Invited Paper

High brightness laser design based on volume Bragg gratings

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ABSTRACT

This paper is a survey of recent achievements at the College of Optics and Photonics/CREOL at the University of Central Florida in the use of newly developed diffractive optical elements which are volume Bragg gratings recorded in a photo-thermo-refractive (PTR) glass. Three levels of semiconductor laser design are proposed to achieve high-power low-divergence output. The first level is the change of a mechanism of transverse mode selection from spatial selection by apertures to angular selection by PTR Bragg gratings. This approach allows increasing of aperture without increasing of length and selecting of arbitrary mode but not only a fundamental one. The second level is coherent coupling of emitters by means of PTR Bragg gratings which provide excitation of the only one common mode in a multichannel resonator. This type of phase locking automatically leads to a narrow spectral width of emission usually not exceeding a few tens of picometers. The third level is spectral beam combining by a stack of PTR Bragg gratings which re-direct radiation from several phase coupled arrays to the same direction within diffraction limited divergence. This approach allows simplifying of thermal management because the only passive device with low absorption (a PTR beam combiner) is placed in a high power laser beam.

Keywords: photo-thermo-refractive glass, volume Bragg gratings, high energy lasers

1. INTRODUCTION

Military applications of high energy lasers (HELs) require delivery of significant power to a remote target. This requirement implies that such devices can be mounted on some portable platform and emit radiation with divergence close to a diffraction limit. A number of HELs are demonstrated but no one of them satisfies both requirements mentioned above. It is important to note that most critical parameter of a high power laser system which determines its ability to provide both low divergence and portability is efficiency. It is easy to estimate power consumption for emitting of 100 kW by means of solid state laser. Let us assume 25% efficiency for a solid state laser, 45% efficiency for pumping laser diodes, and 95% for power supply. Total consumed power would be 935 kW with 835 kW generated heat. It is a serious problem to dissipate such amount of heat in a portable system and it is a serious problem to provide low divergence in an optical system with such heat loading.

It is necessary to increase efficiency of a system dramatically to eliminate the problems mentioned above. There is an attractive approach to decrease heat generation in laser system by eliminating the least efficient element in a laser system, which is a solid state laser. At the Photonics West Conference in January 2006 a number of manufacturers participating in DARPA funded SHEDS program demonstrated efficiency of laser diodes exceeding 70%. Estimation for such emitter shows that for emission of 100 kW, total power consumption would be 150 kW while only 50 kW of heat would be generated. This system definitely can be portable. However, high divergence of high-power laser diode systems prevents their use in applications which require power delivery to a remote target.

We propose three basic levels of integration of a high power laser system where the last stage is a multichannel beam combiner which collect radiation from a number of coherent emitters with shifted wavelengths. Each coherent emitter is a phase locked array of high-efficiency spectrally stabilized single-transverse-mode laser diodes. All main components (spectral beam combiner, phase locked array, and single-mode diode) are designed with the use of volume Bragg gratings recorded in a photo-thermo-refractive (PTR) glass[1].

This technology of high-efficiency volume diffractive optical elements is developed at the University of Central Florida/CREOL[2, 3] and is based on a permanent refractive index change in a special multicomponent silicate glass after

Laser Source and System Technology for Defense and Security II, edited by Gary L. Wood, Mark A. Dubinskii,
Proc. of SPIE Vol. 6216, 621601, (2006) · 0277-786X/06/$15 · doi: 10.1117/12.667196

exposure to UV radiation followed by a thermal development. This PTR glass enables fabrication of phase volume diffractive gratings with absolute diffraction efficiency exceeding 95%, thermal stability of 400°C, laser damage threshold of 40 J/cm^2 for 8 ns pulses, and tolerance to CW laser radiation in the near IR region at least up to several tens of kilowatts per square centimeter. Such Bragg gratings provide narrow spectral selectivity down to 50 pm and narrow angular selectivity down to 100 μrad. These elements have low losses and can be used for high power laser systems design in both intracavity applications and passive elements for laser beam control, e.g. spectral beam combining.

It is important that dispersive properties of volume Bragg gratings are significantly differ from those of conventional elements providing spectral and angular selection in optical systems (Fig.1). If a convention dispersive element, which is a prism or a diffractive grating, is illuminated at the same incident angle by radiation with different wavelengths, refracted or diffracted beams with different wavelengths propagate at different exit angles. Spectral resolution power ($\lambda/\Delta\lambda$) can reach several thousands and angular dispersion can reach several degrees per nanometer. If incident angle is changed, exit angles are changed too demonstrating approximately the same dispersion (compare upper and lower groups of beams in the left part of Fig. 1). Behavior of volume Bragg grating is dramatically different. For almost all incident angles this optical element is simply plane-parallel glass plate. At some incident angle, which is usually called as a Bragg angle, the beam having resonant wavelength is deflected to some angle which can be changed up to 180˚while all other beams do not change direction of propagation. At some other incident angle another beam could be deflected (compare upper and lower groups of beams in the right part of Fig. 1). Spectral resolution power for PTR volume Bragg gratings is demonstrated up to 20,000 while “angular dispersion” for fixed wavelengths can reach several thousands degrees per nanometer.

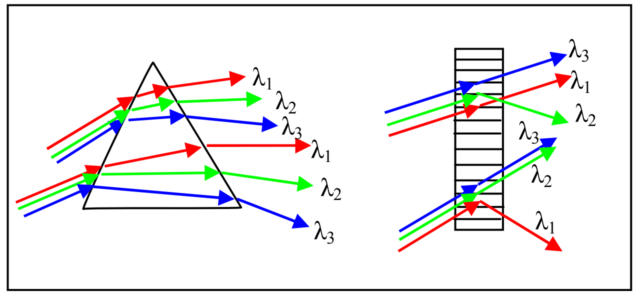

Fig. 1. Comparison of spectral and angular selectivity of a prism and a volume Bragg grating.

These unique properties of volume Bragg gratings recorded in PTR glass are used for high brightness semiconductor laser design described in the paper which summarizes a number of publications by a research group which currently includes Oleksiy Andrusyak, Igor Ciapurin, Larissa Glebova, Julien Lumeau, Vasile Rotar, Eugeniu Rotari, Armen Sevian, Vadim Smirnov, and George Venus.

