwise combinations.

3. COMMERCIALLY AVAILABLE TRANSMISSIVE ZNSE POLARIZING GRATINGS

We were able to find three ZnSe grating polarizers specifically marketed for mid-infrared use in the US commercial market. Although generally terse, the descriptions of the manufacturing process used to produce each of these grating polarizers is similar. Each polarizer undergoes some type of etching process, and then a uniform metal grid is applied to one surface of the ZnSe transmissive optic.

The three polarizers of this type that we tested were purchased from Leonard Research Corporation, Optometrics and Reflex Analytical between 1999 and 2001. We set out to test these optics to determine ultimately which one had the best performance with respect to contrast for use in interferometric nulling experiments being conducted at the Jet Propulsion Laboratory in support of Origins Science programs with the Keck Interferometer Nuller and the Terrestrial Planet Finder.[3, ?]

3.1. Leonard Research Corporation Polarizer

The Leonard Research Corporation (LRC) polarizers are made through a proprietary process in which a holographic grid is etched into a photo-resist layer on the ZnSe substrate. Gold is then deposited onto this grid to serve as the wire mesh that rejects certain polarization components of the incoming beam. The standard LRC polarizer is made from non-anti-reflection coated ZnSe with a high degree of parallelism (< 10 arc seconds) of the two faces. LRC advertises anticipated contrast ratio of their polarizers in the 500-1000 range. One polarizer was used for testing, of 25 mm diameter mounted in its own metal ring, supplied by LRC as part of the package. (Tom, do you want to say anything about your grid spacing, etc....)

3.2. Optometrics Polarizer

The Optometrics (Opt) polarizers are made through a proprietary process in which a holographic grid is etched into a photo-resist coated substrate on the ZnSe. Aluminum is then deposited onto this grid to serve as the wire mesh. While ZnSe polarizers from this company can be purchased with anti-reflection coatings, none was specified for the purposes of these tests. The wire-grid spacing is advertised as 2400 grooves per mm, with better than 3 arc minute parallelism on substrates approximately 2 mm thick. Optometrics advertises contrasts (for which they use the term extinction ratios) for their ZnSe polarizers at 10 μm to be around 300. Two 25 mm diameter, mounted polarizers were purchased for the purposes of these tests.

3.3. Reflex Analytical Polarizer

The Reflex Analytical (RA) polarizers are made through a process assumed to be similar to that of the other two companies although not explained in their literature. Gold is used for the wire mesh deposition on the ZnSe substrates. The wire grid spacing is advertised as 0.25 μm with a transmission efficiency (for one polarization) of 70% at 10 μm and an extinction ratio of 140. The substrate tested is approximately 2 mm thick, 25 mm in diameter, housed in a 35 mm diameter outer ring and mounted in an optical bench mount available from the company. Only one polarizer from RA was tested for this paper.

4. INSTRUMENTAL TEST SETUPS

In order to empirically determine the contrast and degree of polarization of each of the above polarizers, it was necessary to design a setup to test each of the polarizers near 10 μm (the midpoint of our band of interest, and the wavelength at which these polarizers are generally advertised) which would allow us to remain significantly above the intrinsic noise floor in order to insure that we had covered the full range of this contrast without limitations imposed by our instrumentation. Below we describe in full detail the instrumental setup to test the polarization of the optics. All four polarizers were also tested using an infrared FTIR, to determine the intrinsic transmissivity of the optics, and these tests are also described below.

4.1. Polarization Test Setup

The source used for these experiments consisted of a Pb-salt laser diode lasing in single mode at approximately 9.2 μm. The diode was manufactured by Laser Components in Santa Rosa, CA and the liquid nitrogen dewar in which it is housed and associated control electronics and gold-coated collimating off-axis parabola were purchased from Boston Electronics in Brookline, MA. The detector used was a HgCdTe 50 μm square single pixel detector in a liquid nitrogen dewar. The assembly was purchased from Infrared Associates in Stuart, FL and was modified for use in our lab by inserting an F5 aperture and 7 μm wide bandpass filter on the cold Lyot stop of the dewar. Between the source and detector were a series of off-the-shelf optics consisting of an iris for decreasing the 25 mm beam size, a chopper wheel running at 100 Hz, one or two polarizers to be tested, each in rotatable mounts, and a front-surface silver mirror to redirect the beam into an F5 plano-convex ZnSe lens, which focused the beam onto the HgCdTe detector (Figure 1).

