Dense spectral beam combining with volume Bragg gratings in PTR glass

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An incoherent combination of laser radiation from multiple sources into a single near-diffraction-limited beam is an important problem of high power laser design. Energy brightness, but not spectral brightness, can be increased using spectral beam combining (SBC). Initially, SBC was proposed on the basis of conventional surface gratings [1]; however, it was found later that volume Bragg gratings (VBGs) are more efficient for high density SBC with narrow separation between channels [2, 3]. Spectral beam combining by means of VBGs is based on the fact that diffraction efficiency at some wavelength offset from Bragg condition is zero. At this shifted wavelength, the second beam passes the grating without diffraction and is combined with a diffracted beam.

Recently, a technique for high-efficiency VBG recording in photo-thermo-refractive (PTR) glass has been developed [4]. While being photosensitive in the UV, PTR glass offers high transmittance in the near-IR and visible parts of spectrum, comparable to commercial optical glasses. Moreover, this glass has excellent mechanical properties and refractive index independent of temperature, with $dn/dt < 10^{-8}$ K^{-1}. These features of PTR glass enable VBGs in PTR glass to withstand high-power laser radiation, making them ideal elements for high-power SBC. As an example, 165-W near-diffraction-limited beam combined by means of transmitting VBG in an optical setup with two Yb-fiber lasers which have 11-nm-difference in their central wavelengths has been demonstrated [3]. 92% combining efficiency was achieved at the maximal power level.

Multi-kilowatt-power level for spectrally combined beams can be achieved by increasing spectral density of laser channels, i.e. decreasing spectral separation between them. The goal of this work is to explore high density SBC with PTR VBGs and determine limitations to channel density.

VBGs in PTR glass can be designed to have a wide range of spectral selectivity, from hundreds of picometers to tens of nanometers. Practical modeling based on Kogelnik's theory [5] has been presented [6, 7]. A solution of the scalar wave equation gives the following formulae for diffraction efficiency η of transmitting (1) and reflecting (2) VBGs:

$$\eta = \frac{\sin^2\left(\xi^2 + \Phi^2\right)^{1/2}}{1 + \xi^2/\Phi^2} \qquad (1)$$

$$\eta = \left(1 + \frac{1 - \xi^2/\Phi^2}{\sinh^2\sqrt{\Phi^2 - \xi^2}}\right)^{-1} \qquad (2)$$

Phase incursion Φ determines the maximum diffraction efficiency (grating strength) of a VBG in Bragg condition; dephasing ξ describes detuning from the Bragg condition either spectrally or angularly. Φ and ξ can be easily expressed through the basic grating parameters and diffraction geometry [6, 7]. Dependences of diffraction efficiency of transmitting and reflecting gratings on wavelength for plane wave are shown in thick lines in Fig. 1 and 2, respectively. One can see that each grating has one maximum (Bragg condition) and a series of nulls. This means that for efficient beam combining one of the beams should correspond to the Bragg condition and will be completely diffracted. The other beam (or beams) should be detuned from Bragg condition to correspond to one of the minima. This detuning defines channel separation in a beam combiner.

Two geometries, transmitting and reflecting, of Bragg gratings are considered in this work. Spectral dependence of diffraction efficiency of transmitting Bragg grating with spectral selectivity of 2.2 nm (Half Width to

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First Zero, HWFZ) is shown in Fig. 1. Simulations [6] show that spectral width of a laser source should be less than 0.3 nm for this grating to provide diffraction efficiency higher than 99%. Moreover, it is important that such grating has angular selectivity (HWFZ) about 0.7 mrad. This means that angular divergence of a laser source should be below 0.1 mrad for 99% diffraction efficiency. Thus, even for channel separation exceeding several nanometers, significant restrictions are applied to spectral width and divergence of laser beams used for SBC. For beam combining applications, transmitting VBGs provide good performance for low- to mid-density SBC (<1 channel/nm).

