Narrow-Band Tunable Filters For Use In The Far Ultraviolet Region

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I. Introduction

The far ultraviolet (FUV) wavelength regime (912Å - 2000Å) is an important region for scientific research for many of the NASA Explorer Missions, encompassing investigations in astrophysics, space plasma physics, and solar physics. This universality of importance is due to the presence of numerous key spectral line species that exist in the FUV in many different ionization stages, thus enabling a sampling of a wide range of plasma temperatures up to ~ 500,000K. For example, the FUV spectral lines of CIII (977Å), OVI (1032 & 1038Å), NV (1241Å), SiIV (1394 & 1403Å), CIV (1548 & 1550.8Å) are particularly important in sampling the emission from hot gas in the 80,000K - 500,000K range. Emission at these high temperatures arises in astrophysical plasmas associated with supernovae shocks, superbubbles, galactic halos and AGN.

We note that although high resolution (< 5 arc second) astronomical photometric images have been recorded at l > 1400Å by the HST Wide-Field Camera, HST-STIS imager and the UIT instrument on the Astro I & II shuttle mission, the best attempts at performing narrow-band FUV astronomical imaging at l < 1400Å have been the spectro-photometric mappings of the Cygnus Loop in the OVI line (~ 1036Å) by Blair *et al* (1991) and by Ramussen & Martin (1992). Both sets of observations were taken at rather coarse angular resolutions of **only ~ 0.2°** with an associated spectral resolution of FWHM ~ 50Å. The use of high (arc second) resolution imaging in astronomy is particularly important since although spectroscopic studies reveal the underlying physics and kinematics of astrophysical objects, images (especially wide-field views) often give unique insights into which particular processes are at work and over which spatial dimensions they operate on an astronomical object. In the following section we describe a novel type of narrow-band filter we have developed at Berkeley that could have great potential in high spatial resolution astronomical imaging in the far UV.

II. Tunable Alkali Halide Crystal Filter Designs

It is well established that alkali halide filters such as BaF2, CaF2, and LiF have extremely sharp transmission cutoff edges in the ultraviolet region, as shown by the theoretical transmission curves of Figure 1(a) for LiF and Figure 1(b) for CaF2 (Laufer *et al* 1965). These crystal-filter cutoff wavelengths are at ~1225Å for CaF2 and 1045Å for LiF, both wavelengths being not only being conveniently close to the important high temperature plasma diagnostic spectral lines of 1240Å (NV) and 1036Å (OVI), but also close to the intense lines from Lyman-a and Lyman-b, which often prove a severe source of geocoronal (scattering) contamination of weaker, nearby spectral lines of interest. Furthermore, the cutoff wavelengths for many other halides have been reported to be particularly temperature dependent (Laufer *et al* 1965, Baldini & Bosacchi 1968), such that the transmittance curves shift to longer wavelengths as the temperature is increased, and to shorter wavelengths when cooled (Davis 1966). Clearly, if the temperature of an alkali halide filter can be accurately controlled, then this would potentially provide a powerful means of producing an FUV filter with a controlled, sharply defined, variable transmission cutoff wavelength. Such 'tunable' alkali halide filters would be extremely useful in blocking shorter wavelength out-of-band leaks produced by the unwanted nearby intense geocoronal glow from both Lyman-a and Lyman-b radiation. This temperature dependent optical behavior, seemingly unique to the alkali halides, could clearly be utilized in the design of 'tunable' FUV filters.

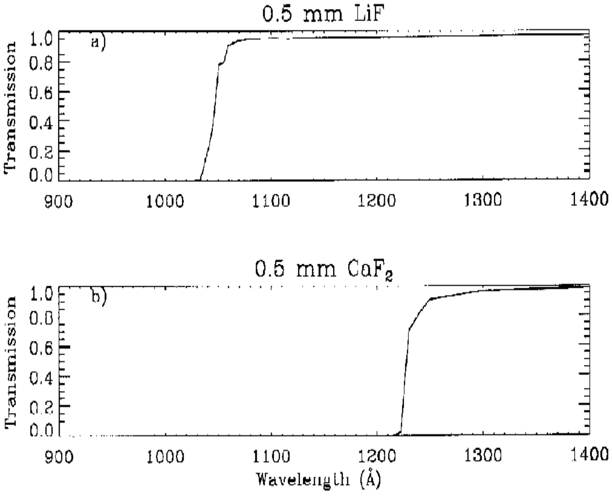

Figure 1.

