Efficient power scaling of laser radiation by spectral beam combining

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The possibility of achieving multikilowatt laser radiation by spectrally combining beams using volume Bragg gratings (VBGs) is shown. The VBGs recorded in a photothermorefractive glass exhibit long-term stability of all its parameters in high-power laser beams with power density >1 MW/cm^2 in the cw beam of total power on a kilowatt level. We consider an architecture-specific beam-combining scheme and address the cross-talk minimization problem based on optimal channel positioning. Five-channel high efficiency spectral beam combining resulted in a >750 W near-diffraction-limited cw beam has been demonstrated experimentally. © 2008 Optical Society of America

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During the past several years there has been significant interest in ways to generate and increase high-power cw laser radiation up to multiple kilowatt levels. Despite considerable efforts in this field, the main difficulty of heat dissipation in systems associated with single-source units has not been overcome. Single-mode fiber sources with an output power of more than 1 kW are not only limited by thermal problems but also by nonlinear effects such as stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS), which are getting worse with increasing of the fiber lengths. However, these problems can be overcome as the sources of heat can be distributed. One of the ways toward the objective is to combine the output beams from multiple laser elements into a single near-diffraction-limited beam.

It can be done in two different ways. First, is the so-called "coherent beam combining," in which a radiation from the master oscillator is split into a number of beams, which are individually amplified and then coherently combined in the interferometer-type device by means of phase equalizing [1–3]. In principle, this approach could provide efficient beam combining, but it requires extremely high precision and stability of multiplexing and phase retardation elements and requires active stabilization of the relative phase of the source. Moreover, the issue of system stability and beam quality is further complicated in high-power laser systems by thermal effects that can lead to severe wavefront distortions. As a result, to our knowledge no experimental demonstration on coherent beam combining for cw power exceeding 10 W has been demonstrated so far.

In the second approach to the efficient power scaling, a method of spectral beam combining (SBC) is used [4–6]. The output beams from several distinct wavelength laser sources are combined into a single-aperture, diffraction-limited beam. Unlike the coherent beam combination, SBC has no requirement on coherency and allows relative preservation of the source beam qualities. Powers of the original beams are incoherently added while the spectrum of the combined beam is a sum of the spectra of original beams. This makes SBC a promising approach due to its simpler design and lower tolerance requirements for system alignment.

Highly dispersive volume Bragg gratings (VBGs) in a photothermorefractive (PTR) glass have been successfully used in high-power laser systems [7]. Both grating types, transmitting and reflecting VBGs, exhibit diffraction efficiency (DE) $>95\%$ for a wide range of spatial frequencies [8] and show good thermal, optical, and mechanical properties suitable for high-power applications. These properties, combined with narrow diffraction bandwidth and small material loss make the use of PTR Bragg gratings exceptionally suited for SBC applications [6]. Owing to its narrow spectral and angular selectivity, VBG offers an advantage of at least 1 order of magnitude in the bandwidth use over a conventional surface diffraction grating. Diffraction angles and wavelengths can be independently tailored, giving the flexibility in configurations when cascading for multiple elements to increase the number of SBC channels.

In the latest experiment, five cw laser beams have been combined with absolute efficiency $>93\%$ at the combined power level >750 W. The inputs of the system are five ~ 160 W near-diffraction-limited beams with a diameter of ~ 3 mm (e^{-2} diameter) and wavelengths from 1062.08 to 1064.55 nm. A set of four identical reflecting VBGs with a resonant wavelength of 1065.0 nm at normal incidence has been fabricated following a multichannel optimization procedure. Spectral selectivity of the gratings is shown in Fig. 1. In an SBC system, Fig. 2, gratings are fine-tuned to match the Bragg condition for the respective source wavelength for simultaneous diffraction of a given channel radiation (with a relative diffraction efficiency of $\sim 99.7\%$) and transmit radiation from the neighboring channels (with relative diffraction efficiency $<1\%$ when the neighboring channel is placed into the third or higher minimum of the spectral se-

