Volume Holographic Elements for Spectroscopy and Laser Applications

Leonid Glebov

CREOL the College of Optics and Photonics
University of Central Florida
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Outline

1. Volume holographic elements
2. PTR glass – new material for volume phase hologram recording
3. Volume Bragg gratings
4. Volume phase masks
5. Monolithic solid state lasers
6. Narrow band spectral filtering
7. Locking, tuning and narrowing of laser emission spectra
8. Shrinking divergence of laser beams
9. Stretching, compression and temporal profiling of laser pulses
10. Coherent beam combining
11. Spectral beam combining
12. Summary
Optical elements

- Optical elements – lamps, lasers, lenses, mirrors, filters, etc. – produce generation and transformation of optical beams which is one of the basic procedures of modern world.

- These elements could be found anywhere from everybody’s cellphone to Moon or Mars.

- Fabrication of optical elements is based on geometrical shaping (surface profiling) of materials that possess proper optical properties – refraction, reflection, absorption and luminescence.

- There are numerous methods of shaping – cutting, grinding, polishing, molding, drawing, etching, deposition, sputtering, etc.

- Great matured industry all over the world supplies optical elements for multiple applications.
Volume optical elements

- This presentation considers a relatively new type of optical elements where optical beam transformations are produced not by surface profile but by means of three-dimensional spatial profile of refractive index in volume of optical materials.

- This spatial profile of refractive index in volume is produced by illumination of properly prepared photosensitive material with a specific optical pattern.

- The spatial profile of refractive index causes redistribution of phase of optical beams and, therefore, provide beam transformations. Materials enabling this procedure are called “Phase Photosensitive materials”. Depending on a recording procedure optical elements based on this technology are called “Volume Phase Holograms” or “Volume Phase masks”.
Phase volume optical elements are produced in a bulk material that provides permanent refractive index change after exposure to actinic optical radiation. Stability of the recorded pattern is usually provided by chemical or thermal development. Spatial refractive index modulation with periods comparable to wavelength results in diffraction of optical beams. Such elements are volume diffractive elements. One of the methods to produce such patterns is a holographic technology and these elements are called holographic optical elements.
Seeing three-dimensional world

Changing position of a three-dimensional object results in two-dimensional imaging of different sides of this object on a retina. If the object is a lens, one can see imaging, magnification, etc.
Changing position of a two-dimensional object (photograph) results in two-dimensional imaging of the same side of the object on a retina. Photograph of a lens cannot work as a lens.
Changing position of a hologram results in two-dimensional imaging of different sides of virtual three-dimensional object on a retina. Hologram of a lens can work as a lens for the wavelength of recording.
The simplest volume hologram is a volume Bragg grating (VBG) which is a system of plane parallel layers with different refractive index. This pattern is produced by interference of two collimated laser beams.
Volume gratings as dispersive elements

Prisms and surface gratings are conventional dispersive elements for different angles and wavelengths. Spectral resolution power for surface gratings is up to 8,000; angular dispersion is below 1 deg/nm.

Volume gratings are dispersive elements for a single wavelength and a single incident angle. Spectral resolution power up to 20,000. “Angular dispersion” for a finite number of wavelengths up to 1000 deg/nm.
Volume Bragg gratings as rejection spectral filters

Both transmitting and reflecting volume Bragg gratings work as spectral rejection filters. Spectral width could be varied depending on thickness and period from tens of nanometers to few of picometers.
Volume gratings as filters in angular space

Transmitting Bragg grating works as a slit and reflecting one works as a round diaphragm in angular space. At the same time those gratings work as slits in spectral space. Therefore, proper adjustment of spectral and angular parameters of gratings and emitters paves the way for effective angular and spectral control of optical beams.
Volume holographic elements were demonstrated and their comprehensive theory was developed in 1960s. It became clear that unique spectral and angular properties of these elements are extremely promising for laser beams control:

- Spectral filtering
- Angular selection
- Spatial filtering
- Variable attenuation
- Beam deflection
- Beam splitting
- Beam sampling
- Beam combining
- Etc.

However, up to 2000s there was no real use of those elements in laser development.
Volume holograms for beam control

- The ideal recording material for holography should have a spectral sensitivity well matched to available laser wavelengths, a linear transfer characteristic, high resolution, and low noise, be indefinitely recyclable or relatively inexpensive.

