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Reflective filters design for Self-filtering narrowband ultraviolet imaging experiment wide-field surveys (NUVIEWS) project

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ABSTRACT

We report the design of multilayer reflective filters for the self-filtering cameras of the NUVIEWS project. Wide angle self-filtering cameras were designed to image the C IV (154.9 nm) line emission, and H_2 Lyman band fluorescence (centered at 161 nm) over a 20° × 30° field of view. A key element of the filter design includes the development of π-multilayers optimized to provide maximum reflectance at 154.9 nm and 161 nm for the respective cameras without significant spectral sensitivity to the large cone angle of the incident radiation. We applied self-filtering concepts to design NUVIEWS telescope filters that are composed of three reflective mirrors and one folding mirror. The filters with narrowband widths of 6 and 8 nm at 154.9 and 161 nm, respectively, have net throughputs of more than 50 % with average blocking of out-of-band wavelengths better than 3×10^{-4} %.

Keywords: Far ultraviolet, narrowband reflection filters and multilayers

1. INTRODUCTION

Rocket borne and satellite borne optical instruments have been used to study emission and absorption features of the sun, stars, and interstellar medium in space and earth's upper atmosphere. In the Far-Ultraviolet(FUV: 120 ~ 200 nm) region where suitable filters were not available spectrographs have been widely used to select required signal and block out-of-band noises.

Imaging spectroscopic observation instrumentation can be divided into two groups. One group is filter-based and the other, grating-based. A filter-based instrument may need either narrow-(FWHM is less than 10 nm) or broad-band (FWHM is 10~20 nm) coatings, while a grating-based instrument mostly needs broad-band high reflective coatings. Reflecting diffraction gratings are extensively used in optical devices over a FUV spectral region. The spectrograph is a grating-based instrument. Use of the reflecting diffraction gratings in space and ground research as tuning elements for laser, has stimulated a great amount of research on coatings for gratings. However a grating-based instrument has poor performance with regard to two-dimensional resolution. Moreover, such system is less cost effective and more complex than the filter based instrument. Therefore, filter based instruments are preferred to grating based instruments whenever high spectral resolution is not required.

The Optical Aeronomy Laboratory (OAL) in UAH has made progress in the design of interference thin films in the FUV region [1] . A major undertaking fundamental to the design of FUV coatings was the need to identify suitable materials, and to develop a technique for the measurements of both the refractive index and the extinction coefficient. Our group has been successful in both these areas and has generated a list of suitable materials for FUV thin film applications with corresponding values of refractive indices and extinction coefficients as a function of wavelength and introduced a new design concept called π-multilayer[2,6]. Utilizing a powerful optimization program[4] , our group was able to design and fabricate narrow-band and broad-band reflection filters with a higher reflectance than the Koppelmann limit[3] .

The OAL group also introduced a new concept of FUV self-filtering camera in which the mirrors provide both imaging and spectral filtering[5,7]. Utilizing the self-filtering approach, the number of reflecting surfaces can be minimized and higher throughput can be achieved. Examples of self-filtering instruments are being employed in astrophysics telescopes/cameras for imaging at a resonant scattering wavelength of a particular element, high resolution heterodyne spectrophotometers[13], high resolution polarimeters, and all other instruments operating within relatively narrow spectral range. The self-filtering approach is not limited to short wavelength imaging spectroscopy; the concept can be applied to the design of any single-wavelength instrument operating within any spectral range. The advantages of the self-filtering concept become obvious whenever extreme requirements are imposed on the instrument in-band transmission and out-of-band rejection.

An important aspect of the self-filtering concept is the insensitivity of the coating to cone angle of the incident radiation. In visible and infrared regions where thin film materials have low absorbing characteristics, it is known that a high refractive index film is less sensitive to changes in incident angles. In the FUV region, however, high refractive index material also has higher absorption than low index film that decreases reflectance of the multilayer. Realizing a less cone angle sensitive multilayer and at the same time maintaining a high reflectance is a challenge to be solved.

In this paper the results of our research about the angular sensitivity of reflective filters are reported. Two sets of filters at 154.9 and 161 nm for NUVIEWS are designed and results are shown.

2. DESCRIPTION OF THE NUVIEWS TELESCOPE AND FIELD OF VIEW

The Narrowband Ultraviolet Imaging Experiment for Wide-field Surveys (NUVIEWS) is a rocket-borne survey experiment designed to map C IV 154.9 nm line emission and to map the global distribution of molecular hydrogen Lyman band fluorescence centered at 161 nm.

The NUVIEWS telescope is composed of four-reflection filters, f/3, e.f.l. 90 mm, system : a spheroidal primary, hyperboloidal secondary, spherical tertiary, and plane folding mirror with the respective cone angles, 26.5±7.0°, 12.9±4.0°, 10.9±6.2° and 45°. The NUVIEWS telescope requires the bandwidth less than 7 nm and net-throughput greater than 50 % at selected wavelengths of 154.9 and 161 nm[12]. A raytrace of the NUVIEWS imaging system is shown in Figure 1.

