Linear Polarizer Design for Application in the Far-Ultraviolet Spectral Range

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ABSTRACT

New mission concepts that are under consideration by NASA call for the design and implementation of Far Ultraviolet (FUV) polarizer technologies that have not been developed yet. A team that includes members from the NASA Goddard Space Flight Center (GSFC), Arizona State University (ASU), and Woodruff Consulting, worked on the design and development of a polarizer design that produce very high extinction ratios in the FUV spectral range (100-200 nm). This polarizer consists of reflecting light through a series of mirrors from a combination of two silicon carbide (SiC) and two lithium fluoride (LiF) crystals positioned at angles of incidence (relative to surface normal) close to the average LiF Brewster's angle in the FUV. The output is a highly linearly polarized beam. This polarizer concept was fabricated and tested in the existing McPherson 225 Vacuum Ultraviolet (VUV) spectrometer located in the Optics Branch at NASA-GSFC. Initial testing using a MgF_2 crystal at the Brewster's angle as an analyzer has shown that this design can produce state-of-the-art extinction ratios at the Hydrogen Lyman-Alpha (Ly-α) wavelength of 121.6 nm, and that the measured extinction ratio of the two crossed polarizers, ≈114, is mostly limited by the MgF_2 analyzer. A polarizer with such a performance at this wavelength has never been reported and it signifies a breakthrough in FUV polarization technology. The levels of effectiveness paired with the polarizer's compact design allows for a new polarizer capability that would one day be implemented in a future FUV spectropolarimetry space mission.

Keywords: Far Ultraviolet (FUV), polarimetry, instrumentation, FUV polarizers.

1. INTRODUCTION

There are currently several missions under development at NASA Goddard Space Flight Center (GSFC) that provide wavelength coverage below 200 nm for a variety of applications that are sensitive to the intrinsic polarization of the reflective surfaces in the observatory and instrument designs [1]. As an example, the Habitable World Observatory (HWO) mission concept require mirrors that are intended to relay light to high-resolution coronagraphs for direct imaging of exoplanets, but that requires exquisite knowledge of the differential polarization at the point of reflection.

Polarization is both a property to be controlled and calibrated, and a unique tool for understanding the universe. For the exquisite challenge of delivering a part in 10^{10} coronagraphy to deliver the exoplanet characterization goals of HWO, the instrumental polarization of the reflective surfaces that feed that instrument must be very well understood, especially since the telescope will be off-axis, a fundamental understanding of the wavefront entering the coronagraph is vital. The scientific goals of HWO using polarization are based at this time on the portfolio defined by the Pollux instrument on LUVOIR-A, and involves mapping mass loss from massive stars, the physics of the emission line regions around AGN, the nature of the interstellar medium energy budget and mechanisms for grain alignment, to mention a few. In addition, for mission concepts dedicated to UV polarimetry, especially spectropolarimetry, like Polstar [1] a fundamental understanding of the polarization properties of mirror coatings is necessary for instrumental polarization for calibration – that mission will seek to understand the impact of stellar rotation and angular momentum loss on the evolution of massive stars, which drives both the cycle of star and planet formation and the evolution of galaxies as a whole Paul Scowen dixit [2].

Consequently, GSFC needs to be able to measure in the 100-200 nm range what impact mirror coatings on the incident polarization states have as a function of position across the optic, both radially and azimuthally. GSFC currently does not have the ability to measure polarization properties in the FUV spectral range between 100 nm and 200 nm. The addition

of this capability would enable GSFC to provide accurate metrology of the instrumental polarization added by any of the coating surfaces it produces. It opens an entire suite of options to produce polarization-sensitive instrumentation at GSFC that will depend on such measurements as part of their calibration. Combined with innovative optical designs, this capability would provide a critical element in the development and metrology of future UV-sensitive space instruments with polarization and coronographic applications [3].

To address this need, we have developed an ultra-compact linear polarizer that utilizes the polarizing effects that reflections near Brewster's angle have in a 4-mirror design (Figure 1) to allow direct measurement of the coating reflectance or transmittance at two perpendicular polarization states within the 100-200 nm range. Previous research like that of Hass and Hunter has shown that 4-mirror designs are capable of strongly polarizing FUV light when using Aluminum + MgF_2 coatings and MgF_2 crystals [4]. Our initial research led our team to believe that other materials such as lithium fluoride (LiF) and Silicon Carbide (SiC) might yield even higher degrees of polarization and extend the polarization capabilities down to the LiF cut-off wavelength (≈100 nm). This led to design our own linear polarizer that would be fitted to our lab's McPherson 225 Visible Ultra-Violet (VUV) spectrometer. The polarizer itself represents a valuable scientific contribution, offering a fundamental advantage in comparison with traditional Rochon FUV polarizers by extending the operational range below ≈130 nm down to ≈100 nm, as shown in Figure 3, which is an important technological advancement. Moreover, the proposed polarizer also presents other advantages such as low weight, compactness which greatly eases their integration in other devices, no beam deviation, and does not require of long propagation distances. This prototype polarizer has the potential to address FUV polarization requirements in space telescopes.

