Thermal tuning of volume Bragg gratings for spectral beam combining of high-power fiber lasers

Derrek R. Drachenberg,[1,2,*] Oleksiy Andrusyak,[1,3] George Venus,[1] Vadim Smirnov,[4] and Leonid B. Glebov[1,4]

[1]CREOL, College of Optics and Photonics, University of Central Florida, 4000 Central Florida Blvd., Orlando, Florida 32816, USA

[2]Currently with NIF-Photon Science and Applications, Lawrence Livermore National Lab, 7000 East Ave., Livermore, California 94551, USA

[3]Currently with IPG Photonics, 50 Old Webster Rd., Oxford, Massachusetts 01540, USA

[4]OptiGrate Corp, 562 South Econ Circle, Oviedo, Florida 32765-4311, USA

*Corresponding author: drachenberg1@llnl.gov

Received 29 November 2013; revised 12 January 2014; accepted 13 January 2014; posted 16 January 2014 (Doc. ID 202123); published 20 February 2014

High-radiance lasers are desired for many applications in defense and manufacturing. Spectral beam combining (SBC) by volume Bragg gratings (VBGs) is a very promising method for high-radiance lasers that need to achieve 100 kW level power. Laser-induced heating of VBGs under high-power radiation presents a challenge for maintaining Bragg resonance at various power levels without mechanical realignment. A novel thermal tuning technique and apparatus is presented that enables maintaining peak efficiency operation of the SBC system at various power levels without any mechanical adjustment. The method is demonstrated by combining two high-power ytterbium fiber lasers with high efficiency from low power to full combined power of 300 W (1.5 kW effective power), while maintaining peak combining efficiency within 0.5%. © 2014 Optical Society of America

OCIS codes: (230.1480) Bragg reflectors; (090.2890) Holographic optical elements; (140.3298) Laser beam combining; (140.3510) Lasers, fiber; (160.2750) Glass and other amorphous materials.

http://dx.doi.org/10.1364/AO.53.001242

1. Introduction

High-brightness lasers are needed for many applications in defense and manufacturing. Rare-earth doped fiber lasers and amplifiers promise robust diffraction-limited high-power output, but thermal and nonlinear effects limit the single-mode output power of single source fiber lasers [1]. Novel fiber geometries and high-order modes are being explored to circumvent these limits, but have not yet been scaled to high power [2–7].

1559-128X/14/061242-05$15.00/0

Ultimately, whatever power can be achieved by a single source can be increased by beam combining. Spectral beam combining (SBC) by volume Bragg gratings (VBGs) is a very promising method for high-radiance lasers that need to achieve 100 kW level power. High-power SBC results have been reported with surface diffraction gratings that typically combine beams with greater than 1 nm of spectral separation [8,9]. VBGs recorded in photo-thermo-refractive (PTR) glass are the key combining elements for very high-density SBC. It is possible to combine beams with high efficiency and beam quality using such elements with less than 0.25 nm spectral separation between beams while keeping the spectral width of an individual laser above 10 GHz

(0.03 nm). Kogelnik's paper on coupled wave theory for thick holograms has formed the basis of theory for the design of VBGs [10]. The engineering principles for the design of VBGs have been previously published [11,12]. High-power, high-efficiency SBC by VBGs has also been previously reported [13,14], as well as a method to optimize the design of VBGs for SBC for an arbitrary number of combined beams [15].

Brightness in a spectral combining system based on VBGs is increased by transmitting a beam of a nonresonant wavelength and diffracting a beam with a resonant wavelength. The two beams must be collinear at the VBG output. However, high-power laser radiation heats the glass, causing thermal expansion and a shift in the VBGs' Bragg wavelength. The VBG and the diffracting beam must then be realigned angularly to satisfy the new Bragg condition at the elevated temperature and to maintain collinearity with the transmitting beam. In a multistage SBC system, each successive VBG stage will experience increasing laser intensity and therefore increasing thermal load and Bragg wavelength shift. The first VBG combines two beams, while the final VBG combines N-1 transmitting beams with one diffracting beam, for an N beam combining system. This means that, without the thermal tuning method described in this paper, all stages of a multistage SBC system would need to be angularly realigned if the power of combined beams is varied.

