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GRID POLARIZERS FOR INFRARED FOURIER SPECTROMETERS

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Abstract--Infrared grid polarizers consisting of copper lines with a $3.6\text{ }\mu\text{m}$ grid constant on a $4\text{ }\mu\text{m}$ thick mylar polyester substrate have been prepared by the techniques of photolithography and sputter-etching. Their polarization properties have been measured and found to be suitable for use at infrared frequencies below 700 cm^{-1} . The polarizers have been used to extend the useful frequency range of a Martin-Puplett polarizing interferometer designed for Fourier transform spectroscopy. The efficiency of the interferometer has been measured over a frequency range from 50 to 700 cm^{-1} and compared to that of a conventional Michelson interferometer. The results are shown to be consistent with the measured properties of the polarizers. Methods are suggested for improving the efficiency of a Martin-Puplett interferometer which employs these polarizers.

1. INTRODUCTION

Polarizing interferometers possess certain important advantages over conventional Michelson interferometers (MI) when used for far infrared Fourier spectroscopy. The Martin-Puplett polarizing interferometer (PI), for example,⁽¹⁾

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produces an interferogram with a zero baseline when used in the chopped mode. As a result, fluctuations in source intensity or detector sensitivity do not cause the spurious Fourier components in the interferogram which are characteristic of an MI used in the chopped mode. In addition, the PI, as well as several other types of polarizing interferometer,^(2,3) can operate over a broad range of frequencies without changes of beamsplitter. This is in contrast to the efficiency of the MI with a dielectric beamsplitter which is high only over a limited spectral range. Until recently, however, the PI has been used only in the frequency range below about 100 cm^{-1} . This has been due to a lack of large area polarizers suitable for higher frequencies. Since the PI uses input and output polarizers in addition to the polarizing beamsplitter, the efficiency of the instrument depends critically upon the performance of the polarizers.

In Section 2 we describe the fabrication of polarizers which are suitable for use in a PI at frequencies up to 700 cm^{-1} . Section 3 presents the results of measurements of the polarization and transmittance properties of the polarizers. Equations are developed in Section 4 which permit a comparison of the relative efficiencies of the PI and the MI. Measurements made with an instrument operated both as a PI and an MI are described in Section 5. Section 6 presents an analysis of these measurements in terms of the equations of Section 3. Finally, Section 7 discusses methods by which the efficiency of the PI could be improved.

2. FABRICATION

The development of high resolution fabrication techniques for the microelectronics industry, particularly of holographic and photolithographic pattern generation and of ion sputter-etching, has permitted the fabrication

of grid polarizers on transparent substrates for use at near infrared wavelengths of 1 to 2 μm ⁽⁴⁾. These polarizers have many advantages over the bulkier Brewster-angle polarizers in that (1) they are physically thin and do not significantly alter the optical path, (2) they can accept incident radiation over a wide angle and thus can be used for beam splitters and diplexers in systems where both the transmitted and reflected polarizations are utilized, (3) they can be made economically to cover large areas, and (4) they can be made durable enough to be used for high power applications.

Typical performance characteristics for wire grid polarizers have shown that for grid period, D , approximately 1/10th the wavelength, λ , of the incident radiation and for the individual metallic line width, d , approximately half of the grid period, then the transmittance for the undesired polarization is $\sim 10^{-3}$ of that for the desired polarization. This leakage decreases as either D/λ decreases or as d/D increases. A grid pattern with 3.6 μm period was selected for use in the polarizing interferometer for $\lambda \geq 30 \mu\text{m}$. The substrate for the polarizer is a 4 μm thick mylar sheet on which was deposited 0.5 μm of copper. The mylar was stretched and secured by epoxy adhesive to an 18 cm x 28 cm open rectangular metal frame. The stretched mylar was coated with photoresist by slowly withdrawing the frame from a tank of the liquid resist. After air drying at 80°C for 30 min the coated mylar was placed in contact with a metallic master grating pattern, scribed through a metal film on a clear glass plate. Contact between the film and the master pattern was enhanced by pneumatic pressurization or by a foam rubber pad used behind the mylar. After exposure and development, sputter-etching by means of a broad area Argon ion beam was used to remove the exposed copper--leaving the conducting grid of wires as shown in Fig. 1. The resist was dissolved off

of the surface and the polarizer was tested in the interferometer system. For shorter wavelength applications the grating patterns (with periods as small as $0.3 \mu\text{m}$) are produced by laser holographic exposure of the photo-resist⁽⁴⁾. Ion beam sputtering or reactive plasma etching can be used for pattern delineation even at these small dimensions.

