

REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-05-

0092

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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE	3. REPORT NUMBER	
			01 JUL 2001 - 30 JUN 2004 FINAL	
4. TITLE AND SUBTITLE INCOHERENT COMBINING OF HIGH-POWER LASER BEAMS BY VOLUME DIFFRACTIVE GRANTING IN A PHOTSENSITIVE SILICATE GLASS			5. FUNDING NUMBERS 61102F 2301/AX	
6. AUTHOR(S) PROFESSOR GLEBOV				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) UNIVERSITY OF CENTRAL FLORIDA 4000 CENTRAL FLORIDA BLVD ORLANDO FL 32816-0150			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFOSR/NE 4015 WILSON BLVD SUITE 713 ARLINGTON VA 22203			10. SPONSORING/MONITORING AGENCY REPORT NUMBER F49620-01-1-0469	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A: Unlimited			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) A model for spectral beam combining by means of transmitting Bragg gratings is developed. > Combining efficiency exceeding 92% for two 100-W Yb-fiber lasers by optimization of Bragg gratings and optical setup is achieved. No deterioration of PTR Bragg grating occurred at this level of laser power. > It is shown that combining efficiency of about 99% by means of PTR Bragg gratings could be reached with the use of high-power lasers with narrow-line and low divergence. > High density spectral combining enables creation of multi-kilowatt laser systems for military and industrial applications.				
14. SUBJECT TERMS			15. NUMBER OF PAGES	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL	

**INCOHERENT COMBINING OF HIGH-POWER LASER BEAMS BY VOLUME
DIFFRACTIVE GRATINGS IN A PHOTSENSITIVE SILICATE GLASS**

(U.S. AFRL, contract # F49620-01-1-0469, ^{final}~~interim~~ report #3)

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Introduction

This report describes efforts carried out during the second year of the contract. Design principles and technical approach for SBC of two high-power Yb-fiber lasers were recently developed (see the interim report [1] and following publications [2,3]). Spectral beam combining (SBC) by volume Bragg gratings (VBGs) uses their feature that the only laser beam corresponding Bragg condition would be efficiently deflected by the grating while for all other beams this element would be just a transparent plate. An elementary cell of such two-beam-combiner is a single VBG having maximal diffraction efficiency for one beam but zero efficiency for the second one. Thus, the SBC approach should result in the generation of higher power laser beams with only passive components constituting the combining system.

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Based on the results of experimental testing of high-efficient VBGs recorded in PTR glass in high-power lasers [3-5], we expect performing of a high-efficient (>90%) combining of two Yb-doped fiber lasers with biased wavelengths by PTR VBG. These gratings exhibit a long-term stability of all their parameters in high-power laser beams, and spatial periodicity and shape of diffraction fringes have no heating-related distortions. It is most important and should be especially noticed, that exposed and thermally developed PTR VBG survived in CW laser beam with power density more than 0.1 MW/cm^2 and they have shown no thermal distortions.

1. Theoretical modeling of beam combiner using transmitting VBG

1.1. Plane monochromatic beams

Let us describe beam combining procedure in details for two spectrally separated plane monochromatic beams directed at the angles $+\theta_i$ and $-\theta_i$ to the surface of transmitting Bragg grating produced by refractive index modulation in the volume of a photosensitive material as it is shown in Figure 1. The Bragg angle in the medium θ_m for a fixed wavelength λ and diffraction efficiency η , as well as a grating spectral and angular selectivity are fully determined by following three independent

parameters of the grating: refractive index modulation δn , spatial frequency f , and thickness t . The average refractive index of the medium with periodical refractive index modulation is n_{av} . For simplicity, we consider a uniform transmitting VBG with the grating vector parallel to the plane-parallel surface of a photosensitive medium. This consideration does not narrow the problem because consideration of an arbitrary oriented grating requires only additional trigonometrical calculations.

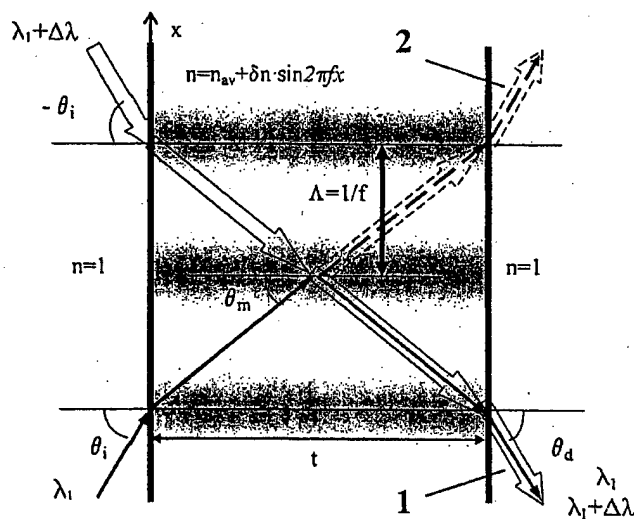


Fig.1. Spectral beam combining by transmitting VBG. 1 – combined, 2 – residual beams.