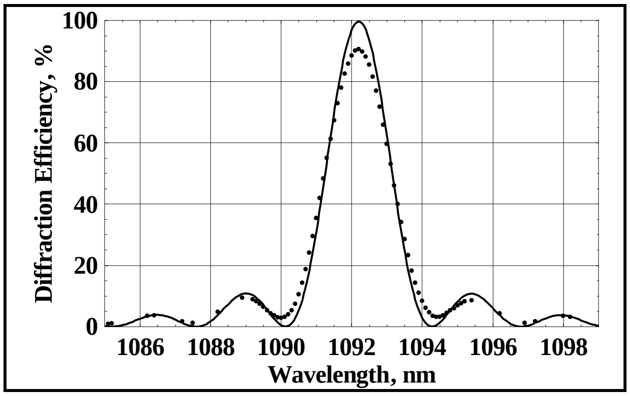

Figure 1. Spectral dependence of diffraction efficiency of a transmitting VBG with 2.2 nm spectral selectivity (Half Width to First Zero). Points – experimental data for near-diffraction-limited beam of ~7 mm diameter; curve – modeling for a plane monochromatic wave.

Reflecting VBGs are much more advantageous for high-density SBC (2 channels/nm and higher) because of the different spectral shape (Fig. 2). Advantages of using reflecting VBG over transmitting VBG for high-density SBC include polarization insensitivity and higher beam divergence tolerance. Higher divergence tolerance means that smaller beams can be used and better grating uniformity can be achieved over the smaller aperture.

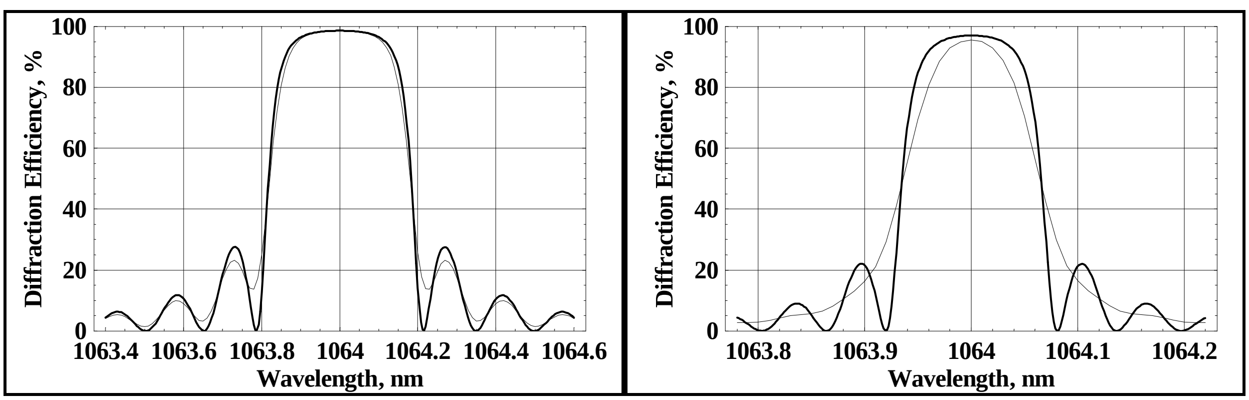

Figure 2. Theoretical spectral dependence of diffraction efficiency for reflecting Bragg gratings with 0.5 nm (left) and 0.2 nm (right) separation from maximum to third zero. Monochromatic plane waves – thick lines; Gaussian beam with divergence of 2 mrad ($FWe^{-2}M$) – thin lines.