3. POLARIZER MEASUREMENTS

The polarizer transmittance was measured and compared to the transmittance of the $4 \mu\text{m}$ thick mylar used for the polarizer substrate. Figs. 2(a), (b), and (c), show the polarizer transmittance (T_p), mylar transmittance (T_M), and the ratio of their transmittances respectively, all measured at normal incidence. The transmittance of the polarizer in Fig. 2(a) shows a significant decrease from the ideal value of 0.50. Most of this decrease is a result of reflection from the mylar substrate. This is evident from the measured transmittance of the mylar shown by the solid line in Fig. 2(b). The dashed line in the same Figure is the theoretical transmittance of mylar, including dispersion, but neglecting absorption. A ratio of the two measured transmittances shown by the solid line in Fig. 2(c), however, reveals a further decrease in the polarizer transmittance which is not due to the mylar alone. It results from the combined effects of the wire grid and the mylar substrate. The spectra in Fig. 2 have not been plotted in the region of substantial mylar absorption between 360 and 520 cm^{-1} where their accuracy is poor because of the mylar beam splitter in the measuring instrument. The performance shown here was obtained in selected regions of the polarizers. The transmittance of other regions which were incompletely etched was as low as 25%.

The transmittance of crossed polarizers for unpolarized light (T_c) is shown in Fig. 2(d). For frequencies between 200 and 700 cm^{-1} only about 1% of the source light is transmitted by each polarizer in the wrong direction of polarization. At 50 cm^{-1} this typically increases to about 3%. An increase as large as 10% was found in some regions which were assumed to be etched excessively. The low frequency performance could be improved with wider or thicker metal lines.

4. THEORETICAL INTERFEROMETER EFFICIENCIES

Unlike the PI, the far infrared MI is characterized by a periodic variation in its efficiency due to interference effects in the beamsplitter. The beamsplitter efficiency of the MI can be expressed as $U_{\text{MI}} \epsilon_{\text{MI}}$ where the absorption in the beamsplitter material is included in the factor U_{MI} , and ϵ_{MI} is a function of the reflection and transmission coefficients, $R(\sigma)$ and $T(\sigma)$,

$$\epsilon_{\text{MI}}(\sigma) = R_{\perp} T_{\perp} + R_{\parallel} T_{\parallel}. \quad (1)$$

In this equation and throughout the paper the symbols $\perp$ and $\parallel$ refer to the direction of polarization of the light incident upon the beamsplitter relative to the plane of incidence. For an ideal beamsplitter which transmits and reflects half the light, $\epsilon_{\text{MI}} = 1/2$.

We now define the spectral output of the interferometer, $S_{\text{MI}}(\sigma)$, to be the intensity in the spectrum at the spectral wavenumber σ obtained from the Fourier transform of the interferogram. For the MI this will be given by

$$S_{\text{MI}}(\sigma) = I_L U_{\text{MI}} \epsilon_{\text{MI}} C_{\text{MI}} Q_{\text{MI}}, \quad (2)$$

where $I_L(\sigma)$ is the spectral intensity of the lamp, C_{MI} is the fraction

of the light passed by the chopper at the frequency of the lock-in amplifier, and $Q_{MI}(\sigma)$ is an attenuation factor due to misalignments.

For a perfect square wave chopper, $C_{MI} = 2/\pi$.

