Tunable narrowband filter based on a combination of Fabry–Perot etalon and volume Bragg grating

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Received April 4, 2006; revised May 26, 2006; accepted May 28, 2006; posted June 1, 2006 (Doc. ID 69594); published July 25, 2006

A new type of tunable narrowband filter is proposed. This filter is a combination of a Fabry–Perot etalon, which permits the selection of a comb of discrete narrow bands, and a high-efficiency rotating volume Bragg grating recorded in photo-thermo-refractive glass, which permits tuning between the Fabry–Perot resonances. A tunable filter for fixed wavelengths in the region of 1.5 μm with a spectral width of 220 pm (FWHM), separation between channels of 800 pm, and throughput of 95% (losses <0.2 dB) is demonstrated.

OCIS codes: 090.7330, 350.2460.

Fabry–Perot etalons (FPEs) as narrowband tunable filters have been widely studied during the past several years. It is well known that the optical thickness of the cavity of a Fabry–Perot filter is directly proportional to its central wavelength. To change its optical thickness, the use of piezoelectric and electro-optic[1] or thermo-optic[2] material as a spacer to Fabry–Perot filters has been proposed. However, this did not result in an easy or reliable solution. The first two effects lead only to very low tunability, and the last one involves the use of very high temperatures. It has recently been demonstrated that the association of several solid-spaced FPEs[3] enables the manufacturing of tunable filters with fixed wavelength; however, the design of such filters for a specific application can be complicated, and the rejection band and tunability are limited to several tens of nanometers. We propose a new technique consisting of the combination of two optical components: a FPE and a high-efficiency reflecting Bragg grating (RBG) recorded in photo-thermo-refractive (PTR) glass[4,5] (see Fig. 1). In this case, the FPE will define a comb of discrete narrowbands (modes) with desirable shape and bandwidth, while the RBG, which has a high spectral and angular selectivity, will select only one of these modes.

The proposed FPE consists of a high-quality optical window with both faces having identical coatings. These dielectric mirror coatings are composed of alternative quarter-wave layers of low (L) and high (H) refractive indices. A quarter-wave layer is a layer with optical thickness $n_i t_i$ (n_i being the refractive index of the layer and t_i its thickness), which satisfies the expression $n_i t_i = \lambda/4$, where λ is the center wavelength of the mirror.[6]

The transmission of a FPE is a discrete channel spectrum (each resonance has a transmission equal to one assuming no losses), and narrow lines are all separated by gaps with constant width defined as the free spectral range [(FSR) typically between 0.1 and 10 nm]. These discrete resonances will define the addressable wavelengths. In this case, the expressions of the spectral width [full width at half-maximum $(\mathrm{FWHM}_{\mathrm{FPE}}, \delta\lambda)$] and the free spectral range $(\mathrm{FSR}_{\mathrm{FPE}}, \Delta\lambda)$ are[7]

$$\delta\lambda = \frac{1-R}{\pi\sqrt{R}}\frac{\lambda_0^2}{2n_0 t}, \qquad \Delta\lambda = \frac{\lambda_0^2}{2n_0 t}, \qquad (1)$$

where R is the mirror reflectance; n_0 and t are, respectively, the refractive index and the thickness of the cavity; and λ_0 is the central wavelength of the mirrors. For spacer thickness between 100 μm and 5 mm the use of mirrors with a small number of layers (between 3 and 9) is enough to reach a very narrow bandpass (typically several tens or hundreds of picometers). Theoretically, a narrower bandpass (~1 pm) could be reached. However, because of the use of extended beams, the lowest FWHM that can be reached is limited by the flatness of each face of the window, the parallelism between them, and the divergence of the input beam. Therefore it is possible to demonstrate that the narrowest spectral width accompanied by high transmittance that can be practically reached is about 10 pm.

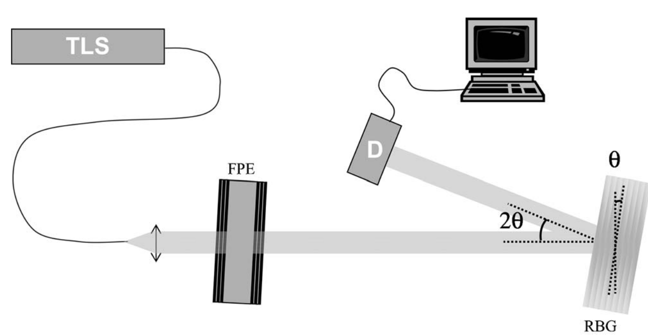

Fig. 1. Tunable narrow bandpass FPB filter. TLS, tunable laser source; D, InGaAs photodiode.