- While several materials have been studied, none has been found so far that meets all these requirements.


- New holographic material is created at UCF/CREOL which is photo-thermo-refractive (PTR) glass. Phase volume holograms were recorded in this material with absolute diffraction efficiency up to 99%. Photosensitivity of 1 ppm mJ⁻¹cm² is ranged from 280 to 350 nm (He-Cd, N₂, and Ar lasers), resolution from 0 to 10,000 mm⁻¹, low noise, non-erasable, thermal stability 400°C, laser stability 100 kW/cm², fabrication cost similar to conventional optical glass.

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Photo-thermo-refractive (PTR) glass is a multicomponent silicate glass (Na$_2$O-ZnO-Al$_2$O$_3$-NaF-KBr-SiO$_2$ glass doped with Ce and Ag) which provides permanent refractive index change resulted from exposure to UV radiation followed by thermal development.
Mechanism of photosensitivity

1. UV exposure ionizes Ce\textsuperscript{3+}. The released electron is trapped by a silver ion converting it to a silver atom. Volume distribution of Ag\textsuperscript{0} is a latent image. No refractive index change.

2. The first heat treatment causes neutral silver atoms to diffuse and aggregate into nucleation centers. No refractive index change.

3. The second heat treatment causes precipitation of NaF crystals in exposed areas. It causes decrease of refractive index comparing to that in unexposed areas.
Photo-thermal crystallization

Development at high temperature produced well known peaks of cubic NaF. Development required for fabrication of a high efficiency hologram results in precipitation of small fraction of available sodium and fluorine. X-ray diffraction pattern corresponds to cubic NaF with broadened lines shifted to smaller angles.
Refractive index in an UV exposed area is changed after crystalline phase precipitation in the process of thermal development. Glass composition is designed to provide proper absorption of actinic UV radiation and enable uniform refractive index change in the bulk of glass.
Photo-thermo-refraction

PTR glass sample irradiated with 1 J/cm² at 325 nm and developed for 1 h. at 520°C. Refractive index change (RIC - difference between exposed and unexposed areas) is measured by a shearing interferometer. RIC is negative - exposed area has lower refractive index. RIC is proportional to XRD signal of NaF. No RIC were obtained in samples with no XRD signal.
Photosensitivity ranged from 280 to 350 nm, transparency from 350 to 2700 nm, absorption in the near IR region below 0.0001 cm\(^{-1}\), refractive index 1.49, Abbe number 60, photoinduced refractive index increment up to \(10^{-3}\), spatial frequencies from 0 (zero) to 10,000 mm\(^{-1}\). Phase pattern stable up to 400°C and cannot be erased by any type of optical or ionizing radiation, laser damage threshold similar to fused silica.
PTR glass was co-doped with Nd, Yb, and Er. This glasses demonstrate high efficiency luminesce typical for multicomponent silicate glasses, combined with photosensitivity. This feature enables creation of monolithic solid state lasers which are not sensitive to vibrations and shocks.
Laser-induced damage thresholds of PTR-glass surface are 10 and 40 J/cm² for pulse width 1 and 8 nm, respectively.

Nonlinear refractive index of PTR glass is the same as that for fused silica $3.3 \times 10^{-20}$ m²/W.
Lowest absorption level in PTR VBGs at 1 µm region is $10^{-4}$ cm$^{-1}$. The main detrimental effects are thermal shift of Bragg wavelength (10 pm/K at 1 µm) and thermal lensing that are mainly determined mainly by thermal expansion of PTR glass. Up to 1 kW – no cooling while diffraction limited divergence in transmitted and diffracted beams. Experiments with artificially discolored gratings show that air cooling can keep low divergence at few tens of kilowatts. Tests at Nufern have shown no beam quality deterioration for a 1 kW beam with $M^2=1.1$. 
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Transmitting PTR Bragg gratings

Deflection angles ranged from 3 to 140°, angular selectivity from 0.1 to 10 mrad, spectral selectivity from 0.3 to 20 nm. Typical losses at current PTR technology are ranged from 0.5 to 2% and caused mainly by induced scattering. Relative diffraction efficiency for plane wave up to 100% for wavelengths ranged from 400 to 2500 nm. Maximum aperture 50x50 mm².

