Narrowband electrooptic tunable notch filter

Richard Lytel and George F. Lipscomb

We describe the theory of a narrowband electrooptic tunable filter based on a Fabry-Perot etalon with distributed Bragg reflectors. The filter can be in either bulk or waveguide form. The input to the filter must be prefiltered to the stop-band of the Bragg mirrors. Once this is accomplished, the etalon possesses a very narrow notch in the Bragg filter stop-band. The notch width is extremely narrow when the Bragg reflectance is high. The location of the notch in the Bragg stop-band is determined by the etalon cavity length and can be tuned by application of an electric field to the electrooptic material comprising the etalon cavity. Absorption in the cavity and Bragg reflectors is included in the theoretical model of the filter. The filter can be constructed from any one of several existing electrooptic organic polymer crystals, if the gratings are made either by partial polymerization of the monomer in crossed-UV beams or by corrugating the surface of the polymer. We show a theoretical example of a notch filter operating at a center wavelength of 1 μm that is 62.75 μm thick, with a notch width of under 1 Å and a transmission of 35%. This type of filter should have applications in high-speed optical modulation and Q-switches for lasers.

I. Introduction

Electrooptic tunable filters can be designed in a variety of different ways.[1–5] These include birefringent, Solc, Fabry-Perot, and tunable Bragg filters. The particular design selected depends on whether narrow transmission, suppression of side lobes, wide field of view, high sensitivity, high-speed response, or other features are desirable.[1] Tunable spectral filters have been demonstrated in a variety of materials for the different configurations with some experimental success.[1–4] Electrooptic tunable filters (EOTFs) offer the potential for electrically controlling the filter bandpass and bandwidth. Furthermore, certain devices have been demonstrated that are polarization-independent and have been used as electrooptic laser modulators.[2]

The objective of this paper is to describe the theory of an electrooptic tunable notch filter capable of very narrow spectral bandwidth, high transmission, and fast modulation. The EOTF is based on a Fabry-Perot interferometric filter with Bragg reflectors bounding the ends of an electrooptic cavity material. The entire structure can be made from a single electrooptic material with surface corrugations on the ends forming the Bragg reflectors. It, therefore, has applications to integrated optics where conventional mirror fabrication is difficult. The filter can also be made in bulk form. For bulk filters, the Bragg mirrors consist of a material with a sinusoidal linear refractive-index grating impressed in the material. Such structures can, for example, be made by partially polymerizing an organic polymer in crossed UV beams[6] at the desired Bragg resonant frequency. This technique has been demonstrated and leads to areas of monomer with slightly different linear refractive index than the polymer. Alternatively, Bragg mirrors can consist of stacks of different polymer layers, where the side groups attached to the polymer chain are altered from layer to layer to produce a molecularly engineered refractive-index grating.[7]

The EOTF is an interference device, and, therefore, absorption effects in the Bragg mirrors and cavity must be minimized to achieve usable transmission levels, i.e., good sensitivity. This is accomplished by judicious choice of Bragg and cavity materials and reduction in the total length of the device to micron dimensions. We show in this paper how to accomplish this and produce narrow notches (of the order of an angstrom) with representative polymer materials.[7]

This EOTF configuration has been studied previously for optical bistability,[8,9] where the cavity is made from a material exhibiting a third-order Kerr nonlinearity. It should be noted that the current EOTF concept could also be optically tuned by using the same effect in the cavity.[9] For this paper, we shall focus exclusively on the electrooptic tunable filter.

Section II describes the device and gives a pedagogical description of how it works. Section III contains the theoretical description of the operation of the EOTF and exhibits some nominal transmission modes for a nonabsorbing device. The effects of absorption

The authors are with Lockheed Palo Alto Research Laboratory, 3251 Hanover Street, Palo Alto, California 94304.

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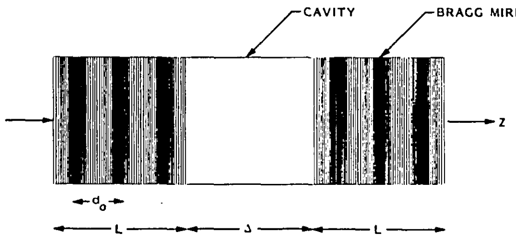

Fig. 1. Schematic of a bulk EOTF based on a Fabry-Perot etalon made from an electrooptic material surrounded by Bragg reflectors. The reflectors of length L have a sinusoidal refractive index with modulation depth n_1/n_0 and period d_0. The mirrors exhibit the greatest scattering at wavelengths $\lambda = \lambda_0$ where $\lambda_0 = 2d_0$. The cavity has length Δ. Electrodes are attached on the ends for longitudinal modulation and on the top and bottom of the cavity for transverse modulation.

are included in Sec. IV, where it is shown that a device only 62.75 μm thick can exhibit a transmission of over 35% despite absorption losses typical of transparent media. Finally, Sec. V concludes with a summary of the filter performance and suggestions on filter construction and application.

