New approach to atmospheric OH suppression using an aperiodic fibre Bragg grating

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Abstract: At near infrared wavelengths, the night sky background seen from the Earth’s surface is almost completely dominated by bright spectral lines due to hydroxyl in the upper atmosphere. In the wavelength range 1-2µm, more than 100 intrinsically narrow spectral lines account for about 98% of the sky background. Now that the performance of infrared detectors is comparable to CCDs at optical wavelengths, the bright infrared sky is the last remaining hurdle to ground-based infrared telescopes reaching sensitivity levels associated with optical telescopes. We demonstrate an aperiodic fibre Bragg grating (AFBG) which performs 94% suppression of OH emission in the 1.50-1.57µm window at a resolving power of R=10,000. This is a working prototype for a device which will allow comparable levels of OH suppression at R=50,000 across the entire near infrared (1.0-2.0µm) spectrum.

OCIS codes: (060.2430) Fibers, single-mode; (010.1080) Adaptive optics

References and Links

1. Introduction

In recent years, the near infrared (1-2.5µm) region of the electromagnetic spectrum has become a key frontier of observational cosmology. Historically, astronomy at optical wavelengths (0.3-1µm) has progressed further because of the much lower intensity of background radiation. This has allowed astronomers to pursue celestial sources in the optical to ever increasing redshifts culminating in recent discoveries at redshifts z ~ 6.6 [5,10,12]. To venture beyond here will require comparable sensitivities at near infrared wavelengths.

The dominant near infrared background arises from OH radicals in a cold layer of 6-10 km thickness at an altitude of 90 km. Astronomers have long searched for a technology to suppress this background signal from OH emission lines (see Fig. 1) but with limited success. This effort intensified when it was realized that the night-glow continuum between the OH lines is very faint [14]. If these lines could be fully suppressed, then the night sky continuum level would be 20-21 mag arcsec⁻², comparable to or fainter than the night sky background at red optical wavelengths [7].

Fig. 1. Night sky spectral atlas taken from [19]. The inset shows a blow up of the emission lines (shown in blue) suppressed by the aperiodic fibre Bragg grating.
During the last decade, several methods of OH suppression have been explored: (i) notched interference filters [9,11]; (ii) medium resolution spectroscopy with software suppression [4]; (iii) mechanical suppression with a grating mask [14, 18].

It has proved difficult to demonstrate substantial gains from any of these methods. First, interference filters which suppress even a few OH lines are both expensive and difficult to make [15]. Secondly, it is often assumed that OH lines can be masked out of spectral images for resolving powers $R \geq 5000$. In practice, as we show in Fig. 2, the instrument profiles of infrared spectrographs have faint wings at the 1% level which extend far beyond the core of the profile. Thus, software suppression does not remove the stray light between the bright OH lines.

In grating mask spectrographs like Cambridge OH Suppression Instrument (COHSI) at the University of Cambridge, the observed spectrum is dispersed at $R \approx 5000$ onto a photoetched mask where the desired spectral regions are reflected towards the camera and the unwanted lines are absorbed [18]. The mechanical tolerances of an OH suppression spectrograph are very tight and the overall efficiency of the system tends to be low (<5%).

2. Fibre bragg grating

We now present our new approach to OH suppression. The basic idea is that light from the sky is focussed onto the entrance aperture of an optical fibre or a bundle of such fibres. A complex fibre Bragg grating printed onto the fibre or fibre bundle then rejects specific wavelengths corresponding to the narrow OH emission lines. The rejected light travels back towards the source and leaks out from the entrance aperture. Conversely, the desired interline
spectrum is allowed to propagate forwards down the optical fibre or fibre bundle. This device acts as a pre-filter ahead of an imager or spectrograph.