Alternative designs with polarization capabilities at wavelengths <120 nm have been reported, such a 3-mirror polarizers [4,5], a pile of LiF plates [6,7], and coating polarizers [8,9,10]

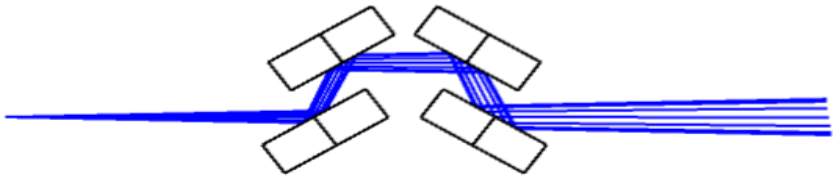


Figure 1. Side profile showing the configuration of the 4-mirror linear polarizer's design. Note the centerline of the incoming optical axis is in line with the outgoing optical axis.

2. DESIGN AND RESULTS

2.1 Polarizer design and fabrication

The polarizer was designed in accordance with the optical and physical characteristics of the McPherson 225 VUV spectrometer. As previously mentioned, this device is composed of four mirrors in a U-shape configuration. These mirrors are held in place by a assembly whose dimensions in length, width, and height is (51.50, 31.75, 38.25mm). These mirrors operate individually in a reflective configuration, but the device operates in transmissive capacity (see Figure 1). This polarizer is based on reflections on four mirrors at an angle of incidence of 56.75°, which is close to the average LiF Brewster's angle across the 120-200 nm range. At this angle, the reflected polarization component within the plane of incidence is virtually zero for LiF, i.e., $R_p \approx 0$, whereas the other component, R_s, is desired to be as high as possible, but usually it reaches modest values. The polarizer assembly was designed to be able to freely rotate about its optical axis (Figure 2 bottom).

The primary limiting factor during the design phase was that the assembly needed to fit into the sample compartment of the McPherson 225 VUV spectrometer. This constraint drove our need for the design to be compact. It also pre-determined our lid size, and position of the polarizer's optical axis. The chamber wall and beam collector come close to the optics (Figure 2. right). Designing the holder for the optics and rotation mechanism had to be very compact for it not to contact the chamber wall and beam collector, leading to the unusual-looking 4-mirror holder (Figure 2. top left). To keep the

design modular and stable, the 4-mirror holder assembly utilizes internal clips to hold each of the mirrors in place. This allows for the mirrors to stay firmly in place while being rotated.

The manipulator gauge shown with the black cap in (Figure 1. top left) has a precision of 1°. To achieve higher angular resolution the beveled gear attached to manipulator gauge was paired in a second beveled gear attached to the polarizer assembly in 1:3 gear ratio. Now one full rotation of the manipulator gauge (360°) only rotates the polarizer through one third of a full rotation (120°). This gear reduction now allows for users to make movements with a precision of 0.333° which fully satisfied the desired precision for this design (better than 1°). Once the design was finalized, we contracted Thermionics to fabricate the polarizer assembly.

