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Tunable Gratings: Imaging the Universe in 3-D with Volume-Phase Holographic Gratings

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Abstract. Volume-phase holographic (VPH) grating technology can enable innovative capabilities for integral field spectrographs beyond that achievable with classical diffraction gratings. VPH gratings can be tuned to maximize diffraction efficiency at the wavelength of interest and complex grating structures can be fabricated to allow the simultaneous observation of different spectral regions. The encapsulated nature of these gratings also allow them to be more robust and easier to handle and clean than classical gratings.

A brief review of the physics and performance for VPH gratings is given along with a presentation of some application concepts. In particular, discussion focuses on the performance of a dual grating that diffracts Hα and Hβ to the same angle. Such a grating may be of interest for IFU applications.

1. Introduction

Technologies that are viable for integral field spectroscopy are rapidly evolving and revolutionizing the design of astronomical instruments. One such area is that of diffraction grating technology. Recent advances have been made in grating immersion and grating mosaics, but these devices are still based upon the classical, surface–relief grating. An alternative diffraction grating has recently become available through advances in holographic technology. These gratings, called volume-phase holographic (VPH) gratings, show superior performance over surface-relief gratings in many applications.

Barden, Arns, and Colburn (1998) present an overview of this technology and its potential for astronomical use. We review some of that discussion and present discussion focused on VPH gratings of particular interest in IFU applications.

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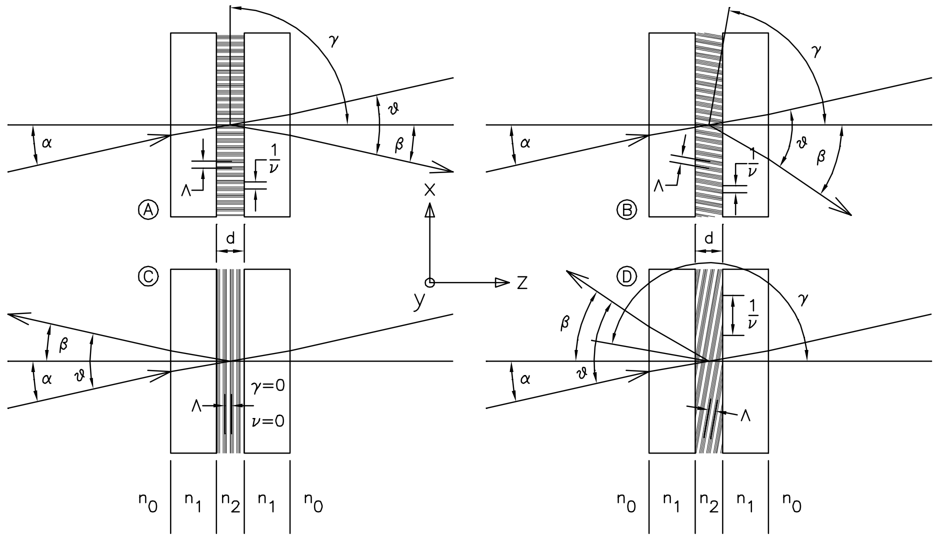

Figure 1. VPH grating structures. A. Littrow transmission grating. B. Non–Littrow transmission grating. C. Non–dispersive reflection grating (notch filter). D. Dispersive reflection grating.

2. VPH Grating Physics

Instead of diffracting light by surface structure, as in either diamond–ruled or holographically generated surface–relief gratings, VPH gratings diffract light by refractive index modulations within the volume of a thin layer of gelatin material. Light is diffracted at angles corresponding to the classical grating equation

$$m\nu\lambda = \sin(\alpha) + \sin(\beta)$$

where ν is the line frequency of the index modulation as it intersects the surface of the grating volume, (α and β are the incident and diffracted angles, respectively; m is the diffraction order; λ is the wavelength of light). A surface–relief grating "blazes" the diffracted energy by having a tilted facet acting like a mirror. VPH gratings, on the other hand, distribute the diffracted energy according to the Bragg condition

$$m\nu_g\lambda = n_g 2\sin(\alpha_g)$$

in which ν_g is the frequency of the index modulation within the grating volume itself, n_g is the average refractive index of the grating material (1.5 for the gelatin), and α_g is the Bragg angle within the grating. Figure 1 shows the relationship of α, β, ν, and $\Lambda = 1/\nu_g$ for the different possible VPH grating structures.

