Dual Etalon Tunable Filter with Feedback Control

by

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1. Abstract

A narrow-linewidth tunable wavelength filter designed for the typical telecom bands of 1530-1570nm is constructed using two etalons on motorized rotation stages. A proposed wavelength discerning detection system controlled with a user interface can determine the accuracy of the filter and provide correction feedback to the rotation motors. A limitation on maximum rotation angle is imposed, challenging the system to align within the tuning range of the etalons' free spectral ranges. The dual etalon system is designed to allow only a single transmission peak within the desired wavelength range by balancing harmonic free spectral range and adjacent line overlap suppression. Simulation models are created to design the system, predict its performance, and plot expected etalon rotation angles for desired output wavelength. A successful demonstration of the dual etalon tunable filter is achieved, with a path forward outlined to finalize an operational feedback control system.

2. Introduction

Filtering is used in many applications to suppress side band noise or to isolate a particular wavelength for test, measurement, or channel selection purposes. A frequently utilized technology for high-quality, in-line, fiber-coupled, bandpass filtering is to use a fiber-Bragg grating, which is a periodic variation of refractive index set into the fiber that reflects a desired wavelength range. Since the periodic refractive index pattern is inscribed into the fiber, this prevents the technology from being tunable.

Free space etalons are therefore a commonly used technology to use for tunable filtering purposes. The disadvantage of using etalons is that the light needs to be collimated and recoupled into the fiber, which causes transmission loss. The great advantage of etalons is that there are a number of ways to tune them, allowing the operator to vary the isolated wavelength.

An etalon produces a transmission comb pattern of peaks with a defined bandwidth spaced apart by the etalon's free spectral range. The ratio of free spectral range to bandwidth is the etalon's finesse. The free spectral range is a function of the optical path length of the light between reflections, and the finesse is a function of the surfaces' reflectance and quality. For most applications, a higher finesse value is considered desirable, as it is a measure of how well the individual transmission peaks can be isolated from each other. There is a practical limit to the reflectance and quality of a surface, which limits the achievable finesse of an etalon. The optical path length, and thus free spectral range, may be modified by adjusting the etalon refractive index, spacing, and angle of incidence. Therefore, etalons are often made tunable by allowing means of actuating one of these three parameters. There are liquid metamaterials that have a tunable refractive index by adjusting the electrical and magnetic environment. The spacing of air-gapped etalons may be actuated using mechanical, pressurized, or piezo devices.

The surface spacing of substrate etalons may be actuated by varying the temperature of the material, which lengthens the dimensions of the etalon by the coefficient of thermal expansion (CTE). Angle of incidence may be adjusted using mechanical rotation or by means of changing the angle of the light incident on a fixed etalon. The two most commonly utilized methods of tuning etalons is by temperature control and mechanical rotation. In both cases, the optical path length is extended by a fraction of the thickness. For temperature tuning, the expansion is directly related to the thickness by the CTE. For mechanical rotation, the expansion is a sinusoidal relation of the thickness by the angular variation. Disadvantages of thermal expansion are that it may add stress to the mounting and non-uniform temperature over the clear aperture, which could cause wavefront transmission errors. An additional consideration is the tunable resolution and speed; it is easier to control a mechanical angle than it is to control a substrate temperature. For these reasons, commercially available tunable etalons are most often by means of mechanical rotation. Examples include Newport's TBF-1550 [1] and DiCon FiberOptics' Motorized Tunable Bandpass Filter [2].

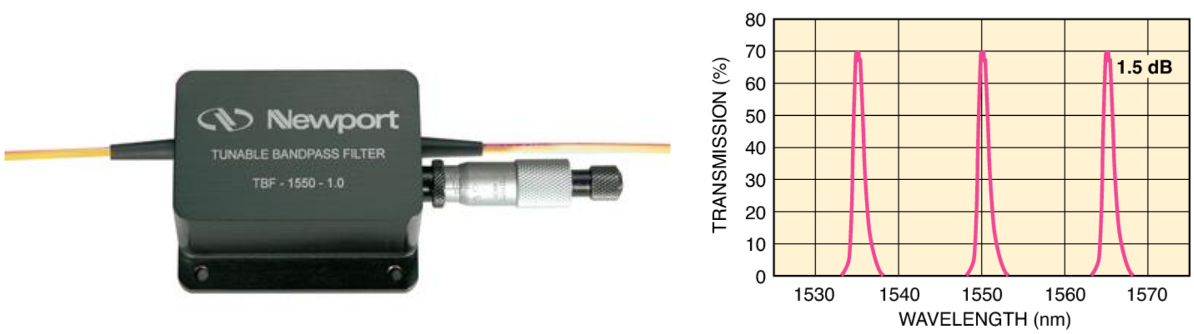

Figure 2.1: Newport's TBF-1550-1.0 Tunable .8nm Bandpass Fiber Optic Filter and Transmission Profile

Tuning resolution	0.05 nm typ.
0.5-dB bandwidth	0.8 nm min.
Repeatability	±0.05 nm typ.
Absolute accuracy	±0.3 nm max.
Insertion loss[2]	1.5 dB typ.
Back-reflection	-50 dB max.
PDL[2]	0.05 dB typ.
Tuning speed	50 ms min., 1400 ms max.
Fiber type	9/125 Corning SMF-28
Fiber jacket	0.9 nm, tight buffer
Operating temperature	0 °C to +50 °C
Storage temperature	-20°C to +70°C
Humidity	40°C/90%RH/5 days
Power requirements	±12 VDC in, 350 mA max.

1. All specifications referenced without connectors.
2. Measured at maximum center wavelength.

Figure 2.2: DiCon FiberOptics' Motorized Tunable Filter and Specification Table

Limitations of these single etalon tunable filters lie in their finesse restriction. Narrow bandwidth systems are only achievable over small tuning ranges before an adjacent free spectral range transmission peak is reached. Large tuning ranges are only achievable with relatively larger bandwidths. Both Newport and DiCon FiberOptics' commercial products offer the same specifications of .8nm bandwidth over the 30nm tuning range of 1535-1565nm. If much finer bandwidths are desired over a large tuning range, alternate methods need to be explored. One such method is to use a series of etalons with narrow bandwidths and slightly offset free spectral ranges. The etalons will produce a transmission peak where the free spectral ranges overlap. The system can be designed so that the adjacent free spectral ranges do not overlap, allowing an increased wavelength domain before they eventually overlap again. The angles of the two etalons may be actuated together to tune over this large isolation range.

This project is a demonstration for this technology: attempting to create a dual etalon tunable filter with two etalons on individual rotation stages to sweep a narrow-linewidth passband over a wide wavelength domain. The accuracy of the two etalon angles to produce the desired narrow-bandwidth signal must be very precise, so a feedback control system is implemented to test the wavelength and self-correct.

3. Etalon Background

At the most basic level, an etalon (commonly referred to as a Fabry-Perot etalon) is the combination of two parallel, partially-reflecting surfaces separated by a fixed distance. The space between these two surfaces (sometimes referred to as a cavity) can be air or a transmissive material, and these have different implications for the etalon's performance.

3.1 *Partially-Reflective Surfaces*:

At any reflective interface, light that is reflected obeys the Law of Reflection.

Law of Reflection $$\theta_i = \theta_r$$ Equation 3.1

At an optical interface of two materials of different refractive indices, angled incident light is refracted according to Snell's Law. It should be noted here that materials with frequency-dependent refractive indices will cause light of different wavelengths to refract at different angles, and thus disperse.

Snell's Law $$n_1 \sin\theta_1 = n_2 sin\theta_2$$ Equation 3.2

The amount of light that is either reflected or transmitted is determined by the Fresnel Equations. As can be seen in the Fresnel Equations, the reflectance is dependent on the polarization of the light. Below about 10 degrees angle of incidence, this polarization difference is minimal, and for the sake of simplicity, will be ignored for discussions in this paper.

Fresnel Equations
$$R_s = \left|\frac{n_1 \cos\theta_i - n_2 cos\theta_t}{n_1 \cos\theta_i + n_2 cos\theta_t}\right|^2, \quad T_s = 1 - R_s$$
$$R_p = \left|\frac{n_1 \cos\theta_t - n_2 cos\theta_i}{n_1 \cos\theta_t + n_2 cos\theta_i}\right|^2, \quad T_p = 1 - R_p$$
Equation 3.3

The reflection properties of an interface can be altered further by applying a thin film coating to the surface. These coatings are very thin layers of different index materials than can be tailored to specific reflection profiles over particular wavelength ranges, angles of incidence, and polarizations. It is often the case that coatings are applied to etalons to obtain specifically desired reflectances, as this plays a large role in the performance of the device.

