Tunable Imaging Filters

While tunable filters are a recent development in night time astronomy, they have long been used in other physical sciences, e.g. solar physics, remote sensing and underwater communications. With their ability to tune precisely to a given wavelength using a bandpass optimized for the experiment, tunable filters are already producing some of the deepest narrowband images to date of astrophysical sources. Furthermore, some classes of tunable filters can be used in fast telescope beams and therefore allow for narrowband imaging over angular fields of more than a degree over the sky.

The physics of tunable imaging

A rich variety of physical phenomena can isolate a finite spectral band: absorption, scattering, diffraction, evanescence, birefringence, acousto-optics, single layer and multi-layer interference, multi-path interferometry, polarizability, and so on. Most of the available optical filter technologies are listed below:

- linear / circular variable filter
- multi-layer dielectric filter
- Fabry-Perot interferometer
- Michelson interferometer
- acousto-optic filter
- solid etalon filter
- solid Michelson filter
- generalized resonant grating filter
- sub-lambda evanescent grating filter
- volume phase holographic grating filter
- Lyot-Öhman filter
- generalized Lyot filter
- generalized Šolc filter
- liquid crystal filter

There is a bewildering array of future possibilities, including tunable crystal lattice structures, and many possible variants on the above technologies. Here, we focus on a few key technologies.

The ideal device

The ideal filter is an imaging device which can isolate an arbitrary spectral band $\delta \lambda$ at an arbitrary wavelength $\lambda$ over a broad, continuous spectral range, preferably with a response function which is identical in form at all wavelengths.

The tilting interference filter is much the worst form of tunable filter. The spectral range covered is almost negligible, and the filter profile varies with tilt angle. Some devices (e.g. Lyot, linear variable filter) work only at a fixed resolving power but have the ability to tune over a wide spectral window. Better devices allow for a wide selection of resolving powers over a wide range of wavelengths.

The different techniques rely ultimately on the interference of beams that traverse different optical paths to form a signal. The technologies which come closest to the ideal tunable filter are the air-gap Fabry-Perot and Michelson (Fourier Transform) interferometers. To understand why, we highlight the Taurus Tunable Filter (TTF) which was the first general purpose device for night-time astronomy (see [http://www.aao.gov.au/local/www/jbh/ttf](http://www.aao.gov.au/local/www/jbh/ttf)). This is a Fabry-Perot filter where interference is formed between two highly reflective, moving plates. To be a useful filter, not only must the plates move through a large physical range, but they must start at separations of only a few wavelengths, as we show.

The condition for photons with wavelength $\lambda$ to pass through the filter is (see Fig. 1)

$$m\lambda = 2\mu \ell \cos \theta$$

from which it follows that

$$\frac{dR}{R} = \frac{dm}{m} = \frac{d\ell}{\ell}.$$  (2)

For an order of interference $m$, the resolving power is $R = mN$ where $N$ is the instrumental finesse. The finesse is determined by the coating reflectivity and is essentially the number of recombining beams. For the TTF, the plates can be scanned over the range $\ell = 1.5 - 15 \mu m$, and the orders of interference span the range $m = 4 - 40$, such that the available resolving powers are $R = 100 - 1000$.

The sharp core of almost all tunable-filter transmission profiles is not ideal. Even a small amount of flatness at peak transmission can ensure that we avoid narrowly missing most of the spectral line signal from a source. In theory, all band-limited functions can be squared off, but in practice this is difficult for all but two devices. Since the
Michelson interferometer (filter) obtains its data in the frequency domain, the profile can be partially squared off at the data reduction stage through a suitable choice of convolving function. For the Šolc filter, the instrumental profile can be modified through the use of partial polarizers and birefringent retarder elements.

**Summary of filter technologies**

Here, we provide a brief outline of some of the key technologies.

**Monolithic filters**

*Interference filter:* The principle relies on a dielectric spacer sandwiched between two transmitting layers (single cavity). The substrates are commonly fused silica in the ultraviolet, glass or quartz in the optical, and water-free silica in the infrared. Between the spacer and the glass, surface coatings are deposited by evaporation which partly transmit and reflect an incident ray. Each internally reflected ray shares a fixed phase relationship to all the other internally reflected rays. For constructive interference, for a wavelength $\lambda$ to be transmitted, it must satisfy eqn. 1 where $\theta = \theta_R$ is the refracted angle within the optical spacer, and the optical gap is the product of the thickness $\ell$ and refractive index $\mu$ of the spacer. The construction of these filters has undergone a revolution through the use of dielectric, multi-layer thin film coatings, and a proper description is more involved. All such filters can be tuned through a small wavelength interval ($\delta\lambda/\lambda = -\theta^2_{R}/2\mu^2$), which amounts to no more than 2% $\lambda$ in practice. Suffice it to say, interference filters make for poor tunable devices.

