Spectral Combining and Coherent Coupling of Lasers by Volume Bragg Gratings

Oleksiy Andrusyak, Vadim Smirnov, George Venus, Vasile Rotar, and Leonid Glebov

(Invited Paper)

***Abstract*—The use of volume Bragg gratings (VBGs) recorded in photo-thermo-refractive (PTR) glass for laser beam control is described. These new optical elements provide extremely narrow spectral and angular selectivity and have a high level of resistance to high-power pulsed and continuous-wave laser radiation. These features of PTR volume gratings are used for transverse and longitudinal mode selection, passive coherent coupling, and spectral beam combining (SBC) of semiconductor, solid state, and fiber lasers.**

***Index Terms*—Holographic optical components, optical fiber lasers, semiconductor lasers.**

I. Introduction

RECENT advances in solid-state, fiber, and diode laser technologies along with various beam combination techniques resulted in a rapid increase of output power available from these devices. Design of high-power laser systems exceeding limits of single-aperture emitters relies on coherent and incoherent combination of radiation from multiple emitters into a single beam with enhanced brightness. Coherent combination requires mutual phase locking of multiple emitters. Therefore, coherent oscillation of a multichannel laser system requires conversion of all emitters to a single-frequency regime (single transverse and single longitudinal modes) and precise control of relative phases of all emitters. There are several approaches to mode selection and phase locking. In this survey, we will consider the passive methods that require narrow spectral and angular selectivity of locking elements. Several methods of incoherent combination of laser beams are currently under investigation. In this survey, we will discuss high-density spectral beam combining (SBC), which requires extremely high spectral selectivity of combining elements. All results described in the current survey are based on the use of new optical elements that are volume Bragg gratings (VBGs) recorded in a photo-thermo-refractive (PTR) glass.

The most critical parameters of a high-power laser system that determine its ability to provide both low divergence and portability are efficiency and brightness. Low efficiency of a laser system means that excessive amount of heat is generated during operation. Maintaining low beam divergence (high brightness) under heat loading and providing efficient heat dissipation in a portable system are the main challenges associated with high-power laser systems. Semiconductor lasers are the highest efficiency laser sources demonstrated up to date. A number of manufacturers have developed high-power laser diodes with efficiency exceeding 70% [1]–[3]. However, poor beam quality and high divergence of high-power diode laser systems prevent their use as primary sources of emission in a number of important applications. They have been extensively used to pump other lasers, particularly solid state and fiber lasers capable of producing high-quality beams at the expense of reduced output power and overall system efficiency. Diode-pumped solid state and fiber lasers are essentially brightness converters for diode laser systems, providing enhanced brightness at the expense of overall system efficiency. While this approach has proved very useful and high efficiency of conversion has been achieved, dissipation of additional heat generated in the system requires significant increase in system size. Direct diode laser systems would make for more efficient and compact laser systems if higher brightness could be achieved without using intermediate lasers. Techniques of transverse mode selection and spectral narrowing of laser diodes together with efficient beam combining techniques enable a new generation of compact high-power laser systems. This high-efficiency portable direct diode system would produce a 10-kW laser beam with near-diffraction-limited divergence, and be scalable to 100 kW [4].

We propose design architecture for high-power laser system where the final stage is a multichannel SBC that collects radiation from a number of coherent emitters with shifted wavelengths into a single beam with enhanced brightness. Each coherent emitter is a coherently coupled array of high-efficiency spectrally stabilized single-transverse-mode semiconductor, solid state or fiber lasers. SBC, coherent coupling, spectral stabilization, and transverse mode selection are performed by VBGs recorded in PTR glass [5]. In this paper, we briefly review applications of PTR Bragg gratings to transverse and longitudinal mode selection in laser sources. Applications of narrow-band reflecting VBGs to coherent coupling and high spectral density beam combining of high-power lasers are covered in greater detail.

II. VBGs in PTR Glass

PTR glass is an Na_2O–ZnO–Al_2O_3–SiO_2 glass doped with silver, cerium, and fluorine. Permanent refractive index change

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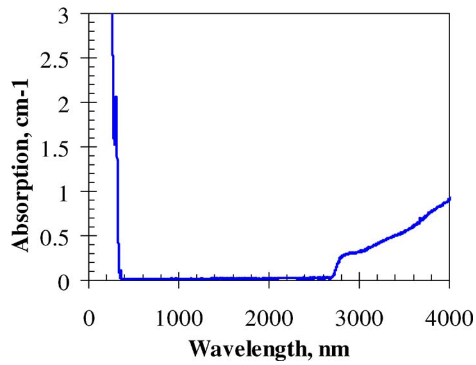

Fig. 1. Absorption spectrum of typical PTR glass.

in PTR glass occurs after exposure to UV radiation followed by thermal development. While being photosensitive in the UV, PTR glass offers high transmittance in the near-IR and visible parts of spectrum (350–2700 nm transparency window, Fig. 1) with absorption in the near-IR region about 10^{-4} cm^{-1}. The history of the study of PTR process and its parameters from the point of view of hologram recording are summarized in surveys [6], [7]. Recent improvements of PTR technology resulted in creation of volume phase holograms (Bragg gratings) with low losses and extremely high diffraction efficiency exceeding 99% [8], [9]. PTR glass has excellent thermomechanical properties with thermal stability of a hologram up to 400 °C, refractive index practically independent of temperature ($dn/dT = 5 \times 10^{-7}$ K^{-1}), coefficient of thermal expansion 8.5×10^{-6} K^{-1}, and thermal conductivity 0.01 W/cm·K. Laser damage threshold of 40 J/cm^2 for 8 ns pulses and tolerance to continuous-wave (CW) laser radiation in the near-IR region at least up to several tens of kilowatts per square centimeter make PTR glass holograms attractive for high-power laser applications.

Volume holographic optical element is an interference pattern recoded in a volume of a photosensitive medium by means of spatial refractive index modulation. Such elements produce transformation of optical beams resulting from diffraction of a propagating wave at a pattern with a modified refractive index. The simplest volume holographic element is a VBG, which is a system of planar layers with a modified refractive index. Depending on diffraction angle and orientation of a grating in the plate, one can distinguish transmitting and reflecting Bragg gratings. Angular selectivity of transmitting VBGs becomes narrower with increase of spatial frequency and thickness of grating. For a grating with thickness of several millimeters recorded in PTR glass [10], variation of the spatial frequency can provide angular selectivity ranging from about 0.1 to several milliradians. Spectral selectivity of transmitting VBGs can vary from several tens of nanometers down to subnanometers range. Reflecting VBGs can have deflection angles from 120° to 180°, angular selectivity from 1 to 100 mrad, and spectral selectivity from 0.01 to 2 nm.

III. Narrowing of Emission Spectra of Lasers With VBGs

The most obvious application of VBGs as dispersive elements in laser resonators for spectral narrowing and stabilization is determined by their narrow spectral selectivity combined with low losses. Lasers that utilize VBGs were named volume Bragg lasers.