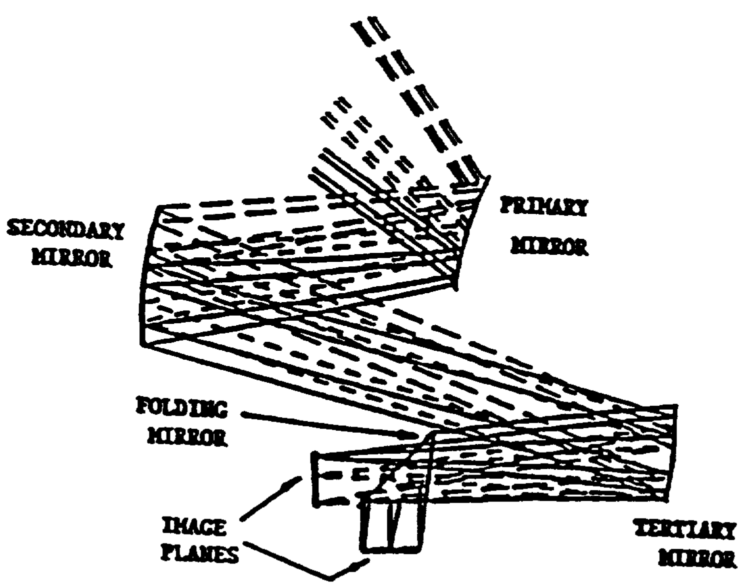


Figure 1. Raytrace of the NUVIEWS optical system.

Reflectors as narrow-band filters were usually designed and fabricated as independent parts of an optical system[11]. The filter design makes the filters independent of the optical instrument characteristics and they can be used in any instrument with a field of view(FOV) within the filter cone angle design range.

In the thin film design for the wide field, self-filtering imaging instruments, we have to consider the effects of FOV. The angle-induced changes in multilayers can be qualitatively divided into two categories: the polarization effects and the wavelength shifts. S- and p-polarization have a different performance curve when incident radiation is at an angle other than the normal to the surface of the reflector. The shift of the peak reflectance is straightforward: performance curves shift to shorter wavelengths as the angles of incidence increase away from the normal. At first glance, it may appear that the performance should shift toward the longer wavelength side because the optical path length of each layer in the design increases as the angle of incidence increases by a factor inversely proportional to the cosine of the angle of refraction inside the angle. The important parameter, however, is not the total phase shift introduced in the waves by the layers. It is the phase difference between the waves that reflect from all the interfaces that enters into the summation of the partial reflected waves. This quantity decreases as the angle increases. Thus the performance shifts toward the shorter wavelength region as the angle increases because the apparent optical phase difference introduced by each layer is decreasing.

The effects of cone angle on a bandpass (FWHM) filter are not simple and there have been just a few studies. In the FUV region, where all the optical materials have absorbtion and dispersion, the angular consideration of the multilayer performance is a new challenge. Ideally, we need a filter design with the minimum spectral sensitivity over the shift angular range with the high reflectance maintained at the center of the cone angle.

3. THEORY OF ABSORBING MULTILAYERS

3.1. π-multilayers

In visible region, where optical thin film materials are not absorbing, a quarterwave (QW) stack is useful in achieving high reflection at specific wavelength. However in the FUV region where low absorption high refractive materials are not available, π-multilayers can bring higher reflection than a QW stack.

A π-multilayer is defined as a multilayer stack with $H+L=\lambda/2$. Here H is the optical thickness of the high refractive index material and L that of the low refractive material. Thus, a QW stack with $L/H=1$ is a special case of a π-multilayer. In a QW stack, light reflected from all interfaces is in phase, while in other π-multilayers light reflected from each HL pair is in phase as shown in Figure 2. Obviously, the QW stack with low-absorbing film materials (available in the visible and infrared parts of the spectrum) provides a higher reflectance with fewer layers than other π-stacks. However, in the FUV where low-absorbing high index film materials do not exist, a π-multilayer with a smaller physical thickness of H relative to L provides lower absorptance and therefore higher reflectance of the stack.