In order to investigate the feasibility and utility of such FUV filters, we have recently undertaken an exploratory program of laboratory measurement of the variation in FUV transmission (1000 - 1600Å) of two promising candidate halide filter materials (LiF and BaF2) over a temperature range of -50°C to +60°C. Samples of 25mm diameter, VUV-grade crystals of 0.5mm-thick LiF and 3mm-thick BaF2 were purchased and mounted into a filter-assembly incorporating a Marlow Industries (UK) vacuum-compatible thermo-electric Peltier cooling device (TEC). This laboratory-grade cooling device is capable of operation over the -50°C to +60°C range, weighs 10g, and requires ~3 watts of input power. The FUV transmission characteristics of both filters were measured in the UCB/SSL Experimental Astrophysics Group Vacuum UV calibration chamber using a microchannel plate photon counting detector with the measurement techniques discussed in Vedder *et al* (1989). In Figure 2 we show the measured transmission characteristics of a LiF crystal as a function of temperature over the -20°C to +60°C range. Note how the sharp cutoff wavelength shifts from 1015Å to 1055Å, and how the transmission at shorter wavelengths is zero. Such a filter could have the clear advantage of isolating the important emission line doublet of OVI at 1036Å that dominates the FUV emisison spectra of SNR's such as the Cygnus Loop & Vela SNR, and is thought to be a prominant emission mechanism in the halos of spiral galaxies and of AGN. In addition, since the cutoff wavelength is temperature variable, this filter material behavior could be utilized to discriminate between low-z red-shifted OVI emission from nearby and more distant extragalactic objects.

Figure 1. Transmission of a) 0.5 mm LiF, and b) 0.5 mm CaF_2 crystals.

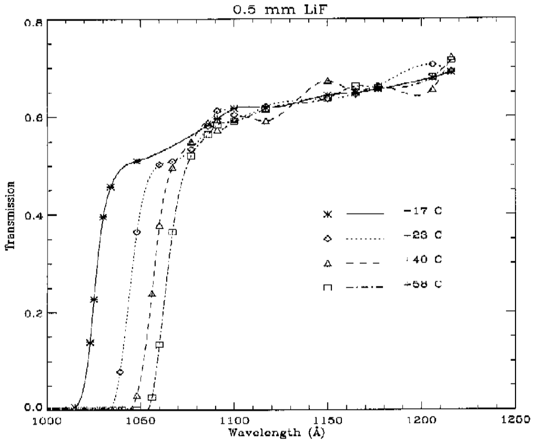

Figure 2. Experimentally determined FUV transmission of LiF over the temperature range -20°C to +60°C.

Figure 2.

In Figure 3 we show similar FUV transmission curves for a 3mm-thick BaF2 filter for crystal temperatures of -32°C and +25°C. Note, again, the well-defined transmission cut-off behavior, and the shift in cut-off wavelength from 1325Å to 1365Å. The BaF2 filter would be an ideal candidate for observations of the strong solar chromospheric CII 1336Å line that samples

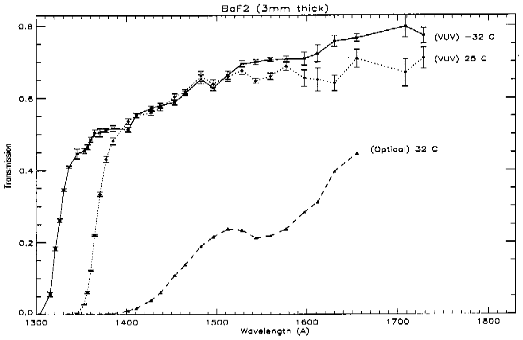

Figure 3. Measured transmission of VUV-grade BaF_2 for -32°C and +25°C. Also shown is a +32°C measurment of an optical quality BaF_2 crystal.