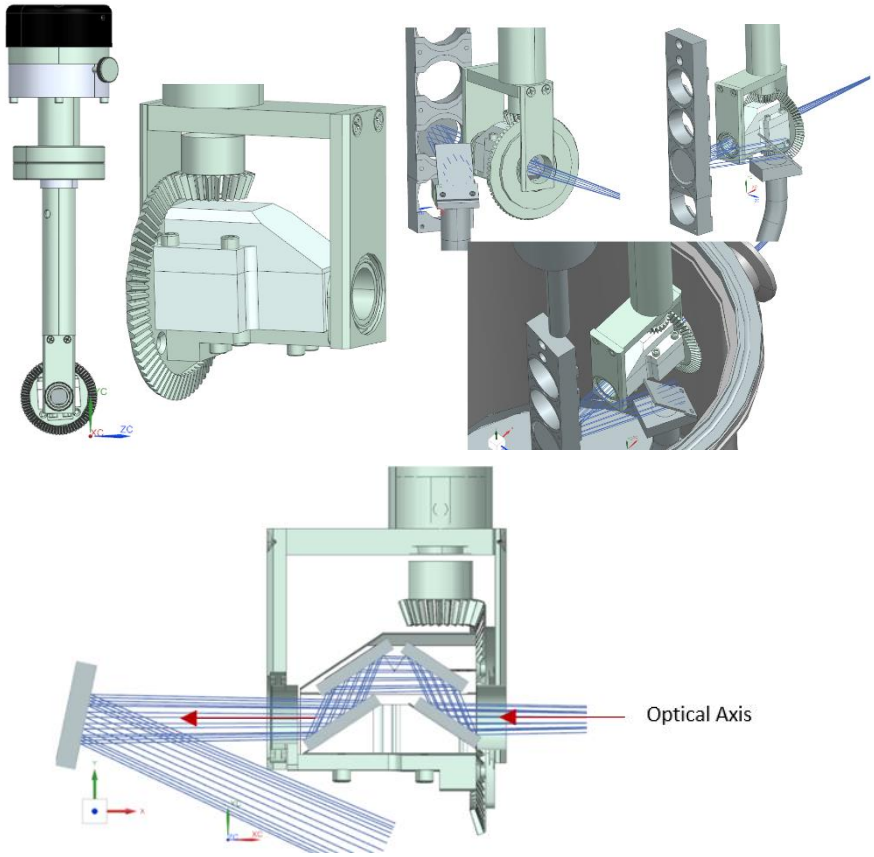


Figure 2. Top Left, overview of the polarizer manipulator and 4-mirror holder. Top Right, three different views of the sample holder for samples 1" diameter, the polarizer assembly, the beam collector and the chamber walls. Bottom, beam path through the sample polarizer assembly, where the positions of the mirrors held inside are displayed. The polarizer assembly can rotate 360° around the optical axis.

The polarizer consists of four mirrors, two made of SiC and two made of LiF. LiF was chosen due to its transparency across most of the FUV range, with a cut-off wavelength at ≈102 nm. As a result, LiF has an almost real Brewster's angle (k≈0) for wavelengths above 102 nm, resulting in high contrast between R_s and R_p polarizations as R_p almost vanishes. However, since LiF is a low-index material, R_s values are modest. SiC was selected for its moderately high FUV reflectivity around the Brewster's angle of LiF in the FUV. This paired with its ability to deliver small contrast between R_s and R_p polarizations, thereby minimizing the impact on the throughput of the 4-mirror polarizer. Figure 3 illustrates the possible mirror configurations, including one composed of 4 LiF mirrors, 3 LiF mirrors and one SiC mirror, 2 LiF mirrors and 2 SiC mirrors, 1 LiF mirror and 3 SiC mirrors, and finally, 4 SiC mirrors.

Several parameters were considered to evaluate the quality of the polarizer, including the extinction ratio $\left(\frac{T_s}{T_p}\right)$, the degree of linear polarization $\mu_T = \left(\frac{T_s - T_p}{T_s + T_p}\right)$ [10] and the throughput (T_s) [9]. All calculations were performed with all mirrors at an angle of incidence of 57°. Figure 3 shows that the configuration using 4 SiC mirrors reach the highest average polarizer

throughput (>10%) in the FUV range, but it has a limited average extinction ratio (<100) and degree of polarization. On the other hand, the configuration with 4 LiF mirrors yields an unprecedented average extinction ratio and degree of polarization in the FUV range but has a poor average throughput (<<1%). Thus, the configuration utilizing 2 LiF mirrors and 2 SiC mirrors was chosen as a trade-off between average FUV throughput (1.5%) and a good extinction ratio and degree of linear polarization.

