

Phase-shifted volume Bragg gratings in photo-thermo-refractive glass

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ABSTRACT

Narrow-band filters based on phase shifted Bragg gratings have been widely investigated in fiber configuration. However, up to now, no experimental demonstration was performed using volume Bragg gratings in free space configuration. In this paper both theoretical and experimental study of this new type of filters is presented. The phase matching conditions that allow obtaining a resonant filter are analyzed. Narrow bandwidth transmission filters based on the coherent combination of two non slanted reflecting Bragg gratings in photo-thermo-refractive glass are studied. A filter with 25 pm bandwidth and 90%+ transmission at 1064 nm is demonstrated. The effect of the phase matching between the two volume Bragg gratings is presented and perfect accordance of experimental and theoretical data are shown. Based on these results, we show that the phase-shifted reflecting volume Bragg gratings recorded photo-thermo-refractive glass pave a way to the fabrication of large aperture extremely narrow band filters with high transmission at resonance and high rejection.

Keywords: Volume Bragg grating, Fabry-Perot, narrow band filter, Lidar

1. INTRODUCTION

In recent years, phase-shifted fiber Bragg gratings have drawn large interests of researchers [1,2]. By introducing a π -phase shift into a refractive index modulation of the fiber Bragg grating during its fabrication, the spectral transmission has a narrow bandpass resonance appearing within the middle of the reflection lobe of the fiber Bragg grating. Such element is very interesting because it allows reaching very narrow bandpass of few picometers. However its range of application is limited to all-fiber applications. Identical components but in free-space configuration would find many additional applications in systems such as LIDARS that require detection of a very narrow lines. Up to recently, due to the lack of reliable photosensitive materials combining good optical quality, high sensitivity and low losses, the fabrication of such elements was not possible. In ref. [3,4], authors taught how to record high efficiency and low losses volume Bragg gratings in photo-thermo-refractive glass. Using this material relative diffraction efficiency as high as 99.9% can be achieved and level of losses can be kept below 10^{-2} cm^{-1} . Hence this photosensitive glass represents an ideal material for the fabrication of phase-shifted volume Bragg gratings. In this paper we will first introduce the main features of this filter. Then we will introduce phenomenological laws that allow prediction of the phase matching of the filter. Finally we will present an experimental demonstration of this filter by combining two identical reflecting Bragg gratings in air.

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2. THEORETICAL DESCRIPTION

2.1. Reflecting Bragg grating in PTR glass

The key element in this work is a reflecting Bragg grating (RBG) recorded in photo-thermo-refractive (PTR) glass. This component is obtained by recording of a sinusoidal refractive index modulation in a photosensitive medium. With such a RBG, plane of iso-refractive indices are parallel to the facets of a wafer in which it was recorded and beam is diffracted in the same side than the reflected one. A RBG is a narrow-band reflection filter. Typical bandwidth is equal to less than 1 nm and angular selectivity is generally between 1 and 100 mrad. A RBG was fabricated by holographic recording at OptiGrate Company inside photo-thermo-refractive (PTR) glass. PTR glass is a multi-component silicate glass which possesses photosensitive properties. When exposed to UV-radiation and then thermally developed, refractive index decrement as high as 1000 ppm can be induced in this glass. Finally, high efficiency holographic elements were previously demonstrated in this glass [4]. Typical spectral selectivity of the transmission of such a grating is shown in figure 1. This RBG is a narrow-band reflection filter for 1064 nm region, it has a spectral selectivity of ~250 pm (FWHM) and a maximum diffraction efficiency of 72%. One can see that oscillations appear around the main lobe of the reflection. These oscillations are typical for uniform Bragg gratings [5]. However, these side lobes can be eliminated by the use of gratings with spatial variations of the magnitude of the refractive index modulation, so called apodized gratings [6].

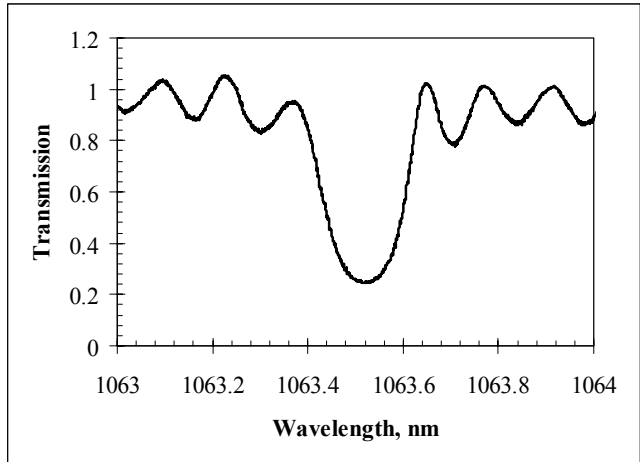


Figure 1. Spectral selectivity (transmission) of the reflecting Bragg grating.

