High spectral contrast filtering produced by multiple pass reflections from paired Bragg gratings in PTR glass

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ABSTRACT

The properties of multiple reflections from narrow bandwidth reflection Bragg gratings are presented. The use of multiple reflections serves to increase the suppression ratio of the out-of-band spectral content such that contributions of grating sidelobes can be mitigated. The result is a device which retains spectral and angular selectivity in a single high efficiency diffraction order but reshapes spectral/angular response to achieve higher signal to noise ratios (SNR). The material for recording these high suppression devices is photo-thermo-refractive (PTR) glass. PTR is a highly homogeneous photosensitive glass with features such as low losses and high laser damage threshold. It has recently been used with good success to record permanent volume Bragg gratings with high efficiency and narrow band selectivity for use in laser cavities. Multiple reflections from the grating surface are achieved using several different arrangements. The multiple pass grating reflections are demonstrated and compared to the performance of a single reflection from a volume Bragg grating.

Keywords: Holography, Volume Bragg gratings

1. INTRODUCTION

Reflecting volume Bragg gratings (VBGs) in photo-thermo-refractive (PTR) glass have been used extensively in laser development and applications in recent years [1-6]. One of the reasons for the success of these devices is excellent homogeneity of PTR which allows fabrication of VBGs with thicknesses on the order of centimeters. Utilizing coupled wave theory to predict the performance of both reflecting and transmitting volume Bragg gratings shows that the spectral acceptance is inversely proportional to the material thickness [7]. Therefore, excellent narrow band filtering can be achieved using a highly homogeneous holographic recording material such as PTR. These thick gratings are capable of narrowband spectral filtering with bandwidths as narrow as tens of picometers in the near infrared. The narrowband filtering that is produced by a reflecting VBG is a notch filter with resonant light being reflected and light outside of the resonance band being transmitted. For filter applications that require high levels of isolation between wavelengths, it is necessary to have steep roll-off at the filter edge. Examples of such filters include multiple micro-ring cavities which produce filter roll-offs of around 50-100 dB/nm for optical communications [8,9]. These filters are able to create a high SNR between the resonant light and the out-of-band light. So while VBGs are capable of excellent narrowband filtering, the spectral sidelobes that are inherent to the device do not provide steep filter roll-off. We present a method for increasing the roll-off of a narrowband reflecting VBG filter within a monolithic device to produce roll-off slopes >100 dB/nm.

The fundamental technology for this steep roll-off filter is the reflecting VBG recorded in PTR glass. Volume Bragg gratings are recorded in PTR using the setup in Fig. 1. This setup is able to produce transmitting and reflecting VBGs with periods from 200 nm to 1 μm by using motorized recording mirrors to change the angle of interference at the recording plane. A HeCd laser at 325 nm is used for the photoexposure of the PTR due to the material's UV sensitivity. Modifications to the setup can produce larger periods, chirped gratings and other specialty gratings. The reflecting Bragg gratings (RBGs) that will be discussed here can act as spectral filters as well as angular selective devices. While RBGs have various properties as discussed in [10], in this paper we will focus exclusively on the narrowband spectral filtering capabilities and methods for creating sharp roll-offs.

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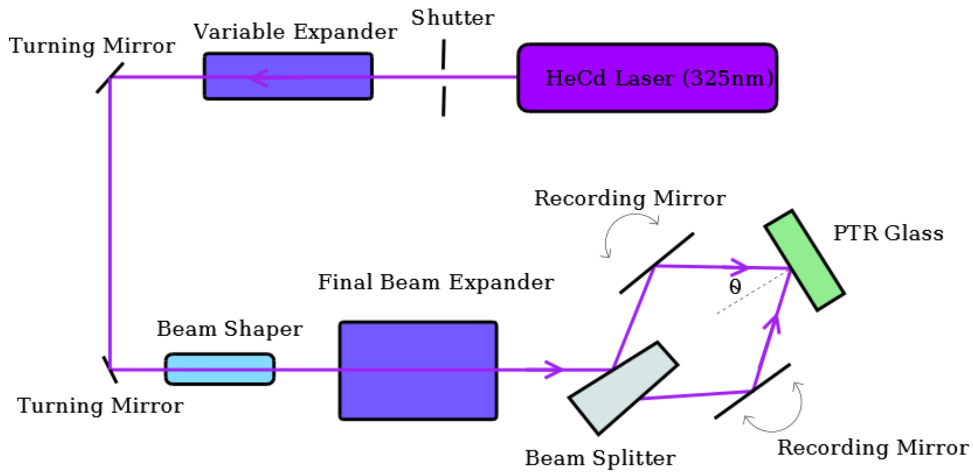