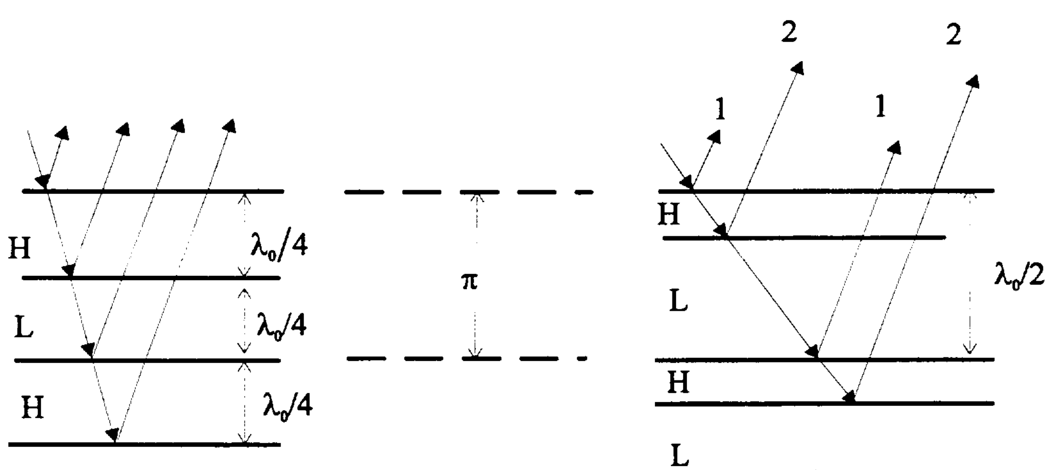


Figure 2. (a) QW-stack: light reflected from all interferences is in phase and (b) π-stack: light reflected from each(HL) pair is in phase.

The dependence of the maximum reflectance on the ratio of L/H and the number of layers is shown in Figure 3. The maximum reflectances for a 154.9 nm line at a 26.5° angle of incidence are calculated as a function of the L/H ratio for several reflection filters, each with different number of layers (99, 79, 59, 39, 19-layers). The low refractive index material is MgF_2 and the high refractive index material is LaF_3. A π-stack with the only 39 layers and with L/H=2 provides a maximum reflectance of almost 95 %.

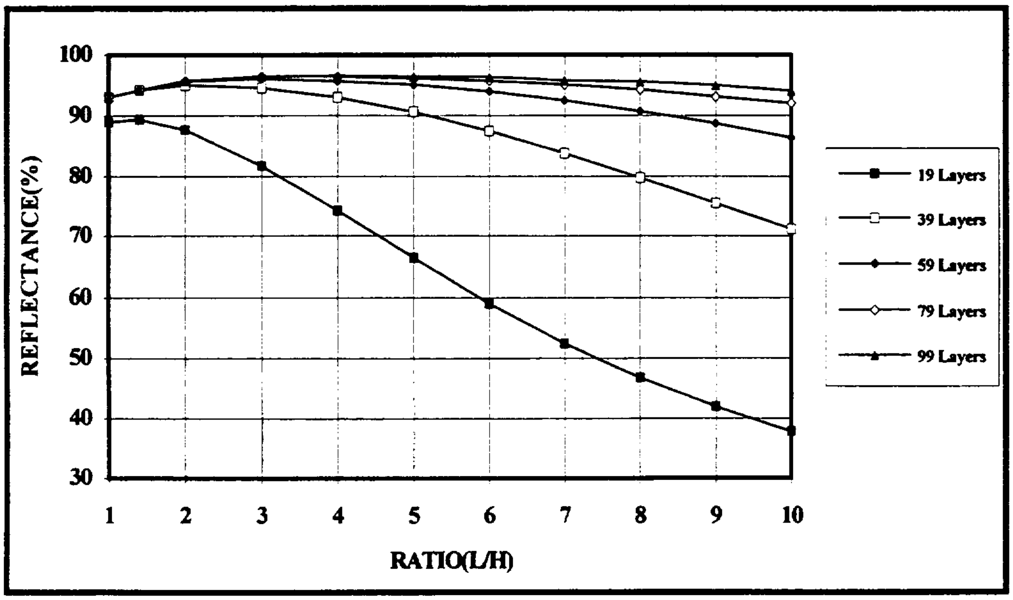


Figure 3. Change in the calculated reflectance of a π-multilayer structure as the ratio (L/H) changes for the various numbers of layers at 154.9 nm, θ_0=26.5°(H : LaF_3, and L : MgF_2). The Koppelmann limit in this case is 92.3 %.

In the FUV, thin film materials exhibit both dispersion and absorption that affect the FWHM and make it difficult to estimate the bandwidth or FWHM. Generally the FWHM decreases as the optical thickness of the L/H ratio increases in the π-stack. However, FWHM saturates after certain number of layers as it is shown in Figure 4. This saturation property is utilized to control the bandwidth of a filter design.