In order to illustrate the utility of thermal tuning of VBGs, let us estimate the parameters for accuracy of alignment of VBGs for high spectral density combining. VBG-based SBC experiments with a spectral separation, $\Delta\lambda$, as low as 0.25 nm have been reported [16]. The VBGs used in that publication had a resonance wavelength of 1064 nm, thickness of 4.78 mm, and refractive index modulation of 211 ppm. The reflection spectrum of such a VBG modeled with Kogelnik's theory [12] is shown in Fig. 1. To reduce interchannel leak, the transmission wavelength is matched to the third minimum of the VBG's efficiency spectrum and is 0.25 nm from the Bragg wavelength. Modeling was carried out for a monochromatic beam with divergence of 0.5 mrad

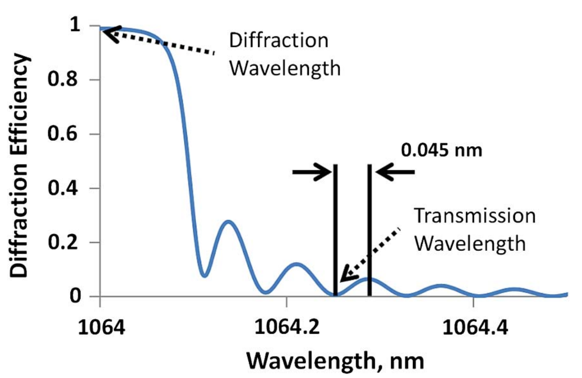

Fig. 1. Diffraction efficiency spectrum for a VBG used for high-density spectral beam combining.

(half-angle), which is diffraction limited for a 1.35 mm diameter beam. The distance between the third minimum and the nearest maxima of reflection efficiency is only 0.045 nm. A wavelength offset of this value would reduce transmittance of the grating by 7%–12% depending on the direction of the wavelength offset. The diffracting beam would also experience a reduction in efficiency for a 0.045 nm tuning error, but only by 1.5%. Maintaining very precise control of the Bragg wavelength is important for the diffracting beam but critical for the transmitting beam.

However, there is an opportunity for Bragg wavelength control by thermal tuning of VBGs that eliminates the need for precise mechanical devices. It is known that refractive index variation with a change in temperature for PTR glass is very low, below 10^{-6}/K [17], and therefore the change in optical path length due to a change in temperature is mainly determined by the coefficient of thermal expansion, which is about 10^{-5}/K [18]. Therefore, the Bragg wavelength of a VBG in PTR glass can be shifted thermally at a rate of 0.01 nm per Kelvin when operating around 1064 nm, and the temperature can be easily controlled with thermo-electric controllers to within 1 K. Thus, the thermal tuning method is proposed in this paper to enable nonmechanical adjustment of a multistage system. This paper will describe the method of thermal tuning of VBGs for SBC (Section 2.A), and the thermal behavior and effect on beam quality of a laser heated VBG with thermal control (Section 2.B), and report the first SBC of two ytterbium fiber lasers by a thermally tuned VBG with high efficiency, beam quality, and a combined output power of 300 W (Section 3).

2. Thermal Tuning of Volume Bragg Gratings

A. Principles of Operation

Typically, a VBG-based SBC system aligned at low power to satisfy the Bragg condition for the diffracting beam(s) must be realigned angularly for high-power operation in order to compensate for the Bragg wavelength shift that occurs when the VBG temperature is changed due to a small absorption of the high-power laser radiation. This requires deployment of high-precision mechanical components and an elaborate realignment algorithm, especially for high-channel-count SBC. In the proposed thermal tuning technique, the temperature of a VBG is pre-elevated to the final operating temperature by heating the edges. A VBG mount with thermal control is shown in Fig. 2. The VBG is surrounded with four thermo-electric coolers (TECs), which are mounted on a water-cooled plate. These TECs provide grating temperature control in the range from ~5 to 90°C with accuracy of about ±0.1 K. The initial angular alignment without any laser-induced heating must be performed at an elevated temperature. An increase in incident laser power heats the VBG center causing a thermal

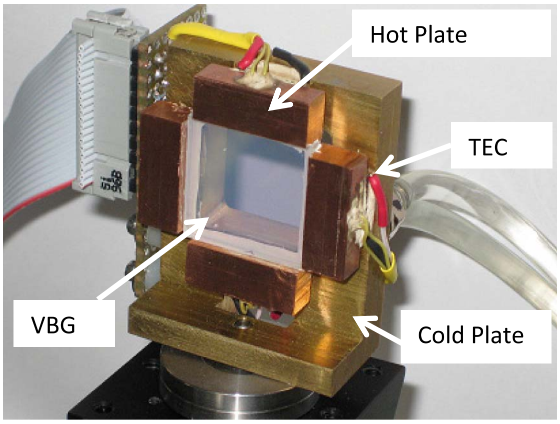

Fig. 2. VBG mount with thermal control.