High-efficiency reflecting VBGs usually have rather high side-lobes in the spectral dependence of diffraction efficiency. Transmitted beam corresponding to a local minimum gets partially diffracted due to finite divergence and spectral width. This parasitic diffraction results in combining losses. Combining losses increase with beam divergence and spectral width and decrease with each successive minimum of the plane-wave efficiency. For reflecting VBGs, combining losses can be minimized if the third minimum is used for the transmitting beam rather than the first. Modeling of Bragg gratings for 0.5 and 0.2 nm channel separation was performed. The first grating (Fig. 2, left) designed for SBC with 0.5 nm channel separation (2.4 mm thick, 400 ppm refractive index modulation and 0.3584 μm period) can be used to combine beams that have < 2 mrad divergence with > 98 % combining efficiency. The second grating (Fig. 2, right) is designed for SBC with 0.2 nm channel separation (6 mm thick, 140 ppm refractive index modulation and the same period) can be used for beam combining with > 96 % theoretical combining efficiency for beams with far-field divergence < 2 mrad. Combining efficiency can be improved slightly if source divergence is reduced, upper limits being 99.3 % and 98.5 % respectively.

A transmitting VBG was recorded in PTR glass to be used as a beam combiner with 2.2 nm channel spacing around 1090 nm. The grating has refractive index modulation of 165 ppm, period of 1.6 µm, and thickness of 3.1 mm. The grating Bragg angle is about 20˚, spectral selectivity (HWFZ) is about 2.2 nm and angular selectivity (HWFZ) is about 715 µrad. Theoretical efficiency for plane wave and measured diffraction efficiency (scanned with near-diffraction-limited 7 mm diameter beam) as functions of wavelength are shown in Fig. 1. One can see good correspondence. Insignificant smearing of minima and maxima is caused by finite divergence and spectral width of the laser beam and variations of grating vector across the aperture.

This grating was used to combine two laser beams with combining efficiency > 90%. The two beams with offset wavelengths (λ_1=1090.0 nm, λ_2=1092.2 nm) are incident on the grating at Bragg angle for λ_2 (about 20 degrees) from the opposite sides of the normal to the grating vector. The second beam is in resonance with the grating and is mostly diffracted (deflected by twice the Bragg angle), while the first beam is in the first minimum of the diffraction efficiency curve (Fig. 1) and is mostly transmitted. The system is aligned so that the two beams emerging from the grating are overlapped and collinear. Propagation properties of the beams (diffracted, transmitted and combined) are studied in two orthogonal planes: horizontal (plane of diffraction) and vertical.

Propagation properties of the studied beams were characterized by the "times-diffraction-limit" (TDL) factor, commonly known as M^2 [8,9]. It shows how many times far-field divergence of a real beam is greater than divergence of a perfect diffraction-limited Gaussian beam of the same size. The International Standard Organization (ISO) determines that beam sizes have to be measured by the second moment definition [9]. To find the TDL factor, the beams are focused with a lens and scanned with 2.5 µm slits in 5 planes along the direction of propagation (*z*). Beam spots in 5 planes are fit to a hyperbolic equation (3) to find the TDL factors (or M^2) along with z_0 and W_0 [9,10].

$$W(z) = W_0\sqrt{1+\left(\frac{M^2\lambda}{\pi W_0}\right)^2 (z-z_0)^2} \qquad (3)$$

Original collimated beams have M^2 ~1.05. It was found that transmitted beam has almost the same TDL factor as an incident beam in both vertical and horizontal planes (Table 1). This result shows that the optical homogeneity and quality of the surfaces of a PTR VBG are high enough not to increase divergence of laser beams significantly. TDL factor of the diffracted beam in vertical plane is almost unchanged by the grating while in the horizontal plane it is increased to 1.3. Since the beam diameter is not changed by diffraction at the grating, diffraction limited divergence is not changed. However, divergence of the beam in the horizontal plane has increased by 30%. It was found that this additional divergence is not caused by imperfections of VBG. The beam acquires additional divergence due to angular dispersion of the VBG. Modeling shows that the grating with parameters described above has angular dispersion of about 670 µrad/nm. The bandwidth of the laser is about 100 pm FWHM, meaning that additional divergence should be on the order of 70 µrad which is approximately 35 % of diffraction limited divergence (~ 200 µrad for 7 mm beam diameter).

