

# Solid, 3-Mirror Fabry-Perot Etalon

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**We present modeling and performance of a solid, fused silica, 3-mirror Fabry-Perot-type etalon. We show the optical cavity design and construction of the new etalon and show >95% peak transmission, improved passband shape and 20 dB better out of band rejection than a similar 2-mirror etalon. © 2015 Optical Society of America**

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Fabry-Perot etalons (FPE) have been a main-stay for high-resolution optical spectroscopy for decades. However, a limitation in the filtering capability of a standard (2-mirror) FPE is the shape of the pass-band. The Airy function describing the transmission versus wavelength curve is triangular in shape [1]. An ideal filter would have a rectangular shape maximizing in-band transmission and out-of-band rejection. Multi-mirror Fabry-Perot cavities that are appropriately designed get significantly closer to this ideal transmission shape. The mathematical basis for this was published by Van de Stadt and Muller [2] in 1985. A similar model was developed for multi-mirror cavities in waveguides [3]. These designs have been implemented in a number of different configurations: with electro-optic materials [4], in fiber [5], with silicon cavities [6], in a MEMS cavity [7] and with liquid crystals [8, 9]. In this work, we show the performance of a solid, 3-mirror etalon made of two identical fused silica plates that are coated and optically contacted. We present the design, construction and performance of this configuration. We will also present design considerations and show the sensitivity of these filters to differences in optical path between the two spacer sections and the importance of matching the reflectivities.

In remote sensing and other applications, etalons are often used to isolate a spectrally narrow signal from background (for example sunlight). The transmission bandwidth is selected to match the bandwidth of the signal, and the free spectral range (FSR) is set to be slightly broader than available interference filters.

In this paper we present a 3-mirror etalon (3ME) designed for a methane absorption lidar instrument used to separate wavelengths sampling the methane spectral absorption line centered at ~1651 nm. For this measurement, eight discrete wavelengths between 1650.8 nm and 1651.1 nm were selected. (Additional details on the application and usage can be found in [10, 11].) We required an etalon FSR of ~300 pm and a full-width at half maximum (FWHM) bandwidth of ~10 pm. Our goal was to maximize the contrast between the in-band transmission peak and out-of-band rejection to minimize wavelength channel crosstalk of the returned signal.

Fabry-Perot etalons (FPEs) provide spectral filtration for electromagnetic radiation. The filtering quality is often characterized by

the finesse and free spectral range (FSR), both of which are functions of wavelength. The FSR is the wavelength difference between adjacent transmission peaks, and the finesse is the ratio of the FSR to the FWHM bandwidth. The transmission function for a FPE is defined as:

$$T = \frac{1}{1 + F * \sin^2(\delta/2)}$$

where  $F$ , the coefficient of finesse, is related to the finesse,  $\mathcal{F}$ , by  $\mathcal{F} = \pi * \sqrt{F/2}$  and  $\delta = 4\pi n d \cos(\theta) / \lambda$ , where  $n$  is the index of the etalon,  $d$  is the etalon thickness,  $\theta$  is the angle of incidence and  $\lambda$  is the wavelength.  $F$  is also related to the mirror reflectivity,  $R$  by the relation,  $F = 4R/(1-R)^2$ . The FPE transmission is shown in Figure 1. The 3-mirror etalon transmission function can be found in [2] and a calculator version is also available online [12].

The contrast ratio between the maximum and minimum transmission is another simple figure of merit for a filter. Given that the maximum transmission occurs at  $\delta = 0$  and the minimum at  $\delta = \pi$ , the contrast ratio increases as  $1 + F$ , which can be approximated as  $F$  for higher finesse FPEs. So for larger finesse FPEs, the contrast ratio increases proportionally to the square of the finesse. However, in practice, increasing the finesse to improve the contrast ratio is generally not a good solution. Increasing the finesse while holding the FSR constant leads to a narrower transmission peak and reduced signal. Increasing the finesse by increasing the FSR improves contrast, but not significantly in the spectral region near the passband. For example, increasing the finesse by a factor of 10 by increasing the FSR and holding the bandwidth fixed increases the maximum contrast by 20 dB, but the minimum transmission now occurs at a wavelength 10x further from the transmission peak. The contrast between the transmission peak and the transmission at the wavelength of the original minimum increases by only ~2.4 times. In other words, increasing the FSR improves the filtering capability far from the passband, but does not significantly improve the filtering capability close to the passband. In real etalons, an increase in finesse is also generally accompanied by a

decrease in transmission, particularly for higher finesse etalons so a designer often needs to balance between desired finesse and desired transmission.