**Gap-scanning filters**

*Fabry-Perot filter:* The air-gap etalon, or Fabry-Perot filter, was introduced in the previous section. The etalon comprises two plates of glass kept parallel over a small separation where the inner surfaces are mirrors coated with high reflectivity $\Re$. The transmission of the etalon to a monochromatic source $\lambda$ is given by the Airy function

$$A = \left(1 + \frac{4\Re}{(1 - \Re)^2} \sin^2(2\pi\mu\ell\cos \theta/\lambda)\right)^{-1}$$

where $\theta$ is the off-axis angle of the incoming ray and $\mu\ell$ is the optical gap. The condition for peaks in transmission is given in eqn. 1. Note that $\lambda$ cannot be scanned physically in a given order by changing $\theta$ (tilt scanning), $\mu$ (pressure scanning), or $\ell$ (gap scanning). Both tilt and pressure scanning suffer from serious drawbacks which limit their dynamic range. With the advent of servo-controlled, capacitance micrometry, the performance of gap scanning etalons surpasses other techniques. These employ piezo-electric transducers that undergo dimensional changes in an applied electric field, or develop an electric field when strained mechanically. Queensgate Instruments, Ltd. have shown that it is possible to maintain plate parallelism to an accuracy of $\lambda/200$ while continuously scanning over several adjacent orders.

Fabry-Perot filters have been made with 15 cm apertures and physical scan ranges up to 3 cm. The etalon is ultimately limited by the finite coating thickness between the mirrors, so it really only achieves the lowest interference orders ($m < 5$) at infrared wavelengths.

*Solid etalon filter:* These are single cavity Fabry-Perot devices with a transparent piezo-electric spacer, e.g. lithium niobate. The thickness and, to a lesser extent, refractive index can be modified by a voltage applied to both faces. For low voltage systems, tilt and temperature can be used to fine-tune the bandpass. High quality spacers with thicknesses less than a few hundred microns are difficult to manufacture, so that etalon filters are normally operated at high orders of interference. The largest devices we have seen are 5 cm in clear aperture.

*Michelson filter:* In the Fourier Transform or Michelson filter, the collimated beam is split into two paths at the front surface of the beam-splitter. The separate beams then undergo different path lengths by reflections off separate mirrors before being imaged by the camera lens at the detector. The device shown in Fig. 2 uses only 50% of the available light. As Maillard has demonstrated at the Canada France Hawaii Telescope, it is possible to recover this light but the layout is more involved.

The output signal is a function of path difference between the mirrors. At zero path difference (or arm displacement), the waves for all frequencies interact coherently. As the movable mirror is...
scanned, each input wavelength generates a series of transmission maxima. Commercially available devices usually allow the mirror to be scanned continuously at constant speed, or to be stepped at equal increments. At a sufficiently large arm displacement, the beams lose their mutual coherence.

The filter is scanned from zero path length \((x = y = 0)\) to a maximum path length \(y = L\) set by twice the maximum mirror spacing \((x = L/2)\). The superposition of two coherent beams with amplitude \(b_1\) and \(b_2\) in complex notation is \(b_1 + b_2e^{i2\pi\nu y}\) where \(y\) is the total path difference and \(\nu\) is the wavenumber. If the light rays have the same intensity, the combined intensity is \(4b_1^2\cos^2(2\pi\nu y)\), where \(b = b_1 = b_2\). The combined beams generate a series of intensity fringes at the detector. If it was possible to scan over an infinite mirror spacing at infinitesimally small spacings of the mirror, the superposition would be represented by an ideal Fourier Transform pair, such that

\[
\begin{align*}
    b(y) &= \int_{-\infty}^{\infty} B(\nu)(1 + \cos 2\pi\nu y) \, d\nu \\
    B(\nu) &= \int_{-\infty}^{\infty} b(y)(1 + \cos 2\pi\nu y) \, dy
\end{align*}
\]

(4) (5)

where \(b(y)\) is the output signal as a function of pathlength \(y\) and \(B(\nu)\) is the spectrum we wish to determine. \(B(\nu)\) and \(b(y)\) are both undefined for \(\nu < 0\) and \(y < 0\): we include the negative limits for convenience. Note that

\[
\begin{align*}
    b(y) - \frac{1}{2}b(0) &= \int_{-\infty}^{\infty} B(\nu)\cos 2\pi\nu y \, d\nu \\
    B(\nu) &= \int_{-\infty}^{\infty} [b(y) - \frac{1}{2}b(0)]\cos 2\pi\nu y \, dy
\end{align*}
\]