2.2. Pi-shifted reflecting Bragg grating in PTR glass

In this study we considered the coherent combination of two identical RBGs (figure 2). The main feature of the resulting filter, compared to a regular RBG is appearance an ultra-narrow bandwidth resonance (less than 100 pm) in the middle of the main reflection band. It corresponds to a high transmission of the filter (Figure 3.). It is important to note that this resonance can be very narrow, even if the gap between the two RBGs is equal to zero. This comes from the fact that the RBG acts as virtual plane mirror situated at a certain distance from its face. This distance depends on the thickness and the diffraction efficiency of the RBG [7]. Hence, each RBG is at the same time a mirror and half of the cavity of the Fabry-Perot filter. Theoretically this resonance is equal to 100% if the two RBGs have identical diffraction efficiencies. However, several factors such as the losses of the material, the distance between the RBGs or the the homogeneity of distance between them influence this transmission. Regarding losses, those are very low in PTR glass (below 10^{-2} cm^{-1})

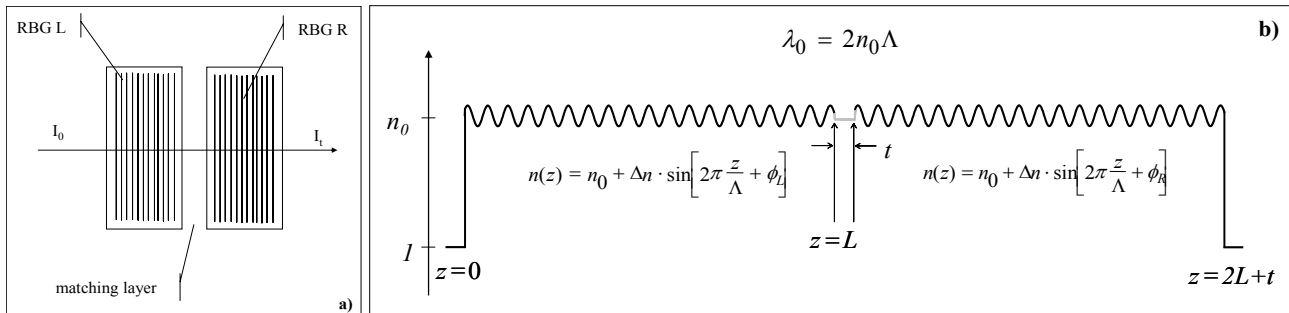


Figure 2. Scheme of the coherent assembly of two reflecting Bragg gratings: a) grating configuration – b) refractive index modulation

and therefore allow obtaining high transmission ultra-narrow band filters. Regarding the homogeneity of distance between two mirrors, this one should be very high. Actually, samples were polished with flatness better than $\lambda/10$ at 633 nm over the combined area. Parallelism between the two samples was controlled using piezoelectric transducers with precision of about 20 nm. Due to the sample holder configuration, this corresponds to a control of the inclination of the RBG with precision of about 1 μ rad. Hence, this high accuracy alignment is enough to minimize effect of wedge between the two mirrors.

2.3. Phase matching condition in pi-shifted reflecting Bragg grating in PTR glass

Let us now define the methods and conditions to make the two RBG being coherent when assembled in air (figure 2). Let us suppose that both RBGs have the same thickness L and the same refractive index modulation:

$$n(z) = n_0 + \Delta n \cdot \sin\left[2\pi \frac{z}{\Lambda} + \phi_i\right]. \quad (1)$$

where n_0 is the PTR glass mean refractive index, Δn the modulation amplitude, ϕ_i the start phase (phase of the modulation at $z = 0$) and Λ the period of the sine modulation. Let us also suppose that the RBGs are separated by a matching layer having the same refractive index than the PTR glass and a thickness t . In this case, it is possible to show that the resonance condition can be written as [8]:

