Invited Paper

Progress in the Development of Far Ultraviolet Etalons

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Abstract

We report on a continuing program to develop and test reflecting coatings suitable for use in Fabry-Perot etalons operating in the far ultraviolet region of the spectrum. UV etalons are of particular interest for solar studies as they have the potential to enable one to make wide-field high resolution diagnostic images such as spectroheliograms, dopplergrams, and density maps in isolated spectral lines formed in the upper chromosphere, transition region and lower corona. The performance of the high-efficiency coatings required by a UV etalon is limited both by the availability of suitable materials, and by the uniformity and accuracy of the deposition process. The lack of UV transmitting materials with a wide range of refractive index is especially troublesome. The latter problem may be partially overcome by using a vacuum-spaced etalon design. A vacuum-spaced etalon with cultured quartz plates was successfully operated at 160 nm in a previous study. In this study, we investigated a family of coating designs based on the fluoride salts of magnesium and lanthanum, finding that usable etalon performance may be achievable at wavelengths as short as 120 nm. Results of theoretical predictions and the performance of test coatings will be presented. This work was supported by NASA under contract NASW-5007.

1 Introduction

The motive for the work to be reported here is the development of a capability to rapidly image the solar atmosphere in isolated far-ultraviolet emission lines. Observation of the structure and dynamics of features that are visible in the resonance lines of ions such as C III, C IV, and O V provide important clues to the underlying physical processes operating in the the solar chromosphere, transition zone and corona. These features have angular sizes ranging from a few arcseconds to a few arcminutes and time scales as short one second or less. Observations requiring both a large, well resolved angular field and high time resolution are impractical with slit spectrographs, but would be feasible with a filtergraph, provided that a suitable narrow-bandpass filter could be produced.

The dominant characteristic of the solar UV spectrum is an emission continuum that increases in intensity by about five orders of magnitude between 1200 and 4000 Å. Superimposed on this

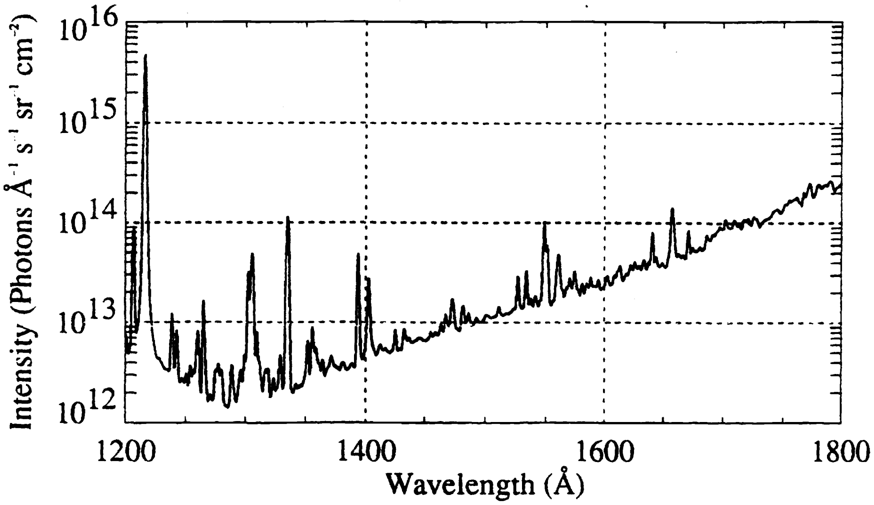

Figure 1: Solar ultraviolet spectrum recorded by the SOLSTICE instrument on the UARS spacecraft (courtesy of Dr. G. Rottman, Univ. of Colorado).

continuum is a series of atomic lines and molecular bands that are seen in absorption above 2000 Å and in emission below about 1800 Å (Figure 1). Both emission and absorption features are found at intermediate wavelengths. Although the emission spectrum below 1800 Å is sparse, the observation of lines such as the resonance doublet of C IV at 1548, 1550 Å is complicated by the presence of nearby lines and the strong continuum. The narrowest interference filters that are currently available have a bandpass of about 30 Å(FWHM), which is wide enough to admit substantial contributions from the unwanted sources. In the TRACE instrument, for example, we found that the C IV resonance lines contributed only 1/3 of the response in the 1550 Å channel, the remaining 2/3 arising from the continuum[1].

