High-brightness narrow-line laser diode source with volume Bragg-grating feedback

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ABSTRACT

Results of a long-term research in spectral narrowing and transverse mode selection in semiconductor lasers by means of volume Bragg gratings recorded in a photo-thermo-refractive (PTR) glass are described. PTR glass is a multicomponent silicate optical glass which changes its refractive index after UV exposure followed by thermal development. This feature enables recording of volume holograms with efficiency exceeding 97% in visible and near IR spectral regions which tolerate high temperatures up to 400°C, high power laser radiation. Transmitting and reflecting volume Bragg gratings recorded in such manner have spectral and angular selectivity down to 0.01 nm and 0.1 mrad, respectively. These spectral and angular selectors were used as transmitting and reflecting elements of external resonators for high-power semiconductor laser diodes (LDs). Transmitting Bragg gratings provide tunability of LDs in the range up to 60 nm, spectral narrowing down to 200 pm, stabilization of wavelength within 500 pm. Reflecting Bragg gratings allow spectral narrowing down to 20 pm, stabilization of wavelength below 100 pm at temperature variations up to 75 K. A single transverse mode emission for wide stripe LDs is observed at pumping currents exceeding 10 thresholds. Narrowing and stabilization of emission spectra of LD bars is demonstrated. It is important that all these features are achieved by passive elements with efficiency exceeding 97% and unlimited lifetime while actual brightness increase exceeded two orders of magnitude.

1. INTRODUCTION

The problem of high-brightness, high-efficient semiconductor laser sources with stable narrow emission spectra and narrow divergence is important for different kinds of their applications. The use of external selective feedback for spectral narrowing and tuning of single semiconductor lasers started in early 70s and was described in numerous original publications and in several classical monographs [1, 2]. After development of laser diode (LD) bars and stacks, the same methods have been adapted to such multichannel devices and a number of recent experiments have demonstrated improvements of spectral width of broad area laser diode bars. Various constructions of external resonators for LDs were proposed and investigated, but up to now no successful commercial product resulted from those researches. First of all, no diffraction limited single lobe emission was obtained for external cavity semiconductor lasers under high pumping current [3-7]. The other reason restraining external cavity applications is an additional number of optical elements, which should be aligned with very high accuracy.

Two types of technical approach were used to narrow spectral width of LD emission, which are optical injection method and external cavity technique with selective spectral elements in a feedback loop. The use of injection wavelength locking and beam quality improvements were recently observed in Oak Ridge National Laboratory [8]. Using a 0.5 mW injection beam from a single-mode and single-frequency LD to each of 125-µm-wide emitter in a bar consisting of 19 diodes, they demonstrated up to 1 W power with narrow spectrum from each emitter. At this power, the line with width of 8 MHz was concentrated near 60% of radiation. The other part of energy was distributed continuously in a wide spectrum similar to that of a free running laser. Injection wavelength locking meets some serious problems from the point of view of compact, cheap and reliable design, which is necessary for pumping stack.

In a more traditional optical design, a spectrally selective feedback with a surface diffractive grating was used for narrowing and stabilization spectral width of laser bar. Theoretically, it was demonstrated in Ref. [9] that for a stabilized LD source with an external cavity, the requirement of a narrow line width is not in a contradiction with the requirement of maximum efficiency. After years of experiments with spectral stabilization of LD stacks, the best efficiency did not

High-Power Diode Laser Technology and Applications III, edited by Mark S. Zediker, Proc. of SPIE
Vol. 5711 (SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.590425

exceed 60-65% compare to that of free running laser under high pumping conditions [10]. An external cavity was designed with the use of Littrow or Littman-Metcalf optical schemes with blazed surface grating; and the similar resultes were observed in both cases. A fraction of the output power in the narrowed peak decreased with increasing current from 85% near threshold to 68% at high pumping condition. Maximum output power in a narrow spectral line of 60 GHz has reached 12.2 W for 20 W LD bar. Decreasing of optical power in narrow line under high pumping condition can be explained by thermal distortions of the surface grating resulted in additional optical losses. The similar gratings behavior was observed in the spectral combining experiments with the use of a metallized surface grating placed in a laser beam with power about 10 W or higher [11].

Thus, a key point for the development of high power semiconductor lasers is availability of dispersive elements which manifest high robustness under laser irradiation. Creation of such dispersive elements became a reality after long term research efforts started almost 20 years ago [12] and resulted in creation of a photosensitive robust material and demonstration of high efficiency robust volume holographic gratings [13]. A technology of photo-thermo-refractive (PTR) glass enabling high efficiency of volume holograms and a number of applications with the use of PTR Bragg gratings were developed at the University of Central Florida [14, 15]. This paper summarizes results achieved in PTR glass, PTR Bragg gratings, and semiconductor volume Bragg lasers.