$$\Phi = \left[\phi_L + 2\pi \frac{L}{\Lambda}\right] + 2\pi \frac{2n_0 t}{\lambda_0} - \phi_R = \pi \quad [2\pi]. \quad (2)$$

where ϕ_L is the initial phase of the refractive index modulation of the so-called *left* RBG (RBG L). The term into brackets therefore represents the final phase (ϕ_L^f) of the refractive index modulation of the *left* RBG. ϕ_R is the initial phase of the refractive index modulation of the so-called *right* RBG (RBG R), and the term in between represents the phase shift that occurs during the propagation through the matching layer. After recording of the RBG, the values of ϕ_L and ϕ_R are fixed. Hence to fulfill the resonance condition, the value of the overall phase term Φ can be adjusted by simply controlling the physical thickness t of the matching layer. Using such a technique, it can be shown that, in order to obtain a perfect phase matching between the two structures, the optical thickness must be controlled with a precision better than $\lambda/40$. In other words, a precision on the mechanical thickness of ~ 20 nm is required. Such a precision can be obtained with piezo-electric transducer and experimental demonstration will be presented hereafter.

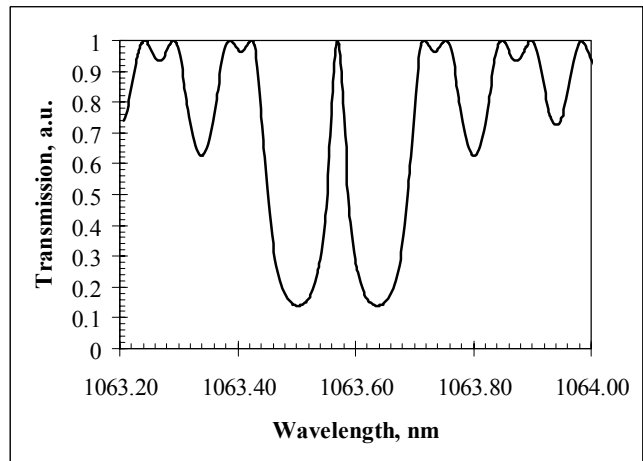


Figure 3. Spectral selectivity (transmission) of the coherent combination of two reflecting Bragg gratings in PTR glass

Moreover, one can see that rejection is higher than the sum of the diffraction efficiencies of the two RBG due to the coherent nature of the combination. However, the width of this rejection band is limited to the bandwidth of the RBG. For application requiring larger rejection band, this one can be increased by incoherently combining this filter with a single RBG as it was shown in ref [9] or any multi-layer dielectric filter with bandwidth narrower than the bandwidth of the two combined RBGs.

2.4. Design of ultra-narrowband pi-shifted reflecting Bragg grating in PTR glass and virtual thickness

In this section we analyzed the ways to decrease the bandwidth of the filter and the parameters of RBG which are required to obtain for example filter with some predetermined parameters (e.g. bandwidth of 4 pm, or 1 GHz, at 1064 nm). Actually the FWHM ($\delta\lambda$) of a regular FPE is defined by the following formula:

$$\delta\lambda = \frac{1-R}{\pi\sqrt{R}} \frac{\lambda_0^2}{2n_0t} \quad (3)$$

where R is the reflectance of the mirrors, n_0 and t are respectively the refractive index and the thickness of the cavity and λ_0 the central wavelength of the mirrors. It is seen that this FWHM can be controlled by either changing the thickness of the spacer or the reflectivity of the mirror. In our case these parameters are controlled by the physical thickness of the RBG and its maximum diffraction efficiency. Figure 4 shows the evolution of the FWHM versus the physical thickness of the RBG for different values of the diffraction efficiency of the RBG. It can be seen that a FWHM of 4 pm can for example be obtained using a 3 mm thick RBG with 95% diffraction efficiency. These parameters are standard parameters that can be achieved in RBG recorded in PTR glass. Therefore, reflecting Bragg gratings recorded at OptiGrate Company pave a way to the fabrication of ultra-narrowband phase-shifted reflecting Bragg gratings.