2. PHOTO-THERMO-REFRACTIVE GLASS

One of the hot practical problems of modern optoelectronics (photonics) is fine spectral, angular and spatial filtering. Theoretically, the most efficient solution of the problem can be achieved by the use of thick volume holographic gratings (Bragg gratings). After several decades of intense work, such diffractive elements may be found in several laboratories. However, they are not widely present on the market. We believe that the main cause restricted the wide use of holographic optical elements for a long time was the absence of the appropriate photosensitive material for volume hologram recording.

Known photosensitive materials for volume hologram recording include: silver halide photographic emulsions, dichromated gelatin, photoresists, photopolymers, photothermoplastics, polymers with spectral hole-burning, chalcogenide glasses, oxide glasses doped with variable valence rare-earth elements, porous glasses doped with photopolymers, germanium doped silica, and photorefractive crystals[4]. Each of these materials has its own merits, combined with considerable drawbacks. In particular, organic materials (photographic emulsions, dichromated gelatin, and photopolymers) have high sensitivity due to multistep process including chemical development. However, they shrink in the development process and are sensitive to humidity. Spectral hole burning does not provide high diffraction efficiency. Photo-thermoplastics have low spatial resolution and low thickness. Porous glasses have high level of scattering and low optical quality. Germanium doped silica has extremely low sensitivity; corresponding gratings are realized in fiber configuration only. Photo-refractive crystals have low tolerance to elevated temperatures and are photosensitive after recording. None of the mentioned materials has tolerance to laser radiation comparable with the main materials for optical design – dielectric glasses and crystals.

Photo-thermo-refractive (PTR) glass is a relatively new photosensitive material for phase hologram recording. It combines high sensitivity achieved due to two-step process and high optical quality resulting from rich experience accumulated in optical glass technology. PTR glass is a Na_2O-ZnO-Al_2O_3-SiO_2 glass doped with silver (Ag), cerium (Ce), and fluorine (F). It is transparent from 350 nm to 2500 nm. The chain of processes, which occurs in these glasses and produces refractive index variation, is as follows[5]. The first step is the exposure of the glass sample to UV radiation, somewhere in the range from 280 nm to 350 nm (gray arrow in Fig. 2). This exposure results in photo-reduction of silver ions Ag^+ to atomic state Ag^0. This stage is similar to formation of a latent image in a conventional photo film; while no significant changes in optical properties of PTR glass occur here. A number of commercially available lasers with long length of coherence can be used for such exposure. The further processing is secured by a thermal development. A number of silver containing clusters arise in exposed regions of glass after aging at elevated temperatures, apparently due to increased mobility of Ag^0 atoms. These silver containing clusters serve as the nucleation centers for NaF crystal growth. Interaction of those nanocrystals with the surrounding glass matrix causes the decrease of refractive index. Refractive index change Δn about 10^{-3} (1000 ppm) can be achieved (Fig. 3). Dependence of refractive index decrement on exposure is a hyperbolic function but not an exponential one[6]. Such Δn enables high efficiency hologram recording in PTR glass wafers with thickness exceeding several hundreds of microns.

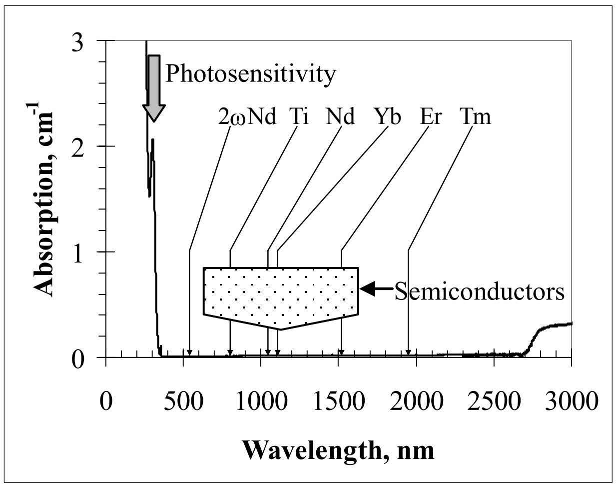

Fig. 2. Absorption spectrum of PTR glass and spectral lines of main laser sources in the window of transparency. Gray arrow shows the region of photosensitivity.

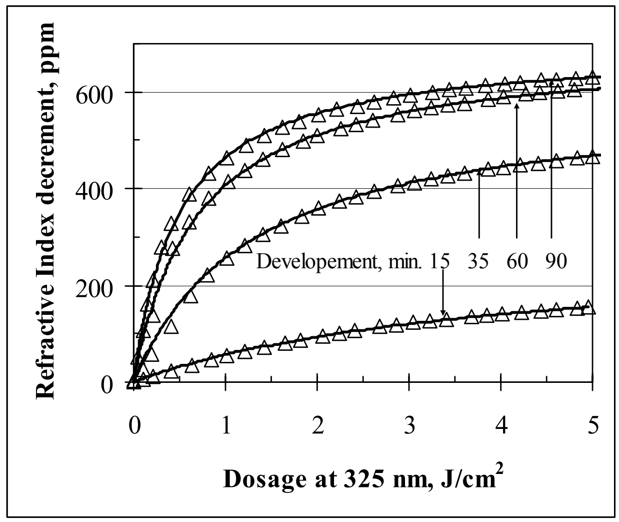

Fig. 3. Dependence of refractive index decrement in PTR glass on exposure at 325 nm after thermal development at 520°C for 2 hours. Solid lines – modeling by hyperbolic functions.

Refractive index modulation resulted from microcrystalline phase precipitation in glass matrix has two important consequences. The first one is negative. Two-phase system usually shows scattering of optical radiation resulted from difference between refractive indices of vitreous and crystalline phases. However, one can see in Fig. 2 that losses in the near IR region are in the range of 10^{-2} cm^{-1}. It was found that induced absorption is in the range of 10^{-3} cm^{-1} while the main contribution to losses is produced by scattering. This level of scattering is low enough to enable the use of such optical elements to laser resonators. The level of induced scattering is not a basic property of PTR glass but strongly depends on conditions of glass technology and processing.