We have been studying the feasibility of improving the spectral purity of these filtergrams through the use of Fabry-Perot etalons. The principle is illustrated in Figure 2, taken from our earlier work[1]. The continuous curve in Figure 2 shows the 1500–1600 Å region of the spectrum; the dashed curve represents the 1550 Å narrow-band interference filter. Also shown are three orders of a hypothetical Fabry-Perot etalon with a finesse of 10. The etalon spacing was chosed such that the free spectral range is about twice the bandwidth of the interference filter. The bandwidth of the central order is well matched to the widths and separation of the C IV lines, and the two adjacent orders lie well outside of the bandpass of the interference filter. The relative contributions of the C IV lines and the remaining continuum may be evaluated by tuning the etalon over a narrow wavelength range.

Initial attempts to produce a working etalon were carried out under the Lockheed Independent Development program. The etalon plates and mounting were fabricated by Queensgate using cultured quartz crystals grown by the Sawyer Research Products, Inc. The coatings were made by the Acton Research Corp. The etalon achieved a finesse of about 4 at 1595 Å; its performance at the design wavelength of 1550 Å appeared to be limited by impurities in the quartz [1].

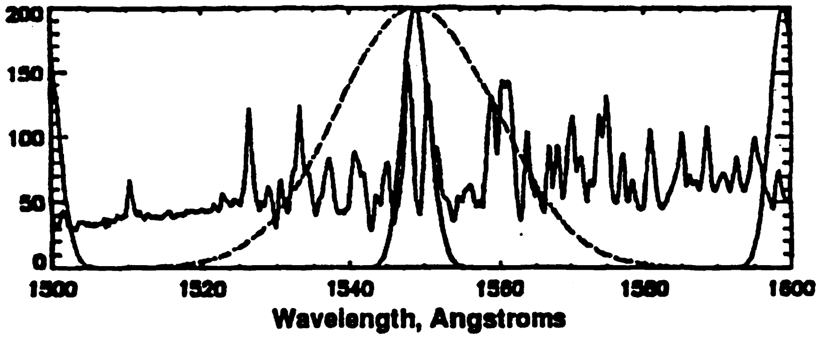

Figure 2: Use of a Fabry-Perot etalon to isolate the C IV lines. The figure shows a typical scan of the 1500 – 1600 Å region of the solar spectrum together with the transmission curve of a narrow-band filter (dashed curve) and three orders of a Fabry-Perot etalon with a finesse of 10. The dashed curve is representative of the performance of the TRACE 1550 Å filter, which has a bandpass of about 30 Å.

2 Theoretical Studies

A Fabry-Perot etalon consists of two parallel reflecting surfaces separated by a small gap (typically a few wavelengths of the light to be analyzed). The development of a successful etalon requires two elements: transparent substrates or spacers of adequate flatness and efficient, high reflectivity coatings. We have considered only vacuum-spaced etalons, both to maximize the range of refractive indices available for the reflector design and to permit the etalon spacing to be varied for wavelength scanning.

In the vacuum ultraviolet, the design of reflecting coatings is severely constrained by the properties of materials. Most materials are opaque except in very thin layers, and the available range of refractive indices is small. The most useful materials tend to be fluoride salts of alkali metals and rare earths such as LiF, MgF_2, BaF_2, LaF_3, etc. Some metals, such as aluminum, have high reflectivity, but their strong absorption coefficients make them difficult to use as an effective etalon coating.

We have chosen to pursue all-dielectric multilayer coatings for this phase of our investigation, based on previous work carried out by one of us (Dr. M. Zukic) at the University of Alabama, Huntsville [2], [3], [4]. The coatings consist of alternating layers of high-index and low-index materials whose optical thicknesses are chosen to produce constructive interference in the reflected beam. Both BaF_2 and LaF_3 are suitable as high-index materials, though both have relatively high absorption coefficients. MgF_2 is a suitable low-index material and transmits well down to about 115 nm.

In the simplest case, the optical thickness of each layer is 1/4 wave, so that all partially reflected beams are in phase. However, as shown by Zukic and Torr [5], the total reflectivity of the multilayer stack may be improved by decreasing the relative thickness of each high-index layer with respect to the low-index one, keeping the optical thickness of each pair at 1/2 wave. Zukic and Torr

Wavelength (nm)	Predicted Finesse	Maximum Transmission
121	4.9	4.74 %
130	5.8	2.84 %
135	6.4	8.38 %
145	14.7	39.1 %
155	34.2	36.5 %

Table 1: Initial results from a theoretical study of Fabry-Perot etalon performance.

have applied the name "π stack" to this design. The resulting coating will reflect strongly at and near the design wavelength. The peak reflectivity of a π stack can be larger than the equivalent 1/4 wave design because of the lower optical path length in the (more strongly absorbing) high-index material. This optimization also minimizes the absorptance at the design wavelength so that the residual energy is transmitted to the substrate; an important characteristic for Fabry-Perot applications.