The efficiency at which light is diffracted when it satisfies the Bragg condition is a function of both the grating depth (d) and the contrast provided by the index modulation (Δn). In general, rigorous coupled wave analysis (RCWA) (Magnusson and Gaylord, 1977 and Gaylord and Moharam, 1985) or modal analysis (Burckhardt, 1966 and Magnusson and Gaylord, 1978) is required to properly model the diffraction efficiency for a VPH grating. Kogelnik (1969) developed a set of scaling relations that provide an estimate for the diffraction efficiency of a VPH grating. The diffraction efficiency for the two planes of polarization for a transmission grating can be estimated by the following:

$$\eta_s = \sin^2[\frac{\pi \cdot \Delta n \cdot d}{\lambda \cdot \cos(\alpha_g)}]$$

and

$$\eta_p = \eta_s \cdot \cos(\alpha_g + \beta_g)$$

in which α_g and β_g are the angles of incidence and diffraction within the grating volume. In general, the p plane of polarization efficiency is not that significantly different from that for the s plane as long as α_g and β_g do not add up to a total of 90 degrees. In that case, the grating becomes a perfect polarization beam splitter in which only one of the polarization planes is diffracted and the other is passed straight through.

Light that meets or nearly satisfies the Bragg condition can be efficiently diffracted for appropriate grating parameters. Both the angle of incidence and the wavelength of light are factors which determine whether or not the Bragg condition is met. The angular Bragg envelope, the diffraction efficiency as a function of incident angle for a fixed wavelength, scales as

$$\Delta\alpha_{FWHM} \propto \frac{\Lambda}{d}$$

and the wavelength or spectral Bragg envelope, the diffraction efficiency as a function of wavelength for a fixed angle of incidence, scales approximately as

$$\Delta\lambda_{FWHM} \propto \frac{\Lambda}{d}\cot(\alpha_g).$$

3. VPH Grating Structure

The VPH gratings discussed in this paper are constructed with Dichromated Gelatin (DCG), a material that has been extensively used in holographic devices over the past several decades. Although there are other materials available for the recording of fringe structures, DCG provides superior diffraction efficiencies and has great clarity and excellent transmittance between 300 and 2700 nm. The index modulations are generated by first photo-sensitizing the gelatin, exposing it to the fringe pattern produced by the properly aligned holographic exposure system, swelling the gelatin with water, and then rapidly drying it in a bath of alcohol. In this bath, the regions that were exposed to light collapse to a different density than those regions which were not as intensely exposed. The resultant variations in density translate directly to a refractive index modulation.

Since DCG is very hygroscopic, it must be encapsulated and sealed from exposure to any moisture or humidity. Properly sealed, DCG can have optimum performance over very long lifetimes (at least 20 years). The encapsulated grating can be handled much more easily than surface–relief gratings that are more easily damaged by handling and environmental conditions. The substrates of VPH gratings can be made of any optically suitable material such as BK7 or Fused Silica. High performance anti-reflection coatings can be applied to the outer surfaces of the grating substrates to further enhance the performance of the VPH grating.

VPH gratings can have line densities ranging from about 300 to 6000 l/mm. The grating depth can vary from 4 to 30 μm. The average refractive index for DCG is about 1.5 and the index modulation can range from 0.02 to about 0.10. Gratings have routinely been fabricated to function in the optical and near–infrared wavelengths.

Grating size is another trait in which VPH gratings are potentially superior to classical, diamond–ruled, surface–relief gratings. Surface gratings are currently limited at about the 200 mm size due to wear on the diamond head making the ruling and to limitations in the grating replication process due to the surface area of such a large grating. Larger surface-relief gratings must be made from mosaicing together a set of smaller gratings. Although not impossible, such mosaics are expensive and delicate. VPH grating technology (and to some extent, holographically generated surface–relief gratings) is limited by the size of the holographic exposure beam, the power of the exposing laser, the stability of the exposure system against vibration and drifts, and the capacity of the DCG processing equipment. DCG holograms of greater than 400 mm have been fabricated and efforts are underway to produce gratings with apertures of 1 meter in diameter. There are also techniques in which DCG gratings might be mosaiced into even larger grating formats, either during the exposure process or by replication techniques. At present, the VPH gratings produced by Kaiser Optical Systems, Inc. (KOSI) are limited in size (75 by 100 mm) by their holographic exposure system dedicated to the fabrication of diffraction gratings. Efforts are currently underway to upgrade their collimators to a size that could expose gratings as large as 300 mm.

