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Advanced Etalon Design Considerations

Tradeoffs in etalon design

The etalon design process has inherent tradeoffs, allowing custom designed etalons to fulfill a range of application requirements. This paper outlines the major factors to consider in designing an etalon and describes the tradeoffs due to design choices.

Overview of etalon design parameters

Fabry-Perot etalons function by interfering light waves through multiple reflections. In a plane-parallel configuration, the multiple reflections are generated in a cavity with two reflecting surfaces. The cavity may be formed inside a material (a solid etalon), or between two surfaces with the cavity formed by an air space between surfaces (an air-gap etalon).

Solid and air-gap etalons both function as optical frequency-to-intensity filters. While both are interferometers, each has its advantages and disadvantages. Table 1 compares the important parameters of solid and air-gap etalons. Engineering tradeoffs must be analyzed so as to construct the most cost efficient final package.

Table 1 Overview of Etalon Engineering Tradeoffs

Parameter	Solid etalons	Air-gap etalons
Dispersion	Manageable	No
Temperature stability	Average to poor	Excellent
Temperature tuning	Yes	No
Angle tuning	Yes	Yes
Pressure tuning	No	Yes
Manufacturing tolerances	Excellent	Good
Cost	$	$$$
Size	Small	Large

Dispersion of solid materials

In etalons composed of solid materials, the ***dispersion*** of the material must be accounted for in the etalon design. Dispersion is the change in index of refraction with wavelength.

As an example, Figure 1 shows the deviation of the etalon transmission signals from the nearest ITU grid frequency, as a function of frequency. The etalon is solid fused silica and temperature controlled to tune the FSR to 50.000 GHz at the center of the wavelength range. The wavelength range covers the C and L telecommunication bands (approximately 12 THz). The deviation from the ITU grid is clearly quadratic, and the measured deviations are in good agreement with the known dispersion of fused silica. The effect of dispersion is readily apparent with the sub-picometer wavelength accuracy achieved with Precision Photonics' Sweepmeter^{TM} technology.

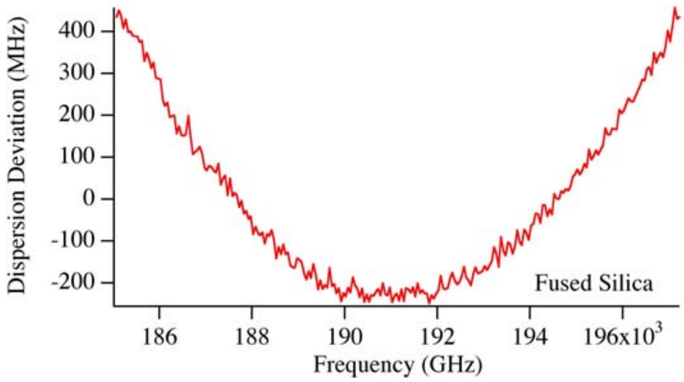

Figure 1 - Measured Dispersion of a Fused Silica Etalon across the C&L Telecom Band

Another way to observe the effect of dispersion is to measure the change in the FSR with optical frequency. For fused silica, dispersion causes the FSR of a nominally 50 GHz etalon to vary linearly from approximately 49.996 GHz to 50.004 GHz over the C band. Different materials exhibit different dispersion, with some having the opposite sign to that of fused silica. Table 2 lists the dispersion for the common etalon materials used by Precision Photonics.

Thermal dependence

The free spectral range and peak location of a solid etalon depend inversely on the product of index of refraction, n, and the length of the etalon, l. Temperature affects the properties of solid etalons through thermal expansion or contraction of the etalon length as well as through index of refraction changes. The effects of temperature may be expressed via temperature coefficients, so the resultant etalon length $l(T)$ due to a change in temperature from initial temperature T_0 to a temperature T is (to first order):

$$l(T) = l(T_0)\ [\ 1 + \alpha\,(T-T_0)\ ]. \qquad \textbf{Eq. 1}$$

An analogous expression may be written for the index of refraction, again to first-order:

$$n(T) = n(T_0)\ [\ 1 + \beta\,(T-T_0)\ ]. \qquad \textbf{Eq. 2}$$

α and β have units of parts per million (ppm) / °C. Therefore, the temperature dependence of the free spectral range (FSR) and peak locations (ν_m) is to lowest order:

$$FSR(T) = FSR(T_0)\ \ [\ 1 - (\alpha + \beta)(T-T_0)\ ], \text{ and} \qquad \textbf{Eq. 3}$$

$$\nu_m\,(T) = \nu_m\,(T_0)\ \ [\ 1 - (\alpha + \beta)(T-T_0)\ ]. \qquad \textbf{Eq. 4}$$

For our example of a solid etalon of fused silica, the thermal expansion coefficient α is 0.5 ppm / °C and the index of refraction thermal coefficient β is 6.6 ppm / °C at 1545 nm, leading to a composite thermal dependence of 7.1 ppm / °C at 1545 nm. This composite thermal dependence results in a temperature sensitivity of 1.35GHz/ °C for fused silica, requiring the etalon to be temperature stabilized for use as a frequency reference. An advantage of the temperature tuning, however, is that the etalon can be fine tuned to align with the ITU grid and completely compensate for the dispersion described in the previous section.

Although different glasses exhibit different thermal coefficients of expansion and refractive index, all the glasses examined by Precision Photonics exhibit similar composite thermal dependence in the range of 6-10 ppm / °C. Other materials such as silicon exhibit markedly different optical and thermal properties (see Table 2).