The second consequence of crystalline phase precipitation in PTR glass is extremely positive. There is no way to destroy crystalline particles of NaF in glass matrix by any type of radiation. This is why PTR holograms are stable under exposure to IR, visible, UV, X-ray, and gamma-ray irradiation. Laser damage threshold is in the range of 40 J/cm^2 for 8 ns laser pulses at 1064 nm (Fig. 4)[7]. Nonlinear refractive index in PTR glass is the same as that for fused silica[8] which allows the use of PTR diffractive elements in all types of pulsed lasers. Testing of PTR diffractive grating under irradiation of 4 kW Yb-fiber laser focused to a 4-mm-diameter spot (IPG Photonics, Inc.) showed its stability while heating did not exceed 15 K (Fig. 5). It should be noted that brittle fracturing of the grating at 2 kW was caused by a surface defect but not the internal glass properties. Thermal variations of refractive index in PTR glass are very low

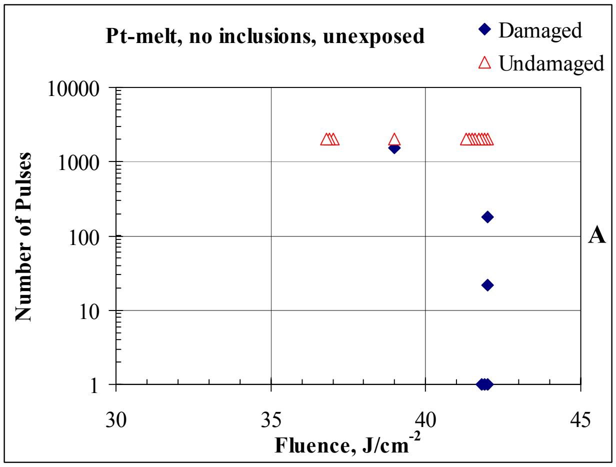

Fig. 4. Laser-induced breakdown thresholds for 1064 nm 8 ns pulses N-on-1 at fixed energy.

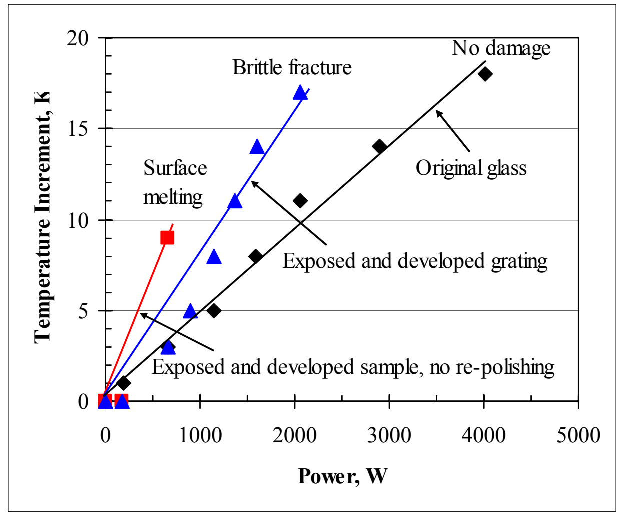

Fig. 5. Heating and damaging of PTR glass and volume Bragg gratings by Yb-doped fiber laser at 1085 nm. Beam diameter 4 mm. Testing was produced at IPG Photonics.

(dn/dt=5×10^{-8} 1/K). This feature leads to thermal shift of Bragg wavelength in PTR diffractive gratings of 7 pm/K. Melting temperature of NaF crystals is almost 1000°C. This is why PTR holograms are stable at elevated temperatures. These diffractive elements tolerate thermal cycling up to 400°C. This temperature is determined by plasticity of silicate glass matrix.

3. VOLUME BRAGG GRATINGS

Volume holographic optical element is an interference pattern recoded in a volume of a photosensitive medium by means of refractive index modulation. Such elements produce transformation of optical beams resulted from diffraction of a propagating wave at a pattern with a modified refractive index. The simplest volume holographic element is a volume Bragg grating 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 several types of Bragg gratings (Fig. 6). A grating is called a transmitting Bragg grating if diffracted beam crosses the back surface, reflecting - if diffracted beam crosses the front surface, and prismatic - if diffracted beam crosses one of the side surfaces.

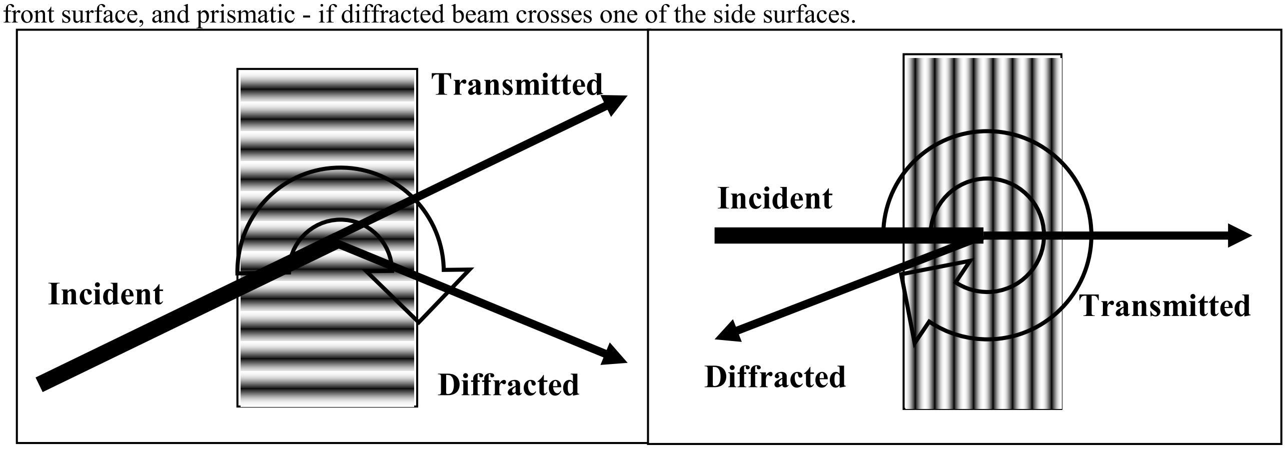

Fig. 6. Transmitting (left) and reflective (right) volume Bragg gratings in PTR glass. Hologram occupies the whole volume the glass plate.

