A New Type of Beam Splitting Polarizer Cube

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ABSTRACT

Beam splitting polarizer cubes consisting of two right angle prisms cemented together after one hypotenuse is coated have become important optical components in many optical systems. Usually the coating stack is of the MacNeille design. We present and compare an alternative coating structure consisting of a very fine wire grid structure on the cube hypotenuse that has performance advantages of improved polarization purity over an extended range of wavelengths and angles. Modern lithography permits wire spacings and dimensions that are small enough for good polarizer performance at visible wavelengths as well as near infrared wavelengths.

Keywords: Beam splitter, polarizer, polarization, wire grid

1. INTRODUCTION

Ideal polarizers provide excellent polarization over a wide range of wavelengths and angles of incidence. These properties are especially important if the polarizers are for display or other imaging applications. Sheet-type dichroic polarizers perform well in these ways[1] but have a relatively low damage threshold because they absorb light of the rejected polarization. They are therefore often unsuitable for high light flux applications such as LCD video projectors or laser systems. Beam splitting polarizers have a much higher damage threshold because the rejected light is reflected out of the system rather than absorbed by the optic.

2. MACNEILLE CUBE

The most convenient beam splitting polarizers reflect the rejected light at 90° relative to the incident direction and MacNeille cubes are the most commonly used type. A MacNeille cube consists of 2 right angle prisms joined along their large faces to form a cube (Figure 1). A thin film stack of alternating high and low index materials on one of these large faces polarizes the incident light reflecting “s” polarized light and transmitting “p” polarized light. These polarizers use no calcite or other expensive material and are manufactured in volume at a reasonable cost. This industry standard polarizer has numerous variants but generally they share the problems of limited achromaticity and strong sensitivity to angular field of view. The wire grid beam splitting polarizer we have investigated here does well against these criteria and it has a high flux tolerance. Furthermore, wire grid polarizer designs lend themselves well to volume manufacturing at costs comparable to the MacNeille cubes.

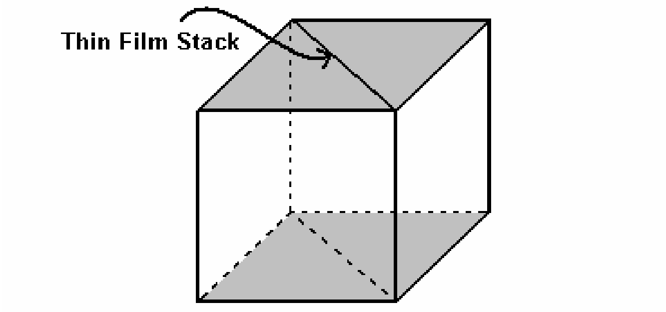
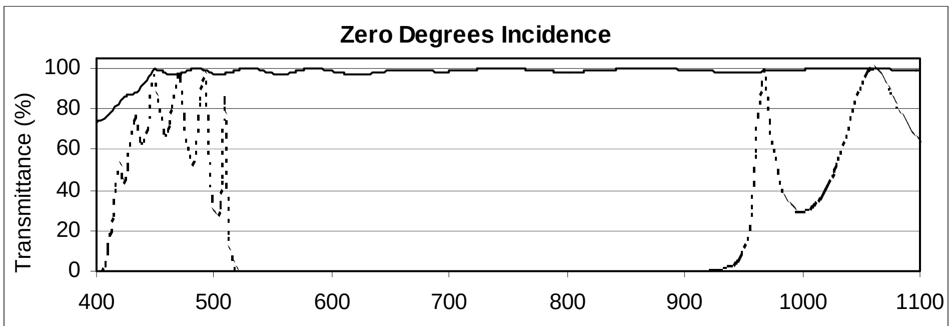
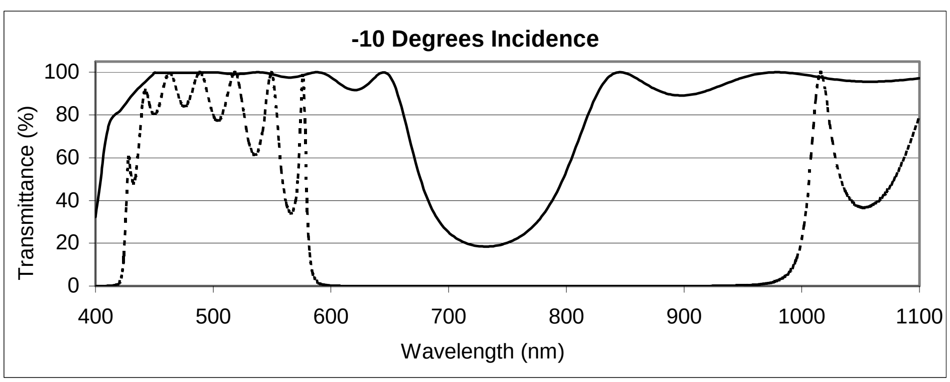