4. Measured Grating Performance

Barden, Arns, and Colburn (1998) presented the analysis of a 600 l/mm VPH grating with a peak efficiency of 80% at 700 nm that provided good performance at other wavelengths and diffraction orders when the grating was tuned to the appropriate angles. Funding from the National Science Foundation was received for the fabrication and analysis of an additional eight VPH gratings. The following gratings are under such evaluation:

- 300 l/mm transmission grating designed for optimal performance at 1064 nm.
- 1200 l/mm transmission grating with peak efficiency at 532 nm.
- 2400 l/mm transmission grating with optimal efficiency at 532 nm.
- 2400 l/mm transmission grating with peak diffraction efficiency at 1064 nm. This grating requires prism substrates to extract the otherwise evanescent first order diffraction at the design wavelength.
- 4800 l/mm transmission grating with prism substrates and optimal performance at 532 nm.

- 1200 l/mm reflection grating at 532 nm.
- 1200/1620 l/mm transmission multiplex grating for optimal performance at both Hα and Hβ. Both wavelengths are diffracted to the same angle.
- 300 l/mm transmission grating with 532 nm in the tenth order of diffraction. This is an attempt to make an echelle–like VPH grating.

As Barden, Arns, and Colburn (1998) pointed out, VPH gratings can be tuned to peak up the efficiency at the desired wavelength of observation. This allows the grating to be used outside the spectral bandwidth of the grating at the design wavelength. Figure 2 demonstrates this for the 300 l/mm grating. In effect, the blaze envelope can be adjusted by tilting the grating. We call the envelope defined by the tunable peak efficiency the "super blaze".

Figure 3 shows the diffraction performance of the 1200 l/mm grating at a specific grating angle along with the "super blaze". This particular grating gives a peak efficiency of 87% for unpolarized light at 500 nm, nearly a factor of two in comparison to a comparable 1200 l/mm surface–relief grating.

Note that the spectrograph camera must also be adjusted in angle to re-center the wavelength that the grating has been tuned to. The camera should either be articulated to directly adjust for the diffraction angle that the grating is tuned for, or a set of prisms could be used to modify the angular deviation back to a fixed camera angle in a similar fashion to classical grisms.

5. VPH Gratings of Particular Interest for IFU Spectrographs

Integral field unit (IFU) spectrographs may be able to take advantage of particular aspects in VPH grating technology that may not be specifically suited for more conventional spectroscopic applications. Two possible VPH configurations are

- VPH multiplex gratings in which two different spectral regions are diffracted to the same angle.
- VPH reflection gratings which can have extremely high diffraction efficiency over a narrow bandwidth while the undiffracted light passes through the grating undispersed.

5.1. Multiplexed Gratings

Kaiser Optical Systems, Inc. can produce VPH gratings containing a stack of more than one grating in a single holographic unit (Owen, Battey, Pelletier, and Slater, 1995). Since the spectral bandwidth of a VPH grating can be controlled by either the depth of the grating or the contrast of the index modulation, one can design a grating pair in which one grating diffracts one spectral region while having minimal diffraction efficiency for another spectral window and the second grating diffracts the second region while being invisible to the first. One can then manipulate these two spectral regions somewhat independently. One possibility is to diffract both regions to the same angle where they could both be simultaneously imaged onto the spectrograph detector. Spatial separation