Bragg gratings in PTR glass were recorded by an exposure to the interference pattern of radiation of a He-Cd laser operating at 325 nm with average power of 35 mW. Spatial frequency of gratings was varied from 50 mm^{-1} up to about

10,000 mm^{-1}. Volume gratings in both transmitting and reflecting mode were recorded with thickness ranged from 0.5 mm to 25 mm. Maximum aperture of grating was up to 35 mm×35 mm. Maximum diffraction efficiency of PTR Bragg gratings exceeded 99 %.

Detailed mathematical modeling of transmitting PTR Bragg gratings is presented in Ref. [9]. Angular selectivity becomes narrower with increasing of spatial frequency and thickness of grating. It is important to note that angular selectivity below 1 mrad can be achieved for Bragg gratings with thickness of several millimeters and spatial frequency exceeding several hundreds of lines per millimeter. Variations of the spatial frequency available in PTR gratings provide narrowing of the value of angular selectivity down to about 0.1 mrad or increasing it up to several milliradians. Spectral selectivity of transmitting grating can be narrowed down to subnanometer region.

An example of angular selectivity of a transmitting PTR grating is shown in Fig. 7. It was found that the experimental profiles of diffraction efficiency coincided with theoretical functions for the uniform sinusoidal Bragg grating within fluctuations which did not exceed 5 %. One can see that angular selectivity of about 2 mrad is achieved in the PTR Bragg grating having thickness of 1 mm. Good coincidence of theoretical and experimental angular distributions shows that the value of refractive index modulation is uniform across the aperture of the hologram. It is important to note that some discrepancy between the model and experimental data are caused not by distortions of a PTR grating but by diffraction limited divergence of a laser beam with an aperture of 1.5 mm. Thus, PTR Bragg gratings can have angular selectivity comparable and even narrower than angular divergence of single-mode laser radiation.

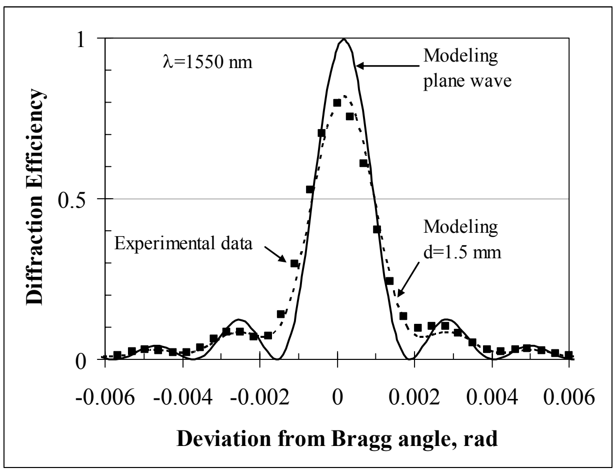

Fig. 7. Angular selectivity of transmitting PTR Bragg grating at 1550 nm. Spatial frequency 703 mm^{-1}, refractive index modulation 640 ppm, thickness 1.16 mm.

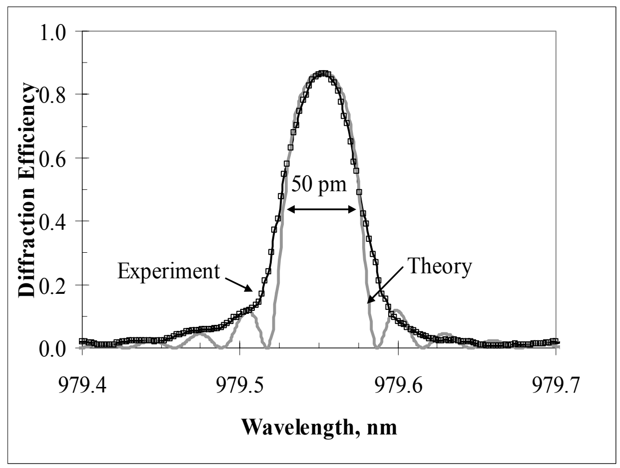

Fig. 8. Spectral selectivity of a reflecting Bragg grating. Thickness 10 mm.

An example of spectral selectivity of a transmitting PTR grating is shown in Fig. 8. Deflection angles could be ranged from 120 to 180˚, angular selectivity from 10 to 100 mrad, spectral selectivity from 0.01 to 2 nm. Absolute diffraction efficiency up to 98.5% and relative diffraction efficiency for plane wave of 99.99% were demonstrated. An example in Fig. 8 shows laser mirror for a semiconductor diode with spectral width of 50 pm and efficiency of about 90%. One can see that spectral width (FWHM) of this filter coincides with the theoretical value within accuracy of few percents. However, side lobes of the reflectivity curve are smeared. This effect resulted from distortions of the recording interference pattern and can be eliminated by the further improvement of a recording setup.

Thus, both transmitting and reflecting gratings with high diffraction efficiency are recorded in PTR glass. These gratings can have different orientation inside a glass plate. Moreover, a number of different gratings can be recorded in the same volume. Low losses in these gratings enable their use as components of laser resonators.

4. VOLUME BRAGG LASERS

It is important that contrary to conventional optical elements, volume diffractive gratings are slits or apertures in space of wave vectors (or in spectral and angular spaces). This feature of thick Bragg gratings allows some unusual approaches for laser design resulting in dramatic decreasing of spectral width, conversion of wide stripe diodes to single mode emitters, and to transformation of high power semiconductor lasers to tunable sources. Such lasers that have volume Bragg gratings as the components of their resonators are called volume Bragg lasers (VOBLAs).