2. PHOTO-THERMO-REFRACTIVE GLASS

One of the hot practical problems of modern optoelectronics (photonics) that must be solved right now 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 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 [16]. 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 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 [17]. The first step is the exposure of the glass sample to UV radiation, somewhere in the range from 280 nm to 350 nm (Fig. 1). A number of commercially available lasers with long length of coherence can be used

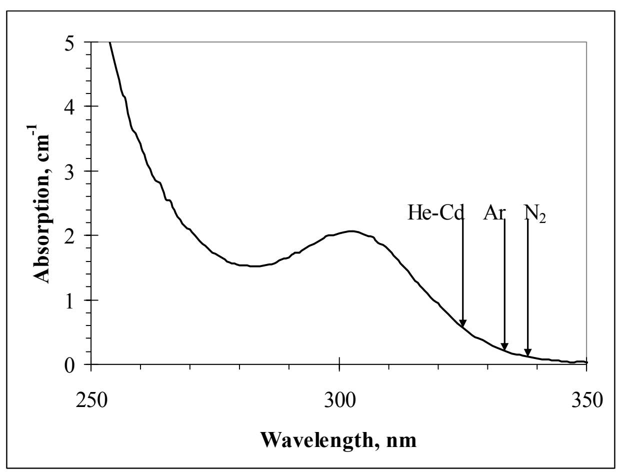

Fig. 1. Absorption spectrum of unexposed PTR glass.

for such exposure. This second stage is similar to formation of a latent image in a conventional photo film; while no significant changes in optical properties of glass occur here. 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. 2). It is important for hologram design that dependence of refractive index decrement on exposure is a hyperbolic function but not an exponential one [18]. Such Δn enables high efficiency hologram recording in PTR glass wafers with thickness exceeding several hundreds of microns.

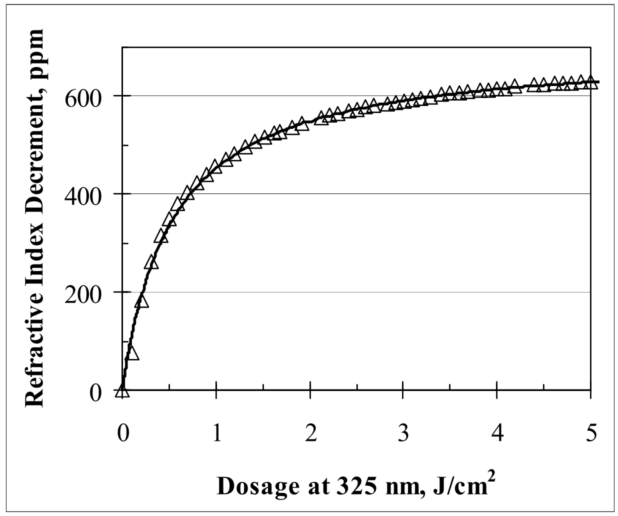

Fig. 2. Dependence of a refractive index difference between exposed and unexposed areas in PTR glass on dosage at 325 nm after thermal development at 520°C for 2 hours. Solid line is a fitting with a hyperbolic function.

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. 3 that induced 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 placing of such optical elements with thickness not exceeding a few of millimeters 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. Intensive research that is conducted to study mechanism of crystalline phase precipitation in PTR glass should decrease induced losses in the nearest future.

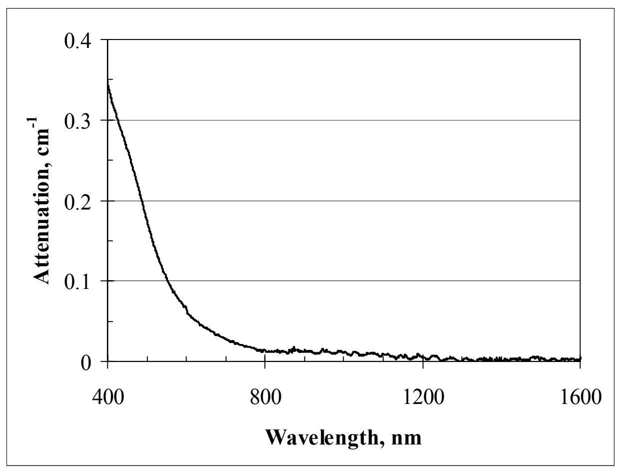

Fig. 3. Spectrum of attenuation (absorption and scattering) of PTR glass after UV exposure and thermal development at 520°C for 2 hours.

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 [19]. Nonlinear refractive index in PTR glass is the same as that for fused silica [20] which allows the use of PTR diffractive elements in all types of pulsed lasers. Testing of PTR diffractive grating under irradiation of 2 kW Yb-fiber laser focused to a 4-mm-diameter spot (IPG Photonics, Inc.) showed its stability while heating did not exceed 15 K. Thermal variations of refractive index in PTR glass are very low ($dn/dt=5\times10^{-8}$ 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. PTR VOLUME BRAGG GRATINGS

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 gratings was up to 35 mm×35 mm. Diffraction efficiency was measured at 633 nm, 1064 nm, 1096 nm and 1550 nm. In all cases, maximum diffraction efficiency of PTR Bragg gratings exceeded 95 %.