II. Description of the Filter

The EOTF consists of an electrooptic material surrounded by Bragg reflectors. It is a Fabry-Perot cavity with low finesse everywhere except in the Bragg reflector stop-band, where the mirror reflectivity can be quite high. In this region, the EOTF acts as a Fabry-Perot etalon with very sharp interference fringes. The number of fringes that fall within the Bragg filter stop-band is determined by the free spectral range of the etalon. We shall show how to design a filter with a single interference fringe in the center of the stop-band and use the EO effect to tune this notch away from the center. We shall also show how other filter designs may be accomplished with this architecture.

Figure 1 illustrates a bulk filter. The Bragg mirrors consist of material whose refractive index varies sinusoidally along the z axis, the direction of light propagation. The period of the variations is d_0, and the wave vector at which Bragg scattering occurs is $\beta_0 = \pi/d_0$. The wavelength at which maximum Bragg scattering occurs is, therefore, $\lambda_0 = 2d_0 = 2\pi/\beta_0$. The refractive index has the form $n(z) = n_0 + n_1 \sin(2\beta_0 z)$ over the length L of the mirror. This length is conveniently described by $N_L = L/d_0$, where N_L is the (integral) number of periods in the length of the mirror. The depth of modulation of the refractive index, n_1/n_0, is conveniently described by a coupling constant $\kappa = (n_1/2n_0)\beta$, where $\beta = 2\pi/\lambda$, and λ is the wavelength of the incident light.[10] The amplitude loss coefficient of the material is α_B.

The etalon cavity is an electrooptic crystal of length Δ with refractive index n_0 and either a longitudinal or transverse electrooptic effect. The electrooptic effect gives rise to a single-pass phase shift equal to $\gamma\Delta$, where γ is the electrooptically induced shift in the optical wave vector. The total single-pass phase shift from the cavity, excluding that contributed by the Bragg mirrors, is $\phi_{\mathrm{F.P.}} = \Delta(\beta + \gamma) = \Delta(\Delta\beta + \gamma) + \beta_0\Delta$, where $\Delta\beta = \beta - \beta_0$ is a detuning parameter. It is convenient to define the cavity length as $\Delta = (N_\Delta + \epsilon_\Delta)d_0$, where N_Δ is an integer and $0 < \epsilon_\Delta < 1$. It will be shown shortly that the choice $\epsilon_\Delta = 1/2$ puts a notch at the center of the Bragg stop-band, i.e., at $\Delta\beta = 0$ when $\gamma = 0$.

The operation of the filter can be described as follows. Assume that the light of the wavelength λ is incident on the filter, where λ falls within the Bragg mirror stop-band. Inside the stop-band, Bragg reflection is high. The limits of the stop-band are defined below for a given Bragg structure. The light enters the device, rattles around the cavity, and exits by reflection and transmission. Some of the light is absorbed by the mirrors and cavity. Absorption must be accounted for in interference devices, since even a small linear loss per pass can lead to a large total loss after many reflections. For wavelengths near λ_0, significant Bragg scattering occurs, and the Bragg filters act as high-reflectivity mirrors. The etalon then exhibits the usual Fabry-Perot transmission fringes. The width of the fringes is determined by the finesse of the cavity, which in turn is determined by the mirror reflectivity. Mirror reflectivities are determined by both the depth of modulation of the refractive index in the Bragg filter and the wave vector difference $\Delta\beta$. Reflectivities are largest for $\Delta\beta = 0$, and so is the cavity finesse.

It is desirable for this reason to choose device parameters to put a single notch at $\Delta\beta = 0$, i.e., at $\lambda = \lambda_0$, when $\gamma = 0$. This is accomplished as follows. Choose $\epsilon_\Delta = 1/2$. Then, the single-pass phase shift in the cavity, excluding the contribution from the Bragg reflectors, is $\phi_{\mathrm{F.P.}} = \Delta(\Delta\beta + \gamma) + \pi/2$ modulo $n\pi$. As will be shown, the Bragg mirrors contribute a phase shift per pass $\psi(\Delta\beta)$, where $\psi(0) = \pi/2$ (resonance). Thus the total single-pass phase shift is $\phi = \Delta(\Delta\beta + \gamma) + [\psi(\Delta\beta) - \psi(0)]$ modulo $n\pi$. Since the etalon exhibits interference fringes at $\phi = n\pi$, where n is integral, a fringe, or notch, appears at $\Delta\beta = 0$ when $\gamma = 0$. The application of an electric field creates a nonzero value of γ and consequently causes a shift in the notch location from $\beta = \beta_0$ to $\beta = \beta_0 + \Delta\beta_N$, where $\Delta(\Delta\beta_N + \gamma) + [\psi(\Delta\beta_N) - \psi(0)] = 0$. In this manner, the notch location can be tuned about the Bragg resonant frequency throughout the entire Bragg stop-band. Multiple notches appear in the Bragg stop-band if Δ gets too large. Specifically, a Fabry-Perot etalon with constant-reflectance mirrors will exhibit notches at $\phi_{\mathrm{F.P.}} = n\pi$. An increase in Δ reduces the free spectral range by constant amounts in β leading to more closely spaced fringes. For the EOTF, however, the Bragg mirrors contribute a wavelength-dependent phase shift $\psi(\Delta\beta)$ to the total round-trip phase so notches appear at wave vectors satisfying $\Delta(\Delta\beta + \gamma) + [\psi(\Delta\beta) - \psi(0)] = n\pi$. The mirrors have the effect of adding an additional wavelength dependence to the single-pass phase shift and

