Compact cavity design in solid state resonators by way of volume Bragg gratings

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ABSTRACT

Volume Bragg gratings (VBG) recorded in photo-thermo refractive glass (PTR) have high stability, and high damage threshold, allowing for many applications to the design of high power lasers. Gratings recorded in the transmitting geometry (TBG) have narrow angular selectivity, and can be used as a spatial filter in a resonator. Such gratings have previously been useful for improving the brightness of high power diodes, and increasing the beam quality in rod geometry solid state lasers. As the gratings have narrow angular selectivity, losses for higher order modes in the resonator no longer depend on the cavity length, allowing for the construction of short cavities with large mode areas. In this paper, we explore the design of short 1cm cavities using two TBGs as a spatial filter and no aperture in the cavity. The M^2 parameter as a function of pump size and angular selectivity of the TBG are explored, using pump diameters ranging from 800um to 2mm and angular selectivity ranging from 11mrad to 1.8mrad. An M^2 parameter of 1.05 is reported for an 800µm pump diameter, a 6.2mrad TBG, and a 1cm long cavity.

Keywords: Volume Bragg grating, PTR, transverse mode selection

1. INTRODUCTION

Typical designs in stable solid state resonators require long cavity lengths and small apertures to produce high beam quality. Often, to reduce thermal loading, large apertures and larger mode areas are more advantageous. However, such designs invariable allow more modes to oscillate, reducing the beam quality. New resonator designs are therefore interesting as a means to allow larger apertures with high beam quality in short cavity lengths.

Volume Bragg gratings recorded in photo-thermo refractive glass have found many applications to the designs of high powered lasers, such as beam combining and spectral narrowing of diodes. The holographic devices also allow for narrow angular selectivity, allowing the devices to act as a spatial filter. This spatial filtering is unusual in that it is performed in the near field, allowing for the compact design of resonators. Previously, this has shown to be useful in improving the brightness of diode lasers[1]. In this manuscript, we will show how the volume Bragg grating can be useful to the design of single transverse mode solid state lasers with a cavity length of 1cm.

2. THEORY

2.1 Volume Bragg gratings

Volume Bragg gratings are holographically recorded in a photosensitive glass known as photo-thermo-refractive glass (PTR)[2]. PTR is a multi-component silicate glass, doped with silver, cerium, and fluorine. It has good thermal properties, and has low absorption (10^{-4} cm^{-1}) in the visible to the near infrared (350nm – 2500nm). It is linearly photosensitive, allowing for holograms to be recorded[3] in the following process. Silver atoms are reduced by UV light, forming the atomic state Ag_0. Thermal treatment allows the silver atoms to react with cerium atoms, forming nucleation sites for growth of NaF crystals. The crystal growth then modulates the refractive index, allowing for refractive index changes up to 1000ppm (Δn is about 10_{-3}).

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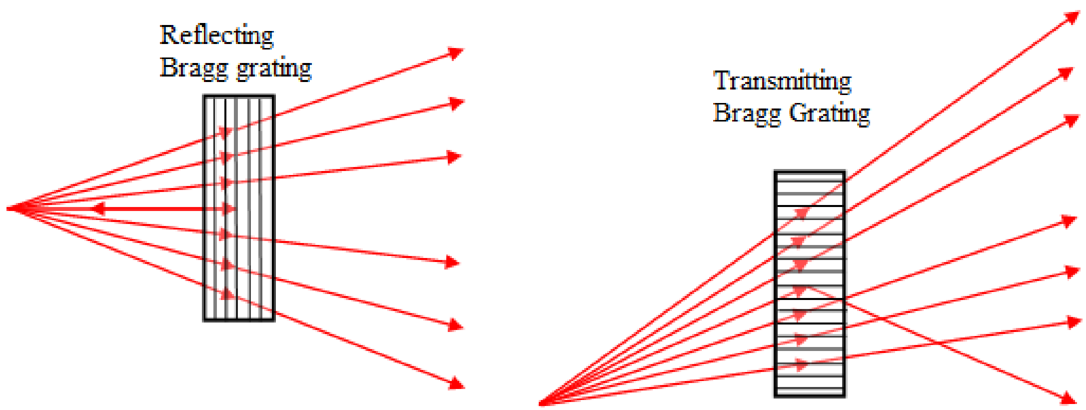

Figure 1: Illustration of orientation of grating and the types of VBGs. For a divergent beam incident on the grating, the VBG acts as a slit in angular space, diffracting only a small portion of the light.