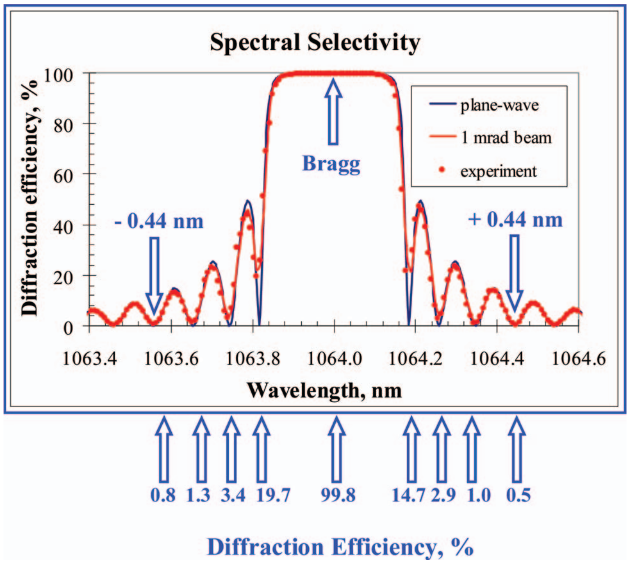

Fig. 1. Measured spectral selectivity of reflecting VBG in a 3 mm diameter beam (circles) and its simulation for a plane parallel beam (solid curve).

lectivity curve). When the system is aligned, the five beams exiting the system are overlapped and collinear, resulting in a single near-diffraction-limited output beam. Propagation properties of the input and output beams were studied at low power by using focusing lens and measuring beam characteristics around the beam-waist region with BeamScope-P7. Five input beams have $M^2 \sim 1.05$; M^2 of the output was found to be ~ 1.11.

It is necessary to note that for real beams with nonplanar wavefronts and broad spectral widths, the first sidelobe of the spectral selectivity sinc-squared function has a greater overlap value with the beam that passes through its null position. This overlap or "secondary diffraction" can be calculated using the convolution procedure. Figure 1 shows the convolution function represented as a dependence of DE on the detuning wavelength from the Bragg condition for a 3 mm diameter beam. The resonant wavelength of the grating, 1065.0 nm, was chosen with the assumption that all nonresonant beams ranging from 1062.08 to 1064.55 nm will diffract from it at small incident angles between 3° and 5°. One can see that the minimum amount of cross-talk loss corresponds to the position of higher order minima of the DE function. The loss around the first and second nulls is significant and, therefore, the grating was designed such that the channel separation requirement exactly matched the distance from the maximum of the DE curve to the third null (0.35 nm). Hence the only difference between the planar and nonplanar cases manifests itself in an upward shift of the nulls, while grating selectivity and sidelobe position do not differ drastically. Reflecting VBGs with 99%+DE at the peak have their first sidelobes of ~30%–40% signal efficiency. By increasing the refraction index modulation, one can achieve DE up to 99.9%, but this "overmodulation" leads to an undesired increase of the sidelobe diffraction in higher orders as well; as a consequence, it leads to a greater loss for passing beams.

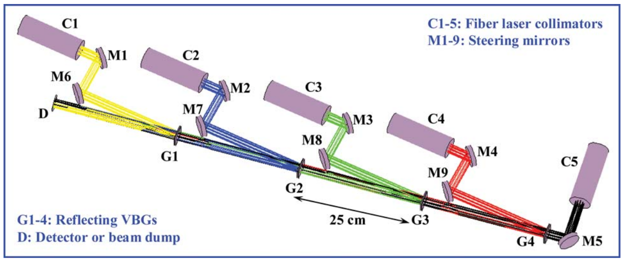

Fig. 2. (Color online) Schematic of SBC setup with five distinct laser sources and identical reflecting VBGs.