In this initial demonstration, the spectral lines are suppressed at an intrinsic resolving power of $R = 10,000$ although in principle this can be pushed to much higher resolving powers. We suppress the 36 brightest lines in the wavelength interval 1500-1575 nm which amount to 94% of the emission line background in this interval. At a resolving power of $R=10,000$, only 18 lines are evident since each of these comprises a closely spaced doublet. The flux-weighted wavelengths are given in Table 1. Our source wavelengths come from [19] who calibrate a theoretical model of OH excitation with spectroscopic observations of the night sky at $R = 8000$. The fitted central wavelengths of the OH line list have rms errors of better than 0.01 nm [19].

The principle of the fibre Bragg grating is that light propagating along an optical fibre can be made to reflect at a refractive index modulation printed on the fibre core. If the modulation describes a grating, light can be made to reflect back with high efficiency in a narrow wavelength interval. If the grating period is given by $\Lambda$ the reflection efficiency is maximised at the Bragg wavelength $\lambda_B = 2n_o \Lambda$ where $n_o$ is the refractive index of the fibre core before the grating is imposed.

The refractive index modulation pattern comes from exposing the fibre core to a spatially varying pattern of UV photons. Below 300nm, the UV photons break down the SiO bonds thus causing microscopic variations in the refractive index of the medium. Our new grating is printed onto a GeSiO$_2$ fibre with a grating period $\Lambda = 0.5\mu$m. The fibre core size of 8.5µm (modal diameter = 10.5µm) allows only single mode propagation. The fibre has a 125µm cladding diameter and a 250µm acrylate buffer diameter.

The peak reflectivity given by

$$R_p = \tanh^2 \kappa L$$

is determined by the grating amplitude $\kappa$ (in units of cm$^{-1}$) and the length of the grating $L$. The grating amplitude (or apodization) is related to the induced refractive index modulation $\Delta n$ along the fibre axis $z$ by

$$\kappa(z) = \pi \Delta n(z) / (2 \Lambda (n_o + <\Delta n>) )$$

In practice, $\kappa$ is the coupling efficiency of the two counter propagating core modes and defines the grating strength. Here $<\Delta n>$ is the average refractive index change within the grating modulation.

We seek to produce a series of aperiodically spaced, rectangular filters with a high degree of suppression (>20 dB) within a narrow wavelength interval (0.1 nm). This can be achieved with a low $\kappa$ material (= 5 cm$^{-1}$) over a long baseline; for our grating, $L = 10$ cm and $\Delta n \sim 10^{-4}$.
Fig. 3. AFBG design represented by amplitude $\kappa$ (top panel) and phase $\theta$ (bottom panel) as a function of fibre axis distance $z$.

A grating structure which attempts to suppress $N$ emission lines with $N$ spatially separate gratings in series results in excessively high levels of absorption for large $N$. The waveguide absorption is proportional to the level of integrated UV exposure and this becomes excessive for large $N$. An alternative scheme is to overlay the $N$ gratings at the same location in the fibre [17]. But this method has serious drawbacks, in particular, that the mean refractive index change $<\Delta n>$ grows in proportion to $N$. A better approach is to design a grating modulation function which treats all $N$ channels simultaneously. For well optimized gratings, $<\Delta n>$ grows in proportion to $\sqrt{N}$ [13].

How do we arrive at an optimal grating design? Light propagation in a fibre Bragg grating is described by a pair of coupled equations

$$\partial E_b / \partial z + i \delta E_b - q(z) E_f = 0$$
$$\partial E_f / \partial z - i \delta E_f - q^*(z) E_b = 0$$

where $E_b$ and $E_f$ are the amplitudes of the backward and forward propagating fields, $z$ is the distance along the fibre axis, * denotes a complex conjugate, and $\delta$ is normalized frequency with respect to the Bragg reflection frequency. These equations present an inverse scattering problem which must be solved iteratively in order to arrive at a practical grating design $q(z)$. This function can be written explicitly in terms of the grating amplitude $\kappa(z)$ and phase (or chirp) function $\theta(z)$.

$$q(z) = \kappa(z) \exp\{ i \theta(z) \}.$$
We note that there are close parallels with rugate filter design [15] which exploits $\Delta n \sim 1$ (high $\kappa$) and $L \sim 10\mu$m. While similar levels of peak reflectivity are possible with rugate filters, practical multilayer dielectric coatings allow for only 100 to 1000 cycles, as compared with $L/\Lambda \sim 10^5$ cycles in our fibre Bragg grating. This means that multiple channels with narrow filter bandwidths are far easier to manufacture in fibre Bragg gratings.

