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A LYMAN-ALPHA TUNABLE ACOUSTO-OPTIC FILTER FOR DETECTING SUPERTHERMAL FLARE PROTONS

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University of Hawaii, Institute for Astronomy

2680 Woodlawn Drive, Honolulu, HI 96822

Donald L. Mickey, Principal Investigator

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Introduction

The goal of this project was to develop and characterize a narrow-band, tunable filter for use near the Lyman-alpha line of hydrogen at 121.6 nm. Such a filter could form the critical component of an instrument to observe asymmetries in the solar Lyman-alpha line, caused by energetic protons accelerated during the impulsive phase of solar flares. Characteristic charge-exchange nonthermal emission at Lyman alpha should be produced when sub-MeV protons are injected into the chromosphere (Canfield and Chang 1985; Orrall and Zirker 1976), but no instrument suitable for their detection has been developed. Such an instrument would require a narrow-band—less than 0.1 nm—tunable filter with aperture and throughput consistent with imaging a solar active region at 0.1 second intervals. The development of acousto-optic tunable filters (AOTF) suitable for use as compact, simple tunable filters for astronomical work suggested an investigation into the use of an AOTF at Lyman-alpha.

Acousto-optic filter design

Acousto-optic filters are constructed from single crystals of any of several birefringent materials, among which are quartz, TeO_2, $CaMoO_4$, CdS and MgF_2. They function by the scattering of light from one polarization into the other by resonant coupling of the optical wave with an acoustic wave in the crystal. Chang (1976) discusses several types of AOTFs. A few materials suitable for AOTFs have anomalous dispersion of birefringence near their absorption band edge. Chang and Katzka (1982) demonstrated a filter using CdS which exploited the dispersion of birefringence to obtain both high spectral resolution and large acceptance angle at wavelengths near 550 nm. Similar behavior of MgF_2 near its band edge suggested that it would be suitable for this type of filter at wavelengths near 122 nm.

Early in this project, a design study for the Lyman-alpha filter was carried out. This study lead to a filter design which predicted a bandpass of approximately 0.025 nm at Lyman-alpha and a diffraction angle of 0.25 degrees. The tuning range for a single transducer is about one octave in acoustic frequency, which corresponds to a very narrow range—about 2 nm—in optical wavelength. The predicted efficiency at 122 nm depends on the acoustic power input, and on the interaction path length between the optical and acoustic beams; estimated efficiency for 4 w power input and a 4 mm interaction length was 30%. At wavelengths in the visible and near ultraviolet, the same filter was calculated to diffract one to three percent of the incident light with a diffraction angle near 0.7 degrees. The filter bandpass in acoustic frequency, for a fixed optical wavelength, was predicted to be about 2.5 MHz throughout the long wavelength part of the tuning curve. The major difficulty with designing a device for Lyman-alpha was that the indices of refraction for MgF_2 were not sufficiently well known in this wavelength range, and the filter tuning range and deflection angle depend quite sensitively on both the birefringence and its dispersion.

Filter fabrication

A contract was let with AOTF Technology in Sunnyvale, CA to fabricate a filter based on the design configuration. The vendor provided several test filters during the course of the project, modifying the fabrication technique in response to problems we discovered with the filter's performance or reliability. Several false starts in filter manufacture delayed the testing program: one of the most difficult aspects of AOTF filter fabrication is bonding the transducer to the crystal in a way that is both durable and acoustically efficient. The most reliable technique appears to be be pressure bonding with tin or another metal under vacuum, but some delay was incurred in development of the needed equipment and expertise for this procedure. Since there was considerable uncertainty about the acoustic frequency required, we initially attempted to make devices with a temporary transducer, planning to determine the appropriate frequency range for the final filter from initial tests. We found, however, that devices made with the temporary bonds could stand only quite low levels of acoustic power, especially in the vacuum test configuration where heat dissipation was less efficient. Several other aspects of the fabrication process—crystal orientation, polishing of the crystal and transducer, and coatings, for example—required special equipment and methods to be developed. Eventually we received three filters for evaluation, each with a permanent transducer, tuned for acoustic frequency ranges of 30-75 MHz, 75-150 MHz, and 175-250 MHz. These devices could be operated with lower transducer efficiency somewhat beyond their nominal frequency ranges, so we had adequate overlap.