Simply put, when light encounters an etalon, at each surface some of the light is reflected and some of the light is transmitted.

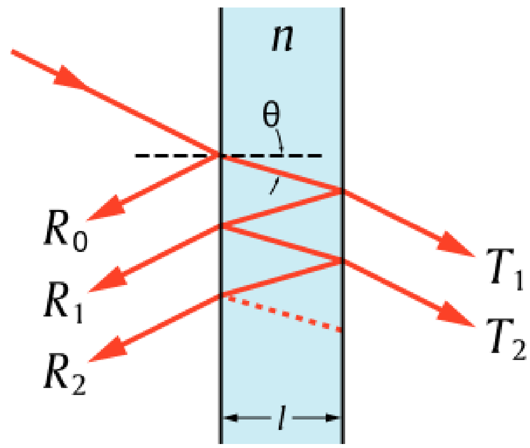

Figure 3.1: A common etalon illustration showing light reflecting and transmitting multiple times at each interface.

3.2 ***Inter-Cavity Material*:**

Between the partially-reflective surfaces of an etalon is a thickness of material through which the light propagates before encountering the next optical interface. The simplest case is that of two surfaces bounding a thickness of vacuum. Vacuum has an ideal refractive index of 1 and is uniform over all wavelengths. The next case is that of two surfaces sandwiching a thickness of air. Air has a refractive index slightly greater than 1 that is not ideally uniform over all wavelengths, and which is dependent on the precise composition of the air.

The more interesting case is that of two surfaces sandwiching a thickness of optical material. This material can be liquid, but is most frequently a solid. In the case of a solid optical material, the reflective coatings are applied directly to the surfaces of the material. An optical material will have a refractive index, which means that the light will have a different wavelength and optical path length inside the material than outside of it. If the incident and exiting media are the same, when the light is transmitted to the other side of the material, its wavelength will return to its incident wavelength.

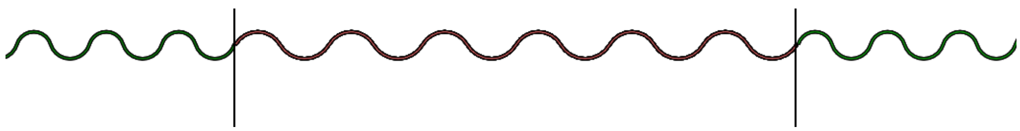

Figure 3.2: Incident light changes wavelength in an optical material, and returns to the original wavelength when it returns to the incident material.

Since the refractive index is frequency-dependent, the different incident wavelengths of light will encounter different internal wavelengths and optical path lengths, and therefore disperse within the material.

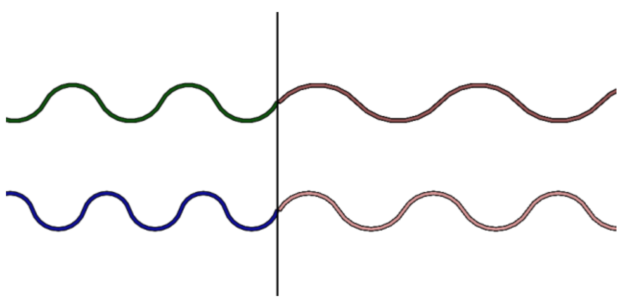

Figure 3.3: Incident light of different wavelengths will encounter different wavelengths and optical path lengths inside a frequency-dependent material.

3.3 ***Wavelength-Dependent Cavity Behavior*:**

It was noted in the previous discussions on surface reflection and cavity propagation that light through an etalon can disperse in multiple fashions. For angled incident light at the material interfaces, light may refract at different angles according to Snell's Law, dispersing the light and causing differing optical path lengths through the material.

An etalon's design encourages many consecutive reflections between the two interfaces, which compound the effects of wavelength dependence. Consider, for example, Figure 3.4, in which two different rays of light refract at very slightly different angles. Initially, the difference is hardly noticeable, but after many reflections the difference is compounded and significant. Although the two rays still emerge parallel to each other, each reflection increases their separation and differing optical path length. This dispersion by refraction may be tailored, however, by the properties of the coating applied to the interfaces.

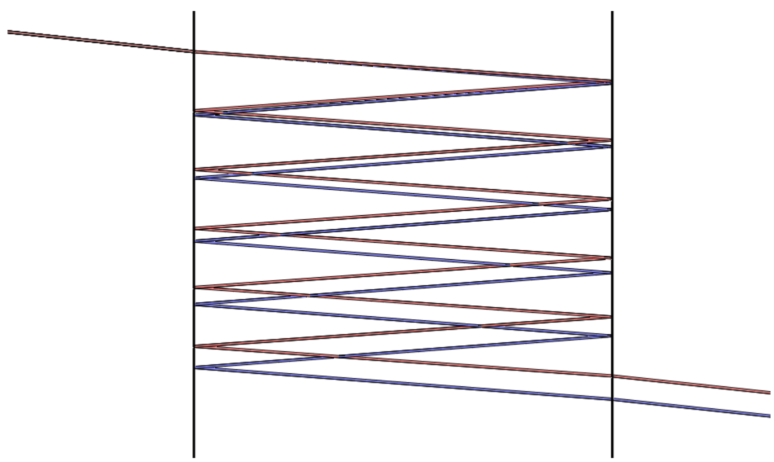

Figure 3.4: Incident light of different wavelengths will refract to different angles, which compounds to significantly different optical path lengths.

For normally incident light, different wavelengths will encounter differing optical path lengths within the cavity because of the material's wavelength-dependent, non-uniform refractive index profile. This can only be altered by varying the dispersion properties of the material.

3.4 *Standing Waves*:

If an exact integral number of internal wavelengths fit within the optical thickness of the cavity, it is considered a standing wave and is described as "supported" by the cavity. No matter how many internal reflections take place for a standing wave, it reaches the exiting interface at the same phase. A cavity of a given thickness has many potential standing waves of any integral number of wavelengths that it may support.

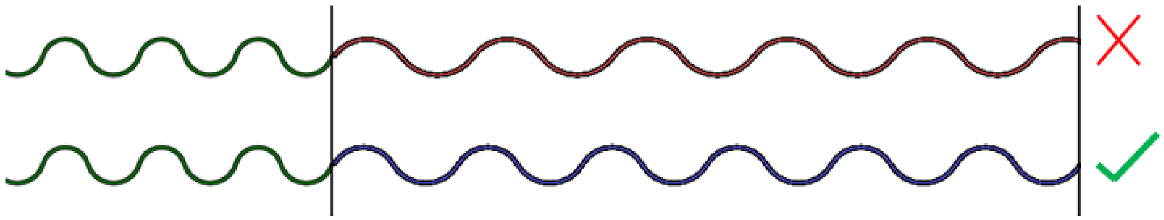

Figure 3.5: An unsupported wavelength and a cavity-supported standing wave with integral wavelengths in the cavity thickness.

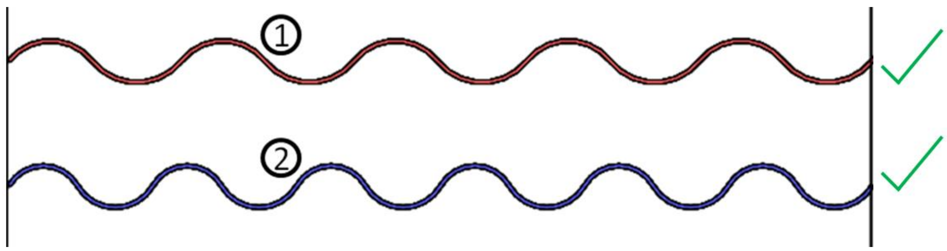

Figure 3.6: Two standing waves of different wavelengths that are both supported by the cavity.

3.5 ***Interference and Transmission*:**

At each interface, some of the light reflects and some transmits through the etalon. The transmission of an etalon is a result of the interference of the waves as they exit the etalon. If the transmitted waves are in phase, they constructively interfere to produce transmission peaks. If the transmitted waves are out of phase, they destructively interfere to produce transmission minima.

The individual reflections or transmissions at each interface are not wavelength-dependent, and a great deal of light is reflected initially or transmitted in the reverse direction. This might lend one to believe that there is less than 100% transmission at the peaks. However, all of the light corresponding to the transmission peaks that would be sent in the reverse direction completely destructively interferes. Conservation of light at those wavelengths allows for 100% peak transmission under ideal conditions. Limitations to transmission arise from imperfections in the etalon, such as surface figure, wedge, spherical error, scatter, and material losses.