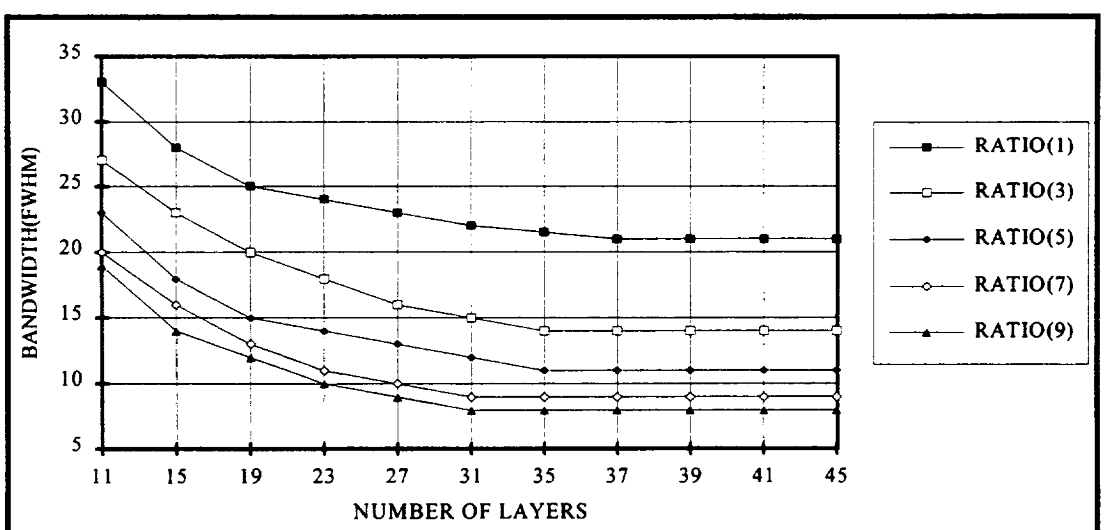


Figure 4. The calculated bandwidth *vs.* number of layers for various (L/H) ratios at 154.9 nm θ_0 = 26.5°. H : LaF_3, and L : MgF_2.

Figure 4 also shows that in the design of a narrow-band reflection filter the L/H ratio has to be as high as possible to provide high reflective narrow bandwidth. However, the maximum value of the L/H ratio is limited by the feasibility of depositing and monitoring extremely thin layers. Other important factors that limit the maximum value of the L/H ratio include the substrate surface roughness and structural properties of the layers. Furthermore, an increase in the L/H ratio decreases the reflectance for fixed number of layers as shown in Figure 3. Therefore, an addition of more layers to the stack is required to maintain the reflectance at its maximum.

3.2. Multilayer angular sensitivity

The phase thickness of the *l-th* film in a multilayer is defined as[8]

$$\delta_l = \frac{2\pi}{\lambda_0} N_l d_l \cos\Theta_l \tag{1}$$

where λ_0 is the vacuum wavelength of the incident light. N_l is the optical constant, d_l is the physical thickness and Θ_l is the complex angle of light within *l-th* film.

Obviously, the multilayer angular sensitivity is mainly controlled by the phase thickness of individual films. From the phase thickness definition, it follows that multilayers with the least wavelength sensitivity for a fixed angle of incidence, such as broad-band reflection filters, have the least angular sensitivity for a fixed wavelength. The best known example of a broadband reflection multilayer is a QW periodic stack. Figure 5 shows calculated reflectance of 45-layer LaF_3/MgF_2 QW-stack designed for 26.5° angle of incidence. Figure 6 demonstrates low angular sensitivity of the QW-stack whose spectral performance is shown in Figure 5. Thus, a simple way to design a multilayer with a minimum angular sensitivity is to select a design with a wide spectral coverage at a fixed angle such as the QW design.

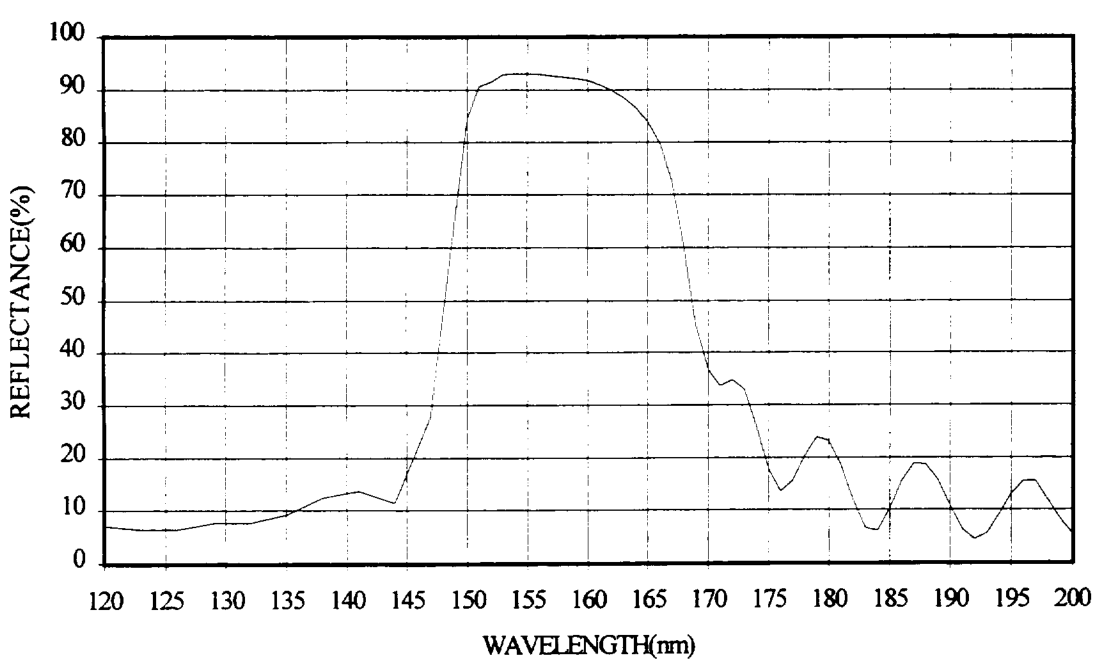


Figure 5. The calculated reflectance of LaF_3/MgF_2 45-layer QW-stack designed for 26.5° incident angle at 154.9 nm.

