Infrared Transmission Polarizers by Photolithography

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The design of a grid polarizer is discussed and the effect of supporting it on various substrates is evaluated using a transmission line analogy. A method of making such a grid polarizer by photolithographic techniques is described, and measurements on a device suitable for use at wavelengths between 20 μ and several hundred microns are presented. Their performance compares favorably with polarizers made by other methods.

I. Introduction

The most popular polarizer at present used in the spectral range 10–200 μ consists of a pile-of-plates inclined at the Brewster angle. The material of the plates depends on its transmission at the wavelength of interest. Selenium, silicon, and polyethylene have commonly been employed.[1,2] The disadvantages of pile-of-plate devices, namely bulk and their limitation to working in parallel beams, have often been pointed out; several workers have made polarizers of the wire grid type.

Since before 1900 it has been known that a grid of parallel wires reflects one polarization of incident radiation while transmitting the other, provided that the wavelength of the radiation is larger than the period of the grid. A survey of the theory of grids and the experiments performed at radio and microwave frequencies has been written by Larsen[3]. Pursley[4] demonstrated that the performance of grids in the microwave region could be extrapolated to the ir if the geometry of the grid was reduced linearly with the wavelength.

Obviously, a grid of unsupported wires becomes difficult to construct and fragile to use at wavelengths less than 100 μ. Bird and Parrish[5] overcame this by supporting the grid on a plastic substrate. Their method was to make a plastic replica from an optical diffraction grating and to evaporate metal onto the tips of the groove faces. This was done by making the direction of evaporation oblique with respect to the plane of the replica.

Hass and O'Hara[6] used this method to prepare ir polarizers on substrates of polymethylmethacrylate and polyethylene plastics. The latter was preferred because it has fewer absorption bands between 7 μ and 14 μ, but it proved more difficult to form into a replica.

The research reported here was designed to discover whether the photolithographic techniques now widely used in the transistor and microcircuit industries could be used as a convenient alternative to the replica method. Such techniques could be used on substrate materials which cannot be formed into replicas or directly ruled into a suitable grating, e.g., germanium or silicon. Because the result of this method of fabrication is strips of metal, of known geometry on a plane base, the performance of these polarizers can be directly compared with theory. This has not been possible with earlier devices.

II. Theory

The grids made were assumed to consist of infinitely thin strips of metal of infinite conductivity at the boundary between air and a dielectric medium, transparent at the wavelengths used. We wish to calculate k_1 and k_2, which are defined as the transmittances of the polarizer for radiation with the electric field perpendicular to and parallel to the grid lines.

A. General Approach

Wait[7] has shown that, for normal incidence, a grid at the interface of two media can be represented by a shunt impedance at the junction of two transmission lines. This is shown schematically in Fig. 1.

For a nonconducting substrate, the characteristic impedance of its equivalent transmission line can be written as

$$Z_s = \frac{1}{n} Z_0, \tag{1}$$

where Z_0 is the impedance of free space and n is the refractive index of the substrate.

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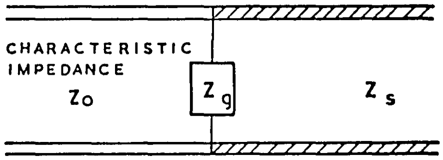

Fig. 1. Equivalent circuit of a grid on a substrate.

The equivalent impedance of a grid of high conductivity material is reactive; expressions for calculating its value have been given by Marcuvitz.[8] If the period of the grid is d and the width of each metal strip is a, for incident radiation with electric vector parallel to the strips,

$$Z_g = jX_g$$

and

$$\left(\frac{X_g}{Z_0}\right)_{\parallel} = \frac{d}{\lambda}\left[\ln\left(\csc\frac{\pi a}{2d}\right) + \frac{Q_2 \cos^4 \pi a/2d}{1 + Q_2 \sin^4 \pi a/2d} + \frac{1}{16}\left(\frac{d}{\lambda}\right)^2\left(1 - 3\sin^2\frac{\pi a}{2d}\right)^2 \cos^4\frac{\pi a}{2d}\right], \quad (2)$$

where

$$Q_2 = [1 - (d/\lambda)^2]^{-1/2} - 1. \quad (3)$$

For incident radiation with electric vector perpendicular to the strips

$$\left(\frac{Z_0}{X_g}\right)_{\perp} = \frac{4d}{\lambda}\left\{\ln\left[\csc\frac{\pi(d - a)}{2d}\right] + \frac{Q_2 \cos^4\pi(d - a)/2d}{1 + Q_2 \sin^4 [\pi(d - a)/2d]} + \frac{1}{16}\left(\frac{d}{\lambda}\right)^2\left[1 - 3\sin^2\frac{\pi(d - a)}{2d}\right]^2 \cos^4\frac{\pi(d - a)}{2d}\right\}, \quad (4)$$

where Q_2 is defined by Eq. (3). Marcuvitz claims that these equations are valid in the range $\lambda/d > 1$ with an error of less than 5% and in the range $\lambda/d > 2$ with an error of less than 1%.