Figure 1. The holographic recording setup for photo-exposure of PTR volume Bragg gratings. Beam conditioning optics shape and expand a UV laser beam. Motorized stages are used to control the period of the VBG by changing the interference angle.

The spectral filtering properties of a single uniform RBG can be modeled using coupled wave theory to determine the spectral response of the device. The effect of a Gaussian beam interacting with the RBG can also be included [11]. These simulations are useful in characterizing manufactured devices and will be used to demonstrate the idea of side lobe suppression by multiple reflections. The reflection spectrum of a typical RBG is shown in Fig. 2a. The simulation uses an RBG with 5 mm thickness and refractive index n_1=320 ppm, designed for a resonant reflection of 1062 nm light at 5° angle of incidence. If the incident light is repeatedly reflected from the same RBG, the sidelobes in the spectrum will decrease but the reflectance of the light within the resonant pass band (reflection band) will maintain high efficiency. This effect is more clearly illustrated by looking at the same spectrum on a logarithmic scale, shown in Fig. 2b. It is clear that the reflection sidelobes extend to wavelengths far outside the reflection band. The use of multiple reflections from the RBG severely lowers the reflectance of this off resonance light and increases the filter roll-off.

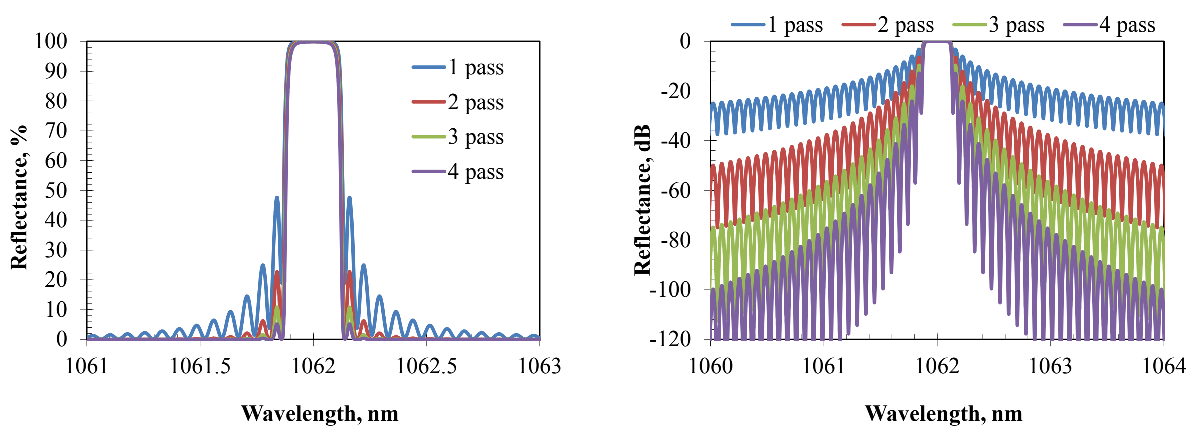

Figure 2. The reflectance spectrum of an RBG after successive reflections. a.) reflectance as a percentage b.) reflectance on a logarithmic scale to show detail of the out-of-band sidelobes.