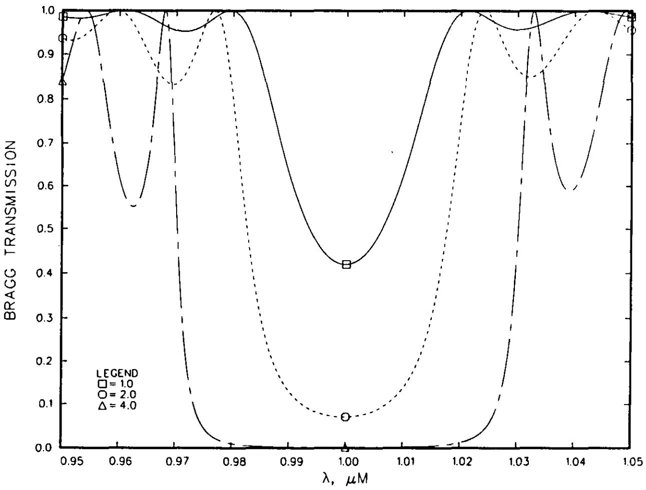

Fig. 2. Transmission function for a Bragg mirror with coupling constant $\kappa L = 1, 2$, and 4, length $L = 25\ \mu$m, and resonant wavelength $\lambda_0 = 1\ \mu$m. The minimum transmission occurring at $\lambda = \lambda_0$ is given by $T_B(\min) = \mathrm{sech}^2(\kappa L)$ and decreases with increasing modulation depth. The width of the Bragg stop-band, where transmission returns to unity, is given by $\lambda_+ - \lambda_-$, where $\lambda_\pm^{-1} = \lambda_0^{-1} \mp (1/2\pi)\sqrt{(\pi^2/L^2) + \kappa^2}$ and increases with increasing modulation depth.

consequently to the free spectral range of the etalon. Usually it is desirable to choose Δ so that the width between notches is greater than the Bragg filter stop-band halfwidth.

It is also desirable to reduce Δ to minimize absorption in the cavity. It is desirable as well to minimize the length of the Bragg mirrors for the same reasons and increase the Bragg modulation depth to maintain a desired value of κL that is sufficient for the high-finesse necessary to achieve a narrow notch.

The next two sections of this paper quantify these results. For clarity, we first consider the EOTF composed of nonabsorbing mirrors and cavity. Finally, the effects of absorption are included in a way which may be applied to any material composing the EOTF.

III. Theory of Operation (No Absorption)

The spectral transmission of the EOTF in Fig. 1 may be calculated by performing a coupled-wave calculation and correctly treating the Fabry-Perot boundary conditions. Alternatively, a simpler approach taken here is to note that the etalon may be treated as a Fabry-Perot interferometer with mirrors that have a complex reflectivity.

The amplitude reflectivity of a Bragg mirror of length L, coupling constant κ, and resonant at wavelength λ_0 is a function of the detuning $\Delta\beta$ and is given by

$$r(\Delta\beta) = \frac{i\kappa \sinh\delta L}{\delta \cosh\delta L + i\Delta\beta \sinh\delta L}, \tag{1}$$

where $\delta = \sqrt{\kappa^2 - \Delta\beta^2}$ for $\kappa \geq |\Delta\beta|$ and $\delta \rightarrow i\sigma = i\sqrt{\Delta\beta^2 - \kappa^2}$ for $|\Delta\beta| > \kappa$. Equation (1) assumes no absorption in the Bragg reflector. The transmission may be calculated from Eq. (1) using $R_B = |r|^2$ and $T_B = 1 - R_B$ and is given by

$$T_B = \frac{\kappa^2 - \Delta\beta^2}{\kappa^2 \cosh^2\delta L - \Delta\beta_2}. \tag{2}$$

The Bragg transmission is plotted in Fig. 2 as a function of wavelength for $\kappa L = 1, 2$, and 4, and $\lambda = 1\ \mu$m. The asymmetry in the transmission is due to the wavelength dependence of the coupling constant κL. For $L = 25\ \mu$m (fifty periods), the values of κL correspond to ~1.25, 2.5, and 5.0% modulation of the linear refractive index. Several important features may be noted from Fig. 2. First, the limits of the Bragg stop-band, where the reflectivity is high, are given by $\Delta\beta_\pm = \pm\sqrt{\pi^2/L^2 + \kappa^2}$ and increase as the coupling constant κL increases. Here we use the edge of the Bragg stop-band to define its limits. Second, the transmission depth of the Bragg filter at resonance is given by $\mathrm{sech}^2\kappa L$ and decreases with κL. The peak finesse of the etalon occurs at $\Delta\beta = 0$ and is given by $\mathcal{F} \approx \pi \sinh 2\kappa L$, which is ~86 for $\kappa L = 2$ and 4.7×10^3 for $\kappa L = 4$. Very narrow notches in the EOTF transmission are achieved by increasing the peak finesse. This widens the Bragg stop-band and thus the required prefilter bandwidth for the EOTF. In addition, when absorption is present, the higher finesse cavity will exhibit greater loss, since there are many more significant reflections in the device.