Assuming there are no losses from absorption or scatter in the etalon, conservation dictates that light not transmitted through the etalon is reflected in the opposite direction. The reflection profile is therefore the inverse of the transmission profile.

Each standing wave produces transmitted light that is in phase, which creates a repeated pattern of transmission peaks corresponding to integral numbers of wavelengths supported by the cavity. This repeated peak transmission spectrum is commonly referred to as a comb profile. The peaks in Figure 3.7 can be thought of as corresponding to the adjacent standing waves in Figure 3.6 labeled 1 and 2. Since this profile is created by interfering waves that constructively or destructively combine to varying extents, the pattern produces repeated Lorentzian distributions rather than finite peaks.

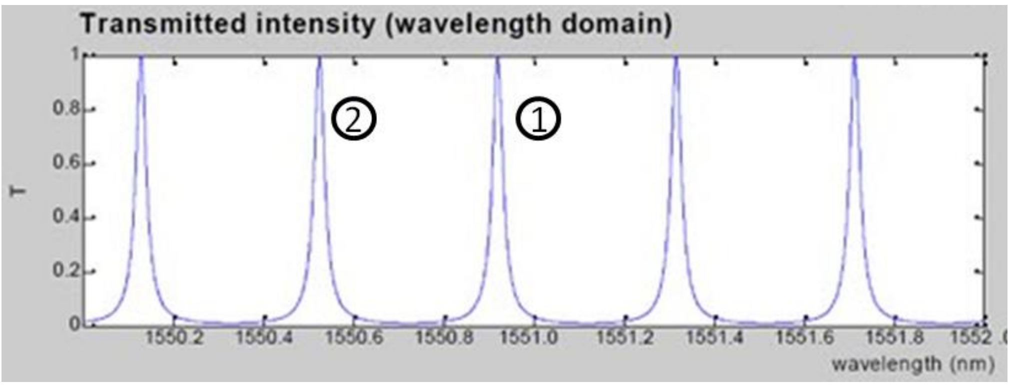

Figure 3.7: Comb profile of repeated transmission peaks corresponding to the standing waves supported by the cavity thickness.

Frequency, ν, and wavelength, λ, are inversely related by the constant speed of light in the medium. Because of this relationship between frequency and wavelength, comb patterns are often produced in either domain. For consistency, this paper will primarily portray transmission profiles in the wavelength domain.

Speed of light in Optical Material $V = \frac{c}{n(\lambda)}$ Equation 3.4

Frequency-Wavelength Relation $V = \nu\lambda$ Equation 3.5

Note that although the light travels through the etalon, it is observed in the exiting medium of air with a refractive index of 1, so for this application, conversions are given by $c = \nu\lambda$. When considering ranges in wavelength or frequency, such as bandwidths, the derivative must be considered. This produces different relations.

Differential Frequency-Wavelength Relation $\Delta\lambda = \frac{c\,\Delta\nu}{\nu^2} = \frac{\lambda^2\,\Delta\nu}{c}, \Delta\nu = \frac{c\,\Delta\lambda}{\lambda^2} = \frac{\nu^2\,\Delta\lambda}{c}$ Equation 3.6

3.6 *Comb Pattern Features*:

A comb transmission pattern can be described by three key features: the free spectral range, bandwidth, and finesse. The free spectral range, Δλ, is the spacing between adjacent transmission peaks. The bandwidth, δλ, is the full width at half maximum of an individual transmission peak. The finesse, Ƒ, is the ratio of the free spectral range and the bandwidth. The finesse can be thought of as a quality factor for the comb pattern, as it is an indication of how relatively isolated the peaks are from each other and the suppression of the wavelengths between peaks. Higher finesse values correspond to more isolated transmission peaks. Visual representations of these features, as well as a comparison of high and low finesse patterns, can be seen in Figure 3.8.

Finesse $Ƒ = \frac{\Delta\lambda}{\delta\lambda}$ Equation 3.7

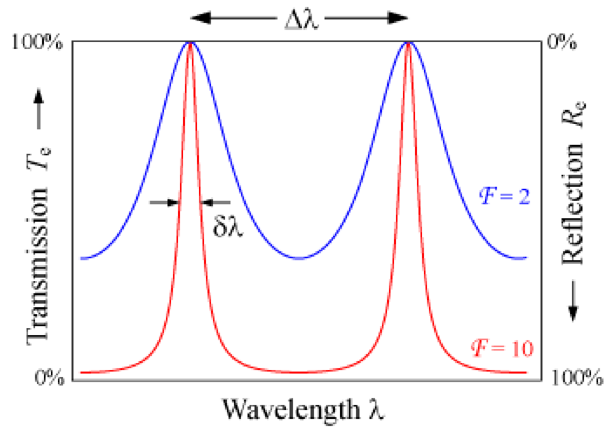

Figure 3.8: Key features of a comb transmission pattern:
Free Spectral Range (Δλ), Bandwidth (δλ), and Finesse (F).

3.7 *Etalon Design Variables*:

When designing an etalon, there are a number of basic variables that may be controlled to obtain the desired comb pattern features. The basic variables that can be controlled are the material refractive index, etalon thickness, internal angle, and surface reflectances. Often it is assumed that the two surface reflectances are equal, in which case $R_1=R_2=R$. For surfaces that have unequal reflectances, R can be approximated as the square root of the product of the two surface reflectances.

Unequal Surface Reflectances Approximation

$$R \approx \sqrt{R_1 R_2} \qquad \text{Equation 3.8}$$

Material Refractive Index	n
Etalon Thickness	l
Internal Angle	θ
Surface Reflectances	R_1, R_2 or R

Table 3.1: Etalon Basic Variables

So many basic variables can make for a complex system to analyze, but all of these basic variables can be simplified down to two key variables: optical path length and reflectance.

Optical Path Length	OPL
Reflectance	R

Table 3.2: Etalon Key Variables

Angled light in a cavity of specific thickness and refractive index has a round trip optical path length given by:

Optical Path Length $$OPL = 2\,n\,l\,cos\theta$$ Equation 3.9

3.8 *Etalon Design Features*:

The key variables (optical path length and reflectance) can be described by the many basic variables. These two key variables can then be used to define the comb pattern features (finesse, free spectral range, and bandwidth), as well as some other design features, such as angle tuning range and transmission.

Finesse is sometimes defined using an intermediate term called the Coefficient of Finesse, F, which is defined solely by the surface reflectances.

Coefficient of Finesse $$F = \frac{4R}{(1-R)^2}$$ Equation 3.10

Finesse as function of Coefficient of Finesse $$\mathcal{F} = \frac{\pi}{2\arcsin\left(\frac{1}{\sqrt{F}}\right)}$$ Equation 3.11

For values of R greater than 0.5, Finesse can be approximated much more simply.

Finesse Approximation, R > 0.5 $$\mathcal{F} \approx \frac{\pi\sqrt{F}}{2} = \frac{\pi\sqrt{R}}{1-R}$$ Equation 3.12

The theoretical finesse is simply a function of the surface reflectances. Actual finesse, however, may be reduced due to imperfections in the etalon. Similar to peak transmission losses, factors that may limit the finesse are surface figure, wedge, spherical error, scatter, and material losses.

The free spectral range is the spacing between adjacent transmission peaks of the comb pattern, and can be defined using the system's optical path length and the wavelength corresponding to the nearest transmission peak to the area of interest, λ_0. For an even better approximation, the group refractive index may be used instead of the local refractive index in the calculation of optical path length. See Section 3.10 for a detailed derivation and discussion of the free spectral range.

Free Spectral Range, Approximation

$$\Delta\lambda = \frac{\lambda_0^2}{2n_g l\, cos\theta + \lambda_0} \approx \frac{\lambda_0^2}{2n_g l\, cos\theta} = \frac{\lambda_0^2}{OPL}$$

Equation 3.13

Having calculated finesse and free spectral range, bandwidth may be derived using the simple relation between these two comb pattern features. Since finesse is a function of reflectance and free spectral range is a function of optical path length, bandwidth can be thought of as a function of both of these key variables.

Bandwidth

$$\delta\lambda = \frac{\Delta\lambda}{\digamma}$$

Equation 3.14

The optical path length is a function of the internal angle of light through the etalon. By changing the internal angle, and consequently the optical path length, the wavelengths corresponding to transmission peaks will shift. It is therefore possible to laterally shift, or “tune,” the transmission profile by adjusting the internal angle. If the angle is tuned enough, it is possible to span the entirety of a free spectral range. The internal light angle is not easily accessible, so it is more convenient to put this relation in terms of the angle of light incident on the etalon by taking into account Snell’s Law. A more detailed description and derivation of the incident angle tuning range is provided in Section 3.11.