At wavelengths outside of the main reflection peak, most of the incident energy is either absorbed or transmitted to the substrate. Increasing the number of periods increases the peak reflectivity and decreases the usable bandwidth. It is also possible to create coatings with two or more reflection peaks by varying the layer period through the coating.

In this portion of the study, we investigated single-band, two-band and three-band coatings designed for wavelengths ranging from 121.1 nm to 155 nm. All designs are based on alternating layers of magnesium and lanthanum fluorides on a magnesium fluoride substrate. The results are very encouraging. The predicted finesse for a single-band etalon can be as high as 34 at 155 nm and it appears that functional etalons may be made for wavelengths as short as 121 nm. Figure 3 shows the optical properties of the 155 nm coating; No attempt has been made to reduce the response outside of the main reflection band and a number of secondary maxima are seen between 120 and 140 nm. Most of the energy at the design wavelength is either reflected or transmitted by the coating; relatively little is lost to absorption. The predicted performance of this coating in an etalon is shown in Figure 4. A summary of the results for the other etalon designs is given in Table 1.

Figure 5 shows a two band coating designed to operate at 140 and 155 nm, achieving 86% and 90%, respectively, at the two wavelengths. An etalon based on this coating would be useful for diagnostic spectroscopy of the solar transition region. The resonance doublet of C IV (154,8 and 155.0 nm) would be observed in the long wavelength band; the resonance lines of Si IV and the density sensitive lines of O IV and S IV all lie in the short wavelength band. An example of a three-band coating design is given in Figure 6.

3 Experimental Work

The second phase of our study involves fabricating and testing the coating designs discussed above to determine the extent to which the predicted performance can be realized. This work is still

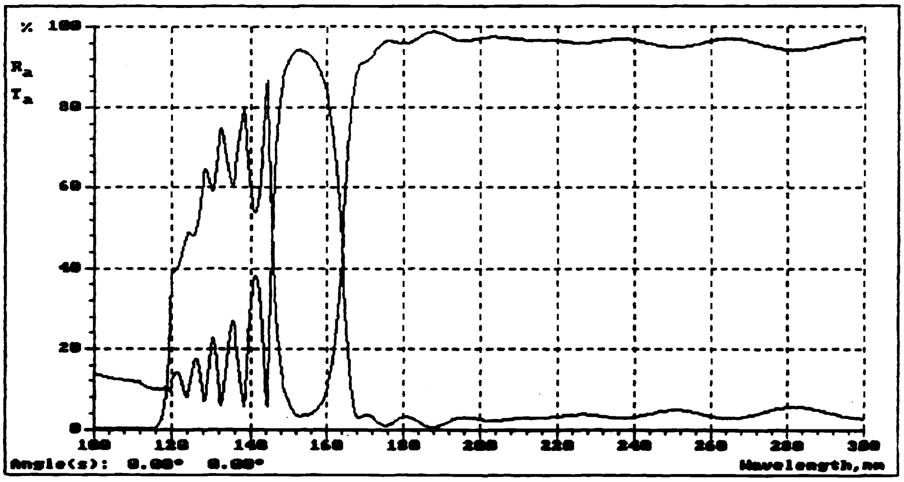

Figure 3: Reflectance and transmittance of a multilayer optimized for use in a Fabry-Perot etalon operating in the 155 nm range. At the design wavelength, the multilayer has a peak reflectance of 91.2%, a transmittance of 5.3% and an absorptance of 3.5%.