The complex reflectivity in Eq. (1) may be written as

$$r(\Delta\beta) = |r(\Delta\beta)| \exp[i\psi(\Delta\beta)], \tag{3}$$

which defines the real amplitude $|r(\Delta\beta)|$ and the phase shift $\psi(\Delta\beta)$ induced by the reflector:

$$|r(\Delta\beta)| = \frac{\kappa \sinh\delta L}{\sqrt{\kappa^2 \cosh^2\delta L - \Delta\beta^2}}, \tag{4}$$

$$\tan\psi(\Delta\beta) = \frac{\delta}{\Delta\beta} \coth\delta L. \tag{5}$$

The phase shift is $+\pi/2$ at resonance as noted in Sec. II.

The transmission τ of the etalon may be calculated by treating the device as a Fabry-Perot interferometer with reflectors whose complex reflectivity is given by Eq. (1). It is straightforward to show that the transmission of an etalon with complex-reflectance mirrors is given by[12]

$$\tau = \left(1 + \frac{4}{T_B^2} \{Im[r \exp(i\phi_{\mathrm{F.P.}})]\}^2\right)^{-1}, \tag{6}$$

where $\phi_{\mathrm{F.P.}}(\Delta\beta)$ is the single-pass phase shift induced in the cavity and is given by $\phi_{\mathrm{F.P.}} = \Delta(\beta + \gamma)$. The total phase shift in the cavity is, therefore, given by

$$\phi = \phi_{\mathrm{F.P.}} + \psi = \Delta(\Delta\beta + \gamma) + \psi(\Delta\beta) + \beta_0\Delta \tag{7}$$

and includes a wavelength-dependent contribution from the Bragg mirrors, as discussed in Sec. II. Note that for $\epsilon_\Delta = 1/2$, $\beta_0\Delta = \pi/2 + N_\Delta\pi$. A straightforward application of Eq. (4) and (5) to Eq. (6) then yields the etalon transmission as

$$\tau = (1 + F \sin^2\phi)^{-1}, \tag{8}$$

where $F = 4R_B/T_B^2$ is given by

$$F = \frac{4\kappa^2}{\delta^4} \sinh^2\delta L(\kappa^2 \cosh^2\delta L - \Delta\beta^2). \tag{9}$$

Thus a standard Fabry-Perot transmission formula applies to the EOTF, where the single-pass shift is given by Eq. (7) and depends on the detuning from resonance and the details of the Bragg reflectors through $\psi(\Delta\beta)$. The F factor, which is normally related to the finesse $\mathcal{F}$ by $\mathcal{F} = (\pi/2)\sqrt{F}$, also depends on the Bragg mirror parameters κL and $\Delta\beta L$.

An important distinction between the EOTF and an ordinary etalon was fixed-reflectivity mirrors is evident from Eq. (8). An ordinary etalon exhibits transmission peak at $\phi_{\text{F.P.}} = n\pi$, and the peaks are uniformly distributed in β space. The EOTF exhibits notches whenever $\phi_{\text{F.P.}} + \psi = n\pi$, so that the notches are not uniformly distributed in β space. Furthermore, the parameter F can vanish outside the Bragg stop-band, where the Bragg reflectivity oscillates to zero about very small values. Thus the EOTF exhibits additional transmission peaks outside the Bragg stop-band. These are not of interest, since the high transmission outside the stop-band precludes filtering. The interesting operating modes lie within the stop-band, where one or more narrow notches can be made to appear.

As noted earlier, if $\Delta = (N_\Delta + \epsilon_\Delta)d_0$ is chosen so that N_Δ is integral and $\epsilon_\Delta = 0.5$, the phase shift $\phi(\Delta\beta)$ in Eq. (7) may be written, mod$n\pi$, as

$$\phi = \Delta(\Delta\beta + \gamma) + [\psi(\Delta\beta) - \psi(0)] \tag{10}$$

and is equal to zero (mod$n\pi$) at $\Delta\beta = 0$ (for $\gamma = 0$). The transmission is then unity at $\Delta\beta = 0$. As $\Delta\beta$ is moved away from resonance, the high finesse of the Bragg mirrors ensures that the interference fringe at $\Delta\beta = 0$ is very sharp. To ensure that the next notch appears outside the Bragg stop-band, Δ must be chosen to be no larger than Δ_{max}, where Δ_{max} satisfies $\Delta_{max}[(\Delta\beta_\pm) + \gamma] + [\psi(\Delta\beta_\pm) - \psi(0)] = \pm\pi$. Conversely, Δ can be made larger if it is desirable to put several notches in the stop-band.