Incident Angle Tuning Range $$\Delta\theta_0 = \sin^{-1}(n \sin(\cos^{-1}(1 - \frac{\lambda}{2nl})))$$ Equation 3.15

In some applications, it may be the case that a particular incident angle tuning range is required. For such a situation, this relation can be rearranged to solve for the minimum etalon thickness necessary to angle tune over a full free spectral range.

Minimum Angle Tuning Thickness $$L = \frac{\lambda}{2n(1-\cos(\sin^{-1}(\frac{\sin\Delta\theta_0}{n})))}$$ Equation 3.16

Through all of these relations, there has yet to be a direct equation to plot the transmission of light through an etalon, and thus map the comb pattern. As stated earlier, the transmission profile is a function of interfering waves as they exit the etalon at varying phases in their wavelength. The phase difference between any arbitrary successive pair of waves is given by δ, which is itself a function of the optical path length.

Arbitrary Wave Pair Phase Difference $$\delta = \frac{2\pi}{\lambda}\, 2\, n\, l\, cos\theta = \frac{2\pi}{\lambda}\, OPL$$ Equation 3.17

The Transmission, T, is a function of both the phase difference and surface reflectances, which can also be written in terms of phase difference and the coefficient of finesse. The transmission of an etalon is susceptible to external factors, such as beam divergence. This is explored in Section 3.12.

Transmission $$T = \frac{(1-R)^2}{1-2Rcos\delta+R^2} = \frac{1}{1+Fsin^2\left(\frac{\delta}{2}\right)}$$ Equation 3.18

Design Feature	Key Variables
Finesse, Ƒ	R
Free Spectral Range, Δλ	OPL
Bandwidth, δλ	OPL, R
Incident Angle Tuning Range, $\Delta\theta_0$	OPL
Min. Angle Tuning Thickness, L	OPL
Transmission, T	OPL, R

Table 3.3: Design Features and their Key Variables

3.9 *Dual Etalon Considerations*:

In optical systems, components are used in series as light passes from the output of one component to the input of the next. In such optical chains, the transmission profiles of each element are multiplied to obtain the final system transmission profile. As such, two etalons may be used in series to further limit the transmission of light through the system.

If two etalons have identical properties and are parallel to each other, their comb patterns will overlap and multiply. The resulting transmission will still yield a comb pattern of the same free spectral range, but the finesse will be improved. For a given peak, the Lorentzian profile will be squared, causing suppression of the peak's wings and a tightening of the bandwidth. Maintaining the same free spectral range while decreasing the bandwidth results in an increased finesse.

If two etalons do not have identical free spectral ranges, their product produces what will be described here as a harmonic comb pattern. Consider the wavelength for which the two free spectral ranges overlap perfectly, as shown on the left side of Figure 3.9. At this point, the transmission product will produce a distinct transmission peak. Since the two profiles have different free spectral ranges, the individual transmission peaks directly to the right of this overlapping peak will not overlap perfectly. The successive peaks for increasing numbers of free spectral ranges will drift further apart until the Nth peak of one pattern overlaps with the (N+1)th peak of the other pattern, producing another transmission peak. The spacing between these product transmission peaks will be described here as the harmonic free spectral range, HFSR. In this example, the fourth free spectral range of the black etalon 1 overlaps with the fifth free spectral range of the blue etalon 2.

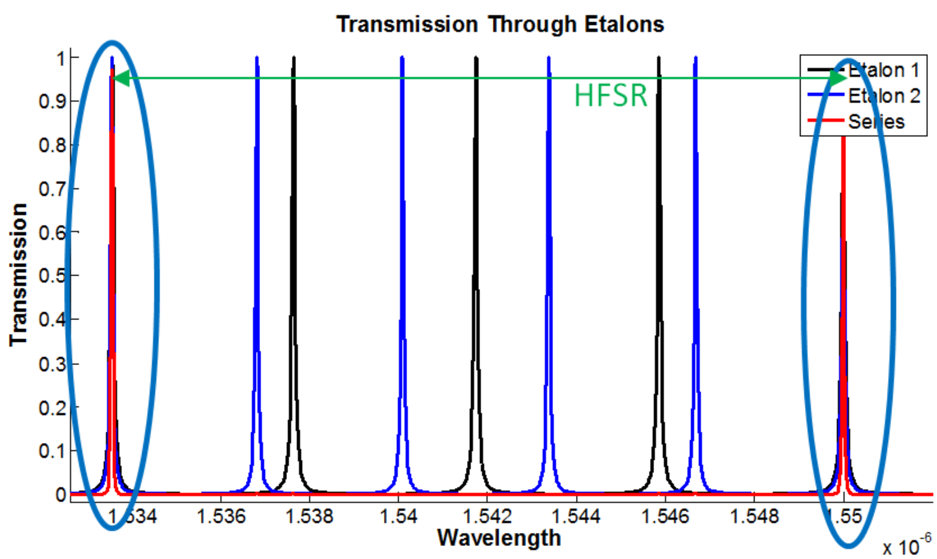

Figure 3.9: Illustration of Harmonic Free Spectral Range, HFSR

The harmonic free spectral range can be computed using the following relation.

Harmonic Free Spectral Range $$HFSR = \frac{\Delta\lambda_1 \Delta\lambda_2}{\Delta\lambda_1 - \Delta\lambda_2}$$ Equation 3.19

The harmonic free spectral range is a function of the differing free spectral ranges of the two individual etalons. As discussed previously, the free spectral range is solely dependent on the key variable of optical path length. Therefore, the harmonic free spectral range can be thought of as a function of the dual etalon system variable of optical path length difference, ΔOPL. For systems at normal incidence that have constant refractive index, the optical path length becomes solely a function of etalon thickness. In this case, the thickness difference necessary to achieve a target harmonic free spectral range may be computed by a simple relation derived in Section 3.13. Note that the HFSR and thickness difference are inversely related.

Maximum Etalon Thickness Difference for HFSR

$$\Delta l = \frac{\lambda_0^2}{2\, n\, HFSR} \qquad \text{Equation 3.20}$$

Unlike single etalon comb patterns, dual etalon harmonic comb patterns have the possibility of being quite messy. Consider a system that has two etalons with comb patterns that have similar free spectral ranges and wide bandwidths. As before, begin with the wavelength for which the two free spectral ranges overlap perfectly, as shown centrally in Figure 3.10. The transmission peaks for the individual etalons adjacent to this central peak do not overlap perfectly, but since they have wide bandwidths, the wings of their distribution falloffs partially overlap. This behavior will be described here as adjacent line overlap.

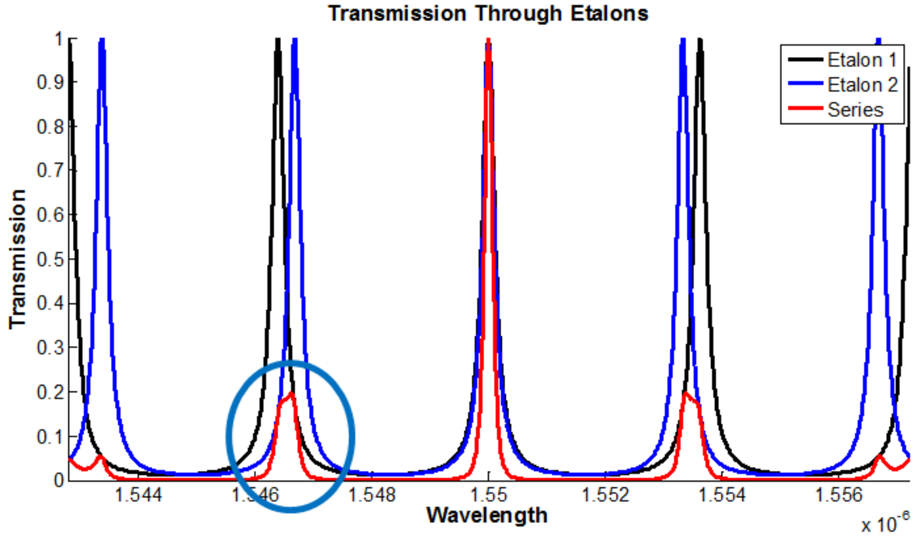

Figure 3.10: Illustration of Adjacent Line Overlap.

Adjacent line overlap occurs when the difference between the individual etalons' free spectral ranges is less than or similar to the bandwidth of the individual peaks. If the free spectral range difference is kept much greater than an individual peak's bandwidth, adjacent line overlap will be suppressed.