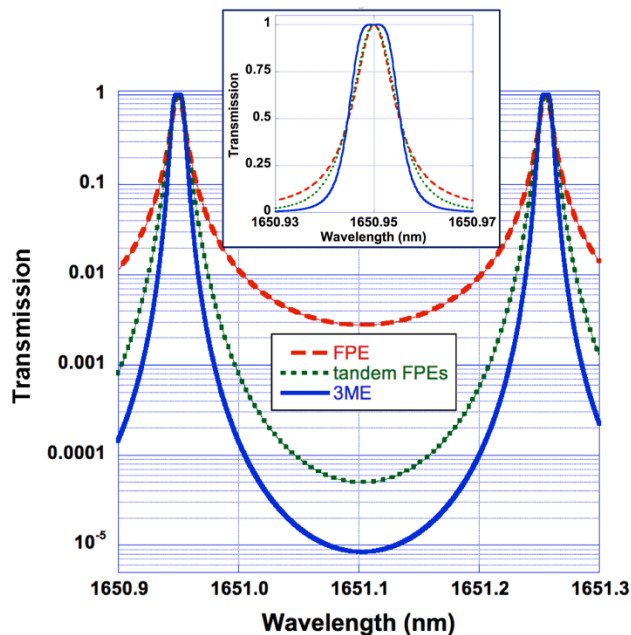


Fig. 1. Transmission as a function of wavelength of an FPE, two FPEs in series and a 3-mirror etalon (3ME) all with the same bandwidth and free spectral range shown on a log scale; inset shows zoomed linear view of the transmission peak demonstrating higher transmission within the passband and faster transition between transmission and rejection.

A more useful increase in contrast can be achieved by moving to a multiple etalon structure. The simplest version of this is two etalons independent from each other where one etalon is tilted relative to the other. Two etalons stacked in tandem with the finesse adjusted so the pair of etalons has the same bandwidth as the original single etalon has significantly improved contrast compared to a single etalon. (This configuration also allows for the potential use of different FSRs which can have additional benefits for some applications, but is not discussed further here.) Care must be taken to keep the two etalons isolated (angled relative to each other), or the net transmission will become highly sensitive to the separation between the two etalons. The transmission of these tandem FPEs is shown in Figure 1.

A further increase in contrast can be achieved by combining two parallel etalons in a mirror-spacer-mirror-spacer-mirror combination as shown in Figure 2. For an ideal 3-mirror etalon, the contrast for the same bandwidth and FSR improves compared to that of two stacked etalons.

Model results of the improved performance of a 3-mirror etalon compared to a single FPE and two tandem FPEs with the same FWHM bandwidth and FSR are shown in Figure 1. Compared to the FPE, the 3-mirror etalon significantly improves both in-band transmission (12% more light is transmitted inside the 50% passband) and out-of-band rejection (>3x more light is rejected outside the passband.) This model shows greater than 20 dB improvement in peak out-of-band rejection with the 3-mirror etalon compared to the FPE while maintaining FSR and FWHM bandpass.

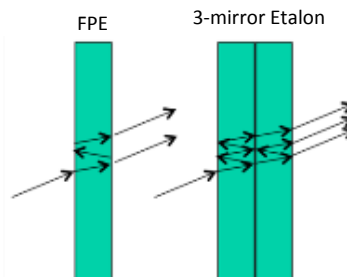


Fig. 2. Graphic Illustration of an FPE and 3-mirror etalon. The additional cavity in the 3-mirror etalon reinforces the desired filtering behavior.