From the transmission line analogy it can be shown that

$$k_1 = \frac{4n(X_g/Z_0)_{\perp}^2}{(1+ n)^2 (X_g/Z_0)_{\perp}^2 + 1} \quad (5)$$

and

$$k_2 = \frac{4n(X_g/Z_0)_{\parallel}^2}{(1 + n)^2 (X_g/Z_0)_{\parallel}^2 + 1}. \quad (6)$$

Here k_1 and k_2 are the transmittances of a grid on an interface. In any practical polarizer, the effect of the back surface of the substrate must be considered. (See Sec. II. E.)

B. Effect of a/d on the Performance of a Polarizer

The calculated variation of k_1, k_2 and degree of polarization P with the width of the metal strips is plotted in Fig. 2 for two values of λ/d. In any polarizer, both k_1 and P should be as large as possible, and inspection of the curves shows that any choice of a/d is a compromise. When $\lambda/d \approx 5$, a value of $a/d = 0.5$ would seem suitable, whereas at longer wavelengths variations of this parameter make little difference.

In order to give a useful wavelength range which is as wide as possible, all the fabricated devices were designed to have $a/d = 0.5$.

C. Effect of Substrate Refractive Index on the Performance of a Polarizer

From Eqs. (2) and (4) it can be seen that if $\lambda \gg d$, $(X_g/Z_0)_{\parallel}$ tends to zero while $(X_g/Z_0)_{\perp}$ tends to infinity Under these conditions, $k_1(n)/k_1(1) = 4n/(1 + n)^2$ and $k_2(n)/k_2(1) = n$. This means that supporting a grid on a substrate of refractive index n not only reduces transmission of the wanted polarization, as compared with an unsupported grid, but also increases the transmission of the unwanted polarization.

Curves for the transmission of grids on the surface of polyethylene and silicon together with curves for an unsupported grid are drawn in Fig. 3 to demonstrate this effect. They show that high refractive index materials such as semiconductors are unsuitable for use as substrates; polyethylene was chosen for the experimental polarizers. It has a low refractive index and negligible absorption bands at wavelengths greater than 14 μ and is also chemically inert. The last property makes it suitable for use in photoetching processes.

D. The Use of Blooming Layers

Using the transmission line analogy (Fig. 4), the following expressions were obtained for the transmissions of a grid on a bloomed substrate:

$$k_1 = \frac{4(X_g/Z_0)_{\perp}^2}{4(X_g/Z_0)_{\perp}^2 + 1},$$

$$k_2 = \frac{4(X_g/Z_0)_{\parallel}^2}{4(X_g/Z_0)_{\parallel}^2 + 1}.$$

These are identical to the equations for an unsupported grid. Thus, in laser applications, where operation at only a single wavelength is required, a bloomed semiconductor substrate might prove superior

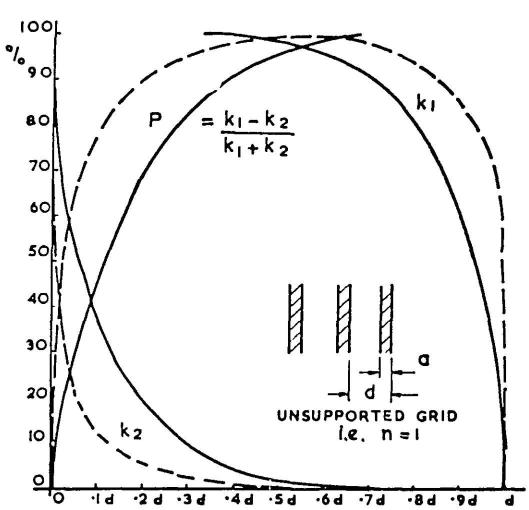

Fig. 2. Predicted variation of k_1, k_2, and P with a/d for λ/d = 5 (——) and λ/d = 10 (- - -).