Adjacent Line Overlap Suppression	$(\Delta\lambda_1 - \Delta\lambda_2) \gg \delta\lambda$	Equation 3.21

This can be quantified by calculating what will be called the adjacent line overlap factor, ALOF. For adjacent line overlap suppression, which is desired to isolate a single clean peak, ALOF should be much greater than 1.

Adjacent Line Overlap Factor	$ALOF = \frac{\Delta\lambda_1 - \Delta\lambda_2}{\delta\lambda}$	Equation 3.22

Similar to the HFSR, the adjacent line overlap factor is a function of the two individual etalons' differing free spectral ranges, which can be reduced to the dual etalon system variable of optical path length difference, ΔOPL. However, it is also a function of an individual peak's bandwidth, which relates back to both the etalon key variables of OPL and R.

Dual Etalon Design Feature	System Key Variables
Harmonic Free Spectral Range, HFSR	ΔOPL
Adjacent Line Overlap Factor, ALOF	ΔOPL, OPL, R

Table 3.4: Dual Etalon Design Features and their System Key Variables

At this point, a great design challenge is observable. Consider a desired system that has a large harmonic free spectral range, but minimal adjacent line overlap. To have a large HFSR, $\Delta\lambda_1 - \Delta\lambda_2$ should be very small. However, to have minimal adjacent line overlap, $\Delta\lambda_1 - \Delta\lambda_2$ should be very large compared to the bandwidth. Compromise must be made on harmonic free spectral range or adjacent line overlap, or the bandwidths must be kept very small with high finesse etalons.

3.10 *Free Spectral Range Derivation*:

Consider two adjacent standing waves in a cavity with optical path length, OPL. Wave 0 can fit N integer wavelengths, λ_0, in OPL, and wave 1 can fit N+1 slightly smaller integer wavelengths, λ_1, in OPL.

$$N\,\lambda_0 = \mathrm{OPL}$$
$$(N+1)\,\lambda_1 = \mathrm{OPL}$$

Solving for wavelengths and taking the difference:

$$\Delta\lambda = \lambda_0 - \lambda_1 = \frac{OPL}{N} - \frac{OPL}{N+1} = \frac{OPL\,(N) + OPL - OPL\,(N)}{N(N+1)} = \frac{OPL}{N(N+1)}$$

Substitute back in $N = \frac{\mathrm{OPL}}{\lambda_0}$

$$\Delta\lambda = \frac{OPL}{N(N+1)} = \frac{OPL}{\frac{\mathrm{OPL}}{\lambda_0}\left(\frac{\mathrm{OPL}}{\lambda_0}+1\right)} = \frac{\lambda_0^2}{OPL+\lambda_0}$$

Free Spectral Range (OPL) $\Delta\lambda = \frac{\lambda_0^2}{OPL+\lambda_0}$ Equation 3.23

The free spectral range is defined using an arbitrary wavelength, λ_0, which is taken to be the nearest transmission peak to the area of interest. Additionally, the optical path length is a function of refractive index, which is itself a function of wavelength, $n(\lambda_0)$. This means that the free spectral range is a function of the local wavelength in two regards, i.e. the free spectral range is not constant over the transmission spectrum. One way to improve this is to consider the optical path length in this context as a function of the group refractive index, n_g, rather than the local refractive index, $n(\lambda_0)$. The group refractive index takes into account the behavior of the material dispersion, $dn/d\lambda$.

Group Refractive Index $$n_g = \frac{n}{1+\frac{\lambda}{n}\left(\frac{dn}{d\lambda}\right)}$$ Equation 3.24

Free Spectral Range (n_g) $$\Delta\lambda = \frac{\lambda_0^2}{2n_g l\ cos\theta + \lambda_0}$$ Equation 3.25

It is a good assumption to say that N is a very large number, meaning many integer wavelengths, λ_0, fit within a given optical path length. With this assumption, OPL >> λ_0, and the free spectral range can be approximated as

Free Spectral Range Approximation $$\Delta\lambda \approx \frac{\lambda_0^2}{OPL} = \frac{\lambda_0^2}{2n_g l\ cos\theta}$$ Equation 3.26

3.11 ***Incident Angle Tuning Range Derivation and Discussion*:**

The comb profile of an etalon is established by in-phase constructive interference transmission peaks corresponding to an integer number of wavelengths fitting within the etalon's optical path length. The definition of the optical path length of an etalon includes the internal angle of light, θ. Therefore, by varying the internal angle of light, and consequently the optical path length, the wavelengths corresponding to integer divisions of optical path length will shift. Thus, changing the internal angle of light will shift the comb pattern along the wavelength axis.

Optical Path Length $$OPL = 2\,n\,l\,cos\theta$$ Equation 3.27

If the angle is tilted enough, it is possible for the comb pattern to span the entire free spectral range, allowing the alignment of the comb pattern to land on any specific desired wavelength. The phase difference between any arbitrary successive pair of waves is given by δ.

Arbitrary Wave Pair Phase Difference $$\delta = \frac{2\pi}{\lambda}\,2\,n\,l\,cos\theta$$ Equation 3.28

For the successive waves to be in-phase, δ= 2π, and thus corresponds to adjacent peaks in the comb pattern, also referred to as successive modes.

Successive Mode Relation $$\lambda = \,2\,n\,l\,cos\theta$$ Equation 3.29

Next consider the situation in which the successive modes are for normal and angled light by taking the difference between θ=0 and θ=Δθ. Solving this for Δθ derives the internal angle tuning range necessary to shift between successive modes at normal incidence.

Normal to Tilted Successive Modes $$\lambda = 2\, n\, l\, (1 - cos\Delta\theta)$$ Equation 3.30

Internal Angle Tuning Range $$\Delta\theta = \cos^{-1}(1 - \frac{\lambda}{2nl})$$ Equation 3.31

The internal angle tuning range is only partially helpful however. What is really desired is the incident angle tuning range, which can be found by incorporating Snell's Law.

Snell's Law $$\sin(\Delta\theta_0) = n\, sin(\Delta\theta)$$ Equation 3.32

Incident Angle Tuning Range $$\Delta\theta_0 = \sin^{-1}(\, \text{n} \sin(\cos^{-1}(1 - \frac{\lambda}{2nl})))$$ Equation 3.33

Solving this equation in terms of material thickness will determine the minimum etalon thickness necessary to be able to tune over an entire free spectral range, $\Delta\lambda$, for a given incident angle tuning range.

Minimum Angle Tuning Thickness $$L = \frac{\lambda}{2n(1 - \cos(\sin^{-1}(\frac{sin\Delta\theta_0}{n})))}$$ Equation 3.34

An alternate approach to angle tuning can be examined. The relationship between a wavelength for a peak at normal incidence, λ_0, and a shifted wavelength peak, $\lambda_{shifted}$, at an internal angle shift, $\Delta\theta$, is as follows:

Wavelength Shift Relation $$\lambda_0 = \lambda_{shifted} \cos(\Delta\theta)$$ Equation 3.35

Rearrange to solve for the internal angle shift, and then use Snell's Law to solve for incident angle tuning. Alternatively, solve for shifted wavelength with angle tuning.

Internal Angle Tuning for Wavelength Shift $$\Delta\theta = \cos^{-1}(\frac{\lambda_0}{\lambda_{shifted}})$$ Equation 3.36

Incident Angle Tuning for Wavelength Shift $$\Delta\theta_0 = \sin^{-1}(n \sin(\cos^{-1}(\frac{\lambda_0}{\lambda_{shifted}})))$$ Equation 3.37

Shifted Wavelength for Incident Angle Tuning $$\lambda_{shifted} = \frac{\lambda_0}{\cos\left(sin^{-1}\left(\frac{1}{n} sin\, \Delta\theta_0\right)\right)}$$ Equation 3.38

Plotting the wavelength shift vs. incident angle tuning produces a nonlinear curve with positive concavity, as shown in Figure 3.11. This implies that further from normal incidence, the wavelength shifting sensitivity for a given incident angular shift is much higher.