In order to generate multiple reflections from an RBG, we propose several schemes shown in Fig. 3. The first employs a single RBG with a mirror to generate multiple passes. A similar scheme uses a second RBG with identical parameters in place of the mirror. Recording matched RBGs can easily be achieved in PTR since the size of the recording substrate is typically large enough to cut multiple RBGs with thickness of ~5 mm out of the same volume. This type of setup has a benefit of adjusting the number of reflections that occur by a relative translation of the two grating as illustrated in Fig. 3b. The final system is a monolithic multipass reflector, shown in Fig. 3c. Two matched gratings are recorded within the PTR glass, spatially separated by a gap and containing entrance/exit windows. Incident light will be reflected between the two gratings multiple times before exiting the device. Because each RBG is identical in period and tilt, the exiting light will be parallel to the incident beam, but shifted in position. The monolithic nature of this device allows the resonant wavelength to be tuned by changing the rotation of the device without inducing any angular deviation in the outgoing beam.

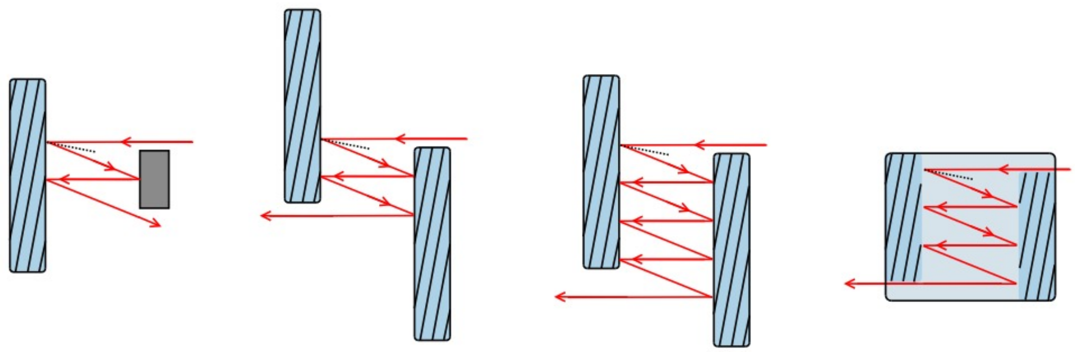

Figure 3. Schemes for achieving multiple reflections from an RBG. a.) a single RBG and a folding mirror b.) two matched RBGs whose relative positions controls the number of reflections c.) a monolithic implementation.

The proposed devices will produce very low levels of reflection outside of the reflection band due to the suppression of RBG sidelobes. In order to measure these low power levels, the measurement system in Fig. 4 was used. This system was chosen because of the good low level detection of the optical spectrum analyzer (Ando AQ6317B). Incorporating a synced tunable laser source allowed us to produce higher incident signal compared to using a broadband source. This is because at any single spectral measurement point, the tunable laser will provide an incident signal containing all of the optical power available, whereas a broadband source will only provide a fraction of the total available power at this same measurement point. Therefore, the SNR of the measurement was significantly higher using a tunable laser source. Sweeping the tunable laser in discrete steps and measuring the power at the appropriate wavelength on the OSA generates the spectral response of the device under test. This combination was found to produce the best SNR for low level detection given our available equipment.

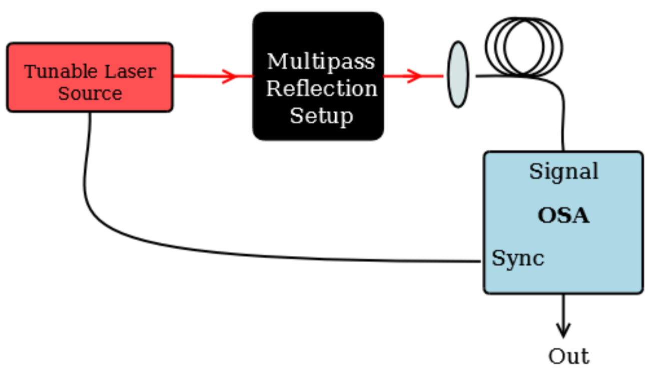

Figure 4. Measurement system for the detection of low optical powers. A tunable laser is sent to the device under test (black box). The reflected light is coupled into a fiber and send to an optical spectrum analyzer (OSA) which acts as a power detector. The OSA is synced to the tunable laser source such that it only measures optical power at the appropriate incident wavelength.