In this case, spectral selectivity of VBG has a central maximum and several decaying side lobes separated by minima with zero intensity [6]. The corresponding formula for the diffraction efficiency is

$$\eta = \frac{\sin^2(P^2 + p^2)^{1/2}}{1 + p^2/P^2} \quad (1)$$

There P is a phase incursion at Bragg condition:

$$P = \frac{\pi t \delta n}{\lambda_1 \cos \theta_m} \quad (2)$$

and p is a dephasing parameter which describes a detuning from the Bragg condition. For small spectral deviation $\Delta\lambda$ from the central wavelength λ_1 , p could be expressed as

$$p = \frac{\pi f^2 t \Delta\lambda}{2n_{av} \cos \theta_m} \quad (3)$$

Bragg angle inside the medium θ_m is determined from the Bragg condition as

$$\sin \theta_m = \frac{\lambda_1 f}{2n_{av}} \quad (4)$$

The condition for efficient spectral beam combining with transmitting VBG is 100% diffraction efficiency the first beam and 0% diffraction efficiency for the second one with shifted wavelength. As Figure 1 shows, the incident angles $+\theta_i$ for the first beam with wavelength λ_1 and $-\theta_i$ for second beam with wavelength $\lambda_2 = \lambda_1 + \Delta\lambda$ are symmetric, and their modules are exactly equal one to other. According to (1), complete Bragg diffraction of the first beam having $p_1=0$ occurs for phase incursion:

$$P_1 = \pi/2 \quad (5)$$

Substitution of (5) to (2) gives us a condition of 100% diffraction efficiency for the first beam:

$$\lambda_1 \cos \theta_m = 2t \delta n \quad (6)$$

According to (1), zero diffraction efficiency for the second beam with $\lambda_2 = \lambda_1 + \Delta\lambda$ is achieved when

$$(P_1^2 + P_2^2)^{1/2} = i\pi, \text{ where } i=1, 2, \dots, n \quad (7)$$

Let us note that diffraction efficiency reaches the zero value at multiple points, but in practice the most important are the first one ($i=1$) and few next ($i=2,3,4$) which could be useful in some cases of a combining design. Substitution of (7) and (5) to (3) gives the expression for zero diffraction efficiency of the second beam:

$$f^2 t \Delta\lambda = 2n_{av} \cos \theta_m \sqrt{4i^2 - 1} \quad (8)$$

System of equations (6) and (8) provides relationships between grating parameters which enable required features (5) and (7) of the VBG. Using the Bragg condition (4), let us transform system (6)-(8) to expressions describing relationships between independent grating parameters:

$$\delta n = \frac{\lambda_1 \operatorname{cosarcsin}\left(\frac{\lambda_1 f}{2n_{av}}\right)}{2t} \quad (9)$$

$$\delta n = \frac{f^2 \lambda_1 \Delta\lambda}{2n_{av} \sqrt{4i^2 - 1}} \quad (10)$$

Formula (9) provides condition of 100% diffraction efficiency for the first beam, while formula (10) provides condition for zero diffraction efficiency for the second beam. Thus, we have two equations which connect three independent parameters. This means that both conditions could be satisfied concurrently with unlimited number of solutions. This feature of spectral beam combining with transmitting VBG gives a freedom for the combiner design by the further tradeoff for satisfying other requirements of an optical system.

Let us illustrate how SBC algorithm works. Figure 2 illustrates combining of two beams with $\lambda_1=1085$ nm and $\Delta\lambda=10$ nm (an example for Yb-doped fiber lasers) and shows an interrelation between refractive index modulation and spatial frequency of the grating which provide simultaneous placement of the first three orders of zero diffraction efficiency at $\lambda_1+\Delta\lambda$ wavelength and 100% diffraction efficiency at λ_1 for different grating thickness. Each of curves 1-3 in Figure 2 corresponds to zero diffraction efficiency of the second beam at shifted wavelength in accordance with formula (10). Each of curves 4-6