Figure 1: MacNeille beam splitting polarizer.

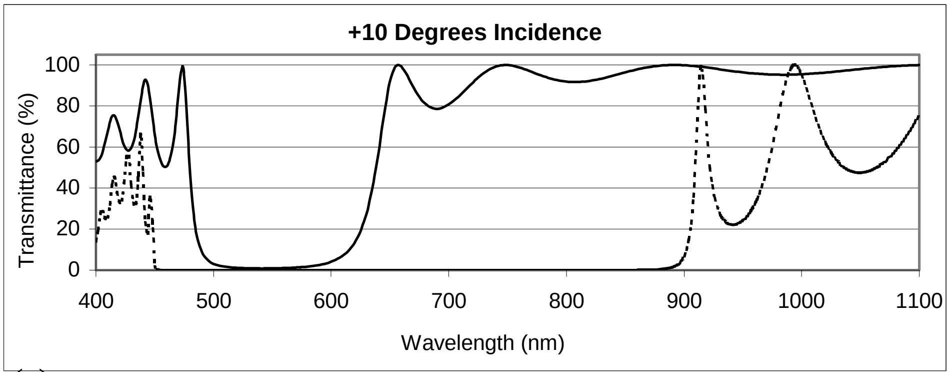
Figure 2 shows our computation of MacNeille cube transmission of "s" and "p" polarization states as a function of wavelength for a common 16 layer design. Notice that the transmission of "p" polarized light is not 100% even for normal incidence on the cube, Figure 2(a). Since almost no light is absorbed in the cube, there is a substantial contamination of as much as 5% of the "p" polarized light in the reflected "s" polarized beam. This limits the polarization purity of this reflected beam such that it has a contrast ratio of about 20:1 measured against a "perfect" polarizer. Contamination of the reflected beam increases dramatically for rays incident off-normal as shown in Figures 2(b) and 2(c). These angular effects add color shifts to the transmitted and reflected beams because of their wavelength dependence. This is particularly troublesome for color displays. Also, the "s" and "p" polarization directions rotate with the plane of incidence for skew rays as others have noted[2,3]. Skew rays experience a relative phase shift for "s" and "p" polarized light which causes a small degree of ellipticity in the output beams as well[3]. These effects limit the angular range (or f no. in imaging systems) over which the MacNeille polarizer can be used.



(a)



(b)



(c)

- - - “s” Polarization —— “p” Polarization

Figure 2: Performance of a MacNeille Polarizer.

\Special retarder plates added to the output face of a MacNeille polarizer can dramatically improve the purity of polarization for skew rays in a fast beam transmitted through the cube[4]. These retarders correct only for the geometric effects resulting from rotation of the plane of incidence for skew rays. In theory the correction is from 0.8% leak for an f/2.0 beam to less than 0.1% leak for a 200nm bandwidth, for example.

3. WIRE GRID POLARIZERS

3.1 General Description

Wire grid polarizers consist of a series of fine parallel metallic lines usually coated on glass or another transparent substrate (Figure 3). The “wires” are usually spaced apart by approximately the same distance as the width of the “wires”. These wire arrays polarize efficiently when the dimensions of the wires and spacings are small compared to the wavelength of the incident light. Light polarized parallel to the wires “sees” a metal surface and the light is reflected. Light polarized perpendicular to the wires “sees” a dielectric surface and is largely transmitted. The theory and resulting performance equations have been worked out in a number of papers listed by Bennett and Bennett[5]. The most important parameters are line width and spacing (less is better), n and k for the metal in the wires, the wavelength of the light and the index of refraction of the substrate and the material between the wires (usually air). Aluminum and gold are the most commonly used wire metals.