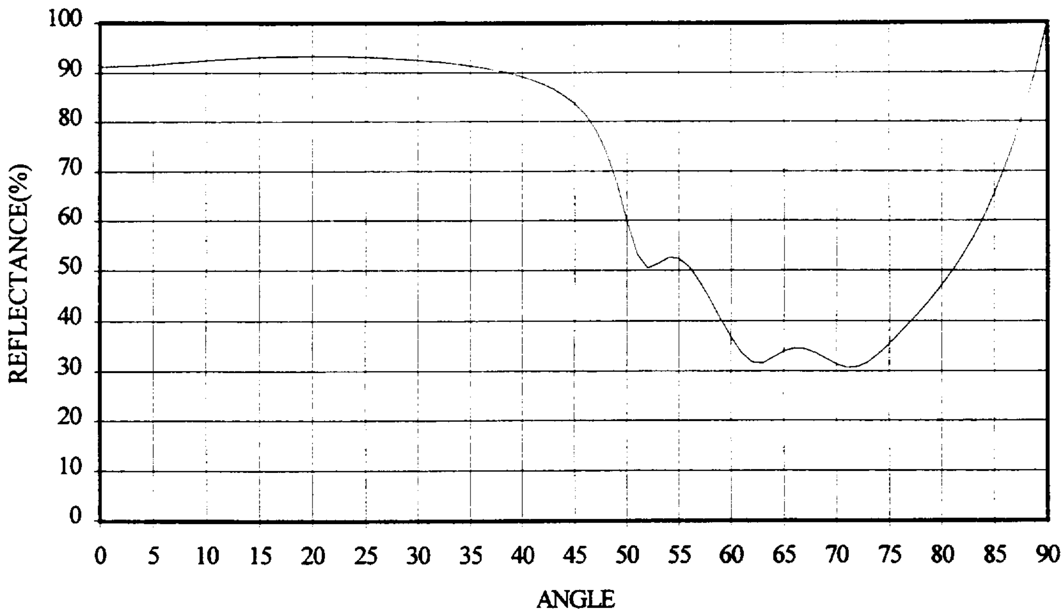


Figure 6. The calculated reflectance of a QW-stack plotted as a function of angle of incidence. The design angle θ_0 =26.5° and the design wavelength is 154.9 nm. The multilayer has 45 layers where L : MgF_2 and H : LaF_3.

Figure 7 shows the distance between reflectance peaks when the light is incident at two end angles of 19.4° and 35.5° on a filter designed for 26.5° angle of incidence at 154.9 nm wavelength. In a QW-stack (L/H=1) the peak reflectance wavelength shift distance at the two end cone angles is 4.0 nm, while in a π-stack with L/H=8 the shift is 5.25 nm. Thus, the angular sensitivity of QW-stack is less than any other π-stack films.