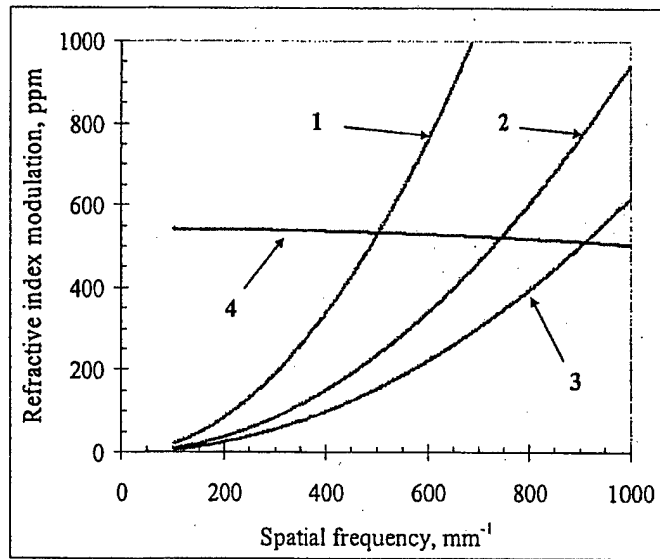


Fig. 2. Interrelations between refractive index modulation and spatial frequency of VBG for optimal beam combining. Curves 1, 2, and 3 correspond to consequent zeros in spectral distribution of diffraction efficiency for the beam with the shifted wavelength $\lambda_1+\Delta\lambda$. Curve 4 corresponds to 100% diffraction efficiency for the beam at unbiased wavelength λ_1 . $\lambda_1=1085$ nm, $\Delta\lambda=10$ nm, thickness 1 mm.

corresponds to condition for 100% diffraction efficiency of the first beam in accordance with formula (9) for some, arbitrary selected grating thicknesses. The intersection points between the curves give the VBG parameters for optimal beam combining. However, they could be varied providing infinite number of optimal combination of grating parameters.

Figure 3 shows theoretical limits for SBC for current PTR glass providing up to 1000 ppm (1×10^{-3}) refractive index modulation and spatial frequency ranged from zero to 10,000 mm^{-1} .

The grating parameters are calculated for combining of beams with different wavelength separation – 0.1, 1 and 10 nm. For generalizing of these results, we choose three different values within a wide set of the grating thicknesses: thin (0.2 mm), mid-thick (2 mm), and thick (20 mm) gratings. One can see that small (0.1 nm) wavelength shift between combined beams requires thick gratings with high (about $1,000 \text{ mm}^{-1}$) spatial frequencies and relatively low refractive index modulation (less than 50 ppm). For spectral separation of 1 nm, there is a variety of choices for a beam combiner design: depending on the refractive index modulation in the

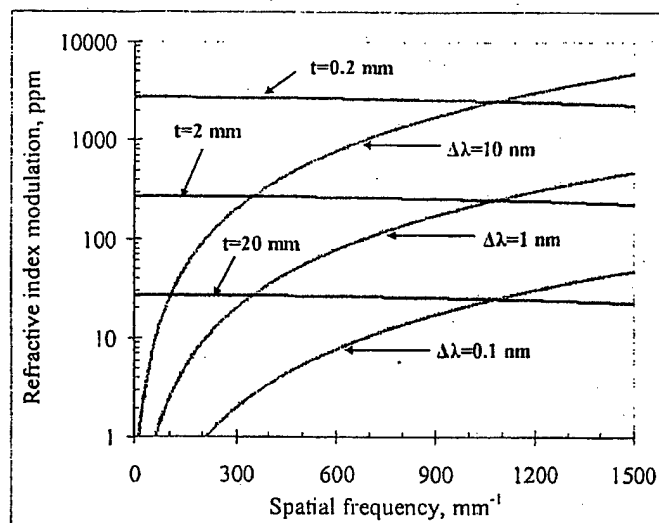


Fig. 3. Interrelations between refractive index modulation and spatial frequency of transmitting VBG for optimal beam combining for different grating thickness and spectral separation between combined beams. Curves with $\Delta\lambda$ equal to 10, 1, and 0.1 nm correspond to the first zero in spectral distribution of diffraction efficiency for the beam with a respective spectral shift. Curves with thickness equal to 0.2, 2, and 20 mm correspond to 100% diffraction efficiency for the beam at unbiased 1085-nm-wavelength.

grating, one can choose either thick samples to record low-frequency gratings at relatively low refractive index modulation or use mid-thick gratings with spatial frequency up to 1000 mm^{-1} and refractive index modulation about several hundred ppm. The thinner the grating, the greater refractive index modulation and spatial frequency should be. Almost the same peculiarities are for spectral shift of 10 nm or more in combining beams, but for thin (0.2 mm) gratings it requires too high refractive index modulation compare to that in an existing PTR glass.