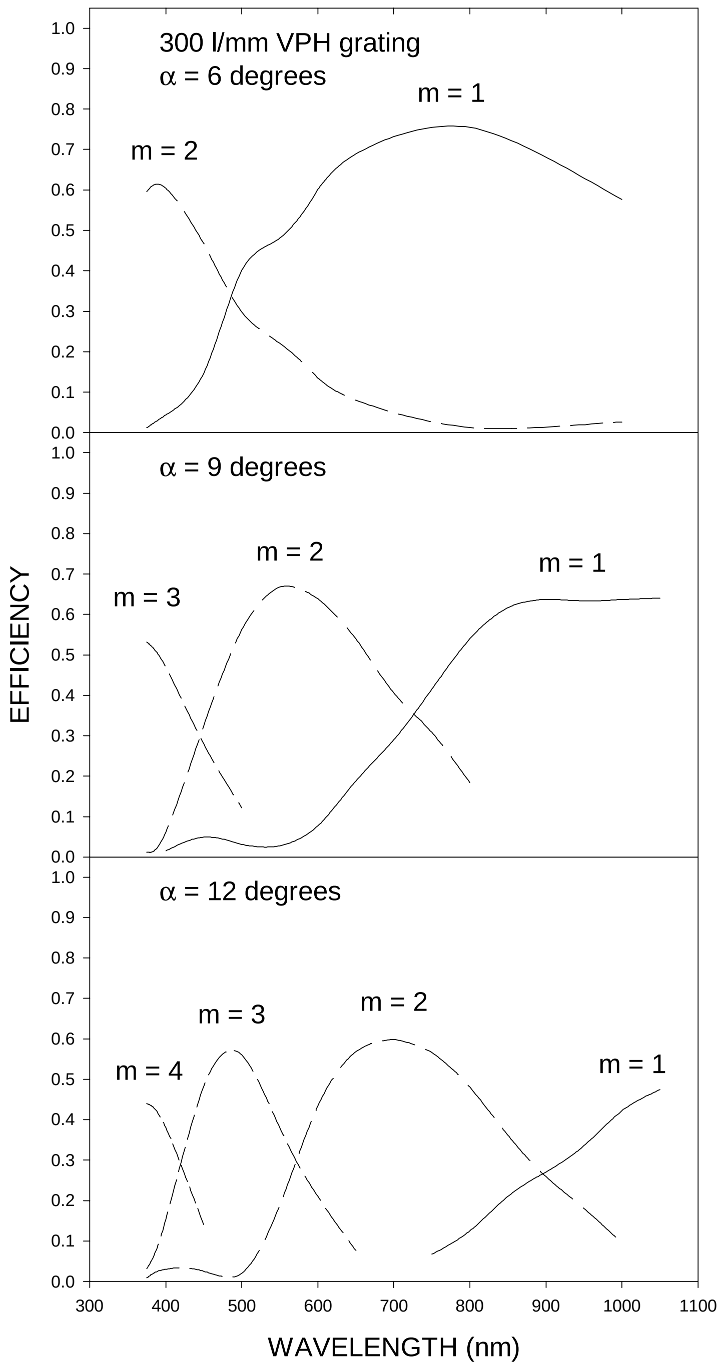

Figure 2. Diffracted energy profiles in unpolarized light for the 300 l/mm VPH grating at three different grating angles.