Theoretical modeling of volume Bragg gratings has been analytically described by Kogelnik[3], by way of coupled-wave theory. This theory accurately predicts the diffraction efficiency of a plane wave incident on a sinusoidal modulated hologram. Small angular deviations from the Bragg condition show a drop off in diffraction efficiency. Based on the orientation of the grating within the glass, the VBG comes in two distinct flavors. With the grating vector oriented near normal to the surface of the glass, the VBG reflects light backwards (reflecting Bragg gratings, RBG). While a grating oriented near parallel to the surface will transmit light through the glass (transmitting Bragg grating, TBG). An example of the types of VBGs is shown in Figure 1.

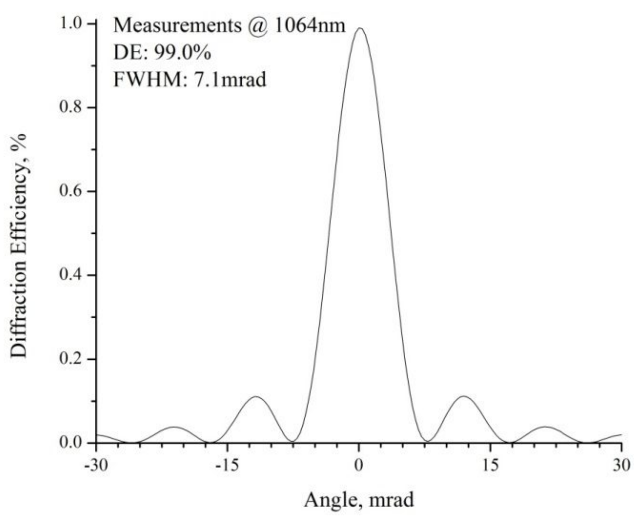

Figure 2: Measured diffraction efficiency for a TBG with 7.1mrad FWHM, and 99.0% diffraction efficiency.

For a transmitting Bragg grating oriented 90° to the normal of the surface, the ratio of the scattered amplitude to the incident amplitude (S) is given as function of the dephasing (ξ) from the Bragg condition and the grating strength (ν) (1). The diffraction efficiency for a plane wave is therefore the amplitude squared of S. The dephasing term (2) shows the change in the diffraction efficiency as the incident plane wave makes small deviations from the Bragg condition, and is a function of the Bragg period (Λ_B), the angular deviation ($\delta\theta$) from the Bragg angle (θ_B) in the medium, and the thickness of the grating (d). The grating strength (3) controls the maximum diffraction efficiency, and is a function of the peak to peak refractive index modulation (n_1), the grating thickness, the wavelength (λ) in the medium, and the Bragg angle in the medium. For a grating strength of $\nu = \pi$, the diffraction efficiency is 100%. An example of the diffraction efficiency as a function of angular deviation is plotted in Figure 2. The maximum diffraction efficiency is 99.0%, and the FWHM of the angular selectivity in air is 7.1mrad.

$$S = -i \frac{e^{-i\zeta d} \sin\left(\sqrt{\xi^2 + \nu^2}\right)}{\sqrt{1 + \frac{\xi^2}{\nu^2}}} \quad (1)$$

$$\xi = \frac{2\pi}{\Lambda_B} \delta\theta d \quad (2)$$

$$\nu = \frac{\pi n_1 d}{\lambda \cos(\theta_B)} \quad (3)$$

Both Hsieh and Hellström have shown that diffraction for arbitrary, near collimated, wave fronts can be described by a convolution between Kogelnik's plane wave solution and the spatial distribution of the electric field for an arbitrary wave front[4,5]. These theories allow for the description of the diffraction efficiency of a VBG interacting with a Hermite-Gaussian beam, and have been used to theoretically model the performance of VBGs in PTR interacting with Gaussian beams[6].

$$E(x, y, 0) = E_0 H_n \left(\sqrt{2} \frac{x}{w_{x,0}}\right) e^{-\frac{x^2}{w_{x,0}}} H_m \left(\sqrt{2} \frac{y}{w_{y,0}}\right) e^{-\frac{y^2}{w_{y,0}}} \quad (4)$$

$$E_{diff} = \mathcal{F}_{2D}^{-1} \left\{ S\left(\delta\theta_x, \delta\theta_y\right) \mathcal{F}_{2D}\{E(x, y)\} \right\} \quad (5)$$

Diffraction efficiencies were calculated for the first 3 modes (n = 0,1,2 & m=0) and are plotted in Figure 3 for a waist size of $w_0 = 400\mu m$. As the far field divergence for a given Gaussian beam is roughly proportional to w_0^{-1}, we can expect that for larger beams the diffraction efficiency for a given angular selectivity will be increased, and for smaller beams the diffraction efficiency will be decreased. When the angular selectivity is reduced to 6.7mrad (4x the far field divergence of the TEM00 mode), losses for the TEM00 mode are increased to 1%, while they are 3% for the TEM10 mode, and 5% for the TEM20 mode. When the angular selectivity of the TBG is reduced to 3.4mrad (2x the far field divergence), the losses for the TEM00 mode are increased to 4%, and are increased to 11% for the TEM10 mode. Above an angular selectivity of 3mrad, a steep drop off in the lowest order losses exist, and losses for the higher order modes dramatically increase. These results indicate that the TBG will be useful in suppressing higher order modes in a resonator.