Thus, there are multiple combinations of practically achievable grating thickness, spatial frequency, and refractive index modulation which provide simultaneously 100% diffraction efficiency to the first beam and 0% diffraction efficiency to the second one with the shifted wavelength ranged from tenths to several nanometers.

1.2. Plane non-monochromatic beams

Beams emitting by semiconductor and fiber lasers have spectral width about several nanometers which is comparable or even exceeding spectral selectivity of Bragg gratings that could be used for spectral beam combining. It might considerably restrict the number of channels for spectral combining of such lasers as well as applies some additional requirements to the VBG design.

Typical spectral separation between modes in laser resonators is usually small enough compare to spectral selectivity of Bragg gratings. Therefore, let us do not take into account mode spectrum of particular laser resonators but expect Gaussian shape of spectra of laser radiation. In this case it could be described as

$$G_1(\lambda, w) = e^{-2\left(\frac{\lambda-\lambda_0}{w}\right)^2} \quad (11)$$

where parameter w is the HWe^{-2}M (Half Width at e^{-2} of the Maximum) spectral width of a beam, and λ_0 is a central wavelength of the emission spectrum. Convolution of the VBG diffraction efficiency from (1)-(3) with the Gaussian spectral distribution from (11) gives us the adjusted value of diffraction efficiency $\eta_\lambda(w)$:

$$\eta_\lambda(w) = \frac{\int \eta(\lambda) G_1(\lambda, w) d\lambda}{\int G_1(\lambda, w) d\lambda} \quad (12)$$

Taking into account the numerical value of a Gaussian-function integral, (12) could be written as

$$\eta_\lambda(w) = \sqrt{\frac{2}{\pi}} \frac{1}{w} \int \eta(\lambda) G_1(\lambda, w) d\lambda \quad (13)$$

Equation (13) allows us to model a propagation of planar broad-spectra beams through transmitting VBG. For illustration, let us describe three gratings shown in Figure 3 with thickness 20, 2.0, and 0.2 mm and corresponding HWZ spectral selectivity (Half-Width-Zero,

interval between maximum and the first zero in a spectral dependence of diffraction efficiency) of 0.1, 1, and 10 nm for the further modeling. Figure 4 shows the dependence of diffraction efficiency $\eta_\lambda(w)$ on beam spectral width w for $\lambda_0=1085$ nm. One can see that the grating diffraction efficiency is about 60% when $HWe^{-2}M$ spectral width w of the beam is equal to the grating HWZ spectral selectivity of the grating. Diffraction efficiency has no deterioration for extremely narrow-bandwidth beams and then decreases to 99% when $HWe^{-2}M$ beam spectral width becomes approximately 8 times less than the grating HWZ spectral selectivity. This ratio is the same for all gratings with 100% diffraction efficiency at certain wavelength, and it should be carefully considered for efficient combining of broad-bandwidth beams to prevent their spectral cutting-out.

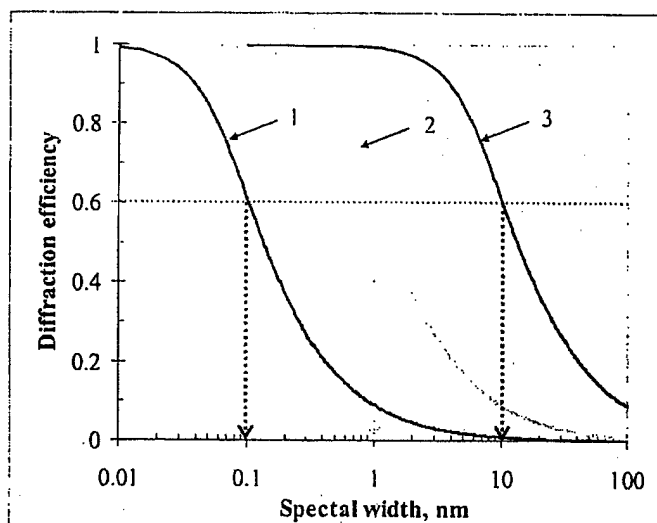


Fig. 4. Diffraction efficiency of transmitting VBG with 100% diffraction efficiency for plane monochromatic wave at λ_0 versus spectral width of laser radiation. Spectral width of laser radiation and spectral selectivity of VBG are determined as $HWe^{-2}M$ and HWZ, respectively. Spectral selectivity of VBG: 0.1 (1), 1.0 (2) and 10 nm (3), shown by dotted arrows. Dotted line corresponds to diffraction efficiency for a beam with spectral width equal to selectivity of VBG. $\lambda_0=1085$ nm.