To obtain analogous expressions for the beamsplitter efficiency and the spectral output of the PI, it is convenient to follow the procedure of a previously published analysis.⁽⁵⁾ In our case the beamsplitter is asymmetric, having the copper grid on one side of the mylar substrate, which results in different complex amplitude reflection and transmission coefficients for the two sides of the beamsplitter. The intensity of a single component of wavenumber σ in the interferogram due to an asymmetric beamsplitter in an otherwise ideal PI is then found to be

$$I_{out}(\sigma) = \frac{1}{2}I_L \{ T_{\parallel} a_{\perp} a'_{\perp} \cos[4\pi\sigma\delta - (\theta_{\perp} - \theta'_{\perp})] + T_{\perp} a_{\parallel} a'_{\parallel} \cos[4\pi\sigma\delta - (\theta_{\parallel} - \theta'_{\parallel})] \}, \quad (3)$$

as compared to the corresponding equation for an ideal PI with a symmetric beamsplitter of

$$I_{out}(\sigma) = \frac{1}{2}I_L \cos(4\pi\sigma\delta). \quad (4)$$

Here δ is the path difference, T is the intensity transmission coefficient of the beamsplitter, a is the amplitude and θ the phase of the complex amplitude reflection coefficients. Unprimed coefficients refer to the side of the beamsplitter nearest the detector.

This equation may be simplified considerably to obtain an approximate expression for the beamsplitter efficiency. In our instrument the metal lines on the beamsplitter are oriented to block the light polarized perpendicular to the plane of incidence. This makes $T_{\perp} \ll T_{\parallel}$. Because $a_{\parallel} a'_{\parallel} < a_{\perp} a'_{\perp}$, the second term on the right hand side of Eqn (3) can be

neglected. The reflected amplitudes a_1 and a_1' are essentially unity for the frequencies at which we are working. Consequently, the beamsplitter affects the output intensity primarily through $T_{||}$. As a result, it may be noted that the output intensity can be maximized by placing the beamsplitter at Brewster's angle with the wires perpendicular to the plane of incidence. The beamsplitter in our instrument, however, was at the more typical 45° angle of incidence. It can also be seen from (3) that one effect of the asymmetry is to introduce a frequency dependent phase shift, $\theta_1 - \theta_1'$, into the interferogram.

The beamsplitter efficiency of the PI may be expressed as $U_{PI}\epsilon_{PI}$, where $U_{PI}(\sigma)$ is again a correction factor for the absorption of the beamsplitter material. A comparison of Eqn (3) with Eqn (4), and consideration of the comments of the previous paragraph lead to the identification $\epsilon_{PI} \cong T_{||}$. Therefore an ideal beamsplitter would have $\epsilon_{PI} = 1$. The spectral output of the interferometer, including the effects of the input and output polarizers,⁽⁵⁾ is then given by:

$$S_{PI}(\nu) = I_L U_{PI} \epsilon_{PI} (X_{P1} T'_{P1}) (X_{P2} T'_{P2}) C_{PI} Q_{PI}. \quad (5)$$

In this equation $T'_{P1}(T'_{P2})$ is the transmittance of the input (output) polarizer, and $X_{P1}(X_{P2})$ is the fraction of the transmitted light from the input (output) polarizer which is polarized. A perfect polarizer would have $T'_p = 1/2$ and $X_p = 1$. For an imperfect polarizer, which transmits a fraction α of the incident unpolarized light in the correct polarization direction and a fraction β in the incorrect polarization direction, $T_p = \alpha + \beta$ and $X_p = \frac{\alpha^2 - \beta^2}{\alpha + \beta}$. It should be noted that the polarizer transmittance, T_p , shown in Fig. 2(a) is actually $\frac{\alpha^2 + \beta^2}{\alpha + \beta}$ due to the manner

in which it was measured. Thus it differs from T'_p by a small amount, $\frac{2\alpha\beta}{\alpha+\beta}$, and therefore may not be directly substituted for T'_p . The modulation efficiency C_{PI} has its maximum value of unity for the case of a perfect output polarizer which is rotated to modulate the instrumental output.