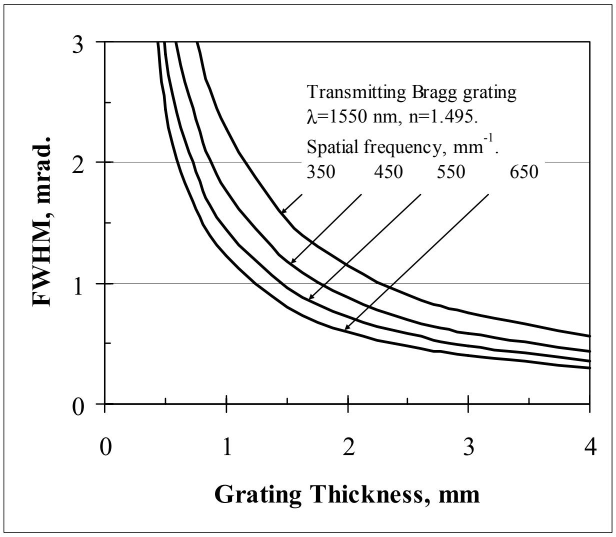

Fig. 4. Dependence of angular selectivity (Full Width at Half Maximum) of transmitting Bragg grating on thickness

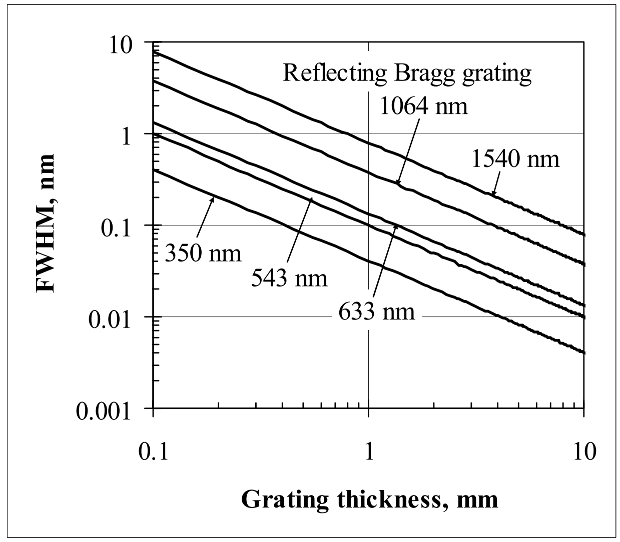

Fig. 5. Dependence of spectral selectivity (Full Width at Half Maximum) of reflecting Bragg grating on thickness

Mathematical modeling has shown that PTR Bragg gratings with deflection angles ranged from a few of degrees to 180° can be designed. Dependence of angular selectivity of transmitting Bragg grating on its thickness is shown in Fig. 4. 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. This means that PTR Bragg gratings with thickness of several millimeters can be used for the angular selection of laser radiation having diffraction limited divergence. Spectral selectivity of transmitting grating can be narrowed down to subnanometer region.

Dependence of spectral selectivity of PTR reflecting Bragg gratings on thickness is shown in Fig. 5. The spectral selectivity of Bragg mirror becomes narrower if wavelength decreases or the thickness of the grating increases. One can see that these gratings with reasonable thickness of several millimeters can show selectivity in the range of 0.01 nm for UV and 0.1 nm for near IR spectral regions. In the case of retroreflecting Bragg mirrors spatial frequency is unambiguously determined by wavelength and cannot be a fitting parameter as for transmitting gratings. The only flexible parameters for Bragg mirrors are the thickness of the grating and refractive index modulation which determine spectral selectivity and reflection coefficient.

An example of angular selectivity of a transmitting PTR grating is shown in Fig. 6. It was measured by rotating the grating along the axis placed in the center of the specimen. These measurements were conducted at 633, 975, 1085, and 1550 nm for gratings having different thickness and refractive index modulation. 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 PTR grating but by diffraction limited divergence of laser beam with 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. Spectral selectivity of PTR Bragg gratings was measured by a number of single-transverse-mode tunable lasers in the range of 980, 1080 and 1550 nm. It is important that dependence of diffraction efficiency on detuning from Bragg wavelength is described by theory with accuracy of about 20%. Once more, strong overlapping of experimental and theoretical profile is an evidence of rather good uniformity of Bragg gratings produced by consequent UV exposure and thermal development. However, some discrepancy between theory and experiment one can see in the range of the first side lobes. This phenomenon is not completely clear and requires an additional study.

