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New Materials Applications in Solar Spectral Analysis*

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Abstract

The use of lithium niobate and liquid crystals in solar instrumentation designed for automatic measurement of spectral line shifts is described. A solid Fabry–Perot etalon of lithium niobate has an acceptance angle 5·3 times greater than an air-spaced Fabry–Perot filter for the same allowed passband broadening, and the lithium niobate device has no moving parts. The use of liquid crystals in Zeeman-effect analysers is also described. For a given phase retardation, liquid crystals require $\sim 1/1000$ the voltage of solid crystals. They hold promise as reliable, long-lived variable retarders because they are free of the high-voltage breakdown problems of crystals such as potassium dideuterium phosphate (KDP). Progress toward implementation of devices with lithium niobate and liquid crystals in a solar telescope is described.

1. Introduction

In the 20 years or so since Leighton *et al.* (1962) discovered the solar oscillations by analysing Doppler shifts in time series of spectroheliograms, understanding of the oscillations' importance as a new tool for solar physics has grown dramatically. Thought at first to be only local disturbances of the solar photosphere set off by the small convective cells called 'granules', the oscillations have since been recognized as a global phenomenon that allows us to probe the Sun's interior.

One of the first indications of the non-local nature of the oscillations is shown by the velocity recordings in Fig. 1 (Musman and Rust 1970), where it is seen that the oscillations are in phase over at least 50 000 km baselines, i.e. much larger than the dimensions of the granules. Deubner (1975) showed that the oscillations are truly global and that the amplitude variations seen in Fig. 1 result from interference of millions of eigenmodes. The modes are primarily acoustic, but there may be gravity-driven modes as well. The usefulness of modal analysis is evident from Fig. 2, which shows that each mode samples a different region within the Sun.

In order to resolve the many oscillatory modes, an ultra-stable Doppler-shift analyser is required. In recent years, most measurements have been done with cells filled with sodium vapour. These magneto-optical filters (Cacciani and Fofi 1978) are

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extremely stable, since the central wavelength passed by the filter is set by the sodium atom. Doppler shifts, and hence velocities, are inferred from differences in brightness between the red and violet solar sodium line wings. One drawback of the method is that the solar sodium line originates in a relatively turbulent layer of the atmosphere. It gives a relatively noisy signal compared with spectral lines formed in lower layers.

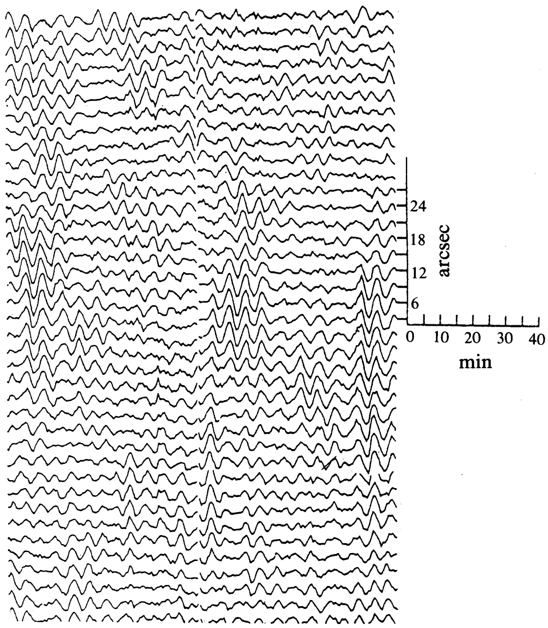

Fig. 1. Observations of Doppler shifts along a line 300 arcsec long on the solar disc. The 5-minute oscillations appear to be wave packets that last for about 30 min. The peak velocity amplitudes may be as great as 1000 $\mathrm{m\,s^{-1}}$.

In the near future, research on solar oscillations will require the freedom from diurnal interruptions that only a space vehicle can provide. The possibly limited lifetime of sodium vapour cells, their sensitivity to variations in the magnets and heaters used with them and their lack of a tuning mechanism may conspire to make them unsuitable for use in a space-based instrument. In order to meet the requirements for longevity, efficiency and tunability that space observations of solar oscillations will pose, we have turned to novel materials. We have also investigated how a Doppler analyser in space can double as a magnetograph, i.e. an instrument that measures Zeeman shifts in Fraunhofer lines as well as Doppler shifts. The following sections describe a stabilized, solid lithium niobate Fabry–Perot filter for the Doppler effect measurements, and a liquid crystal-based polarization analyser for the Zeeman effect measurements.