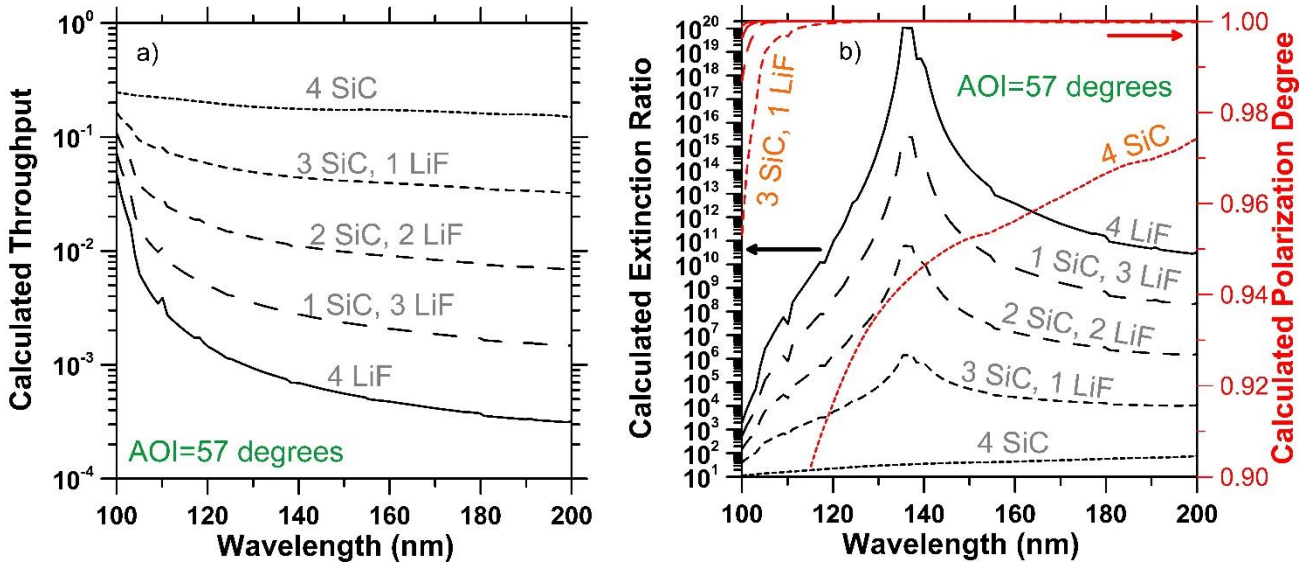


Figure 3. Left: Calculated throughput of the polarizer for the 5 possible mirror configurations described above as a function of the incident wavelength. Right: Calculated extinction ratio and polarization degree for the 5 possible mirror configurations as a function of the incident wavelength. All calculations are made with all mirrors at an angle of incidence of 57°

The surface roughness and figure of the individual mirrors were tested with a Park Systems NX-20 AFM and a Zygo Corp Verifire HD MST interferometer respectively, before the integration into the polarizer assembly. Flatness was the most important characteristic to qualify as it plays a crucial role in the performance of our system. The 8 purchased SiC mirrors were measured using a Zygo Corp Verifire HD MST to verify the Power, Peak-Valley (PV), and RMS. Our requirements for the individual mirrors were a PV of λ/4 and an RMS of λ/10 for the entire area excluding 1 mm from the edges. When measured we determined that none of the samples met either metric. Our average PV was 2.04λ, and average RMS was 0.75λ, which is 8x and 7.5x higher than expected, respectively. The two selected mirrors had a PV of ~1.45λ, and RMS of ~0.5λ in the beam footprint. After determining what samples performed better, the surface roughness of the two selected SiC mirrors was measured. Both samples showed identical results with Sq≈1nm. Unlike the SiC crystals that had the back surface frosted, the LiF crystals came with both surfaces polished. For the LiF crystals, their roughness will increase as exposure to moisture increases. The selected samples presented a surface roughness of Sq=1.96nm and 2.0nm. The other LiF samples presented Sq values ranged from 2.16 – 3.3nm, and thus were kept as spares.

After the two candidate LiF crystals were selected their back reflectance was suppressed by roughening the backside of the crystals. The SiC mirrors are optically opaque, so no further action was necessary. Theoretically the design of the polarizer with the LiF mirrors operating at a quasi-Brewster's angle (note that this angle depends on the incident wavelength, so an averaged value was considered) implies that incident radiation with p- polarization should be mostly transmitted and hence, the LiF mirrors should reflect mostly s-polarization [11]. Residual p-polarization reflected from the back surface of the LiF mirrors should not be an issue, but s-polarization reflected from the back of the LiF mirrors would introduce displaced back reflectance into the system. The displacement is proportional to the LiF mirror thickness. This issue from the first mirror is greatly mitigated since this parasitic reflection is small after 3 more reflections in the polarizer before the light exits the polarizer. However, this issue from the last LiF mirror cannot be mostly ignored, and since we noticed parasitic reflections when the polarizer was aligned in air before the back reflectance of the LiF mirror was suppressed.

Finally, we measured the p- and s- reflectance of the LiF and SiC samples in the DUV as a function of wavelength at 56.75° incidence, which is the operational angle of all mirrors in the polarizer, and we compared our results against a

theoretical calculation using tabulated index of refraction data. Comparing the theoretical model to experimental data we saw good agreement.

2.2 Installation, alignment, and characterization

2.2.1 Initial tests in air

Once all necessary parts were delivered and mirrors were individually tested, the polarizer was assembled and aligned in air using a He-Ne laser. The main purpose of this test was to verify the individual alignment of the optics so that that the optical axis does not experience deviations when the polarizer assembly is rotated around its axis. The test was successful, and no significant deviation of the transmitted beam was noticed.

Next, an initial polarizer characterization at λ>200 nm was performed in air using existing Perkin Elmer Lambda 950 NUV-VIS spectrometer, which includes polarization capabilities down to ≈300 nm wavelength. The results are displayed in Figure 4. We measured in the 300-800 nm range a relatively constant T_s and T_p of about 1% and 0.012%, respectively, and obtained extinction ratios of about ≈50-130. Note that the extinction ratio increases towards the short wavelengths, which agrees with Figure 3, in which the extinction ratio is shown to peak in the FUV range. However, we noticed that the extinction ratio experimentally decreases below ≈350 nm wavelength, probably because the commercial polarizer in the spectrometer became less efficient.