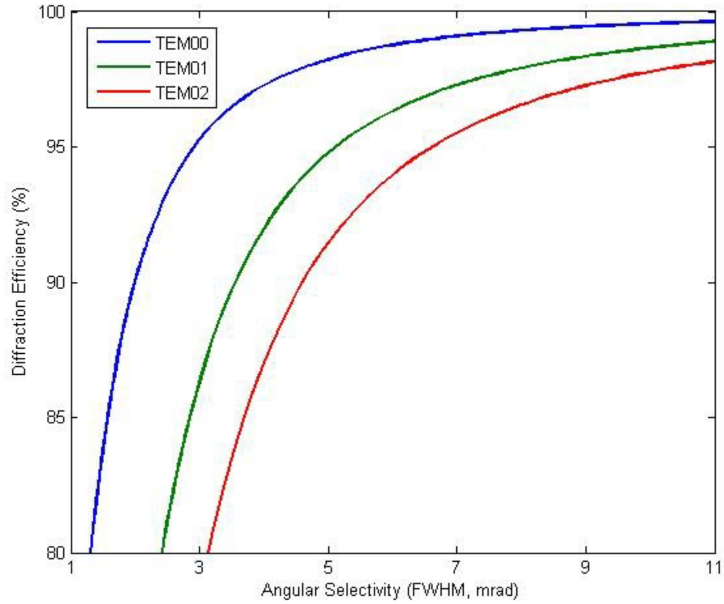

Figure 3: Plot of the diffraction power for the first three Hermite-Gaussian beams with a waist size of 400µm as a function of angular selectivity.

2.2 Output beam quality

As a measure of the modal content and beam quality, the M^2 parameter is used[7]. For a stable cavity generating Hermite-Gaussian modes, the M^2 parameter is roughly proportional to the number of modes generated and the relative power in each mode. Measuring the M^2 parameter for a given beam requires knowledge of the output beams far field divergence and focus size. As shown in (7), the M^2 parameter is proportional to the waist radius (w_0) and the far field divergence (s), and inversely proportional to the wavelength (λ). A Hermite-Gaussian beam propagating with these properties then follows (6), where z is the distance from the waist position z_0.

$$w(z) = \sqrt{w_0^2 + s^2(z - z_0)^2} \tag{6}$$

$$M^2 = \frac{\pi w_0 s}{\lambda} \tag{7}$$

In standard, stable resonators, to reduce the number of modes oscillating in the cavity, an internal resonator is used within the cavity. The Fresnel number (8) is used as a figure of merit to determine the number of modes oscillating within the system. For single mode operation, N should be approximately 1. Our goal is to produce single mode operation in a cavity with L ~ 10mm, and λ = 1.064µm, which ordinarily would require an aperture ~ 100µm.

$$N = \frac{a^2}{\lambda L} \tag{8}$$

The use of the aperture in the cavity is comparable to spatial filtering in the far field, and by combining a long cavity length with a small aperture, the angular content of the output beam is limited. By using a diffractive optical element in the cavity, the angular content of the beam can instead by filtered in the near field, allowing for high beam quality to be produced without the use of an aperture or long cavity length. We intend to show that high beam quality can be produced in cavities with Fresnel numbers of: 15, 60, and 94.

3. EXPERIMENT

A planar laser resonator was designed using a dichroic high reflective mirror and a 90% output coupler. A thin, 1mm thick, a-cut slab of Nd:YVO_4 was used as the active medium. This was chosen due to the high gain in the material, reducing the effect of losses introduced by the VBG for low pumping values, and also due to the high absorption coefficient for the pump at 808nm, allowing for a smaller cavity length. Two transmitting Bragg gratings (TBG) were introduced in the cavity, each rotated 90° relative to the other to remove astigmatism. Several different versions of the TBGs were used, each with a different angular selectivity were used to measure the effect of angular selectivity of the TBG on the M^2 parameter.