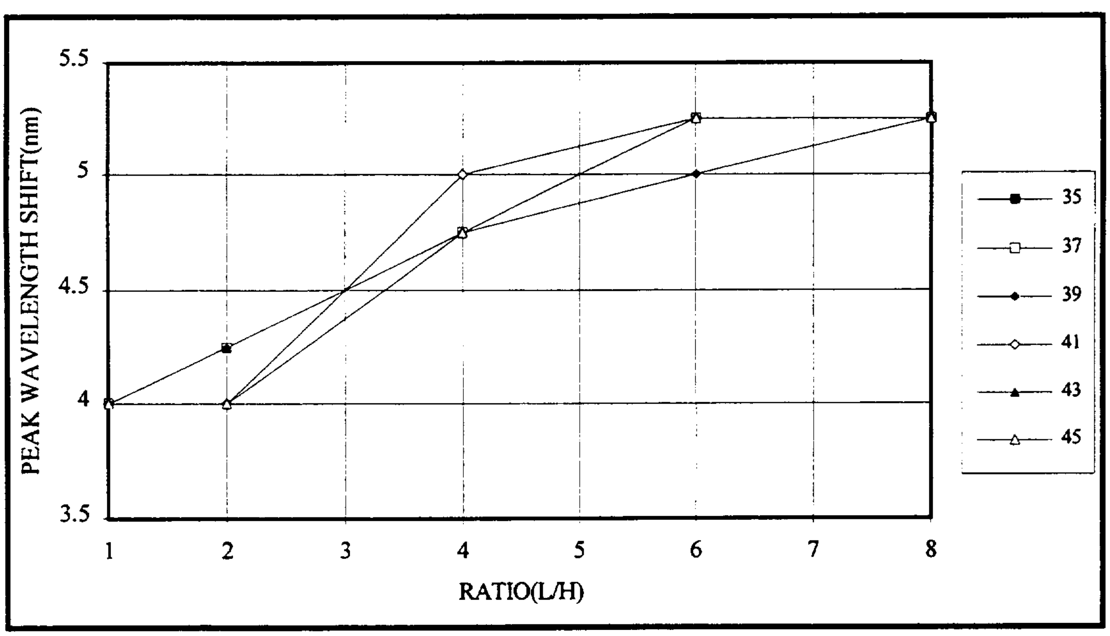


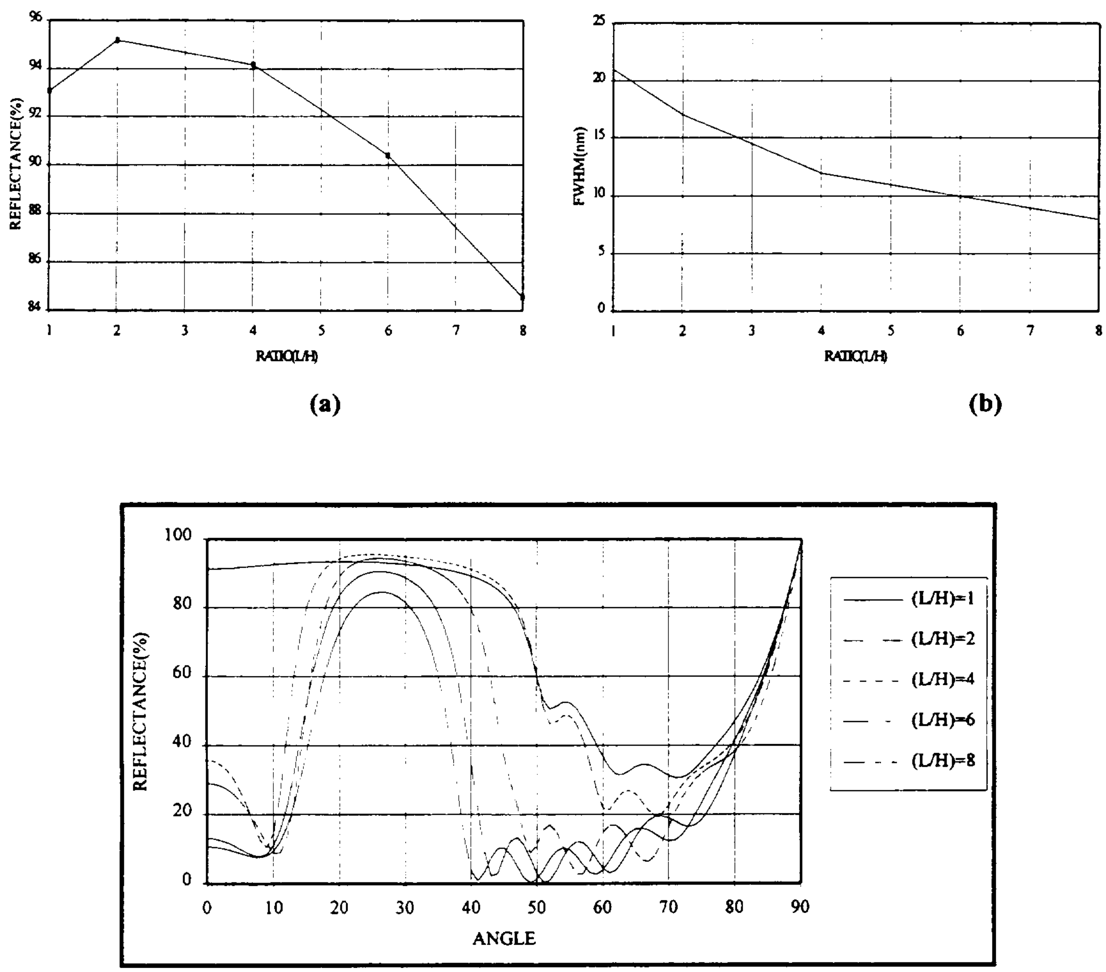
Figure 7. The peak distances at two cone angles(19.4° and 35.5°) for several different number of layers. The central cone angle is 26.5° with half cone angle of 7.1° at 154.9 nm.

4. MAXIMUM REFLECTANCE, BANDWIDTH AND ANGULAR SENSITIVITY

The self-filtering telescope design requires multilayer reflectors with high reflectance, narrow bandwidth and minimum angular sensitivity. Figure 8(a) shows the maximum calculated reflectance as a function of L/H ratio. It also shows that for a particular L/H(2,3,and 4) ratio, π-stack reflectors have a higher maximum reflectance than the QW-stack reflector, since the π-stacks(L/H= 2~4) have less absorption than QW-stack reflector. In this figure the π-stacks with L/H ratios from 1 to 6 have peak reflectance over 90 %. This property gives the advantage in the selection of the L/H ratio. For example, the selection of the L/H=6 ratio provides a maximum reflectance of over 90 % with a bandwidth of less than 10 nm.