When both combining beams would have the same bandwidth parameters, the requirement of their spectral shift for more than 8 times versus beam spectral width will automatically satisfy the additional requirement for efficient transmitting of the second beam throughout the VBG. Thus, in addition to selection of optimal beam combining by tradeoff between grating thickness, spatial frequency, and refractive index modulation, optimization of the ratio between the beams emission spectra and spectral selectivity of the grating should also be considered.

1.3. Divergent monochromatic beams

Diffraction of a monochromatic beam with certain divergence on transmitting VBG will be described here for beam combining optimization. Let us approximate spatial distribution of divergent laser emission by Gaussian function. Actual angular structure of laser radiation could be more complex but it will be shown that high diffraction efficiency could be achieved for beams with divergence significantly narrower than angular selectivity of a grating. In this case, actual structure of emission is not important while total angular width becomes a key parameter. If angles of incidence θ inside the grating medium are not far from the Bragg angle θ_m , this function could be written as

$$G_2(\theta, b) = e^{-2\left(\frac{\theta - \theta_m}{b}\right)^2} \quad (14)$$

where b is beam divergence at the level of $1/e^2$ ($HWe^{-2}M$). If a beam with diameter D is diffraction-limited, its full far-field divergence angle at central wavelength λ_0 is $2b$ which could be determined from

$$b = \frac{2\lambda_0}{\pi D} \quad (15)$$

The lower the diameter, the higher the beam divergence is occurred. To determine diffraction efficiency of VBG for such a divergent beam, convolution in the angular space should be applied:

$$\eta_\theta(b) = \frac{\int \eta(\theta) G_2(\theta, b) d\theta}{\int G_2(\theta, b) d\theta} \quad (16)$$

After substitution of the numerical value of a Gaussian-function integral, (16) could be written as

$$\eta_{\theta}(b) = \sqrt{\frac{2}{\pi}} \frac{1}{b} \int \eta(\theta) G_2(\theta, b) d\theta \quad (17)$$

Angular selectivity of transmitting VBG at HWZ level could be found from (1)-(3) by derivation of (4) for small angular deviations $\delta\theta$ from the Bragg angle θ_m . In this case one can write dephasing parameter p as

$$p = \frac{2\pi n_{uv} t}{\lambda_0} \delta\theta \sin \theta_m = \pi f t \delta\theta \quad (18)$$

Applying of conditions (5) and (7) for equalizing of diffraction efficiency to the first zero value, (18) allows us to have a formula for HWZ angular selectivity:

$$\delta\theta = \frac{\sqrt{3}}{2ft} \quad (19)$$

Again, let us use the data shown in Figure 3 and describe four gratings for optimal beam combining with thickness 20, 2.0 (two gratings with different spatial frequencies), and 0.2 mm, which in accordance with (19) have the angular selectivity of 0.12, 0.4, 1.2, and 4 mrad respectively. In general, thicker and high-frequency gratings exhibit higher angular selectivity.

Figure 5 shows the dependence of diffraction efficiency $\eta_{\theta}(b)$ on the divergence of beam b for VBG with

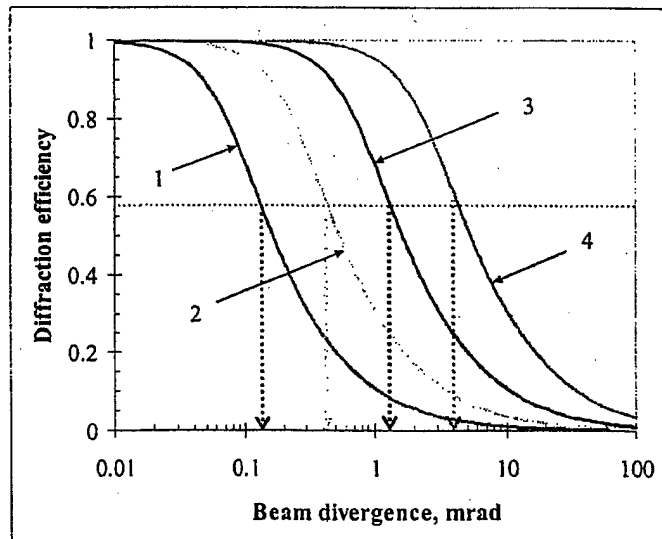


Fig. 5. Diffraction efficiency of transmitting VBG which has 100% diffraction efficiency for plane monochromatic wave at λ_0 versus beam divergence. Angular selectivity of VBG, HWZ: 0.12 (1), 0.4 (2), 1.2 (3), and 4 mrad (4), shown by dotted arrows. Dotted line corresponds diffraction efficiency for a beam with divergence equal to selectivity of VBG. $\lambda_0=1085$ nm.

