The imaging Bragg Tunable Filter:

a new path to integral field spectroscopy and narrow band imaging

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ABSTRACT

An entirely new type of imaging tunable filter has been developed by Photon etc. and the California Institute of Technology. The Volume Bragg Grating based device is able to select a single wavelength for each pixel in a full camera field. The demonstration tabletop prototype was able to select images with a 2 nm bandwidth from 400 to 750 nm. Data cubes were produced through a wavelength scan from which a spectrum per pixel can be extracted. The prototype showed no image distortion, a very stable instrument profile, and high efficiency. The compact and robust tunable filter can operate from 350 nm to 2.5 μm with bandwidths from 3 Å to 200 nm, showing a great potential for both ground based and space astronomy.

Keywords: Astronomical instrumentation, Tunable filter, Volume Bragg Grating, Integral field spectroscopy, Narrow-band imaging, Fabry-Perot, VBG, VPH, VHG

1. INTRODUCTION

Astronomical observations routinely require the use of narrow to intermediate band filters to increase the detection sensitivity. Faint high redshifted cluster of galaxies, emission line comparisons across extended objects, and photometric redshifts are just a few examples of the compelling research relying on band limiting filters. In most cases, fixed interference filters are used, thus limiting the observations to a few spectral features at a limited range of velocities. Observing capabilities are greatly enhanced when a tunable filter is employed in place of fixed filters. For many projects, surveys only then become possible.

Currently available tunable filters are mostly based on low-order Fabry-Perot etalons and acousto-optic Tunable Filter (AOTF). Although very useful and versatile, Fabry-Perot etalons are restricted to very narrow bandwidth ($\Delta\lambda < 2$nm at 1μm). They transmit multiple interference orders and thus necessitate intermediate blocking filters, lowering the total throughput of the system. AOTF are promising for space mission where their intrinsic ruggedness compensate for their low throughput. Lyot filters have also been proposed for wide field imagers [1] but, as AOTF, use polarized light, intrinsically rejecting at least half of the light, besides being optically very complex.

A novel tunable filter concept, based on Volume Bragg Gratings (VBG), has been prototyped at Photon etc. The prototype is continuously tunable from 400 to 750 nm and the instrument can readily be expanded to cover a much larger range. Due to material transparency the usable range is from 350 nm to 2.5 μm. The maximum efficiency can realistically reach 85%. The prototype development is briefly presented herein together with performance and potential science cases that would greatly benefit from the imaging Bragg Tunable Filter.

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2. VPHs AT A GLANCE

A Volume Bragg Grating, also called Volume Phase Hologram (VPH) or Volume Holographic Grating (VHG) consists of a volume in which the index of refraction varies periodically. The orientation of the modulation structure with respect to the incoming light determines whether the grating is reflective or transmissive. Their properties are well described in [2] and [3]. The Bragg diffraction caused by this index modulation affects a narrow region of the spectrum, centered on:

$$\lambda = 2\Lambda \sin(\theta)$$

where λ is the wavelength, Λ is the index modulation period, and θ is the angle of incidence in the modulating medium. The affected bandwidth is also inversely proportional to the thickness *d* of the grating such as:

$$\frac{\Delta\lambda}{\lambda} = \frac{\Lambda \cot(\theta)}{d}$$

Radiation that departs significantly from the Bragg condition simply passes through the grating, undiffracted. This tunability can be advantageously used in spectographs, but it also allows a totally new type of imaging tunable filters.

3. THE CONCEPT

Collimated light from the telescope is diffracted by a first VBG. As explained above, only a small fraction of the spectrum will be affected. By using a second grating, it is possible to recombine, or "undisperse" the light coming from the first grating. An image can thus be reconstructed as long as the gratings are parallel and have the same modulation period . To naturally insure that parallelism and identical index modulation, a retroreflector can be used to redirect the light an a second region of the same grating (figure 1).

