Generalisation of the Lyot filter: application to snapshot spectral imaging

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Summary

We describe a new filter that simultaneously achieves spectral filtering and image replication to yield a two-dimensional, snapshot spectral imager. Filtering is achieved without rejection of light so optical throughput efficiency is, in principle, unity. The principle of operation can be considered as a generalisation of the Lyot filter to achieve multiple bandpasses.

Introduction

Spectral imaging techniques that record a two-dimensional spectral image in a snapshot are notable by their absence; the traditional trichromatic colour camera is a prominent exception, but the basic principle used - multiple dichroic beamsplitters to demultiplex or filter the light - is fundamentally unsuitable to imaging in more than a few spectral bands. We report here a two-dimensional snapshot technique, Image Replicating Imaging Spectrometer (IRIS) that records a spectral data cube in a snapshot directly onto a single, conventional detector array.

The snapshot capability offers the following key advantages:

- Time-resolved spectral imaging of transient phenomena is possible.
- No temporally induced spectral misregistration.
- There are no multiplex losses so signal throughput can be very high
- There are no moving parts.

Generalisation of the Lyot filter

The image replicating imaging spectrometer can be considered as a generalisation of a Lyot filter; this enables high efficiency spectral demultiplexing of broadband light. The Lyot filter[1,2], as used for many years in astronomy, employs polarising interferometry within multiple waveplates to yield a filter suitable for recording narrow-band images. Light not transmitted by the Lyot filter is absorbed by film polarisers. To generalise the Lyot filter, we use Wollaston prism polarising beam splitters in place of film polarizers so that after transmission through each waveplate the light is resolved into polarisations aligned both with, and orthogonal to, the input polarisation state. As with the Lyot filter, for the co-polarised component the transmission function for a single waveplate is given by $\cos^2(\pi\nu(n_o-n_e)t)$ and for the cross-polarised component the transmission function is the complementary $\sin^2(\pi\nu(n_o-n_e)t)$ where ν is optical frequency, n_o and n_e are the ordinary and extraordinary refractive indices of the waveplateand t is its thickness. The two orthogonally polarised components are displaced in angle by the beam-splitting action of the Wollaston prism and this enables two spatially separated and spectrally filtered replica images to be formed for a single poalriser waveplate pair. Consecutive transission through multiple Wollaston prism polariser and waveplate pairs further spectrally filters and replicates the transmitted imagers. After transmission through n Wollaston prism and waveplate pairs, of thicknesses t_i (i=1..n), 2^n replicated images are formed, each with a unique product of $\cos^2(\pi\nu(n_o-n_e)t_i)$ and $\sin^2(\pi\nu(n_o-n_e)t_i)$; transmission functions.

The orientation and magnitude of the splitting angles of the Wollaston prisms determine the locations of the replicated images at the detector; each image can be associated with a vector {$p(1)$, $p(2)$.. $p(n)$} where each element of the vector identifies whether the image is due to refraction in a positive or negative direction at each Wollaston prism. In general, the transmission function for each image at location {$p(1)$, $p(2)$.. $p(n)$} in the image plane can be written as

$$T_{p(1),p(2)..p(n)}(\nu)=\prod_{i=1}^{n}\Omega_{a(n)}\left(\pi\nu\left(n_o-n_e\right)t_i\right) \tag{1}$$

where $a(i)$ refers to either co-polar or cross-polar transmission between Wollaston prisms, so that the respective transmission functions for co-polar and cross-polar transmissions through waveplate i sandwiched between polarisers i-1 and i are

$$\Omega_{a(i)=co-polar}(x)=\cos^2(x), \qquad \Omega_{a(i)=cross-polar}(x)=\sin^2(x) \tag{2}$$

where suffix i=0 indicates the input polarizer and all other values indicate Wollaston prism polarizers. The spectrum associated with each individual image replication is determined by the vector {$a(1)$, $a(2)$,.. $a(n)$} appropriate for each image replication. As can be seen the transmission function corresponding to all co-polar polarisations and for waveplates with thicknesses related by factors of two is identical to the spectral transmission function of the equivalent Lyot filter. If, as for a Lyot filters, the thicknesses t_i are related by simple factors of two, the resulting band-pass functions are bell-shaped and generally exhibit significant sidelobes. Optimisation of the values t_i can improve the band shapes against some metric of the quality of pass-band shapes. Whilst it is not possible to synthesis the contiguous rectangular functions typically employed in spectrometry, in most cases this has been shown to not significantly reduce spectral discrimination performance of IRIS. In Figure 1(b) are shown the eight calculated transmission functions for an eight-band IRIS optimised for the characterisation of retinal blood oxygenation in region of 570 to 620 nm.