Another important figure of merit is the slope of the filter edge. A faster transition between in-band transmission and out-of-band rejection increases the effective resolution of the filter for many applications. The standard definition of etalon resolution is the FWHM band width of the filter and by design the FPE and 3ME shown in figure 1 have the same resolution of 10 pm. However, isolating two wavelengths separated by 10 pm, with one at the transmission peak, the FPE will transmit ~20% of the off-wavelength signal, tandem etalons, ~16% and 3ME, ~7%. The full-width at 10% max (FW10%M) bandwidth of the 3ME has 1.8x better resolution than the FPE. The 3ME FW1%M has >3x better resolution. This means the cross-talk between adjacent wavelengths is significantly decreased by using a 3ME filter. Perhaps a potential figure of merit for comparisons like these might be the ratio of FWHM to the transition between 90% to 10% transmission. For the case discussed here, both FWHM passbands are 10 pm and the FPE takes 13 pm to transition from 90% to 10% transmission where the 3ME takes only 6 pm. This channel resolution indicator is therefore 0.77 for the FPE and 1.67 for the 3ME – more than twice as good.

In practice, the 3-mirror etalon performance relies on very precise matching of the two spacers and the three mirrors. The thickness of the two spacers should be identical, the outer mirror reflectivities should be identical to each other, and the central mirror reflectivity, though much higher than the outer reflectivities, needs to correspond to the outer reflectivities. The thickness of the spacers must be matched to within 1% of the design wavelength in order to get good transmission and close to design bandwidth. In addition, maintaining temperature uniformity and stability are important to achieve optimum performance.

The 3-mirror etalon described in this paper has fused silica spacers each with a thickness of 3.1 mm corresponding to a FSR of 300 pm at 1651 nm. Because of the sensitivity of the etalon performance to differences in thickness of the two spacers—which results in a broadening of etalon transmission peaks, the etalon blanks were matched to within 2 nm on average over the full clear aperture by fluid jet polishing.

The 3-mirror etalon reported here was designed with outer mirror reflectivities of 86%, and a center mirror reflectivity of 99.43% at 1651 nm. LightMachinery, Inc. fabricated both an FPE and a 3-mirror etalon to compare performance. They are shown in Figure 4. The FPE has the same coating reflectivity as the outer mirrors in the 3-mirror etalon and the same spacer thickness so they have the same FSR. This reflectivity choice for the FPE was made to reduce cost by avoiding an additional custom coating run. As a result, the finesse of the FPE is less than that of the 3ME.

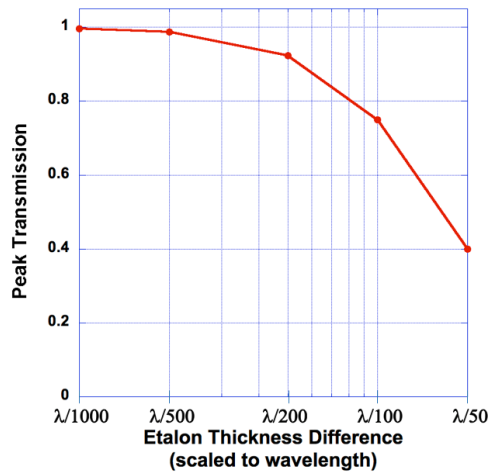


Fig. 3. Modeled results of the effect on the transmission peak of a variation in thickness between the two spacers in the 3-mirror etalon. The difference in thickness is scaled to wavelength units but for absolute conversion,  $\lambda/50 = 33$  nm.

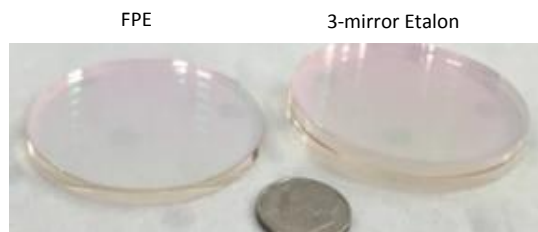


Fig. 4. Image of FPE (left) and 3-mirror etalon (right) fabricated by LightMachinery, Inc.

