

NST Polarization Calibration Optics

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Abstract: The NST polarization calibration unit has to be one of the first optical elements in the light path. The first feasible position is right in front of the flat folding mirror $M3$. This location is shared with the wave front sensor of the active optics system. In this Technical Note, we describe the possible solutions for large-format linear polarizers and retarders. None of these optical elements can satisfy all requirements for the polarization optics and neither of them is available off-the-shelf. Therefore, we only list their positive and negative features and defer the final decision for the time being.

A. Introduction

The f -number of the light beam in front of the flat folding mirror $M3$ is 52. The beam diameter is between 100 and 150 mm. The solar constant is about 1.37 kW m^{-2} , i.e., the total solar energy for a 1.6 m mirror is about 2750 W. Since we only use a $180''$ FOV, the total energy encircled by the beam is about 25 W corresponding to an energy density of 0.3 W cm^{-2} . The following issues should be considered in the selection of polarizers and retarders:

- large-format of 100 to 150 mm,
- wide angle of acceptance,
- transmission efficiency,
- extinction ratio (goal should be 10^{-4}),
- optical quality such as surface flatness and roughness,
- energy damage threshold,
- aging (e.g., UV sensitivity “bleaching”)
- and feasibility and cost.

B. Wire Grid Polarizer

Wire grid spacings of up to $2400 \text{ grooves mm}^{-1}$ are available. Holographic methods are used to create grooves at sub-micron spacings. Typical materials for the use in the infrared include BaF_2 , KRS-5, CaF_2 and ZnSe , which cover the wavelength range from 200 nm to $30 \mu\text{m}$. Wire grid polarizers transmit radiation when the E -vector is perpendicular to the wire while the E -vector parallel to the wire is reflected. Due to surface reflections, the reflected beam contains both polarizations. The extinction ratio of a polarizer is a measure of the ability of the polarizer to attenuate plane-polarized light. The extinction ratio can

be calculated by measuring the the ratio of the maximum transmission τ_{\max} when the polarizer is aligned to the polarization axis and the minimum transmission τ_{\min} when the polarizer is rotated 90° . This ratio $\varepsilon = \tau_{\max}/\tau_{\min}$ is typically in the order of 1:100 or 1:300. However, wire grid polarizers can be used in parallel to improve the extinction ratio (den Boer et al. 1995). The overall extinction ratio is the product of the extinction ratios of the individual polarizers. ScienceTech builds large-format (125 mm diameter) wire grid polarizers for the far infrared. The price of these type of polarizers could be as much as \$10,000. The minimum wavelength of a wire grid polarizer is about four times the line spacing, i.e., if the polarizer should work at 500 nm, a 125 nm spacing would be required corresponding to 8000 grooves mm^{-1} . These polarizers will also work at longer wavelength, i.e., we would only need one linear polarizer for both the visible and the near infrared wavelength region. Typical transmittance values are about 80% or lower so that low light levels of about 50% have to be expected for tandem wire grid polarizers.

The following description of tandem wire grid polarizers is a (verbatim) summary of den Boer et al. (1995). Wire grid polarizers belong to the class of dichroic beamsplitters and have a large acceptance angle. However, their attenuation coefficient α is usually small in the infrared ($10^{-2} < \alpha < 10^{-1}$). A wire grid polarizer generally consists of a substrate that is transparent over a large wavelength range, covered with a grid of evenly spaced conducting wires. For wavelength larger than the wire spacing the component of the incident light parallel to the wires is strongly absorbed, whereas the perpendicular component passes unaffected. When the wavelength decreases to the order of the wire spacing, a substantial part of the parallel component is able to pass without being absorbed. In this case, the polarizer may be regarded as a partial polarizer with an attenuation coefficient α that reflects the quality of the polarizer. In the Mueller formalism, the partial polarizer is described by a matrix

$$\frac{1}{2} \begin{bmatrix} 1 + \alpha & 1 - \alpha & 0 & 0 \\ 1 - \alpha & 1 + \alpha & 0 & 0 \\ 0 & 0 & 2\sqrt{\alpha} & 0 \\ 0 & 0 & 0 & 2\sqrt{\alpha} \end{bmatrix}. \quad (1)$$