Figure 8(b) shows the calculated bandwidth (FWHM) as a function of the L/H ratio. In the design of a narrow-band reflection filter, the L/H ratio has to be as high as possible to lessen the absorption. However, increasing the L/H ratio has a negative effect on angular sensitivity as shown in Figure 8(c).

Figure 8(c) shows the calculated spectral performance of the 45-layer stack reflection filters designed at 154.9 nm and θ_0 = 26.5° as a function of angle of incidence with various L/H ratios. Figures 8(a) and 8(b) also show the QW-stack reflection filter (L/H=1) with maximum reflectance of more than 90 % within the broad angular region of 0° to 40°. The maximum reflectance of π-stacks are confined within narrower cone angle as the L/H ratio increases.



(a) (b)

(c)

Figure 8 (a) The peak reflectance and (b) FWHM as a function of L/H ratio. (c) reflectance as function of incident angles. The filters are designed as LaF_3 /MgF_2 45 layers QW-stack and π-stacks with operating angle of 26.5° at 154.9 nm.

In Figure 9, the performances of BaF_2/MgF_2 and SiO_2/MgF_2 multilayers are compared to the performance of the LaF_3/MgF_2 multilayer. From Figure 9, it follows that the HL pair LaF_3/MgF_2 provides the least angular sensitivity. Hence this pair was selected even though the multilayers made out of this material pair have a higher FWHM than the other two pairs for any L/H ratio.

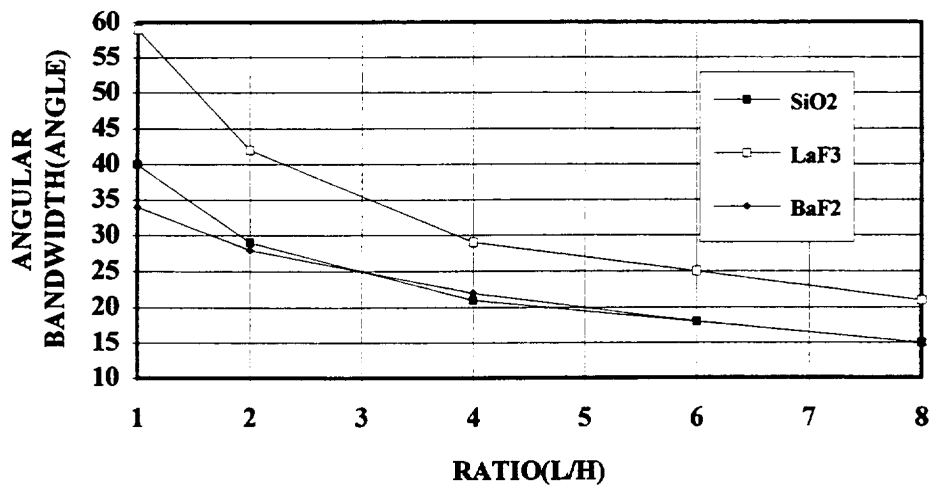


Figure 9. Material dependence of angular sensitivity of BaF_2/MgF_2 , SiO_2/MgF_2 and LaF_3/MgF_2 multilayers.

To obtain a high maximum reflectance, narrow bandwidth, and low angular sensitivity, we may consider the non-periodic multilayer structures. Carniglia and Apfel[10] and Lissberger[9] showed that non-periodic structure with a different L/H ratio for each pair of layers, has a higher reflectance compared to a periodic structure with a fixed L/H ratio for all layers, as long as $L+H=\lambda/2$. We applied their non-periodic method in our reflection filter design. Because of the complexity of the reflectance equations Carniglia and Apfel's two-dimensional optimization methods cannot be applied to the oblique angles of incidence. Instead, a mathematical algorithm is developed which iteratively selects new H and L phase thicknesses until converge at maximum reflectance is realized. A quarterwave layer of high absorbing material on a substrate is used as a starting base structure. The two thicknesses of low and high absorbing materials on top of the base structure is then iteratively adjusted to find a pair of thicknesses which provides the highest reflectance. Using these three layers and a substrate as a base structure, the next pair of thicknesses are sought. The procedure is repeated until the saturation or target reflectance level is reached. However, we found that the bandwidth of the non-periodic stack was as broad as in the case of a QW-stack.

From previous analysis for π-stack, it follows that :

- The reflectance increases as the number of layers increases.
- For a fixed number of layers there is an L/H ratio for which the π-stack has higher reflectance than the QW-stack.
- The FWHM decreases as the L/H ratio increases.
- The peak wavelength shift decreases as the number of layers increases.
- The peak wavelength shift increases as the L/H ratio increases.
- Selection of optimum film materials is very important.

On the basis of these facts, we selected an L/H ratio, number of layers for specific requirements on reflectance, angular sensitivity, and a bandwidth for the reflective filters.