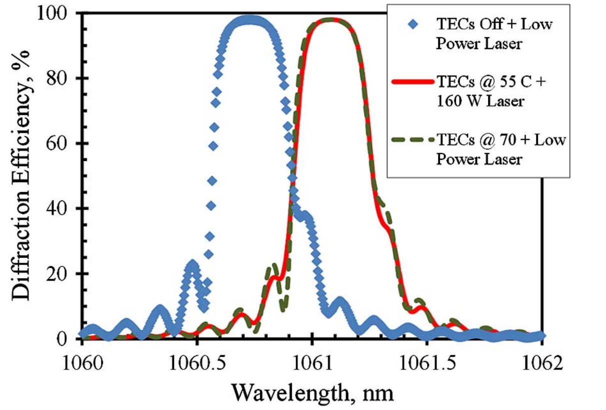

Fig. 4. Diffraction efficiency of a VBG under various heating conditions.

expansion of the grating. The VBG edge temperature is then lowered using thermal tuning to recover the original temperature at the grating center, and to maintain combining efficiency without the need for mechanical adjustment.

In order to probe the VBGs' diffraction behavior while under various heating and laser exposure conditions, a wavelength tunable, low-power probe beam was overlapped on the VBG with the high-power beam. The experimental setup is illustrated in Fig. 3. The wavelength of the probe beam is scanned to collect the diffraction efficiency spectral profiles of the VBG with or without laser-induced heating at various edge temperatures provided by TECs.

The commercially available VBGs in PTR glass have an absorption coefficient (internal optical density divided by thickness in centimeters) as low as 2×10^{-4} cm^{-1}. However, in order to simulate the effect of thermal tuning on higher power systems, a VBG with increased absorption of 1.1×10^{-3} cm^{-1} was used. Due to the increase in PTR glass absorption of approximately five times, the laser-induced heating produced in the following experiments simulates heating of low-absorption VBGs by lasers of five times higher power. The high-power laser used produces a beam with a 6 mm diameter at $FWe^{-2}M$, and ~160 W of output power. This means that the experiments described below correspond to an approximately 800 W laser illuminating a commercial low-absorption VBG. A low-power tunable laser was used with a 6 mm diameter beam at $FWe^{-2}M$, and ~10 mW of output power. Both lasers have close to diffraction-limited beam divergence. The temperature of the VBG may be varied by either the TECs at the edge shown in Fig. 2 or laser-induced heating from the high-power laser.

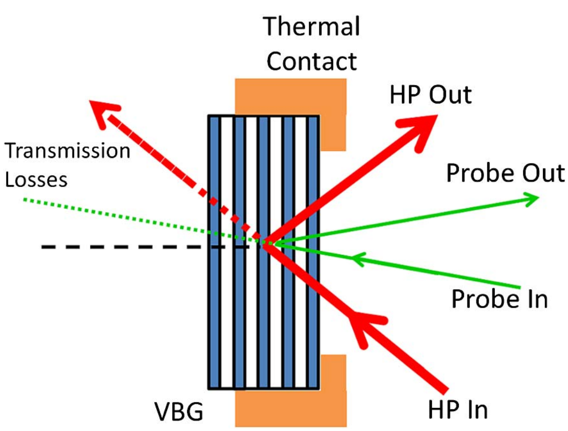

Fig. 3. Experimental setup for measuring the diffraction efficiency spectral profile of thermally controlled VBGs exposed to high-power laser radiation.

The following set of examples illustrates the process of thermally controlled SBC. Figure 4 shows the VBG diffraction efficiency spectral profile for three different cases, measured with a low-power probe beam. The case of a room temperature (25°C) VBG with no laser-induced heating is shown with dots. Next, the TEC temperature was set to 70°C, resulting in a thermally induced Bragg wavelength shift to a longer wavelength of 0.45 nm. Next, the high-power beam was turned on to full power, and the TEC temperature was lowered until peak diffraction efficiency was recovered (55°C, edge temperature.). The diffraction efficiency of a probe beam diffracted from the VBG under exposure to the high-power beam (case 3) was unchanged by the laser-induced heating (compared to edge heating only—case 2). The solid line shows the diffraction efficiency spectral profile of the VBG with the high-power beam at full power and the heater temperature set to 55°C. The two curves overlap, showing identical Bragg wavelength and diffraction efficiency from low to high laser power.