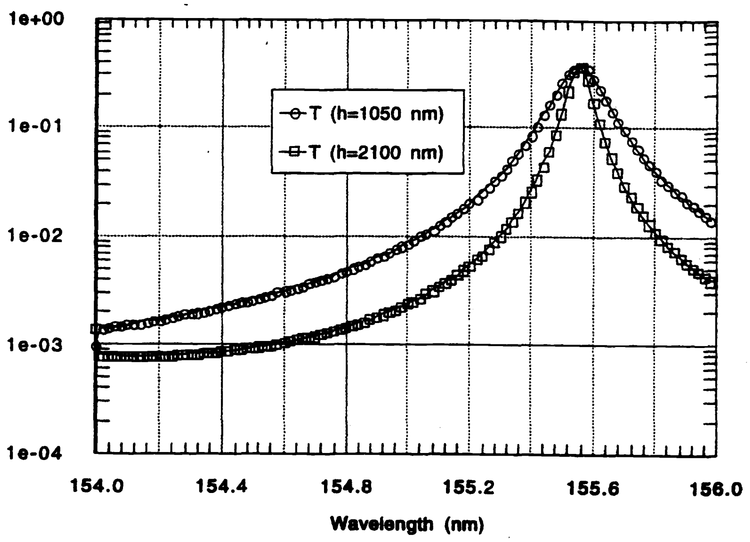

Figure 4: Predicted performance of a Fabry-Perot etalon using the multilayer coatings designed for 155 nm. The two curves correspond to different vacuum gap thicknesses, as shown on the plot. A finesse of 34.2 and a maximum transmission of 36.5% are realized in each case.

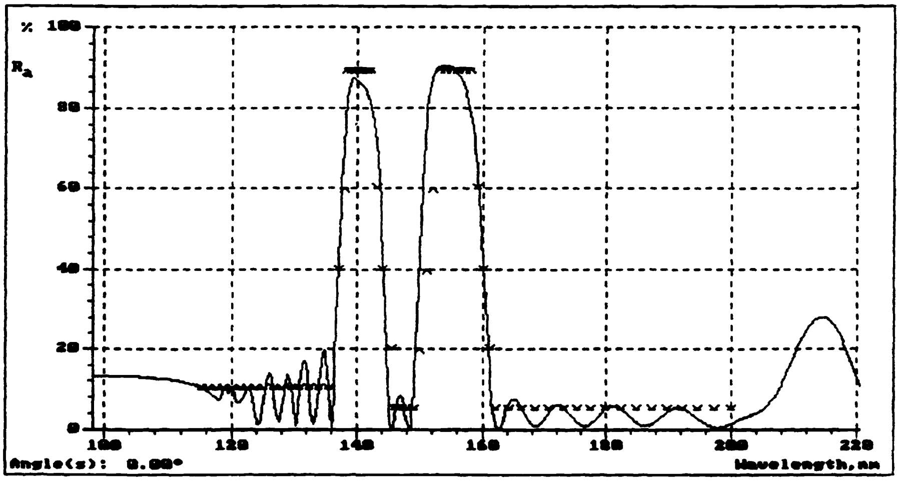

Figure 5: Multilayer dielectric coating designed to cover two spectral ranges. Such coatings would be useful for observing sets of spectral lines whose wavelength separations are too large to fit within a single range. This coating was designed for observing the solar transition region in the C IV, Si IV, O IV and S IV lines.

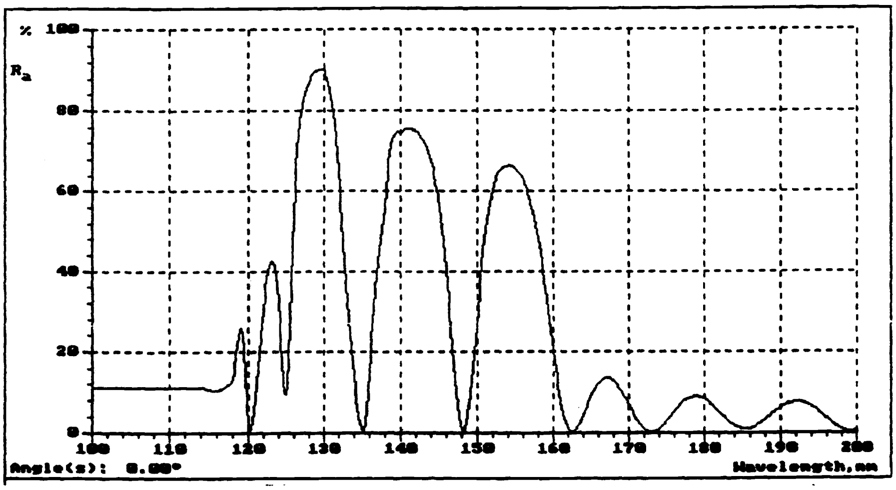

Figure 6: Multilayer dielectric coating designed to cover three spectral ranges.