Figure 3.

emission from plasma at a temperature of ~20,000K, using the 'difference-technique' described in the following section. In the case of ionospheric imaging such a filter could provide an ideal discriminator for isolation of the OI 1356Å line whose observation has historically been affected by out-of-band contamination from the nearby strong OI 1304Å line.

The scientific potential of such temperature-dependent FUV transmission behavior can be realized in 2 different ways, **tunable bandwidth** and **tunable center-wavelength**. In Figure 4 we demonstrate the tunable bandwidth characteristic using the 'difference filtering technique' in which a cold filter transmission is subtracted from a warmer one. The two LiF filters are held at a fixed *average* temperature of +5°C, and temperature differences, DT, from +10°C to +50°C are shown. The central wavelength of 1035Å remains constant and larger DT's produce wider bandpasses centered on this wavelength. Note how the use of this difference filtering technique results in a narrow-band 'difference filter' with a FWHM of only 20 Å and a net transmission of ~ 35% (for DT = +20°C). Such a difference filter combination has the potential for imaging of the important OVI doublet at 1036Å in which images (either of the solar corona or emission from a SNR) taken with different filter temperatures could be subtracted to produce a narrow-band 'difference' response.

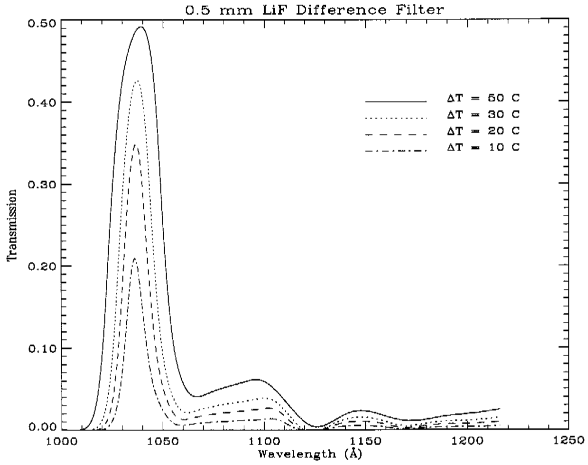

Figure 4.

Figure 5 illustrates the tunable center-wavelength capability. The measured transmission curves of LiF filters with a fixed temperature of 5C, 15C, 25C and 35C are shown. Note how the center-wavelength shifts to longer wavelengths as the temperature increases, *and* how the throughput remains high (35%) along with a narrow FWHM of ~ 20Å. This transmission behavior is common to many other halide materials (see Table 1) that can produce the isolation of several important FUV spectra lines. This unique 'transmission difference tunablity' is the cornerstone of the present proposal, and has immense potential in many aspects of space science observations, but particularly in astrophysics where high resolution OVI images of the hot (T ~

500,000K) Universe could be obtained to reveal the emission characteristics of different valued low-z red-shift objects.

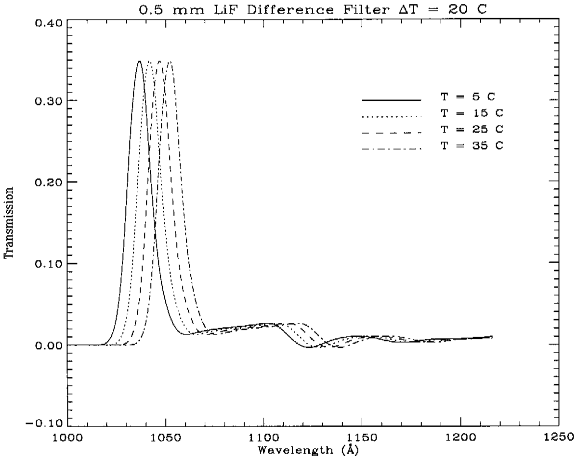

Figure 5. Tunable wavelength of LiF filters, with □T = 20°C over the range of +5°C to +35°C.

Figure 5.