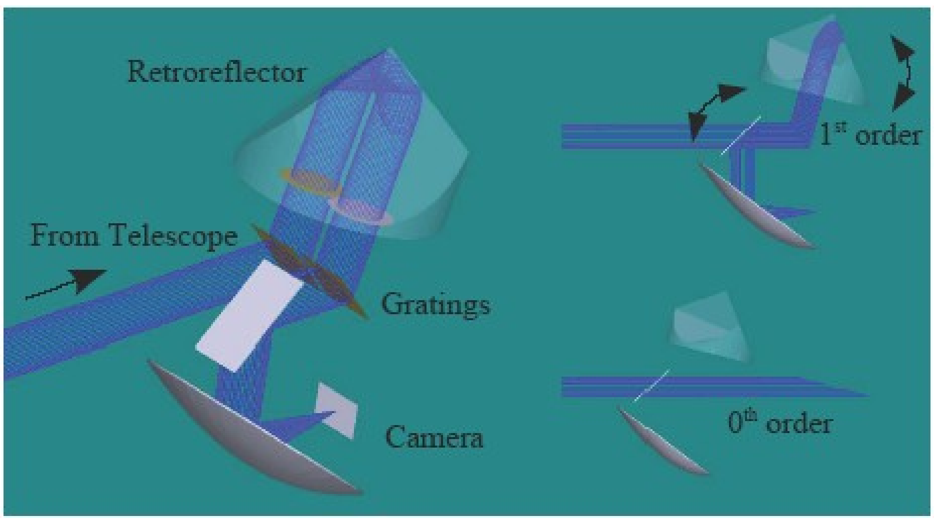

Figure 1 : iBTF optical design with gratings and reflector on independentrotation mechanisms. Left: isometric view of the 1st order. Right: side views of thefirst and 0th orders.

Since only light whose wavelength satisfies the Bragg condition is diffracted, it is possible to adjust the grating and retroreflector angles to effectively tune the filter central wavelength. Moreover, as the undiffracted light just passes through the grating without changing its path, it is possible to cascade these filters to study two (or more) different bands at the same time.

A corollary of this angle based tunability is a gradient in wavelength across the field of view. This gradient is only present in the dimension parallel to the dispersion axis. To get a pure monochromatic image one would the need to scan through a few wavelength and retrieve the proper wavelength for each pixel. This is routinely done with Fabry-Perot observations.

As mentioned above, the thickness of the VBG dictates the bandwidth of the filter. Figure 2 displays three bandpasses for VBGs of different thicknesses. Through simulations, it is possible to tune both the bandwidth and peak transmission wavelength.