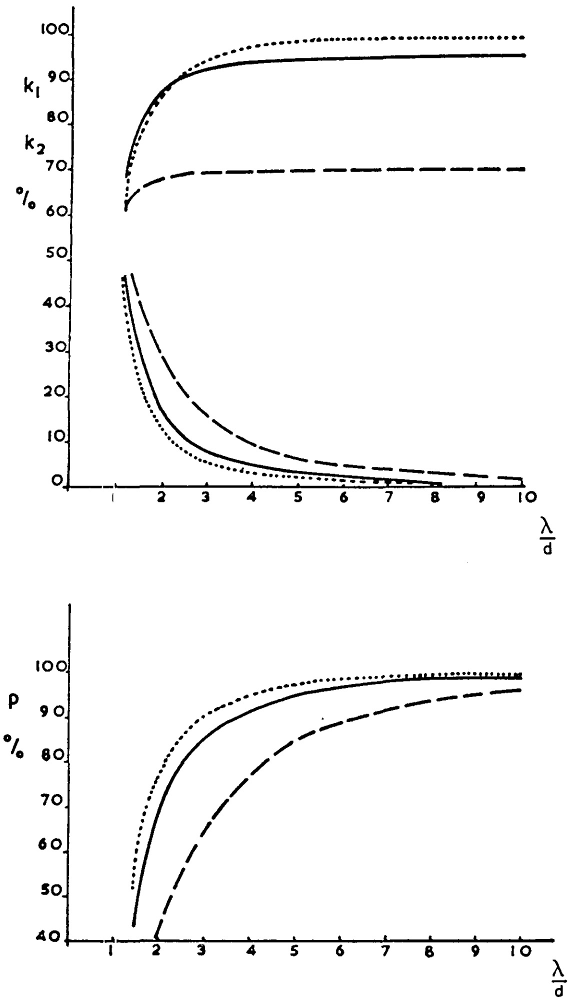

Fig. 3. Predicted variation of k_1, k_2, and P for polarizers with $d/a = 2$ ··· Unsupported grid ($n = 1.0$). —— Grid on polyethylene ($n = 1.5$). - - - Grid on silicon ($n = 3.4$).

to a simple plastic one. The same result is not obtained by putting the blooming layer over the grid. In this case the transmissions are

$$k_{1,2} = \frac{4n^2(X_g/Z_0)_{\perp,\parallel}{}^2}{4n^2(X_g/Z_0)_{\perp,\parallel}{}^2 + 1}.$$

When $\lambda \gg d$, k_1 approaches unity and k_2 approaches $n^2 \times$ (the value of k_2 for an unsupported grid). A device, made in this way is therefore inferior to one with the blooming layer between grid and substrate.

E. The Effect of the Back Surface of the Substrate

For cases in which the coherence length of the incident radiation is greater than the thickness of a plane parallel substrate, an equivalent transmission line can be considered. Analysis of this shows that k_1 and k_2 have a cyclic variation with λ. These variations are caused by interference between the various wavefronts; and as in any Fabry-Perot interferometer, transmission is a maximum if the separation of the reflecting surfaces is an integral number of half wavelengths. A grid on a substrate which fulfills this condition will transmit as if unsupported. This gives another possible method of designing a polarizer to work at a spot frequency.

The polyethylene substrate used in the construction of polarizers showed no interference effects when scanned in a spectrometer. Therefore, it was concluded that the treatment outlined in the previous paragraph was not applicable. In order to calculate the theoretical curves in Fig. 5, it was assumed that after multiple reflection the energies of the various beams could be added. It was also assumed that polyethylene was completely nonabsorbing throughout the wavelength range.

III. Fabrication

A. Mask Manufacture

The basic procedure was to draw the required pattern and successively reduce it to give an image on a high resolution photographic plate. This mask could then be used in a contact printing process. To give the necessary definition on lines only a few microns wide, the drawing must be done 500 times final size on a precision coordinate plotting machine. The limitations, imposed by the equipment, on the size of this drawing meant that after the reduction the pattern was $\sim$1 mm². Since this was not an adequate area for a polarizer, the mask was made up of a 20 × 20 array of these small squares. Provided that care is taken, a mask can be used to make many polarizers.

B. Fabrication of Polarizers

Disks of high density polyethylene were press-polished between optical flats to give substrates approximately 0.25 mm thick and 3 cm in diameter. Several substrates were placed in an evaporator and coated with aluminum on one side. Metal thicknesses between 0.2 μ and 1.0 μ were tried. Standard photoetching techniques were used to reproduce the mask pattern on the substrate.