B. Impact on Beam Quality

In order for VBGs to be used in practical laser systems, it is necessary to understand the impact that thermal tuning has on Bragg wavelength homogeneity, as well as the beam quality of a beam diffracted from a thermally tuned VBG. In this section we discuss both effects. The thermal gradient of a VBG across the aperture of the laser beam can affect both the diffraction efficiency and the beam focusing. Therefore, it is important to minimize the thermal gradient. Heating the edge of the grating while the high-power laser heats the center results in a thermal gradient that is smaller than it would be without edge heating.

A probe beam with a 3 mm diameter is used in order to examine the thermal profile across a VBG that has a controlled edge temperature with and without heating by high-power laser radiation. A change in Bragg wavelength as measured by the probe beam is the result of expansion or contraction of the VBG and the associated grating period at the location of the probe beam. The probe beam is translated across the VBG aperture in order to determine the transverse Bragg wavelength shift in nanometers, which relates to the thermal shift by 0.01 nm/K. To run these measurements, the experimental setup of Fig. 3 was modified by replacing the low-power probe collimator that produces a 6 mm beam with one that produces a 3 mm beam. Figure 5 shows the Bragg wavelength shift as a result of heating across the grating aperture while the VBG is under various heating conditions. The Bragg wavelength shift is the difference between the Bragg wavelenth of the VBG under some external heating and at room temperature (no heating).

The lower solid line shows the Bragg wavelength shift as a result of heating from only the 160 W laser. The upper dashed line shows the Bragg wavelength profile while the VBG is heated from the edges to 70°C. As the higher power laser radiation was turned on, the VBG edge temperature was reduced until peak diffraction efficiency was restored (edge temperature of 55°C). The Bragg wavelength profile that resulted from applying both high-power laser radiation and edge heating is shown by the upper solid line.

As a result of a combination of laser heating in the center and TEC heating from the edges of the VBG, the Bragg wavelength gradient between the center and the edge of the VBG is significantly reduced. Also, the resulting average Bragg wavelength across the beam aperture is maintained, showing that diffraction efficiency was maintained without angle tuning the grating or spectrally tuning the laser. The M^2 beam quality of a full aperture (6 mm) test beam was measured to determine any effect the VBG thermal tuning technique may have on beam quality. Table 1 shows the peak diffraction efficiency and M^2 under various heating conditions. It is clear from these results that the thermal tuning method does not deteriorate beam quality. The first three rows are the results of changing the VBG edge temperature without any high-power radiation, while the final two rows show the results with high-power radiation at two different VBG edge temperatures. In all cases, $M^2 \sim 1.1$, and diffraction efficiency was 98%.

Table 1: VBG Diffraction Efficiency and Test Beam M^2 under Various Heating Conditions

Incident Optical Power	Edge Temperature, °C	Heater (on/off)	Peak Diffraction Efficiency	Probe Beam M^2
0 W	~25°C	Off	98.0%	1.12
0 W	70°C	On	98.0%	1.09
0 W	55°C	On	98.0%	1.10
160 W	37°C	Off	97.7%	1.12
160 W	55°C	On	98.0%	1.09

3. Spectral Beam Combining with Thermally Tuned Volume Bragg Gratings

The novel thermal tuning technique, described above in detail, can be used in SBC to keep the gratings in resonance from low power up to the full power of a given SBC system. Formerly, an SBC system would be aligned such that peak combining efficiency is achieved only for a specific power level. Changing power required mechanical adjustment to maintain SBC efficiency. Angle tuning a VBG set while kilowatt-level radiation is incident on the grating is impractical as it would require high-precision motorized mechanics and a complex tuning algorithm. Thermal tuning eliminates the need for mechanical tuning and may be electronically controlled with proper feedback. Mechanical alignment is used only to make all combined beams overlapped and collinear at the output, while thermal tuning is used to maintain peak combining efficiency throughout the power range of the system.