All measurements were taken in one of two setup modes. For three polarizers (the LRC and both Opt polarizers) there was sufficient throughput with the setup to stop the aperture down to 6.5 mm and test the polarizers in pairs using a lockin amplifier to record all signal and noise measurements. In this configuration the polarizer with the assumed higher contrast was always first in the series. For the fourth polarizer (the RA polarizer) the throughput was too low when combining this polarizer with any of the others to allow for pairwise combinations. Therefore, this polarizer was tested alone using the laser diode source (which we've estimated to be about 90% linearly polarized in the mode in which we were lasing through previous tests) with a 11.5 mm aperture. For this configuration, signal level measurements with no polarizer in place were determined via an oscilloscope and all subsequent measurements with the polarizer in place were determined via the lockin amplifier.

In the crossed polarizer tests, the experimental procedure was as follows. An RMS measurement of the signal, background and noise without any polarizers in place was determined using the lockin amplifier. The phase on the amplifier was locked to the chopped signal, and the lockin was set to AC coupling using a 12

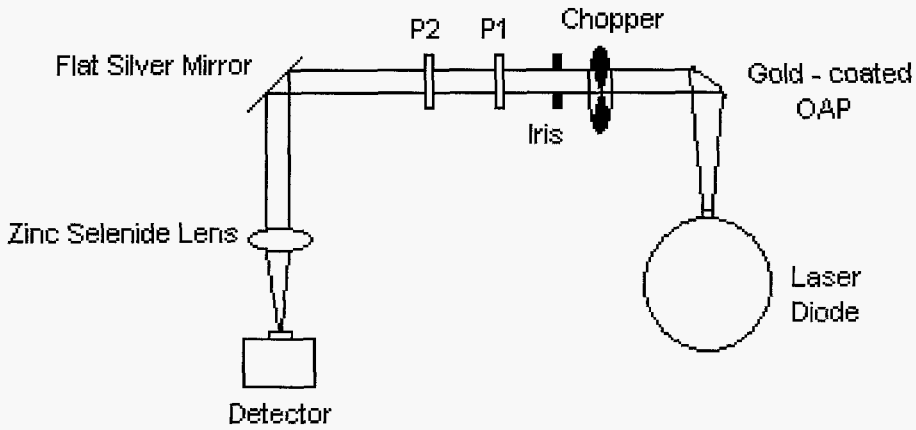

Figure 1. The figure depicts the layout of the polarization experiment for a pair of crossed polarizers. Details of the experimental setup can be found in the text.

dB normal filter for noise suppression. A time constant of 30 ms was used for all measurements, which were taken using a 100 Hz chop frequency, locked from the output signal of the chopper wheel to the amplifier. Background measurements were taken by staring into the liquid nitrogen cooled cavity in which the laser diode is housed, with the diode shut off. As such, these values had a negative sign compared to measurements taken while the laser diode was lasing, and were generally in the tenths of mV range. The noise measurements were taken using the X noise setting of the lockin and were consistently 9-10 μV for all measurements taken. Next a series of signal, background and noise measurements were taken of the higher contrast polarizer in both its aligned and crossed (maximum and minimum throughput) positions. The high contrast polarizer was then set at approximately 45 degrees to the maximum and minimum positions, and signal and background measurements recorded here for the final step in the comparison. Finally, the lower contrast polarizer was placed in position two and signal, background and noise measurements were recorded for its aligned and crossed positions. The measurements from the pair of crossed polarizers were used and solved pariwise to determine the coefficients of each polarizer individually (see Section 4.2 below).

For the fourth polarizer, the steps were very similar except that initial measurements without the polarizer in place were done via an oscilloscope because the lockin was not able to measure RMS signals above approximately 1.0 volts. When the polarizer was in place, it was possible, using the larger aperture (11.5 mm) described above, to obtain enough throughput above both the background and the noise floors to allow measurements of the signal, background and noise determined via the lockin. Because the laser diode source is highly, but not completely linearly polarized, we assume the results for this polarizer are a lower limit.

Each measurement was carefully conducted to insure that the polarizer was well centered on the test beam and that the face of the polarizer was approximately perpendicular to the beam's optical axis by peaking up the signal on the lockin amplifier. Because polarizers at these wavelengths are known to be relatively insensitive to acceptance angles (i.e. a 10-20 degree range of z-rotation with respect to the x-y position of the beam), we do not believe any significant errors were introduced due to possible rotation of the individual polarizers with respect to the beam.

4.2. FTIR Test Setup

For non-polarized transmissivity tests of the polarizers, a Thermo Nicolet Nexus 670 FT-IR operational from HeNe to past 20 μm was used in its standard mode to create scans from 1 to 20 μm for each polarizer tested.