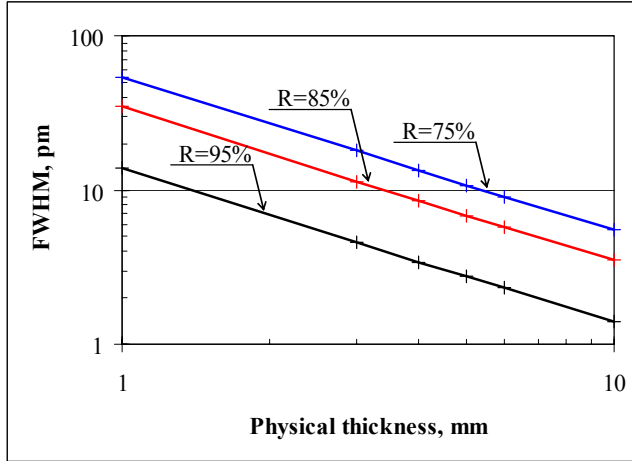


Fig. 4. Dependence of spectral width (FWHM) of hybrid filters on RBG thickness for different diffraction efficiencies of the RBG (R).

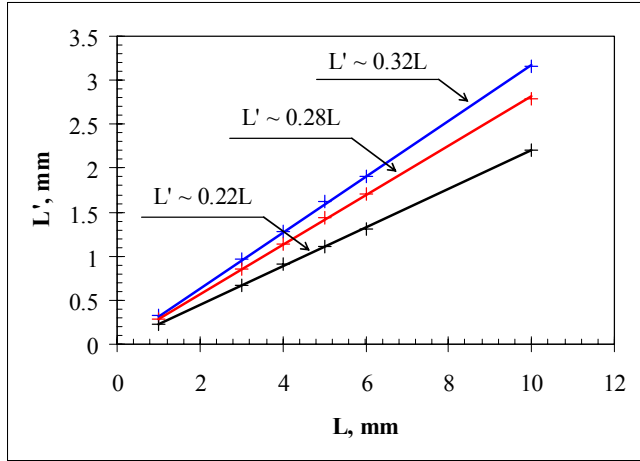


Fig. 5. Dependence of the position of the virtual mirror (L') versus the physical thickness of the RBG (L) for different diffraction efficiencies of the RBG: In blue $R=75\%$, in red $R=85\%$ and in black, $R=95\%$.

As it was mentioned above, it is possible to show that a RBG acts as virtual plane mirror situated at a certain distance from its facet. This distance depends on the thickness and the diffraction efficiency of the RBG. In order to illustrate this property, we combined the results presented in figure 4 and the equation (3) to extract the virtual physical thickness of the Fabry-Perot cavity and therefore the position L' from the combining face of the virtual mirror of the RBG:

$$L' = \frac{1-R}{\pi\sqrt{R}} \frac{\lambda_0^2}{4n_0\delta\lambda} \quad (4)$$

Figure 5 shows the evolution of the position of the virtual mirror as a function of the physical thickness of the RBG for different values of the diffraction efficiency of the RBG. It is seen that for a fixed diffraction efficiency, the distance L' of the virtual mirror from the front facet of the RBG linearly increases with the physical thickness of the RBG. But this distance L' has a non-linear dependence on the diffraction efficiency of the RBG. Actually it is possible to demonstrate that this distance L' follows the following equation [7]:

$$L' = L \frac{\sqrt{R}}{2 \operatorname{atanh}(\sqrt{R})} \quad (5)$$

3. EXPERIMENTAL DEMONSTRATION

In order to illustrate the previous discussion, an experimental demonstration of the coherent combination of two RBGs in air was carried out. The RBG used for this demonstration were recorded inside PTR glass. They have central wavelength at 1063.35 nm, thickness of 2.76 mm and refractive index modulation of 154 ppm. They were recorded inside PTR glass without slant (grating vector coincides with the normal to front facet of a glass plate) and diffraction efficiency was equal

to ~72% (Figure 1.a). The two RBGs were fixed on mirror holders, and one of the holders was motorized with piezo-electric transducer that allowed fine translation and fine angle tuning within the specs defined above. The setup used for the measurement of the spectral response is composed with a tunable laser diode having a 1 pm resolution (figure 6). The laser radiation is filtered by a single-mode fiber and coupled to a collimator. The 1 mm diameter output beam is sent through the RBG assembly and transmitted signal is measured using a silicon amplified photodiode associated with a data acquisition card. In order to perform the adjustment of the parallelism of the two RBG, a fiber coupler is used between the laser and the collimator. Another amplified silicon photodiode is used to measure the power which is reflected from the combined RBGs and re-coupled inside the collimator. It is important to stress that the laser used for the measurement is composed with a circulator that blocks reflected radiation that would be re-injected inside the laser cavity and lock it to the wavelength of the filter. Using this coupler the two RBGs were aligned by auto-collimation. Typical spectral dependence of the transmission of the filter resulting from the coherent combination of the two RBGs is shown in figure 7. This filter presents a transmission higher than 90%. Bandwidth is equal to ~25 pm (i.e. < 7 HGz) and rejection width to 200 pm. Rejection outside the resonance is better than 10 dB and can be improved by combining it with an additional RBG or using RBG with higher diffraction efficiencies.