Polarizers

Since the predicted diffraction angle at 122 nm was only a quarter of a degree, we considered trying to obtain polarizers which could be used at that wavelength. Two possibilities were investigated: some work is being done on "wire-grid" polarizers with spacing small enough to be useful at this wavelength; and multilayer polarizers have been demonstrated at Lyman-α. Neither technology was accessible within the fiscal constraints of this project, however, so we restricted our test plans to those utilizing spatial separation of the transmitted and diffracted beams.

Laboratory test configuration

The filter was mounted in a chamber mounted to the exit slit of a one-meter normal-incidence vacuum monochromator, as shown schematically in Figure 1. The intermediate slit limited the beam width in order to make focusing less critical. The monochromator exit slit was collimated by LiF lens L1, and re-imaged onto the detector slit by L2. The detector slit could be translated in the direction of diffraction by an externally accessible stage. Both monochromator slits, as well as the detector slit, were set to 100 μm. This arrangement gave a spectral resolution of 0.11 nm in the vacuum UV, and resolution in diffraction angle of about 0.1 degree. Two photomultipliers were used as detectors: one for visible and near-ultraviolet measurements, and a CsI-coated Channeltron for the vacuum UV measurements. Both photomultipliers were operated in a pulse-counting mode.

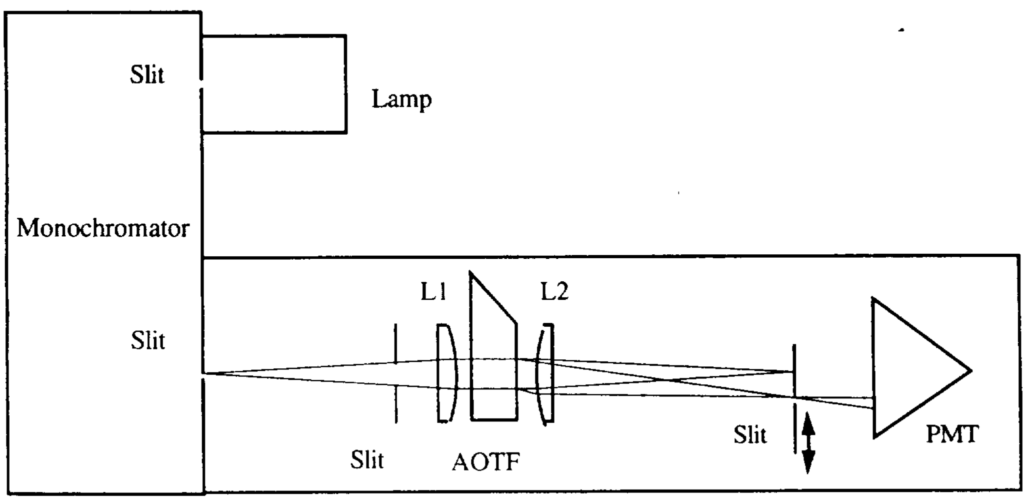

Figure 1. Layout of test configuration.

A small computer was used to control the RF synthesizer and record the count rate from the detector. A given measurement consisted of tuning the acoustic frequency through a certain range, recording the detector output at each step.

Testing of delivered filter

The filter crystals were tested for transmission at Lyman-alpha, and were found to transmit approximately 25% of the incident light. This figure was consistent from one device to another and didn't appear to change with normal handling of the devices, indicating that surface quality was less of an issue than we thought.

We first tested the filters using a mercury-line source. The focal length of the LiF lenses was too long at near-UV wavelengths, so we replaced them temporarily with quartz lenses. At 254 nm we detected the diffracted beam quite easily. One scan in acoustic frequency is shown in Figure 2. The data shown are for filter #10, which was optimized for use at the highest acoustic frequencies. The peak frequency is 161.5 MHz, somewhat lower than the predicted frequency of 168.9 MHz. This particular filter was consistently lower in acoustic frequency for a given wavelength, possibly indicating that the crystal faces were not cut at exactly the design angles. For this measurement, the detector slit was offset from the undiffracted beam by 1.05 mm, corresponding to a diffraction angle of 0.80 degrees. Since the lenses could not be exactly focused due to mounting constraints, there is some uncertainty in the measured diffraction angle, but it agrees reasonably well with the predicted angle of 0.73 degrees. The brightness of the diffracted beam is 0.5% of the brightness of the undiffracted beam. At this wavelength the predicted efficiency is 1.5% into each of the two diffracted beams. We ascribe the difference to a misalignment of the optical path with respect to the active acoustic beam (which filled only a small part of the crystal). Similar results, with better signal-to-noise, were obtained with filter #11, optimized for the middle 75-150 MHz range, at the 297 nm and 312 nm mercury lines. An example is shown in Figure 3. Filter #11 showed very good agreement between the predicted and measured values for frequency, efficiency and diffraction angle, at all the visible and near UV lines we tested.

