Single resonance monolithic Fabry–Perot filters formed by volume Bragg gratings and multilayer dielectric mirrors

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A new class of Fabry–Perot filters produced by a multilayer dielectric mirror deposited on top of a reflecting volume Bragg grating is described. The first fabricated prototype for the 852 nm region demonstrates a 30 pm bandwidth, 90 + % transmission at resonance, and a good agreement with theoretical simulation. © 2011 Optical Society of America

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Since the invention of laser holography, scientists have been looking for the ideal media for hologram recording [1]. Much research has been directed toward holographic data storage in photorefractive crystals and photopolymers. However, these materials are unsuitable for high power laser applications due to their low laser damage threshold. Recently, a new photosensitive material named photo-thermo-refractive (PTR) glass was developed and high-efficiency volume holographic optical elements were demonstrated [2,3]. PTR diffractive optical elements have shown high robustness under harsh conditions of utilization at elevated temperatures and under high power laser irradiation. These elements have been successfully used for high power spectral beam combining [4], selection of transverse and longitudinal modes in different laser resonators, beam deflectors [5], splitters, and attenuators.

High-efficiency reflecting Bragg gratings (RBGs) can be recorded in PTR glass plates with thicknesses of a few millimeters. These elements are narrowband spectral filters with subnanometer spectral widths. However, decreasing the bandwidth to a value below 30–50 pm is very challenging as it requires increasing the thickness of the RBG to more than 15–20 mm. To overcome this limitation, several alternative solutions were previously proposed: the incoherent combination of a Fabry–Perot etalon and an RBG [6], π-shifted volume Bragg gratings [7], the multiplexing of two RBGs within one PTR glass for the fabrication of moiré Bragg gratings [8]. In this Letter, we propose a new approach which is a monolithic Fabry–Perot cavity that consists of a RBG with a multilayer dielectric mirror (MDM) deposited on its surface (RBG/MDM filter) (Fig. 1). Such a filter was demonstrated in guided configuration using fiber Bragg gratings [9], but no experimental demonstration in free space could be done with the unavailability of materials for recording high quality volume Bragg gratings. Spectral response of the Bragg-dielectric filter resulting from the coherent combination of an RBG (Bragg wavelength: 852 nm, thickness: 2.84 mm, refractive index modulation: 170 ppm (1.7×10^{-4}) and an MDM (with nine quarter-wave alternated high/low refractive index layers) was modeled by decomposing the RBG into elementary homogeneous thin layers and applying the admittance theory for thin films on the whole RBG/MDM assembly [10]. A typical spectral shape for the RBG/MDM filter calculated with the mentioned model is shown in Fig. 2. This filter is a Fabry–Perot resonator formed by two mirrors. This filter reflects a broadband corresponding to the reflection band of the MDM, but the main feature of this filter is that an ultranarrow band resonance appears at the Bragg wavelength of the RBG. This resonance corresponds to a high transmission line of the filter. It is important that the resonance can be observed, even if the gap between the RBG and the MDM is equal to zero. This is due to the fact that the RBG is a resonant cavity itself [8] as it acts as a virtual plane mirror situated at a certain distance from its front surface. This distance depends on the thickness and diffraction efficiency of the RBG [11]. Theoretically, this transmission at resonance is equal to 100% if the RBG and the MDM have identical reflection coefficients at the Bragg wavelength. One can see that very close to the resonance (in the range where diffraction efficiency of the RBG is not zero), rejection will be high (generally much better than 15/20 dB) due to the coherent nature of the combination between both types of mirrors. Then, in a broader range, rejection is given by the reflection coefficient of the DM and therefore is

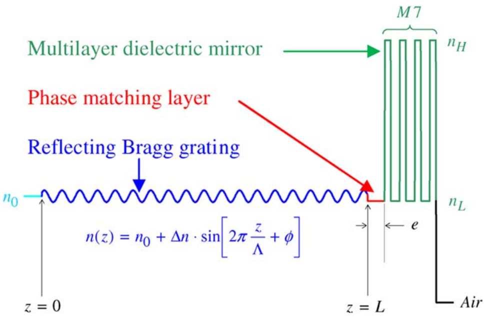

Fig. 1. (Color online) Spatial profile of refractive index in an RBG/MDM filter formed a reflecting Bragg grating and multilayer dielectric mirror with a phase-matching layer.