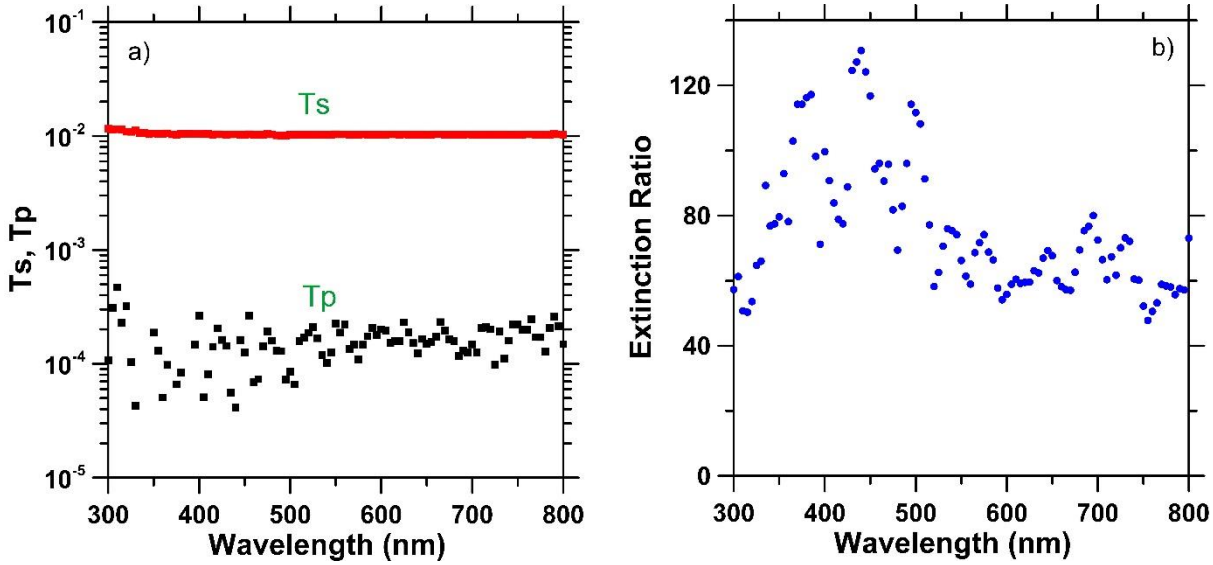


Figure 4. Left: Transmission of the S-Polarization (red) and P-polarization (black) in the 300-800 nm range. Right: Polarizer extinction ratio. The extinction ratio apparently decreases below ≈350 nm as the commercial polarizer in the spectrometer probably becomes less efficient.

2.2.2 Installation in the McPherson 225 VUV spectrometer and characterization at the 121.6 nm wavelength

Next, the polarizer was installed and aligned in the reflectometer chamber of the McPherson 225 VUV spectrometer. The main body of the polarizer that held the LiF and SiC crystals was affixed onto the rotation stage of the plate assembly. The gauge angle of the polarizer was aligned with a chosen polarization state. Out of convention it was chosen that the initial 0°-gauge angle would be aligned with the P-Polarization orientation of the mount. Once the polarizer assembly was mounted in the rotation stage (see Figure 2. top left), and this was installed in one port of the reflectometer chamber top lid, the whole assembly fits into the vacuum chamber of the McPherson. This setup was designed to only need alignment in one degree of freedom, yaw. By clocking the reflectometer chamber top lid, we can adjust the yaw of the system and adjust the polarizer's entrance aperture to be normal incident to the incoming beam generated by the monochromator of

the McPherson. Once we were satisfied with the clocking of the vacuum plate, we rotated the polarizer assembly 360° to ensure that the beam did not deviate.

Following the alignment of the polarizer, a MgF_2 flat plate was placed in the sample holder fixture of the reflectometer to act as an analyzer. The back reflectance of the MgF_2 plate was suppressed by roughening the backside. Then we proceeded with the polarizer characterization; the purpose of this test was to estimate the lower end of the extinction ratio of the 4-mirror polarizer at 121.6 nm wavelength using a MgF_2 plate at Brewster's angle operating as the analyzer. At Brewster's angle, the MgF_2 plate reflects incoming s-polarized radiation and rejects (transmits) p-polarized radiation, so that the p-polarization radiation outputted from the 4-mirror polarizer is nominally suppressed by the MgF_2 plate when the latter is at Brewster's angle. Importantly, and this is key in this section, when two polarizers are crossed, as it happens when the 4-mirror polarizer is rotated at the angle that transmits only p-polarization and the MgF_2 plate at Brewster's angle rejects p-polarization, the total extinction ratio of the two crossed polarizers is limited by the polarizer with the lowest extinction ratio. If the 4-mirror polarizer has a much higher extinction ratio (see Figure 3) than the MgF_2 analyzer, then the extinction ratio derived from the reflectance measurements shown in Fig. 5 represents that of the MgF_2 analyzer, and therefore *it provides a lower limit for the extinction ratio of the 4-mirror polarizer*. A polarizer with a higher extinction ratio, or a polarizer whose Stokes parameters are perfectly known would be needed to directly measure the exact extinction ratio of the 4-mirror polarizer at 121.6 nm wavelength.