Fig. 9 shows a comparison of diffraction limited divergence for coherent sources with different apertures and wavelengths with angular selectivity of volume Bragg gratings with different spatial frequencies and thicknesses. One can see that existing technology of PTR diffractive optical elements covers the whole region of angles from tens of degrees for narrow-stripe semiconductor lasers to tens on microradians for large aperture solid state lasers. The basic difference between a conventional design of laser resonators with mirrors, lenses and apertures versus the use of volume Bragg gratings is that the conventional elements work in geometrical space while volume gratings work directly in angular space (or space of wave vectors). This means that mode selection can be based on their different angular distribution while conventional design could produce this selection based on different spatial distribution. The use of volume Bragg gratings with properly adjusted angular and spectral selectivity as elements of laser resonators allows selecting of arbitrary modes if they have different angular distribution independently of possible total overlapping in geometrical space.

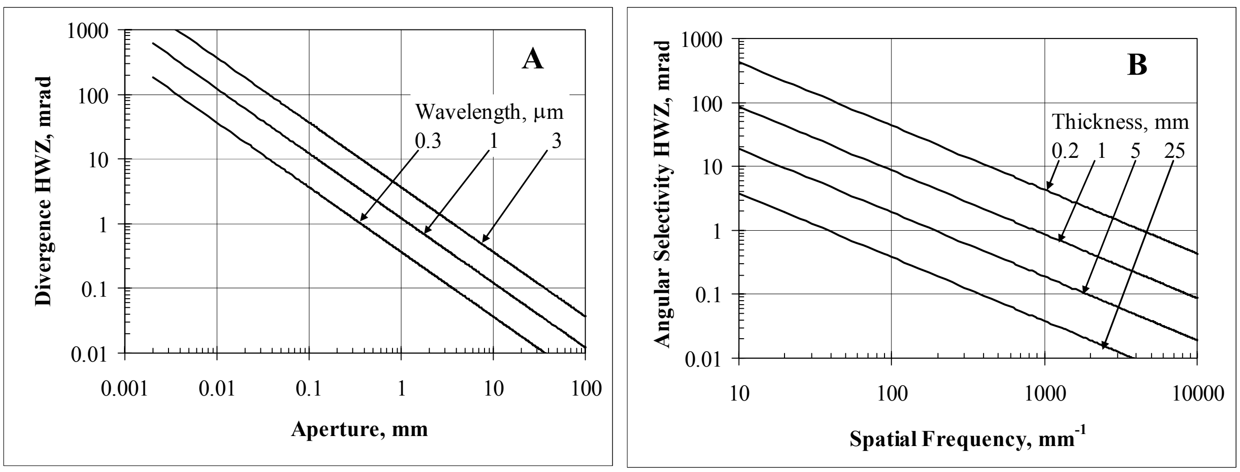

Fig. 9. Comparison of divergence of laser beams (A) and angular selectivity of Bragg gratings (B).

It is important to elucidate this new feature of thick Bragg gratings for design of single transverse mode resonators. Well-known requirement for a single mode oscillation is a necessity of such aspect ratio of a resonator which results in one Fresnel zone at an output mirror. However, the feature of volume Bragg gratings to provide selection in angular space enables a new opportunity to replace this requirement by another one. This new requirement is following. Angular acceptance of output coupling device should provide propagation of radiation within the first Fresnel zone only. This requirement could be satisfied by a proper choice of thickness, spatial frequency and refractive index modulation of Bragg grating. The most important consequence of this new approach is that no restrictions for aperture of the resonator appeared. This means that a proper choice of grating can convert a wide aperture resonator with small aspect ratio to a single mode one. This feature enables increasing of power and decreasing of size for single mode lasers with divergence close to the diffraction limit.

Fig. 10 shows a comparison of longitudinal mode separation in typical resonators of laser diodes and spectral width of Bragg mirrors. One can see that Bragg mirror with thickness of few of millimeters provides spectral selection enough for single longitudinal mode selection in a resonator of one or couple of millimeters length. Thus, a combination of transmitting and reflecting volume Bragg gratings provides an opportunity to select both transverse and longitudinal modes in semiconductor laser resonators.

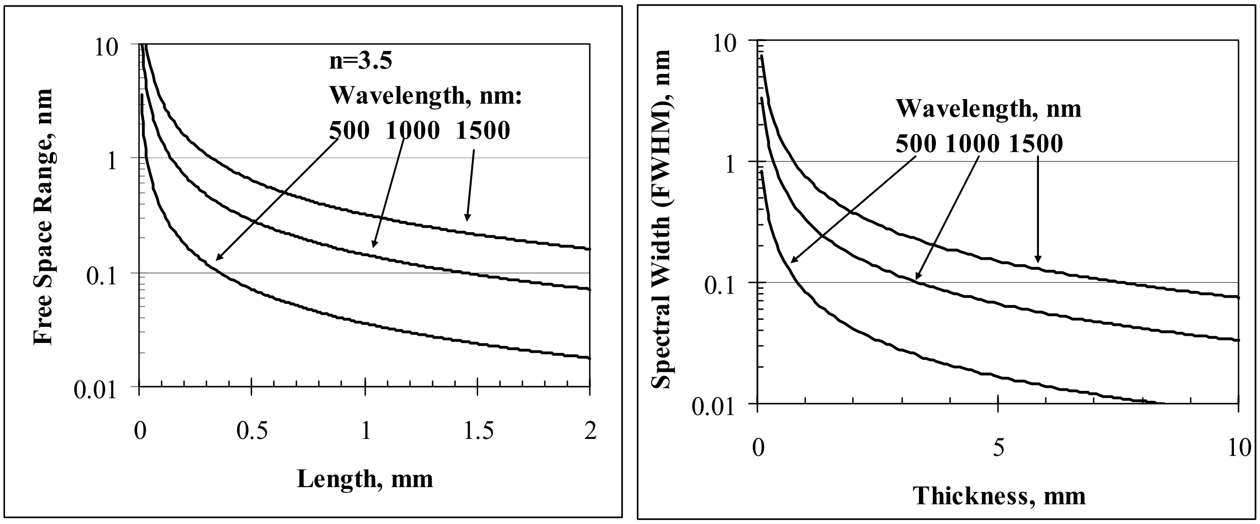

Fig. 10. Distance between longitudinal modes in Fabri-Perot resonator (A) and spectral width of volume Bragg gratings (B).