2. Lithium Niobate Fabry–Perot Filter

Solid Fabry–Perot etalons are lightweight and rugged, and their ability to function in space is established. However, the earlier solid etalons did not have the flatness and substrate uniformity required to yield a sufficiently

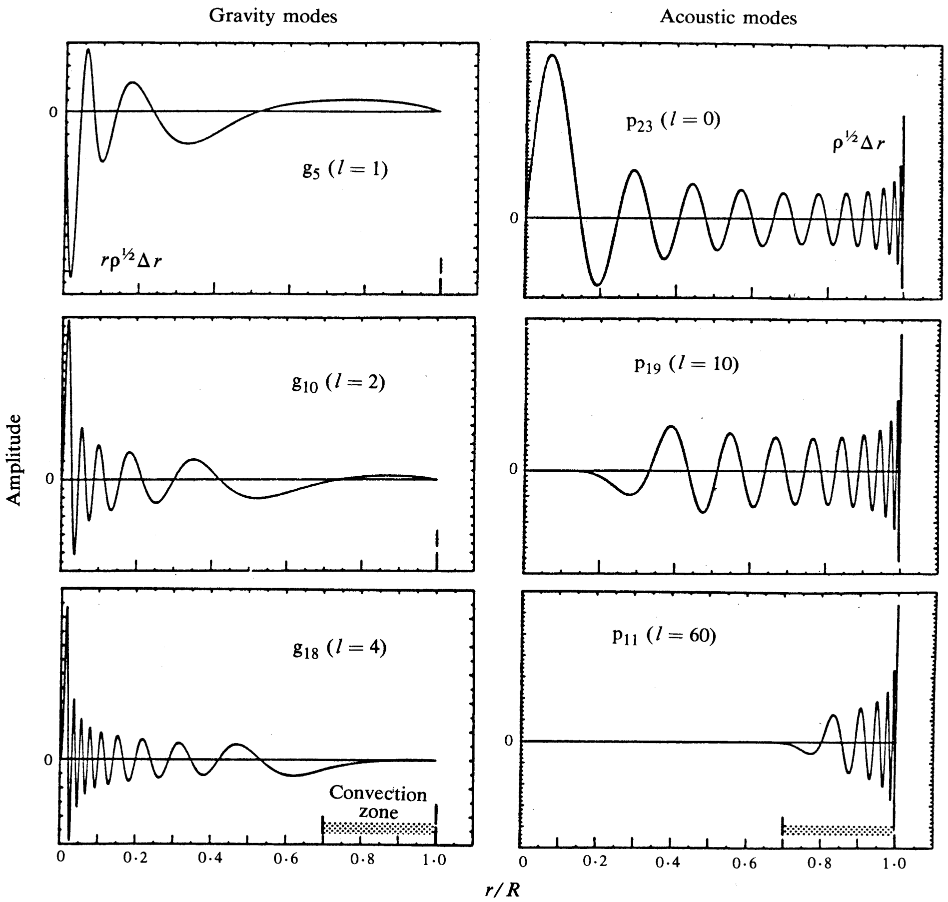

Fig. 2. Scaled displacement amplitudes of some gravity and acoustic oscillation modes within the Sun, as obtained theoretically by Christensen-Dalsgaard and Gough (1985). For the gravity modes, increasing degree l and radial order m produces more concentrated but also more complicated modal structure near the core of the Sun. Acoustic modes of high l are confined to a region close to the surface.

narrow passband, i.e. one approximately equal to the half-width of the spectral lines preferred for the measurements. An air-spaced etalon, which is easier to fabricate, has been used for auroral studies with the Dynamics Explorer satellite, but for reasons described below, a solid etalon is preferable for solar observations.