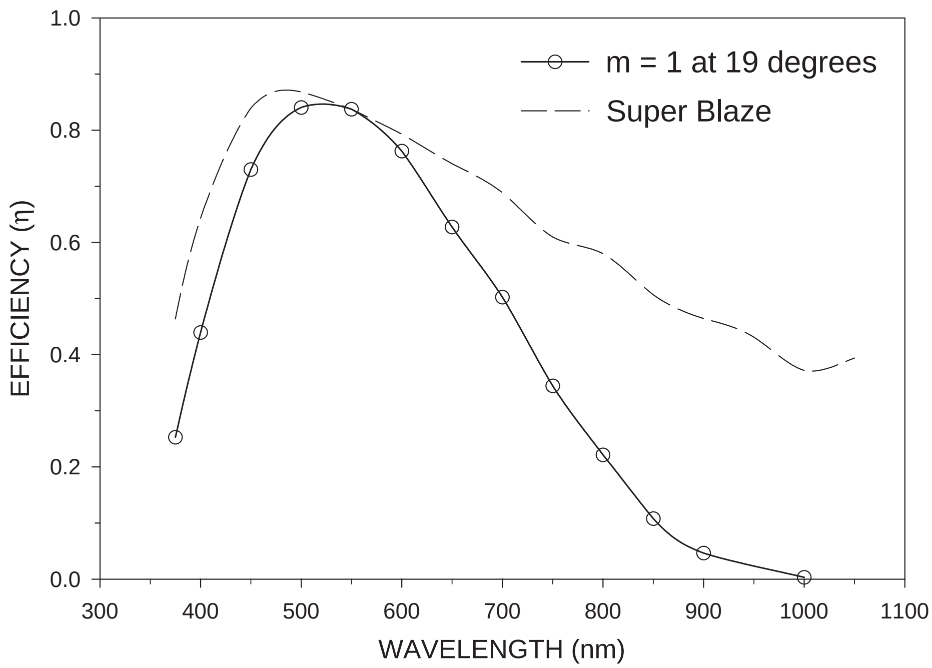

Figure 3. Measured diffraction efficiency for the 1200 l/mm VPH grating in unpolarized light at a grating angle of 19 degrees. The "super blaze" shows the tunable range of this grating.

of the two regions can be achieved by simply having the fringe planes of the two gratings slightly rotated with respect to each other. The zeroth order of diffraction for both gratings would overlap each other, but higher diffraction orders would be well separated. This type of multiplex grating performs the near equivalent of a multi–order grating with cross–dispersion, but without the need for the wavelength regions to be integral multiples of each other or the need for an additional cross–dispersing prism or grating. An IFU instrument could be designed to utilize such a grating to provide simultaneous spectral imaging in two spectral bands.

For the NSF study, a multiplex grating was designed to diffract Hα (656 nm) and Hβ (486 nm) to a diffraction angle of about 23 degrees. A 1200 l/mm grating diffracts 656 nm while the 486 nm spectral region is diffracted by a 1620 l/mm grating component. The bandwidths for the gratings were designed so that at a 23 degree angle of incidence (or diffraction), each would have a minimum in their diffraction efficiencies at the complementary spectral region. Spectral separation is achieved by rotating the gratings by about 5 degrees with respect to each other.

The tunable nature of VPH gratings allows this multiplex grating to be tuned to match the redshifted wavelengths of a particular astronomical target. Adequate diffraction efficiency can be achieved with this grating up to a redshift of about 0.5 (where Hα is shifted to 985 nm and Hβ to 729 nm) by illuminating the grating at 36 degrees. The forbidden lines of Oxygen at 500.7 nm ([OIII]) and 372.7 ([OII]) have a similar wavelength ratio (1.34) to that of Hα and Hβ. Tuning the grating to an angle of 17.5 degrees shifts the diffraction energy envelope to those wavelengths.

Figure 4 and figure 5 show the measured efficiency for the Hα/Hβ grating in unpolarized light and as a function of grating angle. The 1200 l/mm com-

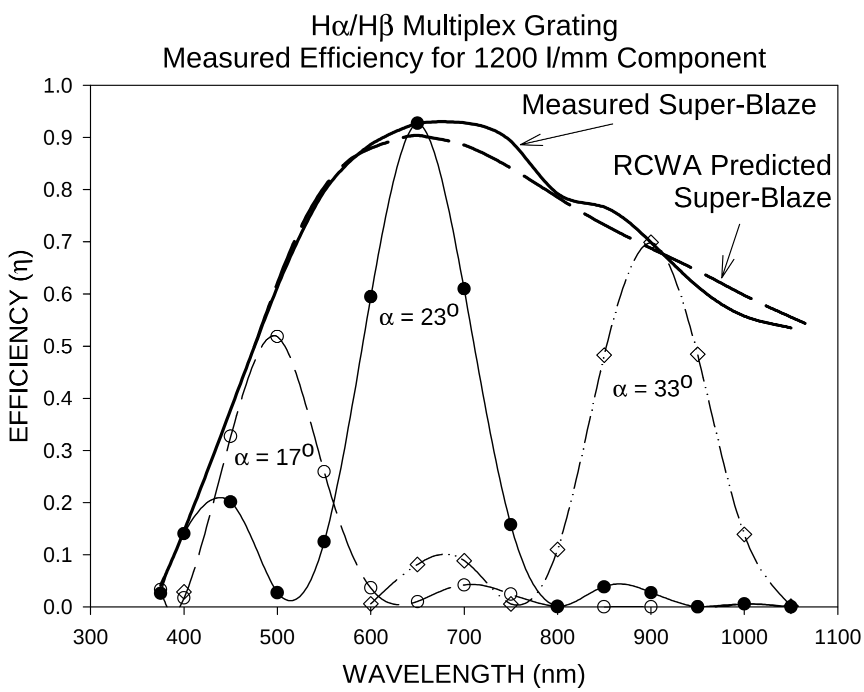

Figure 4. The measured efficiency for the 1200 l/mm component (Hα channel) of the multiplex grating in unpolarized light at grating angles of 17, 23, and 33 degrees. This grating achieves optimal peak efficiency (93%), however the spectral bandwidth minimum falls redward of the design goal so does not quite align with the diffraction efficiency peak of the 1620 l/mm component.