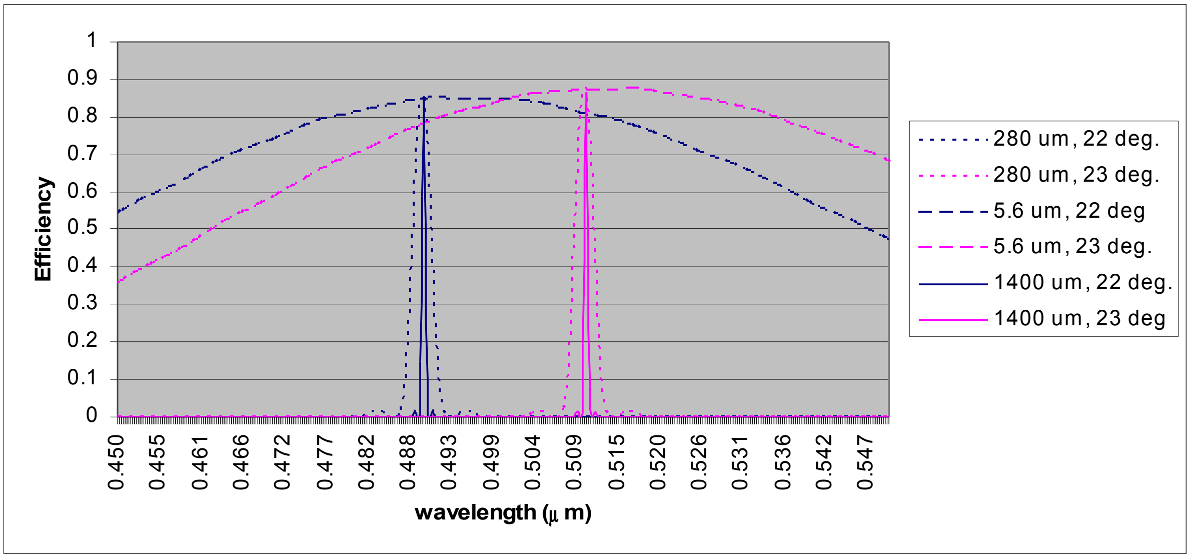

Figure 2 : Bandwidth of VBGs of different thicknesses, shown for two incident light angles.

4. CURRENT DESIGN

An optimum design (figure 3) would try to balance off-axis angles and collimator size. The specific choice depends on the acceptable wavelength gradient across the field of view. For large wavelength-span survey modes, such gradients are not a handicap and a compact instrument can be designed. On the other hand, for targeted observation, one would want a quasi-monochromatic field, implying a large focal ratio and thus a large pupil system. Interestingly, current technology allows the building of very large format VPH gratings (up to half a meter). Such large pupil instruments could allow a low gradient over a reasonable field, even for 10-m class telescopes. Also, as the gradient is only in the dispersion axis, a very large field could be covered with a rectangular detector, with the short axis aligned to the dispersion direction.

As a demonstrator, we used a small 5 mm pupil and a 1 to 1 re-imaging system. The grating was optimize for 350 nm but due to camera and opto-mechanical limitations, the covered wavelength is from 400 to 750 nm.

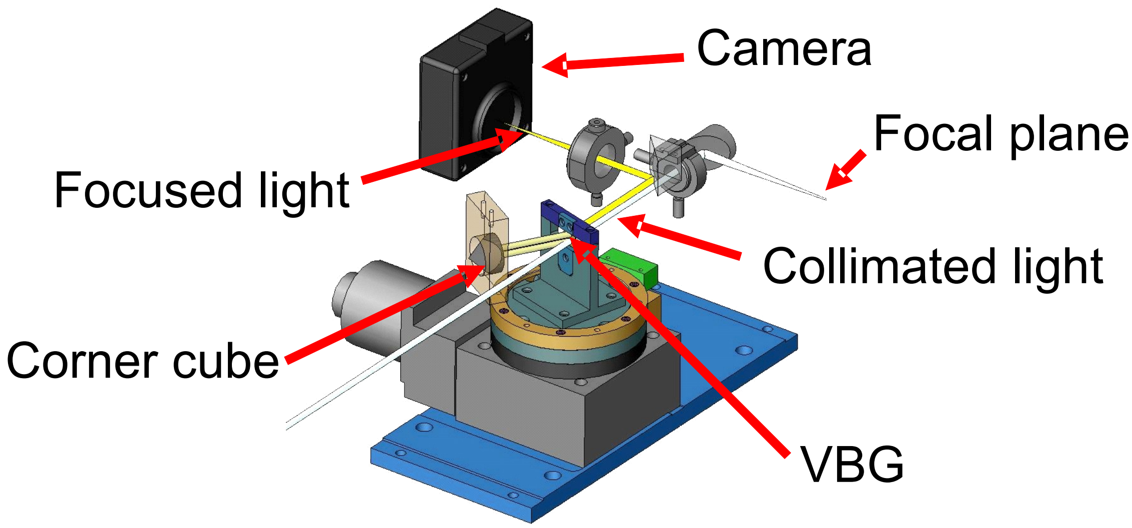

Figure 3 : Current design of a imaging tunable filter using a single VBG.