A. Narrowing of Semiconductor Diodes, Bars, and Stacks

The use of reflecting Bragg gratings as output couplers in external resonators for semiconductor diodes, bars, and stacks were described in a great number of publications [11]–[14]. It was found that PTR output couplers with thickness from parts to few millimeters provide efficient spectral locking of laser diodes at the level of 60–100 pm. Emission wavelength of such lasers is determined by the resonant wavelength of a VBG and does not depend on diode temperature. Efficiency of a volume Bragg laser diode usually exceeds 95% of efficiency of an original diode at power level of several watts. Locking of diode bars and stacks with total power up to 0.5 kW has been demonstrated with efficiency above 90%. It was found that proper selection of grating parameters allows spectral locking of diodes without collimation. On the other hand, a combination of a fast-axis collimator and a Bragg output coupler in the same piece of glass was successfully demonstrated [15], [16]. A new challenge for spectral narrowing was generated by recent development of diode-pumped alkali lasers [17]. To satisfy requirements for efficient absorption of diode radiation by low-pressure Rb cells, a volume Bragg diode laser was developed using a VBG with thickness exceeding 10 mm. Output power up to 2 W CW with 20 pm linewidth at 780 nm was demonstrated from this laser [18]. Recent extension of this approach to a diode bar has resulted in spectral locking of 30 W of output power within 20 pm with total efficiency more than 90% [19].

B. Narrowing of Solid-State Lasers

The use of PTR Bragg mirrors as output couplers in solid-state lasers was described in publications [20], [21]. It was demonstrated that Bragg mirrors with thickness of several millimeters enable spectral narrowing down to a few picometers with approximately the same power as from a laser with a conventional output coupler. A combination of a thick Bragg mirror and a Fabri–Perot etalon enabled selection of single frequency in different rare-earth-ions-doped lasers [22], [23]. Dramatic impact was produced by PTR Bragg mirrors incorporated in Nd:YLF regenerative amplifiers [24], [25]. Spectral filtering resulted in suppression of background and increase of contrast of amplified pulse by about three orders of magnitude.

C. Narrowing of Fiber Lasers

The use of a VBG as an external output coupler for a fiber laser was recently demonstrated [26]. It was found that a complex resonator produced by a combination of a spectrally-wide chirped fiber Bragg grating (FBG) and an external VBG enables locking of emission spectrum to an arbitrary wavelength within the spectral window of a chirped fiber grating and fine spectral tuning of wavelength by the VBG.

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IV. Reducing Divergence of Lasers With VBGs

It is important to note that VBGs work in angular space. Due to their angular selectivity, VBGs can provide angular filtering of laser beams without the need for additional beam transformation. One of the consequences is that it is possible to produce selection of transverse modes in resonators without collimation or refocusing (conventional spatial filtering) radiation. Experiments with wide-stripe semiconductor lasers [12], [13], [27] have shown that the use of VBGs with angular selectivity comparable to diffraction-limited divergence of an emitter provides amplification of only a single mode. It is important to note that the selected mode can be a mode with arbitrary number. Divergence close to diffraction limit was obtained from laser diodes with stripe width up to 250 μm at a power level of several watts. This approach enables overcoming the basic restriction in laser design, which is a requirement for a single Fresnel zone at an output coupler.

V. Coherent Coupling of Laser Diodes

Increasing the brightness of lasers by coherent coupling of multichannel emitters has been intensely studied for more than 25 years and published in numerous papers (see, e.g., one of the recent surveys [28]). There are two basic approaches for coherent coupling. The first one is to inject coherent radiation to separate lasers and force them to emit coherently [29]–[33]. This approach allows oscillation of all components of the system in the same mode. However, changes of refractive index in gain materials under strong pumping results in phase mismatch between different channels. Therefore, the problem of precise phase measurement and control of all channels is the main challenge in this approach. The second approach is to design a multichannel resonator that provides coherent emission of all of its components [34]–[43]. This approach allows avoiding phase control of channels, but the main problem in preventing stable and efficient coupling is a tendency of a multichannel system to switch between different modes of a complex resonator. A number of dispersive elements have been used to eliminate multimode oscillation but stable coherent coupling at high levels of pumping has not been reported. Recently, narrow-band VBGs have been used to create extremely dispersive external resonators for laser diodes that support only one mode. Further use of the same grating for coupling of multiple diodes has resulted in stable coherent coupling of laser diodes [44], [45].

A. Coherent Coupling of Two Laser Diodes

The experimental setup for coherent coupling and observation of the interference pattern between two semiconductor laser diodes is shown in Fig. 2. Two commercial single-transverse-mode 50-mW laser diodes with standard antireflection coatings ($\sim$5%) emitted collimated beams in the 980 nm range. They were placed on separate stages mounted on the same vibration-isolated optical table [see Fig. 2(a)]. The optical axes of the diodes are about 10 cm above the surface of the table, and the distance between the diodes is about 2 cm. Emission spectra of the diodes consist of several fluctuating lines of about 3.5 nm total spectral width [see Fig. 3(a)]. The laser outputs are combined on a screen by a system of mirrors and a beam splitter [Fig. 2(a)]. Of course, these lasers are not coherent and a combined beam manifests a typical speckle pattern [see Fig. 4(a)].

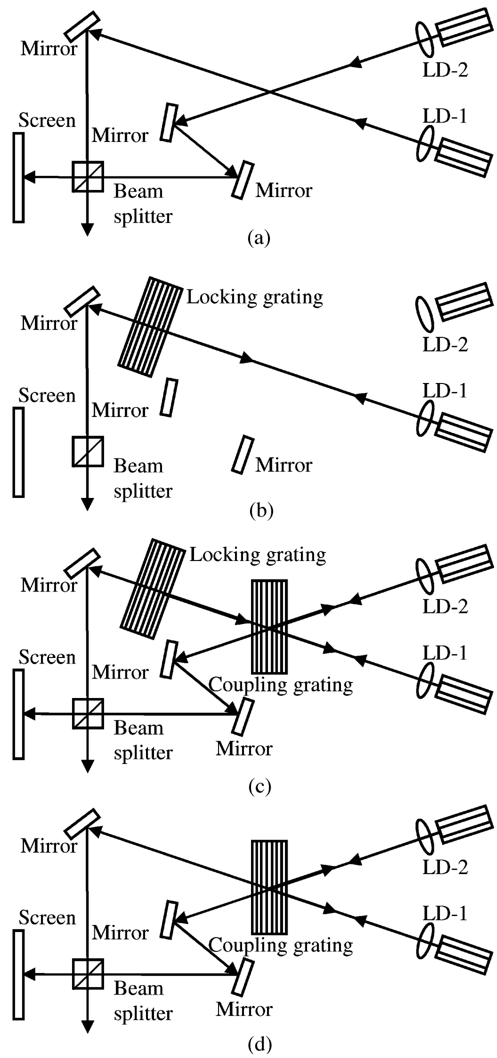

Fig. 2. Optical scheme of coherent coupling of laser diodes. (a) Combining of independent diodes. (b) Spectral locking of LD-1. (c) Spectral locking of LD-1 and phase locking of two diodes. (d) Phase locking of two diodes.