The 1% dope Nd:YVO_4 had a high absorption coefficient, and more than 95% of the pump polarized to the c-axis of the material was absorbed. For the partially polarized pump used in the experiment, the absorption efficiency was 75%. Due to the high absorption coefficient and poor thermal properties of the material, the temperature remained too hot to pump at CW, and quasi-CW pumping was used instead. A pump pulse width of 200µs with a duty cycle 3.1% was used, leading to a maximum average absorbed power of 1.5W. Average powers will be reported in the results section.

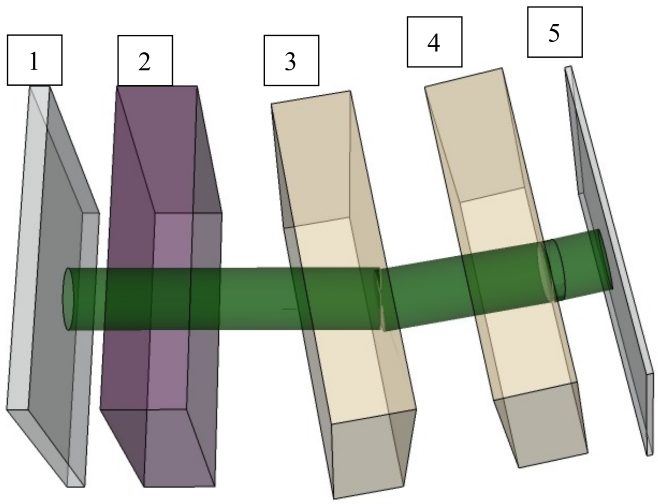

Figure 4: D m, 2)1mm thick 1% NdYVO_4, 3)TBG oriented to diffract in the horizontal plane,4) TBG oriented to diffract in the vertical plane, 5) Planar output coupler

As shown in figure 1, the materials were aligned to reduce the total cavity length. Both the TBGs were approximately 1 - 1.5mm thick, allowing for a cavity length of approximately 1cm to be constructed. The angular selectivity of the TBGs used ranged from 1.8mrad to 11mrad, and the diffraction efficiency of each was more than 97%. The full properties are listed in table 1.

While the diffraction efficiency of the TBGs was high, each grating added some small losses to the cavity. With a diffraction efficiency ranging from 97% to 99%, round trip losses are expected to be 4% - 12%. For the low pumping values we are using, this is expected to reduce the total output power, and shift the optimal output coupling to between 80% and 90%.

Table 1: List of properties for the TBGs used in the cavity experiments.

Angular Selectivity FWHM (mrad)	Diffraction efficiency (%)
1.8	97
2.4	98
4.7	98
6.2	97
7.1	99
10.7	99

The output beam was filtered by a longwave pass filter (OD4 for the pump wavelength) before the beam quality was measured. To measure the beam quality, the filtered beam was focused by a 200mm lens, and a scanning slit was translated across the caustic to measure the e^{-2} diameter. The caustic was fit according to equation 2 via non-linear least squares to measure the focused e^{-2} waist diameter (w_0), waist position (z_0), and far field divergence (full width, e^{-2} of the max peak) (s). The M^2 was then calculated from these parameters. An example of the measured caustic is shown in figure 2.

4. RESULTS

Beam quality and output power was measured as a function of angular selectivity of the TBGs. This experiment was repeated for several different pumping diameters. For an 800μm pump diameter and a cavity length of 1cm (N = 16), the beam quality and slope efficiency are reported in Table 2. From these results it is apparent that a 6.2mrad grating is necessary to produce a diffraction limited beam. However, the slope efficiency drops off sharply between the 7.1mrad and the 6.2mrad grating, showing that the angular selectivity of the 6.2mrad grating is too low and reducing the diffraction efficiency for the lowest order mode.

The slope efficiency of the single mode cavity dropped to 30% from about 53% compared to the multimode cavity. However, at the same time the M^2 had an improvement of more than five times, meaning the trade-off in efficiency compared to brightness is worthwhile. Part of this decrease in efficiency is due to the losses induced by the TBG's themselves, while part of the losses are due to the mode mismatch between the pump size and the preferred mode selected by the TBG. To compare the single mode performance, a 30cm long hemispherical cavity was produced using a high-reflective mirror with a curvature of 50cm, an aperture was placed at the curved mirror and decreased in size until single mode output was observed. This cavity length was necessary to produce high beam quality, without the use of diffractive optical elements, and in order to produce a mode of comparable size to the pump. With this reference cavity, a slope efficiency of 35% was observed, and an M^2 of 1.0 was produced. It's worth noting that this reference cavity is approximately 30times larger than the cavity with the TBGs, and has approximately the same slope efficiency.