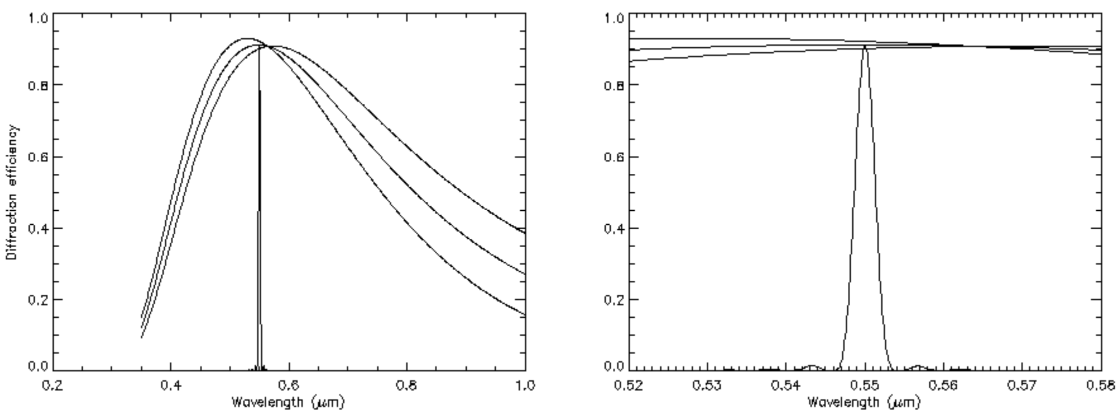

Figure 4 : Diffraction efficiency of a VBG tunable filter (2 passes). Plain line: combined efficiency of parallel and perpendicular polarizations. Dotted line: parallel polarization. Dashed line: perpendicular polarization.

5. PERFORMANCE

A tunable filter using VBGs can reach diffraction peak efficiencies of 90%. However, the diffraction efficiency have to be optimized for a given wavelength. Figure 4 shows the diffracting efficiency over a large extent of the range of such a tunable filter optimized for a peak efficiency at 0.55µm. The left panel shows the the bandpass efficiency (including 2 passes in the grating). In this case, the total efficiency (both polarizations) is greater than 80% from 475 to 650 nm ($\Delta\lambda$ = 175nm) and greater than 60% from 430 to 755 nm ($\Delta\lambda$ = 325nm). To achieve a high efficiency across a large range, one could use many gratings on a turret. An example of the bandpass (2.8 nm) is also shown on the figure. The right panel is a zoom centered on the bandpass. It shows the weak wings and the squareness of theoretical the profile.

The tunability of the filter is accurate to within 50 pm. With the aid of the internal calibration system, the filter can achieve this repeatable tuning precision over the full range.

Figure 5 shows the normalized bandpass of the prototype tunable filter built with the technology described in section 4. The profile closely follows the one of a second order Gaussian. Such a profile is advantageously compared to the Airy profile of a Fabry-Perot interferometer.

The Figure 6 shows a picture of the Imaging Bragg Tunable Filter (iBTF). It illustrates the possibility of using the undiffracted light (where the tunable filter acts as a notch filter) to create a second focal plane. Instead of this second camera, a second tunable filter could be inserted to study a second wavelength. This system has yet to be used on the sky. However, a multicolor Joseph's Coat Plant was observed in 366 monochromatic channel (figure 7). It clearly shows the iBTF capability of being used as an integral field spectrograph.

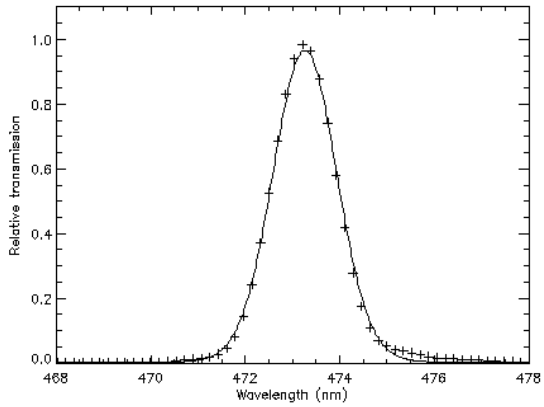

Figure 5 : Bandpass of an iBTF. The crosses shows the actual bandpass. The plain line is the fit of a second order gaussian.

