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## Report Title

Final Report: Laser Setup for Volume Diffractive Optical Elements Recording in Photo-Thermo-Refractive Glass

### ABSTRACT

Recorded in photo-thermo-refractive (PTR) glass volume Bragg gratings (VBGs) have found great applications for enhancement of lasers brightness and fine spectral filtering. However, further increase of size of holographic optical elements, which are required for high power laser applications, is restrained because of absence of available lasers emitting on PTR glass photosensitivity region (300-350 nm) with large coherence length and high power simultaneously. The recently discovered photosensitivity of PTR glass at 355 nm enabled development of specs for a new laser system to record large aperture holograms. This laser was fabricated by Continuum Corp., a hologram recording setup with this laser was assembled at CREOL and successful recording of holographic optical elements was demonstrated. Research programs, which will benefit from the requested instrumentation, are in the areas of high power solid state, fiber and semiconductor laser systems, spectral beam combining of high power lasers, and stretching and compression of ultra-short laser pulses. CREOL will be able to develop new holographic optical elements that recently were considered impossible to create. Moreover, new phenomena recently discovered with this laser would pave a way for extension of spectral range of VBG operation to shorter wavelengths in UV and to longer wavelengths in IR.

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## **Scientific Progress**

Particular research opportunities enabled by this new setup are following.

- ? Dramatic increase of thickness and aperture of volume holographic elements in PTR glass that is vitally important for high power applications.
- ? Enhancement of uniformity of VBGs across the aperture that is a key for large aperture pulse compressors used in high power ultrashort pulse lasers.
- ? A new opportunity to ionize PTR glass with no sensitizers opens an opportunity for creation of holographic optical elements transparent in UV region up to 250 nm.
- ? A new effect was recently discovered in PTR glass doped with Tb<sup>3+</sup> -sensitivity to visible and near IR radiation. This phenomenon enables recording of complex holographic elements operating in these spectral regions. The use of the second harmonics of radiation at 532 nm paves a way to extremely narrow band secondary mirrors for receivers in LiDARs. The acquired laser allows research in this direction.
- ? The fundamental frequency at 1064 nm with high coherence length and high power enabling multiphoton absorption in IR transparent optical materials. This feature opens an opportunity to explore photosensitivity in such materials to realize a golden dream of holographic optical elements operating in 3-5 and 8-12  $\mu\text{m}$ . Such elements could provide spectral beam combining of quantum cascade lasers to reach necessary power for IR counter measures.

In conclusion, this instrumentation demonstrates all required parameters, is very beneficial in fabricating unique diffractive elements with large sizes and will trigger a submission of a number of new joint proposals. This will enhance CREOL's capability in conducting complex projects in the areas of laser development.

## **Technology Transfer**

The developed technology will be licensed to OptiGrate Corp. that already provides holographic optical elements to Army, Navy, Air Force, and DARPA. Researchers in all branches that use holographic optical elements will be informed on new opportunities.

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- 2. Proposal Title: Laser Setup for Volume Diffractive Optical Elements Recording in Photo-Thermo-Refractive Glass**
- 3. Contract/grant number: W911NF-14-1-0455**
- 4. Authors of report: Leonid Glebov, Ivan Divliansky**
- 5. Performing Organization and address: CREOL, the College of Optics and Photonics, University of Central Florida. 4304 Scorpius Str. Orlando, FL 32816**
- 6. Key words: UV laser, third harmonic generation, hologram recording, photo-thermo-refractive glass**
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Recorded in photo-thermo-refractive (PTR) glass volume Bragg gratings (VBGs) have found great applications for enhancement of lasers brightness and fine spectral filtering. However, further increase of size of holographic optical elements, which are required for high power laser applications, is restrained because of absence of available lasers emitting on PTR glass photosensitivity region (300-350 nm) with large coherence length and high power simultaneously. The recently discovered photosensitivity of PTR glass at 355 nm enabled development of specs for a new laser system to record large aperture holograms. This laser was fabricated by Continuum Corp., a hologram recording setup with this laser was assembled at CREOL and successful recording of holographic optical elements was demonstrated. Research programs, which will benefit from the requested instrumentation, are in the areas of high power solid state, fiber and semiconductor laser systems, spectral beam combining of high power lasers, and stretching and compression of ultra-short laser pulses. CREOL will be able to develop new holographic optical elements that recently were considered impossible to create. Moreover, new phenomena recently discovered with this laser would pave a way for extension of spectral range of VBG operation to shorter wavelengths in UV and to longer wavelengths in IR.

# Laser setup for volume diffractive optical elements recording in photo-thermo-refractive glass

US Army DURIP, Contract W911NF-14-1-0455, acc. #6501-6266  
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## 1. Photo-thermo-refractive glass

Photo-thermo-refractive (PTR) glass combines properties of a volume phase photosensitive material and an optical glass. PTR glass is a  $\text{Na}_2\text{O-ZnO-Al}_2\text{O}_3\text{-SiO}_2$  glass doped with silver (Ag), cerium (Ce), and fluorine (F). It is transparent from 350 nm to 2500 nm (Fig. 1). The chain of processes, which occurs in these glasses and produces refractive index variation, is as follows. 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. 1). This exposure results in photo-reduction of silver ions  $\text{Ag}^+$  to atomic state  $\text{Ag}^0$ . 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 except some additional absorption in blue and UV spectral regions. A number of commercially available lasers with long length of coherence can be used for such exposure. They are gas (He-Cd, Ar and N) lasers that are characterized by short lifetime and low power. Actually, the main goal of the project is to find a solid state laser that provide enough power, stability and coherence length to record large aperture, high quality holographic optical elements.

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

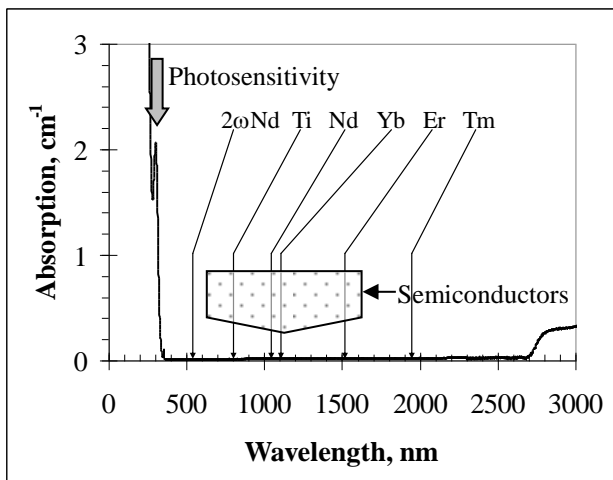


Fig. 1. Absorption spectrum of PTR glass and spectral lines of main laser sources in the window of transparency. Gray arrow shows the region of photosensitivity.



increased mobility of  $\text{Ag}^0$  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 decrement  $\Delta n$  about  $10^{-3}$  (1000 ppm) in exposed area compared to unexposed one can be achieved (Fig. 2). Such  $\Delta n$  enables phase incursion of  $\pi/2$  and therefore high efficiency of phase hologram in PTR glass wafers with thickness exceeding several hundreds of microns. No additional absorption exceeding small parts of inverted centimeter appears after hologram recording. Thus PTR glass is a negative phase photosensitive material.

There is an important consequence of the two-step process of recording which is finished by thermal crystalline phase precipitation in the bulk of PTR glass. 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  $40 \text{ J/cm}^2$  for 8 ns laser pulses at 1064 nm. Nonlinear refractive index in PTR glass is the same as that for fused silica which allows the use of PTR diffractive elements in all types of pulsed lasers. Testing of PTR diffractive grating under irradiation of two 1 kW Yb-fiber lasers (Nufern) combined by a volume Bragg gratings with efficiency of 99% and combined beam quality of  $M^2=1.16$  showed its stability. Thermal variations of refractive index in PTR glass are very low ( $dn/dt=5 \times 10^{-8} \text{ 1/K}$ ). This feature leads to thermal shift of Bragg wavelength in PTR diffractive gratings that is caused mainly by thermal expansion and is about  $10 \text{ pm/K}$  in vicinity of  $1 \text{ }\mu\text{m}$ . These diffractive elements tolerate thermal cycling up to  $400^\circ\text{C}$ .