Angular selectivity of transmitting Bragg grating, λ=1550 nm, n=1.495. Spatial frequency 450 mm⁻¹.

Grating thickness, mm

- 4
- 2
- 1
- 0.5

Experimental data

Modeling

λ=1550 nm

Modeling plane wave

d=1.5 mm
Reflecting PTR Bragg gratings

Deflection angles ranged from 120 to 180°, angular selectivity for normal incidence from 10 to 100 mrad, spectral selectivity from 0.02 to 2 nm. Absolute diffraction efficiency up to 98.5% is demonstrated. Relative diffraction efficiency for plane wave up to 99.99% for wavelengths ranged from 633 to 2500 nm. Maximum aperture 35x35 mm².
Multiplexed Bragg gratings

- 4 Transmitting Volume Bragg Gratings were multiplexed (M₄TBG)
- TBGs recorded symmetrically for 5° angular separation in air
- Average power in five channels @1064 nm is 22% ± 3%
- Insertion loss <1%
Multipass monolithic reflecting gratings

Filter roll off for two-pass monolithic system is -83 dB/nm.
Filter roll off for four-pass monolithic system is -140 dB/nm.
Direction of beam propagation is not changed
Multipass transmitting gratings

Angular side lobes can be suppressed by 10-20 dB. Angular filter that does not change beam direction.
Volume Bragg gratings with variable spatial frequency are called chirped Bragg gratings. If chirp is directed along the beam propagation, it is a longitudinal chirped grating. These gratings allow extending of spectral width of Bragg mirror to tens of nanometers. They produce spatial separation of different wavelengths in a diffracted beam (chirping of laser pulses). Thickness up to 100 mm, aperture up to 6x15 mm².
Volume Bragg gratings with variable spatial frequency across the aperture are transverse chirped gratings. These gratings allow locking of single emitters in an array to different wavelengths. Aperture up to 35 mm, spectral width of locked lasers down to 100 pm.
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Mode Conversion by Binary Phase Plates

Conversion to TEM$_{11}$ mode

φ = π

φ = 0

Conversion to LG$_{04}$ mode

φ = π

φ = 0

Applications

- Mode selection in fibers
- Gaussian beam generation

Theory

Experiment

Theory

Experiment
Vortex

\[ \varepsilon = \frac{\text{Energy in annulus}}{\text{Total Energy}} \]

\[ \varepsilon_{\text{theoretical}} = 0.91 \]
\[ \varepsilon_{\text{experimental}} = 0.82 \]
A hologram of a phase mask is recorded by placing the phase mask in one of the arms of a two-beam holographic system.

- Multiplexing can be achieved via sequential recording of multiple masks
- Broadband phase mask operational wavelength
- Recording wavelength: 325 nm
- Beam diameter: 25 mm
- Fringe period: Controlled by mirrors
- Sample tilt: Adjusted for each phase mask
Broadband Holographic Phase Masks

The same holographic mask converter works at vastly different wavelengths.
Surface and Volume gratings combination

- Surface gratings (SG) will diffract different wavelengths of incident light according to the grating equation.

\[ \Lambda_{SG} \sin \theta = m\lambda \]

- If the period of the surface grating is twice the period of volume Bragg grating, then the Bragg condition will be met for all first order diffracted wavelengths.

\[ 2\Lambda_{V BG} \sin \theta_p = \lambda \]

- Using a second surface grating the converted beam will be diffracted to its initial direction.
Achromatic mode conversion

Far field profile of the diffracted beam after propagating through a holographic four-sector mode converting mask aligned to two surface gratings at (left) 765 nm, (center) 978 nm, and (right) 1071 nm. The sizes shown here are not to scale.
Outline

5. Monolithic solid state lasers
RE doped PTR glass is used to make compact monolithic laser! Spectroscopic parameters of PTR glasses doped with Nd, Yb and Er have are similar to typical silicate laser glasses.
Output power: 550-600 mW (multi-frequency regime due to several transverse modes)
Output power: 50-150 mW (single frequency regime)
Slope efficiency: 20%; M2=1.34; Linewidth ≤250 kHz; Power stability <5%
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Notch filters reject scattered Rayleigh light that “overshadows” good signal.