The solid Fabry–Perot etalon of The Johns Hopkins University Applied Physics Laboratory (APL) and the CSIRO National Measurement Laboratory was designed with two principal goals in mind. The foremost objective was to produce a Doppler analyser that does not require that the solar image be scanned or that the filter be moved in the course of normal full-disc measurements. This allows a durable, simple instrument that will operate reliably and unattended for many years to be built around the Fabry–Perot etalon. The other main goal was to be able to tune the analyser electronically to achieve stability of the passband, high dynamic range and access to a wide choice of Fraunhofer lines.

The above objectives have led to the development of large diameter solid Fabry–Perot etalons made of lithium niobate. This material is available commercially in diameters up to 75 mm. The refractive index of lithium niobate is quite high ($\sim 2 \cdot 3$) and it can be varied without inducing birefringence by application of a voltage parallel to the optic 'C' axis of the crystal. The high index makes lithium niobate an especially appropriate substrate material in a solid etalon because the acceptance angle of a Fabry–Perot filter increases as the square of the refractive index. The passband of the etalon will shift by only 0·012 Å as the angle of view changes from solar disc centre to the limb. In other words, a highly monochromatic image of the whole solar disc can be formed instantaneously on a two-dimensional detector. The half-width of the passband will be about 0·15 Å, which is small enough to allow operation on most Fraunhofer lines and large enough to render the passband shift with view angle a minor effect that is easily corrected during data analysis.

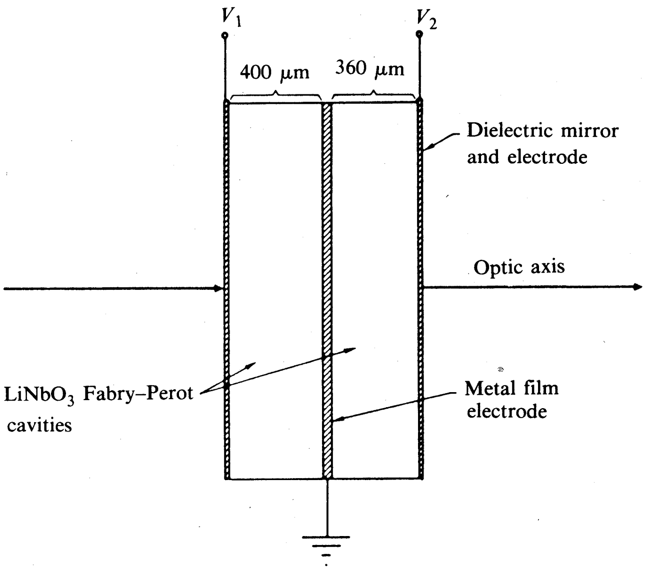

Fig. 3. Double-cavity electro-optically tuned Fabry–Perot filter as described by Gunning (1982).

A double-cavity lithium niobate Fabry–Perot filter has been described by Gunning (1982). A sketch of this device, which was intended for use near a wavelength of 4 μm, is shown in Fig. 3. The double-cavity design facilitates tuning and the suppression of unwanted orders. Our devices have only a single cavity, but we are attempting to make one with a double cavity. Currently, unwanted orders are blocked with a narrow-band thin-film interference filter.

The filter is tuned by tilting and by application of a voltage to the lithium niobate substrate. Coarse tuning, from one spectral line to the next, for example, is accomplished by tilting the etalon and selecting an appropriate narrow-band interference filter. Fine tuning requires $\sim$2500 V Å^{-1}. Thus, a voltage of only $\pm$250 V oscillates the passband between the red wing and blue wing of a spectral line. Successive images are then recorded and subtracted to produce velocity maps. This can be accomplished quite rapidly at all points on a two-dimensional CCD because the images are monochromatic.

The tunability of the solid etalon Fabry–Perot filter can be used to cancel lineshifts due to orbital motion (of a satellite-borne instrument). The electrical tuning feature has also been used to compensate for shifts of the filter passband due to temperature variations in the etalon. All solid etalon Fabry–Perot filters are highly temperature sensitive, and the stability requirements of solar seismology have hitherto appeared to rule out the use of a solid etalon for this reason. However, the Time and Frequency Systems Group at APL has developed a method for locking the passband of the filter to a laser that is stable at the 10^{-13} level for arbitrarily long periods. With this system, we have stabilized the passband of the Fabry–Perot filter at the 10^{-9} level.