Absorption spectra of regular PTR glass and glass matrix free of photosensitive agents after exposure to gamma radiation and fast protons show the main band of induced absorption placed in near UV region with maximum near 365 nm and ascribed to one of intrinsic color centers of multicomponent silicate glass. Coloration of glass in visible and near IR regions are resulted from the long wavelength tail of this absorption band and additional band of color centers centered near to 640 nm. It is important that in spite of strong coloration in visible and UV regions, additional absorption in neat IR region is still small and this glass can be used for different applications. Additional coloration is not completely stable at room temperature and one can see its bleaching after aging for several months. No refractive index changes were detected in gamma- and proton-irradiated samples of virgin PTR glass or PTR holographic elements.

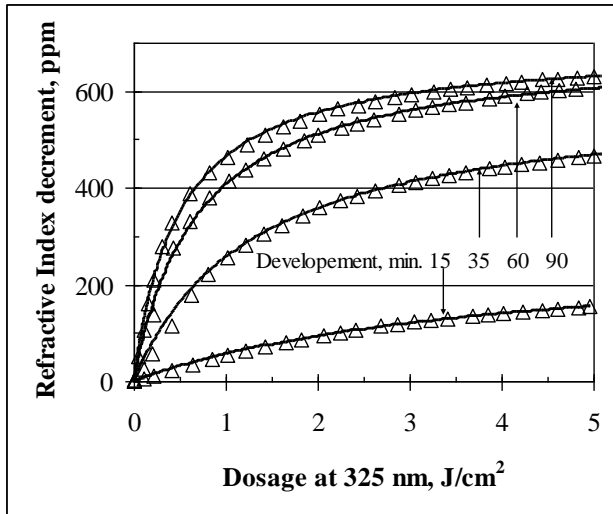


Fig. 2. Dependence of refractive index decrement in PTR glass on exposure at 325 nm after thermal development at  $520^\circ\text{C}$  for 2 hours. Solid lines – modeling by hyperbolic functions.

Thus PTR glass provides enough refractive index modulation combined with low losses for high-efficiency phase hologram recording and exhibits strong tolerance to elevated temperatures, laser and ionizing radiation.

A very important feature of PTR glass was discovered in the project “Volume Bragg gratings– research, testing and high power applications” contract W911NF-10-1-0441 funded by HEL JTO and ARO.

Up to that time, it was commonly accepted that photosensitivity of PTR glass is determined by  $\text{Ce}^{3+}$  absorption band that does not extend beyond 351 nm. Therefore, previously discovered photosensitivity of PTR glass to the third harmonic radiation from a Nd:YAG laser at 355 nm was explained with a non-linear mechanism. With the development of the method and procedures to measure the spectral dependence of the transmission in very thick PTR glass, we were able to re-investigate this effect. Figure 3 shows the spectral dependence of absorption coefficient of pristine PTR glass doped with regular cerium concentration. One can see that cerium appears to contribute to absorption beyond 360 nm. One can see that absorption coefficient at 355 nm is about 60 times smaller than that at 325 nm. However, it was not clear if excitation at longer wavelengths would provide photoionization.

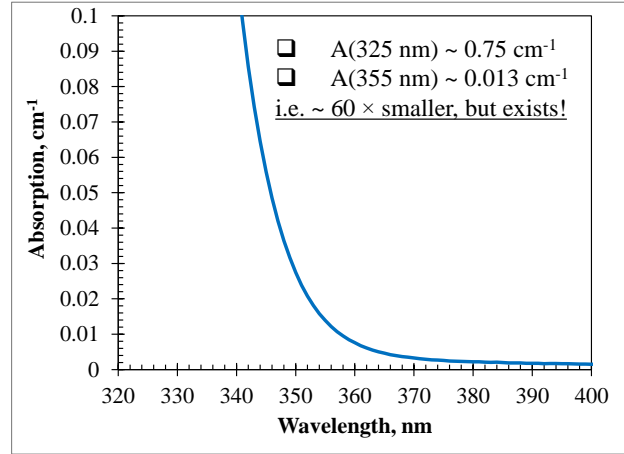


Fig. 3. UV absorption spectrum measured in a 50-mm-thick regular PTR glass.

We therefore tested again the photosensitivity of PTR glass to 355 nm radiation. It is obvious that nonlinear photosensitivity regime of PTR at 355 nm exists and it is hard to avoid it when nano-second pulses from a tripled frequency Nd:YAG laser are used. To minimize nonlinear effects, we increased a beam diameter up to 20 mm. A virgin PTR glass was exposed in this beam until reaching an approximate dosage of  $60 \text{ J/cm}^2$ . This sample was finally developed and placed in a Fizeau interferometer (Zygo Corp.) that allowed analyzing the wavefront distortions after propagating through this plate (Fig. 4). One can see that the exposed area of the PTR glass exhibits wavefront distortions corresponding to a peak-to-valley change of the refractive index equal to about 400 ppm. Power density could be estimated to be about  $100 \text{ kW/cm}^2$ . At such level, the probability to have two-photon absorption is very low and therefore, it is very likely that this result proves that PTR glass presents linear photosensitivity at 355 nm. This result is crucial because it paves a way to the development of new recording techniques that will allow:

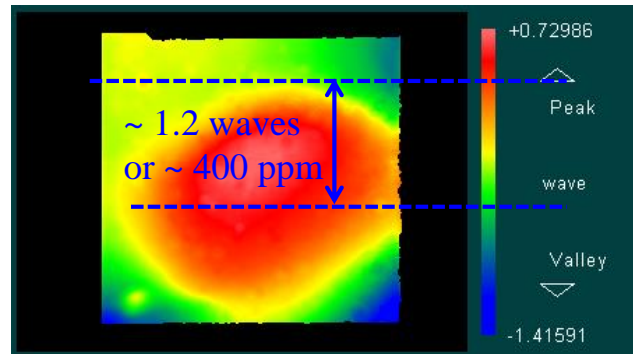


Fig. 4. Fizeau interferogram measured after propagating through a PTR glass plate exposed to  $\sim 60 \text{ J/cm}^2$  at 355 nm and thermally developed.

- Decreasing the recording time due to the availability of Nd:YAG lasers with high energy.
- Further decreasing this recording time if cerium concentration is optimized in order to get an absorption coefficient at 355 nm comparable to the one at 325 nm using the current cerium concentration.
- High energy of Nd:YAG laser will also allow the recording of larger aperture volume Bragg gratings.
- Actual concentration of cerium combined with 355 nm radiation will allow the recording of more homogeneous volume Bragg gratings.

This result described in the report of year 2012 is the scientific basis for development of the new hologram recording system that enables large aperture hologram recording for high power laser applications and fine filtering. The main features of holographic optical elements in PTR glass and areas of their applications are described in the next section.

## 2. Volume Bragg gratings in PTR glass

Volume Bragg gratings (VBGs) are relatively new optical components that appeared on laser market several years ago and already have found wide applications enabling record parameters in different areas of laser design. While basic optical properties and benefits of thick VBGs were understood at very early stages of laser development, real applications were limited by the absence of a proper photosensitive material that should provide necessary refractive index increment, low losses, and high tolerance to laser radiation and harsh environment. The situation was changed when a photo-thermo-refractive (PTR) glass with high optical homogeneity and low losses was created, high efficiency VBGs were recorded, and their applications for lasers were demonstrated.