This effect was experimentally confirmed by observing the spectrum of the beam in the far-field. Peak wavelength shifts by ~90 pm as the far-field beam is scanned in the transverse direction over the beam diameter ($FWe^{-2}M$). In other words, the combined beam is angularly chirped.

Fig. 3 shows dependence of beam diameters on position along the direction of beam propagation. One can see that for vertical plane propagation properties of transmitted, diffracted and combined beams are the same. In horizontal plane, not only beam waist diameters are different but their positions are also different for transmitted and diffracted beams. As the result the combined beam has divergence of 1.35 times diffraction limit. It is important that because positions of the waists for transmitted and diffracted beams are different, the TDL factor of the combined beam is not an average value of the individual beams, but exceeds the TDL factor of both beams. The dispersive component of divergence is diminished when narrow-band sources are used.

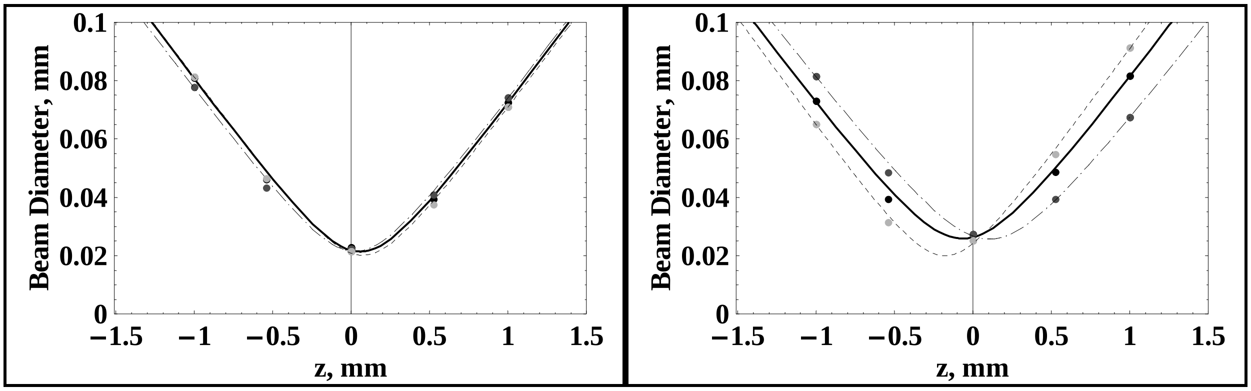

Figure 3. Dependence of beam diameter (by second moment definition) on position along direction of beam propagation after transmitting Bragg grating focused by a lens with f=110 mm. Left – vertical plane; right – horizontal plane. Points – experimental data; curves – fits to Eq. 3. Dashed – transmitted beam; dot-dashed – diffracted beam; solid – combined beam.

	Transmitted Beam	Diffracted Beam	Combined Beam
Vertical Plane	1.08	1.12	1.13
Horizontal Plane	1.09	1.30	1.35

Table 1. TDL factors (M^2) of laser beams in two orthogonal planes (absolute accuracy ±0.05), indicating the ratio of beam divergence to diffraction-limited divergence of a Gaussian beam. Incident beams have M^2=1.05 in both planes.

It was well known that sources with narrow spectral widths are necessary for efficient spectral beam combining, to maximize diffraction efficiency for the diffracted beam and minimize diffraction efficiency for the transmitted beam. We emphasize that the newly found contribution to beam divergence, arising from angular dispersion, imposes more stringent requirements for spectral widths of sources.

Spectral beam combining by means of volume Bragg gratings recorded in PTR glass is proven to be an efficient technique for increasing of power in multichannel high energy lasers. Achievability of combining with efficiency exceeding 90% for subnanometer channel separation is shown for reflecting gratings. Spectral beam combining with efficiency of 90.6% for channel separation of 2.2 nm is demonstrated with a transmitting Bragg grating. Effect of dispersive component of divergence on propagation properties of the combined beam is observed and explained.

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