

## Temperature tunable air-gap etalon filter

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### Abstract

We report on experimental measurements of a temperature tuned air-gap etalon filter. The filter exhibits temperature dependent wavelength tuning of 54 pm/C. It has a nominal center wavelength of 532 nm. The etalon filter has a 27 pm optical bandpass and 600 pm free spectral range (finesse ~ 22). The experimental results are in close agreement with etalon theory.

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### **Abstract**

We report on experimental measurements of a temperature tuned air-gap etalon filter. The filter exhibits temperature dependent wavelength tuning of 54 pm/C. It has a nominal center wavelength of 532 nm. The etalon filter has a 27 pm optical bandpass and 600 pm free spectral range (finesse ~ 22). The experimental results are in close agreement with etalon theory.

### **I. Introduction**

Fabry-Perot etalon filters find use in very narrow band (< 100 pm) optical instruments. Using one or several etalon filters in tandem with an interference filter provides a single narrow optical bandpass. In laser based active instruments, this permits filtering of the backscattered laser light from undesirable optical signals (e.g. sun light).

Laser instruments using Fabry-Perot etalons in the optical receiver have two major issues. First, it is difficult to manufacture the etalon spacing (gap) to the tolerance required for a filter order to match the laser wavelength. Second, the laser wavelength may change with time and drift outside of the filter bandpass. For this reason, either the laser wavelength must be stabilized or the filter must track the change in laser wavelength. A tunable etalon resolves both of these issues, while minimizing laser complexity. Our emphasis is on the development of low-cost, simple, robust, tunable etalon filters. For space flight applications, low parts count and potential for meeting vibration and environmental conditions are very important.

The most popular tunable etalons use piezo-electric transducers (PZT) to provide tuning[1]. These devices are commercially available and have even been deployed in passive space flight instruments [2, 3]. However, PZT etalons require expensive capacitive sensor systems to insure plate parallelism. Liquid crystal [4] and lithium niobate[5] electro-optic etalons have also been developed. Many liquid crystal etalons have optical polarization dependence. In addition, materials issues make liquid crystal use in space flight applications uncertain. Lithium niobate etalons have optical polarization dependence. Polarization dependence reduces throughput (by 50%) for unpolarized backscattered signal light or requires the use of two devices. A temperature tunable ZnS solid etalon for use in fiber telecommunications was demonstrated by Chung[6]. In a separate effort, not yet reported, we are developing a bulk ZnS temperature tuned solid etalon which exploits the large value temperature dependent refractive index of ZnS.

In this letter, we demonstrate for the first time, a temperature tunable air-gap etalon for use in a 532 nm wavelength lidar optical receiver. The temperature tuned etalon may offer a simpler, lower cost alternative to PZT (or other) etalons in applications where high

etalon tuning rates are not required. In our application, a wavelength tuning rate of 20 pm/hour is sufficient.

## II. Air-Spaced Etalon Construction

An air spaced etalon consists of two flat parallel plates separated by an air gap. The plate size and parallelism is controlled by spacers optically contacted to the plates. The sides of the plates facing each other have a partially reflective coating for the wavelength range of interest. The other sides of the plates usually have an appropriate anti-reflection coating.

For etalons having a very narrow gap ( $< 0.5$  mm), the construction is modified with a re-entrant design. This consists of using (1) additional, smaller diameter plates, optically contacted, centrally, to the facing sides of the plates and (2) spacers which are thicker than these additional plates by the value of the required gap. For typical fixed gap etalons, the plates and spacers are fabricated from low expansion materials to provide a thermally stable device. The coefficient of expansion of these structures would generally be less than  $1 \times 10^{-7} \text{ K}^{-1}$ .

For the 532 nm prototype design, it is desired to have the etalon passband thermally tunable in wavelength. To accomplish this, the spacer material is chosen for its thermal coefficient of expansion, allowing inter-order tuning with a reasonable temperature change. For the initial design, this range was conservatively chosen to be approximately  $11^\circ \text{ C}$ . The temperature range must be large enough to hold the etalon at the required wavelength without inordinately tight temperature control and small enough that differential expansion between the materials does not cause delamination.

The construction is depicted in Fig.1. Plates A and B are made of fused silica. Plate C is made of ULE. The spacers, S, are compound structures of fused silica and BK-7, an optical crown glass. The relationship between the length of BK-7 in the spacers and the thickness of 'C' controls the coefficient of expansion of the gap. All interfaces shown are optical contacts. For the spectral requirements of the etalon, the reflective coatings, 'R', are centered at 532 nm and have a reflectivity of 87.75%, and the gap is set at 0.236 mm. Since the fabrication of the temperature tunable etalon is very similar to a fixed gap etalon, it results in a simple, robust device.

### III. Theory

Let  $l_{ULE}$ , denote the Ultra-Low Expansion (ULE) central plate (C) thickness (9.88 mm),  $l_{BK7}$ , the BK-7 spacer thickness (free design parameter calculated below),  $l_{FS}$ , the fused silica spacer thickness (7.16 mm), and  $l_C$ , the coating thickness (0.00106 mm). Near room temperature, the thermal expansion coefficient, for fused silica,  $\alpha_{FS}$ , is  $5.1 \times 10^{-7} \text{ K}^{-1}$ , for ULE,  $\alpha_{ULE}$ , is  $8.0 \times 10^{-8} \text{ K}^{-1}$ , for the coatings,  $\alpha_C$ , is  $3.0 \times 10^{-6} \text{ K}^{-1}$  and for BK-7,  $\alpha_{BK7}$ , is  $7.1 \times 10^{-6} \text{ K}^{-1}$ . Thus, the thermal expansion coefficient,  $\gamma$ , of the etalon gap is:

$$(1) \quad \gamma = \frac{dg}{dT} = (\alpha_{BK7}l_{BK7} + \alpha_{FS}l_{FS}) - (\alpha_{ULE}l_{ULE} + \alpha_C l_C)$$

At 532.2 nm, an expansion of one order represents a change in the length of the gap by  $2.661 \times 10^{-4} \text{ mm}$ . For a design value temperature change of 11 C per order, the required thickness of the BK-7 is calculated as 3 mm.