A number of PTR Bragg gratings, each having a spectral selectivity narrower than 100 pm, half-width to the first zero (HWFZ), and reflection coefficient of 98% for plane monochromatic wave were used for this experiment. First, a locking grating, working in a retroreflecting mode at 979.97 nm, was placed in the beam of laser diode LD-1 [Fig. 2(b)] causing spectral narrowing of this laser from several nanometers to less than 30 pm (Fig. 3), which is the spectral resolution of the used optical spectrum analyzer. Second, a coupling grating was placed in the beam of LD-1 at a distance of 7 cm and aligned to provide efficient diffraction of the narrow-band emission at 979.97 nm from LD-1 to LD-2, thereby coupling these two lasers [Fig. 2(c)]. Both lasers emitted the narrow lines separated by less than 150 pm. A combined beam produced by the coupled narrow-band lasers is still a fluctuating speckle pattern similar to that

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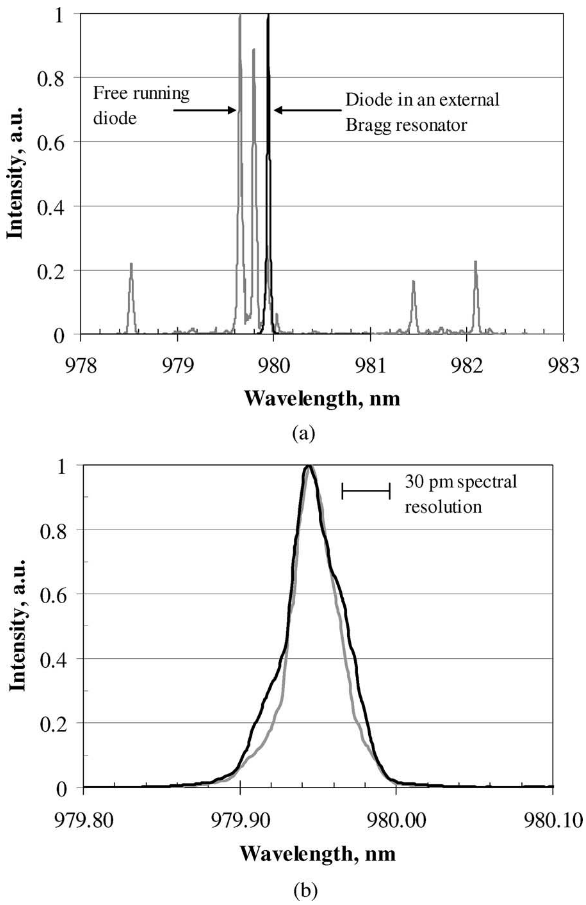

Fig. 3. Emission spectra of laser diodes. (a) Low resolution, light curve—original diode, dark curve—the same diode with a locking grating as an output coupler. (b) High resolution, dark curve—LD-1 locked by a locking grating, light curve—LD-2 locked by a coupling gratings.

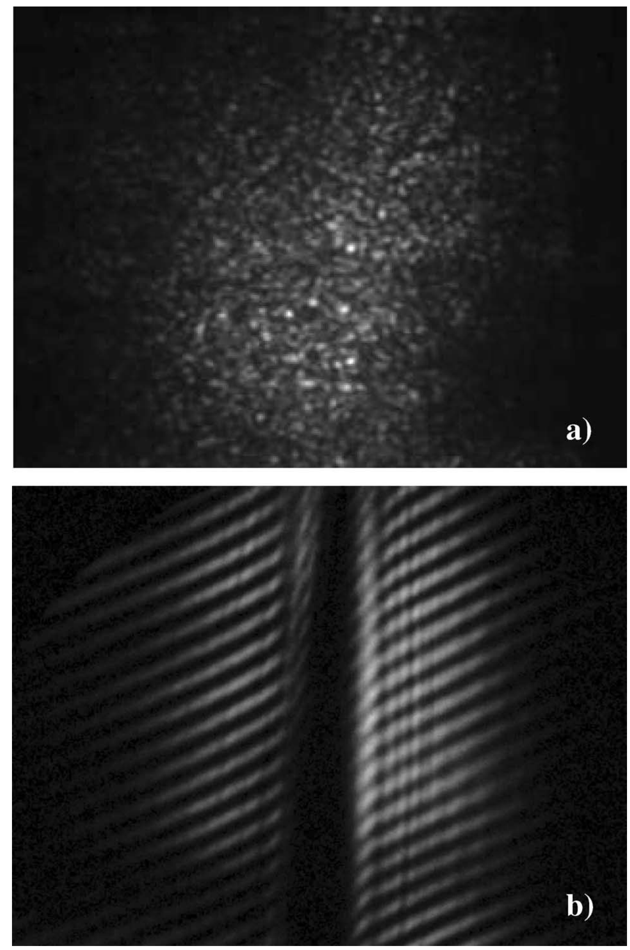

Fig. 4. Interference pattern produced by the beams of two laser diodes. (a) Isolated diodes. (b) Diodes coupled by a narrow-band PTR Bragg grating.

shown in Fig. 4(a) because no phase locking resulted from spectral locking of the laser diodes. After the locking grating was removed from the resonator of LD-1 [Fig. 2(d)], wideband emission of two laser diodes was observed similar to that observed in geometry in Fig. 2(a).

However, it was found that in the case where the spectral width of the coupling grating ($\sim$40 pm HWFZ) was less than the axial mode separation of the internal resonator ($\sim$70 pm) of the laser diodes, tuning of pumping current resulted in locking of the lasers in Fig. 2(c) to the same frequency and phase. In this case, the emission spectrum of both lasers is identical [Fig. 3(b)]. When these two beams were combined, the interference pattern shown in Fig. 4(b) (the dark and light lines at 45°) was produced. After this was done, the locking grating could be removed from resonator [Fig. 2(d)] but spectral width of radiation of both diodes was still below 30 pm and interference pattern was still observed. This interference pattern was stable for a long period, which is remarkable taking into account that the diodes and the coupling grating were mounted on three different stages resulting in the resonator length of 15 cm. It is important to note that coherent coupling was observed at high levels of pumping, above five times the threshold. It was not continuously stable as current was increased from the threshold to the nominal value for fixed temperature of diodes. However, for any fixed current, coherent coupling could be achieved by fine-tuning the temperature of diodes. The total power of the coherent radiation from the coupled lasers was above 80 mW, corresponding to more than 80% of the sum of the powers of the independent lasers.

The black stripe in the middle of the interference pattern in Fig. 4(b) appears for configuration shown in Fig. 2(d) and corresponds to the angle with the highest diffraction efficiency for a coupling grating. Therefore, radiation propagating in this direction was diffracted by the coupling grating to provide coupling between the lasers. Emission at other angles (where the interference pattern can be seen) was not diffracted by the grating, yet the interference pattern shows that the light emitted by the two diode lasers was coherent with stationary locked phases. Thus, this shows that two separated lasers, coupled by a PTR Bragg grating, can behave as a single coherent source of light. This interference pattern has a visibility close to unity. It was stable for hours in continuous operation and this process was the same for more than 11 months of repeatable experiments with the same two devices.

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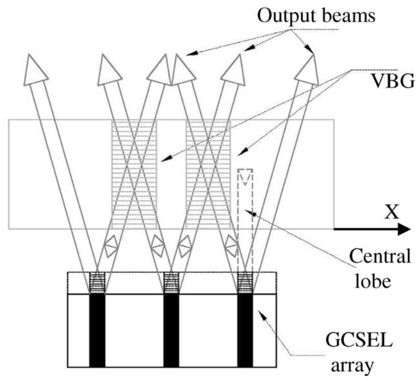

Fig. 5. Three-channel array of GCSELs coupled by a striped reflecting VBG.