IV. Transmission Measurement In The FUV

Preliminary research indicates that CaF2, BaF2, LiF, MgF2, SrF2 and Al2O3 (sapphire) may be excellent candidates for FUV tunable transmission crystal filters. In Table 1 we list the expected room temperature cut-off wavelengths for these filters and the approximate wavelength range over which we believe a tunable difference filter can be fabricated for a temperature range of -50°C to +60°C. Also listed are the prime FUV spectral lines of interest for many applications in space science misisons that could be isolated using such tunable filters.

TABLE 1

Filter Material	Cut-off (20°C)	Potential l Range	Spectral Line
LiF	1035 Å	1020 Å - 1050 Å	OVI(1036Å), Ly ß1 0(1025))
MgF2	1120 Å	1100 Å - 1140 Å	SiIV (1122Å,1130Å)
CaF2	1225Å	1205 Å - 1245 Å	Ly a, NV (1240Å)
SrF2	1310 Å	1290 Å - 1340 Å	OI (1304Å), CII (1336Å)
BaF2	1345 Å	1325 Å - 1365 Å	CII (1336Å), OI (1356Å)
Al2O3	1550 Å	1530 Å - 1570 Å	CIV (1550Å)

V. Long Wavelength Transmission Suppression

Although, as shown in Figure 4, narrow band transmissions can be obtained by the use of 'difference filtering', such a technique is of practical use only if the majority of (line) flux from the incident photon source is contained within the pass-band of the resultant difference filter. This is particularly problematic for any filter aimed at isolating the OVI lines at 1036 Å (or the OI 1336 Å line) in which the intense Lyman-± 1216 Å line completely dominates any long wavelength filter transmittance by many orders of magnitude.

Previous attempts at producing effective Lyman-± suppression filters have largely been disappointing with rejection factors typically only of ~ 100 (Chakrabarti *et al* 1994, Edelstein 1989). Since it is clearly very difficult to produce a single rejection filter that can simultaneously satisfy both high in-band performance and high out-of-band suppression, we have investigated two different methods to suppress the long wavelength transmission leak of cooled alkali halide filters: (a) by use of UV photocathode materials such as KBr and CsI, and (b) filtering by using a thin-film such as In. Preliminary data from our research program indicates that a thin-film (~ 1000Å) of Indium deposited onto the surface of a LiF filter would produce the transmission properties (at 20°C) shown in Figure 6. The peak/Ly a ratio is 250:1, with throughput at 1216Å below 10-5. Further attenuation at 1216Å (perhaps from a thin Indium filter) will likely be required to achieve our rejection goals.

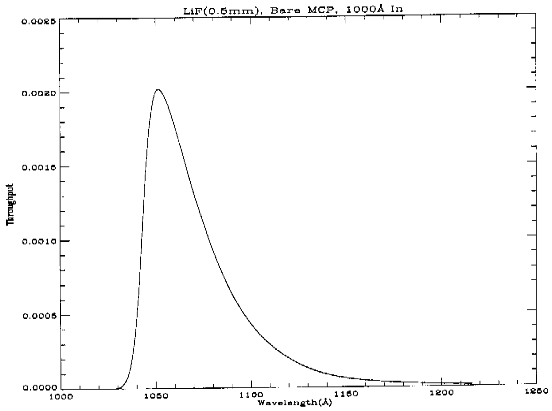

Figure 6. LiF crystal filter with 1000Å Indium thin-film coating

Figure 6.

VI. Filter Thermal Uniformity & Stability

Since the transmission of a halide filter clearly depends on the temperature profile of the crystal, it is critical that the filter assembly does not permit significant differential cooling across the bulk crystal. It is therefore desirable to quickly obtain an isothermal filter temperature (± 0.1°C) at any given cooler power output. Our present laboratory Peltier system is capable of cooling the filter samples at a rate of ~ 2°C/ minute with a temperature stability of < 0.2°C at the final desired operational temperature. Initial measurements on LiF and CaF2 crystal samples indicate that any differences in crystal temperature due to the present TEC device produce insignificant (< 1%) transmission differences. The actual final choice of a spaceflight-worthy thermo-electric device will depend on mass, power, cost and the aforementioned performance considerations, specifically the rate of cooling for utilization of the "difference filter transmission" technique. Typically, such a device will be required to operate over a temperature range of -50°C to +60°C with minimum power consumption (*i.e.* < 5 watts), have low mass, and be mechanically sound to meet the rigors of launch. Currently we are working with the University of Colorado UV Astronomy Sounding Rocket program (Dr. Eric Wilkinson) to fabricate a space-worthy filter+cooler assembly that will be used to obtain images of the Cygnus Loop SNR in the emission line of NV (1238Å).