- Bandwidth of notch filter limits the lower range of frequencies to be measured.
- BragGrate™ Notch Filters enable Rayleigh light rejection as close as 5 cm\(^{-1}\) from the laser line.
Linewidth of BragGrate™ notch filter vs thin film notch filter

The bandwidth of a typical BNF is about 100-200 pm, whereas bandwidth of TF filters can’t be narrower than 2-3 nm. Optical density of single BNF is limited to about OD5 and, thus, to provide sufficient Rayleigh light suppression depending on the measurement wavelength 2 to 3 filters have to be used in sequence.
Raman spectrum of SiGe superlattice
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Spectral locking and narrowing of solid state lasers

Emission spectra of Cr:LiSAF laser with different output. Increase of spectral brightness with low power penalty. This approach was applied for a great number of crystalline and glass lasers.
Spectral locking and narrowing of laser diodes

Semiconductor laser diode in an external resonator with PTR reflecting Bragg grating as an output coupler emits narrow line of few tens of picometers width. Emitting wavelength does not depend on temperature. Power is about 97% of that in a bare diode. This approach is successfully applied to edge emitters, VCSELs and GCSELs. PTR Bragg mirrors are transparent at second harmonic wavelength. Trumpf produces thousands and thousands of such lasers.
Narrow band laser diode bar module

Laser module includes a diode bar with a thermo-controlled VBG coupled to a fiber connector. Power 40 W. Spectral width <20 pm. Absorption in a Rb cell >90%. OptiGrate put these module to commercial production at 780 and 795 nm.

VBG is packed in a thermally controlled housing which provides fine tuning of its maximum of reflection with accuracy ±1 pm.
Conversion of scientific results to practical devices

OptiGrate Corporation produced a laser system operating at 780 nm with spectral width of 20 pm and power up to 1000 W. The system is working for several years.
Tunable Yb-fiber laser

OptiGrate Corporation produced a laser system with the following parameters: single transverse mode, CW regime (no pulsations), output power up to 2.3 W, emission line width – <7 pm, coarse tuning range – 5-10 nm, fine tuning - ~10 pm.
Lasing at wavelengths with small emission cross sections

Combination of selective feedback and rejecting VBGs in laser resonators enables oscillation at very weak transitions because feedback at the main transitions is eliminated. We were able to emit any Stark components of Nd emission band in YAG. The right figure shows luminescence spectrum of Nd in PTR glass and wavelengths that after frequency doubling correspond to positions of Fraunhofer lines in visible.
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Diffraction efficiency is a multiplication in angular space.

- Angular response of TBG has worse overlap with higher order modes, causing higher losses.
Transverse mode selection in laser diodes

Broad area semiconductor laser is converted to a source of narrow band stable radiation with diffraction limited divergence. Power is 97% and brightness is 300 times higher comparing to those for bare diode. Total power of 2 W from a single diode with diffraction limited divergence is shown.
Transverse mode selection in solid state lasers

1cm cavity length

Dichroic HR

1mm thick Nd:YVO₄

TBG

90% O.C.
Transverse mode selection in solid state lasers

- Demonstrated highly multimode cavities with near single mode output
- 0.8 mm diameter pump (N ~ 15) with $M^2$ 1.1
- 30cm long cavity required for single mode operation with 36% efficiency
- 30% efficiency in single mode operation with TBGs and 1cm cavity length
- 1.6 mm diameter pump (N ~ 60) with $M^2$ 1.3
- 2.0 mm diameter pump (N ~ 94) with $M^2$ 1.4
- $M^2$ can remain low in all pump diameters given proper TBG in cavity
- TBGs are an effective means of improving the beam quality in a laser resonator, while allowing the cavity length to remain short
Transverse mode selection in fiber lasers

1 - “Ribbon” fiber, 2 – transmitting VBG as a mode selector, 3 – HR VBG as a feedback mirror, 4 – reflecting VBG as an output coupler, 5 – fiber FAC, 6 - fiber SAC.