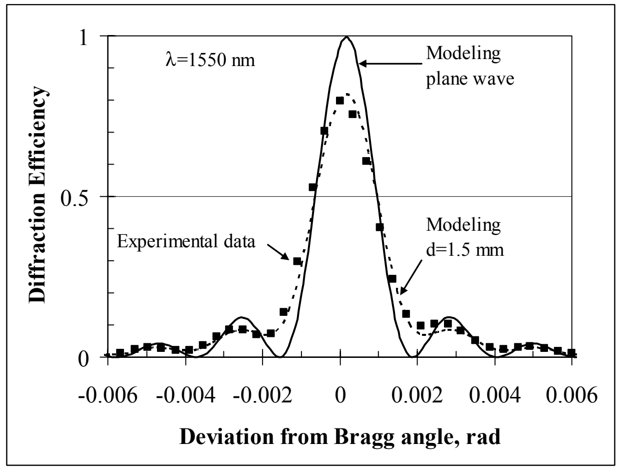

Fig. 6. Angular selectivity of transmitting PTR Bragg grating at 1550 nm. Spatial frequency 703 mm^{-1}, refractive index modulation 640 ppm, thickness 1.16 mm.

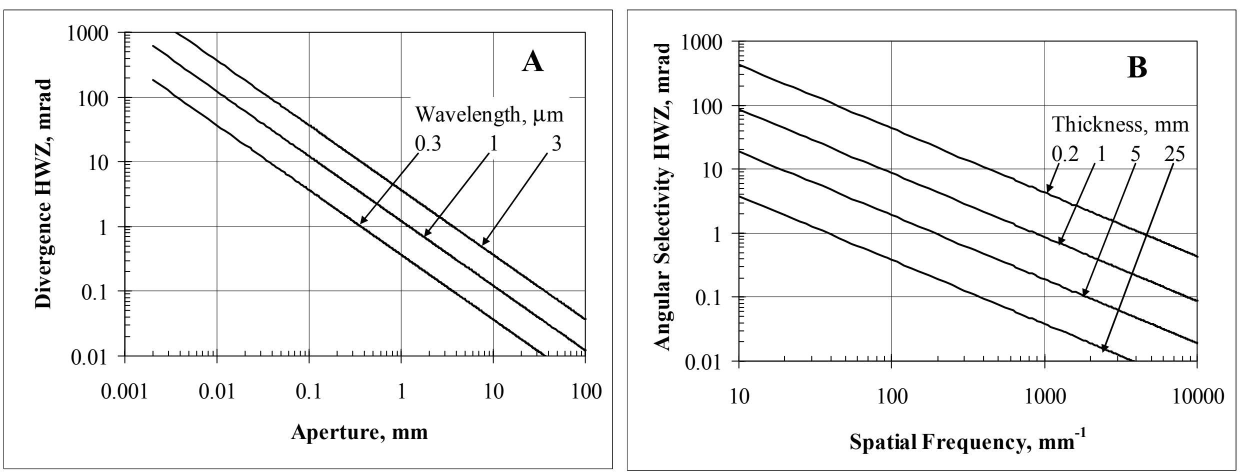

Fig. 7. Comparison of divergence of laser beams (A) and angular selectivity of Bragg gratings (B).

Fig. 7 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 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. This approach is illustrated in Fig. 8 where one can see that transmitting Bragg grating is a slit in angular space while reflecting Bragg grating is a diaphragm in angular space. This means that 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. Such lasers that have volume Bragg gratings as the components of their resonators are called volume Bragg lasers (VOBLAs).

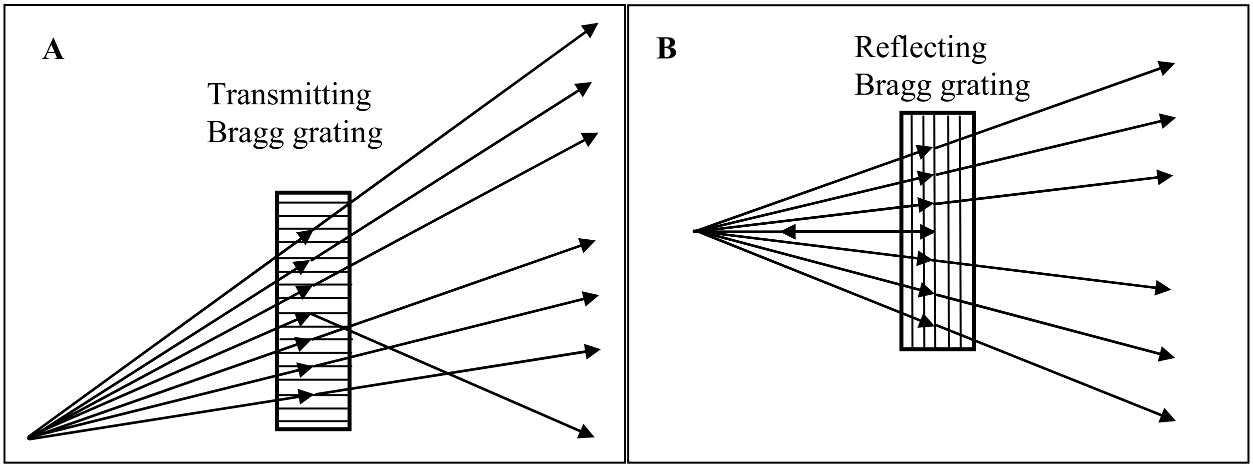

Fig. 8. Illustration of transmitting Bragg grating working as a slit (A) and reflecting one working as a diaphragm (B) in angular space.