100% diffraction efficiency for planar waves. Divergent beams exhibit decreasing less than 1% in diffraction efficiency until the $HWe^{-2}M$ beam divergence is at least 8 times narrower than the grating HWZ angular selectivity $\delta\theta$. This result is very similar to results described in 2.2 for planar beams with certain spectral bandwidth. Increasing of beam divergence (e.g. by decreasing of beam diameter) results in decreasing of diffraction efficiency. Even the $HWe^{-2}M$ beam divergence is equal to the HWZ angular selectivity $\delta\theta$ of VBG, diffraction efficiency $\eta_\theta(b)$ decreases almost twice (up to 55%) in comparison with its 100% value for low-divergent beams.

It should be noticed that even second beam transmitting throughout the combining VBG has no such restrictive limitations to its divergence, the quality of a combined beam will be determined by the worst beam from the combining pair. Hence, the same requirement to limit the divergence of all beams in accordance with VBG angular selectivity should be applied for multiple beams combining.

1.4. Combining of non-monochromatic divergent beams

It should be noticed that if a beam is both divergent and broadband, the total diffraction efficiency after Bragg grating is a product of $\eta_\lambda(w)$ and $\eta_\theta(b)$ according (13) and (17):

$$\eta(w, b) = \eta_\lambda(w) \cdot \eta_\theta(b) \quad (20)$$

Thus both mentioned factors (divergence and spectral broadening) decrease diffraction efficiency of the first combining beam. The second one, which should transmit throughout the VBG without diffraction losses, could be also affected by these factors.

If both incident beams have the same intensity, resulting combining efficiency ϵ would be written as

$$\epsilon = \frac{\eta_{\lambda 1}(w, b) + T_{\lambda 2}(w, b)}{2} \quad (21)$$

where η_N and T_{λ_2} are diffraction efficiency and transmittance of the beams with wavelengths λ_1 and $\lambda_2 = \lambda_1 + \Delta\lambda$, respectively. Therefore, efficient spectral beam combining would be produced when simultaneous achieving of high efficient diffraction of one beam and high transparency of the second one is securing in the condition that both beams approach a VBG at exact Bragg angle for one of the beams.

2. Diffraction and combining efficiency of PTR Bragg gratings

The optical system designed for hologram recording in the UV spectral region, testing of the VBG properties, and spectral beam combining was described in Ref. [1]. The last one includes two 100-Watt CW single-transverse-mode Yb-doped fiber lasers (IPG Photonics Corp., model YLR-100) with the central wavelength shifted on 11 nm (at 1085 and 1096 nm) were used for study. Calculation of optimal design for beam combiner in accordance with the algorithm described above follows us to optimized parameters of PTR Bragg grating: 1.23 mm thickness, 425 mm⁻¹ spatial frequency, and 420 ppm refractive index modulation. This grating has been recorded, tested, and used in the beam combining setup.

Both lasers have single-mode output radiation which was collimated to 5-mm-diameter beams with Gaussian profiles in far field. PTR VBG was mounted at high-precision rotation table for exact matching to Bragg condition on one of the laser beams. The second laser beam approached the Bragg grating exactly at the same angle modulus as the first one (see Figure 1). In this case the 1096 nm laser beam is in the Bragg condition while 1085 nm laser beam is out of it. For VBG spatial frequency of 425 mm⁻¹, the Bragg angle in the air is $\alpha = 13.5^\circ$. Intensities of transmitted and diffracted beams were measured by thermal power meters (Ophir Optronics, model F150A). Spatial superimposing and tracing of diffracted beam from the first laser and transmitted beam from the second one was executed by the high-power gold-coated Cu mirrors placed in Thorlabs mounts. The total optical length was about 7 m for testing of a combined beam in far-field.

