Application of a Liquid Crystal Tunable Filter to Near-Infrared Spectral Searches

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Abstract

Narrow-bandwidth is often cited as a characteristic of artificially generated signals. While the use of bandwidth as a signal-screening tool is common in the microwave region, it is less common in the optical and infrared regions where wavelength-selection devices can be cumbersome, expensive, and difficult to use. Nevertheless, the laser sources frequently used to transmit in this region produce very narrow-bandwidth signals. The Liquid Crystal Tunable Filter (LCTF) uses electronically controlled liquid crystal elements in a Lyot-type birefringent design to select a transmitted wavelength range while blocking all others, providing rapid, vibrationless selection of any wavelength in the visible to IR range. In astronomy, the LCTF can be used for spectrophotometric imaging, or as a tunable pre-filter for even narrower-band etalons of limited free spectral range. Such filters can be combined with CCD or focal plane array (FPA) cameras and software to create a powerful spectral imaging instrument. Near-infrared LCTFs are available over the spectral range from 650 to 2000 nm, and contain no moving parts that impart image shift on wavelength adjustment. This study evaluates an LCTF for a one meter near-infrared telescope. Results of tests yielded wavelength accuracy (0.6 nm), bandwidth (5 nm, < 0.01% average out-of-band transmittance), and speed of random access wavelength selection (50 milliseconds).

Introduction

A number of methods are employed to differentiate naturally occurring signals in space from artificially generated beacons. Pulse modulation is one characteristic of a signal that can indicate an artificial origin (Scherer, 2001). Such modulation schemes permit high peak transmitting power to be utilized to increase S/N (Ross 1965, Kingsley 1995). Low duty cycle, brief-pulse laser modulation with intense peak-power enables transmission of signals over enormous distances with low average power and high efficiency. Each pulse in digital pulse-position modulation can transmit considerable data when the aggregate of possible discrete delays is large. Because the signal energy in a short pulse can overwhelm the noise generated by the broad emission spectrum of the nearby star, exact discrimination of optical frequency is not absolutely necessary. However, frequency selectivity can be applied with pulse modulation to reduce such background interference if desired.

Narrow-bandwidth is often cited as a characteristic of artificially generated signals. While the use of bandwidth as a signal-screening tool is common in the microwave region, it is less common in the optical and infrared regions where wavelength-selection devices can be cumbersome, expensive, and difficult to use. Adding frequency selectivity also increases size of the search space by adding a new dimension. Nevertheless, the laser sources frequently used to transmit signals in this region produce very narrow-bandwidth signals, in contrast to natural sources of visible and near-infrared photon emission. The narrow bandwidth required to achieve high power levels in lasers suggests wavelength discrimination as a means of detecting artificial emission sources.

Several types of devices are used to achieve wavelength selectivity in imaging applications. This paper explores the use of a liquid crystal tunable filter (LCTF) on a one-meter near-IR telescope. The ranges of wavelengths accessible by LCTF and excellent image quality through the filter have led to the use of LCTFs in many applications. These applications include airborne hyperspectral imaging, crop stress analysis, machine vision quality control, astronomy, and semiconductor process control. The flexibility of the LCTF suggests that it could be useful in SETI as well.

Instrumentation

Filter types. The LCTF is one of several filter types that can be applied with framing cameras for sequential wavelength scanning. Rotating interference filters, the Fabry-Perot interferometer (FPI), and the acousto-optic tunable filter (AOTF) are also used with framing cameras.

Interference filters are constructed so rays of most wavelengths incident on the filter suffer destructive interference and only rays within a small wavelength band experience constructive interference and pass through the filter. Interference filters are usually employed sequentially in filter wheels on framing cameras. In such use interference filters offer a large aperture, large field of view, and good optical quality. However, a mechanical system selects the filters so moving parts are necessary, and image registration problems can result. A limited number of filters fit on wheel, and time on the order of seconds can be required to step filters in a preset sequence. The band shape characteristics are usually slightly different for each filter. Interference filters can also be tuned to longer wavelengths by tilting them out of the plane of rotation of a filter wheel. Tuning the filters in this fashion also introduces image registration problems. The FPI (etalon) functions like a tunable interference filter by varying the gap between the two reflective plates, changing the wavelengths that undergo constructive interference.