Table 1. Target and measured wavelengths in the aperiodic fibre Bragg gratings

<table>
<thead>
<tr>
<th>Channel Number</th>
<th>Target Wavelength</th>
<th>AFBG#1 Wavelength</th>
<th>FWHM</th>
<th>R(%)</th>
<th>AFBG#2 Wavelength</th>
<th>FWHM</th>
<th>R(%)</th>
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<tbody>
<tr>
<td>01</td>
<td>1505.087</td>
<td>1505.081</td>
<td>0.166</td>
<td>99.88</td>
<td>1505.075</td>
<td>0.161</td>
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<td>1505.344</td>
<td>0.164</td>
<td>99.87</td>
<td>1505.346</td>
<td>0.166</td>
<td>99.89</td>
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<td>1506.697</td>
<td>1506.690</td>
<td>0.169</td>
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<td>1506.692</td>
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<td>99.88</td>
<td>1508.622</td>
<td>0.175</td>
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<td>05</td>
<td>1518.514</td>
<td>1518.507</td>
<td>0.176</td>
<td>99.89</td>
<td>1518.508</td>
<td>0.174</td>
<td>99.92</td>
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<tr>
<td>06</td>
<td>1523.895</td>
<td>1523.893</td>
<td>0.173</td>
<td>99.87</td>
<td>1523.890</td>
<td>0.166</td>
<td>99.90</td>
</tr>
<tr>
<td>07</td>
<td>1528.579</td>
<td>1528.577</td>
<td>0.160</td>
<td>99.82</td>
<td>1528.584</td>
<td>0.172</td>
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<td>1533.040</td>
<td>1533.040</td>
<td>0.160</td>
<td>99.74</td>
<td>1533.044</td>
<td>0.165</td>
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<tr>
<td>09</td>
<td>1539.333</td>
<td>1539.387</td>
<td>0.165</td>
<td>99.79</td>
<td>1539.362</td>
<td>0.154</td>
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<tr>
<td>10</td>
<td>1543.016</td>
<td>1543.065</td>
<td>0.161</td>
<td>99.74</td>
<td>1543.043</td>
<td>0.154</td>
<td>99.61</td>
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<tr>
<td>11</td>
<td>1550.777</td>
<td>1550.827</td>
<td>0.159</td>
<td>99.73</td>
<td>1550.807</td>
<td>0.157</td>
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<tr>
<td>12*</td>
<td>1553.771</td>
<td>1553.879</td>
<td>0.279</td>
<td>99.81</td>
<td>1553.853</td>
<td>0.263</td>
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<tr>
<td>13</td>
<td>1554.414</td>
<td>1554.456</td>
<td>0.157</td>
<td>99.66</td>
<td>1554.434</td>
<td>0.149</td>
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<tr>
<td>14</td>
<td>1559.563</td>
<td>1559.611</td>
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<td>99.62</td>
<td>1559.592</td>
<td>0.150</td>
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<td>1563.002</td>
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<td>0.147</td>
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<td>0.149</td>
<td>99.54</td>
<td>1565.331</td>
<td>0.148</td>
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<tr>
<td>17</td>
<td>1570.054</td>
<td>1570.094</td>
<td>0.137</td>
<td>99.43</td>
<td>1570.088</td>
<td>0.143</td>
<td>99.24</td>
</tr>
</tbody>
</table>

Centre wavelength measured at +25°C, 0g tension; FWHM measured at -3dB. Wavelengths and bandwidth FWHM in nm; reflectivity in %. Channel 12 has been widened to suppress two closely spaced, bright lines.
3. Results

We present our grating design for $\kappa(z)$ and $\theta(z)$ in Fig. 3: we solve for both amplitude and phase using equation (3). There is an extensive literature on how best to optimize a complex grating design: one such method used here involves the dephasing of partial gratings (e.g. [2]). We manufactured two gratings (AFBG#1, AFBG#2) in order to test the repeatability of the printing process. The target wavelengths and the measured wavelengths of the suppressed bands for both gratings are presented in Table 1. The wavelength response of AFBG#2 is presented in Fig. 4.