A measure of the relative efficiencies of the PI and MI is obtained from the ratio of their spectral outputs:

$$\frac{S_{PI}}{S_{MI}} = \frac{\epsilon_{PI}(X_{P1}T'_{P1})(X_{P2}T'_{P2})C_{PI}Q_{PI}U_{PI}}{\epsilon_{MI}C_{MI}Q_{MI}U_{MI}}. \quad (6)$$

Equation (6) will be used to analyze the experimental results of the next section. Using the values previously given for ideal components in each instrument, the ideal efficiency ratio is found to be:

$$\frac{S_{PI}}{S_{MI}} = \frac{1 \cdot (1 \cdot \frac{1}{2}) (1 \cdot \frac{1}{2}) \cdot 1 \cdot 1 \cdot 1}{1 \cdot \frac{1}{2} \cdot (2/\pi) \cdot 1} = \pi/4. \quad (7)$$

Since the zero baseline of the interferogram is an important feature of the PI, we must also consider the effect of the polarizer substrate on the baseline. The complete expression for the interferogram of a PI contains a term of the form⁽⁵⁾

$$I_L \text{Re}(T_{\parallel} t_{\perp}^* r_{\parallel}'^* r_{\perp}' + t_{\parallel} t_{\perp}^* r_{\parallel}'^* r_{\perp}')/4 \quad (8)$$

added to Eqn (3). Here r and t are the complex amplitude reflection and transmission coefficients of the beamsplitter. The asterisk denotes complex conjugation. In the case of a conventional wire grid beamsplitter, $r_{\parallel} = r_{\parallel}' \cong 0$, so the baseline term is negligible. This is not true, however, for grids on a reflecting substrate. The baseline in this case will still be negligible as long as the polarizer does not leak any radiation of the wrong polarization,

so that $t_{\perp} = 0$. For spectral regions in which $t_{\perp} > 0$, the baseline term will be proportional to $r_{\parallel}$ which is essentially the reflectivity of the substrate.

5. INTERFEROMETER MEASUREMENTS

A laboratory PI which has been described elsewhere⁽⁵⁾ was fitted with a beamsplitter and input and output polarizers made from the polarizing material discussed above. The spectral output, S_{PI} , was measured with a Hg-arc source and a Golay detector with a diamond window and a 4 mil black polyethylene filter. It is shown in Fig. 3. The same instrument was then operated as an MI using a 4 μ m mylar beamsplitter and a sector wheel chopper. The spectral output, S_{MI} , obtained in this way is also shown in Fig. 3. Channel spectra from the black polyethylene filter, and the mylar absorption bands between 350 and 520 cm^{-1} are clearly visible in both spectra. These spectral outputs give directly the spectral distribution available for broad band Fourier spectroscopy using the PI and the MI. Although the spectral range over which the PI can be used is very broad as expected, we find that $(S_{PI})_{\text{expt}}$ is significantly less than $(S_{MI})_{\text{expt}}$ over much of the range. This result will be considered in the next section.

The interferogram measured with the PI had a non-zero baseline which depended on the spectral range. For low frequencies this baseline was $\leq 3\%$ of the peak of the interferogram. If the spectral band was left open to 1000 cm^{-1} so that light was detected that was partially polarized, but not efficiently interference modulated, then the baseline shift was as large as 20%.

Two additional spectral outputs were measured to aid in the analysis of the instrumental efficiencies. When the instrument was operating as an MI, extra pieces of 4 μm mylar were placed at the locations of the input and the output polarizers of the PI. The spectral output for this case will be denoted S_{MI}^{m} . As will be seen in the next section, this provided a convenient way of eliminating the effect of the mylar substrate in the input and output polarizers when comparing the spectral output of the PI to the spectral output of the MI. The MI was also operated (with the extra mylar) in an unconventional manner with roof mirrors instead of plane mirrors. When operated in this manner the interferometer will be called an RI with spectral output S_{RI}^{m} . The small m superscript again refers to the fact that extra pieces of mylar were located at the input and output of the interferometer. This spectral output was useful for determining the degradation of the MI due to misalignment, and will also be discussed in the next section.