For a cascaded series of gratings, Fig. 2, we calculate the total combining efficiency of the system. By setting all individual VBGs to be highly transmissive at wavelengths $\lambda_1, \lambda_2, \ldots, \lambda_{N-1}$, and highly reflective only at λ_N, all beams can be combined into one beam without sacrificing the brightness. If we assume the material loss of the VBG to be η_T, DE to be η_D, and power from each laser to be P, combined power $P_{\text{tot}}(N)$ can be written as

$$P_{\text{total}}(N) = P\left(\eta_T^{N-1} + \eta_D \frac{1-\eta_T^{N-1}}{1-\eta_T} \right). \tag{1}$$

Therefore, the total combining efficiency $\eta_{\text{total}}(N)$, the fraction of the power from all N source lasers that is transmitted to the combined beam through $N-1$ VBGs is

$$\eta_{\text{total}}(N) = \frac{1}{N}\left(\eta_T^{N-1} + \eta_D \frac{1-\eta_T^{N-1}}{1-\eta_T} \right). \tag{2}$$

Let us now incorporate the cross-talk loss into this consideration. We start with the transmission of the first channel through $N-1$ gratings. The power of the beam after exiting the last grating is $P_1 = P(\eta_T^{N-1}\eta_{1c}\eta_{2c}\cdots\eta_{(N-1)c})$, where $(\eta_{1c}\eta_{2c}\cdots\eta_{(N-1)c})$. Similarly for the remaining channels

$$P_i = P(\eta_T^{N-i+1}\eta_D\eta_{1c}\eta_{2c}\cdots\eta_{(N-i)c}) \quad \cdots \quad P_N = P(\eta_T\eta_D).$$

The total transmitted power is the sum of all beams incoherently combined and the total efficiency is

$$\eta_{\text{total}}(N) = \eta_D\left(\sum_{n_i=1}^{N-n_i-1} \eta_T^{N-n_i-1} \prod_{n_i=1}^{N-n_i-1} \eta_{ic} \right) + \eta_T^{N-1}\prod_{n_i=1}^{N-1}\eta_{ic}. \tag{3}$$

The convenience of this representation is in the fact that the cross-talk parameter η_{ic} can be modeled as a power function of channel number, n_i $\eta_{ic} = \eta^{[\alpha/n_i^{\beta}]}$. Indeed, function $1-\eta^{[\alpha/n_i^{\beta}]}$ well approximates the diffraction loss of the real grating around its null positions, with α, β being fitting coefficients. The combined plot of the diffraction signal (solid curve) and cross talk (dashed curve) is shown in Fig. 3.

We now examine the effects of the diffraction and transmission losses to the total combination loss. It was found that the total combining efficiency does not suffer much from the diffraction loss, maintaining fairly constant total combining efficiency with increasing diffraction loss of up to a few percent. How-

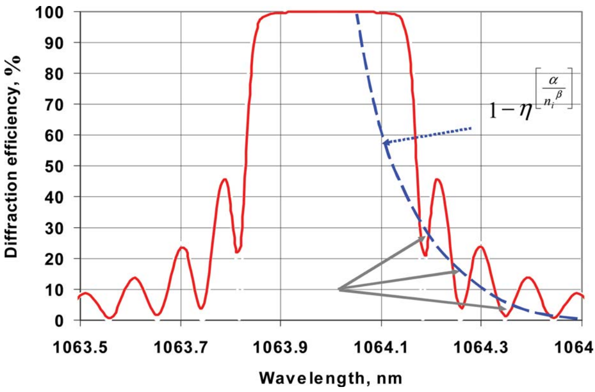

Fig. 3. (Color online) Combined plot of VBG spectral selectivity (solid curve) and cross talk (dashed curve).

ever, the total combining efficiency is significantly affected by the transmission loss. If η_D is assumed to be 0.98, the difference in effects of the losses to the total efficiency is because the transmission loss affects the throughput multiple times, particularly for the output in the upstream along the combination chain.