(6) (7)

The quantity \(b(y) - \frac{1}{2}b(0)\) is usually referred to as the interferogram although this term is sometimes used for \(b(y)\). The spectrum \(B(\nu)\) is normally computed using widely available Fast Fourier Transform methods. The construction of a Michelson filter is a major optomechanical challenge. The ideal Fourier Transform pair is never realized in practice. However, the Michelson filter probably comes closest to achieving the goal of an ideal tunable filter.

The Michelson does not suffer the coating thickness problems of the Fabry-Perot filter, and therefore reaches the lowest orders even at optical wavelengths.

**Grating filters**

**Resonant grating filter:** These novel filters are inspired by the diffractive colours in many insects, and constitute dielectric gratings with three-dimensional, sub-micron microstructure. The zeroth order reflection exhibits a broad to intermediate bandwidth \((R \sim 20)\), is highly polarized and maintains useful efficiency over a \(\pm 30^\circ\) tilt (or rotation) range. Gale (1998) presents one grating design that produces a roughly self-similar bandpass from 450 to 850 nm over this tilt range. Grating filters, and their close relatives, evanescent gratings, show great promise but most have yet to leave the drawing board. However, since much of the research is driven by bank note security, we anticipate rapid progress. Volume phase holographic gratings – in reflection – can produce a highly efficient grating filter through Bragg diffraction.

**Acousto-optic filter (AOTF):** These are electronically tunable filters that make use of acousto-optic (either collinear, or more usefully, non-collinear) diffraction in an optically anisotropic medium. AOTFs are formed by bonding piezo-electric transducers such as lithium niobate to an anisotropic birefringent medium. The medium has traditionally been a crystal, but polymers have been developed recently with variable and controllable birefringence. When the transducers are excited to 10-250 MHz (radio) frequencies, the ultrasonic waves vibrate the crystal lattice to form a moving phase pattern that acts as a diffraction grating. The diffraction angle (and therefore wavelength) can be tuned by changing the radio frequency. These devices are often water cooled to assist the thermal dissipation, although this is less important in the UV where AOTFs are particularly useful. The largest devices are 2.5 cm in diameter since it proves to be difficult to maintain a uniform acoustic standing wave over larger areas. An additional problem is the 15\(\mu\)m structure in the LiNO\(_2\) crystal which is not always optimal for good image quality. But the acceptance angle of the AOTF is generally larger than the Fabry-Perot.

**Birefringent Filters**

The underlying principle of the birefringent filter is that light originating in a single polarization state can be made to interfere with itself. An optically

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(4) (5)

where \(b(y)\) is the output signal as a function of pathlength \(y\) and \(B(\nu)\) is the spectrum we wish to determine. \(B(\nu)\) and \(b(y)\) are both undefined for \(\nu < 0\) and \(y < 0\): we include the negative limits for convenience. Note that

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anisotropic, birefringent medium can be used to produce a relative delay between ordinary and extraordinary rays aligned along the fast and slow axes of the crystal. (A birefringent medium has two different refractive indices, depending on the plane of light propagation through the medium.) Title and collaborators have discussed at length the relative merits of different types of birefringent filters. The filters are characterised by a series of perfect polarizers (Lyot filter), partial polarizers, or only an entrance and an exit polarizer (Šolc filter). The highly anisotropic off-axis behaviour of uniaxial crystals give birefringent filters a major advantage. Their solid acceptance angle is one to two orders of magnitude larger than is possible with interference filters although this is partly offset by half the light being lost at the entrance polarizer.

Lyot filter: This is conceptually the easiest to understand and forms the basis for many variants. The entrance polarizer is oriented 45° to the fast and slow axes so that the linearly polarized, ordinary and extraordinary rays have equal intensity. The time delay through a crystal of thickness \( d \) of one ray with respect to the other is simply \( d \Delta \mu/c \) where \( \Delta \mu \) is the difference in refractive index between the fast and slow axes. The combined beam emerging from the exit polarizer shows intensity variations described by \( I^2 \cos(2\pi d \Delta \mu/\lambda) \) where \( I \) is the wave amplitude. As originally illustrated by Lyot (see Fig. 3), we can isolate an arbitrarily narrow spectral band-pass by placing a number of birefringent crystals in sequence where each element is half the thickness of the preceding crystal. This also requires the use of a polarizer between each crystal so that the exit polarizer for any element serves as the entrance polarizer for the next. The resolution of the instrument is dictated by the thickness of the thinnest element. With quarter-wave plates placed between each of the retarder elements, \( \lambda \) can be tuned over a wide spectral range by rotating the crystal elements. But to retain the transmissions in phase requires that each crystal element be rotated about the optical axis by half the angle of the preceding thicker crystal.

