Chirped volume Bragg grating recording in photo-thermo-refractive glass

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Abstract. Volume chirped Bragg gratings (volume CBG) recording optical scheme is implemented and calculated. Chirped gratings are recorded in photo-thermo-refractive (PTR) glass and can be used in near-infrared (near-IR) spectral range. The set of elements of optical scheme is optimized in order to realize recording of chirped Bragg gratings with various characteristics using limited set of elements.

1. Introduction
Currently, holographic optical elements (HOE) play an increasing role in various fields of science and technology connected with managing and/or conversion of optical radiation. In the first place it is due to progress in creation and development of holographic media. Thus, volume holographic media are of great demand for production of spectral and spatial selectors, combiners/decombiners of optical beams, narrow-band optical filters, Bragg mirrors for increasing of spectral radiance and thermal stabilization of emission wavelength of semiconductor lasers [1, 2].

Physical properties of bulk crystalline and glass holographic materials enable recording of chirped Bragg grating (CBG) within them. Chirped grating is a volume 3-D hologram with its period variation along the direction of the beam propagation (along the grating vector). In this grating Bragg condition for different wavelengths of incident radiation is occurred at appropriate depth inside the grating. The main functions of chirped grating are stretching of ultra-short laser pulse in time to amplify it (spectral chirp acquisition) and subsequent pulse compression to duration close to initial one. Stretched pulses have lower power density and can be amplified without damage of elements of amplifying system. This technique called chirped pulse amplification (CPA) was proposed in [3]. Initially, pulse stretching and compression in CPA systems were carried out almost exclusively by pairs of surface diffraction gratings [4, 5]. But such stretchers and compressors are bulky, difficult to align, and sensitive to vibrations.

An important advancement in the development of CPA systems was made by the use of fiber-chirped Bragg gratings [6, 7]. Their use enabled creation of much more simple and flexible schemes. But limited aperture of chirped fiber Bragg gratings lead to limitations on the peak power achievable with fiber-based pulse compressors.

To increase the peak power of stretched/compressed laser pulses the use of volume chirped Bragg gratings (volume CBG) was proposed [8]. The sufficient progress in formation and implementation of volume CBGs is strongly connected with the development of a new bulk holographic material – photo-thermo-refractive (PTR) glass, which enables recording of high-efficient volume holograms [9-
The use of PTR-based stretchers and compressors decreased the size and weight of amplifying optical systems, enhanced the robustness of CPA systems to effects of vibration and shocks [12–15]. Volume CBGs recorded in photo-thermo-refractive glass can be used in the spectral range from 0.4 to approximately 2.5 μm with diffraction efficiencies exceeding 90%. They provide pulse stretching up to 1 ns and compression down to 200 fs for laser pulses with energies and average powers exceeding 1 mJ and 250 W, respectively, while keeping the recompressed beam quality M2 < 1.4 [16].

In the present paper calculation of volume CBG recording optical scheme is carried out. Chirped gratings are recorded in PTR glass produced in ITMO University and intended for use in near-IR spectral range. Set of cylindrical lenses of optical scheme is optimized in order to realize recording of chirped Bragg gratings with various characteristics. Using the designed calculation algorithm, one can calculate feasible combinations of lenses and spatial parameters of the optical scheme for volume CBGs recording with preassigned characteristics.

2. Properties of PTR glass
The fluoride PTR glass was designed and synthesized in ITMO University, Russia [17]. The fluoride PTR glass is a photosensitive multi-component sodium–zinc–alumo-silicate one containing fluoride (6 mol.%) and a small amount of bromine (0.5 mol.%) also doped with additives (cerium, antimony and silver) that are responsible for the photo-thermo-induced precipitation of silver nanoparticles and sodium fluoride crystals. Untreated fluoride PTR glasses are transparent in a wide spectral range of 250–2500 nm. The selective UV irradiation (325 nm) into the Ce³⁺ absorption band in the spectra of these glasses results in the formation of neutral silver molecular clusters. The subsequent heat treatment of UV-irradiated PTR glasses near the glass transition temperature (T_g) induces the silver nanoparticle formation. The thermal treatment of these glasses at temperatures above T_g leads to the growth of silver bromide shell on a silver nanoparticle [18] and then to the precipitation of sodium fluoride cone on it [17, 19].