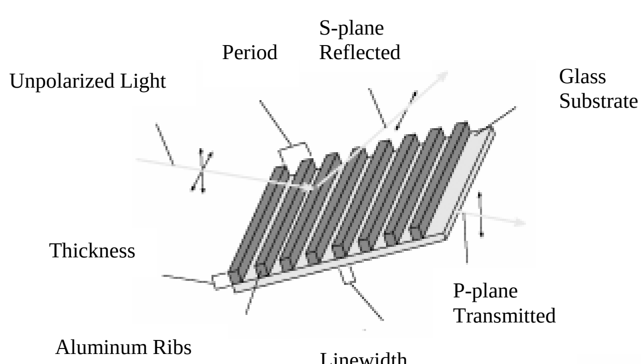


Figure 3: Wire Grid Polarizer

Moxtek, Inc. recently introduced the first wire grid polarizers for broadband visible light[6]. They have achieved wire grid dimensions of less than 100nm. Generally, if the wire grid period is less than half the wavelength of the incident light, the grid acts as a linear polarizer and if the period is longer than twice the wavelength of the incident light it acts as a diffraction grating. The region from half to twice the wavelength of incident light shows abrupt reductions at certain wavelengths or angles of incidence θ in the transmission for light polarized orthogonal to the wires. The longest wavelength λ_{max} for which these Rayleigh resonances or Wood's anomalies occur is given by equation (1)[7].

$$\lambda_{max} = p(n+\sin\theta) \qquad (1)$$

where p = grating period
n = index of refraction of the medium surrounding the grating

This longest wavelength resonance λ_{max} must be kept shorter than the shortest intended wavelength of use for a broadband linear polarizer.

3.2 Structure of the New Polarizer

We built and tested a beam splitting polarizer consisting of a VersaLight wire grid made by Moxtek, Inc. on a substrate of Corning type 1737F glass cemented between the large faces of two one inch BK7 right angle prisms to form a cube (Figure 4). The adhesive for the test polarizer is Norland 61 which has an index of refraction of 1.56 for visible wavelengths slightly higher than BK7 and 1737F, both of which have an index of refraction of approximately 1.52.

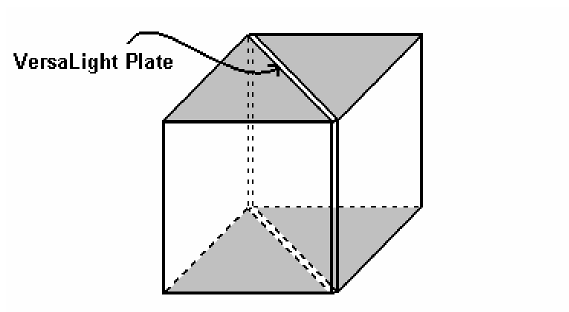


Figure 4: New beam splitting polarizer with an embedded VersaLight wire grid.

Notice that embedding the wire grid in a cube has the undesirable consequence of shifting the resonance wavelength toward longer wavelengths by equation (1) both because the angle of incidence is increased to 45° and because the average index of the medium surrounding the wires is increased by the adhesive. This limits the shortest useful wavelength to the mid-visible region.

4. OTHER BEAM SPLITTING POLARIZERS

4.1 3M PBS

3M has developed another beam splitting polarizer that achieves improvements over the MacNeille polarizer[3,8]. The beam splitting surface in the cube contains hundreds of layers of birefringent polymers. There are 2 alternating polymers in these stacks. For light of one polarization the indices of refraction match for the two materials and there is no reflection loss at the interface. In the orthogonal direction there is a mismatch in the indices and part of the light polarized along this orthogonal direction is reflected. This reflection is enhanced if the polymer layers have a quarter wave optical thickness as in the structures commonly used in dielectric mirrors and MacNeille polarizers.