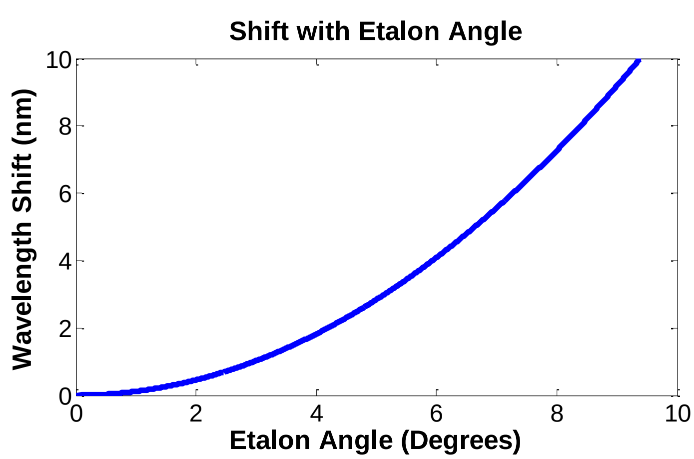

Figure 3.11: Wavelength Shift with Incident Angle Tuning

Substituting $\lambda_{shift} = \lambda_0 + \Delta\lambda$ into Equation 3.37 provides an alternate equation for the incident angle tuning range necessary to span a free spectral range.

Incident Angle Tuning Range $$\Delta\theta_0 = \sin^{-1}(n \sin(\cos^{-1}(\frac{\lambda_0}{\lambda_0 + \Delta\lambda})))$$ Equation 3.39

3.12 *Divergence Considerations*:

In the ideal case, the light incident on an etalon is a perfectly collimated spot, meaning all of the light is travelling along the same incident angle. In practice, however, beams have minimum angular divergence relating to the wavelength of light and beam waist, w_0.

Diffraction Limited Beam Divergence $$\theta \approx \frac{\lambda}{\pi\, w_0}$$ Equation 3.40

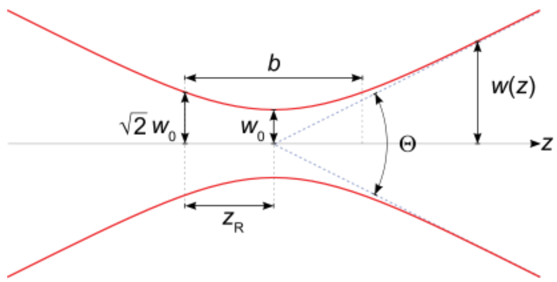

Figure 3.12: Beam Divergence

With beam divergence, some of the light is incident on the etalon at angles slightly off of the central incidence angle. Light at unintended angles of incidence undergo a shift in transmission peak wavelength. This causes an individual transmission peak distribution profile to smear, causing a reduction in peak transmission and wider bandwidth, as shown in Figure 3.13. As shown in Figure 3.11 in Section 3.11, wavelength shift sensitivity increases at angles further from normal incidence, making this smearing effect worsen with greater incidence angle.

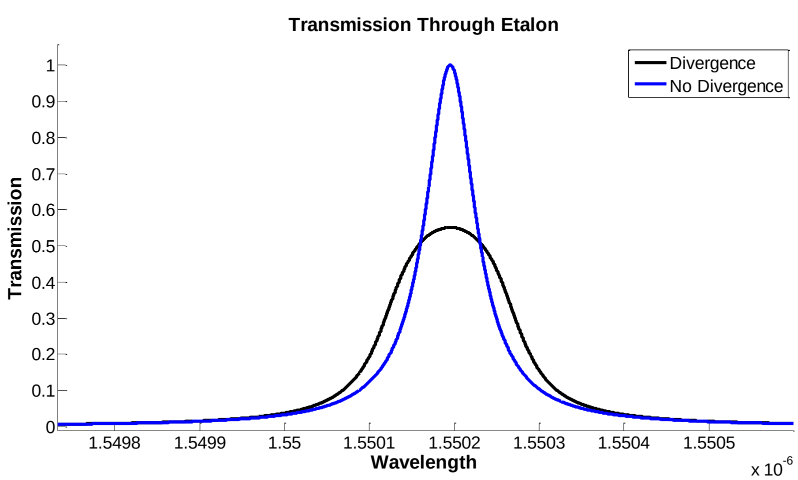

Figure 3.13: Divergence of Individual Transmission Peak

3.13 *Etalon Thickness Difference and Harmonic Free Spectral Range*:

The harmonic free spectral range is a function of the two individual etalons' differing free spectral ranges. The free spectral range is solely dependent on the optical path length. Therefore, the harmonic free spectral range is a function of the dual etalon system's optical path length difference, ΔOPL. For systems at normal incidence that have constant refractive index, the optical path length becomes solely a function of etalon thickness. In this case, the maximum thickness difference necessary to achieve a target harmonic free spectral range may be derived.

Free Spectral Range Approximation

$$\Delta\lambda \approx \frac{\lambda_0^2}{OPL} = \frac{\lambda_0^2}{2n_g l\, cos\theta} = \frac{\lambda_0^2}{2\,n\,l} \qquad \text{Equation 3.41}$$

Harmonic Free Spectral Range

$$HFSR = \frac{\Delta\lambda_1 \Delta\lambda_2}{\Delta\lambda_1 - \Delta\lambda_2} \qquad \text{Equation 3.42}$$

$$HFSR = \frac{\left(\frac{\lambda_0^2}{2\,n\,l_1}\right)\left(\frac{\lambda_0^2}{2\,n\,l_2}\right)}{\left(\frac{\lambda_0^2}{2\,n\,l_1}\right)-\left(\frac{\lambda_0^2}{2\,n\,l_2}\right)} = \frac{\left(\frac{\lambda_0^2}{2\,n}\right)\left(\frac{\lambda_0^2}{2\,n\,l_1\,l_2}\right)}{\left(\frac{\lambda_0^2}{2\,n}\right)\left(\frac{1}{l_1}-\frac{1}{l_2}\right)} = \frac{\lambda_0^2}{(2\,n\,l_1\,l_2)\left(\frac{1}{l_1}-\frac{1}{l_2}\right)} = \frac{\lambda_0^2}{2\,n\,(l_2 - l_1)} = \frac{\lambda_0^2}{2\,n\,(\Delta l)}$$

Maximum Etalon Thickness Difference for HFSR

$$\Delta l = \frac{\lambda_0^2}{2\,n\,HFSR} \qquad \text{Equation 3.43}$$

4. Design Process

The goal of this project is to create a tunable dual etalon wavelength filter with an alignment feedback loop. The filter will be tuned by adjusting the angles of the individual etalons. The objectives for this project are outlined in Table 4.1.

Design Guideline	Specification
Wavelength Range	1530-1570 nm
Output Continuity	Continuous Spectrum
Incidence Angle Limit	~6°
Material	Fused Silica
Bandwidth	<10GHz ≈ <.08nm

Table 4.1: System Design Guidelines

Fused Silica is a common optical material and is used frequently for manufacturing components such as etalons. It is chosen because it is a readily available component. This selection defines the refractive index profile. To calculate the refractive index as a function of wavelength, the Sellmeier Equation may be used using the 6 coefficients for Fused Silica. For hand calculations, the value of n=1.444 at 1550nm will be used.

The wavelength range of 1530-1570nm is chosen as it is a standard telecommunication bandwidth, commonly referred to as the C-band, and is centered on 1550nm with a range of 40nm. For the filter to be able to isolate only a single transmission peak in this range, the harmonic free spectral range (HFSR) must be greater than this 40nm range.

The continuity guideline implies that the filter should be able to tune to any wavelength within the 40nm range. This means that the system must be able to angle tune over its entire free spectral range. The incidence angle limit here indicates that it must tune over its entire free spectral range within 6°. This defines the incident angle tuning range. It also defines the minimum thickness of each etalon to be able to angle tune over the full free spectral range within this angular limit.

Using λ=1550nm, n=1.444, $\Delta\theta_0$=6°, and Equation 3.34,

Minimum Angle Tuning Thickness

$$L = \frac{\lambda}{2n(1-\cos(\sin^{-1}(\frac{\sin\Delta\theta_0}{n})))} = 0.205\text{mm} \quad \text{Equation 4.1}$$

This system will be designed for the initial angle of incidence to be normal and the maximum angle of incidence to be the incidence angle limit of 6°. For the minimum angle tuning thickness, the free spectral range at normal incidence may be found.

Using λ_0=1550nm, n=1.444, l=L, θ=0°, and Equation 3.13,

Free Spectral Range (n_g)

$$\Delta\lambda = \frac{\lambda_0^2}{2n_g l\cos\theta + \lambda_0} = 4.066\text{nm} \quad \text{Equation 4.2}$$

Using the normal incidence free spectral range and the design guideline bandwidth, the finesse and target reflectance may be calculated. This design is assuming the same reflectance for both surfaces, as is common practice.