The repeatability is a measure of the stability of the manufacturing process. In Table 1, the standard deviation between the AFBG#1 wavelengths and the target wavelengths is 0.034nm; for AFBG#2, the standard deviation is 0.024nm. We believe that this error can be reduced to 0.005nm quite readily. This small error is comparable to the measurement error in the OH line wavelengths [19].

In Table 1, the target wavelengths have been slightly offset to shorter wavelengths. The gratings are sensitive to thermal and strain effects amounting to approximately 0.013 nm K$^{-1}$ and 0.001 nm $\mu$e$^{-1}$ (equivalent to 0.01 nm g$^{-1}$) respectively. To allow for tuning, we offset the printed wavelengths by 0.2 nm to shorter wavelengths at 0g axial strain. We can therefore use 20g of positive axial strain to fine tune the wavelength response of the comb at room temperature. A larger strain is required to tune fibres for operation in a cold environment.
Defects in the fibre induced by UV exposure produce absorption within the grating. For our test grating, internal absorption is at the level of 0.02 dB cm\(^{-1}\) which gives rise to a 4% loss in efficiency. For a grating filter which suppresses the entire near infrared region (1-2\(\mu\)m), this loss would become substantial within our current fibre material. More sophisticated grating designs and/or materials that require lower UV exposure, or materials that have lower UV loss characteristics, will be required to combat absorption losses.

4. Discussion

Our work constitutes the first application of an AFBG in a single photonic device in any scientific arena. Our test grating is designed to remove the 18 brightest doublets amounting to 94% of the OH background over the wavelength interval 1500 – 1570 nm. These lines are suppressed to better than 20 dB (<1%) at 0.15nm bandwidth, i.e., a resolving power of R = 10,000. In our first prototype, no attempt was made to optimize the suppression level. A significant improvement, currently under investigation, is to suppress the OH lines to a degree that is inversely related to the line strength. This allows for a twofold increase in the number of suppressed OH lines at a given suppression level for the same overall fibre loss.

In any grating design, there is a need to balance the desired grating resolution (R), the level of suppression, the number of suppressed lines, and the total absorption losses within the fibre. Further tests have shown that we can achieve a bandwidth of 0.028nm at 1550nm (equivalent to R = 55,000) at 99.7% rejection. With a sufficiently sophisticated grating design, we may be able to achieve this for all lines in the near infrared. We anticipate that almost total suppression can be achieved over the entire near infrared window in a single low loss (<10%) device.

In a future paper, we present observations of the atmosphere taken through a prototype OH suppressing fibre. Efficient coupling to a single mode fibre requires careful consideration of the optical design [3,6]. The small core size of our first prototype is well matched to diffraction limited imaging at near infrared wavelengths. Our prototype already has immediate application to spectrographs fed by high-“Strehl ratio” adaptive optics. With the advent of air-silica fibres, our AFBG technology is no longer limited to small cores.

The successful prototype bodes well for extensive use of AFBGs in astronomy, remote sensing and aeronomy. There are numerous other sources of interference confined to bright emission lines which can be suppressed with the same technology. These include bright laser lines due to backscattering from artificial laser guide stars [8], scattered light from space-borne optical laser communications [1], backscattered light from street lamps [16], and auroral emission that is particularly prominent at polar sites [20].

We see no insurmountable obstacles to printing an OH-suppression grating into large-core “holey” fibres, coherent imaging fibre bundles or 3D photonic devices. Future devices can be optimized to include many more spectral lines, deeper suppression, narrower bandwidths, with moderate to low absorption. It has not escaped our attention that the same grating design embedded within a multimode fibre has applications beyond those described here. While the atmosphere continues to be a worthy adversary, we believe that its ultimate defeat is at hand.