A uniform VBG is a trivial phase volume hologram produced by recording of an interference pattern of two collimated beams. This recording results in creation of numerous planar layers with modified refractive index in the volume of a photosensitive optical material. These layers provide resonant diffraction of optical beams. It is important to note that properties of volume diffraction gratings are dramatically different from those of conventional surface diffraction gratings. Therefore, applications of VBGs are dramatically different from those of surface diffraction gratings. Let us consider the main types of VBGs and their basic properties.

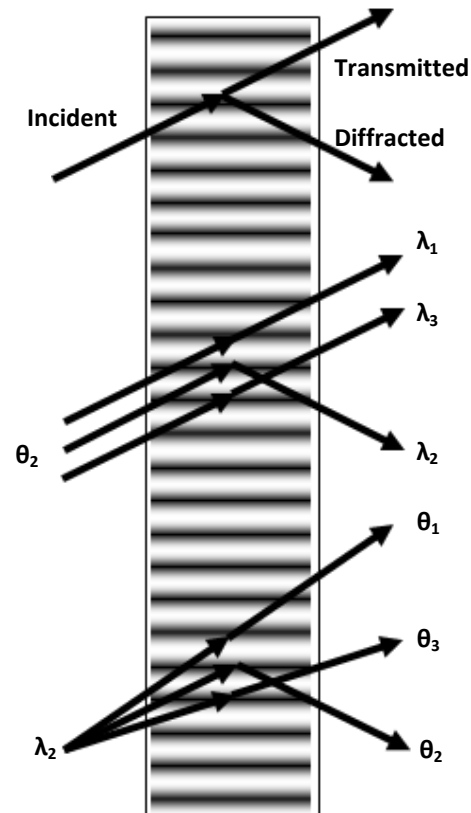


Fig. 5. Transmitting volume Bragg grating (VBG). Diffracted beam crosses the back surface. An incident beam with wavelength  $\lambda_2$  approaching a VBG at incident angle  $\theta_2$  is diffracted. All other beams with different wavelengths and/or different incident angles are transmitted through the VBG without changing direction of propagation.

A transmitting VBG (Fig. 5) recorded in a plane-parallel glass plate is a volume diffractive element where both transmitted and diffracted beams cross the back surface.

Diffraction occurs only if both a wavelength ( $\lambda_2$ ) and an incident angle ( $\theta_2$ ) of the launched beam correspond to Bragg condition. Contrary to surface gratings, at all other combinations of incident angles and wavelengths beams transmit the VBG without changing the direction of propagation. For the same VBG, an incident angle for a particular wavelength could be varied from normal to grazing because the VBG can be arbitrary oriented

inside of a glass plate (by changing of recording angles or by different cutting a recorded grating from an exposed glass slab). Grating orientation can be changed in such manner that diffracted beam would cross the front surface of the VBG (Fig. 6). This grating is a reflecting VBG or a Bragg mirror. Contrary to surface gratings where diffraction occurs for all wavelengths and angular dispersion can be about 1 deg./nm, VBGs deflect a narrow line for large angles up to  $180^\circ$  (Fig. 5, middle, for  $\theta_2$  approaching  $90^\circ$ ). This means that angular separation of adjacent narrow lines could be orders of magnitude higher if compared to that for surface gratings. For example, a Bragg mirror with spectral selectivity of 0.1 nm deflecting beam for  $180^\circ$  provides angular dispersion of 1800 deg./nm. Spectral selectivity of VBGs in PTR glass could be varied from tens of nanometers in large period transmitting gratings to tens of picometers in reflecting gratings.

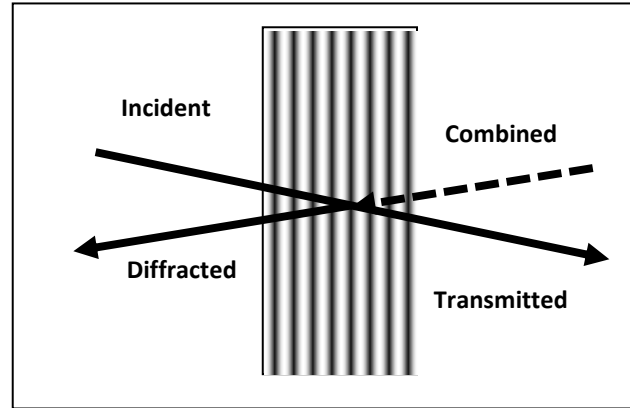


Fig. 6. Reflecting VBG. Diffracted beam crosses the front surface.

An important feature of VBGs is their ability to provide not only spectral but also angular selectivity (Fig. 5, bottom). Conventional angular filtering is produced by spatial filters that include a lens for Fourier transform from angles to spatial coordinates, spatial filtering, and Fourier transform back to an original beam. A VBG works in angular space (or in space of wave vectors) and it provides direct angular filtering. Transmitting VBGs are slits in angular space. Their angular selectivity could be narrowed down to tens microradians. Reflecting VBGs are round diaphragms in angular space and their angular selectivity could be narrowed down to few milliradians.

Dependences of diffraction efficiency on wavelengths and incident angles for VBGs are not smooth functions as they are for surface gratings. An example of a diffraction efficiency spectrum for a reflecting VBG is shown in Fig. 7. It has a sharp central

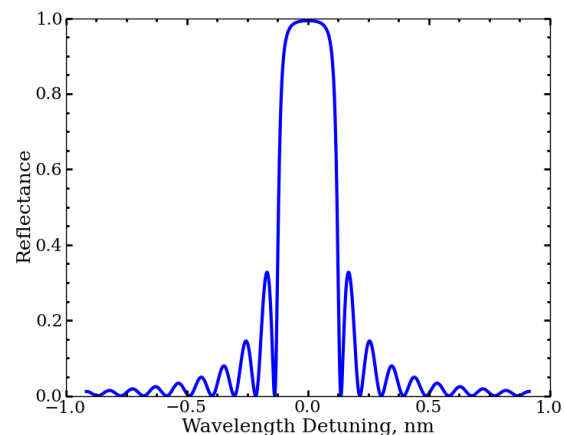


Fig. 7. The spectrum of diffraction efficiency for an RBG with a period of 360 nm, thickness of 4.0 mm and refractive index modulation of 270 ppm for  $\lambda=1064\text{nm}$  and  $\theta=10^\circ$ .

maximum and several side lobes separated by points with zero efficiency. An angular response of this VBG has the same shape. Similar spectra are observed for transmitting VBGs. This is a key feature that enables the use of VBGs for spectral beam combining and for angular magnification in laser beam steerers.

PTR glass enables multiplication of high efficiency VBGs in the same volume. Two gratings recorded in a glass plate with the same direction of grating vectors but with different periods produce a moiré pattern (Fig. 8, top) where spatial profile of refractive index has a fast-frequency component with a period average of periods of recording interference patterns and slow-frequency envelope determined by difference of those periods (Fig. 8, bottom). A fraction of moiré pattern between two zeros of a slow-frequency envelope is a Bragg mirror with apodized refractive index modulation profile. Two such fractions correspond to a Fabry-Perot interferometer. Unique features of such an interferometer are automatic alignment of “mirrors” naturally having a phase shift of  $\pi$  and a single transmission maximum. The narrowest band of such a filter having thickness of 6 mm was 9 pm at 633 nm.

It is possible in the same glass plate to record two or more gratings with different Bragg wavelengths that are oriented to have a common Bragg angle (Fig. 9, top). While these VBGs are overlapped in the same space, they are optically independent. Therefore, illuminating this complex element along a normal to the front surface at fixed wavelengths would result in diffraction of the beams with proper wavelengths in different directions. Figure 9, bottom demonstrates that a number of such VBGs with high efficiency can be recorded in PTR glass. It is clear that illuminating this grating by beams with proper wavelengths launched at proper angles would result in combing of those beams within the same aperture along the arrow in Fig. 9, top.

