Flat top liquid crystal tunable filter using coupled Fabry-Perot cavities

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Abstract: In this paper, a coupled Fabry-Perot cavities filter, using the liquid crystal as the tunable medium, is investigate to achieve tunable flat top filtering performance across the C and L bands. A tandem coupled Fabry-Perot is presented for a tunable passband filter with flat top and minimum ripple in the passband. The overall tuning range of the filter is 172 nm. Several designs are shown with comparable performance to the commercial available 100 GHz fixed single channel filters.

OCIS codes: (060.2340) Fiber optics components; (120.2230) Fabry-Perot; (120.2440) Filters; (350.2460) Filters, interference; (310.6860) Thin films, optical properties

References and links

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1. Introduction

Tunable optical filters are widely needed in managing channels at the optical layer in DWDM systems. Tunable liquid crystal Fabry-Perot filters (TLCFP-F) are one of the technologies considered for filters realizations. TLCFP-F has the compact size, wide tuning range, low operating

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voltages, and no mechanical parts which provide noteworthy advantages over the conventional mechanical tunable filters [1, 2]. Although many studies of TLCFP-F are presented with differing configurations [1]-[7], the research efforts in these types of filters failed to address the critical channel shape requirements for low distortion of high data rate signals. No one to our knowledge has investigated combining the liquid crystal with the multiple coupled cavities. A flat top transmission profile with minimal ripple in the passband is critical to maintain signal quality. By using coupled Fabry-Perot (FP) cavities improved channel shapes can be obtained [7, 8]. In this paper, several coupled liquid crystal Fabry-Perot cavities were investigated to achieve broad tunable across the C and L bands while maintaining channel shape. The transmission profile for several configurations of coupled FP cavities analyzed and compared to the commercially available single fixed channel filters profiles.

2. Tandem and coupled Fabry-Perot interferometers

This section provides a background review for the coupled cavities and the tandem FP configurations. The tandem technique is commonly used for increase the sharpness of transmission profile [10]. On the other hand coupled FP cavities are not frequently used. In this paper, coupled FP cavities are used to improve the channel shape, the flat top passband and the sharpness, in order to maintain the signal quality.

For the tandem technique the simplest case is the two tandem Fabry-Perot interferometers (FPIs) system. In order to minimize the interaction between the two FP, the second one is tilted to minimize the reflections between the two of them. Another approach is to make the separation distance between the two FPIs is larger than the coherence length. The multiple pass FPI is an equivalent technique to the tandem (with large separation distance). In this setup an external reflector are used to force the outcome light to again pass through the same FPs cavity. The overall transmittance of the tandem FPIs systems is the multiplication of the individual transmittance for each FPI [10, 12].In the tandem FPIs configuration, the transmission profile provide high extinction but does not provide the flat top passband and the almost rectangular shape profile.

The coupled FPIs configuration is used to achieve the needed transmission profile shape improvements. The simplest case of a coupled Fabry-Perot filter is a two coupled FPIs. Two coupled FPI can be thought of as a 3-mirror FPI. This achieved by merging the two inner mirrors in a two tandem FP into one mirror. The transmission of the resulted filter for two identical FPIs is [8, 11]:

$$T = \frac{(1-R_m)(1-R_1)(1-R_2)}{\left|1-\sqrt{R_mR_1}\exp(-i2\varphi)-\sqrt{R_mR_2}\exp(-i2\varphi)+\sqrt{R_1R_2}\exp(-i4\varphi)\right|^2} \qquad (1)$$

Where R_m, R_1, R_2 are shown in Fig. 1(a). φ is the phase shift due to the cavity, $\varphi = (2\pi nd)/\lambda$, where n is the LC refractive index, d is the cavity thickness, and λ is the wavelength. In order to get a unit transmittance Eq. (1) should be equal to 1. Solving for R_m yields in [7, 8]:

$$R_{mc} = \left[\frac{(\sqrt{R_1}+\sqrt{R_2}}{1+\sqrt{R_1R_2}}\right]^2 \qquad (2)$$

R_{mc} is the critical value for the middle mirror to have a unity transmittance. R_{mc} could be realized by using the same two end mirrors R_1, R_2, separated by a $\pi/2$ phase shift ($\lambda/4$ thickness layer).