Finesse

$$\mathcal{F} = \frac{\Delta\lambda}{\delta\lambda} = 50.76 \quad \text{Equation 4.3}$$

Coefficient of Finesse

$$F = \frac{4R}{(1-R)^2} \quad \text{Equation 4.4}$$

Finesse as function of Coefficient of Finesse

$$\mathcal{F} = \frac{\pi}{2\arcsin\left(\frac{1}{\sqrt{F}}\right)} \quad \text{Equation 4.5}$$

For surface reflectances of 94%, a theoretical finesse of 50.76 is achievable.

To allow for some margin and to target a thickness that is easier to manufacture, the etalon thickness of 0.230mm will be used. The reflectance will be kept at 94%. For this thickness and reflectance, the new incident angle tuning range, free spectral range, and bandwidth are calculated as shown in Table 4.2.

Incident Angle Tuning Range

$$\Delta\theta_0 = \sin^{-1}(\text{ n} \sin(\cos^{-1}(1 - \frac{\lambda}{2nl})))$$

Equation 4.6

Design Variable or Feature	Value
Reflectance, R	94%
Finesse, Ƒ	50.76
Thickness, l_1	.230mm
Incident Angle Tuning Range, $\Delta\theta_{0,1}$	5.66°
Free Spectral Range, $\Delta\lambda_1$	3.608nm ≈ 450.27GHz
Bandwidth, $\delta\lambda_1$	0.071nm ≈ 8.87GHz

Table 4.2: Etalon 1 Design Variables and Features

Arbitrary Wave Pair Phase Difference

$$\delta = \frac{2\pi}{\lambda}\ 2\ n\ l$$

Equation 4.7

Transmission

$$T = \frac{(1-R)^2}{1 - 2R\cos\delta + R^2} = \frac{1}{1 + F\sin^2\left(\frac{\delta}{2}\right)}$$

Equation 4.8

Using the equations for phase difference and transmission, the performance of this etalon at normal incidence over the design wavelength range may be plotted, as shown in Figure 3.8.

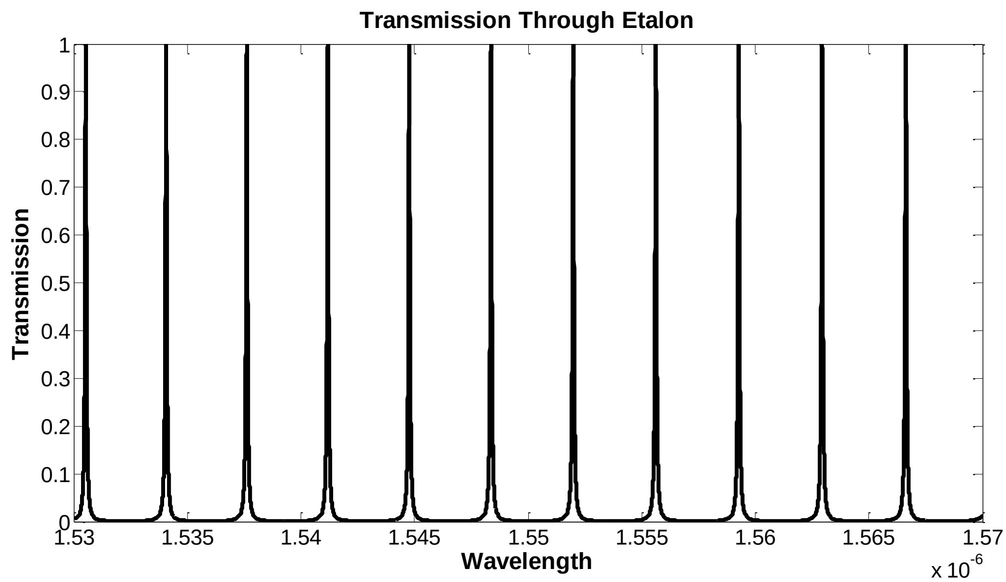

Figure 4.1: Etalon 1 Design

This single etalon produces the expected comb pattern. The next step is to design a complimentary second etalon to produce the desired filter characteristics. The remaining design features to consider are harmonic free spectral range and the adjacent line overlap factor.

Harmonic Free Spectral Range $$HFSR = \frac{\Delta\lambda_1 \Delta\lambda_2}{\Delta\lambda_1 - \Delta\lambda_2}$$ Equation 4.9

Adjacent Line Overlap Factor $$ALOF = \frac{\Delta\lambda_1 - \Delta\lambda_2}{\delta\lambda}$$ Equation 4.10

The minimum harmonic free spectral range necessary for this design is 40nm. Assuming nominally normal incident light and equal refractive indices, the maximum etalon thickness difference to achieve this minimum harmonic free spectral range can be calculated.

Maximum Etalon Thickness Difference for HFSR $$\Delta l = \frac{\lambda_0^2}{2\, n\, HFSR} = 0.021\text{mm}$$ Equation 4.11

This thickness difference results in an ALOF of 4.20, which is appreciably greater than 1. To allow some slight margin on the minimum HFSR, a lower thickness difference than the maximum is desired, but reducing the thickness difference too much would result in a low ALOF. Suppressed adjacent line overlap is desired in this system, which means as large of a thickness difference as allowable is preferred. To increase the ALOF and suppress adjacent line overlap, a thickness difference of 0.020mm will be used. To further reduce the incident angle tuning range of etalon 2, a thickness of 0.250mm will be chosen instead of 0.210mm. For the pair of etalons with thicknesses of 0.230mm and 0.250mm, and reflectances of 94% all system characteristics may be calculated.

Design Variable or Feature	**Value**
Reflectance, R	94%
Finesse, Ƒ	50.76
Thickness, l_2	.250mm
Incident Angle Tuning Range, $\Delta\theta_{0,2}$	5.43°
Free Spectral Range, $\Delta\lambda_2$	3.320nm ≈ 414.33GHz
Bandwidth, $\delta\lambda_2$	0.065nm ≈ 8.16GHz

Table 4.3: Etalon 2 Design Variables and Features

Dual Etalon Design Feature	**Value**
Harmonic Free Spectral Range, HFSR	41.6nm ≈ 5190.2GHz
Adjacent Line Overlap Factor, ALOF	4.05

Table 4.4: Dual Etalon System Design Features

The expected theoretical performance of this dual etalon system is plotted in Figure 4.2 and Figure 4.3.

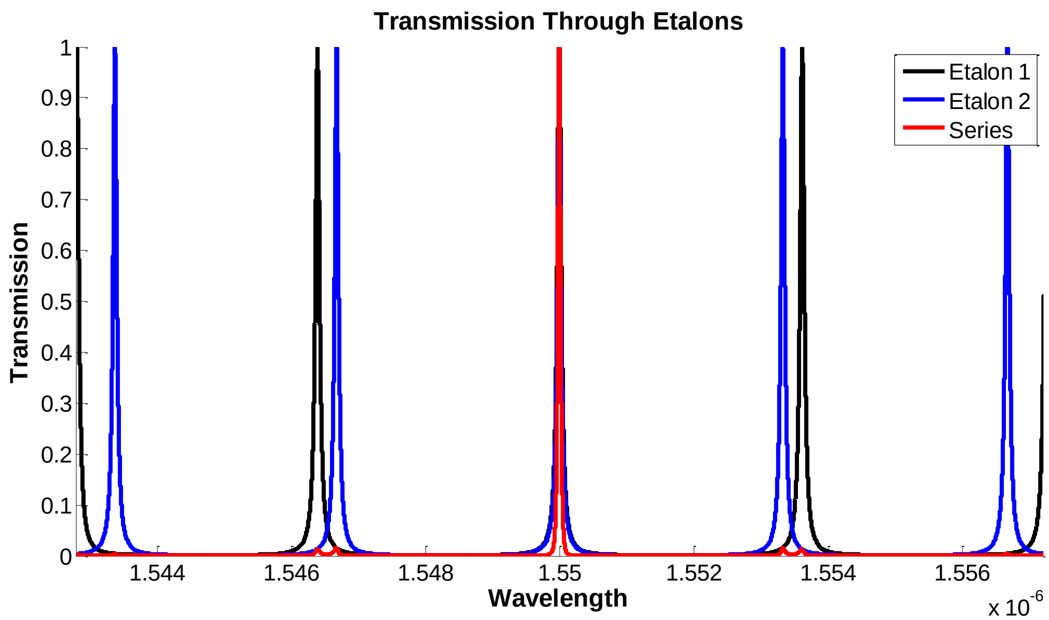

Figure 4.2: Individual Etalon Transmissions and Resulting Dual Etalon System Transmission