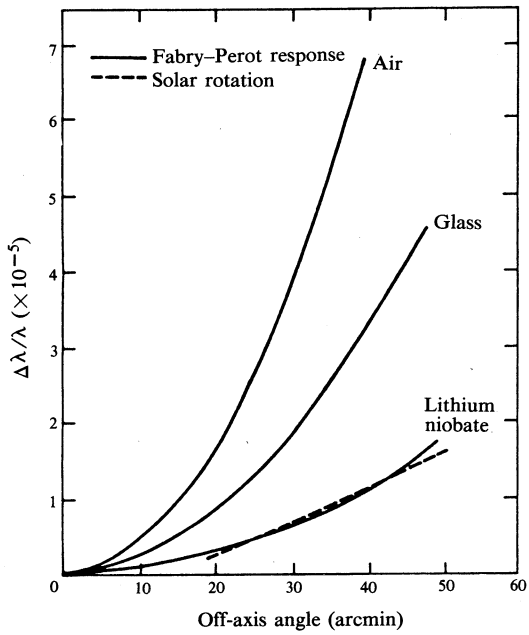

Fig. 4. Relative shift in wavelength of the transmission peak of a Fabry–Perot etalon against the angle between an incident ray and the normal to the etalon face. Higher index spacers lessen the angular sensitivity. Solar rotation (dashed line) produces a shift across the visible disc that can be compensated for by tilting a lithium niobate Fabry–Perot filter. This compensation cannot be accomplished as well with air-spaced or glass etalons.

Fig. 4 illustrates one advantage of solid etalons over air-spaced ones. The higher the refractive index of the spacer, the less the passband shifts for off-axis rays. The wavelength shift is given by $\Delta\lambda/\lambda = \phi^2/2n^2$, where ϕ is the angle between the incoming ray and the normal to the filter and n is the refractive index of the spacer. This equation shows immediately that our etalon cannot be used with a highly convergent beam. Even an $f/50$ beam broadens the filter profile unacceptably. A solution to this problem that will maintain high spectral purity for the entire solar disc is to place the filter in front of the telescope objective, where maximum deviation of the rays from the normal is only $0°{\cdot}25$. Thus the passband of a Fabry–Perot filter with a $LiNbO_3$ spacer shifts only $-0{\cdot}012$ Å for rays at the solar limb, whereas it will shift by $-0{\cdot}09$ Å in an air-spaced etalon. The larger shift is unacceptable, since most Fraunhofer lines of interest are $<0{\cdot}2$ Å wide.

Comparison of the off-axis behaviour of a lithium niobate etalon and the Doppler shifts due to solar rotation shows that, if the etalon is operated at a tilt of 35 arcmin from the solar-centre-to-telescope ray, the rotational Doppler shifts are matched to one part in seven, or $0{\cdot}008$ Å at 8468 Å. Thus, a solid etalon with a $LiNbO_3$ spacer provides a passband that is correctly positioned on the wing of the line simultaneously everywhere on the visible disc.

There are difficulties with the 'before the telescope' design that have yet to be resolved. Lithium niobate is a birefringent material, so polarization analysis (for the Zeeman effect) must be accomplished before the light passes through it. Also, the filter (or the polarization analyser) will determine the aperture of the instrument. If 2 arcsec spatial resolution and adequate throughput are to be maintained, then one must be able to fabricate a 75 mm diameter etalon. To give the required spectral resolution, the etalon must be flat and parallel to within $\lambda/50$, or better (Ramsay 1969). To facilitate the separation of orders with a thin-film filter, the etalon must be $<0{\cdot}25$ mm thick.

Fortunately, the tuning requirements of a solar magnetograph are modest. Only temperature drifts in the instrument and Doppler shifts due to orbital motion of the satellite must be compensated for and both are $<0{\cdot}2$ Å. Further, for photospheric velocity measurements, it is usually desirable to shift the passband from one wing of the spectral line to the other, and this also requires $\sim 0{\cdot}2$ Å tunability. Thus, ± 250 V will provide adequate control over the passband. Higher voltages would be needed in a more versatile instrument, one that can be used in conjunction with several narrow-band order-isolation filters to study many spectral lines.