Introducing an aligned liquid crystal (LC) film in the cavity, the filter provides the tuning capability. The LC refractive index will be changed by the applied voltage. Figure 1(b) shows a two cavities coupled liquid crystal Fabry-Perot (LCFP). A stack of thin film layers of quarter

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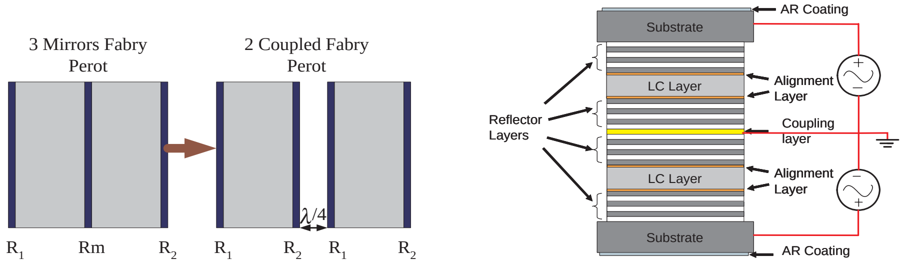

(a) (b)

Fig. 1. (a) Three-mirror FP filter and the middle mirror equivalent realization. (b) Detailed layers structure of a two coupled cavity Fabry Perot with the driving voltage connections.

wavelength thickness is used to design the mirrors. An alternating between high and low index material layers is used. Silicon ($n = 3.5$) is used as the high index material while SIO2 ($n = 1.444$) used as the low index one. Each mirror consists of six alternating layers. For the LC alignment two polyimide layers ($n = 1.6$) are used.

The LC used here is BL006 from Merck. The thickness of the LC layer is 1.826 μm, and 100 nm for the polyimide layer. The mirrors thicknesses were approximately 246 nm and 100 nm for the low index material and high index material respectively. The calculated reflectance of the mirrors is 99.02%. An electrically conductive coupling layer of 124 nm thickness is used between two each successive cavities.

3. Simulation results

The performance of the TLCFP-F design can be described by the following parameters; the tuning range, the passband (-0.5 dB is chosen here), ripple in the passband, channel spacing, and the adjacent channel isolation. The design parameters that affect this performance are the mirrors design, the coupling layer thickness, and the FPIs cavity. Scanning the LC refractive index value (for BL006 $n = 1.5 - 1.72$) for normal incident light, will produce different channels for the telecommunications bands. A MATLAB code using the Rigorous Coupled Wave Analysis (RCWA) algorithm is used to perform the simulation process. TE polarization is assumed in all the simulations. In order to achieve the required characteristics of the filter and especially the flat top passband different number of coupled Fabry-Perot cavities, and different configurations are presented. Figure 2 shows the transmittance for different number of coupled and tandem cavities FPIs.

Figure 2 shows that the sharpness of the transmittance curve is increased with the number of coupled cavities as expected. Also, the coupled cavities are more attractive than the tandem ones in the flatness in the passband and the sharpness of the transmission profile. As the number of coupled cavities increases, the passband ripple is also increases. In the case of 3-coupled cavities the ripple is about 0.22 dB, while in the 4-coupled cavities it is almost 1 dB. The ripple in the higher order design can be reduced by optimizing the mirrors reflectivities using the techniques developed by Melloni, et al. [13]. However, from the fabrication point of view, the 2-coupled cavities system is the more feasible and meets or exceeds the commercial fixed filter characteristics. A practical approach to improve the critical channel shape issue and achieve extinction is to use a combination of tandem-coupled FPI cavities in which two 2-coupled-cavities systems (2×2) are separated from each other, i.e. two stages system each stage is a 2-coupled-cavities, these stages are not directly coupled to each other the separation distance between the stages is larger than the coherence length. The overall transmittance from

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the two stages system is the multiplication of the individual transmittance for each stage (the two coupled FPIs transmittance).

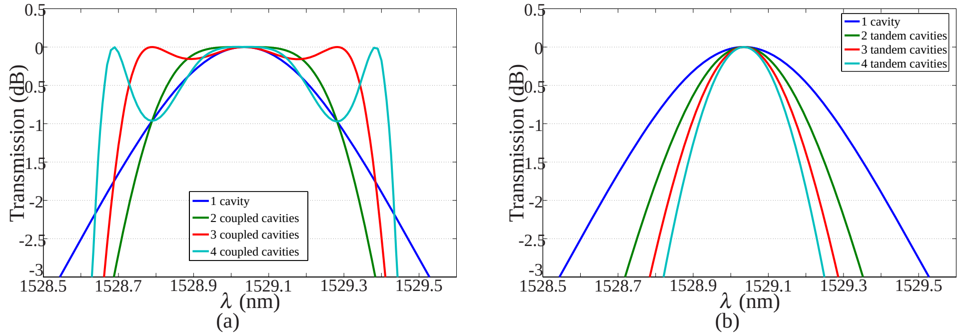

Fig. 2. (a) Transmission profiles for one FPI, two, three, and four coupled FPI cavities (b) Transmission profiles for different number of tandem FPIs.