6. ANALYSIS

In this section we will examine in detail the factors which limit the efficiency of the PI. Our approach is to start with the easily measurable ratio of spectral outputs of the two instruments given by (6). Since we are primarily interested in the properties of the PI we remove ϵ_{MI} from the measured ratio by computing it from the known properties of mylar (including dispersion, but excluding the region of strong absorption between 360 and 520 cm^{-1}). Both the estimate of ϵ_{MI} and the product $\epsilon_{\text{MI}}(S_{\text{PI}}/S_{\text{MI}})_{\text{expt}}$ are

shown in Fig. 4. If both interferometers were otherwise ideal this product would be a straight line at $\pi/8 = 0.39$, rather than the experimental value of 0.1 to 0.2. We can account for the discrepancy by successively considering the differences between the ideal and measured values of the factors in Eqn (6).

The beamsplitter efficiency factor ϵ_{PI} in Eqn (6) is approximately equal to the transmittance $T_{\parallel}$ for light incident at 45° which is polarized parallel to the plane of incidence on a polarizer with wires perpendicular to the plane of incidence. It can be expressed in terms of the ratio T_p/T_m which is measured at normal incidence with unpolarized light,

$$\epsilon_{PI} \approx T_{\parallel} = 2 T_{\parallel}^m T_p/T_m, \quad (9)$$

where $T_{\parallel}^m$ is the transmittance of mylar for light incident at 45° which is polarized parallel to the plane of incidence. The factor $T_{\parallel}^m$ is computed from the known properties of mylar, again neglecting absorption.

The factor X_p in Eqn (6) which describes the performance of the polarizers, was computed from the measurements of single polarizer transmittance $T_p = \frac{\alpha^2 + \beta^2}{\alpha + \beta}$ and crossed polarizer transmittance $T_c = 4\alpha\beta$ shown in Fig. 2.

$$X_p = \frac{\alpha - \beta}{\alpha + \beta} = \left(\frac{T_p^2 - T_c + T_p \sqrt{T_p^2 + 2T_c}}{T_p^2 + T_c + T_p \sqrt{T_p^2 + 2T_c}} \right)^{1/2}. \quad (10)$$

For most of the spectral range X_p is close to unity. At low frequencies, however, it drops due to the rise in T_c . At 50 cm^{-1} , X_p is 0.9.

Measurement of the actual chopper modulation pattern in the MI gave an estimate of $C_{MI} = 0.63$, and physical supports in the output polarizer of the PI partially obscured the beam reducing C_{PI} to 0.90. Thus the ratio $(C_{PI}/C_{MI})_{\text{expt}} = 1.43$ was 9% below the ideal value of $\pi/2 = 1.57$.

The reduction in efficiency due to misalignment, lack of flatness of the roof mirrors, and optical thickness variations in the mylar, was estimated in the following way. We first assume that the misalignment of the PI is nearly the same as the misalignment of the RI. This is reasonable because the tilt, rotary shear, and dihedral angle misalignments⁽⁵⁾ due to the roof mirror positions will be the same for both instruments. Only that part of the lateral shear misalignment due to imperfections in the beamsplitters and output polarizer will differ between the two instruments. With this assumption it is then possible to determine the ratio of these "misalignment" factors by making use of the spectral outputs of the RI and MI. In analogy with Eq. (2), the spectral output of the RI can be written

$$S_{RI} = I_L U_{MI} \epsilon_{RI} C_{MI} Q_{RI}, \quad (11)$$

where we have assumed that the effects of absorption in the beamsplitter are the same for the RI as for the MI, and where $\epsilon_{RI} = 2(R_{\perp} T_{\perp} R_{\parallel} T_{\parallel})^{1/2}$.

From Eqns (2) and (11) we obtain

$$\frac{Q_{PI}}{Q_{MI}} \approx \frac{\epsilon_{MI}}{\epsilon_{RI}} \frac{S_{RI}}{S_{MI}} = \frac{\epsilon_{MI}}{\epsilon_{RI}} \frac{S_{RI}^m}{S_{MI}^m} \quad (12)$$

Values of Q_{PI}/Q_{MI} obtained from values of $\epsilon_{MI}/\epsilon_{RI}$ computed from the properties of mylar, and measured values of S_{RI}^m/S_{MI}^m were frequency dependent, being as low as 0.62 for some frequencies and having an average value of 0.94 over the spectral range of interest. We believe that this ratio could be made closer to unity by improving the precision of the roof mirror adjustments.