In many mathematical treatments of FPEs [e.g. 1-p. 409], the reflections at the mirrored surfaces are approximated to happen at a 2-dimensional plane, meaning the mirrors are infinitely thin. This is a reasonable assumption in many situations however the dielectric coating thickness is not small compared to a wavelength and cannot be neglected in this case. Another possible treatment is a matrix formulation [1- p. 419]. This treatment can take coating dimensions into account, but the actual layer thicknesses must be used to accurately predict performance. (This is essentially the same treatment that would be used for dielectric band-pass filters. What sets this apart from the bandpass filter is that the spacer here is much larger than can be practically grown in a coating chamber.) In a dielectric coating, there is an effective penetration depth into the coating that cannot be neglected because a multi-layer coating thickness is comparable to the wavelength. In this case where we need to match *effective* thickness of the coupled etalons to a very small fraction of a wavelength as shown in Figure 3, special care must be taken. The effective thickness includes the fused silica spacer plus the penetration into the dielectric coatings. Our modeling took the coating structure into account to predict performance. To achieve the desired performance in hardware, we needed to ensure symmetry of the etalon spacers and the etalon coatings. The two outer mirror coatings were applied simultaneously in one coating run. The center mirror coating was applied so half of the coating was deposited on each plate in a second coating run. The two plates, each with a half the desired coating on their inner surface, were

then optically contacted to produce the full coating. In this way, there is an exact plane of symmetry along the bond surface.

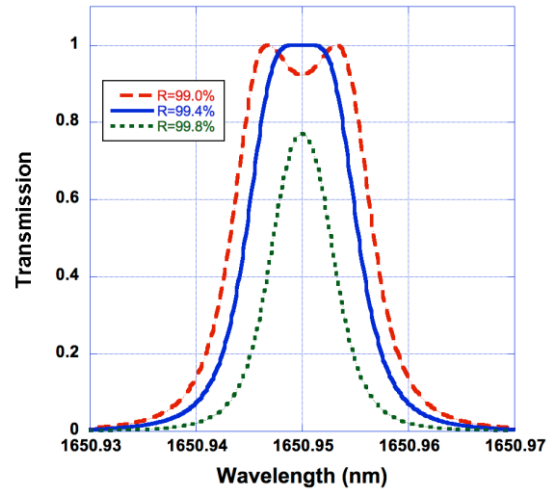


Fig. 5. Illustration of the sensitivity of center mirror reflectivity on the central transmission performance.

The 3-mirror etalon design is quite sensitive to the relative reflectivities of the outer mirrors and the center mirror. The exact ratio varies depending on the desired finesse. A general formula for determining the correct reflectivity relationship for optimum transmission can be found in [2]. If the center coating reflectivity is less than ideal, the transmission peak of the 3ME splits into two with a dip at the center and the FWHM passband broadens. If the center reflectivity is higher than ideal, the transmission peak does not split, but the peak transmission drops and the FWHM passband narrows. This sensitivity to center mirror reflectivity on the 3-mirror etalon performance is illustrated in Figure 5 with fractions of a percent change in reflectivity having a dramatic impact on modelled performance.

In practice, manufacturing is achievable with careful application of available methods. Matching the thicknesses of the two substrates is conceptually simple – measure and adjust as required, but the degree of precision required suggests special techniques. First, you could make a large uniform piece and cut out smaller pieces to be used. Another option is to use deposition techniques to fine tune one substrate thickness to another. Finally, the method used by the authors was to finely polish one substrate until it matched the other. Matching the reflectivities of the outer coatings is reasonably straightforward if the coatings are done simultaneously as noted earlier. Getting the central reflectivity to the correct value corresponding to the outer mirrors requires care, but the tolerance is achievable with available techniques and practices.

To characterize both the FPE and 3ME, we used a simple lab set-up to measure the transmission through the filter. We tuned the laser wavelength over multiple FSRs by changing the operating temperature of a distributed feedback (DFB) laser. We monitored the wavelength and optical power while measuring the transmitted power. In addition, we had the etalon mounted on a computer-controlled rotation stage to measure the angular dependence on transmission. Using this arrangement, we measured the performance of both the FPE and 3ME. The laboratory setup is shown in Figure 6.

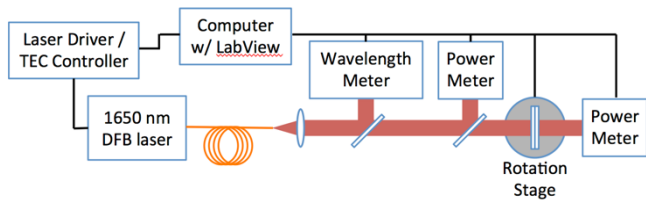


Fig. 6. Measurement Block Diagram of lab set-up to characterize etalon transmission.