ponent has a peak efficiency of 93% at 656 nm! Both grating components were fabricated with peak efficiencies near that predicted by RCWA. However, the spectral bandwidth for the 1200 l/mm grating turned out to be slightly narrower than that desired. The efficiency minimum for that grating does not align with the wavelength for peak efficiency in the 1620 l/mm grating. This has the effect of lowering the effective efficiency of the 1620 l/mm grating by about 15% at 486 nm.

On-sky testing was carried out for this grating by using a fiber optic feed on the 2.1–meter telescope at Kitt Peak National Observatory. The 30 meter long fiber subtended 2.5 arc-seconds on the sky and fed into the QDS (quick and dirty spectrograph). The QDS consisted of three achromatic lenses, the VPH grating, and a 2048 by 2048 CCD detector (T2KB). The detector was binned into a 512 by 512 format in order to better sample the image formed by the

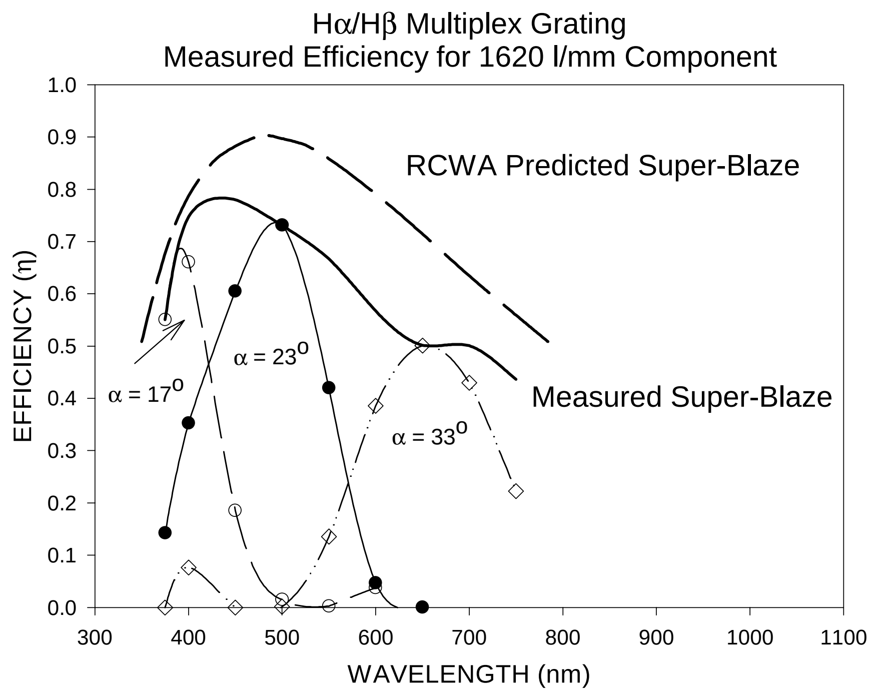

Figure 5. The measured efficiency for the 1620 l/mm component (Hβ channel) of the multiplex grating in unpolarized light at grating angles of 17, 23, and 33 degrees. Light inadvertently diffracted by the 1200 l/mm component lowers the efficiency performance of the 1620 l/mm component by about 15%.

spectrograph. The seeing and sky conditions were quite good during one night of the five night run, with seeing measuring at about 1.2 arc-seconds. Observation of a spectrophotometric standard yielded total detected quantum efficiencies (inclusive of telescope, fiber, seeing, spectrograph, grating, and detector) of 29% for the 1200 l/mm grating at Hα and 18% for the 1620 l/mm grating component at Hβ! The spectrum of a blue compact galaxy (B=17) with a redshift of 0.0217 is displayed in figure 6. Obvious features are Hα, [SII], Hβ, and the [OIII] doublet.