It is important to note that absorption in PTR glass has a very low value. Preliminary experimental data show that PTR glass absorption in near IR radiation not exceeds several

hundreds of ppm ($2-4 \times 10^{-4} \text{ cm}^{-1}$). Scattering of PTR glass in this spectral region is at low level, too. We measured the total power in combined and residual beams (Figure 1). One can see from Figure 6 that the combined beam achieves power more than 155 W while power in the residual beam is less than 15 W. It means that combining efficiency is more than 92% at 100 W in each of the incident beams. The combining efficiency was

determined as an average value of transmitting efficiency of the out-of-Bragg beam and diffraction efficiency of the beam in Bragg condition. Figure 7 shows the dependence of absolute values of combining efficiency along with diffraction and transmitting efficiencies of combined beam components on the power in each incident beams. One can conclude that decreasing of total combining efficiency from 95% at 15 W to 92% at 100 W in each incident beam is due to corresponding decreasing of

transmitting efficiency from 97.5% to 95% for a transmitting beam and diffraction efficiency from 93% to 87% for a diffracting beam. Because the last decreasing is the most critical for total decreasing of combining efficiency, let us describe it.

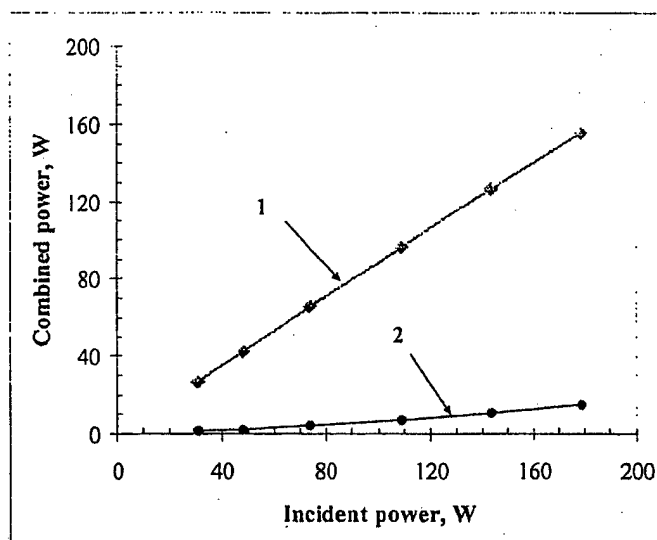


Fig. 6. Dependence of power in combined (1) and residual (2) beams on incident power.

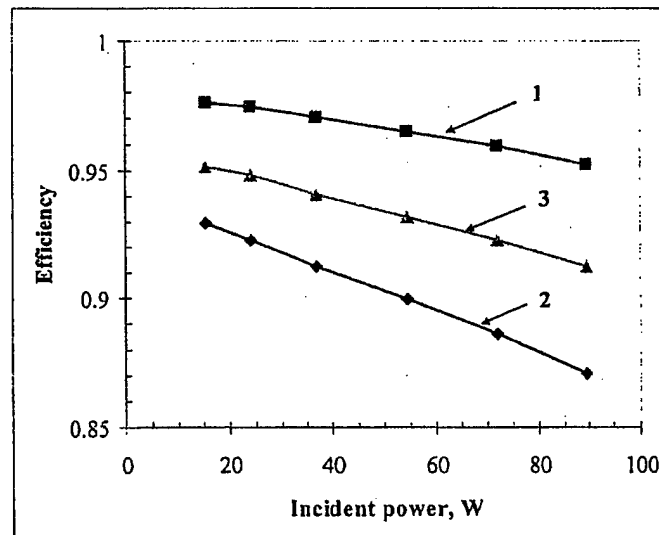


Fig. 7. Dependence of transmitting (1) and diffraction (2) efficiency of combined beams and resulting combining efficiency (3) on power in each incident beam.

As it was noted in Ref. [3], the main source of such losses is spectral widening of Yb-doped fiber lasers. Results of measurements of YLR-100 laser spectrum widening are shown in Figure 8. When the output power rises from 15 to 100 W, HWe⁻²M spectral width of the beam (line 1) increases almost twice, from 2.7 to 4.7 nm. Line 2 in Figure 8 shows the spectral width of laser radiation which corresponds to 99% of diffraction efficiency for this grating. This feature is typical for all high power fiber lasers and should be considered for optimal beam combining design.