Table 2: M^2 results for the planar cavity with a pump diameter of 0.8mm.Fresnel number is estimated to be 16. *A hemispherical single mode reference cavity was built to compare the slope efficiency.

Angular Selectivity (FWHM, mrad)	M^2	Slope Efficiency
None	>5	53%
None*	1.00	35%
10.7	1.45	30%
7.1	1.18	30%
6.2	1.05	23%

The pump diameter was increased to 1.6mm (N = 60), allowing a larger number of higher order modes to be generated within the cavity. M^2 and slope efficiency results are shown in Table 3. It is observed that an angular selectivity of less than 2.4mrad is required to reduce the M2 parameter to less than 1.4 in this highly multimode cavity.

A general trend of reduced efficiency is seen. This is because the waist size of the lowest order mode is not increasing the with pump beam, reducing the overlap and reducing the efficiency. Furthermore, absolute efficiency was reduced due to the decreased overlap with the generated lowest order mode and the pumped area. Additionally, due to the larger diameter modes generated in the planar cavity, a lower angular selectivity was needed to reduce the M^2 to near diffraction limited. The best M^2 of 1.3 was produced with an angular selectivity of 1.8mrad. However, a sharp drop off in efficiency was seen for an angular selectivity below 4.7mrad.

Table 3: M^2 results for the planar cavity with a pump diameter of 1.6mm, fresnel number of 60.

Angular Selectivity (FWHM, mrad)	M^2	Slope Efficiency (%)
10.7	3.0	18
7.1	1.8	14
6.2	2.4	13
4.7	2.2	16
2.4	1.4	13
1.8	1.3	10

The experiments were then repeated for a pump diameter of 2mm and an estimated Fresnel number of 94 (Table 4). The lowest M^2 achieved was 1.3 with an angular selectivity of 1.8mrad. Due to the significantly reduced pump density, generation could only be achieved with an output coupler of 98%. Due to the losses of the TBG (8% combined round trip losses), the slope efficiency was significantly reduced and not easily compared to previous results.

Table 4: M^2 results for the planar cavity with a pump diameter of 2mm (N = 94). Due to the decreased pump density a 98% output coupler was needed to get generation, and slope efficiency is therefore drastically reduced.

Angular Selectivity (FWHM, mrad)	M^2
2.4	1.7
1.8	1.3

5. CONCLUSION

A new solid state cavity design has been demonstrated with high beam quality despite being a highly multimode resonator, with large pump area and short cavity length. It was found that while increasing the pump diameter hurt the efficiency, high beam quality could still be maintained using a TBG with smaller angular acceptance. Increasing the pumped area allowed for higher order modes to be generated, but resulted in a larger mismatch between the lowest order mode and the pump beam, reducing efficiency. It was found that for a pumped diameter of 0.8mm, a TBG of 6.1mrad could improve the M^2 to less than 1.1, while for a pumped diameter of 1.6mm, a TBG of 1.8mrad was necessary to reduce the M^2 to 1.3. In the design of an actual device, care must be made to insure proper matching of the pumped diameter, the lowest order mode of the cavity, and the angular selectivity of the TBG to insure high efficiency output and high beam quality.

References

[1] Venus, G.B.,Sevian, A.,Smirnov, V.I., and Glebov, L.B. "High-brightness narrow-line laser diode source with volume Bragg-grating feedback," Proc. SPIE 5711, 166–176 (2005).

[2] Glebov, L. "Photosensitive glass for phase hologram recording," Glass Sci. Technol. 71, 85-90 (1998).

[3] Kogelnik, H. "Coupled wave theory for thick hologram gratings," Bell Syst. Tech. J. 48, 2909-2947 (1969).

[4] Hsieh, H., Liu, W., Havermeyer, F., Moser, C., Psaltis, D., "Beam-width-dependent filtering properties of strong holographic gratings," Appl. Opt. 45, 3774-3780 (2006).

[5] Hellstrom, J. E., Jacobsson, B., Pasiskevicius, V., Laurell, F., "Finite beams in reflecting volume Bragg gratings: Theory and Experiments," IEEE J. Quantum Electron. 44, 81-89 (2008).

[6] Ciapurin, I.V., Glebov, L.B., Smirnov, V.I., "Modeling of Gaussian beam diffraction on volume Bragg gratings in PTR glass," Proc. of SPIE 5742, 183-194 (2005).

[7] Siegman, A.E., Townsend, S., "Output beam propagation and beam quality from a multimode stable-cavity laser," IEEE J. Quantum Electron 29, 1212-1217 (1993).