4. SEMICONDUCTOR VOLUME BRAGG LASERS

This paper summarizes the first results observed last few years with volume Bragg semiconductor lasers. A number of different transmitting and reflecting gratings were studied with different single- and multimode LDs and laser bars.

4.1. Mode selection by transmitting Bragg gratings

One of examples of the use of transmitting Bragg grating for a conversion of a LD to a tunable laser is shown in Fig. 9. Transmitting PTR grating with 100% diffraction efficiency is placed an output beam of a single-mode LD in such manner that one of the wavelengths within a natural emission spectrum of diode is totally deflected to the lower mirror. The mirror reflects this radiation back to the resonator. It is clear that feedback is efficient for the narrow range of wavelengths which is determined by spectral width and position of the grating. However, this resonator has total reflection at both ends and output power is low. To provide optimal coupling coefficient, the second mirror is placed to the upper position in Fig. 9 and aligned parallel to the lower one. In this case, detuning of the grating from Bragg angle results in decreasing of diffraction efficiency while the same wavelength returns to the resonator. This means that tuning of the grating while the mirrors are fixed provides variable coupling coefficient for any fixed wavelength and allows achieving maximum output power. Rotating the whole system, including mirrors and grating, results in varying the wavelength which returns to the resonator. Additional rotating of the grating provides optimization of coupling coefficient for each wavelength. Dependence of central wavelength of a commercial Hitachi HL 6312 LD on detuning of transmitting PTR grating is shown in Fig. 10. One can see that even standard commercial semiconductor laser can

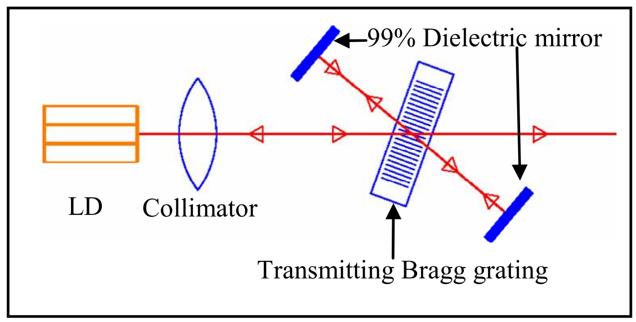

Fig. 9. Tunable laser with variable coupling coefficient by means of rotating transmitting Bragg grating.

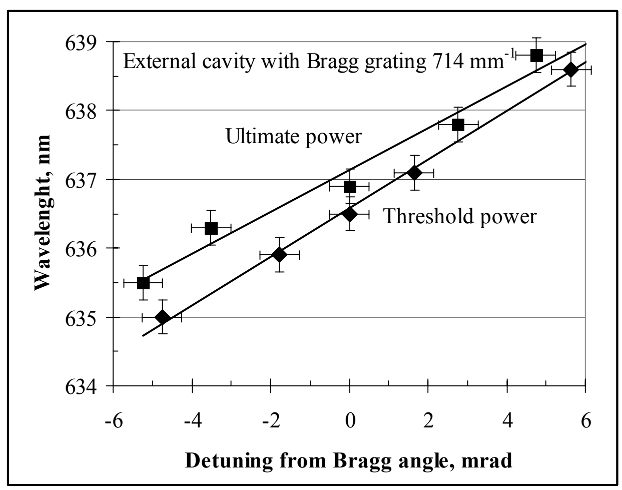

Fig. 10. Tuning of a commercial single-mode diode by a transmitting PTR grating.

become a tunable system with tunability of a few of nanometers by means of VOBLA configuration with transmitting PTR Bragg grating. Total power of tunable laser is about of 90% compare to that of an original LD. Placing of additional reflector to a resonator decreases the threshold of lasing. VOBLA is locked to a single wavelength while pumping threshold is lower compare to that in bare diode. The range of tunability for laser diode with optimal reflection from the front facet about 5% is about 3 nm. The range of tunability for diodes with reflection from the front faced about 0.5% can be extended to 30 nm and more. Spectral width of emission depends on spectral selectivity of the used grating and usually is below 500 pm.