Subsequently, the first test conducted was to measure the H Lyman alpha radiation (121.6 nm) outputted through the McPherson 225 at various states of polarization, i.e. with the 4-mirror polarizer oriented at a different angles. The way this was accomplished was by moving the detector into the direct path of the optical axis, removing the analyzer (MgF_2 window) from the beam path, and then by taking a series of measurements while rotation the polarizer only. The data gathered during this test will be later used to normalize the R_s and R_p of the MgF_2 analyzer shown in Figure 5. Since each angle is a separate measurement, it was determined that for this stage rotating the polarizer in 10° increments (30° on the gauge) provided a reasonable angular resolution while hitting all major angles (0°, 90°, 180°, 360°) directly. A second important parameter to choose was the integration time. While less important as this parameter can be changed between tests it has been found that 100s offers enough data to be fast enough to be verifiable while also being robust enough to cancel any issues caused by noise and flickers in the light source (hydrogen lamp). Taking data for 100s for each polarizer angle and averaging them yields the average intensity of the radiation outputted from the polarizer at each polarizer angle.

Tabulated data of refractive index of MgF_2 thin films was used to estimate the Brewster's angle of the MgF_2 analyzer, and it was found that it should be at about 58.5° at 121.6 nm wavelength [7]. As the refractive index of a window is expected to differ from thin film, polarization measurements were done with the MgF_2 analyzer at angles from 58° to 64° with step of 1°. In terms of polarizer orientation, in the context of this test it is only strictly necessary to take measurements for 5 angles on the 4-mirror polarizer (0°, 90°, 180°, 270°, and 360°) to determine the s, -s, p, and -p polarizations. However, any slight misalignment of the polarizer on its mount can cause these values to not yield the desired data, so for each analyzer angle (the MgF_2 plate) we used the same measurement configuration than for the polarization of the direct beam measurement. A final measurement was taken with the shutter of the reflectometer closed to get a dark signal (noise floor) that will later be averaged and then subtracted from each datapoint before normalization.

Figure 5. shows the normalized reflectance of the MgF_2 analyzer at 7 different angles of incidence, ranging from 58° to 64°, at as a function of the 4-mirror polarizer rotation angle. Since the MgF_2 analyzer is in a fixed configuration in which only s polarization is reflected, there are two maxima at around 90° and 270° when the 4-mirror polarizer transmits s and -s polarization, respectively, and three minima at around 0°, 180°, and 360°, when the 4-mirror polarizer transmits p, -p, and again p polarizations, respectively. Due to the polarizer design, the data at 0° and 360° should be the same, and both the s and -s, and p and -p configurations should deliver similar results, but we appreciate small differences, probably due to small alignment issues. Nevertheless, the data follows well the well-known Malus's law, where for linearly polarized light with intensity I_0, the intensity transmitted through a second ideal polarizer, I, can be described by $I = I_0 \cos^2 \theta$ [12], where θ is the angle between the polarization axes of the polarizer and analyzer.