Woodgate (NASA Goddard Space Flight Center) has made a Lyot filter utilising eight quartz retarders with a 10 cm entrance window. The retarders, each of which are sandwiched with half-wave and quarter-wave plates in addition to the polarizers, are rotated independently with stepping motors under computer control. They achieve a bandpass of 0.4–0.8 nm tuneable over half the optical wavelength range (350–700 nm).

Šolc filter: These highly non-intuitive filters use only two polarizers and a chain of identical retarders with varying position angles (Evans 1958). There are folded (zigzag) and fanned designs with the former having the better performance. Title has made a tunable Šolc filter with 7 cm clear aperture. It has the extraordinary capability of tuning the spectral profile: an \( n \)-element Šolc filter can have a profile that is determined by \( n \) Fourier coefficients. The same can be achieved with polarizing filters by proper choice of crystal lengths.

Liquid crystal filter (LCTF): These are rapid switching, electronically tuned devices which employ either ferroelectric or nematic liquid crystals (LC). The more commonly used nematic LCTF (Morris, Hoyt & Treado 1994) comprises a series of liquid crystal elements whose thicknesses are cascaded in the same way as the Lyot filter. However, the tuning is achieved by electronically rotating the crystal axes of the LC waveplate. When no voltage is applied, the retardance is at a maximum; at large applied voltages, the retardance reaches a minimum. The retardance can be tuned continuously to allow the wavelength to be tuned.

Liquid crystal filters are now commercially available from Cambridge Research & Instrumentation, Inc. The biggest device we have seen has a clear aperture of 4 cm, requires about 5 V to scan a single order of interference, and appears to have good image quality. The tunable band for a single stage device is about \( R \sim 5 \) but can be tuned over the optical window. The peak transmissions are 30% or less.

**Differential imaging**

There are many important reasons for pursuing tunable filter imaging, as demonstrated by the TTF since the mid 1990s at the Anglo-Australian 3.9m and William Herschel 4.2m telescopes. Conventional imaging has a major limitation in that images are taken sequentially which is not ideal.

\(^{1}\)The proper Czech pronunciation is ‘Sholtz’.
at even the best sites. Even small detector, instrument or atmospheric variations lead to systematic error between images. A better approach is a multi-band camera so that different bands are observed in parallel. However, even this is not ideal in that the optical path is different for each filter. A tunable filter provides a powerful alternative since band switching can be linked to charge shuffling with the CCD. This is a truly differential technique which leads to much smaller systematic errors than is possible with conventional imaging.

Wide-field imaging

Few telescopes offer more than a wide-field imager at prime focus simply because it is very difficult to exploit the fast beam spectroscopically. Spectral passbands are degraded in converging beams which is unfortunate as the widest fields are achieved at the fastest f/ratios. The wide-field expanded Lyot filter is (almost) the last word in exploiting the widest possible field with a given telescope. Remarkably, beams as fast as f/2 can be compensated with crossed birefringent elements, in concert with half-wave plates, such that even a constant sub-Angstrom bandpass is possible over a degree-sized field. This opens up many new astronomical programs, e.g. Lyot filters can be vastly more efficient for redshift-targetted surveys of galaxies (e.g. high redshift clusters) compared with existing multi-aperture spectrographs. To our knowledge, a wide-angle Solc filter using half-wave plates has not been attempted although it is entirely feasible.

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Figure captions

Fig. 1. (i) Interference filter: the internal structure is not shown. (ii) Fabry-Perot etalon. (iii) Wedged Fabry-Perot etalon which avoids the problem of the plates behaving like interference filters.

Fig. 2. Schematic of a two-beam Michelson (Fourier Transform) interferometer.

Fig. 3. The transmission profile of a simple Lyot cascade with (top to bottom) 1, 2, 3, 4 and 5 stages. The thinnest element has retardance R and the following elements have thicknesses which are multiples of this element. The polaroids P are aligned with each other and oriented at 45° to the retarders.
Etalon
reflective coatings
anti-reflective coatings

Filter

Etalon
reflective coatings

Wedged Etalon
reflective coatings

\( \theta_I \quad \theta_R \)