4.2. Spectral narrowing and stabilization by reflecting Bragg gratings

One can see from Fig. 7 that divergence of typical semiconductor laser, which is a single mode emitter along the fast axis with aperture about 1 µm and corresponding diffraction limited divergence in the range from 30 to 40°. Typical divergence of multimode wide stripe LD along the slow axis is about 10°. Typical Bragg mirror with thickness of about 1 mm has angular selectivity about 3°. This means that an external resonator consisting of such mirror placed in an un-collimated beam would reflect back of about 3% of radiation if a reflection coefficient is 100%. However, small aperture of the front facet of LD would decrease a portion of radiation returned to resonator for about two orders of magnitude and total coupling coefficient would not exceed 10^{-4}. This value is enough for demonstration of locking of a laser diode but is too low for reliable operation at high levels of pumping. This is why collimation along one or two axes is used for VOBLA design. An example with collimation along the fast axis only is shown in Fig. 11. An interesting feature of wide stripe semiconductor diodes is that highest gain is observed not for a zero mode but for modes with large numbers having two main maxima directed usually from 5° to 10° in respect of the diode's axis. It was found that most efficient locking is observed when a Bragg mirror is tuned to reflect one of these maxima. It is clear that even for distances of few millimeters between the front facet of LD and Bragg mirror some part of reflected radiation would not return to the resonator but would be absorbed and reflected by the facet. To avoid this losses one can use the second collimator along the slow axis. In this case the all radiation reflected by a mirror would be collected by a gain medium. However, this approach means some complication of a design and one should chose between efficiency and reliability.

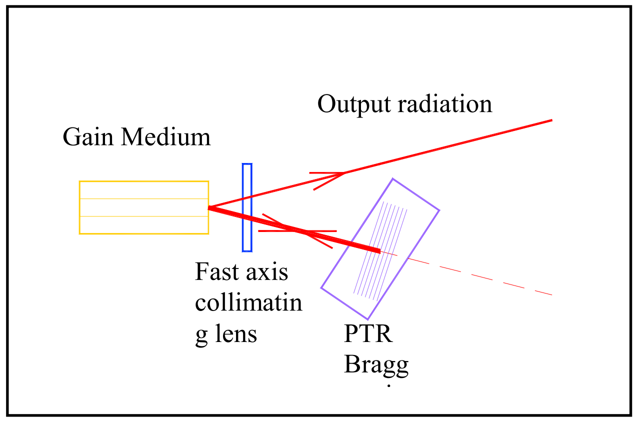

Fig. 11. Spectral stabilization of a wide stripe laser diode by a reflecting Bragg grating.

We studied a number of VOBLAs with different LDs having stripe widths from 30 to 150 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. 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. 12. One can see that while a bare LD has a wide emission spectrum which is thermally shifted for about 0.3 nm/K, VOBLA has narrow emission band which is completely locked by a PTR Bragg grating. Spectral width of the emission band is usually about order of magnitude narrower compare to a spectral selectivity of PTR grating. Total losses in this case do not exceed 3% while spectral brightness increases for almost two orders of magnitude.

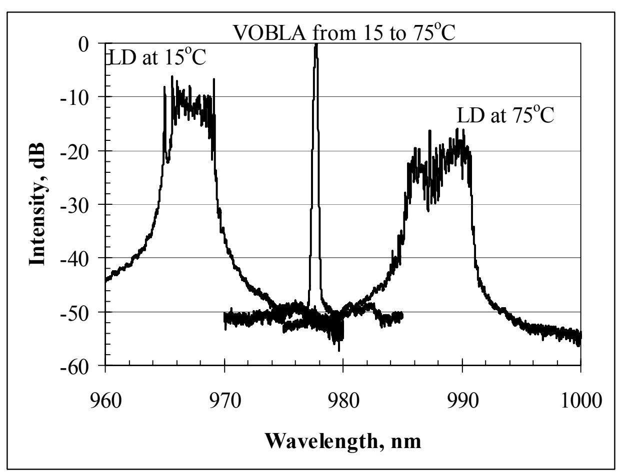

Fig. 12. Emission spectra of bare diode and VOBLA. Laser diode 100 µm wide, 2 mm long waveguide, 1.5% reflection from the front surface (AlfaLight).

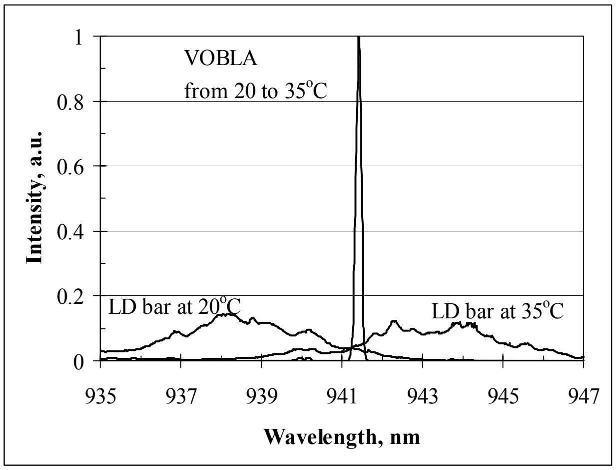

Fig. 13. Emission spectra of a conventional laser bar and VOBLA. 1 cm long bar, fill factor 30%, 150-mm-wide stripes, 0.5% reflection from the front facet (nLight).