To describe the temperature tuning, we assume the etalon gap,  $g$ , changes linearly with temperature  $g = g_0 + \gamma\Delta T$ , where  $g_0$  is the etalon gap at a fixed temperature ( $T_0$ ), and  $\Delta T$  is the temperature change (measured from  $T_0$ ). Substituting this into the standard etalon equation[7] gives the etalon transmission as:

$$(2) \quad \frac{I_t}{I_0} = \frac{1}{1 + \frac{4R}{(1-R)^2} \left( \sin \left[ \cos(\theta) \frac{2n\pi}{\lambda_0} (g_0 + \gamma \Delta T) \right] \right)^2}$$

where  $I_t$  is the intensity of the transmitted light,  $I_0$  is the intensity of the incident light,  $R$  is the mirror reflectivity,  $\theta$  is the incoming light angle of incidence,  $n$  is the air refractive index, and  $\lambda_0$  is the optical wavelength in vacuum. The theoretical transmission vs. temperature curve, for normal incidence ( $\theta = 0$ ) using the aforementioned parameter values in equation 2, is shown in Figure 2. The peak transmission value was taken as 0.91 (rather than 1) to account for absorption, scattering and other losses.

Note that in equation (2), the etalon filter peak transmission wavelength can be adjusted with angle,  $\theta$ . Therefore, it is possible to angle tune the etalon filter, seemingly eliminating the need for temperature tuning. However, for a fixed wavelength, due to the nonlinearity of Eq. (2), the etalon filter acceptance angle (field of view) changes severely with input angle. Angle tuning, even over a small fraction of a FSR, is extremely difficult where optical system throughput is a major concern. To obtain high system (instrument) optical transmission, wavelength tuning by changing the optical path length of the etalon gap is necessary.

For the 532 nm wavelength etalon prototype with reflectivity,  $R = 87.75\%$ , the theoretical finesse,  $F$ , defined as  $\pi R^{1/2}/(1-R)$ , is 24. With a nominal 0.236 mm gap,  $g$ , the free spectral range, FSR, defined as  $\lambda_0^2/(2ng)$ , is 600 pm. The theoretical etalon filter optical bandpass is given as  $\text{FSR}/F = 25$  pm.

#### IV. Experimental Results

The transmission of the etalon was measured using a diffraction limited, single-frequency, 532.2 nm wavelength, 15 mm diameter laser beam. The angle of incidence was controlled by an electronic steering mirror. The etalon was placed in a closed cell which was temperature controlled using a heater and thermistor. The cell was set to a specific temperature and the etalon soaked at that temperature. Care was taken to insure the etalon stabilized at each temperature recorded. The temperature sensor was cross checked by an additional independent sensor to insure calibration. The experimental transmission vs. temperature data for the etalon is shown in Figure 2. There is excellent agreement with the theory. The finesse was calculated from the experimental data to be 22, using the equation:  $F = \Delta T_{\text{FSR}}/\Delta T_{\text{BP}}$  with  $\Delta T_{\text{BP}} = 0.5$  C and  $\Delta T_{\text{FSR}} = 11.1$  C. This is in close agreement to the theoretical value of 24. As a cross check in a separate experiment, we measured the optical bandpass (full width at half maximum in wavelength) at a fixed etalon temperature as 27 pm, by tuning the wavelength of the laser source. This is also in close agreement with theory and consistent with the finesse measurement. To date, we have noticed no degradation of the etalon finesse after several free spectral range temperature cycles.

In addition to normal incidence measurements, the angle of incidence was swept through 25 mrad, at each etalon temperature. The measured transmission vs. angle of incidence at several temperatures (gap spacings) is shown in Figure 3 along with the theoretical curves from Eq. 2. Again, the measured values show excellent agreement with

the theoretical model. Figure 3 also clearly illustrates that angle tuning is unacceptable due to the change in the etalon field of view as a function of angle.

## **V. Conclusion**

We have demonstrated a temperature tuned air-gap etalon for the first time, to our knowledge. The experimental results of our prototype 532 nm center wavelength etalon filter are in very close agreement with the well known simple theoretical model. The temperature tuned etalon may offer a simpler, lower cost alternative to PZT (or other) etalons in applications where high etalon tuning rates are not required.



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## Figure Captions

Figure 1. Air-gap temperature tuned etalon diagram

Figure 2. Theoretical and Experimental Transmission vs. Temperature of air-gap etalon. Experimental curve measured @ 532.289 nm (vacuum wavelength) using 15 mm diameter optical beam. Field of View (FWHM) = 13 mrad, Bandpass = 27 pm, Free Spectral (Tuning) Range = 600 pm, Finesse = 22

Figure 3. - Theoretical and Experimental Transmission vs. Angle of Incidence at several temperatures (as noted) of the air-gap etalon.