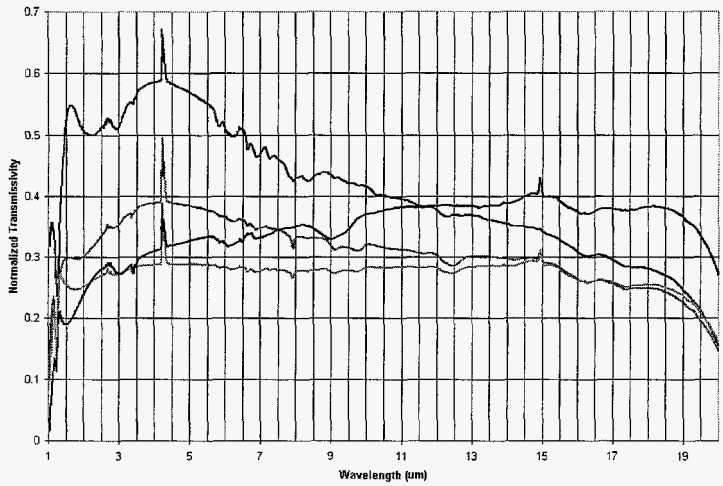

Figure 2. This figure shows the FTIR transmission curves for all four polarizers from 1 to 20 μm. From top to bottom (at 4 μm) the curves are RA (blue), Opt1 (red), Leo (black) and Opt2 (green). Spectral features are indicative of grating parameters for the wire grids (see text).

This FT-IR utilizes an internal, single-pixel HgCdTe detector cooled with liquid nitrogen, and various beam splitters and sources to create the incident wavelengths for testing. Backgrounds are typically taken, with no optic in the beam, and divided out of the resultant scans. The polarizers were set in the beam path in no particular orientation, with the expectation that because the source and detector in this system are not explicitly polarized/polarization sensitive, the measured response at peak transmission should be about half of the total transmission, because one linearly polarized component of the beam will be rejected.

5. RESULTS AND CONCLUSIONS

5.1. Transmissivity tests

The transmissivity tests of the polarizers reveal that the polarizers "turn-on" at just before 1 μm and have spikes in their transmission curves near 1.25, 4.235 and 14.95 μm, and at 7.92 μm for the two Opt polarizers (Figure 2). Their transmissivity begins to fall off significantly past 19 μm in all cases. We note that the transmission curves are relatively smooth throughout the 9 to 9.5 μm region, and there are no serious dips in the RA polarizer's curve, indicating that the difficulties we encountered in testing this optic were not due to transmissivity. The sharp, ringing features seen in these scans between 1 and 2 μm is indicative of interference effects that are commonly seen in gratings. The frequency of the ringing and the points where it begins and ends are functions of the wavelength of incident radiation, the wire diameter and grid spacing themselves. Standard transmission grating theory can be used to analyze the data in this fashion, but will not be discussed here as it is beyond the scope of this paper.

5.2. Polarization tests

The results of the polarization tests show that all the polarizers exhibit a high degree of polarizability (Table 1). However, when the contrast of the individual polarizers is examined, it is evident that there is a great deal of difference in these optics. In particular, we note that the two Opt polarizers are extremely different. Upon visual inspection of these polarizers, we do note that the Opt1 polarizer seems to be smudged in the center of the optic, and has some type of halo along the edges. This is possibly indicative of some damage that may have been incurred to its surface, and so this measurement may be considered atypical. However, if this difference is actually indicative of the spread of ranges that are available due to anomalies in the manufacturing process,

then it is important to be aware of this when purchasing a polarizer. Due to monetary and manufacturing limitations, we were not able to purchase more than one polarizer from either RA or LRC, and so similar comparisons cannot be made for those company's products.

As stated in Section 4.1, the RA polarizer did not produce very high throughput during testing, regardless of the orientation of the polarizer, or its acceptance angle with respect to the test beam. Because the RA polarizer could not be tested in a pairwise combination, and because the total polarization of the laser diode beam was not known absolutely, we conclude that the values of polarizability and contrast for the RA polarizer are a lower limit. The LRC polarizer had both the highest contrast and polarizability of the three different company's optics. Differences seen between these polarizers are likely due to the details of the etching processes, the wire widths and spacings, the uniformity of the grids themselves and the metal used for conduction of the electromagnetic field. Because these details are not available to us in the published literature from all the individual companies, we choose not to speculate on the specifics. We do note, however, that if anti-reflection coatings can be sucessfully applied to these polarizers, then it might be reasonable to place two polarizers from any of these companies in series in an optical experiment and attain a high degree of polarization and contrast, while maintaing reasonable throughput in the optical system.

Table 1. Results of polarization characterization for four polarizers tested. The LRC and Opt polarizers were tested in pairwise combination, while the RA polarizer was tested alone due to throughput issues (see text). Values for the RA polarizer are likely a lower limit, although no suitable explanation was found for why the throughput of this polarizer was anomalously low.

Polarizer	k_1	k_2	C	P(%)
LRC	0.3613	0.0008	451.6	99.6
Opt1	0.3846	0.0054	71.2	97.2
Opt2	0.4168	0.0014	297.7	99.3
RA	0.0043	5.3E-5	80.7	97.7

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