References

Baldini, G. and Bosacchi, B., 1968, Phys. Rev. **166**, 863.

Chakrabarti, S. et al, 1982, Applied Optics, **21,** 3417.

Chakrabarti, S. *et al*, 1994, Opt. Eng, **33**, 409.

Davidsen, A., Science, 259, 327, (1993)

Davis, R.J., 1966, J.Opt. Soc. Am., **56**, 837. Delaboudiniere, J.P. *et al* (1996), Solar Phys. **162**, 291.

Edelstein, J. 1989, Proc. SPIE, **1160**, 5.

Edgar, M. *et al*, 1996, SPIE, 2808, 313

Glenar, D.A., John J. Hillman, Babak Saif, and Jay Bergstralh, 1994, Applied Optics, Vol. **33**, No. 31, 7412-24.

Hurwitz, M. *et al*, 1985, Appl. Opt., **24**, 1735.

Jelinsky, S. et al.1987, Proc. SPIE, **830**, 620.

Keller, G.L. *et al*., 1986, Proc. SPIE, **689**, 231.

Keski-Kuha, R. *et al*, 1991, Proc. SPIE, **1546**, 614.

Kohl, J. *et al* (1997), BAAS, **188**, 4906.

Kondo, Y. "Exploring the Universe with IUE", Kluwer Academic Pub, (1987)

Koppleman, 1960, Ann. Phys. (Leipzig), **5**, 388.

Laufer, A.H. *et al*, 1965, J. Opt. Soc. Am., **55**, 64.

Lemaire, P *et al* (1997), Solar Phys. **170**, 105.

Marsh, D., O.H.W. Siegmund, and J. Stock, Proc. SPIE, **2006**, 51-81 (1993).

Mrowka, S. *et al*., 1985, Proc. SPIE, **597**, 160.

Paxton, L. et al, Proc. SPIE, **1764,** 65 (1992)

Rasmussen, A. and Martin, C., Ap.J., 396, L103, (1992)

Rubloff, G.W., 1972, Phys. Rev., **5**, 662.

Seely, J. and Hunter, W., 1991, Appl. Opt., **30**, 2788.

Siegmund, O.H.W. *et al*, 1987, Proc. SPIE, **868**, 18.

Siegmund, O.H.W. *et al*., 1992, ESA SP-356.

Siegmund, O.H.W. Mark Gummin, Joseph Stock, Daniel Marsh, Richard Raffanti and Jeffrey Hull, *Proc. SPIE*, (1994).

Siegmund, O.H.W., M.A. Gummin, J. Stock, D. Marsh, R. Raffanti, T. Sasseen, J. Tom, B. Welsh, G. Gaines, P. Jelinsky, and J. Hull, *Proc. SPIE*, **2280**, 89-100 (1994b).

Siegmund, O.H.W. *et al*, 1995, funded for NASA Advanced Missions Concepts for Astronomy.

Stock, J., O.H.W. Siegmund, M. Hurwitz, R. Raffanti, S. Bowyer, and M. Lampton, *Proc. SPIE*, **2006**, 128-138 (1993).

Torr, D. *et al* (1995), Sp.Sci. Rev., **71**, 329.

Tropf, W.J. 1995, Opt. Eng., **34**, 1369.

Vedder, P. *et al*, 1989, Proc. SPIE, **1159**, 392.

Welsh, B.Y. *et al*., 1988, Proc. SPIE, **982**, 335.

Zucik, M. *et al*., 1990, Applied Optics, **29**, 4284.

Zukic, M. and Torr, D., 1992, Applied Optics, **31**, 1588.

Zucik, M. *et al*., 1992, Proc. SPIE, **1744**, 178.