Let us consider the effect of cross talk on the overall efficiency of the beam combiner. We use Eq. (3) to calculate the system efficiency as a function of the number of channels n with the following parameters: $\eta_T=0.99$, $\eta_D=0.98$, $\eta_c=0.95$, and coefficients $\alpha=1$ and $\beta=2$, which well approximate the diffraction signal curve. Figure 4 shows the dependence of the system efficiency on the total number of channels. The interesting feature of this dependence is the fact that loss in the overall efficiency due to cross talk quickly saturates in the first 10–20 channels and remains relatively constant over a significantly larger number. The contribution of neighboring channels is the dominant source of the loss. This leads us to conclude that the system efficiency can be improved if exact positioning in the zeros of the diffraction function can be achieved. In case of smaller losses, the cross talk appears to be the dominant loss factor.

In conclusion, 93%+efficient spectral beam combination of five lasers emitting from 1062.08 to 1064.55 nm, using reflecting VBGs in cascaded geometry was demonstrated. The efficiency is limited mainly by the material and cross-talk losses. Modeling of the combination of multiple lasers reveals that, to achieve power scaling for a very large channel count (200–300) with overall efficiency $>90\%$, material loss of the gratings and the system cross talk must be kept at levels less than 6×10^{-4} cm^{-1} and 1%, respectively.

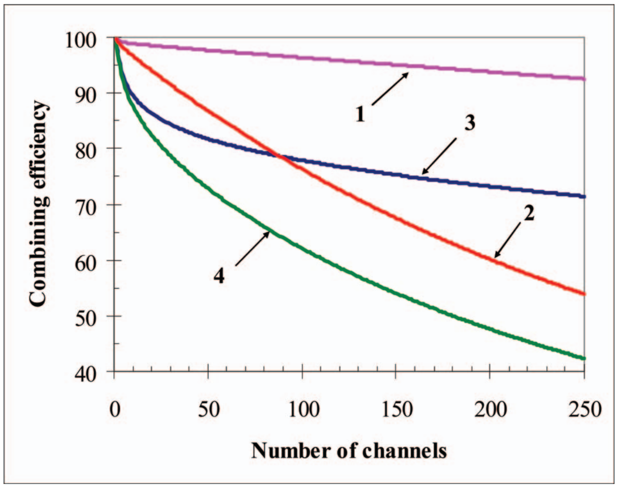

Fig. 4. Dependence of system combining efficiency on the number of channels (1,2) without and (3,4; $\eta_c=0.95$) with the cross talk. Transmittance η_T is (1,3) 0.9994 and (2,4) 0.9945.

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References

1. A. Shirakawa, T. Saitou, T. Sekiguchi, and K. Ueda, Opt. Express **10**, 1167 (2002).
2. G. T. Moore, Appl. Opt. **41**, 6399 (2002).
3. S. J. Augst, T. Y. Fan, and A. Sanchez, in *Conference on Lasers and Electro-optics/Quantum Electronics and Laser Science Conference* Technical Digest (Optical Society of America, 2003), paper CMK5.
4. E. J. Bochove, IEEE J. Quantum Electron. **38**, 432 (2002).
5. S. J. Augst, A. K. Goyal, R. L. Aggarwal, T. Y. Fan, and A. Sanchez, Opt. Lett. **28**, 331 (2003).
6. I. V. Ciapurin, L. B. Glebov, L. N. Glebova, V. I. Smirnov, and E. V. Rotari, Proc. SPIE **4974**, 209 (2003).
7. L. B. Glebov, V. I. Smirnov, C. M. Stickley, and I. V. Ciapurin, Proc. SPIE **4724**, 101 (2002).
8. O. M. Efimov, L. B. Glebov, and V. I. Smirnov, U.S. patent 6,673,497 (January 6, 2004).