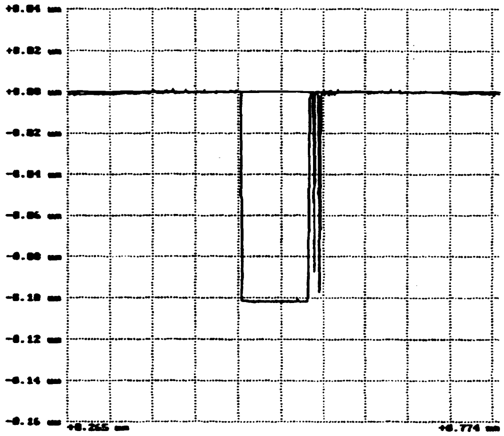

Figure 7: Surface profile of a single-layer MgF_2 test coating. The rectangular step corresponds to an area where the coating has been scratched away, revealing the substrate. The vertical scale is 200 Å / division; the thickness of the coating is about 1020 Å.

underway at the time of this writing, and only a progress report can be given at this time. Most of the previous work by Zukic and collaborators ([2], [3], [4], [5]) was carried out at the Center for Space Plasma and Aeronomic Research at the University of Alabama, Huntsville. The equipment used for those studies is unavailable to us, requiring a new coating chamber to be prepared and calibrated. This is being done at Cascade Optical Coatings, Inc. of Santa Ana California.

3.1 Calibration Coatings

Since the equipment at Cascade Optical Coatings had not previously been used for vacuum ultraviolet applications, a number of calibration runs were required to determine the operating parameters for the evaporation sources and to calibrate the quartz crystal microbalance used for real-time thickness monitoring. A series of single-layer samples were prepared for both MgF_2 and LaF_3. Part of each substrate was masked in an attempt to produce a sharp step whose height could be measured.

Thickness measurements of the test coatings were made at the Marshall Space flight Center, using a Rank Taylor Hobson Nanostep 2. The extremely thin coatings were very difficult to measure, as the step produced by the coating mask was not sufficiently sharp. Instead, a paperclip was used to scratch through the coating down to the substrate and the depth to the substrate was typically measured at five transects across the scratch and an average obtained. Tests on uncoated portions of the substrate revealed that the paperclip did not make a measurable scratch in the substrate surface. In the thick coatings the variation in depth was as much as plus/minus 20 angstroms at different positions along the scratch and and in very thin coatings the scratch depth varied by a much as plus/minus 5 angstroms from point to point across the scratch. Though rudimentary, the scratch technique turned out to be surprisingly successful. A typical scratch profile is shown in Figure 7.

3.2 Test Coatings

Development of the final coating parameters is an iterative process, requiring several coating runs before the required performance levels are achieved. Pyrex substrates are being used for the initial coatings in order to minimize cost; MgF_2 will be used once the design begins to converge. To date, two coating runs have been made, and additional ones are scheduled.

Reflectometry of the test coatings is being done at Lockheed Martin in our general-purpose soft x-ray / UV calibration facility. The system includes an ARC Model DS775 deuterium lamp, a McPherson glancing-incidence VUV monochromator, a glancing incidence parabolic collimator, and an experiment chamber with a motorized sample and detector positioning system. Intensities of the incident and reflected beams are measured with the same detector, an EMR 541-F photomultiplier operated in the pulse counting mode. The background counting rate for this detector is less than 1 count/sec. The deuterium source is sufficiently stable that separate wavelength scans of the incident and reflected beams can be made without introducing intensity-drift errors. Scanning and data recording are under the control of a desk top computer. Measurements in this facility are made at an incidence angle of 10° and cover the 1200-1800 Å wavelength range. A Carey Model 3E spectrophotometer is used to measure the reflectivity above 2000 Å.

The initial attempts produced coatings that reflect in the desired wavelength range, but with less than optimum performance. Maximum reflectivities achieved were around 70% and were found at wavelengths from 50 to 300 Å longer than the target values. Further refinement of the coating process is expected to improve these values.

4 Conclusions

Fabry-Perot etalons operating in the far ultraviolet have the potential to be promising research tools. High-efficiency all-dielectric coating designs suitable for use in far UV etalons have been found for wavelengths as short as 1200 Å Designs with two or even three bandpasses appear to be feasible, providing additional wavelength coverage. Initial test results are encouraging, and further development effort is clearly warranted.

5 Acknowledgements

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