B. Phase Locking of Three GCSELs Array by a Spatially Profiled VBG

One of the main effects complicating phase locking of two laser diodes described in the previous section was an oscillation in the internal cavity produced by a rear mirror and residual reflection from the front facet with an antireflection coating. To eliminate this phenomenon, we used grating-coupled surface-emitting lasers (GCSELs) [46] with advanced grating output couplers [47]. A grating with tapered duty cycle and groove depth minimizes backreflection to the active waveguide and provides a symmetric near-field profile [47].

The phase locking between two single-transverse-mode laser diodes was produced by radiation exchange through a reflecting Bragg grating with spectral width narrower than longitudinal mode spacing of the diodes. This result proves feasibility of this new approach to passive phase locking but does not provide a simple architecture scalable to multichannel phased arrays. The new proposed architecture is based on the results of transverse mode selection by VBGs. It was found [14], [27] that thick Bragg gratings in multimode external resonators of laser diodes provide angular selection of transverse modes and lock them to a single-transverse-mode regime. It was possible to select a single high-order transverse mode with main lobes out of the axis of a resonator. Therefore, the basic idea of the approach to coherently couple multiple devices is to lock broad-area laser diodes to a high-order single-transverse-mode regime with out-of-axis main lobes and provide phase locking between them. The proposed geometry of a scalable laser system is shown in Fig. 5. A thick reflecting Bragg grating is placed in front of a GCSEL array in such a manner that radiation of one of the side lobes is diffracted back to the adjacent emitter. To eliminate lasing of low-order modes propagating along the axes of individual emitters, we developed a new design of thick Bragg mirror that has alternating stripes of high- and low-efficiency VBGs. Such grating prevents backreflection of radiation in front of each GCSEL and provides redirection of side lobes to adjacent emitters in accordance with its spectral and angular selectivity.

An array of three broad-area GCSELs with periodicity of 1 mm was used in these experiments. A single emitter included a 1-mm-long active section with 200-μm-wide stripe and a 0.75-mm-long internal grating output coupler. With external optical feedback provided by the striped VBG placed at a distance of 2–4 mm from diodes, lasing in the form of two sets of side lobe beams is observed above threshold current density of 280 A/cm^2. Lasing wavelength of the coupled array is 976 nm and spectral width is less than 70 pm (FWHM). Phase locking of individual emitters in the array is confirmed by the far-field interference of the beams (see Fig. 6). At pumping current up to 1.5 thresholds, visibility of interference pattern close to unity is observed, meaning that all three GCSELs are phase-locked and emitted coherent radiation. At this level of pumping, all lasers that are originally multimode emitted in single transverse mode. At higher pumping, a complex interference pattern of coherent multimode beams was observed. This result enables a new approach to multichannel passive phase locking that can be used to increase the power of coherent emission from semiconductor and other types of lasers.

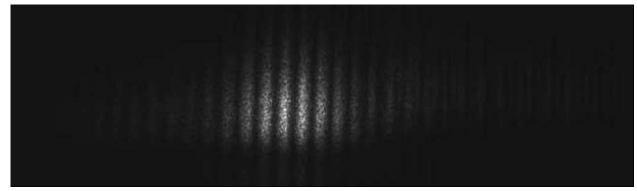

Fig. 6. Far-field emission of a three-channel array.

VI. High-Density SBC

SBC offers an effective solution to scaling output power and brightness of laser systems beyond the limits of coherent coupling. Output beams of an array of lower power laser sources operating at normal conditions are combined by external optical elements, producing a single beam with increased power. Assuming that combining elements have high-energy throughput and introduce no significant beam distortion, energy brightness of the combined beam is increased by a factor equal to the number of combined channels. Power scaling laser systems to multikilowatt level requires high spectral density beam combining in order to combine radiation from a large number of channels within a limited bandwidth. Available bandwidth is typically determined by the gain bandwidth of laser medium and application requirements. For example, consider a laser system operating within a 50-nm low-altitude atmosphere transparency window around 1040 nm. With power per channel of 500 W, such system combining 200 channels with channel separation of 0.25 nm is capable of producing 100-kW-level near-diffraction-limited output.

Initially, SBC was proposed on the basis of conventional surface gratings [48]; however, limited dispersion of surface diffraction gratings complicates system design for narrow spectral separation of channels. More compact and rugged high spectral density beam combining system can be constructed using reflecting VBGs. These gratings can be designed with arbitrary deflection angle for any channel spacing. Significant advantage of reflecting VBGs in comparison with surface diffraction gratings is their polarization insensitivity.

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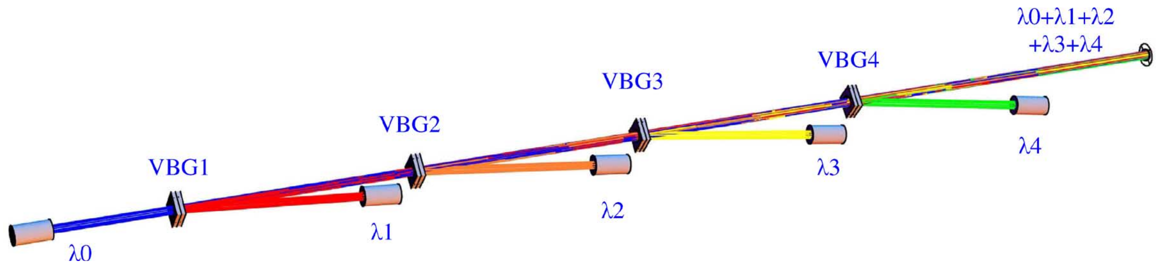

Fig. 7. SBC of five laser sources using a stack of identical reflecting VBGs. VBGs are angle-tuned to diffract beams with corresponding wavelengths, while beams with other wavelengths are transmitted.

SBC by means of VBGs utilizes unique spectral response of VBGs: diffraction efficiency is close to unity when Bragg condition is satisfied and is close to zero at multiple points corresponding to particular wavelength offsets from Bragg condition [49]. Two beams with shifted wavelengths incident on a grating at conjugate angles emerge overlapped and collinear if wavelength of one matches the Bragg condition (the beam is diffracted) and wavelength of the other is offset to match one of the zeros (the beam is transmitted).

SBC with high spectral density of channels can be achieved with narrow-band reflecting VBGs recorded in PTR glass. Five-channel SBC systems with channel spacing 0.4–0.5 nm around 1064 and 1550 nm with absolute efficiency exceeding 92% and near-diffraction-limited output have been recently demonstrated [50], [51]. Stacks of reflecting VBGs are used in these systems (see Fig. 7). Further decrease of spectral separation between channels does not lead to significant deterioration of system efficiency or output beam quality. We have achieved SBC of five beams within 1 nm bandwidth (0.25 nm channel separation) around 1550 nm with 91.7% absolute efficiency. Spectrally combined output beam is near-diffraction-limited ($M^2 = 1.13$).