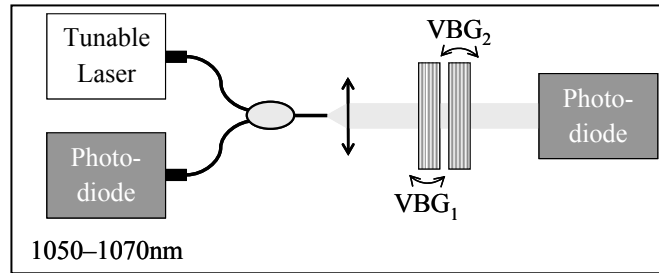


Figure 6. Setup used for the demonstration of the coherent combination of two RBGs in PTR glass.

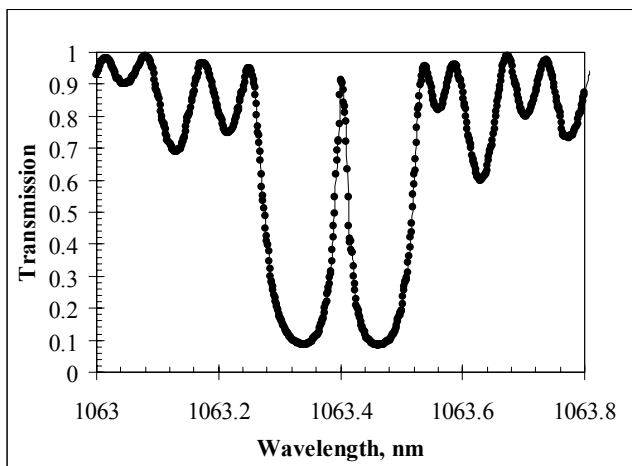


Figure 7. Experimental demonstration of the coherent combination of two reflecting Bragg gratings

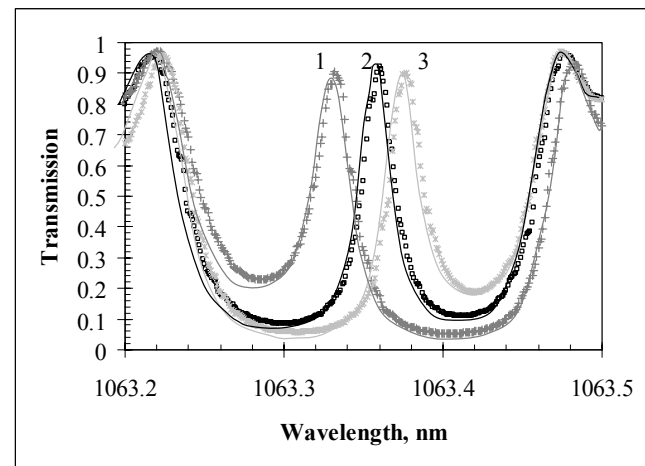


Figure 8. Effect of the phase matching between the two reflecting Bragg gratings on position of the resonance – 1: $\Phi < \pi$; 2: $\Phi = \pi$; 3: $\Phi > \pi$

To illustrate the principle of phase matching between the two RBG, we changed the distance between them and recorded the transmission for each distance (Figure 8). One can see that according to the distance between the two RBGs, the resonance moves within the main reflection lobe of the RBG. When distance is optimized and the phase Φ equals to π , then resonance is centered in the middle of the reflection lobe. If this phase is different from π , resonance is shifted to one of the edge of the reflection lobe.

4. CONCLUSION

We have demonstrated for the first time the filter resulting from the coherent combination of two reflecting volume Bragg gratings. Features of this filter are similar to those obtained with a phase-shifted fiber Bragg grating but aperture is several orders of magnitude higher. Filter with 7 GHz (25 pm) bandwidth and 90%+ transmission at 1064 nm was experimentally demonstrated.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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