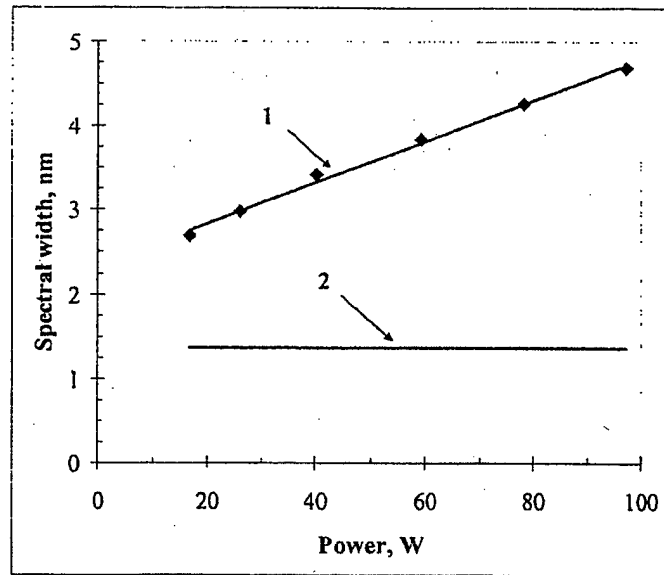


Fig. 8. Broadening of HWe⁻²M spectral width of Yb-doped fiber laser with 1096 nm central wavelength (1) and the level corresponding to 1/2 of HWZ spectral selectivity of VBG (2).

Based on theoretical modeling results described above, let us evaluate how spectral width and divergence of the beams emitted by Yb-doped fiber laser affect diffraction efficiency of VBG. For planar wave, we calculated diffraction efficiency depending on spectral width of the beam; calculation results are shown as line (2) in Figure 9. These data were compared with experimental results from series (2) in Figure 7, which are presented as line (4) in Figure 9. One can see that there is a significant difference

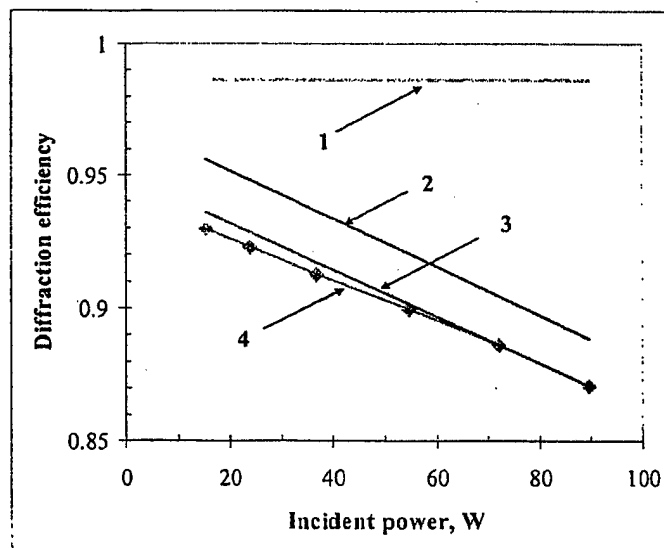


Fig. 9. Dependence of calculated diffraction efficiency of single-wavelength 0.2-mrad-divergent beam (1), plane-wave spectrum-wide beam (2), both spectral-wide and divergent beam (3) compared with experimental data (4) on incident beam power.

between lines (2) and (4), but their slope is about the same. Another effect that should be considered is divergence of laser beam. Yb-doped fiber laser beam with 5-mm-diameter has divergence about 0.2 mrad. This divergence results in 98.6% diffraction efficiency for monochromatic wave (line 1). Both effects lead to decreasing of diffraction efficiency from 100% to 87% for 100-W-beam as a result of multiplication of lines (1) and (2), - line (3), and confirmed by experimental results (4). We experimentally proved that divergence of combined beam was the same as divergence of incident beams (0.2 mrad).

Thus, decreasing of the spectral width of radiation of Yb-doped fiber laser to the level below 1 nm and increasing of aperture to 1 cm would result in 98% combining efficiency by means of PTR volume Bragg grating. The current technology of PTR hologram recording provides maximum aperture up to 35 mm. There are several reports describing narrow-band fiber laser with spectral width well below 1 nm. This means that the way for high efficiency of spectral beam combining by means of volume Bragg gratings is open. The use of PTR glass for such gratings enables creation of multi-kilowatt laser systems with diffraction limited divergence.

Study of beam combining with reflective volume Bragg gratings and development of a model for high-density spectral beam combining would be the goals for the final stage of the project.

Conclusion

- A model for spectral beam combining by means of transmitting Bragg gratings is developed.
- Combining efficiency exceeding 92% for two 100-W Yb-fiber lasers by optimization of Bragg gratings and optical setup is achieved. No deterioration of PTR Bragg grating occurred at this level of laser power.
- It is shown that combining efficiency of about 99% by means of PTR Bragg gratings could be reached with the use of high-power lasers with narrow-line and low divergence.
- High density spectral combining enables creation of multi-kilowatt laser systems for military and industrial applications.

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