Fiber core: 107.8μm x 8.3 μm, Yb³⁺ doped with 2.1dB/m absorption at 915nm; 13 modes guided along slow axis.
Transverse mode selection in fiber lasers

- $M^2$ improved from 11.3 to 1.45
- Slope efficiency reduced from 76% to 53%
- Brightness improved from $0.878\ \text{W/(mm}^2\text{mrad}^2)$ to $4.45\ \text{W/(mm}^2\text{mrad}^2)$
- Beam quality remains steady at more than 10 times threshold
- No nonlinearity seen in mode profile or output power
Transverse mode conversion by double grating

1. A higher order mode diverges into the two lobed far field pattern,
2. With each lobe aligned to the Bragg condition of the gratings, a lens reimages the mode onto the multiplexed VBG,
3. Each lobe constructively interferes within the MTBG to diffract along a common channel,
4. The two lobes propagate along the same angle to produce a diffraction limited Gaussian beam.
Single mode LMA fiber laser s

Such a resonator support a higher order single mode in a gain element while emits a fundamental single mode (Gaussian beam).
Transverse mode conversion in fiber lasers

- Main peak is diffraction limited
- Better than 50% slope efficiency
  - Equal to single mode efficiency of fiber
- Side lobes aren’t insignificant
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Laser pulses stretching and compression

- Power increase by $10^4$ as compared to FBG
- Reciprocal stretching and compression
- Compact geometry, self-alignment, environmental stability
- Diffraction efficiencies exceeding 95%
- High power operation (>1 kW average power)
- High energy operation (> mJ pulse energy)
- Preserves diffraction limited beam quality

2 mJ CPA fs-laser system
Courtesy of QPeak Inc.
Laser pulses stretching and compression

Top: Folded stretcher design which is still ~80 cm in length.

Bottom: 2-cm CBG which provides 200-ps stretch pulse duration, 2 cm thick.
Laser pulses temporal shaping

Double pass CBG provides spectral dispersion in direction perpendicular to direction of beam propagation. Placing phase masks between a CBG and a retroreflecting mirror enables shaping of spectral and temporal components. Effect of binary mask with Pi shift between section is shown in bottom figure.
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Emission of two commercial single transverse mode laser diodes

A combination of the wide spectra beams emitted by commercial LDs with no VBG control produces a uniform pattern at the screen.
Spectral locking by PTR Bragg mirror

Spectral narrowing results in a speckle pattern on the screen
Phase locking of semiconductor lasers

If spectral width of the locking grating is narrower than the free range of the internal Fabri-Perot resonator, the diodes emit coherent radiation that was observed several months in spite of the fact that the diodes and the Bragg mirror were mounted at three different stages.
Coherent beam combining of 2 fiber lasers using reflecting $M_2$-VBG

> 90% Combining Efficiency!

Slope Efficiency: 48%
Combining Efficiency: 91%

Normalized Intensity:

- Diff-1
- Diff-2
- CBC (avg)

Wavelength, nm

Launched Pump, mW

Output Power, mW

- Broad Window
- Narrow Window
- Total Losses

70 dB
Coherent beam combining of 4 fiber lasers using reflecting M$_4$-VBG

Laser amplifiers are in a common resonator; phase-locking achieved via radiation exchange, common feedback and self-organization.

Advantages of VBGs compared to surface DOEs:
- Polished Surface
- Single diffraction order with >99% combining efficiency is possible
- Multiplexing of VBGs allows combining of 2D arrays
Power Scaling using LMA Fibers

- 25/250 PM Yb-doped
- 2 – 2.5 m Long Fiber
- 30 W 976 nm Pump per Channel
- High DE M-VBG

Joint experiments with AFRL with higher power pumping in large area fiber amplifiers. Two-loop ring cavity was implemented to avoid spatial burning in the resonator.
Power Scaling using LMA Fibers

- >88% Combining Efficiency!
- Stable Continuous Wave!
- Bandwidth < 20 pm resolution limited!
- Beam Quality the same as for original beams
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Spectral Beam Combining by Reflecting VBG

Spectral Selectivity

Beam combining metrics:
- Total combined beam power
- Combined beam $M^2$
- Combining efficiency

Beam Combining Factor (BCF)

$$BCF = \frac{(P/M^2)_{\text{Combined}}}{\sum (P/M^2)_{\text{unit}}}$$
Combining of 5 Beams with 0.25 nm Channel Separation (DARPA ADHELS)