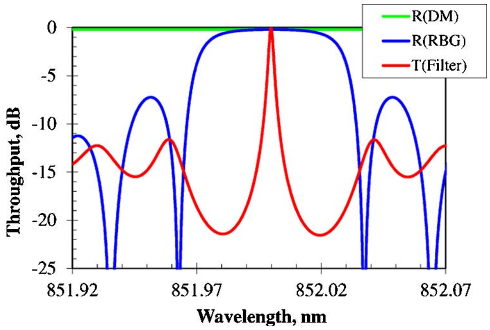

Fig. 2. (Color online) Transmission spectrum of an RBG/MDM filter (gray; red online), and reflection spectra of an MDM (straight line across top, green online) and an RBG (black; blue online).

limited to 10 dB for 90% reflection MDM but can be increased by increasing the MDM's reflection coefficient.

The main challenges in fabricating this class of filters consist of having a resonance condition between the Bragg mirror and the dielectric mirror. In [9,11], it was shown that the coherence conditions can be met by controlling the distance between the RBG and the MDM. Let us also suppose that the RBG and the MDM are separated by a matching layer having refractive index n_L and a thickness t (Fig. 1). Then, the resonance condition can be fulfilled by simply controlling the physical thickness t of the matching layer. Further analysis shows that, in order to obtain phase matching between the two structures, the optical thickness of a matching layer must be controlled with a precision better than $\lambda/10$. In other words, a precision on the mechanical thickness of $\sim$50 nm is required.

At this point, it must be noted that the Fabry–Perot cavity in the proposed device is not formed by two reflecting surfaces, but it is produced by an effective reflecting surface of an MDM and an effective reflecting surface of a volume RBG. These effective reflecting surfaces in both structures are composed with the sums of reflecting planes (planes of iso-refractive index changes) with a total number of several planes for an MDM, but several thousand for an RBG. In order to obtain a high throughput, these planes must be perfectly parallel to each other and very flat. In a classical Fabry–Perot etalon composed with regular plane mirrors, flatness of each mirror must be better than $\lambda/10$ and the wedge between the two mirrors must be lower than a few arcseconds in order to have the appearance of a very narrow band filter with high throughput [12]. By analogy, both the MDM and RBG must have plane of iso-refractive index with high flatness. This condition is easily achieved with the current technology of the MDM,s and such conditions are met in high-efficiency volume diffractive elements in PTR glass at OptiGrate Corp. In addition, a wedge between the RBG and the MDM must also be very small and comparable to the one required between the mirrors of a regular Fabry–Perot etalon.

The technology developed at OptiGrate Corp. also allows fabricating reflecting Bragg mirrors with grating vector tilt in regards to one of the glass surfaces well below 1 mrad. Therefore, it is possible to directly deposit a matching layer (the layer that provides phase matching between the RBG and MDM) and a dielectric mirror on one of the facets of an RBG. The fabricated filter will have an ultranarrow bandwidth and minimum losses resulted from misalignment between mirrors. To fabricate such a filter, a 17 mm × 17 mm RBG in PTR glass with a thickness of 2.89 mm and a diffraction efficiency of ~65% was manufactured. Then a matching layer and a quarter-wave alternated dielectric mirror were deposited on a facet of the RBG by the electron beam deposition with ion assistance. The high refractive index layers of an MDM were obtained by depositing tantalum pentoxyde layers (Ta_2O_5) while low refractive index layers were obtained by deposition of silica layers (SiO_2). The matching layer was obtained by depositing a silica layer. Thickness monitoring of each layer was realized by acoustic wave measurement of its weight using a quartz microbalance associated with an *in situ* measurement of the transmittance of the assembly with the help of the tunable laser source for a 850 nm region and a 1 pm spectral resolution, connected to a collimator and a photodiode associated with a data acquisition card. The control was realized after each layer by scanning the wavelength and measuring the transmitted power. The deposition sequence was then started by depositing an SiO_2 matching layer to correct the end phase of the RBG. Then, a five-layer mirror (Ta_2O_5/SiO_2) was deposited to match as close as possible to the reflection coefficient of the RBG. The final reflection coefficient of the dielectric mirror (75%) was however higher than the Bragg mirror (65%). The modeling shows that for such a combination, the maximum transmission at resonance is limited to about 90%. The transmission spectra after each stage of filter fabrication are shown in Fig. 3. One can see how the filter is forming and how the resonance is appearing while the reflection coefficient of the dielectric mirror is changing. It should be noted that the reflection coefficient of the dielectric