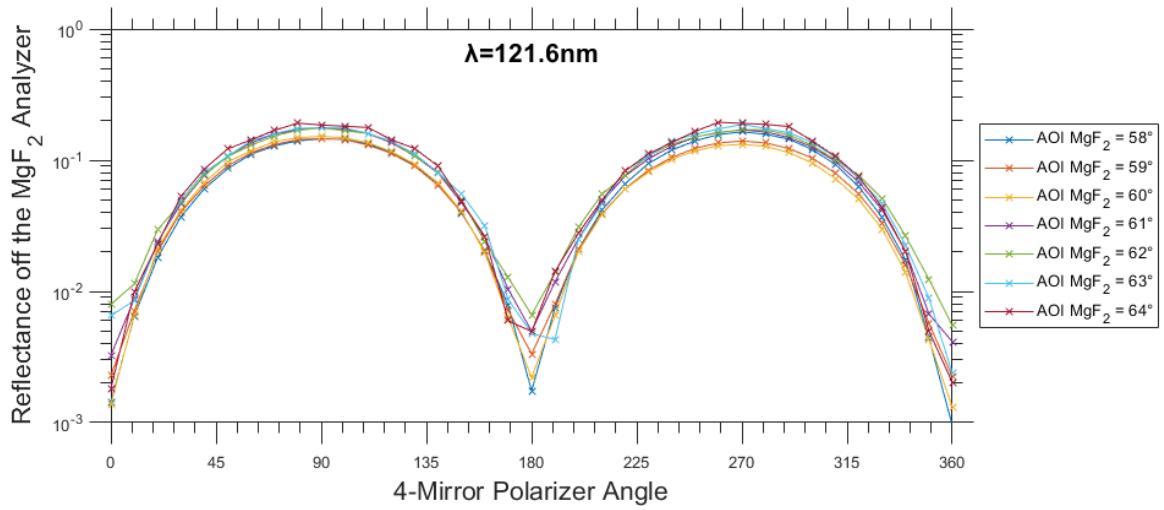


Figure 5. Normalized reflectance (in log scale) of the MgF_2 analyzer at 7 different angles of incidence, ranging from 58° to 64°, at as a function of the 4-mirror polarizer rotation angle, at 121.6 nm wavelength.

Using the terminology that the first maxima is to be labeled as s, the second as -s, the first minima as p and second minima as -p we can then calculate from Figure 5. the extinction ratio $\frac{s}{p}$ and the degree of lineal polarization, $\left(\frac{s-p}{s+p}\right)$ of the 4-mirror polarizer and MgF_2 analyzer system for each combination of maxima-minima. These values are averaged to obtain an overall estimation, and the results are displayed in Fig. 6. As mentioned above, if we assume that the 4-mirror polarizer delivers higher extinction ratio than the MgF_2 analyzer, the values shown in Fig. 6 mostly reflect the polarization properties of the MgF_2 analyzer, and therefore indicate a lower end of the expected extinction ratio and degree of polarization of the 4-mirror polarizer. Figure 6 shows that the extinction ratio of the crossed 4-mirror polarizer and MgF_2 analyzer system decreases as the angle of incidence of the MgF_2 analyzer increases. This suggests that the actual Brewster's angle of the MgF_2 plate at a wavelength of 121.6 nm is close to or below 58°.

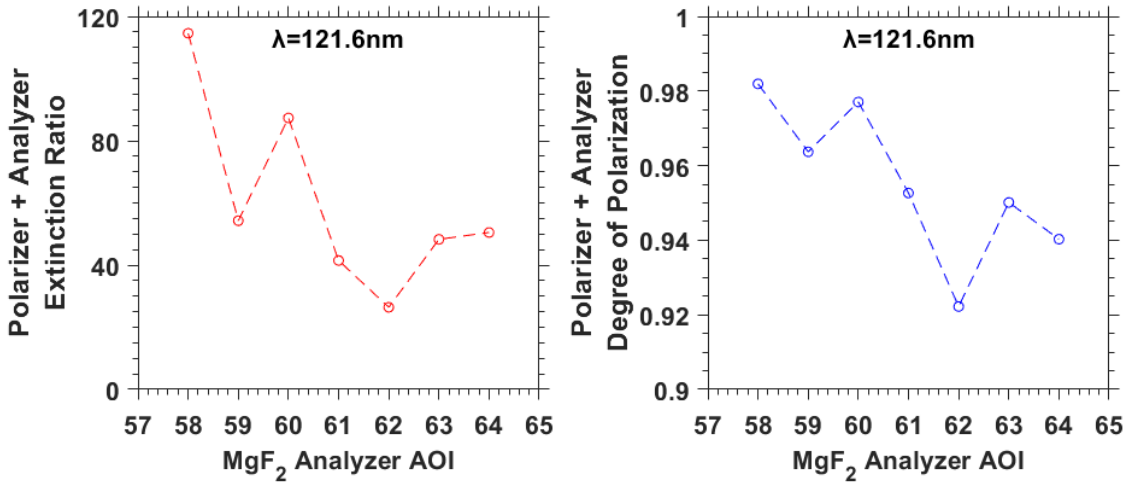


Figure 6. Measured extinction ratio (left) and degree of lineal polarization (right) of the 4-mirror polarizer and MgF_2 analyzer in crossed configuration at 121.6 nm wavelength as a function of the angle of incidence of the MgF_2 analyzer.

However, the theoretical extinction ratio of an ideal MgF_2 plate at its Brewster's angle at 121.6 nm wavelength should be several orders of magnitude higher than what is observed in Figure 6 at 58°-59°. There are several possible factors that could explain the differences between calculations and experimental data, which are listed below:

I. Misalignment on the rotation of the 4-mirror polarizer with the selected polarization state may result in a small offset, therefore a small amount of s polarization could be leaked along with p, even when we believe that the polarizer transmits only p.
II. The angular divergence of the incident beam.
III. The wavelength purity due to the monochromator slit configuration in the McPherson spectrometer.
IV. Changes in the optical properties on the surface of the MgF_2, such as an increased extinction coefficient due to surface contaminants, and surface roughness translated into a gradient in the refractive index.
V. The 4-mirror polarizer has overall lower extinction ratio than the MgF_2 plate at 121.6 nm. However, we believe this scenario is highly improbable, although the real extinction ratio of the 4-mirror polarizer is expected to be significantly lower than shown in Fig. 3 due to the factors listed above that not only affect the MgF_2 analyzer but also the 4-mirror polarizer.
VI. Miscellaneous, such as stray light due to surface roughness, non-uniformity of the incident beam or the detector, etc. These possible factors are difficult to quantify, and hence, are not discussed further.