By these means two sizes of grids were laid down, one having a period of 10 μ, the other of 4 μ. Figure 5 is a microscope photograph of a 4-μ grid. It shows 2-μ lines with good definition, and was taken so that the junction of four of the patterns forming the matrix can be seen. Provided that any discontinuities are small compared with the wavelength, they should have little effect. Flaws in the pattern were caused by scratches on the

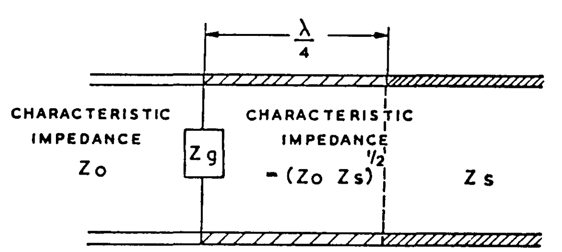

Fig. 4. Equivalent circuit of a grid on a bloomed substrate.

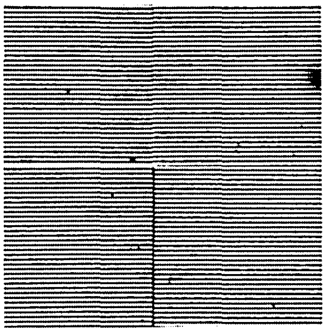

Fig. 5. A typical 4-μ period polarizer.

substrate and by dust: these grids were not made under dust-free conditions.

Although the strip width was made half the period on the original drawing, this did not necessarily ensure that $a/d = 0.5$ on the polarizer because the length of exposure time in both the microphotography and the photolithography affected not only definition but also the width of metal on the final grid. Undercutting during etching gave a tapered profile to the edge of the strips, but this was only noticeable under a microscope on the thicker aluminum films. When the photolithographic exposure time was optimized for best definition, the masks used gave an average value of $a/d \approx 0.5$ for a 4-μ period grid and $a/d \approx 0.42$ for the 10-μ grid. These values were obtained by measurements made on enlargements of photographs taken through a microscope.

IV. Measurements

A. Method of Evaluation

Measurements were made at wavelengths between 20 μ and 120 μ, using a Beckman spectrophotometer and a large Czerny-Turner spectrometer which has been briefly described by Harding *et al.*[9] Because no perfect polarizer is available to enable one to measure k_1 and k_2 directly, gratings were tested in pairs using the method given by Rupprecht *et al.*[10] This method assumes that an identical pair of polarizers is available and allows for the partial polarization of any spectrometer beam. The assumption can be tested during the measurement procedure.

The following measurements were made: (1) E_0 = total power transmitted by system with no polarizers in the beam; (2) E_H = power transmitted by a single polarizer with its grid lines horizontal; (3) E_V = power transmitted by a single polarizer with its grid line vertical; (4) $E_\perp$ = power transmitted by a pair of polarizers with grids crossed.

From these measurements k_1 and k_2 can be calculated:

$$k_1 = \frac{E_H + E_V}{2E_0}\left\{1 + \left[1 - \frac{4E_\perp E_0}{(E_H + E_V)^2}\right]^{1/2}\right\},$$

$$k_2 = \frac{E_H + E_V}{2E_0}\left\{1 - \left[1 - \frac{4E_\perp E_0}{(E_H + E_V)^2}\right]^{1/2}\right\}.$$

Table I. Transmittance of 4-μ Period Grid Polarizers

λ (μ)	k_1 (%)	k_2 (%)	P (%)	Theoretical k_2 (%)
16	63	3.5	89.5	—
20	72	2.5	93.3	2.85
40	82	1.0	97.5	0.71
>72	>84	<0.5	>98.8	<0.22

The degree of polarization was defined as $P = (k_1 - k_2)/(k_1 + k_2)$. This definition is widely used but is not the one given by Rupprecht *et al.*[11]

B. Results

Measurements made on a typical 10-μ period grid are given in Fig. 6 together with theoretical curves obtained from Eqs. (2)–(6). In the wavelength range shown, the predicted values of k_2 are critically dependent on the ratio a/d. Since this parameter varies by up to 10% over the grid pattern, the experimental points are within the bounds of accuracy for the predicted values.

Measured values of k_1 are lower than expected, but some of this discrepancy can be accounted for by absorption in the polyethylene. Measured values of transmittance of a substrate without a grid are also marked in Fig. 6.