In a practical multichannel high-power laser system, stack geometry of Fig. 7 can be modified. Design of a novel compact monolithic multichannel beam combiner with multiple VBGs having offset Bragg wavelengths and tilted grating vectors multiplexed in a single element is shown in Fig. 8. A four-channel implementation of such a combiner has been demonstrated with 0.7 nm spectral separation of channels and absolute efficiency exceeding 90%. Such combiner can be used as an elementary cell for a high-power laser system with a large number of channels.

Behavior of narrow-band VBGs in PTR glass under high-power radiation has been studied [50], [52]. It was found that diffraction efficiency and spectral bandwidth of gratings are not changed under laser irradiation with power up to 570 W, and no residual phenomena were revealed in gratings irradiated by laser beam with power density up to 5 kW/cm^2. The main effect of high-power radiation was reversible thermal shift of grating resonance to a longer wavelength caused by absorption of laser radiation in PTR glass. This shift can be accounted during grating manufacturing or compensated during alignment by adjusting source wavelength or angle of incidence.

Following the schematic of Fig. 7, five commercially available randomly polarized Yb-doped fiber lasers with 160 W output power and central wavelengths offset by 0.5 nm are combined into a single near-diffraction-limited beam using narrow-band reflecting VBGs. Four narrow-band reflecting VBGs with clear aperture of 20 mm are used in this experiment. Gratings are designed to provide optimum system efficiency: grating thickness 3.5 mm and refractive index modulation 300 ppm (3×10^{-4}). Period of each grating was selected to match Bragg condition for wavelength of each laser at small angle of incidence (5°–7°). Each grating provides peak efficiency in excess of 99% for a collimated beam at specified wavelength. Spectral selectivity of one of the gratings used in the SBC experiment is shown in Fig. 9, where a collimated Gaussian beam with 6 mm diameter is used for scanning. Small difference between the measured spectral selectivity and theoretical plane wave profile is due to finite beam divergence [53] and nonuniformity of grating vector across the large aperture. With 91.7% absolute combining efficiency, maximum output power of the system is 770 W. No thermal-induced beam distortion is observed at maximum power for a diffracted beam with $M^2 = 1.16$ [26]. Remarkable stability of combining efficiency and output power of the system is observed for many hours of operation as well as for multiple starts over a period of many months, without the need for any additional alignment. For achieved parameters of PTR Bragg gratings, the system can be scaled to multikilowatt power level by increasing channel count and

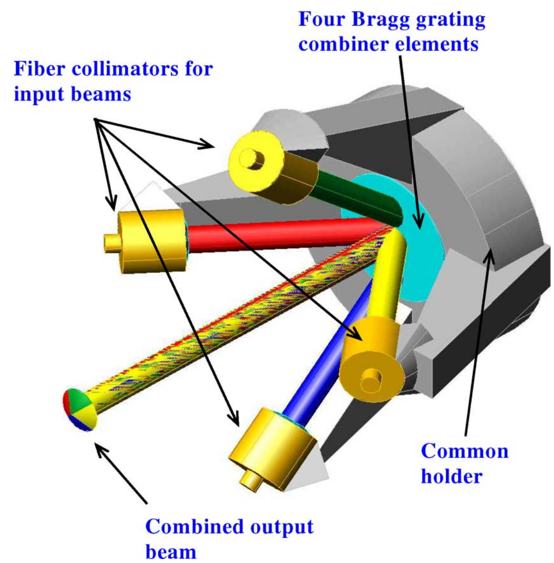

Fig. 8. Compact monolithic four-channel beam combining module based on multiplexed VBGs.

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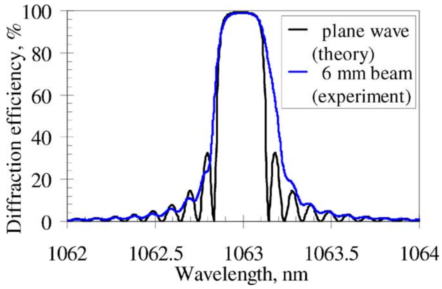

Fig. 9. Spectral dependence of diffraction efficiency of a large-aperture narrow-band VBG used for dense high-power SBC.

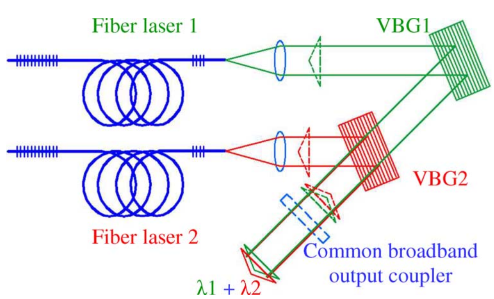

Fig. 10. Common cavity SBC by VBGs with channel wavelengths passively controlled by the same VBGs.

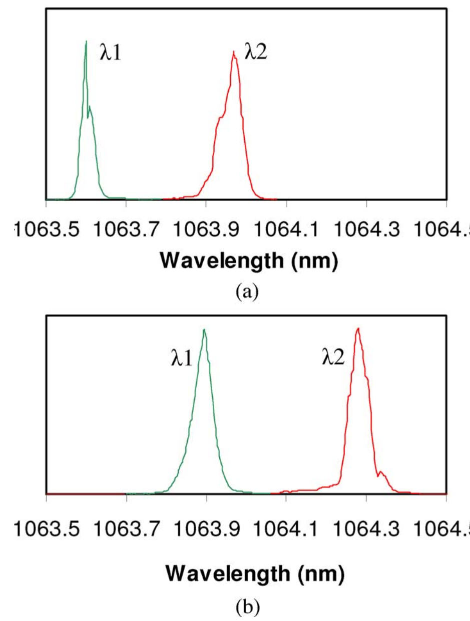

Fig. 11. Thermal shift of resonant wavelengths in a two-channel SBC system as a result of heating the gratings. (a) Room temperature. (b) $T = 60$ °C.

power of each channel with total system efficiency exceeding 80% [54].

VII. SBC With Automatic Wavelength Control

Efficient operation of a high-power SBC system with external VBGs (see Fig. 7) requires that thermal equilibrium is not disturbed during operation. Ambient temperature fluctuations of more than a few degrees or failure of one of the channels require realignment of the system to restore original efficiency. This complication can be avoided if wavelengths of sources can be controlled. Spectral narrowing and control of fiber lasers can be implemented by using narrow-band VBGs in an external cavity configuration. We suggest a novel design of a multichannel self-aligned high-power SBC system. In this approach, a common cavity is created for all channels such that wavelengths of the sources are passively controlled by the combination of a common output coupler and intracavity VBGs, which also act as combining elements. SBC with high efficiency is achieved by matching spectral offset between channels to spectral selectivity of VBGs. In this case, each VBG reflects the beam of a respective channel wavelength while transmitting the beams with offset wavelengths corresponding to the rest of the channels. Such an SBC system retains perfect alignment as power of individual sources is increased. As resonant wavelengths of VBGs are thermally shifted due to absorption of high-power radiation, lasing wavelengths are automatically adjusted to match Bragg condition of VBGs. Automatic adjustment of wavelengths occurs as long as they are within the gain bandwidth of the amplifiers. The concept is illustrated in Fig. 10 for a two-channel beam combiner.