- Spectral distance between channels - 250 pm
- Total combined power – 755 W within 1 nm with efficiency 91%
- Beam quality of combined beam $M^2 \approx 1.5$
- Spatial brightness 270 TW/Sr•m²
- Beam combining factor 0.51
Spectral Beam Combining by doubled VBG

<table>
<thead>
<tr>
<th></th>
<th>$\lambda_1$ (1062.8 nm)</th>
<th>$\lambda_2$ (1064.2 nm)</th>
<th>$\lambda_3$ (1063.3 nm)</th>
<th>Combined 2 beams</th>
<th>Combined 3 beams</th>
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<tr>
<td>Power, W</td>
<td>135</td>
<td>150</td>
<td>143</td>
<td>282</td>
<td>420</td>
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<td>$M^2_x$</td>
<td>1.05</td>
<td>1.05</td>
<td>1.13</td>
<td>1.15</td>
<td>1.38</td>
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<tr>
<td>$M^2_y$</td>
<td>1.05</td>
<td>1.05</td>
<td>1.16</td>
<td>1.08</td>
<td>1.20</td>
</tr>
</tbody>
</table>

- Up to 99% combining efficiency
- $M^2$ of the combined beam is very close to $M^2$ of the individual beams
Spectral combining of kilowatt beams

- Experiments at Nufern facility
- Spectral distance between channels 2nm
- Beam diameter 5.8 mm
Spectral combining of kilowatt beams

- VBG absorption $2.15 \times 10^{-4}$ cm$^{-1}$
- Cooling air flow 2.5 cfm
- Temperature increase 9.5°
- Distance between channels 2.05 nm
- Combined power 2.02 kW
- $M^2 = 1.16$ ( $M^2_x = 1.13$ $M^2_y = 1.18$)
- Combining efficiency 98%
- Astigmatism - 0.197 mm
- Rayleigh Length 1.959 mm
High refractive index modulation VBG

Transmission spectra of a reflecting VBG with refractive index modulation of 1300 ppm. Such high value enables recording gratings with extremely high diffraction efficiency (above 99.99%) and wide angular acceptance. This feature provides an opportunity to combine beams of semiconductor lasers with high divergence.
Commercial fiber coupled LD pumping module was efficiently spectrally locked through a delivery fiber.

30 W pumping module having 3 LDs inside (IPG Photonics) coupled to 105 µm fiber with 0.12NA was used. The module was locked by a VBG placed in a collimated beam after the fiber. Locking VBGs had about 90 pm spectral width (FWHM), 40% diffraction efficiency and different Bragg wavelengths detuned for 1 nm.
Laser diode modules: spectral locking

External VBG feedback allowed locking LD emission and narrowing spectral width down to 150pm in the whole interval of applied current. Side mode suppression was more than 40dB outside 1 nm spectral interval at maximum applied current.
Laser diode modules: beam combining

Three LD pumping modules, locked by reflecting VBGs through fiber were combined by two reflecting VBGs. Spectral distance between channels was 1.1 nm. Such spectral distance allows combining up to 7 channels inside of 976 nm Yb$^{3+}$ absorption band.
Laser diode modules: beam combining

- 10 W LD modules coupled to 100 μm 0.12 NA fibers emitting at 976 nm are used
- The modules locked through fibers by VBGs to narrow lines with Δλ<0.2 nm
- Three modules emitting 30.1 W are combined by two VBGs with efficiency of ~90%
- Spectral distance between channels ~1.1 nm
- Combined beam can be coupled to a 100 μm 0.12 NA fiber – 3x brightness increase
Volume Bragg gratings (VBGs) recorded in photo-thermo-refractive (PTR) glass are narrow band filters working in both spectral and angular domains.

It is possible to record several VBGs in the same volume of a glass plate while all gratings would be optically independent.

VBGs can be used in multikilowatt laser beams inducing minimum thermal distortions.

VBGs effectively provide spectral and angular narrowing and stabilization for solid state, fiber and semiconductor lasers.

Transverse chirped VBGs provide smooth spectral tuning.

Longitudinal chirped VBGs provide stretching, compression and temporal shaping of laser pulses.

A stack of VBGs (or multiplexed VBGs) provide high efficiency spectral beam combining for fiber and semiconductor lasers increasing their spatial brightness.

Multiplexed VBGs provide phase locking and coherent combining of fiber and semiconductor lasers.