Figure 3 exhibits several transmission curves as a function of wavelength for an etalon near resonance. The resonant wavelength was chosen at $\lambda = 1\ \mu$m. The Bragg mirror thickness is 25 μm. The cavity length was chosen to be 12.75 μm, which puts the next notch near, but just inside, the edge of the Bragg stop-band for both curves. The κL for the two curves is 1 and 2, and the electrooptic effect is zero. The full width of the Bragg stop-band for $\kappa L = 2$ is ~480 Å, while the notch widths are ~100 and 20 Å, respectively. The peak finesse of each etalon, at resonance, is $\mathcal{F} \approx 11$ and $\mathcal{F} \approx 86$ for $\kappa L = 1$ and 2, respectively. Several important features are worth noting. First, the device is only 62.75 μm thick. As shown later in Sec. IV, this is critical since absorption effects can cause severe losses in thicker interference-based devices. Second, the notches have been made narrow, of the order of 10–100 Å, simply by employing Bragg reflectors attached directly to the cavity. Third, the etalon can be designed to possess a notch anywhere in the stop-band by changing Δ, i.e., by changing ϵ_Δ.

Figure 4 illustrates the effect of increasing the free spectral range of the etalon by decreasing the cavity length to 5.25 μm. The edge of the Bragg stop-band is now evident in the etalon transmission function, because the fringe that was near the edge in Fig. 3 has now moved further out from the center of the stop-band.

Figure 5 illustrates the effect of decreasing the free spectral range of the etalon by increasing the cavity length to $\Delta = 25.25\ \mu$m. Several notches appear in the Bragg stop-band where the reflectivity is high. Several observations can be made. First, the width of the notches increases as the wavelength moves away from

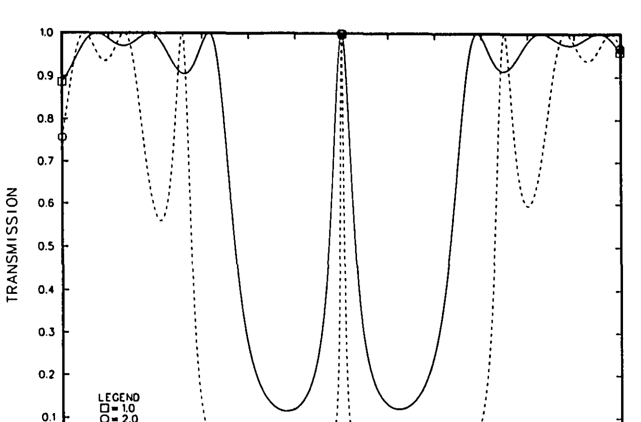

Fig. 3. Transmission of the EOTF for Bragg mirrors with $\kappa L = 1$ and 2. Absorption effects have been excluded. The cavity length $\Delta = 12.75\ \mu$m, and $L = 25\ \mu$m. The free spectral range of each etalon depends on κL, but in both cases it is slightly less than the halfwidth of the Bragg stop-band.

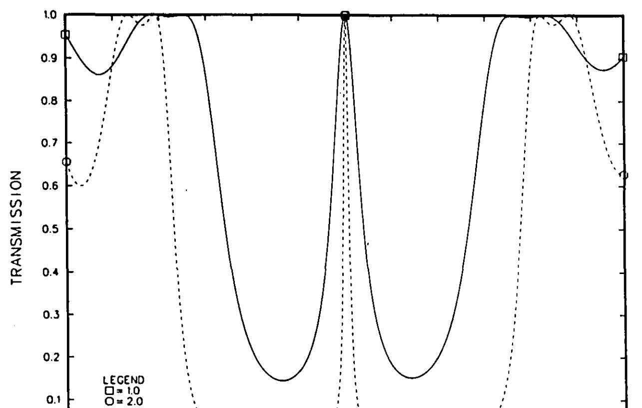

Fig. 4. Transmission of the EOTF for Bragg mirrors with $\kappa L = 1$ and 2. Absorption effects have been excluded. The cavity length is $\Delta = 5.25\ \mu$m and $L = 25\ \mu$m. The free spectral range of each etalon is larger than the halfwidth of the Bragg stop-band, and the edges of the transmission function are given by the edges of the corresponding Bragg mirror stop-band.

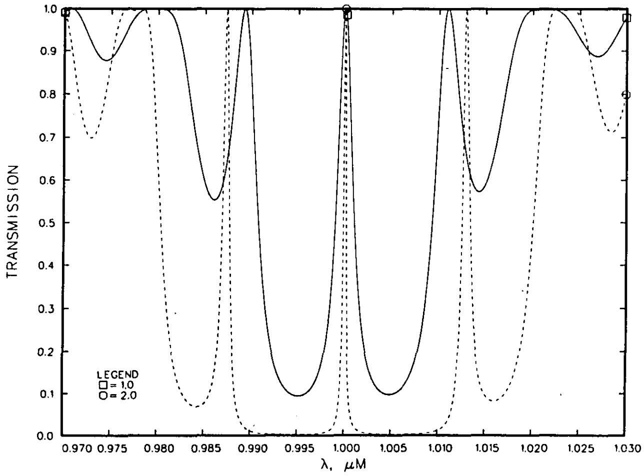

Fig. 5. Transmission of the EOTF for Bragg mirrors with $\kappa L = 1$ and 2. Absorption effects have been excluded. The cavity length $\Delta = 25.25\ \mu$m and $L = 25\ \mu$m. Several notches now appear in the Bragg stop-band for both filters because the free spectral ranges are smaller than the Bragg stop-band halfwidth.