3. Progress

As of June 1985, two 50 mm etalons have been made at CSIRO. One of them has been under test since March 1985 and a 75 mm etalon is being fabricated. This is the largest lithium niobate etalon that can be contemplated in the foreseeable future. In our design for an analyser-equipped telescope, the etalon is the limiting aperture: it limits the resolution to ~ 2 arcsec. The resolution could be increased somewhat by using a more complex telescope than our simple refractor and by sacrificing bandwidth. For example, the filter could be restricted to operation on broad lines, e.g. Na D1 and D2, in order to gain spatial resolution. The measured properties of the best 50 mm etalon are as follows:

diameter: 50 mm;
thickness: $0{\cdot}0222$ cm;
free spectral range: $3{\cdot}25$ Å;
coatings: silver (reflectance approximately $0{\cdot}91$);
fringe shift for applied voltage of $+500$ V $= +0{\cdot}205$ Å;
fringe shift for applied voltage of -500 V $= -0{\cdot}225$ Å.

The lithium niobate filter program has been in progress for only one year and the filter is not as well developed as some other devices. However, the advantages of the lithium niobate filter are great enough to justify a substantial instrument development program. Doppler observations of the Sun have been made at APL with a 38 mm glass etalon borrowed from the National Solar Observatory. These observations were made with a 1000 mm focal length refractor that formed a full-disc image on a General Electric CID camera. We have obtained two-dimensional images that show solar rotation. We are now developing a CCD camera in order to obtain much higher sensitivity. We hope to have this camera and one of the lithium niobate filters operating soon at the new APL observatory, which consists of a photoelectrically guided Zeiss refractor mounted on a vibration-free pier and protected by a 3 m dome. The data will be analysed at the APL image processing laboratory, where most of the routines necessary for registration and subtraction of successive images have already been developed.

4. Liquid Crystal Polarization Modulator

New approaches to the task of detecting the polarization state of the incident solar light will be required if a satellite-borne magnetograph is to operate for very long. Hagyard *et al.* (1985) have described the problems encountered with the frequently used potassium dideuterium phosphate (KD*P) crystal modulators. These include hysteresis effects, breakdown under the high voltages required to achieve modulation, and a very narrow-angle acceptance cone. To avoid these problems, we have been investigating twisted-nematic liquid crystal devices.

Modulation in a liquid crystal device (LCD) is achieved by destroying the twisted crystal structure by application of an electric potential, typically 5–6 V for a 10 μm layer. Unfortunately, the retardation of the light is strongly dependent upon the thickness of the liquid crystal layer, which is difficult to control. One novel technique for maintaining a uniform spacing between the confining plates is used in the Tektronix pi-cell, in which 10 μm glass beads are dispersed throughout the liquid crystal. We describe the Tektronix device in more detail below; general details about LCDs may be found in the articles by Scheffer (1978), Baur (1981) and Clerc (1981).

The response time for most LCDs is ~ 100 ms, which is rather slow for light modulation in a magnetograph. This drawback has been overcome recently with the introduction of the pi-cell, which has a 2 ms response time (Bos *et al.* 1983). This new device also has a very high acceptance angle since, as Fig. 5 shows, the surfaces that confine the liquid crystal have been designed to orient the molecular directors to give only a small net deviation from the on-axis index of refraction, regardless of ray angle.

Tektronix claims that the new LCD has an expected lifetime of 10 years. Probably the principal factor limiting lifetime is breakdown of the complex liquid crystal molecules. Their behaviour in the radiation fields encountered in space is unknown.

At APL we measured the contrast ratio and response characteristics of a prototype pi-cell. When we placed the cell between crossed polaroids, the contrast ratio (on-state transmission to off-state transmission) was 25 : 1. It was not strongly dependent on wavelength, which is an important quality for a versatile instrument.