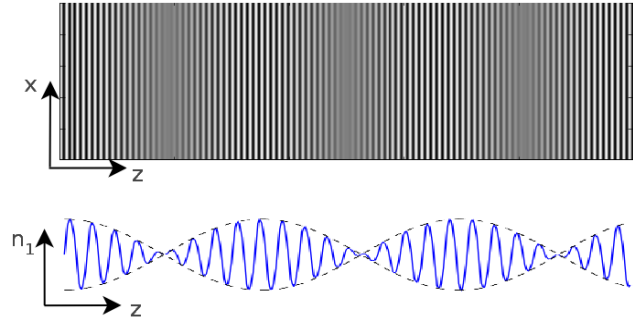


Fig. 8. Moiré grating recorded by sequential exposure to UV interference patterns with different periods (top) and spatial profile of refractive index (not in scale).

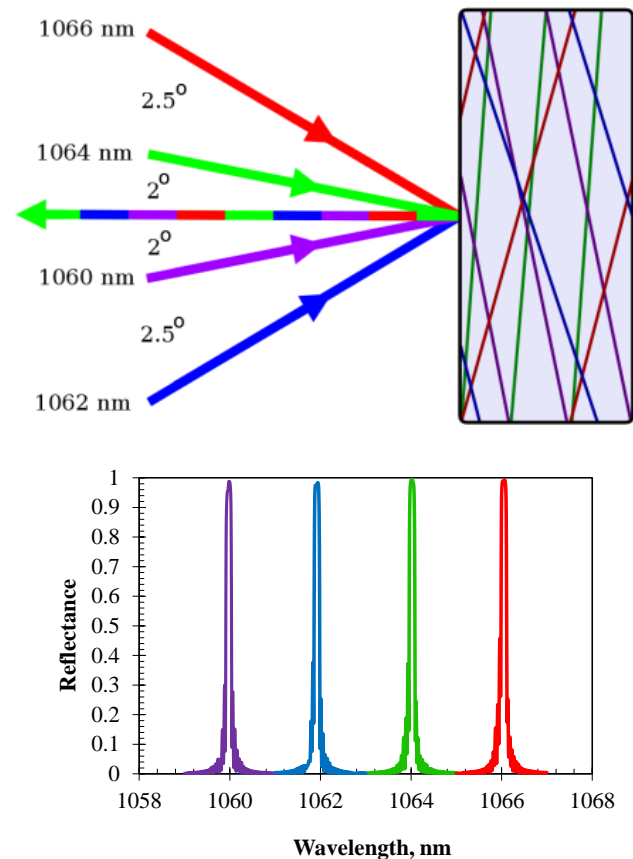


Fig. 9. Multiplexed reflecting VBG that includes four gratings with different periods and a common Bragg angle (top) and its reflection spectrum if illuminated along the normal to the front surface (bottom).

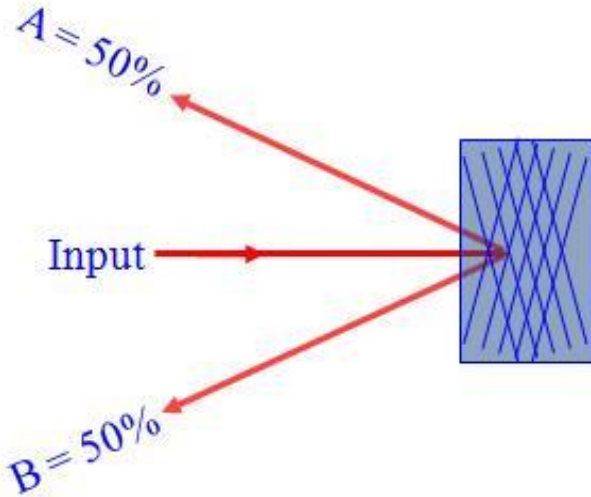


Fig. 10. Two identical VBGs recorded symmetrically in PTR glass act like a 1:2 splitter/combiner when the Bragg conditions are satisfied.

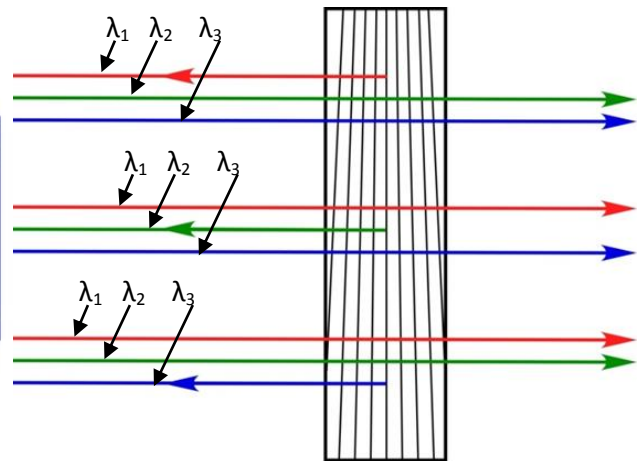


Fig. 11. Transverse chirped VBG with lateral variation of Bragg wavelength.

This is one of the promising approaches for spectral beam combining (multiplexing).

It is possible in the same glass plate to record several gratings with the same Bragg wavelengths that are oriented to have a common Bragg angle. These gratings are optically dependent because diffraction to the common Bragg angle would cause further diffraction to another grating. Figure 10 shows two identical gratings that work as a 1:2 beam splitter if illuminated the arrow from left to right. However, illumination of this multiplexed grating by coherent beams launched from directions A and B would result in coherent combining within a common aperture. Multiplexed gratings that provide splitting 1:2, 1:4 and 1:5 were recorded. Such elements enable coherent combining.

While uniform VBGs are recorded using an interference pattern produced by two collimated beams, it is possible to combine a divergent beam with and a convergent one. In this case the interference pattern consists of dark and bright planes with a period gradually changed in direction perpendicular to a bisector of the recording beams. If convergence and divergence angles are equal, the resulting VBG would have a grating with a linearly varied period. If the period variation directed across the aperture, it is a transverse chirped reflecting VBG or a Bragg mirror with a variable resonant wavelength (Fig. 11). Such a grating being placed as an output coupler for a laser array would lock it to a series of predetermined wavelengths. This output

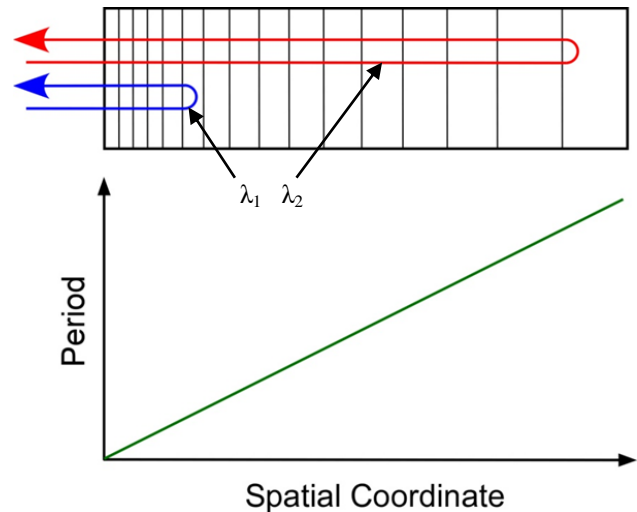


Fig. 12. Longitudinal chirped VBG (top) with period linearly varied in direction of beam propagation (bottom).

coupler being slid in lateral direction would tune emission wavelengths. If period variation is directed along the beam propagation, it is a longitudinal chirped reflecting VBG (Fig. 12). Such a grating can work as a wide band filter with spectral width extended up to tens of nanometers or as a pulse stretcher/compressor.