The attenuation coefficient α is defined as the ratio of minimum and maximum transmittance. Thus, $\alpha = 0$ and $\alpha = 1$ describe a perfect polarizer and a non-polarizing component, respectively. The extinction ratio ε is related to the attenuation coefficient by

$$\varepsilon = \frac{1}{2\alpha} \quad \text{with} \quad \alpha \ll 1. \quad (2)$$

In wire grid polarizers, the grid introduces a phase difference between the transmitted and attenuated components. To account for the phase difference, we multiply matrix 1 by a Mueller matrix for a retarding component with a retardation δ and with the fast axis parallel to the transmission axis of the polarizer. Multiplication leads to the matrix

$$\frac{1}{2} \begin{bmatrix} 1 + \alpha & 1 - \alpha & 0 & 0 \\ 1 - \alpha & 1 + \alpha & 0 & 0 \\ 0 & 0 & 2\sqrt{\alpha} \cos(\delta) & 2\sqrt{\alpha} \sin(\delta) \\ 0 & 0 & -2\sqrt{\alpha} \sin(\delta) & 2\sqrt{\alpha} \cos(\delta) \end{bmatrix}. \quad (3)$$

The attenuated component lags the transmitted component typically by 90° . The exact value of the phase difference depends on the the ratio of the wire thickness to the wire spacing and on the wavelength of the incident light, but is within 10% of this value in any usable region of the spectrum.

To improve the performance of wire grids, two such polarizers can be used in tandem. Mathematically this means that we multiply two matrices of the kind of matrix 3. If we assume that the transmission axes are parallel, it is not necessary to rotate the coordinate basis of either of the polarizers. Multiplication then

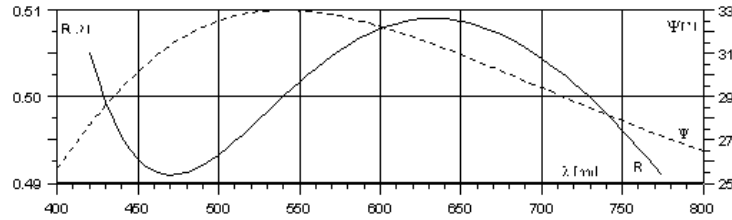


Figure 1: Retardation R and axis orientation Ψ as a function of wavelength λ . (Bernhard Halle)

yields

$$\frac{1}{2} \begin{bmatrix} 1 + \alpha^2 & 1 - \alpha^2 & 0 & 0 \\ 1 - \alpha^2 & 1 + \alpha^2 & 0 & 0 \\ 0 & 0 & 2\alpha \cos(2\delta) & 2\alpha \sin(2\delta) \\ 0 & 0 & -2\alpha \sin(2\delta) & 2\alpha \cos(2\delta) \end{bmatrix}. \quad (4)$$

Comparison of matrix 3 with matrix 4 shows that the single polarizer and the tandem polarizer are similar in appearance except for the attenuation coefficient α and the retardation δ . α appears to be squared, whereas δ is doubled. Thus, the quality of the polarizer appears to have improved quadratically, e.g., two polarizers with an attenuation coefficient of 0.01 will make a tandem polarizer with an attenuation coefficient of 0.0001. The attenuation coefficient is only in second order dependent on the alignment error, whereas the transmission error is relatively insensitive to changes in the alignment

C. Mica Retarder

When any form of polarized light is incident on a birefringent waveplate, it is resolved into two linearly polarized components which vibrate perpendicular to each other and travel with different velocities in the crystal. This phase delay or retardation is dependent on the birefringence of the crystal. Birefringence at a specific wavelength is the difference in refractive index of the extraordinary and ordinary resolved components. Because of the dispersion of the birefringence, i.e., its dependence on the wavelength, there is a variation of retardation with wavelength. Quarter wave mica waveplates are available as thin cleaved zero order retarder at a specified wavelength between 450 and 1600 nm cemented between BK7 glass plates or as bare mica. Mica is a bi-axial, optically inactive crystal which has about 3% to 5% absorption in the visible region of the spectrum. Commercially available size are only 25 mm. However, Bernhard Halle indicated that they manufactured retarders of up to 100 mm diameter. Larger formats might require new tool and machines for the optical manufacturers, which might result in a prohibitive price. Achromatic mica retarders can be manufactured by cementing three mica plates between plane parallel plates of crown glass BK7. The optical quality of the outer surfaces can be as good as $\lambda/10$. In the wavelength region from 430 to 680 nm, the accuracy of the path difference for a $\lambda/4$ waveplate is about $\pm 3\%$. The outer surface can also be multilayer anti-reflective coated. Due to the considerable absorption of mica, the transmission of the achromatic plates can be reduced to as little as 50% at 500 nm.