In order to realize a 4-coupled cavities system; two tandem 2-coupled cavities systems (2×2) are used, also a 6-coupled cavities system can be realized by using two tandem 3-coupled cavities systems (3×2). A comparison of the channel shape of several design configurations are shown in Fig. 3(a). From Fig. 3 the (2×2) system has superior performance even over the 4-coupled cavities system in order of the flat top and the ripple in the passband, while the (3×2) system has more than 0.5 dB ripple in the passband. The best two designs that meet the specifications of the available commercial filters are the (2×2), and the 3-coupled cavities (see Fig. 3(b)). The (2×2) has the advantages of minimum ripple, fabrication feasibility, also from the electronic point of view for the driving voltage connections to the configuration as shown in Fig. 1(b).

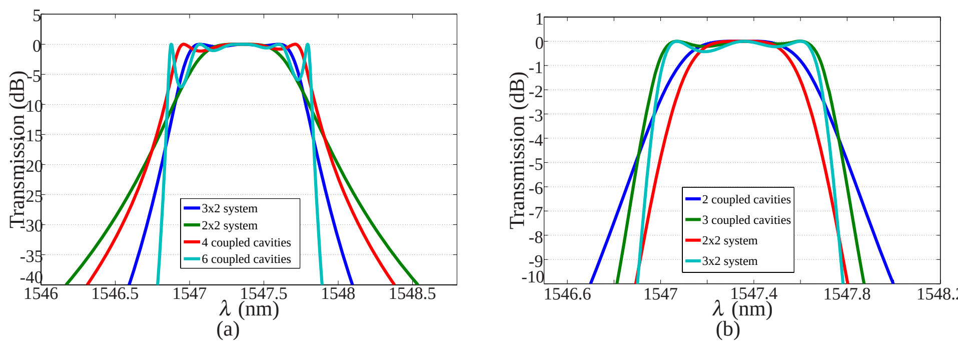

Fig. 3. Transmission of (2×2) system, (3×2) system, 4-coupled, and 6-coupled cavities. (b) Transmission of (2×2) system, (3×2) system, 2-coupled, and 3-coupled cavities.

Table 1 shows the detailed specifications of the (2×2) system, 3-coupled cavities, and the available commercial single channel filters. The minimum values are calculated at the beginning of the C band while the maximum values at the end of the L band. The channel spacing is 100 GHz. The adjacent channel cross talk (isolation) between the channels is ($>$ 23.4 dB) for 0.22 nm or 27.5 GHz passband to be consistent with commercially available fixed filters used in telecommunication systems [15]. Note that it is calculated at the edge of the neighboring passband. The isolation can be increased further by adding a third stage of the 2-coupled cavities.

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In this case, the isolation becomes ($>$ 35.8 dB) and the passband is reduced but remains $>$ 0.22 nm or 27.5 GHz.

Table 1. The specifications of the designed filter in the C and L bands and the available commercial single channel 100 GHz filters.

Parameter	2×2	3 coupled	Commercial filters
over all wavelength Range	1496.2-1668.2 nm	1496.2-1668.2 nm	C-L Bands
passband (-0.1 dB)	λ_c+/- 0.115 nm (min) +/- 14.74 GHz (min)	NA NA	NA NA
passband (-0.5 dB)	λ_c+/- 0.170 nm (min) +/- 21.8 GHz (min)	λ_c+/- 0.29 nm (min) +/- 37.17 GHz (min)	λ_c+/- 0.11 nm +/- 13.75 GHz
passband (-3 dB)	λ_c+/- 0.265 nm (min) +/- 33.96 GHz (min)	λ_c+/- 0.355 nm (min) +/- 45.52 GHz (min)	NA NA
passband (-30 dB)	λ_c+/- 0.765 nm (min) +/- 98.04 GHz (min)	λ_c+/- 0.93 nm (min) +/- 119.18 GHz (min)	NA NA
Ripple	0.008 dB (max)	0.52 dB (max)	0.5 dB (max)
overall Tuning Range	172 nm	172 nm	NA
Channel spacing	100 GHz	100 GHz	100 GHz
Adjacent channel Isolation (λ_c+/- 0.11 nm passband)	23.4 dB (min)	19 dB (min)	25 dB (min)

By comparing this filter to the available commercial 100 GHz single channel filters [15]. This filter design has superior performance in terms of the ripple and passband in principle. Also this filter is a tunable filter with a board tuning range.

