Ultranarrow bandwidth moiré reflecting Bragg gratings recorded in photo-thermo-refractive glass

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An experimental demonstration of a moiré reflecting Bragg grating in photo-thermo-refractive glass is carried out. This narrowband filter is obtained by the recording of two reflecting Bragg gratings with different periods. Filters with central wavelength at 1550 nm, bandwidth of 50 pm, and transmission higher than 95% are demonstrated. The methods to decrease bandwidth to 1 pm are finally investigated. © 2010 Optical Society of America

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Over the past 15 years, a new phase photosensitive material called photo-thermo-refractive (PTR) glass [1] has been developed for the recording of volume holographic elements such as high-efficiency volume Bragg gratings [2]. The main advantage of such elements is that they allow obtaining narrowband filters in both spectral and angular spaces [3]. These elements have been successfully integrated in several laser systems, such as selector for transverse and longitudinal modes in solid-state [4] or semiconductor lasers [5]. With the fast growing demand of high power laser applications such as the spectral beam combining [6] and the mode locking of laser bars [7], PTR glass properties have been extensively studied [8] and allowed the decrease of losses down to levels of several 10^{-3} cm^{-1} in 1 μm region. Such low level of losses therefore allows fabricating of volume Bragg gratings with absolute efficiencies higher than 99%. However, the decrease of the spectral bandwidth represents a technical problem and is, thus, limited to values ranged between 50 and 100 pm depending on the central wavelength. For some applications such as light detection and ranging (LIDAR) [9] or the longitudinal mode selection of Nd:YAG aluminum garnet lasers [4], bandwidth in the range of a few picometers or tens of picometers would be required. Hence, a new technology must be developed in order to achieve such ultranarrowband filtering. Several approaches for narrowing spectral selectivity were proposed over the last years. The first one consisted of incoherently combining a Fabry–Perot etalon with reflecting Bragg gratings [10] and therefore combining the best of each, i.e., the spectral narrowband properties of Fabry–Perot etalons and the single resonance and wide spectral rejection band of reflecting Bragg gratings. One of the main drawbacks of such configuration is that it is composed of two distinct elements and the fabrication of ultranarrowband Fabry–Perot etalons is very expensive. Another alternative solution was recently proposed. It consisted in replacing both mirrors of the Fabry–Perot etalon with reflecting Bragg gratings and forming the equivalent of a π-shifted volume Bragg gratings [11]. Filter with bandwidth of 25 pm at 1064 nm was demonstrated. However, this combining was performed in air and therefore did not allow robust applications as required for laser systems. In this Letter, we propose to extend the last technology to a monolithic component. We describe the fabrication of moiré Bragg gratings (MBGs). We investigate the spectral and angular selectivity of these MBGs and analyze the opportunity to decrease the bandwidth to the level corresponding to 1 GHz.

A moiré pattern is an interference pattern created by two grids having slightly different periods. The phenomenon of moiré pattern is illustrated by a well-known formula of trigonometry

$$\cos(\alpha) + \cos(\beta) = 2\cos\left(\frac{\alpha+\beta}{2}\right)\cos\left(\frac{\alpha-\beta}{2}\right). \quad (1)$$

Formula (1) shows that a combination of two elementary periodic functions with different periods results in a complex pattern that has a high-frequency component with a period that is average between elementary periods and a low-frequency envelope with a period determined by the difference between elementary periods. When each grid is produced by the interference of two beams, we obtain the superposition of two shifted Bragg gratings and the recording of so-called MBG (Fig. 1). It is worth mentioning that the zero of the refractive index modulation is equivalent of a π-phase shift of the refractive index modulation. Such structure was widely investigated in the past in fibers [12]. However, due to the unavailability of bulk photosensitive materials with high optical homogeneity, no experimental demonstration of MBGs was performed. PTR glass allows recording of high efficiency reflecting Bragg gratings (RBGs) in a several-millimeters-thick glass samples, and losses can be kept low below 1%. Hence, PTR glass makes an ideal candidate for the recording of a MBG with very high transmission at resonance. For the recording, the beam from a single transverse mode He-Cd laser at 325 nm is expanded from 1 to 25 mm using two beam expanders. This beam is split into two beams with

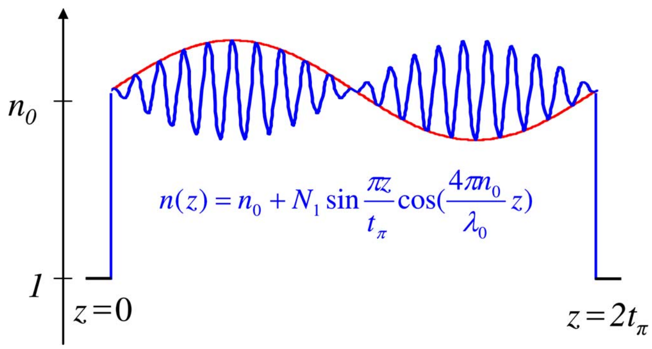

Fig. 1. (Color online) Spatial profile of refractive index modulation in an MBG with one moiré period, i.e., two semiperiods t_π with π phase shift between them.