If we assume that the absorptions U_{PI} and U_{MI} in the beamsplitters are equal, we have sufficient information to express the measured ratio of instrumental efficiencies S_{PI}/S_{MI} in Eqn (6) in terms of the quantities T_P^3/T_M . In order to check the consistency of our analysis it is useful to divide Eqn (6) by T_M^2 so that it gives S_{PI}/S_{MI}^m in terms of $(T_P/T_M)^3$. The value of T_P/T_M which is deduced in this way from the measured ratio S_{PI}/S_{MI}^m is plotted as a dashed line in Fig. 2(c). The agreement between the two curves is quite good in view of the approximations we have made. This suggests that the main factors contributing to the decreased efficiency of the PI have been correctly identified.

7. CONCLUSIONS

It is clear from our analysis that the efficiency of the Martin-Puplett interferometer operated with our polarizers is not as large as could be hoped. Much of this loss comes from reflection losses at the two new surfaces (the input and output polarizers).

If the wires of a polarizer on a dielectric substrate are oriented so that the transmitted E-field is in the plane of incidence, then the polarizer transmittance will be a maximum at Brewster's angle. Measurements were made of this transmittance using polarized light over the broad

frequency band from 100 to 700 cm^{-1} . The average polarizer transmittance increased from 0.75 at normal incidence to a peak value of 0.86 at 60° . The transmittance of $4\text{ }\mu\text{m}$ mylar increased from 0.82 to 0.93. Both of these results lie significantly below the values of 0.85 and 1.00 for an ideal dielectric sheet $4\text{ }\mu\text{m}$ thick with index adjusted for a Brewster's angle of 60° . They do suggest, however, that an improvement in average efficiency of $\sim 32\%$ could be obtained by operating the input polarizer and beamsplitter at Brewster's angle. The optimum orientation of the output polarizer is $\sim 20^\circ$ from normal incidence, where the performance is not very different from that at our experimental angle of 45° . Other losses in our PI which could in principle be eliminated are up to 38% from misalignment and 10% from the output polarizer supports. A total improvement by a factor ~ 1.5 to 2.3 over this frequency range seems feasible with the present polarizers.

A total improvement by a factor 3.7 in the PI efficiency would have to be obtained before the PI would become as efficient as the MI over its entire spectral range. This does not seem possible with the present polarizers. Although for a given narrow frequency range the conventional Michelson interferometer with a suitable beamsplitter is more efficient, the large frequency range of the Martin-Puplett interferometer with the new polarizers plus its additional advantage of producing a zero baseline interferogram, make it an excellent choice for many applications.

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Fig. 1. Grid polarizer consisting of Cu lines on a mylar substrate.

Fig. 2. Polarizer properties: (a) transmittance of polarizer, (b) measured transmittance of 4 μm mylar (solid line) and calculated value neglecting absorption (dashed line), (c) ratio of measured transmittances of polarizer and 4 μm mylar (solid line) and calculated value from measurements of interferometer spectral outputs as described in the text (dashed line), and (d) measured transmittance of crossed polarizers. All measurements were made with unpolarized light. The spectra have not been plotted in the region of substantial mylar absorption between 360 and 520 cm^{-1} where their accuracy is poor.

Fig. 3. Spectral outputs of polarizing interferometer, and conventional Michelson interferometer with a 4 μm mylar beamsplitter. This gives directly the spectral distribution available for broad band Fourier spectroscopy. These spectra were measured with a Hg-arc source and a Golay detector with a diamond window and a 100 μm black polyethylene filter.

Fig. 4. Efficiency of a 4 μm mylar beamsplitter in a Michelson interferometer (ϵ_{MI}), and relative efficiencies $\epsilon_{\text{MI}} \left(\frac{S_{\text{PI}}}{S_{\text{MI}}} \right)$ of the polarizing and Michelson interferometers corrected for the beamsplitter efficiency ϵ_{MI} of the MI. This latter quantity would be a straight line at $\pi/8 = 0.39$ for an ideal PI and for an MI with either an ideal dielectric beamsplitter, or an ideal (50%) beamsplitter.

Figure 1

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Figure 2

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Figure 3

Figure 4

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