### **3. Laser applications of volume holographic elements in PTR glass**

One of the important applications is the use of spectral narrowing and stabilization for semiconductor diodes, bars and stacks to improve stability and efficiency of pumping solid state and fiber lasers. 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 from 60 to 100 pm. Emission wavelength does not depend on temperature of a diode. 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 were demonstrated with efficiency above 90%. The narrowest high power laser diode system was demonstrated for pumping Rb vapor. It provided 750 W within 20 pm at 780 nm.

The use of PTR Bragg mirrors for solid state lasers enabled spectral narrowing down to couple picometers with approximately the same power as for a laser with a conventional output coupler. This means that spectral brightness of those lasers was increased by three orders. It is important that even for fiber lasers with large length of resonators and, therefore, small distance between longitudinal modes, it was possible to make an external resonator with a VBG output coupler and to observe single frequency operation. A combination of a thick Bragg mirror and a Fabri-Perot etalon provides an opportunity to select a single transmission maximum of the etalon and enables successful operation in a single frequency regime for different rare earth ions doped solid state lasers. This approach brings numerous opportunities for design of narrow band laser systems.

Availability of new spectral filters that could be used in laser cavities resulted in creation of different tunable narrow band lasers. It is clear that rotation of a Bragg mirror results in variation of a reflected wavelength and can be used for spectral tuning. However, this tuning requires a concurrent realignment of an additional mirror to provide feedback. It is well known that a combination of two mirrors fixed at  $90^\circ$  is a one-dimensional retroreflector. If one of these mirrors is a Bragg mirror, it is still a retroreflector. However, variation of an incident angle would change the wavelength of the reflected beam. Such a device was used as a tunable output coupler for Yb:KYW laser. Emission of narrow line with 0.1 nm width and tunability for about 50 nm in vicinity of 1025 nm were demonstrated. Another approach for spectral tunability can be realized with the use of a transverse chirped VBG (Fig. 11) placed in a resonator as an output coupler. Sliding of this grating in direction perpendicular to the resonator axis would change a feedback wavelength. This scheme was realized for Yb doped fiber laser that have shown narrow emission line of 0.007 nm tunable within 5 nm range.

An important opportunity is provided by the use of VBGs not for positive feedback but for rejection of spectral components that are not desirable. This approach allows decoupling the most intensive spectral components from a resonator and, therefore, to obtain lasing at weak transitions of a gain medium. Laser emission at different Stark components of Nd in solid state lasers was successfully demonstrated. It should be noted that the use of filtering in the spectral



domain produces improvement of laser parameters in the time domain. Dramatic impact was produced by PTR Bragg mirrors incorporated in Nd:YLF regenerative amplifier. Spectral filtering resulted in suppression of background and increasing of contrast of amplified pulse for about three orders of magnitude.

As it was described in the previous Section 2 (Fig. 5), VBGs possess angular selectivity and therefore can serve as transverse mode selectors in laser resonators. The well-known requirement for a single-transverse-mode resonator is to provide a single Fresnel zone at an output coupler. Usually this requirement is satisfied by proper ratio between length and aperture of a resonator. However, a resonator that includes an optical element, which transmits radiation within a solid angle corresponding the first Fresnel zone, would support only a fundamental mode even for apertures significantly exceeding the size of the first Fresnel zone. Angular selectivity of VBGs was first realized for mode selection in semiconductor lasers where fast axis divergence is naturally diffraction limited while slow axis divergence is determined by interaction of large number of transverse modes. Angular selection along the slow axis was performed by both reflecting VBGs in convergent beams and by transmitting VBGs in collimated beams. It was shown that while typical width of a semiconductor waveguide to support a single transverse mode regime should be below 5  $\mu\text{m}$ , the external resonators with VBGs were able to keep single mode operation with waveguide widths up to 150  $\mu\text{m}$ . Spatial brightness of laser diodes was enhanced by an order of magnitude while spectral brightness was increased by three orders of magnitude. This approach was recently applied for solid state lasers where two dimensional mode selection was produced by reflecting VBGs in convergent beams and by pairs of transmitting VBGs in collimated beams. Both approaches have shown opportunities for decreasing divergence in resonators with large Fresnel numbers.

The problem of precise beam steering or receiver pointing is one of the key problems for both free space and waveguide communication systems. Large angle mechanical devices are bulky and slow, while electro-controlled devices steer within small angles. However, beam steering at small angles (below  $5^\circ$ ) produced by conventional electro-optical, acousto-optical or liquid crystal devices can be magnified by a stack of VBGs. This magnification is based on a specific profile of angular dependence of diffraction efficiency that includes a central lobe and a number of side lobes separated by zeros. This profile is similar to the spectral one depicted in Fig. 7. Deflection of a laser beam from a Bragg angle to the nearest zero causes deflection of the beam for a doubled Bragg angle. This angular magnification could exceed  $100\times$ . A stack of VBGs with difference between adjacent incident angles of  $0.1^\circ$  and difference between corresponding diffraction angles of  $10^\circ$  was designed and realized. Such approach for angular magnification in fast electro-optical switches was demonstrated and has shown dramatic decrease of their size.

High power ultrashort laser pulses in picosecond and femtosecond regions are in great demand for medical and industrial applications. However, direct amplification of such pulses is restricted by different nonlinear processes. Therefore, the main method of generation of high power and high energy ultrashort pulses is chirped pulse amplification (CPA) where an ultrashort laser pulse with a corresponding wide spectrum is stretched by a chirped fiber Bragg grating or a pair of diffraction gratings that provide different delays for different spectral components. The pulse with decreased power is amplified and then compressed back by one of these devices. Both methods have restrictions resulted from small aperture of fiber Bragg gratings (and



corresponding low laser damage threshold) and high sensitivity of diffraction grating pairs to misalignment (and corresponding low tolerance to vibrations and shocks).

Longitudinal chirped VBGs (Fig. 12) can produce operations with laser beam directly in the time domain. Such chirped Bragg mirror would reflect different wavelengths from different positions in direction of beam propagation. This means that reflection of different spectral components of a femtosecond laser pulse with wide spectrum would cause stretching the pulse in time and space domains. The width of a stretched pulse is determined by the delay time between extreme spectral components and it is equal to the time of double pass between corresponding points in the chirped VBG. The stretched pulse being directed to the same chirped VBG from the opposite side would be compressed back to its original state. Such gratings were fabricated and it was shown that stretching and compression could be performed with efficiency exceeding 98%. High laser damage threshold and low absorption of PTR VBGs enabled generation of high power laser pulses in CPA laser systems. Efficient stretching and compression of pulses was demonstrated for all types of ultrashort pulse lasers emitting from 0.8 to 2  $\mu\text{m}$ . Small size of VBG compressors (three orders of magnitude less volume if compared to that for a Treacy compressor) and high tolerance to shocks and vibrations enable great improvement of compactness and reliability of ultrashort CPA systems.