The three mirrors are designed for NUVIEWS telescope reflective filters as LaF_3/MgF_2 45 layers with L/H ratios 7,5, and 7 that have operating angles of 26.5°, 12.9° and 10.9° at 154.9 nm respectively . At 161 nm, the three mirrors are designed in the same way as in the 154.9 nm case, except that L/H ratios 7, 7, and 5 are selected by the computer iteration. Figure 10 shows the calculated net throughput after four reflection (primary, secondary, tertiary and folding) mirrors.

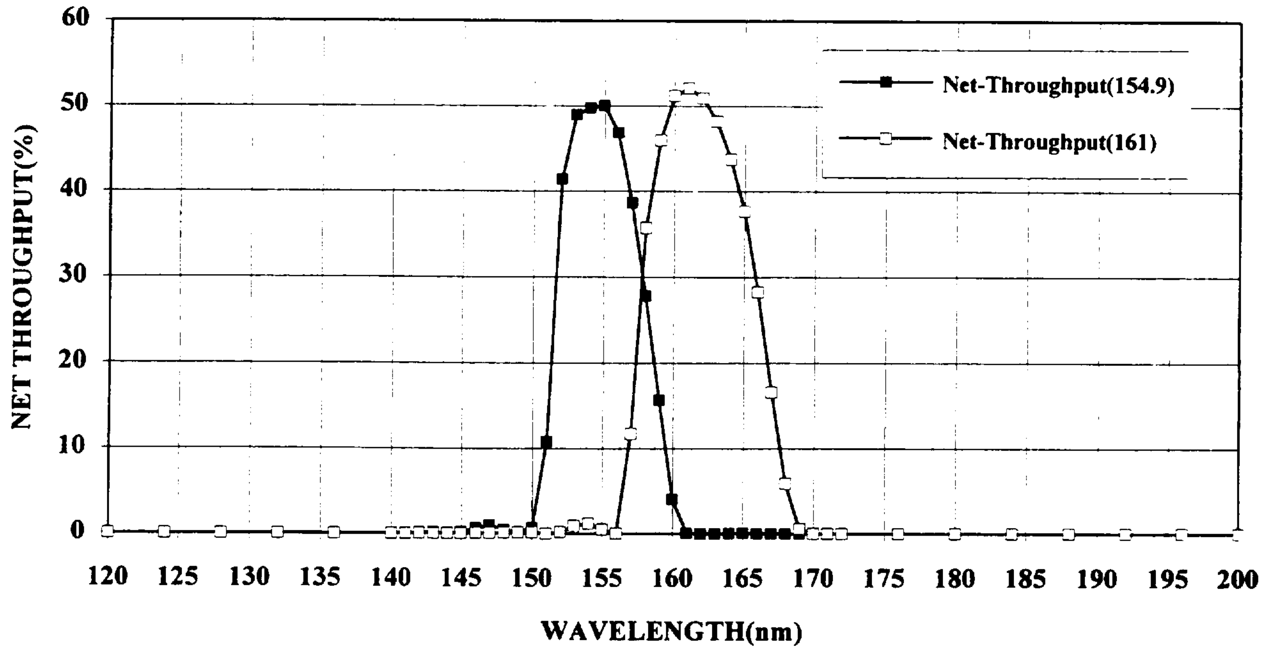


Figure 10. The calculated net throughputs at 154.9 and 161 nm through self-filtering instrument (three imaging mirrors coated multilayers and one folding(flat) mirror with Al/MgF_2 coating).

The maximum reflectances attained at 154.9 and 161 nm are between 66.5 % and 75.2 % and FWHM 5 ~ 8 nm after three reflections. The measured reflectance of a flat folding mirror(quartiary mirror coated with Al/MgF_2) at 45° angle of incidence is higher than 70 % in the region from 130 to 200 nm. The net throughput is 50.04 %, bandwidth 6 nm and out-of-band rejection 2.53×10^{-4} % at 154.9 nm and net throughput 52.16 %, bandwidth 8 nm, out-of-band rejection 2.3×10^{-4} % at 161 nm after four mirrors.

5. SUMMARY

To design reflection filters for the NUVIEWS self-filtering telescope, the angular sensitivity of the QW- and π-stacks were examined. The high reflective multilayer coatings for the narrowband reflection filters are designed by using π-multilayer stacks with L/H>1 instead of the classical QW-stack with L/H=1. It is shown that the π-stacks with L/H>1 have a higher reflectance and smaller bandwidth than QW-stack, and therefore these stacks are more suitable for the design of narrow-band reflection filters.

Using a multiple narrow-band reflective filter gives the desirable performance in bandpass and out-of-band blocking. For the NUVIEWS self-filtering telescope, we applied the self-filtering concept to design NUVIEWS telescope filters composed of three mirrors and one folding mirror. The filters with narrowband width of 6 and 8 nm at 154.9 and 161 nm, respectively have net-throughputs more than 50 % and average blocking of out-of-band wavelengths better than 3×10^{-4} %.

6. ACKNOWLEDGMENTS

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