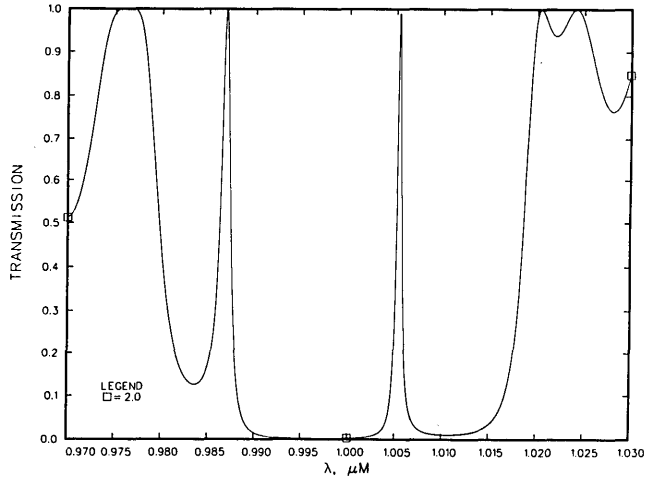

Fig. 6. Transmission of the EOTF for the same device as in Fig. 3 with $\kappa L = 2$ except a voltage has been applied to the cavity to tune the notch away from $\Delta\beta = 0$. The shift corresponds to an electrooptic-induced phase shift of 0.855 rad, i.e., a voltage $V = 0.272 V_\pi$, where V_π is the halfwave voltage of the cavity material. Larger voltages induce larger phase shifts and can tune the notch to any desired location within the stop-band.

resonance. This is due to the (slight) decrease in the cavity finesse for $\Delta\beta \neq 0$; i.e., the decrease in Bragg mirror reflectivity as the wavelength is detuned from resonance. Second, the distance in microns between the notches is not given by the standard Fabry-Perot-free spectral range, $\phi_{\mathrm{F.P.}} = n\pi$ (n = integer), but is instead given by $\phi = n\pi$, with ϕ given by Eq. (10), where $\psi(\Delta\beta)$ is the (wavelength-dependent) Bragg mirror phase shift calculable from Eq. (5). By selectively choosing Δ, one or more notches can be made to appear within the Bragg stop-band. It should be noted that once Δ is selected at its maximum value to permit a single notch in the stop-band, further decreasing Δ changes mainly the transmission of the device outside of the stop-band, where the device is not operated anyway. Minimization of the cavity length is required to reduce absorption by the cavity.

The notch can be tuned to either side of the resonance by applying a voltage to the EO crystal. Consider, as an example, a waveguide EOTF made from 2-methyl,4-nitroaniline (MNA), an organic crystal with an exceptionally large room-temperature electrooptic effect,[13] and a very low dc dielectric constant. For MNA, the transverse EO coefficient has been measured to be $r_{11} = 67 \pm 25 \times 10^{-12}$ m/V.[13] For $\lambda = 1\ \mu$m, the halfwave voltage $V_\pi = 930$ V for $n_0 = 2.0$. If the cavity length is 12.75 μm and the waveguide width is comparable, a voltage of 253 V moves the notch from $\lambda = 1\ \mu$m to $\lambda = 1.005\ \mu$m. Larger voltages can move the notch anywhere in the Bragg stop-band. Since the dielectric constant of MNA is small despite the large EO coefficients,[13] the EOTF can be used as either a very narrowband tunable EO filter with extremely fast response or a modulator or Q-switch in a laser cavity. Figure 6 illustrates the tuning of the notch for the same device described in Fig. 3 with $\kappa L = 2$ when $V = 253$ V for MNA. The devices with transmission as exhibited in Fig. 3 is only one example of the myriad devices that can be designed to specification based on this structure. Bulk devices using large area multiple-thin-film structures with normal-incident light are also possible, assuming suitable transparent electrodes (such as ITO) and longitudinal EO crystals are employed. Many notches may be located in the stop-band; the stop-band width can be designed to a particular desired value, or the depth of the stop-band and width of the notch can be designed to specification. This device represents a potentially interesting form for fast electrooptic tuning, filtering, or modulation. However, absorption effects must be accounted for to predict accurately the transmission of a real device. This is discussed next.