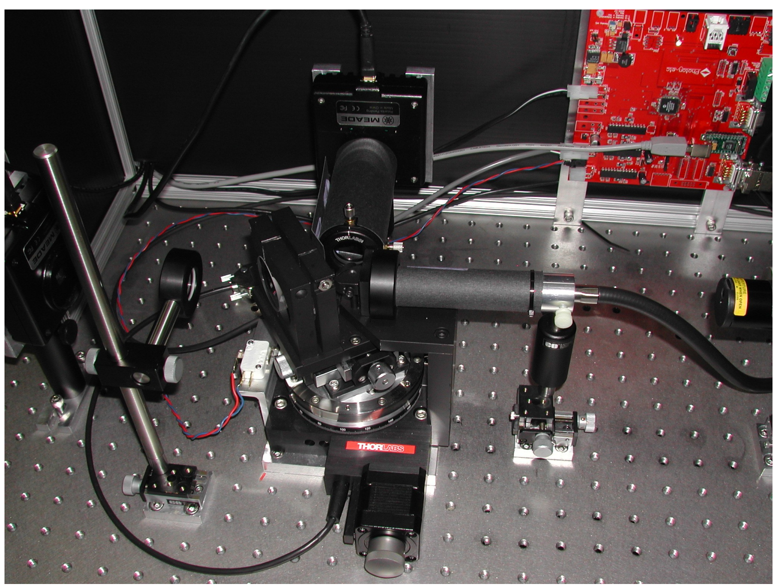

Figure 6 : Picture of the actual Imaging Bragg Tunable Filter. The diffracted beam (monochromated) imaged on the camera in the center of the picture. The white beam passes through the filter and is imaged on the camera on the left of the picture.

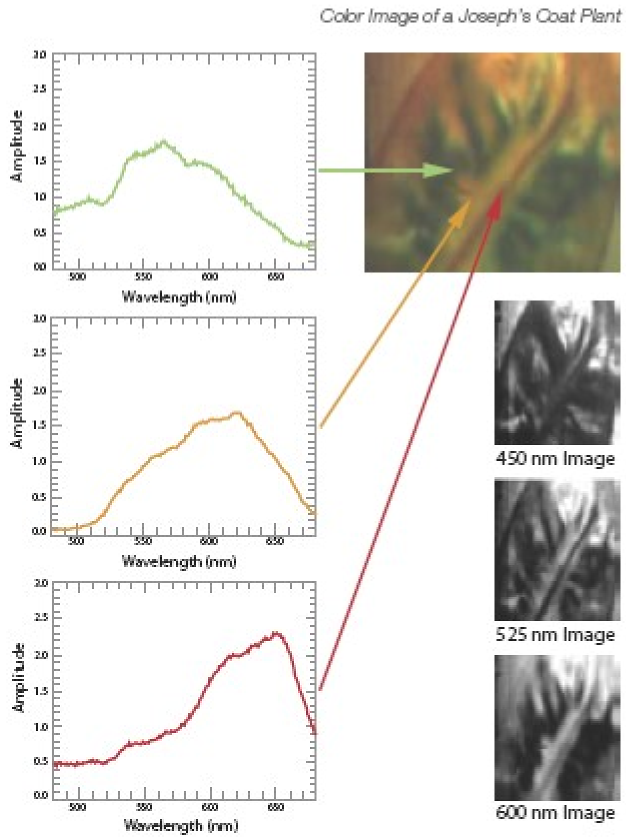

Figure 7 : Monochromatic images, spectras and false-color image of a Joseph's Coat Plant imaged with iBFT.

6. SCIENTIFIC APPLICATIONS

The range of scientific applications is extensive. Many current observations made with conventional interference filters will be facilitated by the availability of a simple, versatile and efficient tunable filter. Rather than enumerating all such science cases, we focus on science projects that are essentially reliant on a tunable filter.