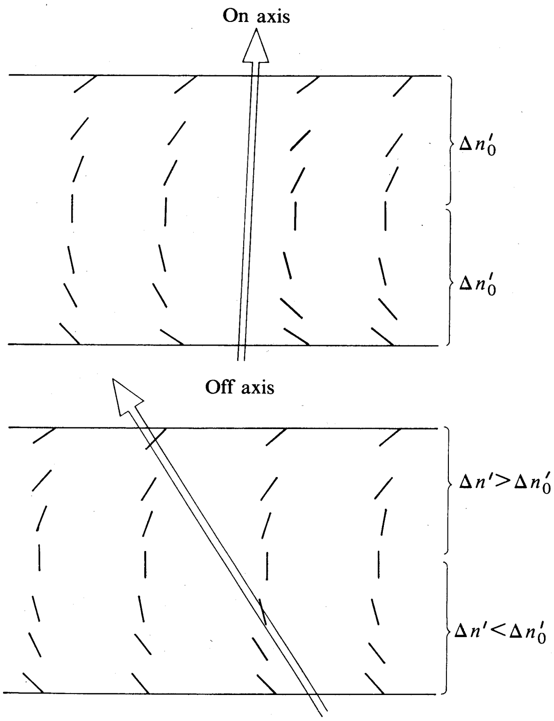

Fig. 5. Illustration of how the wide-angle response of the Tektronix pi-cell LCD is achieved. The obliquely incident ray will be more nearly parallel to the directors (short vectors) of the liquid crystal molecules in the bottom half of the device than for normally incident rays, but in the top half, the oblique ray will be at a greater angle to the directors. The net retardation, therefore, is relatively insensitive to beam angle ($\Delta n_0'$ is the effective birefringence of the liquid crystal, while $\Delta n'$ is the 'local' birefringence).

The transmission between crossed and parallel polaroids was measured in the green (5300 Å) and red (6300 Å) wavelengths at various chopping rates. At 60 Hz, the contrast ratio was somewhat less than 25 : 1 because of the ~3 ms time required for the transmission to drop when switching from the 'on' state to the 'off' state. Fig. 6 shows oscilloscope traces of some of our results. Curves of transmission and phase shift against voltage are shown in Figs 7*a* and 7*b*. Results for red and green light were identical.

The curves in Fig. 7 show that 4% of the light is passed even at the highest voltages (where an ideal 'pi-cell' would have no residual retardation and would, therefore, be limited only by the leakage in the polaroids). The residual retardation is possibly due to some permanent orientation of the directors at the liquid crystal–glass plate interfaces and to electrical resistance of the glass. The resistance slows down the cell's response to the 1 kHz square wave carrier necessary for the cell's operation so that some light leakage occurs at each change in sign in this carrier.

A magnetograph requires a precisely variable retarder with fast response time. The pi-cell has a sufficiently fast response but, since it cannot reach either zero or π retardation exactly, it is not suitable. However, if the cell thickness were increased by a factor of ~2·5, the resultant device could be operated between ~11·5 and