IV. Effect of Absorption

Both the Bragg mirrors and the etalon cavity will have some nonzero linear amplitude absorption coefficient denoted α_B and α_C, respectively. The effects of absorption are most easily accounted for in a two-step process. First, the effect of cavity absorption is to replace Eq. (8) for the etalon transmission by[14]

$$\tau = (A + F \sin^2\phi)^{-1}, \tag{11}$$

where $A = (1 - R_B)^2/T_B^2$, $F = 4R_B/T_B^2$ and $R_B \rightarrow R_B \exp(-2\alpha_C\Delta)$, $T_B \rightarrow T_B \exp(-\alpha_C\Delta)$. Equation (11) then yields the correct transmission for an absorbing cavity with ideal Bragg mirrors. To account for absorption in the Bragg mirrors, the reflectivity R_B and the transmission T_B are replaced by[11]:

$$R_B = \frac{|i\kappa \sinh\Gamma L|^2}{|(\alpha_B + i\Delta\beta) \sinh\Gamma L + \Gamma \cosh\Gamma L|^2}, \tag{12}$$

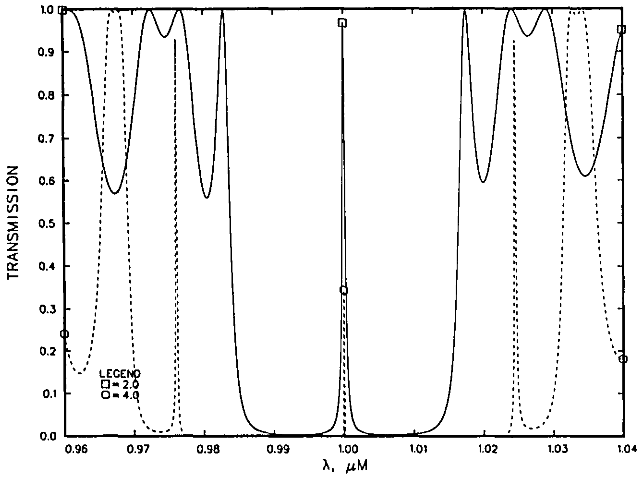

Fig. 7. Transmission of the EOTF for Bragg mirrors with $\kappa L = 2$ and 4. The loss coefficients are $\alpha_B = \alpha_C = 0.25\ \mathrm{cm}^{-1}$. The cavity length $\Delta = 12.75\ \mu\mathrm{m}$, and the mirror length $L = 25\ \mu\mathrm{m}$. Despite loss, the transmission is still very high for $\kappa L = 2$. For $\kappa L = 4$, the peak cavity finesse $\mathcal{F} = 4.7 \times 10^3$, so the small absorption length $\alpha_C\Delta \approx 3.19 \times 10^{-4}$ can still produce a 65% reduction in the peak intensity.

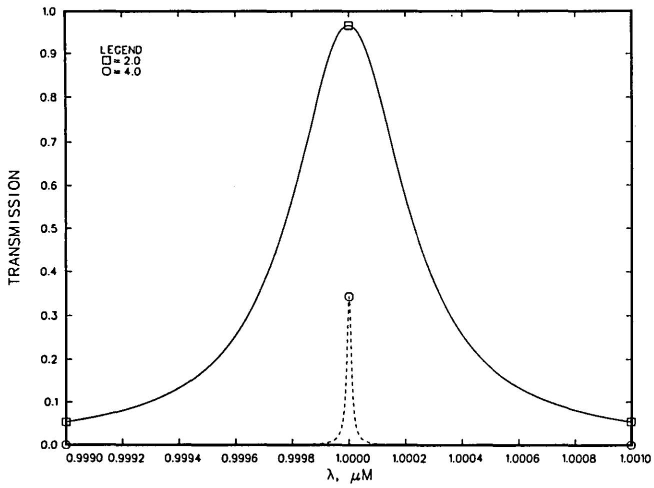

Fig. 8. Close-up view of the transmission of the EOTF illustrated in Fig. 7 for $\kappa L = 2$ and 4. The notch widths are seen to be ~20 and 1 Å, respectively. Transmission is over 95% for $\kappa L = 2$ and is ~35% for $\kappa L = 4$. Reduction of transmission for higher finesse etalons is expected due to multiple reflections in the device.

$$T_B = \frac{|\Gamma|^2}{|(\alpha_B + i\Delta\beta)\sinh\Gamma L + \Gamma\cosh\Gamma L|^2}, \tag{13}$$

where $\Gamma^2 = \kappa^2 + (\alpha_B + i\Delta\beta)^2$. Note that $R_B + T_B \neq 1$ due to the absorption. Writing $R_B = |r(\Delta\beta)| \exp[i\psi(\Delta\beta)]$ as before leads to a new phase $\psi(\Delta\beta)$, which is now a function of the absorption coefficient. Equations (11), (12), and (13) provide a complete description of the transmission of the EOTF for finite absorption in the cavity and mirrors.