In our experiments, we use diode-pumped Yb-doped photonic crystal fiber with chirped FBGs on both ends. A high-efficiency chirped FBG on one end acts as an end mirror, while a low-efficiency chirped FBG on the other acts as a weak output coupler in order to prevent fiber damage due to self-pulsing during alignment of an external cavity. Stable operation of a two-channel SBC system in a common cavity configuration with automatic wavelength control of sources (see Fig. 10) is achieved with 0.4 nm spectral separation of channels around 1064 nm [55]. Channel wavelengths were initially set to $\lambda_1 = 1063.60$ nm and $\lambda_2 = 1063.97$ nm by angles of VBGs, with spectral separation of channels larger than spectral selectivity of VBGs to provide high efficiency of combining [see Fig. 11(a)]. At 4 A pumping current, the output power was 5.1 W, linewidths of individual channels were less than $\sim$100 pm, and no coherent interaction between channels occurred during oscillation. Radiation of two lasers was combined incoherently into a single near-diffraction-limited output beam.

At current power level of up to 10 W, resonant wavelengths of VBGs are virtually unchanged due to low absorption of PTR glass. In order to imitate behavior of VBGs under the influence of a high-power laser resulting in heating of the grating, we have designed a copper grating holder with four 25-W miniature cartridge heaters. Temperature control was accomplished by a thermistor as a feedback element set into the holder. Heating of both gratings resulted in spectral shift of both channels without significant deterioration of power in the combined output beam. When both gratings were heated to $\sim$60 °C, the SBC system output consisted of two lines shifted to 1063.89 and 1064.28 nm [see Fig. 11(b)], with the initial spectral separation between channels preserved. Performance of the two-channel SBC system was investigated at pumping current up to 6 A. In this case, the output power of the system was more than 10 W and losses

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of the system did not exceed 10% compared to the total power of individual channels. These results were obtained for an SBC system with external output coupler of 20% reflectivity. It was also found that stable operation of such an SBC system requires an output coupler with reflectivity not less than 10%.

This SBC system can be easily scaled by adding more channels and/or increasing power per channel. Performance of such a system does not deteriorate when beam combining VBGs are heated to 60 °C, which is equivalent to heating of VBGs by ∼1 kW of laser radiation around 1064 nm. It is shown that wavelengths of individual sources automatically adjust to satisfy Bragg condition of the heated VBGs. Addition of new channels, failure of channels, and increase of power per channel will have no effect on system efficiency. Moreover, a common cavity SBC system can be operated in a wide range of ambient temperatures without realignment.

VIII. Architecture of High-Brightness Laser System

Presented experimental results and modeling of systems with higher channel count allow proposing the following architecture of a high-brightness laser system. First, a large-aperture gain medium (wide-stripe diode, large core diameter fiber, or large-aperture solid-state element) is placed in an external resonator that includes PTR Bragg gratings with angular selectivity narrow enough to provide single-transverse-mode oscillation at high pumping levels. Second, a number of single-transverse-mode lasers are coupled in a phase-locked array by PTR Bragg gratings with spectral selectivity narrow enough to prevent hopping between longitudinal modes. Third, a number of phase-locked arrays emitting narrow spectral lines with shifted wavelengths are spectrally combined by a stack of PTR Bragg gratings.

One of the possible versions of a phase-locked array of semiconductor lasers is shown in Fig. 12. A bar of wide-stripe laser diodes emits single-transverse-mode radiation along the fast axis that is collimated by a cylindrical lens. After the collimator, each diode emits a multimode beam with high divergence in the slow-axis direction. Such beams have a far-field distribution with two out-of-axis main lobes with total divergence of about 10°. A locking grating placed after the fast-axis collimator provides partial diffraction of the beam in the vicinity of the main lobe maximum to the adjacent emitter. The next grating is designed in such a manner that it can select one of the transverse modes in the vicinity of the main lobes in angular distribution. The third grating, which is a PTR Bragg mirror, provides feedback only at very narrow spectral band, thus preventing mode hopping in the resonator. Such device emits coherent beam with very narrow spectral width and divergence close to the diffraction limit.

The last stage of the system is an SBC, which is a stack of multiplexed Bragg gratings, similar to the one from Fig. 8. This compact element deflects beams from several channels in the same direction without deteriorating the original beam quality. It is important to note that this beam combiner is transparent for all wavelengths outside of its resonant values. A stack of PTR beam combiners with shifted resonant wavelengths (see Fig. 13) provides further scaling to a desirable number of channels.

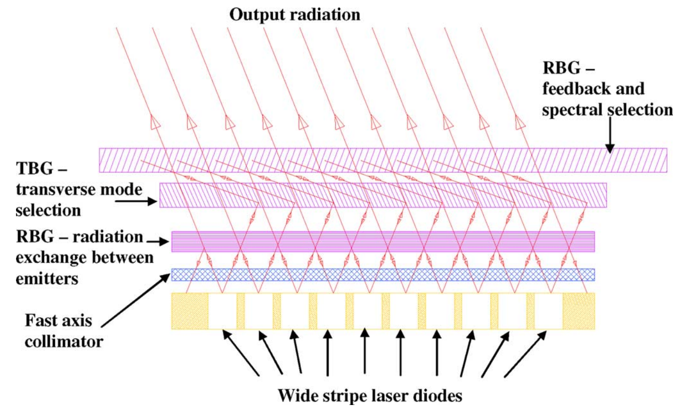

Fig. 12. Phase-locked array of laser diodes.

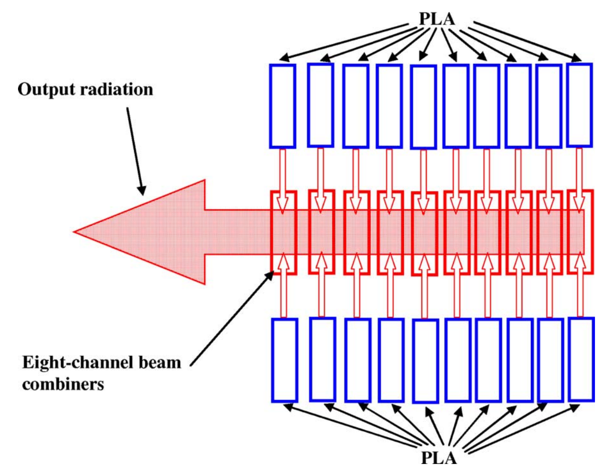

Fig. 13. Stack of PTR beam combiners.

IX. Conclusion

VBGs in PTR glass can be used for extremely narrow spectral and angular selection of high-power laser beams. These gratings are utilized for locking of large-aperture solid-state and semiconductor lasers to a single-transverse-mode operation without deterioration of efficiency, coherent coupling of multiple emitters, and SBC with high spectral density of channels. Coherent radiation from two- and three-channel arrays of semiconductor lasers is achieved by providing radiation exchange between emitters by means of VBGs with spectral width narrower than distance between adjacent longitudinal modes. Stacks of reflecting gratings are used for spectral combination of high-power laser beams with offset wavelengths. SBC with spectral density up to five channels per nanometer, efficiency exceeding 90%, and output power up to a kilowatt level has been demonstrated without deterioration of beam quality or thermal lensing. Architecture of high-power multichannel laser systems, which includes both coherent coupling and SBC by means of VBGs, is proposed.