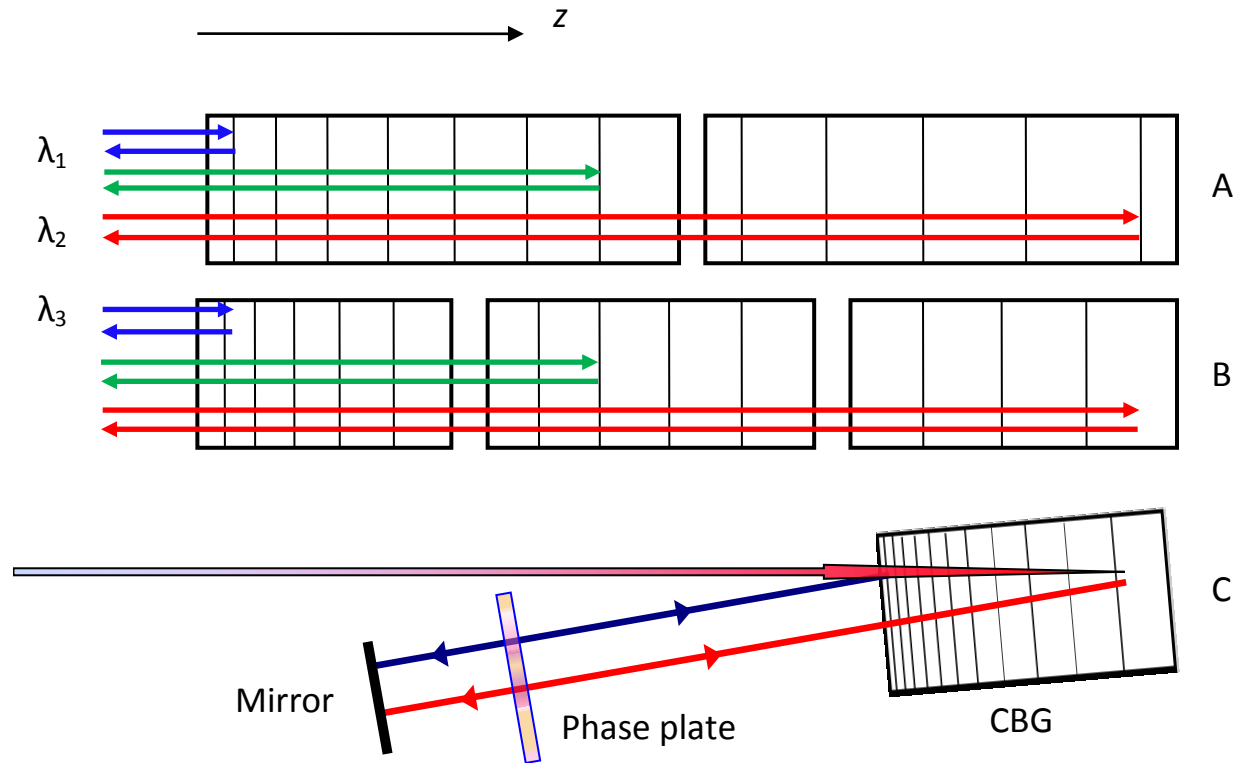


Fig. 13. Complex devices for temporal shaping ultrashort laser pulses. A – two section chirped VBG, B – three section chirped VBG, C – double pass chirped VBG with phase plate.

Additional capability to shape ultrashort pulses is provided by an opportunity to make sectional chirped gratings and multipass chirped gratings with phase correctors. It was found that two or

more sequential chirped VBGs (Fig. 13, A and B) with adjacent reflection spectra placed with a phase shift between sections multiple of  $2\pi$  work as a single monolithic grating with such an extended reflection spectrum. This approach enables increase of total delay time and spectral width beyond current technological limits. Moreover, varying the phase shift between sections allows wide manipulations with pulse shape including double pulses, pulses with precursors, super Gaussian pulses, etc. Another method to increase stretching time is the use of chirped VBGs in a multipass regime by the use of a retroreflecting mirror (Fig. 13, C). In this case, spectral width of the device is not changed but stretching time can be doubled, quadrupled, etc. In space between the VBG and the mirror, different spectral components of the laser pulse are dispersed in lateral direction. Therefore, placing a phase plate between the grating and the mirror provides different delays for different spectral components. This shaping in spectral domain causes reshaping in time domain.

A few years ago PTR glass was co-doped with  $\text{Nd}^{3+}$  and it was shown that this glass provides good luminescent parameters while keeping photosensitivity. CW laser action in this glass was demonstrated in a plane-concave resonator with diode pumping. Later PTR glass was successfully doped with Yb and Er and high efficiency reflecting VBGs were recorded in these glass plates. CW laser action was observed in Yb doped PTR glass in both distributed Bragg reflection (DBR) and distributed feedback (DFB) configurations (Fig. 14). It was found that completely monolithic solid state DFB laser emits up to 200 mW of single frequency radiation with spectral width about 250 kHz that can be tuned without mode hopping for about 130 GHz. This result paves a way to extremely robust narrow band solid state lasers for a great number of applications.

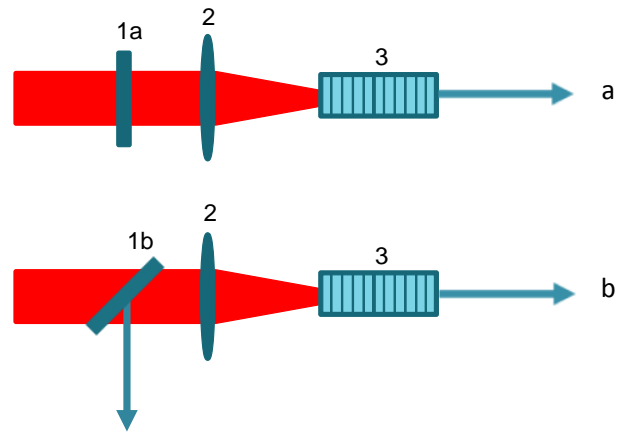


Fig. 14. Schematic of a DBR (a) and DFB (b) lasers in Yb doped PTR glass. 1a and 1b – dichroic beam splitters with HR at 1066 nm and HT at 976 nm, 2 – lens, 3 – Yb-doped PTR glass slab with 99% Bragg mirror.

It is common understanding that all types of lasers have restrictions for power scaling resulted from different nonlinear processes. Therefore, achievement of extremely high power of solid state and fiber laser systems would require different types of laser beam combining. There are two types of combining that enable increase of brightness – coherent combining, when several coherent beams are overlapped by proper phase control, and spectral combining, when several incoherent beams with different wavelengths are overlapped by proper spectral selective elements. The use of VBGs could play significant role in beam combining because of their extremely sharp spectral selectivity and their ability to provide phase locking of different lasers.

Spectral combining is based on a specific shape of diffraction efficiency spectra of VBGs (Fig. 7) where the central maximum and side lobes are separated by zeros. This means that a beam with a proper wavelength launched to a VBG at a Bragg angle (incident beam in Fig. 6) would

be diffracted. Another beam with a wavelength corresponding to one of zeros in the spectrum launched at the Bragg angle from the opposite side of the VBG (combined beam in Fig. 6) would pass the grating without diffraction and completely overlap with the first beam. For a lossless VBG, spatial brightness of a combined beam would be doubled. The sequence of such gratings designed for diffraction of specified wavelengths and transmission of all additional wavelengths provides an opportunity to combine a great number of laser beams. This approach has demonstrated highest spectral brightness of combining – five beams of Yb doped fiber lasers with wavelength separation between adjacent channels of 0.25 nm were combined with efficiency exceeding 90% to a single beam with divergence close to diffraction limit and total power of 750 W.

There are several improvements in the area of spectral beam combing. First, fabrication of multiplexed VBGs (Fig. 9) enabled combining of three (by a doubled VBG) and five (by a quadrupled VBG) lasers by means of a single optical element. This approach enabled dramatic decrease of a beam combiner size. Second, air cooling was demonstrated as an efficient method of increasing tolerance of VBGs to high power laser radiation. It was shown that VBGs can be used in multikilowatt laser beams without degradation of diffraction efficiency and divergence of the diffracted beams.

Ability of VBGs to provide phase locking of lasers was first demonstrated with semiconductor lasers. It was found that, if a spectral width of the VBG was less than the distance between adjacent longitudinal modes of internal resonators of the laser diodes, the use of a VBG for radiation exchange between two laser diodes produced phase locking and resulted in emission of coherent beams. This phase locking was stable and could be observed for a long time.

This approach was successfully used for coherent combining of fiber lasers. However it is not simple to scale of this combining to multiple channels. Development of multiplexed VBGs dramatically improved the situation. This complex optical element with several VBGs having a common Bragg angle for a specified wavelength works as a beam splitter as it is shown in Fig. 10. However if this element is illuminated by two coherent properly phased beams in opposite direction, it would work as a beam combiner. This property was used for active coherent combining of five fiber lasers with total power in a combined beam of 670 W. This scheme provides two features – radiation from an output coupler is completely mixed by a VBG before the redistribution between channels, and a combined high power beam propagates in free space not affecting fiber amplifiers. High efficiency passive combining of two and four fiber channels was recently demonstrated.