Table 1 provides a rough estimate of the effect of each of the factors i-iv discussed above on the theoretical extinction ratio of a MgF_2 plate at 58.5° at 121.6 nm wavelength, which is ≈114. The calculations shown in Table 1 are straightforward with any software that deals with Fresnel formalism. However, one intermediate step may require clarification: the rotation offset in the 4-mirror polarizer was translated into incident beam polarization, f, for the posterior calculation of the multiplier effect on the MgF_2 analyzer extinction ratio. The approximate f value was calculated from the ratio of $\frac{S_1}{S_0}$ entries of the Stokes [13] vector resulting from the multiplication of a unpolarized Stokes vector[6,14] $(1 \quad 0 \quad 0 \quad 0)$ by the Mueller matrix for a generic linear polarizer (to model the 4-mirror polarizer), with the angle of rotation of the polarizer set at 0.2°, 0.5°, and 1°.

Table 1. Estimate of the effect of different factors on the extinction ratio of a 4-mirror polarizer combined with a MgF_2 plate at Brewster's angle

Calculations parameters	**Cause**	**Amount**	**Multiplier effect on the extinction ratio of the MgF_2 analyzer**
λ=121.6 nm 4-mirror polarizer at 0°→ transmits p polarization only MgF_2_AOI=58.5° SiC, LiF, and MgF_2 optical constants from Palik compilation [15]	Rotation offset in 4-mirror polarizer when delivering p pol. (thus, residual s pol. included)	0.2°: $(f = -0.999976)^*$	x 0.0074
		0.5°: $(f = -0.999848)^*$	x 0.0012
		1.0°: $(f = -0.999391)^*$	x 0.0003
	Angular divergence of the beam	0.5°	x 0.499
		1°	x 0.220
		2°	x 0.105
	Spectral impurity ($\Delta\lambda/\lambda$)	0.1%	x 0.557
		0.5%	x 0.113
		1%	x 0.057
	Increased extinction coefficient (k) of surface of MgF_2 plate	$\approx 5\cdot10^{-7}$ to 10^{-6}	x 1
		$\approx 5\cdot10^{-7}$ to $5\cdot10^{-6}$	x 0.9997
		$\approx 5\cdot10^{-7}$ to 10^{-5}	x 0.9989
	Roughness of the MgF_2 plate (calculated as a gradient in the refractive index n on the MgF_2 surface)	0.1 nm	x 0.0880
		0.5 nm	x 0.0038
		1 nm	x 0.0010

* The rotation offset is "translated" into incident beam polarization (f) of the radiation outputted from the 4-mirror polarizer. We use the convention $f = 1$ means pure s polarization, and $f = -1$ means pure p polarization.

Interestingly, we note that the factors with potentially significant impact on the extinction ratio of the MgF_2 analyzer are the rotation offset in the 4-mirror polarizer, the roughness of the MgF_2 plate, as gradients in the MgF_2 surface translated into gradients in the refractive index, n, significantly displace the Brewster's angle away from 58.5°, and the spectral

purity, as the Brewster's angle changes fast with wavelength variations at around 121.6 nm due to the proximity of the MgF_2 cut-off wavelength at 113 nm. As an example, the nominal extinction ratio of the MgF_2 plate can be reduced from $\approx 10^7$ to $\approx 10^2$ with a hypothetical combination of a 0.2° offset in the 4-mirror polarizer, a 0.5° beam divergence, a spectral impurity of 0.5%, and a MgF_2 surface roughness of 0.5 nm. Although these values are all hypothetical, they do not appear unreasonable.

3. CONCLUSIONS, ACKDOWLEDMENTS, AND FUNDING

3.1 Conclusion

Our team has developed a state-of-the-art 4-mirror polarizer based on 2 LiF and 2 SiC crystals positioned at angles of incidence (relative to surface normal) close to the average LiF Brewster's angle in the FUV. This polarizer concept was fabricated and tested in the existing McPherson 225 Vacuum Ultraviolet (VUV) spectrometer located in the Optics Branch at NASA-GSFC. The device was tested with MgF_2 plate at Brewster's angle operating as the analyzer. By crossing the 4-mirror polarizer with the MgF_2 plate analyzer we measured extinction coefficients as high as 114 and has a degree of polarization as high as 0.98 at the H Lyman α wavelength (121.6 nm).
This polarizer enables GSFC polarization capabilities in the FUV spectral range.

3.2 ACKNOWLEDGMENTS & FUNDING

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