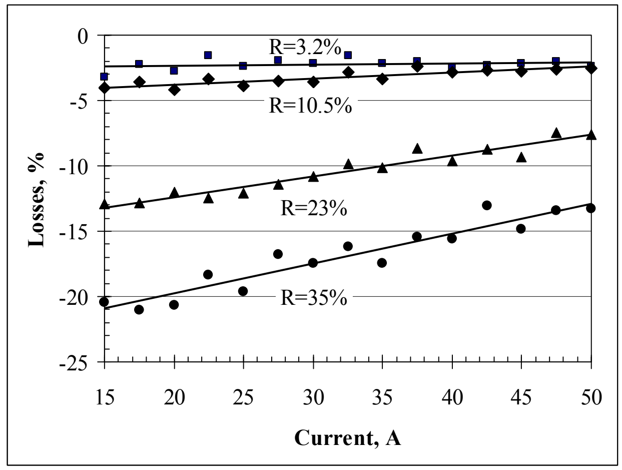

Fig. 14. Losses in VOBLA compare to the bare bar. 1 cm long bar, fill factor 30%, 150-mm-wide stripes, 5% reflection from the front facet (nLight).

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.

Similar approach was applied for different laser bars. Once more, any types of tested bars were successfully locked by existing PTR gratings. The main difference compare to the single diodes is connected with fluctuations in positions and directions of elementary emitters in bars caused by different imperfections of packaging technologies. This dispersion of parameters results in narrower range of thermal stabilization and wider emission spectra bar VOBLAs compare to single diode VOBLAs (Fig. 13). While single diodes can be locked for more than 50 K, typical bar is locked in the same wavelength for about 20 K. While single diodes show spectral width below 100 pm, bars have spectral width in the range of 500 pm. It is important that these parameters of bars are optimal from the point of view of efficiency of pumping of rare earth doped solid state and fiber lasers. The further narrowing of pumping lines does not result in the further increasing of pumping efficiency. The most important result of this work is extremely low price for spectral stabilization (Fig. 14). One can see that total losses for optimal grating do not exceed 3% while only one new passive element is introduced in the whole laser system while requirement for temperature control are loosen for about order of magnitude. Increasing of losses for high reflection coefficients in VOBLA without collimation along the slow axis caused by divergence of radiation and, therefore, low coupling coefficient for feedback.

4.3. Selection of single transverse mode by reflecting PTR gratings

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. Fig. 11 shows a basic design of an external resonator with a reflecting volume Bragg grating for effective transverse mode selection. The collimating Lens 1 provides diffraction limited divergence long the fast axis of a wide stripe LD which has a multimode structure along the slow axis. Angular selectivity of a grating should be matched to divergence of a selecting mode and by proper alignment and reflected radiation should be redirected back to resonator. Complementary radiation of this mode is out of angle of acceptance of the grating and therefore transmits through the grating. If coupling efficiency should be higher, an additional Bragg grating partially reflecting the second branch of a mode could be recorded in the same glass blank to provide additional back reflection to resonator. The drawing shows alignment of a grating for an

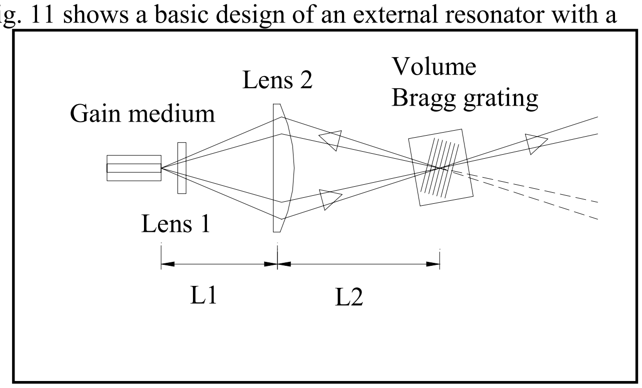

Fig. 15. Selection of single transverse mode in VOBLA with a wide stripe diode by a reflecting Bragg grating.

off-axis mode with large number. However, it is clear that the grating can be tuned to any mode of the resonator. Additional opportunity for adjustment of mode divergence and grating selectivity could be done by means of additional re-focusing element in the resonator (Fig. 15). For such design, divergence of the mode radiation is inversely proportional to magnification of the focusing system which is illustrated as Lens 1 and Lens 2. The last design is very convenient for experiments because if allows adjustments of laser and gratings in wide range of angles with the use of the same components.