These multilayer polymer films have a physical polarization transmission axis just as in a dichroic polarizer film. Consequently, the transmission axis is fixed to the film and does not rotate with the plane of incidence as it does for the MacNeille polarizer. Reported test results give a photopic contrast ratio in an f/2 beam greater than 1000:1 in double pass[3]. (Input and output beams are at 90° with input beam reflected off a mirror preceded by a quarter wave retarder.) The transmission of p polarized light "exceeds 92% across most of the visible". One drawback of the 3M polarizer is that the polymer film is not flat and this degrades the reflected image. The transmitted wavefront distortion is reported to be less than two waves because of index matching.

4.2 FTIR Thin Film Beam Splitting Polarizer

A new polarizer has been proposed and built by Li and Dobrowolski[9] that uses frustrated total internal reflection in thin film structures. It has a wider angular field (±15.8° for one design) than the MacNeille polarizer but not as wide as the VersaLight cube. It has a wavelength range, for this design, of at least 400nm to 800nm. This type of polarizer exhibits inherently low absorption but requires a high index prism substrate (n=1.85 for the design discussed here). Also, the prisms required are quite bulky since the angle of incidence on the 53 layer thin film stack is quite oblique, centered at 71.5°.

5. PERFORMANCE OF A VERSALIGHT BEAM SPLITTING POLARIZER

The performance of the VersaLight polarizer was measured in a collimated beam of white light from an incandescent filament source. Interference filters limited the wavelength range to approximately 10nm, full width at half maximum. Flux measurements were made using a silicon photodiode detector (450nm, 649nm and 1009nm) and an indium gallium arsenide detector (1550nm). The contrast ratio was measured with a Glan-Thompson polarizer following the cube polarizer. No correction is made in the data in Table 1 for the slightly imperfect performance of this Glan-Thompson polarizer since its contrast ratio exceeds 10^5 over the wavelength range tested. Thus, the contrast ratio as defined here is the ratio of k_1 to k_2, the major and minor principal transmittances, following the notation of Shurcliff[10]. That is, the contrast ratio defined here is measured against a perfectly linearly polarized beam.

θ	450nm	649nm	1009nm	1550nm
-30°	29	490	1,000	4,100
-20°	29	570	1,100	2,000
-10°	29	580	1,400	4,000
0°	36	680	2,000	8,300
+10°	39	790	1,400	18,000
+20°	36	760	1,300	20,000
+30°	43	760	3,200	67,000
0° Plate	390	1,300	1,300	3,700

Table 1: Contrast ratio of a "p" polarized transmitted beam for a VersaLight beam splitting polarizer cube.

In Table 1, θ is the external angle of incidence on the VersaLight cube. A positive angle indicates an increasing angle of incidence on the wire grid surface along the hypotenuse of the right angle prisms comprising the cube. For reference, the performance of the VersaLight wire grid in air at normal incidence is shown on the last line. The contrast ratio is for the transmitted beam only. The "wires" are oriented vertically, i.e., perpendicular to the triangular (unpolished) faces of the prisms. Consequently, the polarizer transmits "p" polarized light and reflects "s" polarized light. The contrast ratio improves with increasing wavelength as expected and it generally increases with increasing angle of incidence on the beam splitting surface. The polarizer shows a very large wavelength range of performance in the transmitted beam. In practice MacNeille polarizers show a contrast ratio of about 1000 for the transmitted beam. Thus the performance of this new polarizer is competitive with that of the MacNeille polarizer from a wavelength of about 700nm to at least 1550nm.

The contrast ratio is lower in the reflected, "s" polarized beam and is not measured extensively for this study. Table 2 lists this parameter for wavelengths of 649nm and 1009nm. The reflected beam contrast ratio is comparable to that for a MacNeille polarizer on axis.

	Contrast Ratio	
θ	649nm	1009nm
-30°	120	29
-20°	67	68
-10°	36	340
0°	18	78
+10°	11	17
+20°	6	6
+30°	4	3

Table 2: Contrast ratio of an "s" polarized reflected beam for a wavelength of 649nm.