Photo-thermo-induced crystallization in a form of NaF microcrystals growth within the glass volume leads to the local refractive index modulation (Δn). Nowadays, the maximum refractive index modulation amplitude (RIMA) for the fluoride PTR glass can be as high as 1.5×10⁻³. If scattering by the crystalline phase inside the glass is not critical, the maximum RIMA magnitude can be even greater (like 3.5×10⁻³). Volume Bragg gratings recorded in these glasses reveal a unique combination of working characteristics such as the high angle and spectral selectivity, high diffraction efficiency, high mechanical and optical strength, and high thermal and chemical durability [17].

3. Optical scheme for volume CBG recording
In volume CBG the condition of Bragg diffraction appearance for different wavelengths at variation of the refractive index n_{eff}(z) or/and the period of the grating d(z) along the direction of the beam propagation is as follows:

$$\lambda_{Bragg} = 2n_{eff}(z)d(z)$$

(1)

In the present paper the Bragg condition (1) is realized via variation of the grating period, d(z), with the refractive index, n_{eff}(z), remaining constant.

Recording of volume CBG in the PTR glass is produced in a standard transmission two coherent-wave mixing scheme (figure 1). The system of cylindrical lenses is included in each recording channel to form the shape of the recording’s wavefronts – the first one is convergent and the second one is divergent. Points S_0 и R_0 are located symmetrically relatively to y axis and at the same distances from z axis. Such scheme enables formation of parallel planes of CBG along its length within PTR glass volume.

Experimental optical scheme for CBG recording based on the concept, illustrated in figure 1, is shown in figure 2. Recording laser beam is formed by collimator 8 and illuminates the beamsplitter 1.
Cylindrical lens 5 forms diverging beam with desired focal length. In the second arm of the recording scheme lenses 4 and 6 form converging beam with the same focal length.

**Figure 1.** Volume CBG recording method [20].

**Figure 2.** Experimental scheme for volume CBG recording in PTR glass. 1 – beamsplitter, 2, 3 – plane mirrors, 4, 5 – negative cylindrical lenses, 6 – positive cylindrical lens, 7 – sample of PTR glass, 8 – laser beam collimator, 9 – plane mirror, 10 – recording laser. $F_{rec}$ – points similar to $S_0$ and $R_0$ ones in figure 1.

### 4. Optical scheme parameters calculation

In order to calculate parameters of the optical scheme in figure 2 (focal lengths of lenses, linear distances between elements), the following initial data were used:

1. center wavelength of CBG ($\lambda$, nm);
2. spectral width of CBG ($\Delta\lambda$, nm);
3. CBG length ($l$, mm);
4. He-Cd recording laser wavelength – 325 nm ($\lambda_{rec}$);
5. diameter of the recording beam at the beamsplitter 1 – 1–20 mm ($d_{laser}$);
6. refractive index of PTR glass – 1.498 ($n$).

On the basis of $\lambda$ and $\Delta\lambda$ values maximum ($d_{max}$), middle ($d_{mid}$) and minimum ($d_{min}$) periods of CBG were calculated.

$$d_{max, min} = \frac{\lambda \pm \frac{\Delta\lambda}{2}}{2n}$$  \quad (2)

$$d_{mid} = \frac{\lambda}{2n}$$  \quad (3)

Corresponding convergence angles of the recording beams are as follows

$$\theta_{max,mid, min} = \arcsin\left(\frac{\lambda_{rec}}{2d_{min,mid,max}}\right)$$  \quad (4)