The result of the use of reflecting PTR Bragg grating in geometry depicted in Fig. 15 is shown in Fig. 16 and 17. 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. This result means that that a wide stripe laser diode operates in a single mode regime emitting almost 1 W radiation with M^2=1.7. This approach can be applied for different types of lasers providing diffraction limited divergence for resonators having high Fresnel numbers. Emission spectrum of a single mode VOBLA is shown in Fig. 17. Spectral width of this laser is about 60 pm which includes several longitudinal modes of an external resonator. 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.

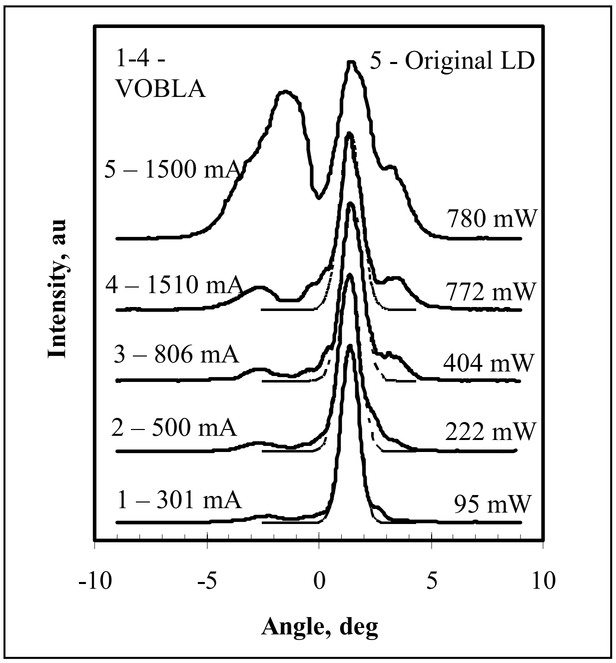

Fig. 16. Far field pattern for volume Bragg laser with reflective volume Bragg grating. Laser diode of 700×35 μm^2. The front facet has AR coating with reflection less than 0.5%. Thin lines show diffraction limited divergence.

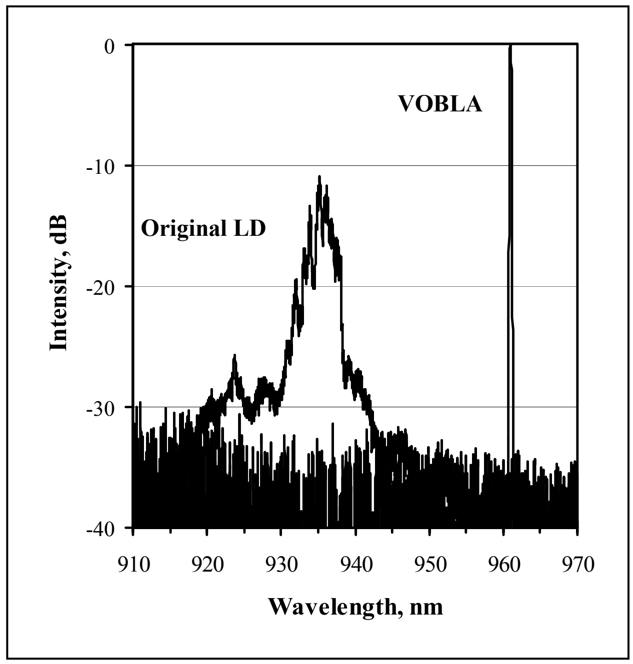

Fig. 17. Emission spectra of original LD and volume Bragg laser with PTR grating in an external resonator depicted in Fig. 15. Pumping current 1525 mA.

It is important to elucidate this new feature of thick Bragg gratings for design of single 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 (Fig. 8) 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 proper choice of grating can convert 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.

CONCLUSIONS

- New technology of photo-thermo-refractive (PTR) glass is developed which provides recording of phase holograms for near UV, visible and near IR regions with diffraction efficiency exceeding 95%. These holograms are stable under high power laser and ionizing radiation and tolerate elevated temperature.
- Transmitting and reflecting volume diffractive gratings (Bragg gratings) with spectral selectivity down to 100 pm and angular selectivity down to 100 μrad having apertures up to 25 mm are demonstrated.
- Volume Bragg lasers with the use of PTR diffractive gratings are demonstrated to show spectral and spatial stabilization.
- Emission spectra of single laser diodes are narrowed down to 50 pm with position stabilized within 100 pm for at least 50 K temperature variation.
- Emission spectra of laser bars are narrowed down to 500 pm with position stabilized within 500 pm for at least 20 K.
- Single mode emission for laser diodes with stripe width up to 100 μm and power above 1 W is demonstrated.
- Power of all locked lasers exceeds 97% of the original diodes and bars.

ACKNOWLEDGMENTS

The work was supported by DARPA SHEDS program; contract HR-01-1041-0004. Authors are grateful to L. Glebova, E. Rotari, and I. Ciapurina for PTR glass development, fabrication, certification and processing.

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