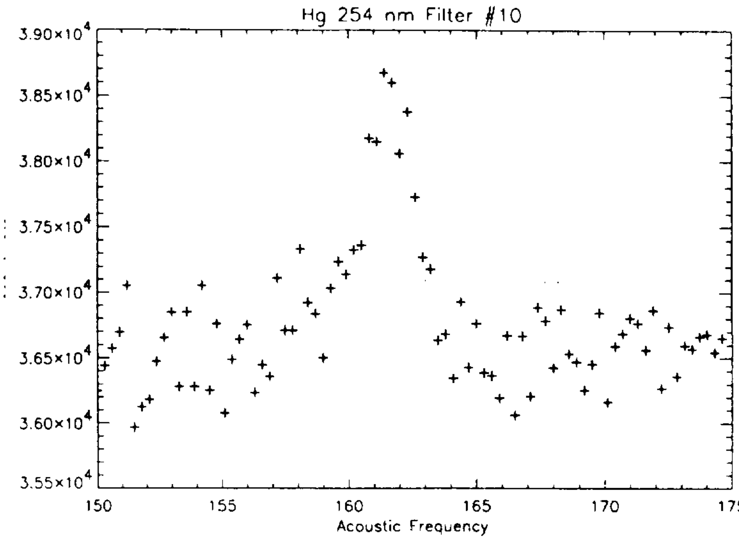

Figure 2. Diffracted light vs. acoustic frequency (MHz), for the mercury line at 254 nm. The background level is the result of diffuse scattered light in the test filter and lenses.

For measurements in the vacuum ultraviolet, the LiF lenses and the Channeltron photomultiplier were installed. An argon continuum lamp was used as the light source, but the continuum intensity was extremely low. We needed relatively narrow spectrometer slits to maintain spectral purity, but were only able to get count rates of between 30 and 150 counts/sec in the undiffracted beam. We tried a variety of techniques, but were never able to detect diffraction of light from the central beam. Besides offsetting the slit to the predicted (0.2 to 0.3 degree) diffraction angle, we tried looking for the reduction in intensity in the central beam as the acoustic frequency was tuned through the range corresponding to a chosen wavelength. The advantage is that the magnitude of the change is twice

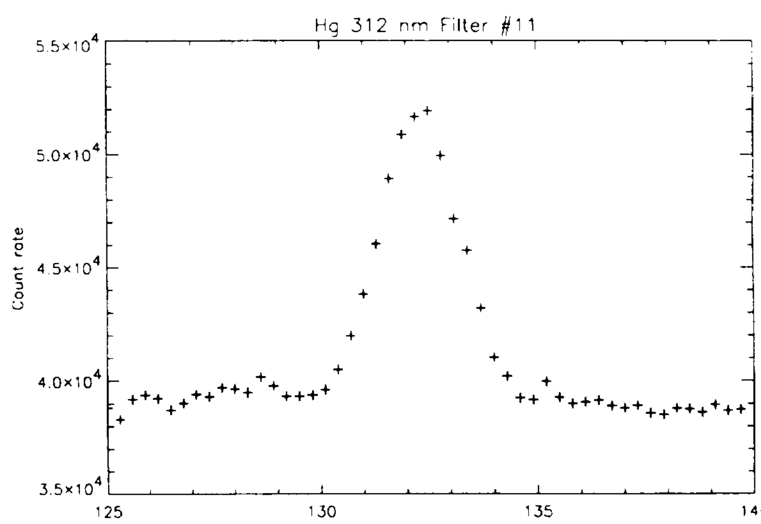

Figure 3. Diffracted light vs. acoustic frequency (MHz), for the mercury line at 312 nm. The background level is the result of diffuse scattered light in the test filter and lenses.

as large—equal to all the diffracted intensity rather than the half one sees by offsetting the detector slit to one side—and that one doesn't need to know the exact angle of diffraction, so long as it is larger than the angle subtended by the detector slit. The disadvantage is, of course, that the background level is higher so the relative contrast of the expected signal is lower.