Figure 7 illustrates the transmission of the EOTF for $\Delta = 12.75\ \mu\mathrm{m}, L = 25\ \mu\mathrm{m}, \lambda_0 = 1\ \mu\mathrm{m}, \kappa L = 2,4$ and for absorption coefficients given by $\alpha_B = \alpha_C = 0.25\ \mathrm{cm}^{-1}$. The impact of absorption is dramatic particularly for the higher-finesse etalon ($\kappa L = 4$), where many more multiple reflections and consequently more absorption occur. The products $\alpha_B L = 6.25 \times 10^{-4}$ and $\alpha_C\Delta = 3.19 \times 10^{-4}$ are very small for this device, but multiple reflections cause significant absorption anyway. Figure 8 is a close-up view of the notch width for the two etalons, near resonance. It can be seen that, even with absorption, the wider notch (20 Å) has ~95% transmission, while the very narrow notch (1 Å) still has 35% transmission. The latter could still be usable in a narrowband filter application. These figures illustrate the need for extremely thin Bragg mirrors and etalon cavities, if absorption of this level is present.

V. Conclusions

We have described a concept for a narrowband electrooptic tunable filter based on high-reflectance Bragg reflectors surrounding an electrooptic crystal in a Fabry-Perot etalon configuration. The notch width can be made extremely narrow (of the order of angstroms) by appropriate choice of device parameters, and absorption losses can be made quite small by scaling the device to micron dimensions along the light propagation direction. The active region of the device is determined by the center (Bragg) wavelength λ_0 of the mirrors, and the width of this region is determined by the Bragg coupling constant (i.e., the refractive-index modulation depth). This width is the difference $\beta_+ - \beta_-$, where $\beta_\pm = \sqrt{\pi^2/L^2 + \kappa^2}$. One notch, or several notches, can be located within the active region of the device. The notch width is determined by the cavity finesse, which in turn is determined by the Bragg reflectivity near β_0. Very large reflectivities may be obtained, on-resonance, with thin-film mirrors ($L = 25\ \mu\mathrm{m}$) and modest modulation depths (of the order of a few percent).

This type of optical filter is, of course, similar to an ordinary Fabry-Perot interferometer in terms of its spectral characteristics. It offers much more potential, however, for spectral filter applications. In waveguide form, it is unique in that it can use corrugated end reflectors, as in distributed feedback lasers. In bulk form, there may be several advantages to this filter over an ordinary interferometer. First, the entire etalon could be formed from a single material through organic polymer chemistry and the deposition of thin layers. There is sufficient reason to believe that molecular engineering of organic materials as they are crystallized or deposited by Langmuir-Blodgett techniques could produce the required refractive-index changes for Bragg reflection.[7] The formation of gratings in polymer structures by partial polymerization of the monomer in crossed UV beams has been demonstrated[6] and would produce exactly the required periodic refractive index for Bragg reflection.

Second, the finesse of the cavity can be made quite large and the notch width made very narrow by increasing either the modulation depth n_1/n_0 or the mirror thickness L (i.e., the product κL). However, this cannot be done without limit, since higher finesse mirrors increase the absorption by the device. We have demonstrated that for absorption typical of transparent materials far from resonances it should be possible to achieve notch widths of the order of an angstrom with 35% transmission without sacrificing the dynamic range or contrast of the filter.

This type of filter seems less flexible than others, since it must be initially designed to a given center wavelength λ_0. However, the electrooptic effect can be used to change the refractive index of the mirror material as well as the cavity. This has the effect of changing the Bragg center wavelength. Thus some additional tuning capability may be possible by constructing the entire device out of an electrooptic material whose ends are prepared as Bragg reflectors. Finally, the cavity tuning could be accomplished by purely optical control by replacing the electrooptical material with a nonlinear optical material and employing a control beam to change the cavity refractive index by the Kerr effect.[8,9] This has already been suggested for bistable optical switch applications where high speed is primarily the interest.

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14. See, for example, H. M. Gibbs, *Optical Bistability: Controlling Light with Light* (Academic, New York, 1985), p. 56.

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For example, many of the contracts made in recent years between universities and corporations give the sponsoring company exclusive rights to the research results despite the fact that the presidents of several leading research institutions concluded four years ago that such restrictions on the university's publication rights should be avoided. "The fact of the matter," said one Stanford University dean, "is that often when we refuse to give exclusive rights, we don't get the contract."

And a recent Harvard study of biotechnology researchers across the country, published in June in *Science*, concluded that biotechnology researchers receiving industrial funds "are much more likely than other biotechnology faculty to report that their research has resulted in trade secrets and that commercial considerations have influenced their choice of research projects."

Industrial Researchers Publish More Frequently

The study also concluded that nearly a quarter of the scientists working with industrial funds have entered contracts that make the research results the property of the sponsor, not the university. But it found that contrary to many early fears, researchers receiving industry funds probably published their results more frequently than colleagues without industrial support.

Citing the complications of mixing academia with business, most universities appear to have steered clear of starting their own companies, a move Harvard attempted unsuccessfully in 1980. University administrators were taken by surprise when faculty members objected strongly to the plan, complaining that Harvard scientists might be steered into potentially profitable lines of research, rather than into work that contributed to scientific understanding.

"The idea was to establish a steady source of funding for our research, rather than depending on the ups and downs of budgets," Daniel Steiner, Harvard's general counsel, said recently. But the issues raised in the ensuing debate, he said, "have made us a lot more cautious. Now, I think it's fair to say that we are at the conservative end of the spectrum." "Universities that are better off," he concluded, "can afford to be cautious."