The VersaLight polarizer has a principal transmittance azimuthal orientation that is fixed by the orientation of the wires. The orientation is not tied to the plane of incidence as with the MacNeille polarizer and thus does not rotate with the plane of incidence for skew rays. In fact, it is possible to orient the "wires" so that "s" polarized light is transmitted by the cube and "p" polarized light is reflected. A VersaLight cube built with the "wires" oriented horizontally has a measured contrast ratio of 865 on the "s" polarized transmitted beam at wavelength of 649nm and at zero degrees incidence on the cube. The reflected "p" polarized beam has a contrast ratio of 12 at 649nm. Other orientations are possible such as ±45° to the cube edges for example.

Figure 5 shows the maximum transmission k_1 of typical VersaLight plate before lamination between prisms. This transmission is less than 100% because of:

1. Absorption in the aluminum "wires";
2. Reflection of a small amount of the light of polarization that should be passed, and;
3. Reflection from the uncoated back surface of the plate.

The back surface loss is removed by index matching when the plate is cemented to the prisms but the other 2 loss mechanisms remain. At a wavelength of 649nm k_1 is .82 for a wire grid oriented to transmit "p" polarized light. Since the contrast ratio in the reflected beam is 18 for the "s" polarized reflected beam (Table 2) , we may conclude that about 5% of the "p" polarized light is reflected. Then approximately 13% of the "p" polarized is absorbed assuming no scatter losses. Similarly, we measure that 81% of "s" polarized light is reflected and since almost no "s" polarized light is transmitted, the remaining 19% is presumably absorbed.

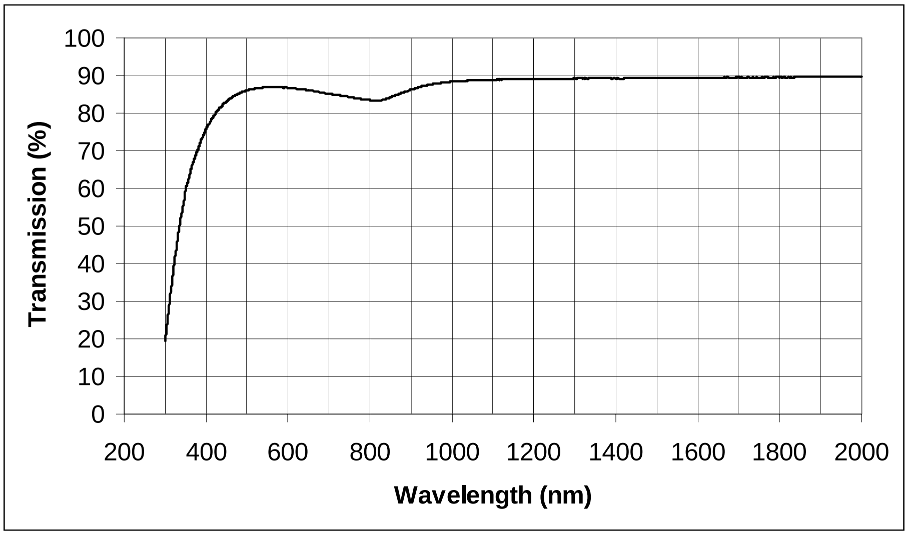


Figure 5: Transmission of polarized light through an optimally oriented VersaLight plate at 0°.

6. CONCLUSIONS

The new VersaLight beam splitting polarizer provides polarization purities similar to those of the MacNeille Polarizers for wavelengths longer than about 700nm. This performance extends out to a wavelength of at least 1550nm as compared to about 1200nm for a MacNeille polarizer designed for a lower wavelength limit of 700nm. Also, this new polarizer performs well in the transmitted beam over a much larger range of angles, at least ± 30° in air.

The polarization directions selected in the new cube are set by the orientation of the “wire” on the grid and not by the orientation of the plane of incidence. Consequently there is no rotation of the plane of polarization for skew rays when the polarizer is used in an imaging system and the polarizer can split along any orthogonal directions designated by the wire grid direction.

The new polarizer absorbs 10% to 20% of the incident light at the wavelength tested (649nm). This is a limitation for applications where light efficiency is important.

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