D. Polaroid Films

Dichroic sheet polarizers are constructed by laminating a thin, stretched, and dyed polymer film between two polished and anti-reflection coated glass windows. The resulting compact component offers excellent value but is limited to flux densities below 1 W cm^{-2} , which is very close to the energy density encountered just before $M3$. In addition, UV bleaching might contribute to aging of the polarizer and change its performance with time. This might add too much complexity to the overall calibration procedure.

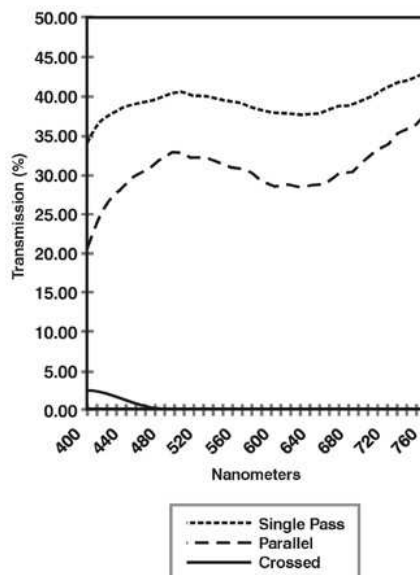


Figure 2: Spectral transmission data for the HN38 thin film polarizer. (American Polarizers, Inc.)

API manufactures a variety of thin film polarizers, which have been used in the Advanced Stokes Polarimeter (ASP) and other polarimeters. A typical product is HN38, a 38% transmission, neutral density linear polarizer. Description: A linear polarizing Polyvinyl Alcohol-Iodine filter that polarizes in the visible light spectrum. The visible light transmission is 38% transmittance of 0.38%. A key characteristic of this polarizer is its lack of color distortion. Optical density is measured using a beam of 100% linearly polarized light. Polarizers are available in 0.006", 0.010" and 0.030" thicknesses. The 0.010" thick material can be laminated to acrylic to increase thickness and durability. Applications: Camera filters, polariscopes, studio light filters, polarized light experiments, etc. The thin film polarizers are produced as 19" × 50" sheets. Wave retarders and infrared polarizers are also available.

BK7 is a borosilicate crown optical glass with high homogeneity and low bubble and inclusion content. Its good physical and chemical properties make it widely used in visible NIR windows, lenses and prisms. BK7 glass might be unsuitable for the enclosure thin film polarizers, since they have a relatively high index of birefringence (> 10 nm/cm).

Fused silica is an amorphous form of silicon dioxide glass and is readily available in a variety of grades and material classes with high transmittance as low as 193 nm. VUV grade calcium fluoride (CaF_2) transmits from 157 nm to about 8 μm in the IR spectral region so is a good choice for either IR or deep UV applications. The birefringence can be (< 1 nm/cm).

Check the available list of glass materials for materials with low index of birefringence and low transmittance in the UV to avoid bleaching of the Polaroids.

E. Manufacturers

- **API American Polarizers, Inc.**
41 South Seventh Street
Reading, PA 19602
Phone: (800) 736-9031 or (610) 373-5177
Fax: (610) 373-2229

E-Mail: sales@apioptics.com WWW: <http://www.apioptics.com/>

- **Bernhard Halle Nachf. GmbH**

Hubertusstrasse 10
D-12163 Berlin, Germany
Phone: 011-49-30-7974296-0
Fax: 011-49-30-7918527
E-Mail: bhn@b-halle.de
WWW: www.b-halle.de
Contact: Dr. Göt Zinner goetz.zinner@b-halle.de

Products: Laser optics, mechanics, mirrors, objectives, plates, polarizers, prisms, retarders (up to 100 mm, larger optics requires new equipment), special constructions

- **Carl Lambrecht Corporation**

4204 N. Lincoln Ave.
Chicago, IL 60618
Phone: (773) 472-5442
Fax: (773) 472-2724
E-Mail: sales@klccgo.com
WWW: www.klccgo.com