The AOTF is based on a birefringent TeO_2 crystal tuned with a RF generator and piezoelectric transducer. The AOTF is capable of rapid and precise wavelength selection. It may be used as a monochromator in the UV through mid-IR regions. The AOTF offers high resolution, high-speed random or sequential wavelength access. In addition, the AOTF has no moving parts and is compact in size. However, the field of view through an AOTF is typically less than that of an LCTF. The telescope used in this research has as its basis a wide-field, f/1 optical system.

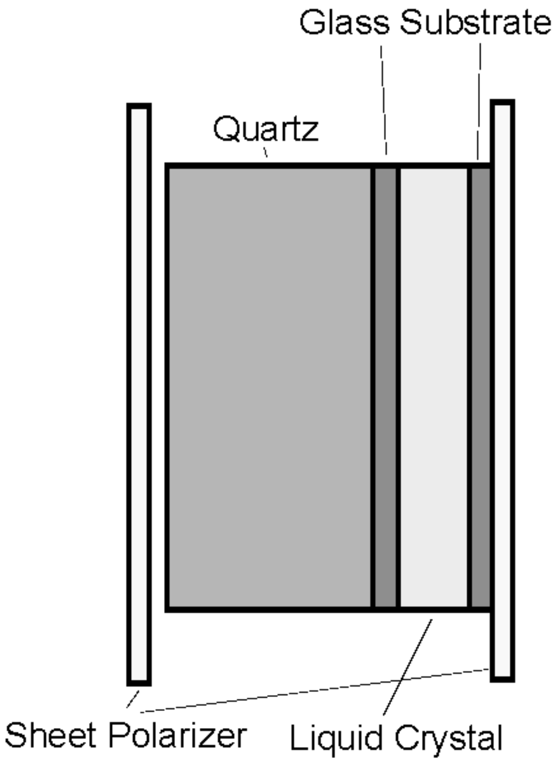

Figure 1. A single Lyot stage of the LCTF system is a "sandwich" of birefringent liquid crystal, glass, quartz, and sheet polarizers. To achieve monochromatic optical throughput in the LCTF, a series of these "sandwiches" are stacked horizontally in order of increasing retardance.

The LCTF (see Figs. 1 and 2) is also an optical filter with no moving parts and a large aperture, large field of view, and good optical quality. The LCTF uses electronically controlled liquid crystal elements to select a transmitted wavelength range, while blocking all others. A single Lyot stage of the LCTF system is a "sandwich" of birefringent liquid crystal, glass, quartz, and sheet polarizers (see Fig. 1). To achieve monochromatic throughput in the LCTF, a series of these "sandwiches" are stacked horizontally in order of increasing retardance. The bandwidth of the LCTF is constant in frequency space. The filter pass band is electronically tunable over a wide range, and time on the order of milliseconds is required to step through wavelengths or to provide random wavelength access. Because the filter does not move, there are fewer problems with image registration across many wavelengths.

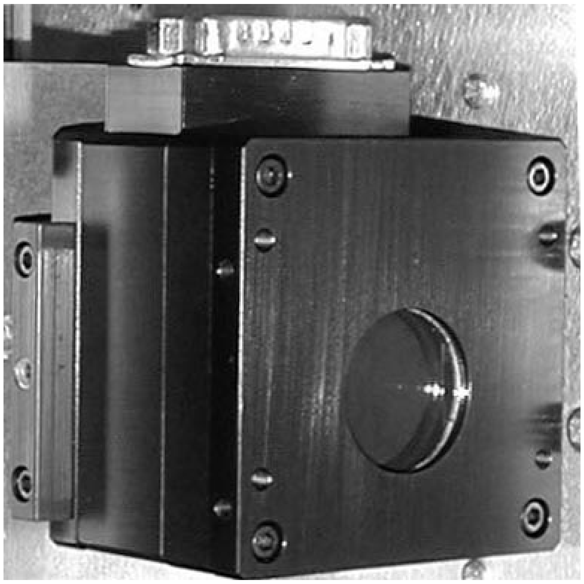

Figure 2. Photo of the LCTF with DB-15 connector mounted on the top surface.

Equipment. A near-IR telescope was constructed using an aluminum compound parabolic concentrator and a 1 m diameter visible / infrared Fresnel lens (Lodder, 2001). The CPC was machined and polished from a solid block of aluminum with a light entrance-port diameter of one cm and an exit port diameter of one mm (Lodder, 2001). The CCD array (Edmund), LCTF, IR detector, and cooler (Biorad) inside the telescope were mounted on a translation stage (Arrick Robotics, Hurst, TX).