References

[1] P. Crump, W. Dong, M. Grimshaw, J. Wang, S. Peterson, D. Wise, M. DeFranza, S. Elim, S. Zang, M. Bougher, J. Peterson, S. Das, J. Bell,

Authorized licensed use limited to: University of Central Florida. Downloaded on April 27, 2009 at 03:40 from IEEE Xplore. Restrictions apply.

J. Farmer, M. DeVito, and R. Martinsen, "100-W+ diode laser bars show >71% power conversion from 790-nm to 1000-nm and have clear route to >85%," *Proc. SPIE*, vol. 6456, pp. 645660M-1–645660M-11, 2007.

[2] M. Peters, V. Rossin, M. Everett, and E. Zucker, "High-power, high-efficiency laser diodes at JDSU," *Proc. SPIE*, vol. 6456, pp. 64560G-1–64560G-11, 2007.

[3] M. Kanskar, T. Earles, T. J. Goodnough, E. Stiers, D. Botez, and L. J. Mawst, "73% CW power conversion efficiency at 50 W from 970 nm diode laser bars," *Electron. Lett.*, vol. 41, pp. 245–247, 2005.

[4] C. Martin Stickley, M. E. Filipkowski, E. Parra, and M. Sandrock, "High power laser diodes and applications to direct diode HELs," in *Proc. Lasers Electro-Opt. Soc., LEOS 2006 19th Annu. Meet. IEEE*, pp. 468–469.

[5] L. B. Glebov, V. I. Smirnov, C. M. Stickley, and I. V. Ciapurin, "New approach to robust optics for HEL systems," in *Laser Weapons Technology III*, W. E. Tompson and P. H. Merritt, Eds., *Proc. SPIE*, vol. 4724, pp. 101–109, 2002

[6] L. B. Glebov, "Photosensitive glass for phase hologram recording," *Glass Sci. Technol.*, vol. 71 C, pp. 85–90, 1998.

[7] L. B. Glebov, "Volume hologram recording in inorganic glasses," *Glass Sci. Technol.*, vol. 75 C, no. 1, pp. 73–90, 2002.

[8] O. M. Efimov, L. B. Glebov, V. I. Smirnov, and L. N. Glebova, "Process for production of high efficiency volume diffractive elements in photo-thermo-refractive glass,", U.S. Patent 6 586 141, 2003.

[9] O. M. Efimov, L. B. Glebov, and V. I. Smirnov, "High efficiency volume diffractive elements in photo-thermo-refractive glass,", U.S. Patent 6 673 497, 2004.

[10] L. Glebov, "Fluorinated silicate glass for conventional and holographic optical elements," in *Window and Dome Technologies and Materials X*, R. W. Tustison, Ed., *Proc. SPIE*, vol. 6545, pp. 654507, 2007.

[11] B. L. Volodin, S. V. Dolgy, E. D. Melnik, E. Downs, J. Shaw, and V. S. Ban, "Wavelength stabilization and spectrum narrowing of high-power multimode laser diodes and arrays by use of volume Bragg gratings," *Opt. Lett.*, vol. 29, pp. 1891–1893, 2004.

[12] G. Venus, V. Smirnov, L. Glebov, and M. Kanskar, "Spectral stabilization of laser diodes by external Bragg resonator," presented at the Solid State Diode Lasers Technol. Rev., 2004, Albuquerque, NM.

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

[14] L. B. Glebov, "High brightness laser design based on volume Bragg gratings," *Proc. SPIE*, vol. 6216, pp. 621601-1–621601-11, 2006.

[15] C. Schnitzler, S. Hambuecker, O. Ruebenach, V. Sinhoff, G. Steckman, L. West, C. Wessling, and D. Hoffmann, "Wavelength stabilization of HPDL array: Fast-axis collimation optic with integrated VHG," *Proc. SPIE*, vol. 6456, pp. 645612-1–645612-7, 2007.

[16] L. B. Glebov, "Spectral stabilization of diode bar by volume Bragg grating incorporated in fast axis collimator," in *Proc. Solid State Diode Lasers Technol. Rev.*, Diode1–1, 2007.

[17] W. F. Krupke, R. J. Beach, V. K. Kanz, and S. A. Payne, "Resonance transition 795-nm rubidium laser," *Opt. Lett.*, vol. 28, pp. 2336–2238, 2003.

[18] A. Gourevitch, G. Venus, V. Smirnov, and L. Glebov, "Efficient pumping of Rb vapor by high-power volume Bragg diode laser," *Opt. Lett.*, vol. 32, pp. 2611–2613, 2007.

[19] A. Gourevitch, G. Venus, V. Smirnov, D. A. Hostutler, and L. Glebov, "Continuous wave, 30 W laser-diode bar with 10 GHz linewidth for Rb laser pumping," *Opt. Lett.*, vol. 33, pp. 702–704, 2008.

[20] T. Chung, A. Rapaport, V. Smirnov, L. Glebov, M. Richardson, and M. Bass, "Solid-state laser spectral narrowing using a volumetric photothermal refractive Bragg grating cavity mirror," *Opt. Lett.*, vol. 31, pp. 229–231, 2006.

[21] T. Chung, A. Rapaport, Y. Chen, V. Smirnov, M. Hemmer, L. B. Glebov, M. C. Richardson, and M. Bass, "Spectral narrowing of solid state lasers by narrow-band PTR Bragg mirrors," *Proc. SPIE*, vol. 6216, pp. 621603-1–621603-10, 2006.

[22] B. Jacobsson, V. Pasiskevicius, and F. Laurell, "Tunable single-longitudinal-mode ErYb: Glass laser locked by a bulk glass Bragg grating," *Opt. Lett.*, vol. 31, pp. 1663–1665, 2006.

[23] B. Jacobsson, V. Pasiskevicius, and F. Laurell, "Single-longitudinal-mode Nd-laser with a Bragg-grating Fabry–Perot cavity," *Opt. Exp.*, vol. 14, pp. 9284–9292, 2006.

[24] A. V. Okishev, C. Dorrer, V. I. Smirnov, L. B. Glebov, and J. D. Zuegel, "Spectral filtering in a diode-pumped Nd:YLF regenerative amplifier using a volume Bragg grating," *Opt. Exp.*, vol. 15, pp. 8197–8202, 2007.

[25] C. Dorrer, A. V. Okishev, I. A. Begishev, J. D. Zuegel, V. I. Smirnov, and L. B. Glebov, "Optical parametric chirped-pulse-amplification contrast enhancement by regenerative pump spectral filtering," *Opt. Lett.*, vol. 32, pp. 2378–2380, 2007.

[26] O. Andrusyak, I. Ciapurin, V. Smirnov, G. Venus, N. Vorobiev, and L. Glebov, "External and common-cavity high spectral density beam combining of high power fiber lasers," *Proc. SPIE*, vol. 6873, pp. 687314-1–687314-9, 2008.

[27] G. Venus, L. Glebov, V. Rotar, V. Smirnov, P. Crump, and J. Farmer, "Volume Bragg semiconductor lasers with near diffraction limited divergence," *Proc. SPIE*, vol. 6216, pp. 621602-1–621602-7, 2006.

[28] A. F. Glova, "Phase locking of optically coupled lasers," *Quantum Electron.*, vol. 33, pp. 283–306, 2003.