Products: crystal polarizers, retardation devices, thin film polarizers, anti-reflection coatings

- **CVI Laser**

200 Dorado Place SE
Albuquerque, NM 87123
Phone: (800) 296-9541
Fax: (505) 298-9908
WWW: www.cvilaser.com

Products: laser mirrors, ultra-fast laser mirrors, output couplers, optical windows, etalons, optical isolators, beamsplitters, beam expanders, lenses, prisms, polarizers, waveplates, optical mounts, optical filters, up to 75 mm diameter mica retarders

- **Meadowlark Optics**

5964 Iris Parkway
Frederick, CO 80530
Phone: (303) 833-4333
Fax: (303) 833-4335
E-Mail: sales@meadowlark.com
WWW: www.meadowlark.com

Products: polarizers, retarders, liquid crystal optics, wire-grid polarizers, custom orders, expensive

- **Melles Griot - Optics Group**

55 Science Parkway
Rochester, New York 14620
Phone: (800) 775-7558 or (585) 244-7220
Fax: (585) 244-6292
WWW: www.mellesgriot.com
Contact: Reda Benhouhou

Products: optics and opto-mechanics, plate polarizers of up to 75 mm diameter, mica wave plates of up to 50 mm, interested in custom designs for larger diameters

- **MOXTEK, Inc.** 452 West 1260 North Orem, UT 84057 Phone: (801) 225-0930 Fax: (801) 221-1121
WWW: www.profluxpolarizer.com

Products: ProFlux micro wire-grid polarizers suitable for 400 nm and larger, sizes up to 75 mm, however the wavers are up to 6"

- **Nu-Tek Precision Optical Corporation**

1202 Technology Drive Suites L-P

Aberdeen, MD 21001

Phone: (410) 273-7070

Fax: (410) 273-7618

E-Mail: info@nu-tek-optics.com

Contact: Fred Dimpfel fdimpfel@nu-tek-optics.com

Products: optical design services; optical testing services; plano optics such as windows, wedges, and beamsplitters; spherical transmissive optics; flat and spherical mirrors; aspheric mirrors to f/0.5 and faster; massive optics to 60"; metal optics, including bare aluminum and al & nickel; diamond turned optics, including post polishing; standard and gradient index lens and assemblies

- **Optical Components, Inc.**

1175 E. Edna Place

Covina CA 91724-2508

Phone: (626) 967-5281

Fax: (626) 967-2513

E-Mail: MIopez@ocioptics.com

WWW: www.ocioptics.com

Products: Optical Components, Inc. is a custom fabrication and coating facility which does not carry stock items. All optics are produced to customers' specifications and the prices depend on the complexity and size of an order. Our cutting-edge substrate manufacturing and coating capabilities enable us to flexibly meet a large array of specifications. Our thin film coatings include antireflective, reflective, dielectric filters, metallic and dielectric mirrors, beamsplitters, polarizers and transparent conductive coatings. We can fabricate windows, spherical lenses, prisms, wedges and other substrate configurations utilizing visible glasses, filter glasses, fused silicas, Pyrex and infrared materials such as silicon, germanium, zinc sulfide and zinc selenide. However, we do not fabricate or coat plastic substrates and our facilities constrain us from producing narrow bandpass and neutral density filters.

- **Thorlabs**

Thorlabs, Inc.

435 Route 206 North

Newton, NJ 07860

Phone: (973) 579-7227

Fax: (973) 300-3600

E-Mail: sales@thorlabs.com WWW: www.thorlabs.com

Products: optics and opto-mechanics, large-format NIR wire-gird polarizers

F. References

- Arnold, S., Gardener, E., Hansen, D., Perkins, R., 2001: *An Improved Polarizing Beamsplitter LCOS Projection Display Based on Wire-Grid Polarizers*. SID 01 Digest, **52/3**, 1282-1285
- den Boer, J. H. W. G., Kroesen, G. M. W., de Zeeuw, W., and de Hoog, F. J., 1995: *Improved Polarizer in the Infrared: Two Wire-Grid Polarizers in Tandem*. Optics Letters **20/7**, 800-802.
- Kahn, F. J., 2001: *Focus: Doing it with Stripes*. Private Line Report **7/10**, 1-14.