equal intensity. Both beams are reflected by two high-quality mirrors and overlapped in the plane of recording (Fig. 2). Two gratings were recorded sequentially by changing of the incident angles of pairs of beams from 1–2 to $1'-2'$. The period of each of the gratings (Λ_1, Λ_2) is determined by the angle between the two interfering beams inside of the photosensitive plate,

$$2n_0\Lambda_{1,2} = \frac{\lambda_R}{\sin(\theta_{1,2})} = \lambda_B, \qquad (2)$$

where n_0 is the refractive index of a recording medium, λ_R the wavelength of recording, θ the angle between the two beams inside the recording medium, and λ_B the wavelength diffracted by the recorded grating at normal incidence along the Z axis in Fig. 2. It is therefore possible to change the period of the grating by changing the angle between the two beams. With high-precision rotary stages, angle between the two beams can be controlled with precision better than 0.001°. The change of Bragg wavelength corresponding to such a change of angle is given by

$$\Delta\lambda_B = \frac{\lambda_B}{\tan(\theta)}\Delta\theta. \qquad (3)$$

With such resolution, the shift of Bragg wavelength can be controlled with a precision better than 50 pm

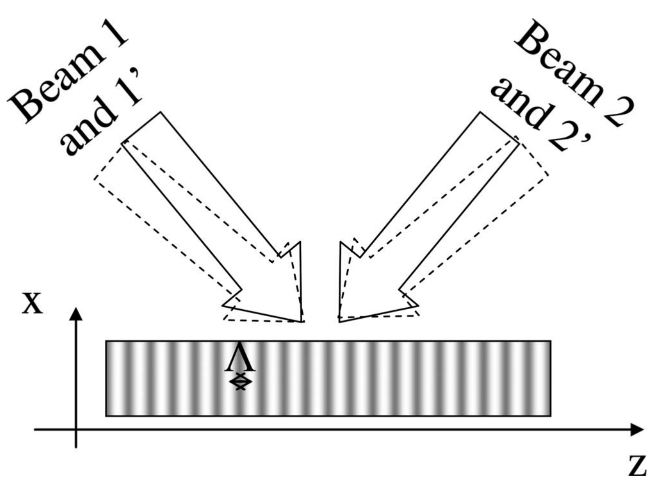

Fig. 2. Sequential recording of a moiré grating by two pairs of beams: 1–2 and $1'-2'$.

at 1 μm. As will be shown later, such shift allows obtaining filter with bandwidth in the range of a few picometers in a few millimeters PTR glass substrates. By means of sequential two-beam recording with the same bisectors, the vector of a MBG can be perpendicular to the normal of the photosensitive plate surface, i.e., along the z-axis in Fig. 2. A part of the recorded doubled grating with t_π thickness along Z-axis in Fig. 2 can be cut from the photosensitive plate to keep only one low-frequency period of the refractive index modulation for obtaining an ultra-narrowband transmitting filter.

To confirm these theoretical modeling, a MBG was experimentally demonstrated. The moiré grating was recorded in a PTR glass wafer using the two-beam sequential technique described above. The two recorded RBGs had central wavelengths of 1547.2 and 1547.4 nm. The sample was thermally developed and then positions of zeros at the refractive index modulation profile were determined by scanning of a He–Ne laser beam with diameter of 1 mm along Z axis in Fig. 2. This sample was cut in the vicinity of the zeros of the refractive index modulation profile to thickness equal to 6 mm, i.e., one low frequency period ($2t_\pi$) and then ground, polished and antireflection coated. Overall refractive index modulation was estimated in the range of ~120 ppm. Spectral selectivity of this moiré grating was characterized using a high resolution setup (Fig. 3). This setup was composed with a tunable Santec TSL 220 laser diode source operating at 1550 nm and having 1 pm resolution. The laser radiation was filtered by a single-mode fiber and coupled into a collimator. The 0.5 mm diameter beam was launched to the moiré grating and transmitted signal was measured using an InGaAs amplified photodiode associated with a data acquisition card. In order to adjust the filter at normal incidence, a 3 dB fiber coupler was used between the laser and the delivery fiber. Another amplified InGaAs photodiode was used to measure the power reflected from the moiré grating, recoupled to the fiber and directed to the second photodiode by the coupler. Using this scheme the MBG could thus be aligned by auto-collimation. Typical spectral transmission measured at the throughput of the filter is shown in Fig. 4. This filter shows transmission higher than 95%. Bandwidth is equal to ~50 pm at full width at half-maximum (FWHM) and rejection bandwidth to 200 pm. Rejection outside the resonance is in the range of 10 dB. Parameters of such a filter can be improved by optimization of a fabrication process and combining it with an additional RBG or by using an RGB with higher diffraction efficiencies in [10].