Table 2 Summary of material properties

Material	Refractive index, n (at 1545 nm)	Dispersion in FSR 1510-1570 nm (MHz)	Thermal expansion coefficient (α) (ppm / °C)	Thermal refractive index coefficient† (β) (ppm / °C)
Air	1.000	0.0	0.0	1.0
Fused silica	1.444	13.1	0.55	6.57
Silicon	3.477	198.1	3.25	160
LaSFN9	1.813	9.4	7.4	1.3‡

† At 1545 nm
‡ At 1060 nm

Precision Photonics has investigated a variety of glasses with a range of optical properties useful for construction of solid etalons. Table 2 above summarizes the high index, low dispersion materials used at Precision Photonics for solid etalons. Properties have been verified in-house by PPC to ensure accuracy in etalon construction and design.

Input beam requirements

Angular alignment

Angular alignment sensitivity of an etalon is due to the dependence of the optical path length through the etalon on the angle of incidence. Due to Snell's law, the beam angle inside a solid etalon is less than the incidence angle in air. The optical path length is a function of the cosine of the angle within the etalon so that, near normal incidence, the sensitivity to alignment is quadratic in angle. For fused silica etalons, the sensitivity of the maximum transmission frequencies to alignment is 14 GHz/deg^2 near normal incidence, where the angle is measured in air before entering the optical structure. For best results, PPC recommends alignment within 0.5 degrees of normal, where etalon placement tolerance can be compensated by temperature tuning. Alternatively, active angle control can be used at angles other than 0 degrees..

Guidelines for basic etalon design: Finesse and reflectivity

The coating of a solid etalon determines its reflectivity and, in part, the finesse of the etalon. Higher reflectivity coatings give a higher finesse, or equivalently, a peak with a narrower frequency width relative to the spacing between peaks. When using an etalon to lock a laser frequency, a steep slope in the transmission versus frequency plot is often desirable. The finesse of the etalon directly determines the slope of the peak at the locking point, or the locking slope. The locking slope in turn determines the sensitivity of the wavelength-locking system. A large slope provides larger feedback signals for smaller deviations in frequency from the locking point than a smaller slope. However, a high finesse etalon does not have a large capture range for acquiring lock. Therefore an engineering tradeoff must be analyzed for locking slope versus capture range for acquiring lock. There are many parameters to take into consideration when constructing an etalon with a specific finesse. The reflectivity of the surfaces, surface roughness and surface flatness must be factored into design tolerances and then verified during manufacturing. When mounting the etalon into a wavelength-locking system, the incident angle of the laser beam and its collimation must also be accounted for in the optomechanical design. These system level limitations in angular orientation may impact etalon design considerations. Both system and component tolerances are significant in finalizing the design of a solid material etalon to be used in a wavelength-locking system.

Reflectivity

In manufacturing a solid etalon, the reflectivity of the applied coating is a key factor in determining the finesse. Typical reflectivity values are in the 20-60% range for moderate finesse etalons, while a reflectivity greater than 80% defines a high finesse etalon for the purpose of wavelength locking. The choice of reflectivity affects the locking slope.

Flatness

Plane-parallel solid etalons function through the interference between multiple reflections in the etalon. Consequently, the parallelism of the two interfaces that generate the reflections is important. One problem with non-parallel surfaces is that the multiple reflections do not overlap well, reducing the interference contrast between the beams. A second problem is the optical path length changes as a function of the position of a beam in the etalon, with the result that the interference across the etalon is non-uniform. Typically, Precision Photonics produces fused silica and silicon etalons with local parallelism less than one arcsecond.

Surface roughness

Just as parallelism affects the finesse through changes in optical path length and beam overlap, surface roughness also can affect etalon performance. Surface roughness is defined here as the deviation from flatness for spatial scales less than 1mm. Surface roughness of ~1nm is adequate for the low finesse values of wavelength locking etalons.

Beam incident angle and collimation

As stated in the design section, system parameters also may affect the finesse of an etalon. The reflectivity of the coatings will change with the angle of incidence, directly affecting the finesse of the etalon. Also, walk-off loss, defined as reduced overlap for multiple bounces within a tilted etalon, reduces the finesse of an etalon. Therefore, both beam direction and beam collimation must be well understood and controlled in manufacturing a frequency locking system using an etalon. For fused silica etalons in the telecom band, Precision Photonics recommends keeping the incident angle to within 0.5 degrees and beam collimation within 12 mRad for moderate finesse etalons. Higher finesse etalons demand stricter control of these angles.

Conclusion

A plane-parallel etalon provides easily customized frequency-to-intensity conversion with a small form factor and high precision. The periodic filtering of optical frequencies provided by an etalon can be used as a tool for absolute wavelength measurements and for referencing the frequency spacing within an ITU frequency grid.

Proper design of an etalon based locking system does require attention to a few key parameters and concepts. Foremost, the choice of material type and thickness for the etalon determines both the peak transmission frequencies and the free spectral range, or frequency spacing between peaks. These parameters are not independent and must be chosen based on the application. Second, the dispersion of the chosen material must be factored into the expected performance of the etalon. Third, thermal changes affect etalon performance and therefore need to be accounted for as well. Fourth, the etalon performance changes with angle of incidence and beam collimation. Finally, coating selection determines the finesse, of the etalon and thereby the frequency locking properties of its transfer function.

For further information on this topic, Precision Photonics has experts to help in completing any portion of the design of an etalon for wavelength-locking systems available.