The LCTF (CRI, Woburn, MA) was tunable over the range from 650-1100 nm. The LCTF electronics provided an RS-232 interface and a TTL sync port, enabling the filter to respond to signals and synchronization pulses generated by a computer. The use of wavelength selectivity diminishes background light reaching the detector, offers discrimination against distant broadband sources, and enhances measurements made during daylight hours. In typical use, the telescope is locked into an azimuth and elevation and the detector is translated to track a specific region of the sky with the robotic translation stage. An optical chopper is used for focusing and star tracking in the visible spectral region, and it can be pivoted over the detectors or away from the detectors as needed. The JFET preamplifier (26-dB gain) is configured as a high pass filter to amplify short pulses. An 8-bit A/D (Wittig, Boeblingen, Germany) is used to digitize the signals. The light source for testing the LCTF in the near-IR was a 100W tungsten-halogen lamp (Sylvania) with wavelengths selected by a monochromator (CVI Laser, Albuquerque, NM) with adjustable slits. Programs to collect data and perform analysis were written in Speakeasy IV Eta+ (Speakeasy Computing Corp., Chicago, IL) and Mathematica 4.1 (Wolfram Research, Champaign, IL).

Results and Discussion

The LCTF is like a high-quality interference filter, but the wavelength of the light it transmits is computer-controllable, providing rapid, vibrationless choice of any wavelength within its near-IR range (hundreds of nanometers). Its compact, low power design fits easily inside the telescope. The clear aperture of the LCTF is 20 mm. The field-of-view is 14° wide (± 7° from normal). The bandwidth (FWHM) measured with the monochromator as a reference is 5 nm, with a wavelength accuracy of 0.6 nm. Fig. 3 shows the relative transmission of the LCTF at several wavelengths over the 650-1100 nm range (750, 850, 925, 1000, and 1100 nm). The transmission of the LCTF is greater at longer near-IR wavelengths, which favors application to SETI because it parallels the transmission of the galaxy. The wavelength-selection response time is 50 milliseconds at 25° C in random access mode, anywhere within the wavelength range.

The bandwidth of a pulsed signal that might be received from interstellar space is unknown, of course. Bandwidth is a function of the equipment used to generate the light, the pulse duration, and the transmission path. Very short pulses of laser light are necessarily

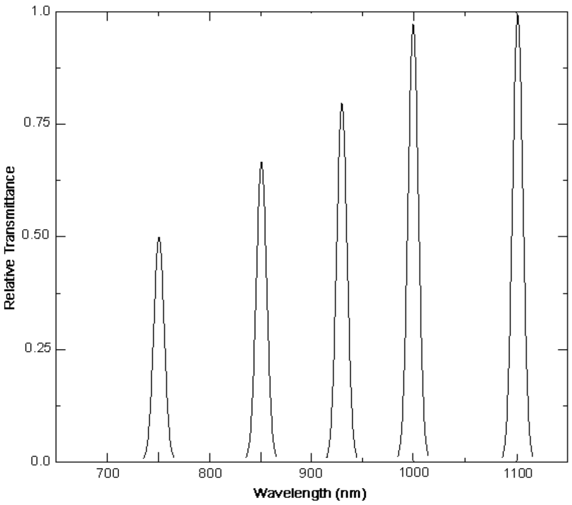

Figure 3. A sampling of tuning curves for the LCTF at different wavelengths shows the bandwidth and tuning range of the filter.

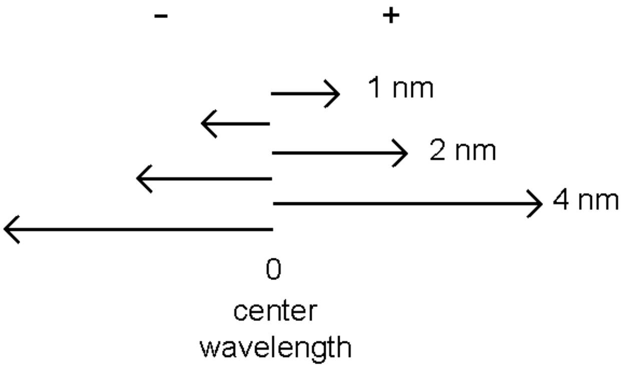

Figure 4. The Ping-Pong method for checking peak bandwidth starts with the assumption that the pulsed signal detected is narrow in bandwidth. The method checks the bandwidth by traveling back and forth across the pulses in progressively larger steps (+/- 1, 2, 4, 8, 8, and 16 nm, 8 and 16 not shown). The method is used to discriminate against broadband light sources in nature and from artificial sources like satellites.