Thus, there are a great number of laser applications that enable dramatic increase of brightness of different laser systems by the use of volume Bragg gratings. Very often these applications require significant increase of aperture or thickness of VBGs that is a problem because of low power of all commercially available lasers applicable for high quality hologram recording. The effect of sensitivity of PTR glass to 355 nm described in Section 1 makes development of a narrow band solid state laser extremely beneficial for further enhancement of laser parameters.

Table 1. Quotation for narrow band laser system operating at 355 nm.

**Continuum**  
The High Energy Laser Company  
140 Baytech Drive  
San Jose, CA 95134  
USA

**Quotation**  
**No: 12362 - 108-14**

October 10, 2014

Page No. 1 of 1

TO: Dr. Leonid Glebov  
University of Central Florida  
CREOL  
Orlando FL

Quote valid for: 30 Days

Customer Ref. No:

Verbal

Leonid Glebov [mailto:lbglebov@creol.ucf.edu]

WE ARE PLEASED TO QUOTE THE FOLLOWING:

ITEM	QTY	DESCRIPTION	UNIT PRICE	TOTAL
<b>Pulsed UV laser system</b>				
01	1	Powerlite® Precision II Series, Model 8020: Q-switched Nd:YAG Laser, 20 Hz, 1200 mJ at 1064 nm.	78,800.00	78,800.00
02	1	DS-1, TS: Second (Type I) and Third Harmonic Generators for Powerlite® Series; provides maximum 355nm output	8,600.00	8,600.00
03	1	WSP-2: Wavelength Separation Package for second and third harmonic outputs for Powerlite® Series.	3,150.00	3,150.00
04	1	Stabilized SI-2000P Fiber Optic coupled Injection seeder for SLM operation of Powerlite series lasers, 0.003 cm-1.	30,250.00	30,250.00
05	1	<b>Narrow linewidth Variance: for an average output power of 4.5W @ 20Hz</b>	25,000.00	25,000.00
06	1	List details of Handling and Shipping Fees	1,100.00	1,100.00
Price includes installation, operator training, and all manuals. See attached documents for Terms and Conditions and Warranty specifications.				
Subtotal				146,900.00
<b>F.O.B.</b>		<b>Terms</b>	<b>Delivery Schedule</b>	Sales Tax % 0.00
San Jose, CA		Net 30 days	16 weeks ARO	Transportation
			Total US\$	\$146,900.00

For additional information contact:  
Jules Parent  
819-682-9982  
j.parent@continuumlasers.com

**Jules Parent**  
Continuum Lasers  
Jules Parent - Scientific Sales Engineer

Digitally signed by Jules Parent  
Date: 2014.10.10 15:24:56 -0400

#### 4. Target setting and principles of operation

The specs for the laser system were developed using the results of hologram recording produced in MRI project “Volume Bragg gratings— research, testing and high power applications”. The main challenge for development of the proposed laser is concurrent requirements of extremely narrow band and stability of wavelength to eliminate smearing of interference pattern in the process of holographic recording, high average power to overcome decrease of photosensitivity at longer wavelengths, and high peak power to provide efficient convergence of radiation to third

harmonic. Analysis of those requirements resulted in the following specifications for UV laser system.

Wavelength: 355nm (-15nm/+2nm)

Long term stability of wavelength within 30 min.:

goal 100 MHz (0.04 pm); acceptable 250 MHz (0.1 pm)

Spectral width:

Goal 100 MHz or less; acceptable - 250MHz

Pointing stability: 0.1 mrad

$M^2=1.1$  for a Gaussian beam or a single transverse mode for a super Gaussian beam

Average power

Goal 10 W; acceptable 5 W

Regime – pulsed

Power stability better than 5%

Water cooling is acceptable

Work environment – research laboratory

In the process of the proposal preparation, Coherent Corp. quoted such a laser system at \$150K. However, after awarding the DURIP contract, discussions with the Company and all available solid state laser companies have shown that no commercially available laser systems satisfy the specs shown above. Several companies proposed a development of a required laser. However, cost of such a development was dramatically higher comparing with available budget. The single company that agreed to improve their laser Powerlight Precision II Series, Model 8020 by the use a new injection seeder. However, they required an additional time to make preliminary experiments before accepting the order. The final quote is shown in Table 1.

The laser system includes an injection seeder that provides low power narrow emission line of 0.003 nm at a very well stabilized wavelength of 1064 nm. This signal is amplified to about 1 J.

Table 2. Specifications of Powerlight 8020 laser

### Powerlite DLS Series Specifications

Powerlite DLS Model	8000	8010	8020	8030	8050	9010	9020	9030	9050	Plus	Plus 2 J	Plus 2.5 J
Repetition Rate (Hz)	10	10	20	30	50	10	20	30	50	10	10	10
Energy (mJ)												
1064 nm	1200	1650	1200	650	550	2000	1800	1600	1200	3000	3500	3500
532 <sup>1</sup> nm	600	800	550	300	210	1000	900	800	600	1500	2000	2500
355 <sup>2</sup> nm	310	450	300	150	95	550	475	400	350	800	NA	NA
266 nm	120	150	80	50	30	160	110	90	75	160	NA	NA
Pulsewidth <sup>3</sup> (nsec)												
1064 nm	6-8	6-8	6-8	7-9	7-9	5-9	5-9	5-9	5-9	5-9	5-9	5-9
532 nm	5-7	5-7	5-7	6-8	6-8	4-8	4-8	4-8	4-8	4-8	4-8	4-8
355 nm	5-7	5-7	5-7	6-8	6-8	3-7	3-7	3-7	3-7	3-7	NA	NA
266 nm	5-7	5-7	5-7	6-8	6-8	3-6	3-6	3-6	3-6	3-6	NA	NA
Linewidth <sup>4</sup> (cm <sup>-1</sup> )												
Standard	1	1	1	1	1	1	1	1	1	1	1	1
Injection Seeded, SLM	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
Divergence <sup>5</sup> (mrad)	0.45	0.45	0.45	0.5	0.5	0.45	0.45	0.5	0.5	0.45	0.45	0.45
Beam Pointing Stability <sup>6</sup> (μrad)	30	30	30	30	30	30	30	30	30	30	30	30
Beam Diameter	9	9	9	7	7	9	9	9	9	12	12	12

Notes:

1. Using Type II doubler
2. Using Type I doubler
3. FWHM full width half max
4. FWHM (1cm<sup>-1</sup> = 30 GHz)
5. Full angle for 86% (1/e<sup>2</sup>)
6. 99.9% shots will be <±30 μrads with ΔT<sub>room</sub> <±3°C

After this its frequencies doubled and then tripled by two sequential nonlinear crystals. Pulse energy at 532 nm is up to 0.5 J and at 355 nm up to 0.3 J. Then radiation at different wavelengths is separated and launched to output windows.

## 5. Actual parameters of the Powerlite laser system

The system purchased with the DURIP funding was manufactured by Continuum Lasers. It was custom made to meet the strict demands for high coherence length of the emission while providing approximately 250 mJ per pulse. The specification for the system provided by the manufactures is shown if Table 2. The photo of a Powerlight is depicted in Fig. 15. The main element of the system is a solid state laser with tripled frequency that is seeded by a single mode diode. The final parameters of the delivered system are:

- 1) Output energy per pulse: 250 mJ
- 2) Laser emission wavelength: 355 nm or 532 nm
- 3) Coherence length: few meters
- 4) Repetition rate: 20 Hz
- 5) Output beam diameter: 7 - 8 mm
- 6) Beam profile: flat top



Fig. 15. Powerlite<sup>TM</sup> DLS 8000 laser system

The assembled laser system demonstrated parameters in accordance with the required specs while coherence length was even higher than we have requested.