We studied a number of volume Bragg lasers with different LDs having stripe widths from 30 to 250 μm and reflection from the front facet from 0.5 to 5% combined with PTR Bragg gratings having reflection coefficients from 3 to 99% and spectral widths from 1 nm to 100 pm[10-11]. It was found that any type of laser diode can be locked practically by any of tested gratings if its central wavelength is not away from a maximum of a diode emission spectrum for more that several nanometers. The typical example of spectral locking of a wide stripe laser diode is shown in Fig. 11. One can see that while a bare LD has a wide emission spectrum of several nanometers, a volume Bragg laser can have wavelength outside of this spectral region because of very wide luminescence bands of semiconductors. It is important that for bare diode emission line has a thermal shift of about 0.3 nm/K, while VOBLA has narrow emission band which is completely locked by a PTR Bragg grating. Spectral width of the emission band can be easily narrower to the range of tens of picometers. Total losses in this case do not exceed 3% while spectral brightness increases for almost two orders of magnitude. The ranges of pumping current, temperature variation or spectral detuning are wider if reflection coefficient from front facet is lower, length of a diode is shorter, and reflection coefficient of Bragg mirror is higher.

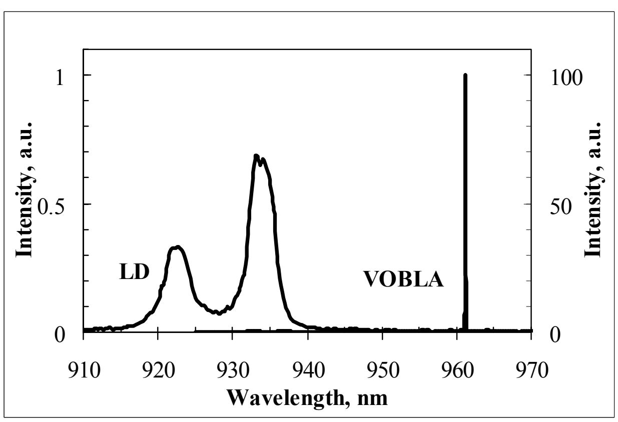

Fig. 11. Emission spectra of an original laser diode and a volume Bragg laser consisting of the same diode and reflecting PTR grating.

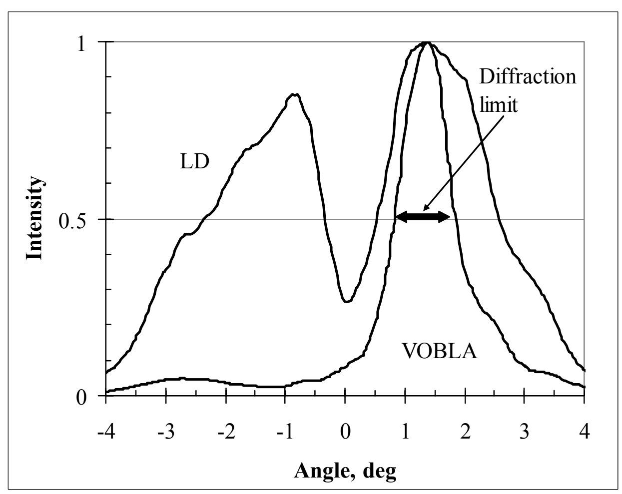

Fig. 12. Divergence of an original laser diode and a volume Bragg laser consisting of the same diode and reflecting PTR grating.

Selection of a single transverse mode in VOBLA is possible if angular divergence of a particular mode is adjusted with angular acceptance of Bragg grating used in the resonator. The result of the use of reflecting PTR Bragg grating is shown in Fig. 12. One can see that external resonator with reflecting PTR Bragg grating provides angular selectivity of output radiation close to the diffraction limit even at high levels of pumping exceeding threshold for more than 10 times. Single transverse mode emission from a wide stripe laser diodes were obtained for stripe widths up to 250 µm with total power of 2 W in a beam with diffraction limited divergence. This approach can be applied for different types of lasers providing diffraction limited divergence for resonators having high Fresnel numbers. Thus, the use of a properly adjusted PTR Bragg grating as an output coupler of an external resonator allows single mode operation for wide stripe semiconductor laser diodes at high levels of pumping.

5. PHASE LOCKED ARRAYS OF LASER DIODES

In our experiments with coherent coupling of two laser diodes[12] we used two commercial single-transverse-mode LDs with standard antireflection coatings (~5%). They emitted collimated beams in the 980 nm range with emission spectra consisting from several fluctuating lines with 3.5 nm total spectral width. The laser devices were placed on the separate mechanical stages with distances between lasers and coupling PTR Bragg grating near 70 mm. For observation of an interference pattern the laser outputs were combined on a screen by a system of mirrors and a beam splitter. A combination of laser spots on the screen produced a homogeneous pattern.

A locking grating, working in a retroreflecting mode, was placed in the beam of one of the laser diodes causing spectral narrowing of its emission. After this, a coupling grating was placed in the beam to provide efficient exchange of radiation between laser diodes, thereby coupling these two lasers. In experiments when the PTR Bragg grating had spectral selectivity near 100 pm (half width to the first zero, HWFZ), both coupled lasers emitted the narrow lines. Their overall spectral width was less than 150 pm and usually included 2-3 longitude modes of an internal laser diode cavity. Overlapping beams of such spectrally locked lasers with multimode spectra produced a pattern depicted in Fig. 13A. The pattern is uniform and has a dark stripe in the middle. This dark stripe corresponds to the range of angles which were diffracted by the locking gratings for diode coupling. The vertical structure corresponds to the side lobes in angular selectivity of a Bragg grating similar to a curve depicted in Fig. 7. Uniformity of the pattern shows that two lasers emit incoherent radiation and no stable interference pattern could be generated.