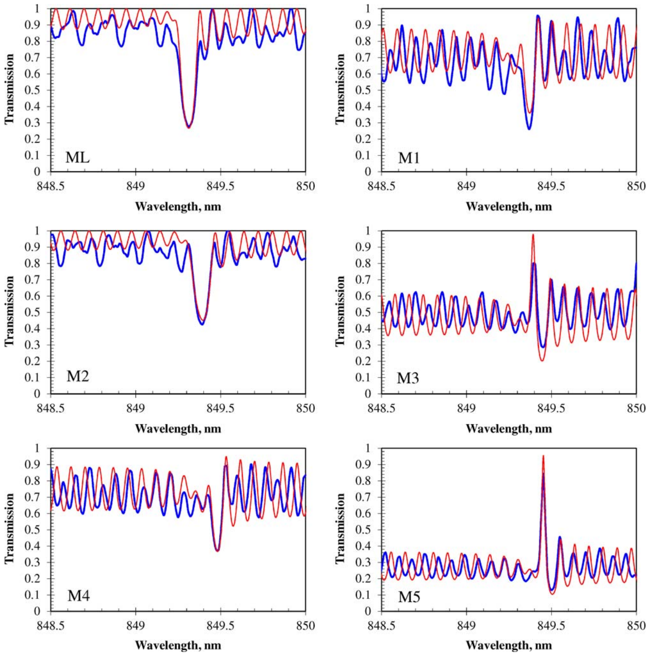

Fig. 3. (Color online) Evolution of the transmission spectra of the filter during the process of fabrication, i.e., after deposition of the matching layer and each of the layers of the dielectric mirror. Gray (blue online) curve is the measurement, and black (red online) curve is the modeling.

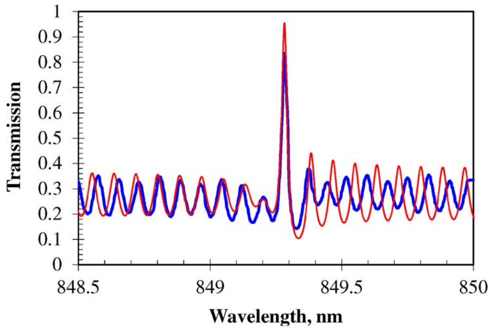

Fig. 4. (Color online) Transmission spectrum of the RBG/MDM filter in air. Black (blue online), measurement; gray (red online), theory.

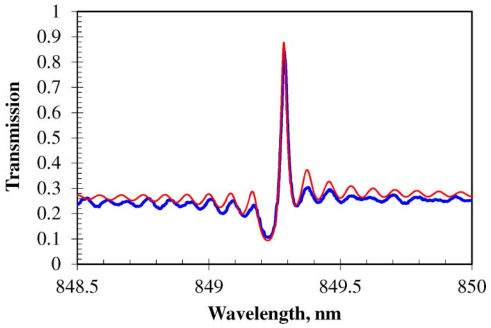

Fig. 5. (Color online) Transmission spectrum of the filter in air after AR coating. Black (blue online), measurement; gray (red online), theory.

mirror increased after deposition of a quarter-wave layer of a high refractive index while it decreased after the deposition of a quarter-wave layer of a low refractive index. Therefore, a resonance can only be seen after deposition of the third and fifth layers of the mirror. Also, it can be seen that the measured transmission spectrum and the theoretical one match quite well.

Finally, after opening the deposition chamber, we measured the transmittance of this RBG/MDM filter around the resonance wavelength (848.5–850 nm). The comparison of these experimental results with the theoretical predictions is presented in Fig. 4. One can see that the filter transmits more than 80% with a FWHM of ~30 pm. There are some oscillations outside of the main resonance that can be associated with an additional Fabry–Perot cavity produced by the Fresnel reflection on the uncoated facet of the PTR glass plate and the sidelobes of the RBG. Some dissymmetry of the transmission spectrum of the filter can be explained by a ~20% error in the thickness of the matching layer.

In order to remove the oscillations in the transmission spectrum outside of the resonance, we then deposited an antireflection coating on the rear facet of the RBG. We used a two-layer AR-coating with classical formula 0.3 H/1.3 L centered at 850 nm, with theoretical reflection below 0.1%. Then we remeasured the spectral transmission (Fig. 5). One can see that the filter now has very small oscillations outside the resonance. Moreover, it transmits more than 85% and the bandwidth is below 30 pm in the 850 nm region. When comparing with theory, one can see that the maximum transmission at the resonance is very similar. This limited transmission is due to a mismatch between the reflection coefficients of the Bragg grating (65%) and the dielectric mirror (75%).

We have demonstrated a class of spectral filters combining a reflecting Bragg grating recorded in PTR glass with a matched multilayer dielectric mirror. The fabricated filter has a bandwidth of 30 pm and a throughput of ~90%. The transmission is limited by the difference of the reflection coefficients of the two mirrors of the cavity. This result paves a way to the fabrication of filters with an ultranarrow bandwidth, high transmission, and broadband rejection width.

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