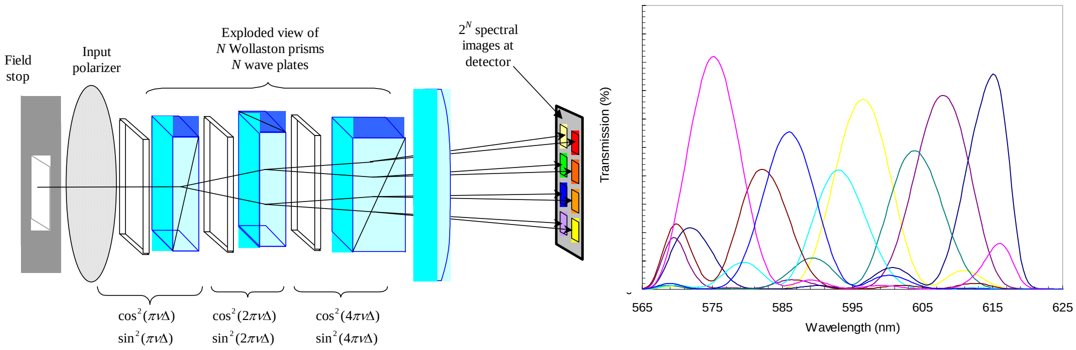

Figure 1 (a) Depiction of principle of operation of an eight-band Image replication imaging spectrometer and (b) measured optimised bandshapes for use in the 570nm to 620 nm region.

A field stop at an intermediate focal plane, is required to prevent overlapping of the replicated images at the detector plane. The Wollaston prisms and waveplates are assembled into a common block with index matching fluid to reduce stray reflections and to reduce the effect of non-flatness of the birefringent elements.

A snapshot spectral imaging capability can be readily added to a conventional imaging system by colocating the field stop with the output image plane of IRIS – spectrally filtered narrow-band images of the output image plane are then formed at the detector. As an example, an IRIS system with the filter functions shown in Figure 1(b) was mounted onto a conventional retinal camera as shown in Figure 2(a). A snapshot capability is highly desirable in spectral imaging of the retina to avoid the motion and calibration artifacts introduced by eye saccades and the arterial pulse. An example image is shown in Figure 2(b). Images such as this enable the optical density of blood at a range of wavelengths between 580 and 620 nm to be calculated to enable the effect of blood oxygenation to be separated out from variability introduced by other occular pigments, such as melanin, to enable blood oxygenation to be calculated. Although flash-lamp illumination was used to record these images, it was also possible to record real-time spectral images of the retina, albeit of lower quality, using only low-power, tungsten filament inspection lamp.

Conclusions

We have described a new concept in spectral imaging instrumentation that combines polarising interferometry and polarising beam splitters to simultaneously implement image replication and spectral demultiplexing. This enables snapshot spectral imaging in two dimensions, promising the extension of spectral imaging to transient and unstable phenomena. Moreover, in contrast to other high throughput techniques there is no data inversion and so the associated SNR advantage is retained even in shot-noise limited imaging conditions.

Preliminary *in vivo* images of the retina have been recorded that will enable quantitative blood oximetry, and some live-cell imaging has been recorded. The snapshot capability is vital in both these cases in that it removes significant and fundamental problems associated with coregistration of images and calibration. Eight-band spectral imagers have been demonstrated, but extension to a thirty two-band imager is currently under devlopment.

Acknowledgements

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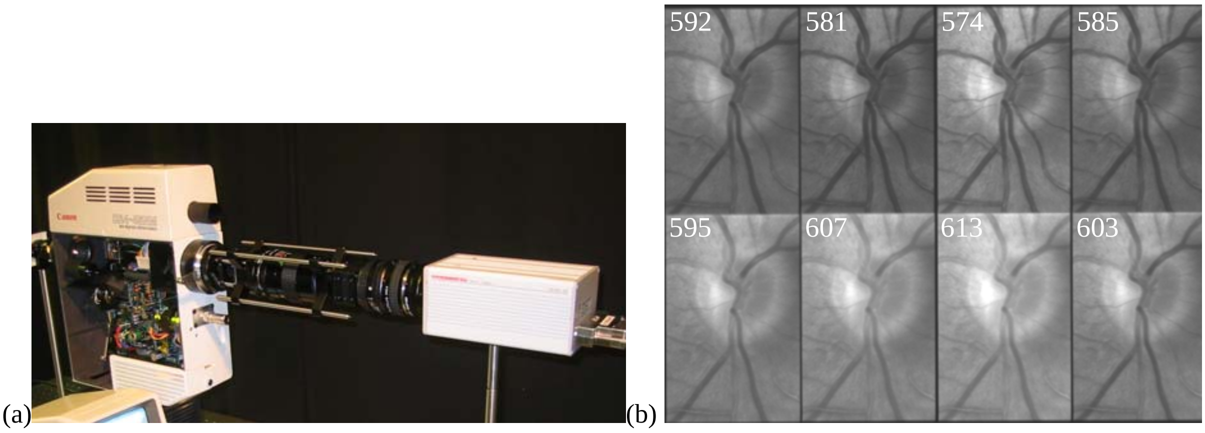

Figure 2 (a) An eight-band IRIS fitted to a retinal camera and (b) eight narrow-band images of an optic disc recorded at the detector

References

[1] B. Lyot, Filter monochromatique polarisant et ses applications en physique solaire, Ann. Astrophys. 7, 32 (1944)

[2] Y. Ohman, On some new birefringent filter for solar research, Ark. Astron. 2, 165 (1958).