According to convergence angles and CBG length values focal lengths of the recording beams, $f_{rec}$, were calculated (these are the distances from the center of the sample 7 to $F_{rec}$ points – see figure 2)

$$f_{rec} = \frac{l \cos(\theta_{mid})}{\sin(\theta_{max} - \theta_{min})}$$  \quad (5)
Using formulae (2)–(5) focal length values of lenses 4–6 \((f_4, f_5, f_6)\) and optical diameter of lens 6 \((d_6)\) were calculated (diameters of lenses 4 and 5 are determined by the diameter of laser beam and should be less or equal to the value of 20 mm). Initial diameter of the recording beam \((d_{\text{laser}} = 10 \text{ mm})\), distance from the imaginary focus of lenses 4 and 6 to the lens 6 \((L_{4,6} = 1300 \text{ mm})\) and distance between elements 6 and 7 \((L_{6,7} = 300 \text{ mm})\) were taken under the assumption of calculation convenience but may be varied slightly.

\[
d_6 = l \cos(\theta_{\text{mid}}) \frac{f_{\text{rec}} + L_{6,7}}{f_{\text{rec}}} \quad (6)
\]

\[
f_4 = L_{4,6} \frac{d_{\text{laser}}}{d_6} \quad (7)
\]

\[
f_5 = f_{\text{rec}} \frac{d_{\text{laser}}}{l \cos(\theta_{\text{mid}})} \quad (8)
\]

\[
f_6 = \left( \frac{1}{L_{4,6}} + \frac{1}{f_{\text{rec}} + L_{6,7}} \right)^{-1} \quad (9)
\]

Calculations using formulae (5)–(9) were carried out for the central wavelength of CBG equal to 1053, 1064, 1550 nm, spectral width of 10–30 nm and CBG length of 10–30 mm. Analysis of the resulting array of parameters showed that the maximum number of CBGs with desired characteristics can be recorded using the following optimal set of focal lengths of lenses 4–6 – see table 1.

### Table 1. Optimal set of lenses for CBG recording.

| Element | Focal length (mm) |
|---------|------------------|
| Lens 4  | 500              |
| Lens 5  | 500              |
| Lens 6  | 500              |

Lenses 4 and 5 are negative cylindrical with diameter not less than 30 mm; lens 6 is a positive cylindrical with the diameter not less than 38 mm. One can calculate the ranges of the main CBG parameters that can be realized using different combinations of lenses from table 1 (see table 2).

### Table 2. Feasible lenses combinations and corresponding CBG parameters.

| \(f_4\) (mm) | \(f_5\) (mm) | \(f_6\) (mm) | \(\lambda\) (µm) | \(l\) (mm) | \(\Delta\lambda\) (nm) |
|-------------|-------------|-------------|-----------------|----------|---------------------|
| 500         | 500         | 500         | 1.0–1.5         | 2–30     | 3.6–120             |
| 500         | 500         | 1000        | 1.0–1.5         | 2–50     | 3.6–80              |
| 1000        | 500         | 1000        | 1.0–1.5         | 2–27     | 3.6–81              |
| 500         | 2000        | 1000        | 1.0–1.5         | 2–25     | 0.9–24              |
| 1000        | 2000        | 1000        | 1.0–1.5         | 2–30     | 0.9–40              |

Using above deduced formulae one can estimate all variants of lenses combinations and linear dimensions of the optical scheme for the recording of CBG with preassigned characteristics. It can be useful in situation of the limited number of optical elements (especially cylindrical lenses). As an example, we made such calculation for the CBG with the following parameters: \(\lambda = 1053 \text{ nm}\), \(l = 30\)
mm, $\Delta \lambda = 30$ nm, $f_{rec} = 1790$ mm. In theory, several combinations of lenses from table 2 can be used for the recording. But calculation showed that the unique set of lenses ($f_4 = 500$ mm, $f_5 = 500$ mm, $f_6 = 1000$ mm) provides the diameter of lens 6 and linear distances between elements of the optical scheme that can be realized in practice. Using of all other sets leads to negative or extremely large values of linear distances and cannot be implemented.

5. Conclusions
Optical scheme for volume CBGs recording in PTR glass is proposed and calculated. Calculations were carried out for CBG central wavelength from near-IR spectral range. The set of optical elements is optimized to cover the wide range of CBG’s parameters. Formulae deduced allow estimating all variants of lenses combinations and linear dimensions of the optical scheme for the recording of CBG with preassigned characteristics. It can be useful in situation of the limited number of optical elements.

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