Some measurements made on 4-μ grids are listed in Table I. Because of the absorption band in polyethylene centered at 14 μ, measurements not seriously

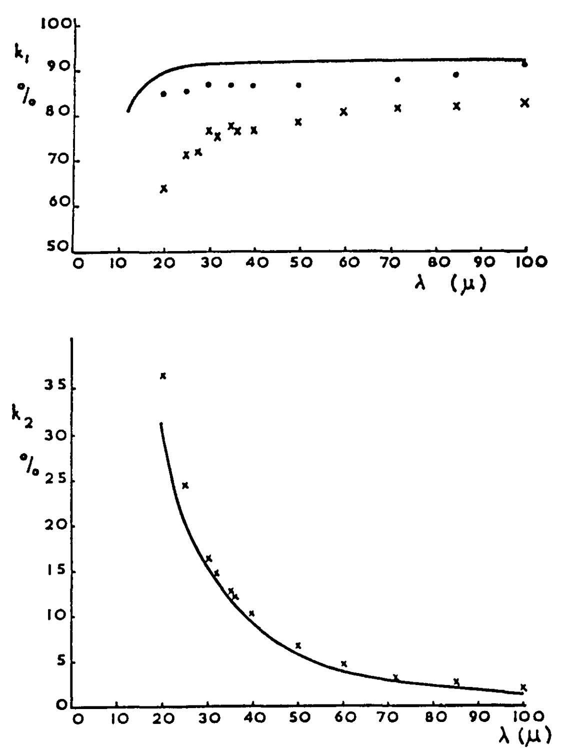

Fig. 6. Transmission of a polarizer on a polyethylene substrate, $a = 4.2\ \mu$, $d = 10\ \mu$. —— Theoretical values assuming negligible absorption in polyethylene. × Measured values. • Measured values of transmission of polyethylene substrate (no grid).

affected by absorption cannot be made at wavelengths less than 18 μ. At wavelengths greater than 24 μ the value of $E_\perp$ was too small to be measured with any accuracy, and it is estimated that the errors in k_2 could be 25% of k_2 at 24 μ. As the value of $E_\perp$ decreases, the values of k_2 calculated could be even more inaccurate.

Neither the 4-μ nor the 10-μ period grids showed any significant change in performance when the thickness of the grid lines was changed. Presumably this was because even the thinnest aluminum films used had a thickness of 0.2 μ, which is almost an order of magnitude greater than the skin depth at the longest wavelength at which measurements were made.

V. Conclusions

The procedure for predicting the performance of grid polarizers using a transmission line analogy appears to be satisfactory and provides a useful guide in choosing substrate materials for future polarizers.

At wavelengths greater than about 24 μ the 4-μ period grids gave transmittances similar to those quoted by Hass *et al.*[6] for their grids made by the grating techniques. Thus, in this region of the ir spectrum, photolithography gives an alternative approach to the production of polarizers. The two methods are complementary, some substrate materials being more suited to one than the other.

Present photolithographic techniques can produce lines as thin as 1 μ in the manner outlined in Sec. III. Thus, the lower wavelength can be extended to below 10 μ. More sophisticated techniques now being developed promise to give still finer grids.

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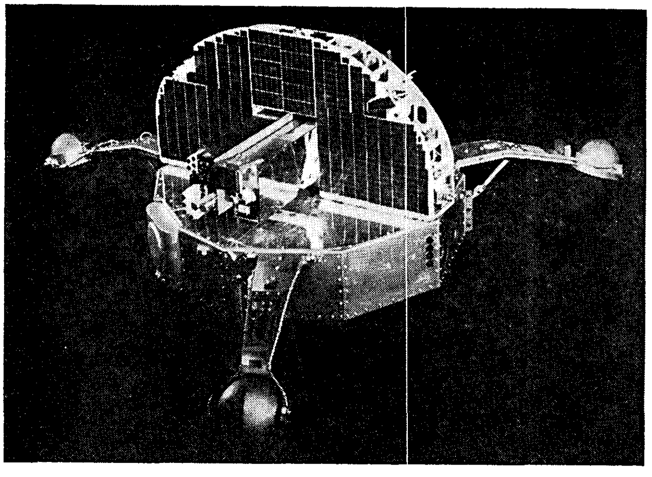

On NASA's satellite OSO III, launched 8 March from Cape Kennedy, solar cell arrays made by Spectrolab, Sylmar, Calif., convert sun's energy into the sole power source (about 40 W) for operating all electrical equipment. The new Orbiting Solar Observatory is performing series of far-reaching scientific experiments to gather data covering a broad spectral range of solar radiation.

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