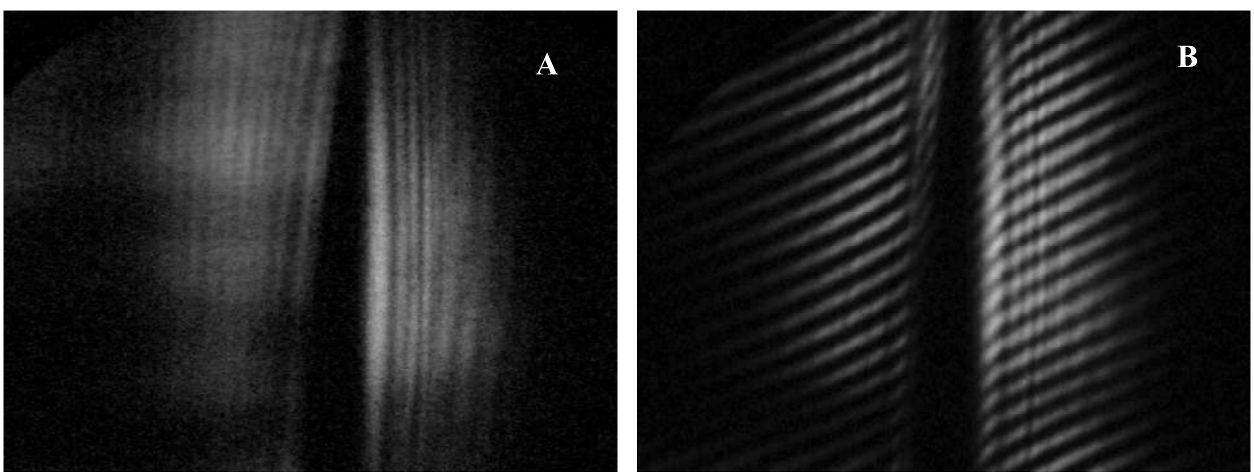

Fig. 13. Image on the screen produced by the beams of two laser diodes coupled by PTR Bragg grating with spectral width at HWFZ 100 pm (A) and 40 pm (B).

Nevertheless, in the case where the spectral width of the coupling grating was less than the separation of longitudinal modes in the internal resonators of the diodes, the emission spectrum of the both lasers became identical (below 30 pm which was spectral resolution of a spectral analyzer) and the stable interference pattern was observed on the screen (Fig. 13B). This interference pattern was stable for a long period. This is remarkable taking into account that the diodes and the coupling grating were mounted on three different stages resulted in the resonator length of 15 cm. It is important to note that coherent coupling was observed at the high levels of pumping, above 5 times the threshold. The total power of the coherent radiation from the coupled lasers was above 80% of the sum of the power of the independent diode lasers.

Thus, this result shows that two separated lasers, coupled by a PTR Bragg grating, can behave as a single coherent source of light. It was stable for hours in continuous operation and this process was the same for more that 10 months of repeatable experiments with the same two devices. Therefore, a one can expect that a phase coupled array of single-transverse-mode laser diodes with individual power of about 10 W would emit several hundred watts of coherent radiation with diffraction limited divergence.

6. SPECTRAL BEAM COMBINING

The general principle of the proposed incoherent procedure is a spatial combination of two beams with shifted wavelengths in a Bragg grating[13-16]. This combining results from total diffraction of a beam with λ_1 in direction of "+" order of Bragg grating and total transmission of a beam with λ_2 launched from direction which corresponds "–" order for the first beam (Fig. 14). In other words, the first beam corresponds to maximum diffraction efficiency while the second one corresponds to null in the spectral selectivity curve. Spectral selectivity of the Bragg grating should be narrower than the wavelength shift between beams to provide zero diffraction for the second beam but wider than the spectral width of each beam to prevent spectral distortions of the beams. Similarly, angular selectivity of the grating should be greater than the beams divergence but narrower than difference between absolute values of their Bragg angles.

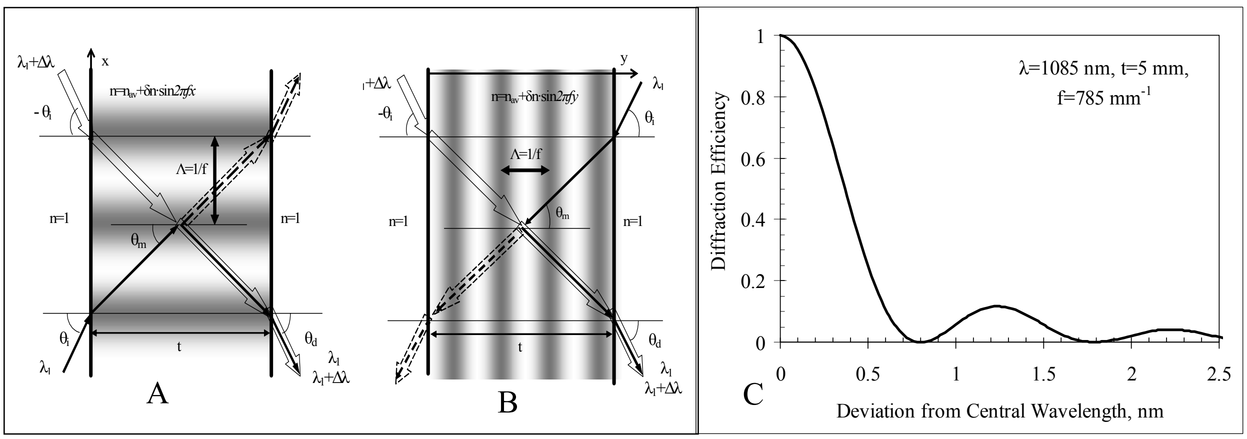

Fig. 14. Spectral beam combining (multiplexing) by PTR Bragg grating. A- transmitting grating, B – reflecting grating, C – spectral selectivity of grating.

To prove this concept, an experimental setup for beam combining was designed on the basis of two single mode Yb-doped fiber lasers. These lasers had spectral width varying from 3 to 5 nm at FWHM with power increasing from 10 to 100 W and divergence close to the diffraction limit. Central wavelengths were shifted for 11 nm. A transmitting PTR Bragg grating with spatial frequency of about 450 mm^{-1} was used for beam combining. Beam combining efficiency of 92% was observed at maximum power of the lasers. It was found that the main part of losses resulted from spectral broadening of laser emission spectra at high power. In this case, a grating designed to have the first null at the wavelength of the second laser cuts those tails in emission spectra of lasers. The second source of losses was angular selection by the grating. It was found that one of the laser beam collimators was heated by radiation and thermal aberration caused increasing of beam divergence at high power. This part of radiation propagating at large angle in respect to the axis was cut off by grating. It is interesting that divergence of a combined beam was narrower that that of one of the original beams. This means that PTR Bragg combiner provided additionally beam cleaning. Finally it was found that for monochromatic beams with diffraction limited divergence efficiency of such spectral beam combining was about 98%.