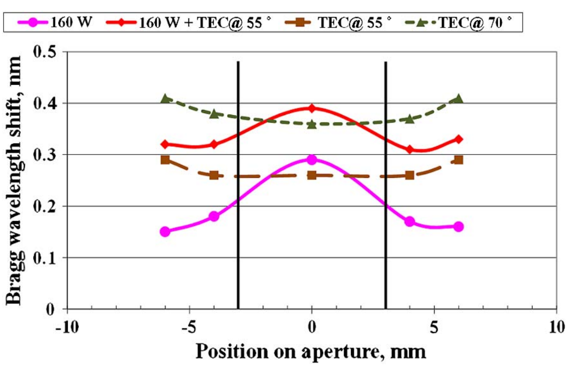

Fig. 5. Bragg wavelength profile across the VBG aperture under various heating conditions.

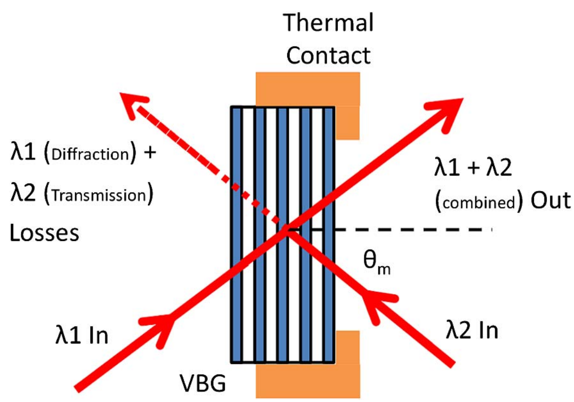

Fig. 6. Two-channel high-power SBC experimental setup.

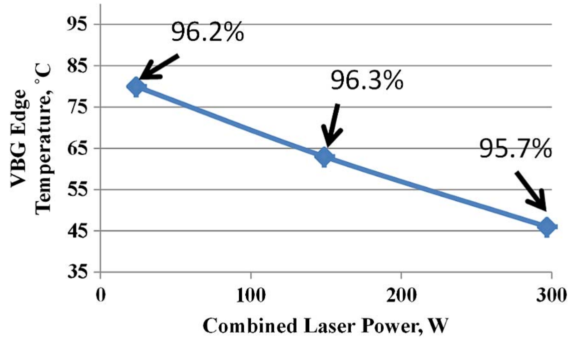

Fig. 7. Two-channel beam combining efficiency at different power levels and VBG edge temperatures.

Figure 6 shows the experimental setup for two-channel high-power SBC. One VBG with thermal tuning was used to combine two high-power lasers with a spectral separation of 0.50 nm (1064 and 1064.5 nm). Figure 7 shows the experimentally found optimal VBG edge temperature as a function of output laser power. The combining efficiency for each data point is also given. From 25 to 300 W, beam combining efficiency remained virtually unchanged without any angular tuning required. It should be noted that the VBG used in this demonstration had an intentionally increased absorption coefficient of $\alpha = 1.1 \times 10^{-3}\ \mathrm{cm}^{-1}$, 5× higher than the state of the art, in order to experimentally simulate thermally tuned SBC with a laser-induced heat load equivalent to 1.5 kW of combined laser power.

4. Conclusions

In high-power laser systems with SBC using VBGs, heating of VBGs by laser radiation requires angular realignment of the system for each power level. A novel thermal tuning technique is demonstrated that allows tuning of the Bragg resonance of a VBG, and was shown to maintain the beam combining efficiency of an SBC system from 30 to 25 W without affecting beam quality by maintaining the temperature and hence Bragg period in the center of a VBG at the peak of the incident laser radiation. The result is an experimental simulation of SBC of 1.5 kW of power due to the 5× increased absorption in the glass used for this experiment compared to VBGs with the lowest absorption available. With low-absorption PTR glass, this tuning technique could be applied to multikilowatt laser applications.

This research was funded by the Defense Advanced Research Projects Agency (DARPA), ADHELS Program, contract No. H0011-06-1-0010. D. Drachenberg acknowledges the support of the Directed Energy Professional Society (DEPS) Graduate Scholarship.