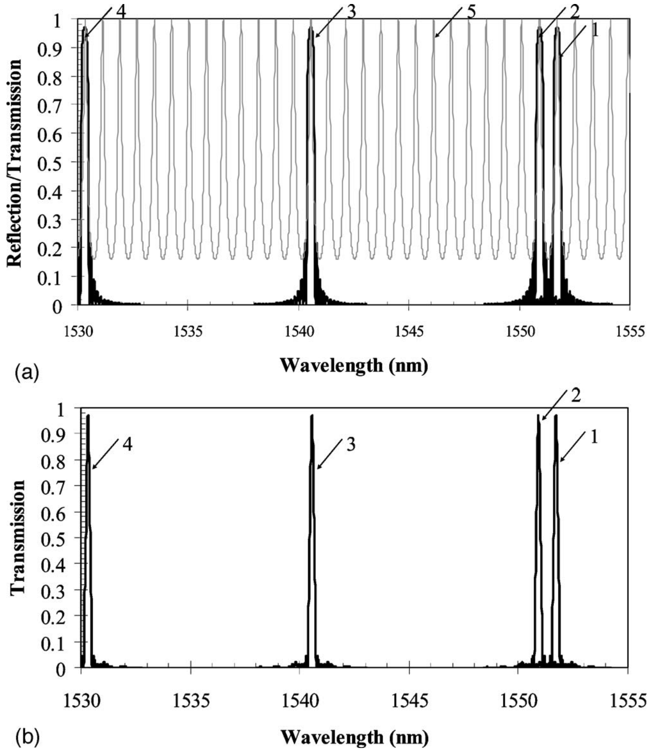

Fig. 2. Modeling of a combined FPB filter. (a) Reflection of the RBG for different increasing inclinations of the RBG (curve 1, $\theta=3.06°$; curve 2, $\theta=4.13°$; curve 3, $\theta=10.79°$; curve 4, $\theta=14.70°$) and transmission of the FPE (curve 5). (b) Transmission of the assembled filter for different increasing inclinations of the RBG. Values of θ for curves 1–4 are the same as in (a).

A FPE with the structure air/HLH/silica/HLH/air centered at 193.10 THz (1552.52 nm) is modeled. The spacer is a 1.036 mm thick fused-silica window. Each three-layer mirror stack (HLH) has a reflection coefficient of ~43%. Figure 2(a) shows the transmission (ratio of transmitted to incident intensity) for this FPE with a spectral width of 220 pm and a FSR of 100 GHz (~800 pm).

The second element used in our simulations is a RBG. This component is obtained by the recording of a sinusoidal refractive index modulation in a photosensitive medium. The RBG that we considered has the following parameters: 5 mm thickness, central wavelength (λ_R) 1552.52 nm defined as $\lambda_R=\Lambda/(2n_0)$, where Λ is the grating period and n_0 is the refractive index of the photosensitive medium. The dependence of the reflection coefficient of such a grating on wavelength is shown in Fig. 2(a). This RBG is a narrowband reflection filter, has a spectral selectivity of 320 pm (FWHM), and has a diffraction efficiency of 97%. The key point of this filter is that the central wavelength of the RBG can be tuned by rotating the Bragg grating and therefore changing the incidence angle on the grating[8]:

$$\lambda_0=\cos\left(\operatorname{asin}\left(\frac{\sin(\theta)}{n_{\mathrm{PTR}}}\right)\right)\lambda_R, \qquad (2)$$

where θ is the angle of incidence and λ_0 is the resonant Bragg wavelength. Therefore, the central wavelength of the Bragg grating can be tuned from 1552.52 to 1530.33 nm by only tilting it with an angle of about $\theta_4=15°$ [Fig. 2(a)].

Moreover, it is important to note that for effective selection of a single band from the comb produced by the FPE, the spectral width of the RBG ($\mathrm{FWHM}_{\mathrm{RBG}}$) should satisfy the following conditions:

$$\mathrm{FWHM}_{\mathrm{FPE}} \leqslant \mathrm{FWHM}_{\mathrm{RBG}} < \mathrm{FSR}_{\mathrm{FPE}}. \qquad (3)$$

When these conditions are satisfied, the proposed filter should have a spectral bandwidth determined primarily by the FPE, which can be very narrow, and a broad rejection band determined by the RGB.

The transmission of the filter resulting from the incoherent combination of the RBG and the FPE is shown in Fig. 2(b). The spectral selectivity of the FPE is equal to ~220 pm. Simulations show that shifts of the central wavelength of the filter can be made by switching from one channel to another without a change in spectral shape. The identity of all channels is due to the fact that their shape is fixed by the FPE. Moreover, even if the FPE presents a very bad rejection ($T_{\min}\approx 15\%$), the final rejection will be highly improved because of the high spectral selectivity of the RBG. In Fig. 2(a), one can see side lobes next to the main maxima of the volume Bragg grating. These oscillations are typical for uniform Bragg gratings.[8] However, these side lobes can be eliminated by the use of gratings with special variations of the magnitude of the refractive index modulation, so-called apodized gratings.[9]