This encouraging result allowed us to extend this approach to a higher number of channels. The system for 5 channels (Fig. 15) with 0.5 nm spectral separation was designed[17]. The modeling of this system shows that its efficiency should exceed 90% for power in each channel exceeding

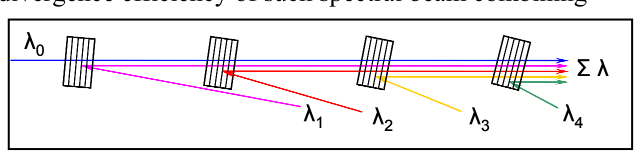

Fig. 15. Beam combining setup for five laser sources by means of reflecting volume Bragg gratings.

100 W. It was found that for realistic values of diffraction efficiency and material losses in PTR glass efficiency of combining exceeding 80% is possible for a number of channels exceeding 100. This estimation shows a feasibility of a portable laser system at multi-kilowatt level.

7. ARCHITECTURE OF HIGH-BRIGHTNESS DIODE LASER SYSTEM

Totality of presented experimental results and modeling allows proposing the following architecture of high-brightness laser diode system. First, a semiconductor wide-stripe diode is placed in an external resonator which 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 diodes 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.

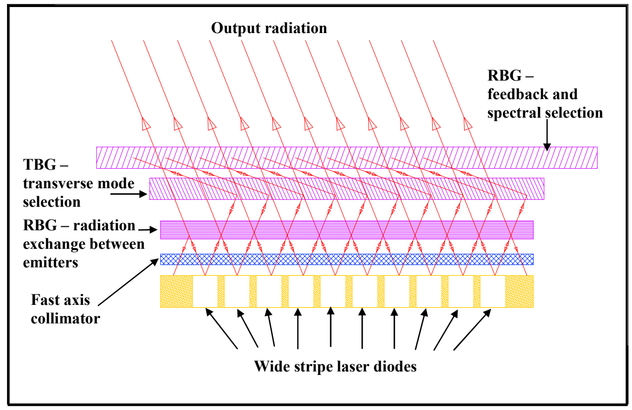

Fig. 16. Phase locked array of laser diodes.

One of the possible versions of such phase locked array is depicted in Fig. 16. A bar of wide-stripe laser diodes emits single transverse mode radiation along the fast axis which is collimated by a cylindrical lens. After this collimator, each diode emits a multimode beam with high divergence in slow axis direction. Usually such beams have far field distribution with two out-of-axis mail lobes with total divergence of about 10˚. A locking grating is placed next after the fast axis collimator which provides partial diffraction of a beam in the vicinity of maxima of the main lobes to the adjacent emitter. The next grating is designed in such manner that it can select one of the transverse modes in the vicinity of the main lobes in angular distribution. The third grating is a PTR Bragg mirror which provides feed back at very narrow wavelength. Thus, such a device should emit coherent beam with very narrow spectral width and divergence close to the diffraction limit.

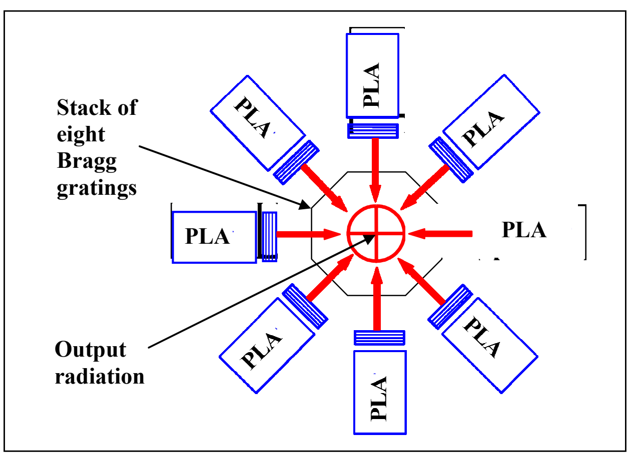

Fig. 17. Eight-channel combining of beams of phase locked arrays by means of a stack of PTR Bragg gratings.

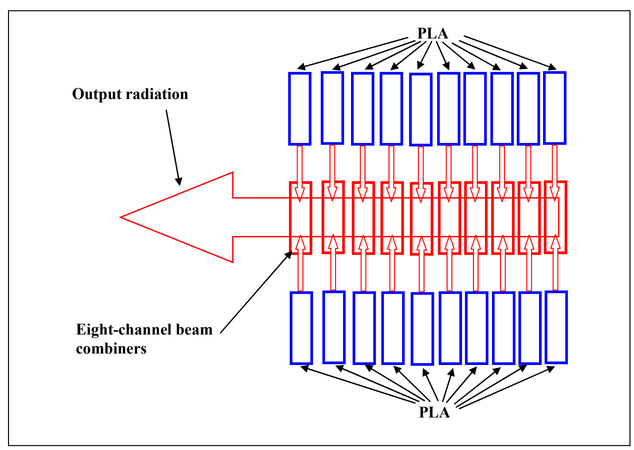

Fig. 18. Stack of PTR beam combiners.

Figure 17 shows a spectral beam combiner which is a stack of eight Bragg gratings recorded in a single slab or a stack of PTR glass slabs. This compact element deflects all eight beams to the same direction without deterioration of their quality. It is important that this beam combiner is transparent for all wavelengths outside of its resonant values. A stack of PTR beam combiners with shifted wavelengths (Fig. 18) can provide a desirable number of channels.

CONCLUSION

Architecture of high-brightness high-power laser system based on semiconductor lasers is proposed. This approach is based on the use of new optical elements which are volume Bragg gratings recorded in a photo-thermo-refractive (PTR) glass. These grating are used for conversion of wide-stripe laser diodes to emitters of single transverse mode radiation, coherent coupling of individual laser diodes, and for spectral combining of a number of beams with shifted wavelengths.

Acknowledgments: The work was supported by SHEDS and ADHELS programs at DARPA.

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