Extragalactic line ratios and abundance gradients

The understanding of several properties of galaxies relies on the accurate derivation of relative abundances of HII regions, such as gradients or abundances differences among galaxies. These radial abundance gradients are now known to be a common feature in the Galaxy (Shaver et al. 1983) and in several nearby galaxies (Belley & Roy 1992). The abundance of HII regions may be determined by observing the intensity of nebular lines that are correlated with the abundance. However, as the emissivity of such lines may also be function of the electron temperature, it is therefore easier to determine the abundances of HII regions where the temperature can be directly determined from temperature-sensitive line ratios, such as [OIII] 4959+5007/4363 or [NII] 6548+6584/5755 (for temperatures higher than 8000K). One may thus derive the abundance gradient for many HII regions with complete radial coverage of the surface of the galaxy with many narrow-band filters, such as Halpha, Hbeta, [NII] and [OIII]. It is also necessary to observe many HII regions to explore the differential trends among galaxies.

The gathering of these data requires the narrow-band observation of HII regions of sparsely redshifted galaxies. Since many HII regions are to be observed in a single galaxy, integral field spectroscopy is to be considered. Most of the time, this work is accomplished by means of narrow-band interference filters imaging. Then, one would need a set of filters for every galaxy. The use of a tunable filter with a single or multiple output would allow large surveys to be observed, allowing the ISM of galaxies to be better understood.

Primeval galaxies

Deep narrow band imaging enables the detection of primeval galaxies. A VBG Tunable Filter will be a powerful tool for investigating galaxy formation, as already suggested by the detection of LEGOS (Lyman-α Emitting Galaxy-building ObjectS) (REF!) on the VLT: In a 7 x 7 arcmin field of view, with 10 hours exposures through a 2 nm FWHM filter in FORS1, they detected 35 Lyman-α emitting galaxies (all in the same redshift range: $z=2.85\pm0.03$). For a survey of this type, a tunable filter is virtually required, in order to obtain a statistically meaningful sample in the redshift domain.

Several groups are now pushing to $z=5$ and beyond, also looking for the detection of Lyman-α. The candidates are generally selected from multicolor imaging surveys such as the Solan Digital Sky Survey or targeted narrow-band imaging such as the Large-Area Lyman Alpha Survey (REF!) which have recently confirmed three Lyman-α emitters at $z=5.7$ (REF!). Also recently, $z\sim6$ quasars (REF!) have been detected through a similar multi-band imaging and spectroscopic follow-up technique. There are being used to probe the nature of the Gunn-Peterson effet.

A truly efficient and wide-field tunable filter would allow such programs to scan regions of the sky at arbitrary redshift, increasing the potential candidates by an enormous factor. No other device can achieve the expected 75% average throughput, full optical band tunability, and a decent field-of-view. Bandwidth can moreover be designed to match the application, giving the most versatile imaging device.

For these projects and may others, a VBG tunable filter would provide a substantial increase in detection sensitivity by its very high efficiency and its arbitrary large bandpass, enabling science of more distant objects and of more statistically complete samples. Certainly additional applications will follow as well, as is being discovered by other tunable filter projects.

7. CONCLUSION

VBG allows the building of filters that are tunable over the full optical and near-infrared range and that reaches efficiencies in the range of 90%. These Imaging Bragg Tunable Filters are readily available... nanan

REFERENCES

1. J. Bland-Hawthorn, W. van Breugel, P. R. Gillingham, I. K. Baldry, and D. H. Jones, "*A Tunable Lyot Filter at Prime Focus: a Method for Tracing Supercluster Scales at z ˜ 1*," ApJ **563**, pp. 611–628, Dec. 2001.

2. S. C. Barden, J. B. Williams, J. A. Arns, and W. S. Colburn, *"Tunable Gratings: Imaging the Universe in 3-D with Volume-Phase Holographic Gratings (Review)*," in ASP Conf. Ser. 195: Imaging the Universe in Three Dimensions, pp. 552–+, 2000.

3. Blais-Ouellette, Sebastien; Wishnow, Edward H.; Shopbell, Patrick L.; van Breugel, Wil; Taylor, Keith; Smith, Roger, « Double Bragg grating tunable filter », in Proceedings of the SPIE, Volume 5492, pp. 779-786 (2004)

4. Shaver et al. 1983
5. Belley & Roy 1992

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