References

1. J. W. Dawson, M. J. Messerly, R. J. Beach, M. Y. Shverdin, E. A. Stappaerts, A. K. Sridharan, P. H. Pax, J. E. Heebner, C. W. Siders, and C. P. J. Barty, "Analysis of the scalability of diffraction-limited fiber lasers and amplifiers to high average power," Opt. Express **16**, 13240–13266 (2008).
2. D. R. Drachenberg, M. J. Messerly, P. H. Pax, A. K. Sridharan, J. Tassano, and J. W. Dawson, "First selective mode excitation and amplification in a ribbon core optical fiber," Opt. Express **21**, 11257–11269 (2013).
3. A. Sridharan, P. H. Pax, J. E. Heebner, D. R. Drachenberg, P. J. Armstrong, and J. W. Dawson, "Mode-converters for rectangular-core fiber amplifiers to achieve diffraction-limited power scaling," Opt. Express **20**, 28792–28800 (2012).
4. D. Rockwell, V. Shkunov, and J. Marciante, "Semi-guiding high-aspect-ratio core (SHARC) fiber providing single-mode operation and an ultra-large core area in a compact coilable package," Opt. Express **19**, 14746–14762 (2011).
5. S. Ramachandran, J. M. Fini, M. Mermelstein, J. W. Nicholson, S. Ghalmi, and M. F. Yan, "Ultra-large effective-area, higher-order mode fibers: a new strategy for high-power lasers," Laser Photonics Rev. **2**, 429–448 (2008).
6. A. L. Bullington, P. H. Pax, A. K. Sridharan, J. E. Heebner, M. J. Messerly, and J. W. Dawson, "Mode conversion in rectangular-core optical fibers," Appl. Opt. **51**, 84–88 (2012).
7. D. R. Drachenberg, M. J. Messerly, P. H. Pax, A. K. Sridharan, J. Tassano, and J. W. Dawson, "First multi-watt ribbon fiber oscillator in a high order mode," Opt. Express **21**, 18089–18096 (2013).
8. C. Wirth, O. Schmidt, I. Tsybin, T. Schreiber, R. Eberhardt, J. Limpert, A. Tünnermann, K. Ludewigt, M. Gowin, E. ten Have, and M. Jung, "High average power spectral beam combining of four fiber amplifiers to 8.2 kW," Opt. Lett. **36**, 3118–3120 (2011).
9. T. H. Loftus, A. Liu, P. R. Hoffman, A. M. Thomas, M. Norsen, R. Royse, and E. Honea, "522 W average power, spectrally beam-combined fiber laser with near-diffraction-limited beam quality," Opt. Lett. **32**, 349–351 (2007).
10. H. Kogelnik, "Coupled wave theory for thick hologram gratings," Bell Syst. Tech. J. **48**, 2909–2947 (1969).
11. I. V. Ciapurin, L. B. Glebov, and V. I. Smirnov, "Modeling of phase volume diffractive gratings, part 1: transmitting sinusoidal uniform gratings," Opt. Eng. **45**, 015802 (2006).
12. I. V. Ciapurin, D. R. Drachenberg, V. I. Smirnov, G. B. Venus, and L. B. Glebov, "Modeling of phase volume diffractive gratings, part 2: reflecting sinusoidal uniform gratings, Bragg mirrors," Opt. Eng. **51**, 058001 (2012).
13. O. Andrusyak, V. Smirnov, G. Venus, and L. Glebov, "Beam combining of lasers with high spectral density using volume Bragg gratings," Opt. Commun. **282**, 2560–2563 (2009).
14. O. Andrusyak, V. Smirnov, G. Venus, V. Rotar, and L. Glebov, "Spectral combining and coherent coupling of lasers by volume Bragg gratings," IEEE J. Sel. Top. Quantum Electron. **15**, 344–353 (2009).
15. D. R. Drachenberg, O. Andrusyak, G. Venus, V. Smirnov, J. Lumeau, and L. B. Glebov, "Ultimate efficiency of spectral beam combining by volume Bragg gratings," Appl. Opt. **52**, 7233–7242 (2013).
16. D. Drachenberg, I. Divliansky, V. Smirnov, G. Venus, and L. Glebov, "High-power spectral beam combining of fiber lasers with ultra high-spectral density by thermal tuning of volume Bragg gratings," Proc. SPIE **7914**, 79141F (2011).
17. L. Glebov, "Fluorinated silicate glass for conventional and holographic optical elements," Proc. SPIE **6545**, 654507 (2007).
18. J. Lumeau, L. Glebova, V. Golubkov, E. D. Zanotto, and L. B. Glebov, "Origin of crystallization-induced refractive index changes in photo-thermo-refractive glass," Opt. Mater. (Amst.) **32**, 139–146 (2009).