[29] J. P. Hohimer, A. Owyoung, and G. R. Hadley, "Single-channel injection locking of a diode-laser array with a CW dye laser," *Appl. Phys. Lett*, vol. 47, pp. 1244–1246, 1985.

[30] J. Mercier and M. McCall, "Stability and dynamics of an injection-locked semiconductor laser array," *Opt. Commun.*, vol. 138, pp. 200–210, 1997.

[31] A. P. Napartovich and D. V. Vysotsky, "The theory of radiation injection into a diode laser array," *Opt. Commun.*, vol. 141, pp. 91–98, 1997.

[32] L. Bartelt-Berger, U. Brauch, A. Giesen, H. Huegel, and H. Opower, "Power-scalable system of phase-locked single-mode diode lasers," *Appl. Opt.*, vol. 38, pp. 5752–5760, 1999.

[33] Y. Liu and Y. Braiman, "Synchronization of high-power broad-area semiconductor lasers," *IEEE J. Sel. Topics Quantum Electron.*, vol. 10, no. 5, pp. 1013–1024, Sep./Oct. 2004.

[34] C. J. Chang-Hasnain, J. Berger, D. R. Scifres, W. Streifer, J. R. Whinnery, and A. Dienes, "High power with high efficiency in a narrow single-lobed beam from a diode laser array in an external cavity," *Appl. Phys. Lett.*, vol. 50, pp. 1465–1467, 1987.

[35] J. R. Leger, G. Mowry, and D. Chen, "Modal analysis of a Talbot cavity," *Appl. Phys. Lett.*, vol. 64, pp. 2937–2939, 1994.

[36] S. Y. Kourtchatov, V. V. Likhanskii, A. P. Napartovich, F. T. Arecchi, and A. Lapucci, "Theory of phase locking of globally coupled laser arrays," *Phys. Rev. A*, vol. 52, pp. 4089–4094, 1995.

[37] J. R. Leger, G. Mowry, and L. Xu, "Modal properties of an external diode-laser-array cavity with diffractive mode-selecting mirrors," *Appl. Opt.*, vol. 34, pp. 4302–4311, 1995.

[38] G. L. Schuster and J. R. Andrews, "Coherent beam combining: Optical loss effects on power scaling," *Appl. Opt.*, vol. 34, pp. 6801–6805, 1995.

[39] V. V. Apollonov, S. I. Derzhavin, V. V. Kuzminov, D. A. Mashkovskii, A. M. Prokhorov, V. N. Timoshkin, and V. A. Filonenko, "Phase-locking of a linear array of high-power laser diodes," *Quantum Electron.*, vol. 29, pp. 839–841, 1999.

[40] E. K. Gorton and R.M. Jenkins, "Theory of 1-N-way phase-locked resonators with perturbations in the array elements," *Appl. Opt.*, vol. 40, pp. 6663–6669, 2001.

[41] D. Sabourdy, V. Kermene, A. Desfarges-Berthelemot, M. Vampouille, and A. Barthelemy, "Coherent combining of two Nd:YAG lasers in a Vernier–Michelson-type cavity," *Appl. Phys. B*, vol. 75, pp. 503–507, 2002.

[42] S. Riyopoulos, "Coherent phase locking, collective oscillations, and stability in coupled vertical-cavity-surface emitting laser arrays," *Phys. Rev. A*, vol. 66, pp. 53820-1–53820-17, 2002.

[43] D. Sabourdy, V. Kermène, A. Desfarges-Berthelemot, L. Lefort, A. Barthélémy, P. Even, and D. Pureur, "Efficient coherent combining of widely tunable fiber lasers," *Opt. Exp.*, vol. 11, pp. 87–97, 2003.

[44] G. B. Venus, A. Sevian, V. I. Smirnov, and L. B. Glebov, "Stable coherent coupling of laser diodes by a volume Bragg grating in photo-thermo-refractive glass," *Opt. Lett.*, vol. 31, pp. 1453–1455, 2006.

[45] G. Venus, V. Rotar, V. Smirnov, O. Smolski, V. Smolski, E. Johnson, and L. Glebov, "Phase locking of the surface emitting laser diode array by a spatially profiled volume Bragg grating," *Opt. Lett.*, to be published.

[46] J. Jiang, O. Smolski, C. Roychoudhuri, E. Portnoi, G. Venus, I. Gadjiev, and J. McKillop, "Broad tunability of grating coupled surface emitting laser with external cavity," *Electron. Lett*, vol. 35, pp. 1847–1848, 1999.

[47] L. Vaissié, O. Smolski, A. Mehta, and E. Johnson, "High efficiency surface-emitting laser with subwavelength antireflection structure," *IEEE Photon. Technol. Lett.*, vol. 17, no. 4, pp. 732–734, Apr. 2005.

[48] S. Augst, A. Goyal, R. Aggarwal, T.-Y. Fan, and A. Sanchez, "Wavelength beam combining of ytterbium fiber lasers," *Opt. Lett.*, vol. 28, pp. 331–333, 2003.

[49] H. Kogelnik, "Coupled wave theory for thick hologram gratings," *Bell Syst. Tech. J.*, vol. 48, pp. 2909–2945, 1969.

[50] O. Andrusyak, I. Ciapurin, V. Smirnov, G. Venus, and L. Glebov, "Spectral beam combining of fiber lasers with increased channel density," in *Fiber Lasers IV: Technology, Systems, and Applications*, D. J. Harter,

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A. Tünnermann, J. Broeng, and C. Headley III, Eds., *Proc. SPIE*, vol. 6453, pp. 64531L-1–64531L-7, 2007.

[51] O. Andrusyak, V. Rotar, A. Sevian, V. Smirnov, G. Venus, and L. Glebov, “Spectral beam combining by stack of volume Bragg grating in PTR glass,” in *SSDLTR-2007 Tech. Dig.*, 2009, Paper BC2–2, 2007.

[52] O. Andrusyak, V. Smirnov, G. Venus, and L. Glebov, “Narrow-band volume Bragg gratings in PTR glass under high-power CW laser radiation,” in *SSDLTR-2007 Tech. Dig.*, Paper P-1, 2007.

[53] I. Ciapurin, L. Glebov, and V. Smirnov, “Modeling of Gaussian beam diffraction on volume Bragg gratings in PTR glass,” in *Practical Holography XIX: Materials and Applications*, T. H. Jeong and H. Bjelkhagen, Eds., *Proc. SPIE*, vol. 5742, pp. 183–194, 2005.

[54] A. Sevian, O. Andrusyak, I. Ciapurin, V. Smirnov, G. Venus, and L. Glebov, “Efficient power scaling of laser radiation by spectral beam combining,” *Opt. Lett.*, vol. 33, pp. 384–386, 2008.

[55] N. Vorobiev, O. Andrusyak, V. Smirnov, G. Venus, and L. Glebov, “Spectral beam combining of fiber lasers with automatic wavelength control,” in *SSDLTR-2008 Tech. Dig.*, Poster Session, 2008

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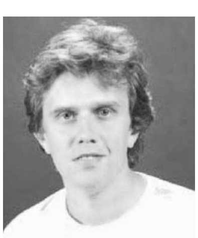

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