The first system that was tested is the RBG/mirror combination shown in Fig. 3a with two reflections from the RBG. The measurement system in Fig. 4 was used to measure the reflection spectrum. The results are shown in Fig. 5 along with the theoretical spectrum from coupled wave theory. The reflection spectrum of single reflections from two points on the RBG where reflections occur are included for reference. The insertion loss is low at 0.1 dB. The dashed line follows a slope of -65 dB/nm.

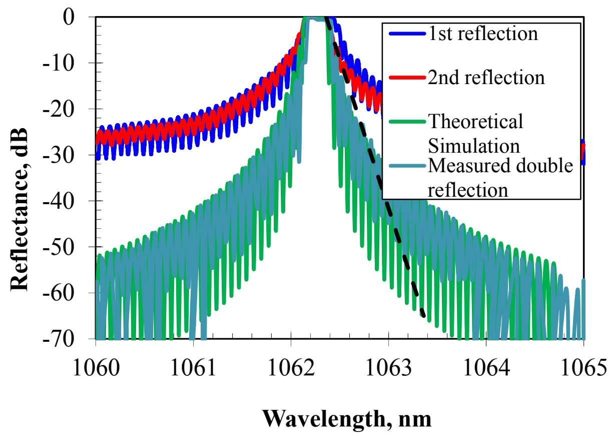

Figure 5. The reflection spectrum (light blue) of the multipass scheme in Fig. 3a. Theoretical simulation (green) is produced using coupled wave theory. The reflection spectrum measured at two locations on the RBG (red and dark blue) are shown for reference.

To increase the number of reflections and further reduce the sidelobes, the mirror was replaced with a matching grating, creating the system in Fig. 3b. The reflection spectrum after four passes is shown in Fig. 6 along with the expected spectrum from theory. The out-of-band sidelobes have been suppressed further. The detection limit of the measurement system is reached at approximately -60 dB. While the oscillations of the sidelobes do not show up well in the measured data, the trend of the spectral response follows the simulated spectrum well. The dashed line shows a slope of -167 dB/nm and the system has an insertion loss of 0.2 dB.

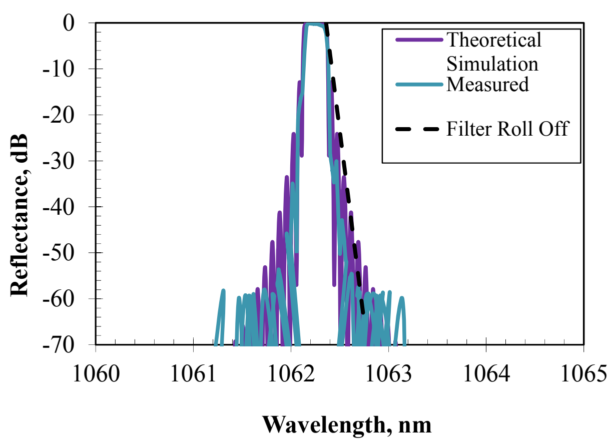

Figure 6. The reflection spectrum (blue) of the multipass scheme in Fig. 3b with four reflections. Theoretical simulation (purple) is produced using coupled wave theory. The dashed line following the filter roll-off has a slope of -167 dB/nm.

Finally, two monolithic multipass RBGs devices were recorded according to Fig. 3c. The first is designed to produce two reflections and the second produces four reflections. Both devices contain two gratings, each with thickness of 5 mm and a tilt angle of 20° with respect the entrance surface. The resonant wavelength of the device depends on the incident angle of light but is centered in the vicinity of 1064 nm. The spectrum of the double pass device is shown in Fig. 7. The measured data matches well with simulation for a refractive index modulation of 200 ppm. The simulation includes the effects of a Gaussian beam with a 3 mm waist. The dashed line shows a roll-off of -83 dB/nm.