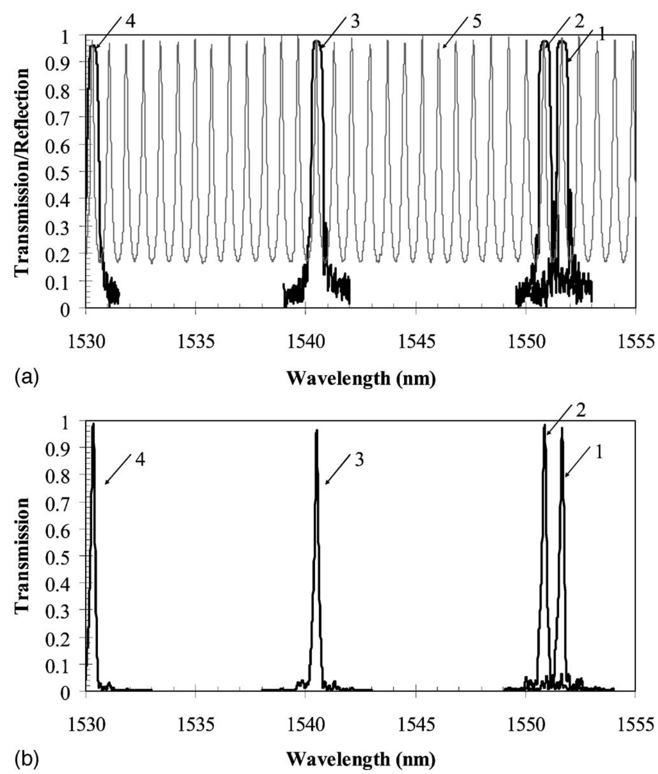

Fig. 3. Experimental data for a FPB filter. (a) Reflection of the RBG for different increasing inclinations of the RBG (curves 1–4) and transmission of the FPE (curve 5). (b) Transmission of the assembled filter for different increasing inclinations of the RBG (curves 1–4).

Let us discuss the thermal stability of such a combined Fabry–Perot–Bragg (FPB) filter. The thermal shift of the central wavelength of volume Bragg grating in PTR glass at 633 nm is equal to about 7 pm/K.[10] For a thick fused-silica spacer of the FPE, the thermal dependence of the central wavelength is ~13 pm/K. However, the FWHM of the RBG is larger compared with FWHM of the FPE [see Eq. (4)]. Consequently, for relatively low temperature variations within several degrees, the thermal dependence of the FPB filter will be determined by the thermal dependence of the spacer of the FPE. A possible solution to reduce this dependence is to use an air-spaced FPE instead of a solid-spaced FPE. In this case this thermal dependence can be decreased to less than 1 pm/K, and therefore a thermally very stable filter can be manufactured.

The setup used for the measurements is presented in Fig. 1. It is composed of a tunable SANTEC TLS 220 laser source that can continuously change its output wavelength from 1530 to 1590 nm with a 1 pm step. The laser radiation is filtered by a single-mode fiber and coupled to a collimator. The 1 mm diameter probing beam is sent through the FPE and then reflected by the RBG. The RBG is fixed on a rotating stage that allows it to precisely control the angle of incidence of the beam. The reflected beam is finally collected by an InGaAs photodiode, associated with a data acquisition card, to process the acquired signals. It is seen in Fig. 1 that the system is designed in such a manner that no backreflection would affect the stability of the laser.

A commercial 100 GHz (800 pm) FPE centered at 1552.52 nm with a finesse of 3.8 (FWHM = 220 pm) was used in this work. The RBG was manufactured at OptiGrate Company. The recording medium is a PTR glass. PTR glass is a multicomponent silicate glass doped with cerium, silver, and fluorine. A refractive index change is the result of a two-step process of UV exposure followed by thermal development. It appears as a precipitation of a crystalline phase inside the glass matrix, which results in a refractive index decrease.[4,5] The recorded reflecting phase Bragg grating has a resonant wavelength of 1552.71 nm and an absolute diffraction efficiency of 97%. Figure 3 shows the transmission of the FPE, the reflectance of the RBG for different angles of incidence, and finally the transmittance of the combined FPB filter. The transmission and the reflection are defined as the ratio of the transmitted and the reflected power to the incident power, respectively, and each resonance of the FPE corresponds to a channel of the International Telecommunication Union grid. The FPE shows resonances with more than 98% transmittance of the incident beam. Then the rotation of the RBG permits the tuning of the filter between channels of the FPE without any deterioration of its transmission. Finally, the measured spectra are in perfect accordance with the theoretical results, demonstrating 220 pm spectral width accompanied with 95% throughput.

A tunable narrowband filter combining a reflecting Bragg grating and a Fabry–Perot etalon is proposed. The advantage of such a configuration is that the spectral width is defined by the etalon, while the volume Bragg grating increases the rejection band to infinity. A tunable Fabry–Perot–Bragg filter with a spectral width of 220 pm, spectral steps of 800 pm, and throughput of 95% is demonstrated.

This work has been supported by NASA contract NNL06AA42P. J. Lumeau's e-mail address is jlumeau@creol.ucf.edu.

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