5.2. Reflection Gratings

A VPH reflection grating has the potential for achieving diffraction efficiencies of nearly 100%. Unfortunately, the spectral bandwidths for these gratings tend to be quite narrow with widths of only a few hundred Å. Many applications in IFU spectroscopy, however, are often concentrated on specific spectral features that don't require wide spectral bandwidths. As such, VPH reflection gratings may be ideal dispersing elements for such IFU systems. An additional benefit of a VPH grating is the fact that the wavelengths that are not diffracted (ie. fall outside the spectral bandwidth) will pass through the grating unaffected. This minimizes the need for bandwidth limiting filters and allows the possibility

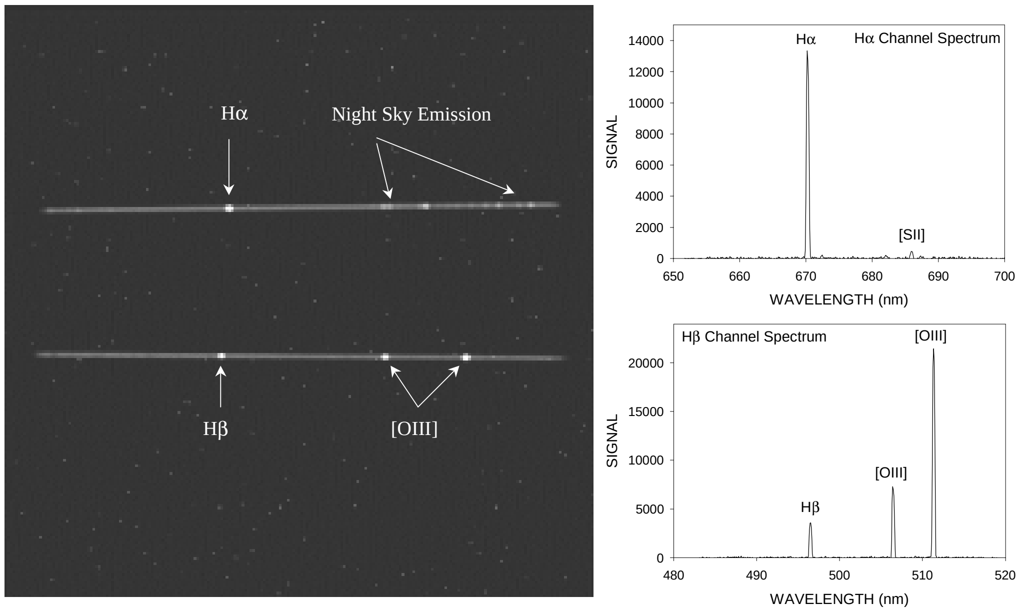

Figure 6. Spectrum of an 18th magnitude, blue compact galaxy. The CCD image of the spectrum is displayed on the left. The extracted spectra on the right have had the sky spectrum subtracted. Note the slight tilt between the two spectra in the CCD image. The spectra would intersect each other at the location of zeroth order.

of utilizing the undiffracted light for simultaneous imaging or dispersion by an additional spectroscopic channel in the instrument.

A 1200 l/mm VPH reflection grating has been fabricated through the NSF effort. The grating was designed to have optimal diffraction at 532 nm, corresponding to a laser wavelength that allowed monitoring of the gratings performance during the grating processing. Figure 7 shows the theoretical diffraction performance for the NSF grating.

The grating has been fabricated, but at the time of writing this paper, it has not been fully evaluated for its actual diffraction efficiency. Figure 8 shows the transmittance of the actual grating when the grating is tilted by 4 degree. Except for material absorption losses of a few percent, the diffraction efficiency can be estimated by the inverse of this plot. The wider bandwidth of the actual grating compared to the predicted curve is probably a result of a "warping" of the fringe structure during the processing of the grating. Intentional warping of the fringes is a way of increasing the spectral bandwidth of VPH reflection gratings.