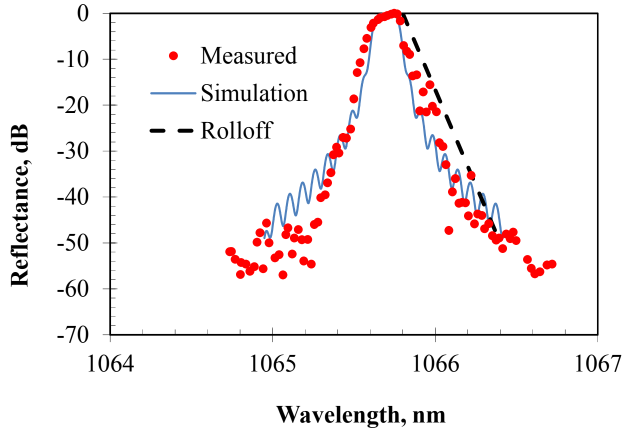

Figure 7. The reflection spectrum (red) of the multipass scheme in Fig. 3c with two reflections. Theoretical simulation (blue) is produced using coupled wave theory and the effects of a Gaussian incident beam. The dashed line following the filter roll-off has a slope of -83 dB/nm.

Next the four pass monolithic grating was measured. The spectrum is shown in Fig. 8 along with simulation using a refractive index modulation of 375 for each grating and using a Gaussian beam with a 3 mm waist. The measured results match well with theory, though they do not exhibit the intensity oscillations expected in the sidelobes. The insertion loss of this device is high at -1.6 dB. This is primarily caused by poor quality of the device facets. Due to unconventional substrate dimensions the facets were only roughly polished. This insertion loss can be reduced easily by producing better facet surface quality. The roll-off of the filter is -140 dB/nm.

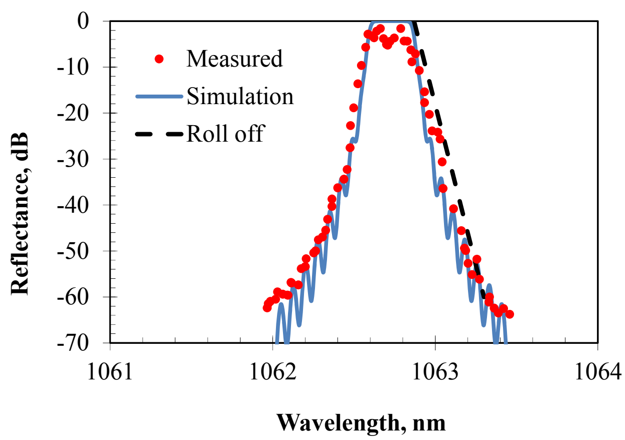

Figure 8. The reflection spectrum (red) of the multipass scheme in Fig. 3c with four reflections. Theoretical simulation (blue) is produced using coupled wave theory and the effects of a Gaussian incident beam. The dashed line following the filter roll-off has a slope of -140 dB/nm.

In conclusion we present three different geometries for producing multiple reflections from reflecting volume Bragg gratings. The measurement system used to obtain reflection spectra of each device is sensitive to -60 dB. The various multipass devices are demonstrated producing two or four successive reflections and effectively suppress the spectral sidelobes well below the level of a single reflection from an RBG. The multipass configuration that utilizes two match RBGs is able to tune the number of reflections by a simple translation of the gratings with respect to each other. This setup produced a filter roll-off of -167 dB/nm with insertion loss of only 0.2 dB. The final type of device that was demonstrated is a monolithic implementation of the two RBG configuration. All alignment of the device is produced during recording, therefore there is no alignment necessary when such a filter is used in practice. The reflections exit the filter parallel to the incident light with a lateral offset. This device has been shown with up to four passes and produced a filter roll-off of -140 dB/nm. These schemes for producing multiple reflections from a PTR volume Bragg grating allow for narrowband spectral filtering with sharp filter roll-offs, giving a filter with excellent resolution and SNR.

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