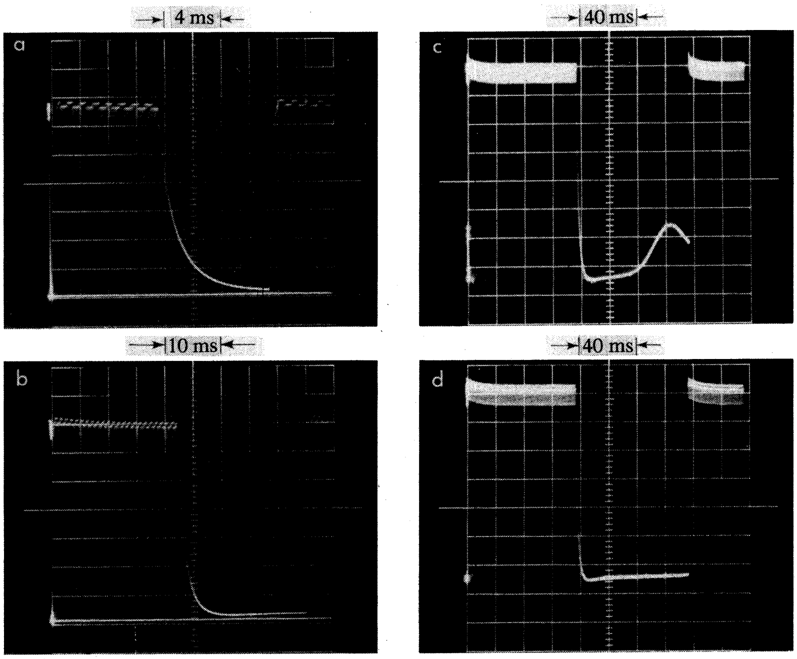

Fig. 6. Transmission through crossed polaroids separated by the Tektronix pi-cell at (*a*) 60 Hz, (*b*) 20 Hz, (*c*) and (*d*) 6 Hz. In (*d*) a small voltage was applied in the 'off' state to suppress an instability that develops in the pi-cell when no voltage is applied.

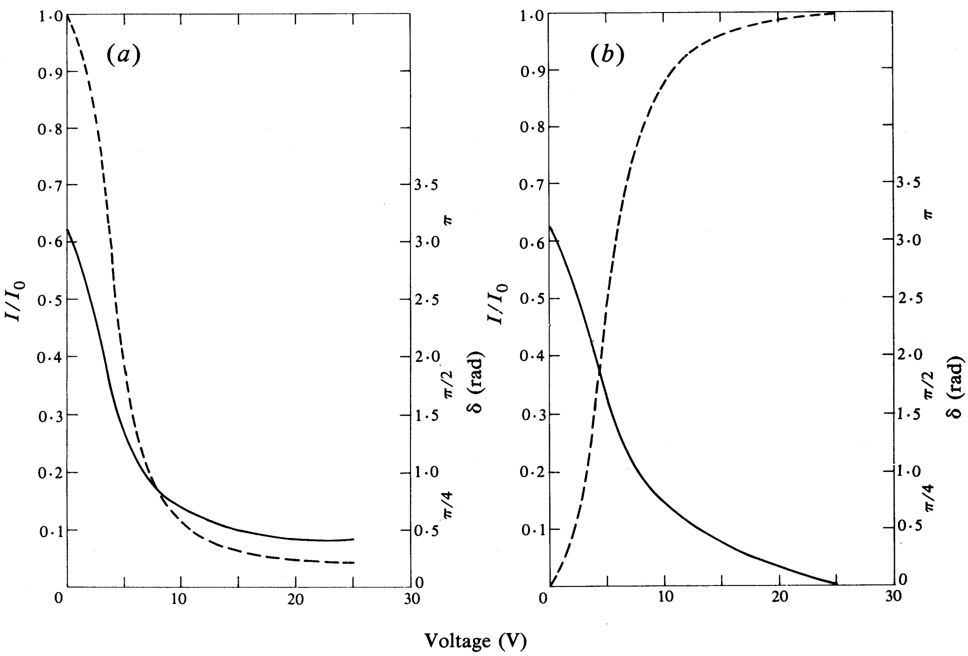

Fig. 7. Relative transmission I/I_0 (dashed curves) and phase shift δ (solid curves) against r.m.s. voltage applied to the Tektronix pi-cell for (*a*) polaroids crossed and (*b*) polaroids parallel ($\lambda = 6300$ Å).

3·5 V on the more or less linear part of the phase shift curve to produce easily any retardation between and including $\frac{1}{2}\pi$ and $\frac{3}{2}\pi$, as required for analysis of circularly polarized light.

5. Conclusions

The new technologies for filters and polarization modulators now becoming available are important for the realization of a small, lightweight and durable Doppler analyser/magnetograph for satellite-based operation. Spectral selection can be accomplished with a solid Fabry–Perot etalon located in front of the telescope objective. Lithium niobate appears to be an excellent etalon substrate.

The search for the perfect electro-optic polarization modulator continues, since none of the usual devices—KDPs, quartz plates in oscillation, PLZT wafers, or LCDs—operates reliably at low voltage, for long intervals, at any retardation, and with a wide acceptance angle. A recently introduced LCD holds the most promise, if some minor changes from the prototype that we tested can be implemented. Since the Tektronix pi-cell can be fabricated with a 10 cm or larger aperture, we plan to install it in the new telescope at APL for operational tests.

Acknowledgments

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