The performance results of the FPE and 3ME are shown in Figures 7 and 8. Figure 7 shows the normalized transmission as a function of wavelength on a log scale where the red dotted line is the 2-mirror FPE performance and the blue solid line is the 3-mirror etalon performance. Figure 8 shows that both etalons have a transmission of greater than 95%. The two filters have the same FSR (300 pm), but the 3-mirror etalon has a narrower FWHM passband due to the fact that its mirror coatings are the same as the outer coatings of the 3ME as mentioned previously. Both filters have essentially the same performance above 90% of their peak transmission. The FPE has a finesse of 15 (FWHM passband of 20 pm) and the 3ME has a finesse of 23 (FWHM passband of 13 pm) using the standard convention of the ratio of FSR to FWHM. The 3ME FWHM passband was slightly larger than the designed value of 10 pm. The 3ME significantly improves the out-of-band rejection compared to the FPE, rejecting greater than 20 dB more light at the transmission minimum. The 3ME also has a much steeper transition between in- and out-of-band. The peak rejection missed the theoretically predicted value by  $\sim 10$  dB so there is room for improvement in the performance. In addition, the 3ME, while having an improved passband shape, did not achieve the predicted flat top at the peak of the transmission band and this is probably due to the center reflectivity being slightly higher than optimum.

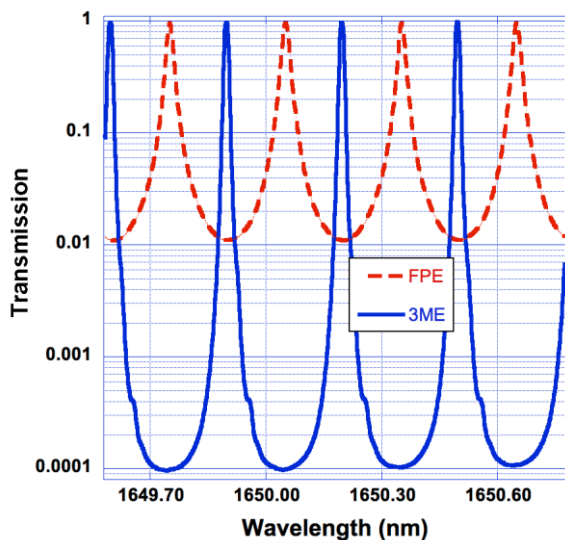


Fig. 7. Normalized transmission vs. Wavelength (logarithmic scale) of similar Fabry-Perot and 3-mirror etalons.

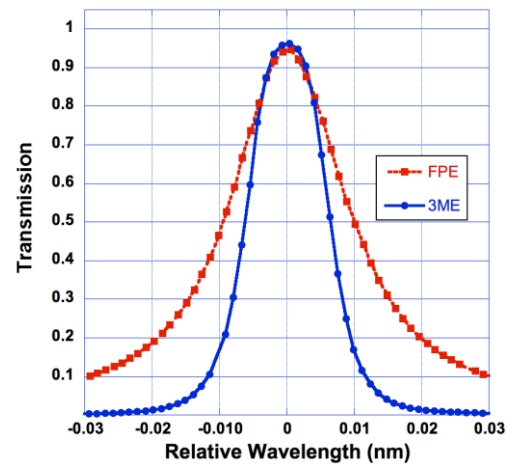


Fig. 8. Transmission vs. relative wavelength on a linear scale to show the pass band performance.

Significant improvement to the etalon contrast can be made by adding a parallel optical cavity to a standard FPE. We have demonstrated the improved performance of a solid 3-mirror etalon made with two identical fused silica plates and compared the performance to an FPE. Care must be taken in both the design and fabrication of the multi-cavity etalon to optimize the optical performance. The improved in-band transmission and out-of-band rejection of the 3-mirror etalon improves the effective spectral resolution of the etalon and reduces the cross-talk between adjacent wavelength channels. Further improvements are theoretically attainable by adding additional mirror surfaces [2] and given the success in the manufacturing of the current device, this improvement appears achievable. There is added complexity to the manufacturing process, but, once built, this variety of the 3ME is very rugged due to it being an optically contacted assembly, so none of the optical surfaces can become misaligned relative to each other.

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