6. Concluding Comments

VPH gratings show excellent efficiencies and provide unique diffraction properties that are either difficult or impossible to achieve with the classical, surface–

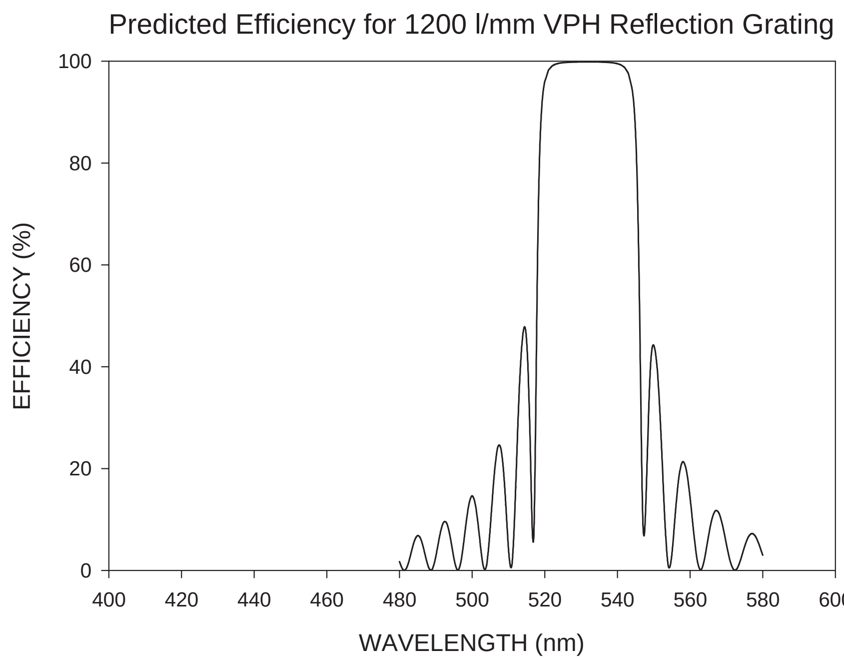

Figure 7. Plot showing the RCWA predicted diffraction efficiency for the VPH reflection grating according to the initial design parameters for that grating. Note that the efficiency peaks out at nearly 100%.

relief gratings. The high efficiencies, multiplex capability, and narrow bandwidths can all be exploited by integral field spectrographs. As implied by the title for this paper, it will indeed be possible to do 3-dimensional imaging of the Universe with volume-phase holographic gratings.

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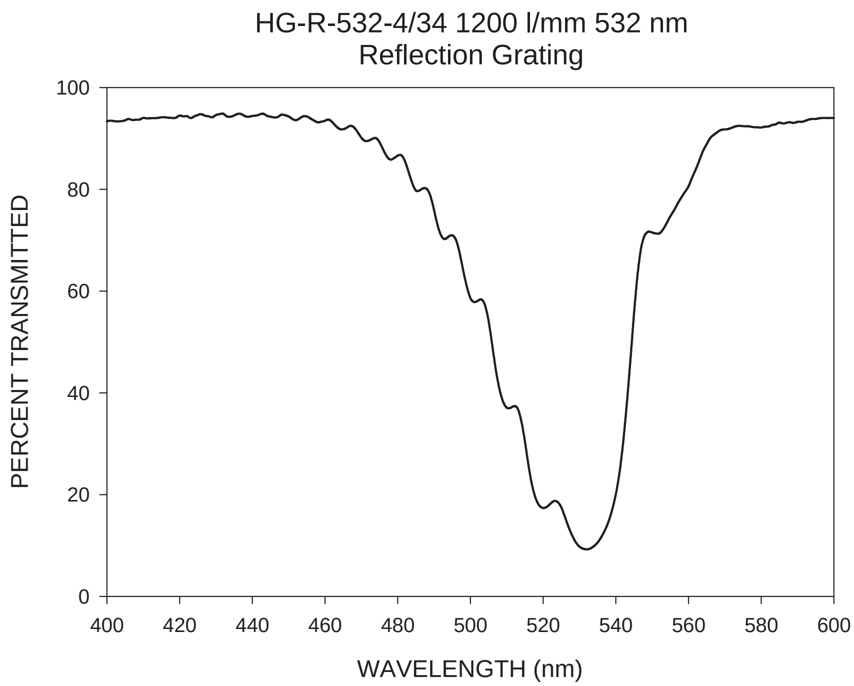

Figure 8. The measured transmittance in unpolarized light for the 1200 l/mm VPH reflection grating. The diffraction efficiency can be estimated by taking the inverse of this plot.