## 6. Preliminary results of application of the Powerlite laser

As a first iteration, the beam at 355 nm was expanded to a size of 40 mm. Then it was split and recombined to a pattern of plane parallel fringes. We were able to successfully record



transmitting Bragg gratings (TBGs) using the laser system in the same PTR glass as we used for recording at 325 nm (He-Cd laser). Figure 16 shows the angular spectrum of such TBGs recorded at 355 nm. In this particular sample, two TBGs with different strength were recorded.

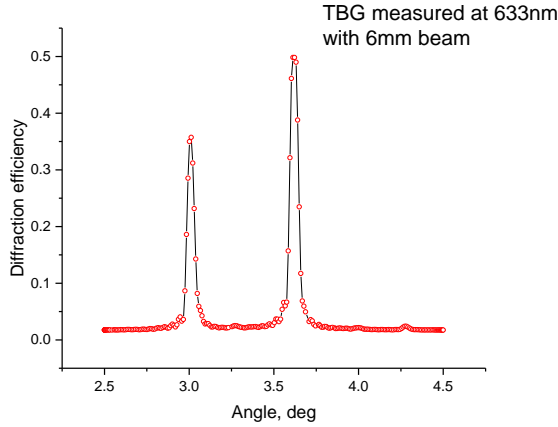


Fig. 16. Angular pattern of diffraction efficiency characteristics for two transmitting VBGs recorded in standard PTR glass using the third harmonic of a Nd:YAG laser at 355 nm.

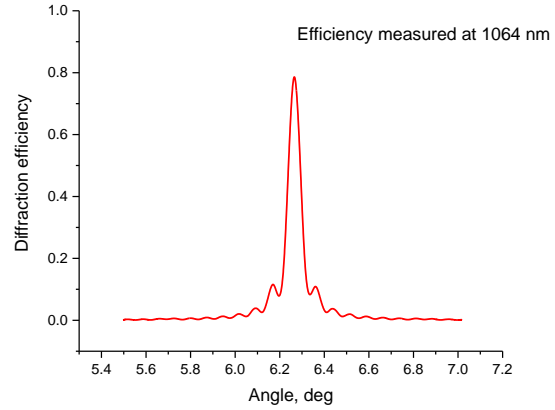


Fig. 17. Angular spectrum of diffraction efficiency of a TBG recorded by laser illumination at 355 nm in PTR glass with 10 times greater  $Ce^{3+}$  concentration comparing to conventional PTR glass.

It is important to stress on the differences and advantages gained by the use of the newly acquired laser system. First, we were able to use much larger recording beam diameter (40 mm instead of 25 mm, with potential to expand to 75 mm). Second, the exposure time when using standard PTR glass for recording was decreased from 15 min down to 3 min. This reduction in the recording time greatly improves the VBG quality by minimizing fringe smearing. Such smearing is mainly due to thermal drifts in the air that are different for each of the two recording beams but also due to mechanical instabilities in the optical setup. In parallel, due to the smaller absorption at 355 nm, the gratings are more uniform in depth when compared to the ones recorded at 325 nm.

We also started investigations in two new directions that were not conceivable without the purchase of this 355 nm laser system. First, in order to decrease even more the recording time we developed a new PTR glass with higher concentration of  $Ce^{3+}$ . The higher concentration leads to higher photosensitivity of the glass. We were able to record an 85% efficient TBG with only 30 s exposure time and standard thermal development. The grating angular efficiency properties are shown in Fig. 17. It is very important that even though the UV absorption at the recording wavelength is higher in the glass with more  $Ce^{3+}$ , it is still much lower if compared to the absorption of a regular PTR glass at 325 nm. Therefore, we not only can record now holograms using very short exposures but also can make very thick ones with minimal change of the hologram properties in depth.

The second direction is a new venue that we can explore only due to the large pulse energy the new laser provides. At energy levels of 250 mJ per pulse for 355 nm, two-photon absorption in multicomponent silicate glasses (e.g. PTR glass) becomes possible and therefore there it is

possible to eliminate photosensitizers in glass composition and, therefore, to extend transparency window to UV spectral region. To prove this idea, we illuminated a PTR glass, which had no  $\text{Ce}^{3+}$  in its composition, by pulsed radiation at 355 nm. We were able to acquire refractive index change on the order of 600 ppm by only 1 min exposure. Figure 18 shows an interferometric picture of the border between the exposed and unexposed regions of PTR glass after thermal development. The fringe pattern confirms the change of the refractive index happening at the edge of the laser beam exposure area.

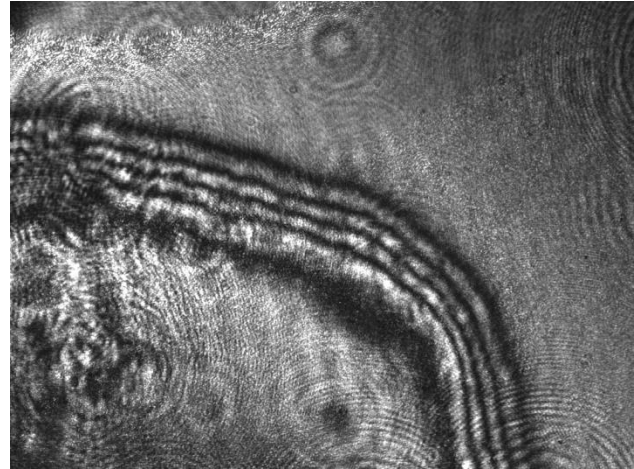


Fig. 18. Interferogram of the border between exposed and unexposed areas of PTR glass after illumination at 355 nm and further thermal development.

**Thus the acquired laser system demonstrated required specifications and provided recording of high quality holograms and will be used in further research projects.**

## **7. New horizons enabled by Powerlite laser based hologram recording system**

The acquired instrumentation will not only enhance the current ARO funded projects but will affect a number of research directions which utilize the use of PTR Bragg gratings for creation of lasers with narrow spectral width and narrow angular divergence. Research programs, which will benefit from the requested instrumentation, are in the areas of:

- High power solid state lasers (ARL)
- High power diode laser systems (DARPA),
- Spectral beam combining of high power fiber lasers (JTO)
- Stretching and compression of ultra-short laser pulses (Navy, Army)

Particular research opportunities enabled by this new setup are following.

- Dramatic increase of thickness and aperture of volume holographic elements in PTR glass that is vitally important for high power applications.
- Enhancement of uniformity of VBGs across the aperture that is a key for large aperture pulse compressors used in high power ultrashort pulse lasers.
- A new opportunity to ionize PTR glass with no sensitizers opens an opportunity for creation of holographic optical elements transparent in UV region up to 250 nm.
- A new effect was recently discovered in PTR glass doped with  $\text{Tb}^{3+}$  -sensitivity to visible and near IR radiation. This phenomenon enables recording of complex holographic elements operating in these spectral regions. The use of the second harmonics of radiation at 532 nm paves a way to extremely narrow band secondary mirrors for receivers in LiDARs. The acquired laser allows research in this direction.



- The fundamental frequency at 1064 nm with high coherence length and high power enabling multiphoton absorption in IR transparent optical materials. This feature opens an opportunity to explore photosensitivity in such materials to realize a golden dream of holographic optical elements operating in 3-5 and 8-12  $\mu\text{m}$ . Such elements could provide spectral beam combining of quantum cascade lasers to reach necessary power for IR counter measures.

## **Conclusions**

In conclusion, this instrumentation demonstrates all requires parameters, is very beneficial in fabricating unique diffractive elements with large sizes and will trigger a submission of a number of new joint proposals. This will enhance CREOL's capability in conducting complex projects in the areas of laser development.