broader in wavelength. Wavelength broadening of photon pulses can occur in transit through mechanisms such as Thomson scatter in plasmas in space. (Thomson scattering is the scattering of electromagnetic radiation by a point particle with charge and mass. The scattering takes place at a frequency and field strength such that the particle is displaced very little during the period of the incoming wave.) Because electrons have the lowest mass of the particles in plasma, the largest Doppler shifting of radiation comes from electrons in plasma. Electrons Thomson-scatter sunlight to a brightness level of tenth magnitude per square degree of sky near just our own solar system (Jackson, 2001).

To test the ability of the LCTF (which has a 5 nm bandpass FWHM) to discriminate between narrow bandwidth pulsed (100 Hz) near-IR light and more broadband light, a test was performed with 800 nm light from a monochromator with the slits set at 0.5, 1.0, 10.0, and 20.0 nm. A computer was programmed with a "Ping-Pong" algorithm to control the center wavelength of the LCTF (see Fig. 4). Fifty milliseconds passed between measurements at each wavelength. When a pulse was detected by the computer, the Ping-Pong algorithm shifted the wavelength one nm higher and looked for the signal again. If the pulse was still detectable, the intensity was recorded and the LCTF wavelength was shifted to one nm less than the starting (center) wavelength, where pulse detection was tested again. If no pulse was detected, the computer was programmed to shift the LCTF back to the center wavelength and start again. The Ping-Pong algorithm was continued for LCTF shifts of ±1, 2, 4, 8, and 16 nm. The results are shown in Fig. 5. The dotted line represents a source bandwidth of 0.5 nm, the solid line 1 nm, the, the short-dashed line 20 nm, and the dot-dashed line 10 nm. The 0.5 nm line is nearly coincident with the 1.0 nm line. The relative signal intensity drops nearly two orders of magnitude for signals with narrow bandwidth (0.5 and 1.0 nm).

The manufacturer's rating of maximum optical input through the LCTF is only 500 mW/cm^2. While that limits its use slightly in terrestrial spectrometry, it is not a problem in SETI research. The manufacturer also specifies an operating temperature range between 20° and 40° C. This range does limit the use of the LCTF in SETI research, as substantial periods exist during the year in Kentucky in which the outdoor temperature is not within the specified range. Telescopes are traditionally not heated, but plans for providing heat to the filter while avoiding heat transfer to the rest of the telescope are under study.

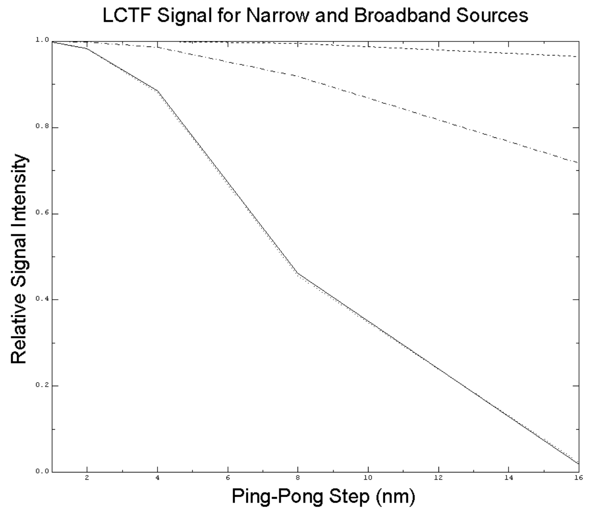

Figure 5. The dotted line represents a source bandwidth of 0.5 nm, the solid line 1 nm, the, the short-dashed line 20 nm, and the dot-dashed line 10 nm. The 0.5 nm line is nearly coincident with the 1.0 nm line.

Conclusions

LCTFs are compact, lightweight, and use little power. LCTFs lack moving parts, and coregistration is feasible with LCTFs on moving optical platforms. High S/N is possible using commercially available components, and varying integration time enables constant S/N to be achieved across a spectrum.

Narrow-bandwidth is frequently mentioned as a characteristic of artificially generated signals. Laser sources used to transmit photons produce very narrow-bandwidth signals in comparison to natural sources of photons of similar energy. The LCTF may provide an effective means of utilizing bandwidth as a discriminator in near-infrared SETI.

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