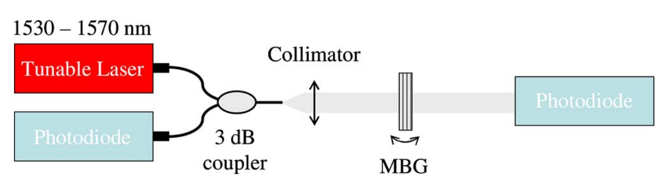

Fig. 3. (Color online) Experimental setup for measurement of spectral selectivity of a moiré grating recorded in PTR glass.

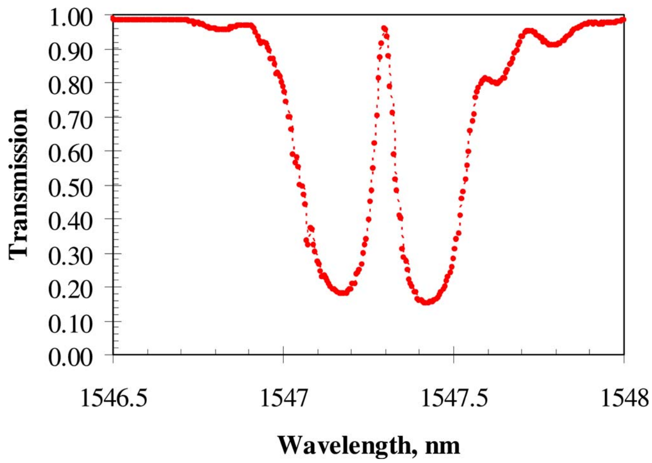

Fig. 4. (Color online) Experimental spectral selectivity of a moiré grating recorded in PTR glass. Separation between resonant wavelengths of elementary RBGs—200 pm. Thickness—6 mm. Refractive index modulation—120 ppm.

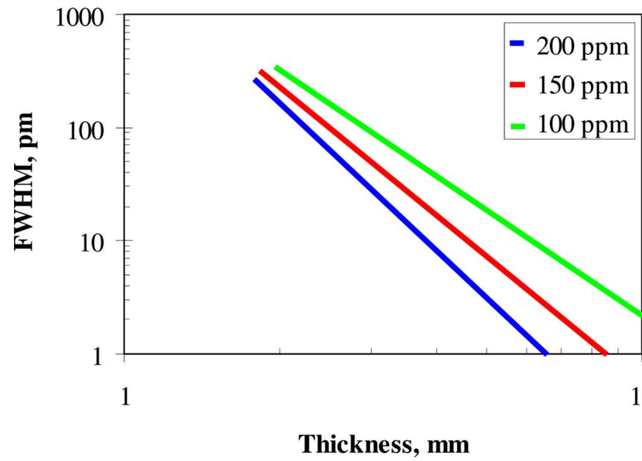

Fig. 5. (Color online) Dependence of spectral selectivity (FWHM) of a moiré grating on thickness for different values of refractive index modulation at constant separation between Bragg wavelengths of elementary RBGs of 100 pm.

Let us now analyze the parameters of the RBG required to obtain an ultranarrow bandpass filter centered in 1 μm region and with bandwidth at FWHM of a few picometers. Three main parameters define the final bandwidth of such a moiré Bragg filter:

- The difference between periods of the two RBGs, i.e., difference between central Bragg wavelengths.
- The thickness of the MBG.
- The amplitude of refractive index modulation of each RBG.

The dependence of the spectral width (FWHM) of a transmission peak on thickness of the MBG for different values of refractive index modulation at constant separation between Bragg wavelengths (100 pm) is shown in Fig. 5. For all simulations, we supposed that π phase shift occurs in the center of the MBG, resulting in a symmetric and resonant filter. It is seen that for reasonable parameters of gratings, it is possible to fabricate a filter with a few picometers bandwidth for 1 μm region in a PTR glass with thickness less than 10 mm. Moreover, due to monolithic nature of the filter no problem of alignment between the two VBGs would be encountered.

In conclusion, we have demonstrated the fabrication of a MBG in PTR glass for 1.5 μm region with bandwidth of 50 pm (0.5 Å, 5 GHz) and transmission higher than 95%. This result paves a way to the fabrication of large aperture, high throughput ultranarrowband filters. Moreover, due to very low losses and absorption, such a filter would find wide range of application in LIDAR, Raman spectroscopy or high-power laser applications.

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