We tuned each of the three filters through their full frequency range, with the monochromator set to pass Lyman-alpha. The continuum lamp contains hydrogen as an impurity, so emits Lyman-alpha with an intensity about equal to the continuum intensity. The average count rate was under 30 counts per second in many of the tests, so we averaged the data from 16 frequency scans. The standard deviation within any given scan was close to the square root of the number of photoelectrons collected per point, and was low enough to permit unambiguous detection of a ten percent intensity decrease. We never saw a decrease in the central beam, at any frequency between 30 MHz and 250 MHz. Nor were we able to detect any increase from the background scattered light when we positioned the detector slit at 0.25 degrees from the axis and tuned the filters through their entire range. We also looked at a number of other wavelengths between 120 and 126 nm, with the same lack of results.

Discussion

The clear and unambiguous agreement with theory for these filters at the near UV wavelengths, together with the results reported for the CdS filter near its band-edge by Chang and Katzka (Chang and Katzka 1982) lead us to believe that both the basic theory of operation and the filter construction are adequate. There are several technical issues, however, which make testing difficult and may be responsible for our negative result.

One possible problem is that the refractive indices of MgF2 are not as precisely known near the absorption edge as they are in the visible and near UV. The acoustic frequency corresponding to a given optical frequency depends on both the birefringence and its dispersion; and the diffraction angle is proportional to the birefringence. Thus locating the diffracted beam at a particular wavelength requires searching over both acoustic frequency and detector slit position.

Another difficulty may be that as the filter is heated by dissipation of the acoustic beam, the band edge shifts toward longer wavelengths. Unfortunately we did not have a means of actively controlling the filter temperature in our test configuration. It is conceivable that during the fifteen or twenty minutes need to accumulate a statistically adequate data sample, the device temperature changed enough to both shift the tuning curve and the diffraction angle.

Outlook

Prospects for development of a real-world acousto-optic filter for Lyman-alpha are uncertain at this time. A few companies are building various types of acousto-optic filters, so manufacturing techniques are gradually being established. Our initial tests have been at least partially encouraging, and the characteristics of the proposed device would permit observations not otherwise possible. But our original hopes were overly optimistic: considerable effort in fabrication and testing is still needed before one could consider building a flight-capable filter. To continue this study, we will build upon our present experience by improving the test configuration in several ways.

First, it may be necessary to actively control the temperature of the device. Several watts of power are dissipated in the crystal, and the birefringence—and thus the diffraction angle—depends sensitively on temperature. Cooling the filter below room temperature would push the band edge to shorter wavelengths, somewhat increasing the diffraction angle. In addition, excessive heating may damage the transducer.

Second, we would like to build an all-reflective optical system. The refractive index of LiF changes so much between the visible region and Lyman-alpha that focusing and alignment for the VUV is extremely difficult. The filter mounting also needs more positional adjustment, so that the light path can be made to properly intercept the acoustic beam.

Third, we will try to increase the light level in the VUV, probably by using a lamp with strong Ly-α emission. In addition, the filter diffraction efficiency can be increased somewhat by increasing the acoustic power. However, one would probably want to pulse-modulate the RF power to limit heating of the device. Although the average power usable is limited by device heating, we could reduce the background due to scattered light in the system by gating the detector system synchronously with the RF.

Fourth, we have seen from our present tests that the general background scattering is much larger than we expected. Better surface quality will be required on any device which is to be used in an instrument—and even in basic testing we found that the scattered light was a serious problem.

Our present plans are to continue testing the present filters, using our existing test configuration with minor modifications as appropriate. Positive results, i.e. demonstration of efficient acousto-optic diffraction at Lyman-alpha, would encourage us to consider a real instrument using such a device.

References

Canfield, R. C. and C. R. Chang (1985). "Ly-alpha and H-alpha emission by superthermal proton beams." *Astrophysical Journal* **295**: 275-284.

Chang, I. C. and P. Katzka (1982). "Enhancement of acousto-optic filter resolution using birefringence dispersion in CdS." *Optics Letters* **7**: 535.

Chang, I. C. (1976). "Tunable acousto-optic filters: an overview." *Acousto-optics*, SPIE.

Orrall, F. Q. and J. B. Zirker (1976). "Lyman-alpha emission from nonthermal proton beams." *Astrophysical Journal* **208**: 618-632.