4. Tolerance analysis

In the proposed structure the most sensitive layers are the mirror layers. The transmission profile is significantly impacted by a reflective layer error of 3%. Although this tolerance seems strict, it is commercial achievable. The coupling layer is more tolerant and can handle up to +/- 30 nm in thickness difference and still have the same results just a small shift in the -3 dB regime due to the difference in the optical path. The passband ripple becomes an issue when the error in the coupling layer is 60nm. The optical path distance of the liquid crystal cavities have to be perfectly matched or the transmission profile will significantly degrade. As shown in Fig. 4(a) the performance of the cavities with 5%thickness error or less still provides reasonable performance. When the number of coupled cavities increases, these tolerances become very tight. For example the LC cavity thickness for the 4-coupled cavities is more critical now than the one for the 2 coupled cavities as shown in Fig. 4(b).

LC materials tend to have a relatively high refractive index dependence on temperature. This leads to a temperature dependent shift in the center frequency of the transmission profile. The thin film layers of the reflectors as well as the substrate have temperature dependence. This can be related to the thermal expansion coefficient of each layer. The filter over all temperature dependence resulted in shifting the center frequency. The temperature of the filter will need to be accurately controlled or active monitoring with voltage compensation must be integrated into the design. Both methods have been used in similar commercial products.

The fabrication process for a proposed new component is a continuously changing recipe developed from designed experiments and trial and error. In the proposed process, standard LC

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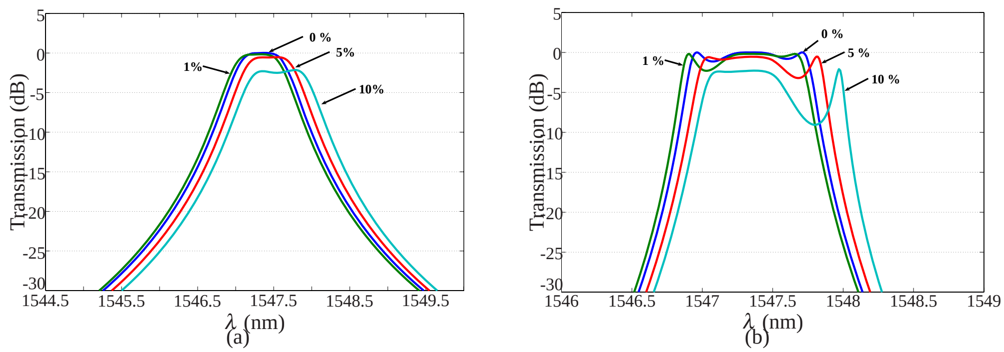

Fig. 4. (a) Transmission profile for 2-coupled cavities system (see Fig. 1(b)) with mismatched LC cavities with 1, 5, and 10% difference in cavity length. (b) For 4-coupled cavities system.

processing is integrated with standard SOI, MEMs, and thin film processes. Although challenging in many ways, the processes provide a path to meet the tolerances presented in this section. The process starts with two wafers. One wafer is conductive silicon that is doubled polished with an antireflection coating on one side. The other wafer is an SOI wafer with a thin layer of conductive silicon on top of an oxide layer. A reflector layer stack is deposited on both wafers. Numerous physical and chemical vapor deposition processes are available to fabricate such a structure. Optical monitoring during deposition is critical and an evaporated process perhaps with an ion beam assist will be used.

The next step is the deposition or application of an alignment layer on top of the reflector stack. The first choice for alignment layer is a high glass temperature polyimide which is spun on, fully imidized, and then rubbed. After the alignment layer is deposited, the spacer layer must be applied. Both silicon dioxide and numerous polymer coatings (i.e. photoresists, polyimides, etc.) are being considered. The ideal candidate would be a photodefinable, reproducible dielectric film that could serve as both the spacer and bonding material.

Once the spacer layer is applied, the two wafers are bonded together. The most common bonding techniques are anodic bonding, low temperature glass bonding, eutectic bonding, and adhesive bonding. Our preferred choice is the adhesive bonding because high bond strengths at low process temperatures ($<$ 100 C is some cases) are possible. After the bonding, the thin silicon layer must be released. The procedure requires a KOH etch through the carrier wafer and is followed by a buffered oxide etch. The process steps then repeat themselves for the number of cavities being formed. Once the last cavity is formed, vias must be etched for electrical contact and fill ports. Finally the LC material is vacuum filled through the fill ports.

5. Conclusion

A 100 GHz tunable filter is presented by integrating the liquid crystal tuning capability in the thin film technology. The coupled Fabry-Perot cavities tunable filters using liquid crystal are investigated. The tandem coupled Fabry-Perot has a superior performance in the passband flatness and minimizes the ripple (0.008 dB max). Also it has a narrow passband of 0.34 nm (43.6 GHz) for the -0.5 dB band. Further more this design provides a broad tuning range of 172 nm. The analysis shows a feasible design to fabricate will achieve a tunable bandpass filter meets or exceeds the specifications of available commercial 100 GHz fixed single channel filters. The tolerance analysis leads us to conclude that such a structure is possible with present SOI processing techniques.

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