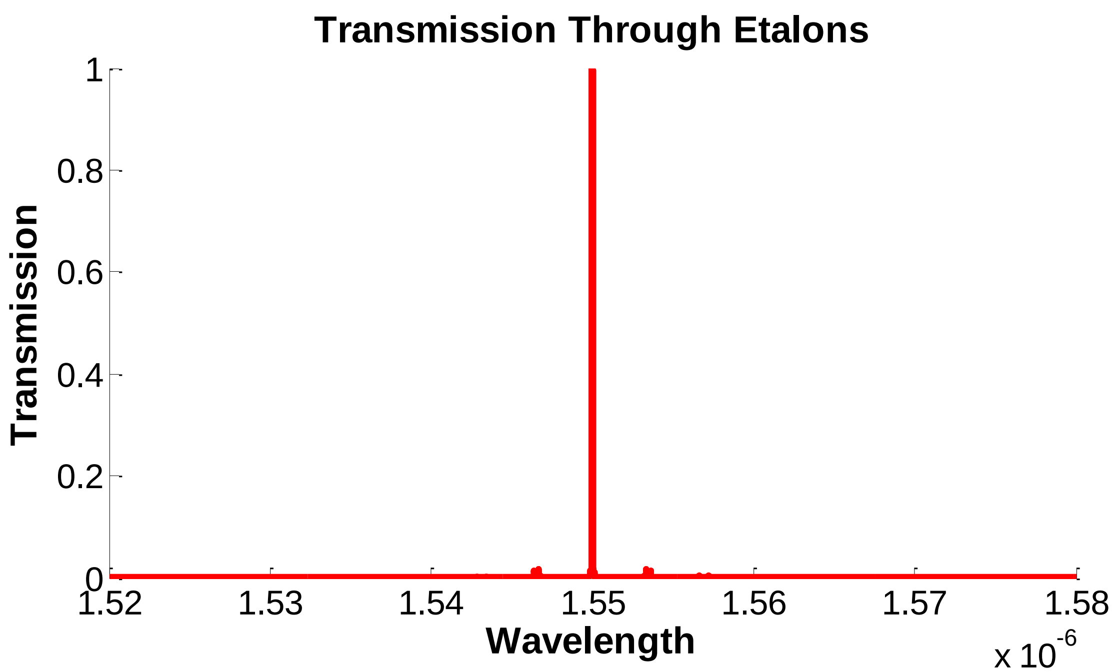

Figure 4.3: Dual Etalon system Transmission

5. System Modeling

To better understand the entire system and try to predict its behavior, it is advantageous to model the expected performance. Modeling here was performed using Matlab, but any equivalent simulation software is acceptable.

5.1 *Basic Transmission vs. Wavelength:*

The first simulation to perform is to plot the expected transmission vs. wavelength for a single etalon. For this, the independent variable is wavelength and the dependent variable is the corresponding transmission values. To create the corresponding transmission values, a couple equations are necessary.

Transmission
$$T = \frac{(1-R)^2}{1 - 2R\cos\delta + R^2} = \frac{1}{1 + F\sin^2\left(\frac{\delta}{2}\right)}$$
Equation 5.1

Arbitrary Wave Pair Phase Difference
$$\delta = \frac{2\pi}{\lambda}\, 2\, n\, l\, \cos\theta = \frac{2\pi}{\lambda}\, OPL$$
Equation 5.2

To fulfill these equations, values must be defined for refractive index, thickness, internal angle, and reflectance. For a first pass, the values in Table 5.1 are used to create the plot in Figure 3.8. For increased accuracy, the refractive index may be set up as a function of wavelength using the Sellmeier equation. Initially, the internal angle will be considered as 0° for normal incident light. Alternatively, it can be a used input. It can also be defined by incident angle by factoring in Snell's Law.

Variable	Value
Refractive Index, n	1.444 or Sellmeier Equation
Thickness, l	0.230mm
Internal Angle, θ	0° or Used Defined
Reflectance, R	.94

Table 5.1: Transmission vs. Wavelength Plot Constants

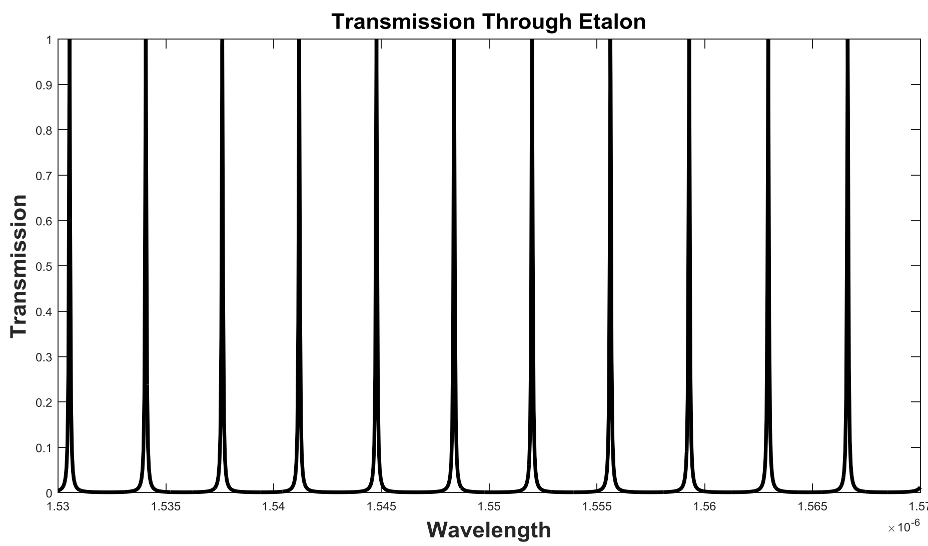

Figure 5.1: Transmission vs. Wavelength Plot

5.2 *Adjust OPL for Center Wavelength:*

In this plot, the transmission peaks fall as a matter of where an integer number of wavelengths fit in the optical path length. The end goal is to simulate the transmission through two etalons. To line this up as desired, it is necessary to define a center wavelength (λ_0) and alter the OPL slightly to match an integer number of this center wavelength. Using this trick, the transmission plot can be recreated to be centered on any desired wavelength.

Adjusted OPL for Centered Wavelength

$$OPL_{centered} = \lambda_0 * round\left(\frac{OPL}{\lambda_0}\right)$$

Equation 5.3

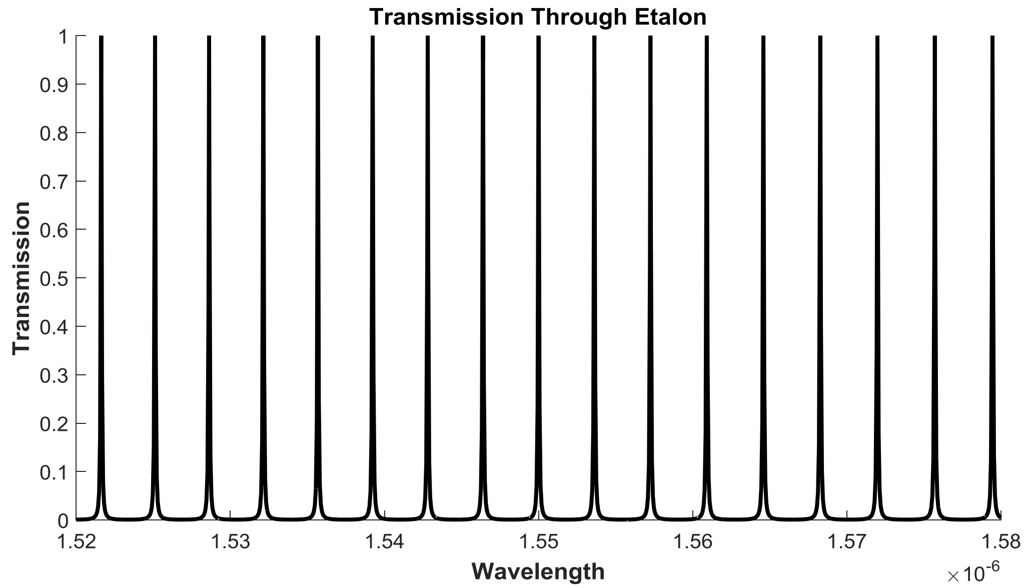

Figure 5.2: Transmission vs. Wavelength Plot Centered on 1550nm

5.3 *Dual Etalon Plot:*

To plot the behavior through two etalons, repeat the process for a single etalon using altered parameters as desired for the second etalon, such as a thickness of 0.250mm. Making sure to center both OPLs to the same center wavelength, simply multiply the resulting individual transmission profiles to obtain the transmission profile for the etalons in series. This is shown in Figure 5.3 and Figure 5.4.

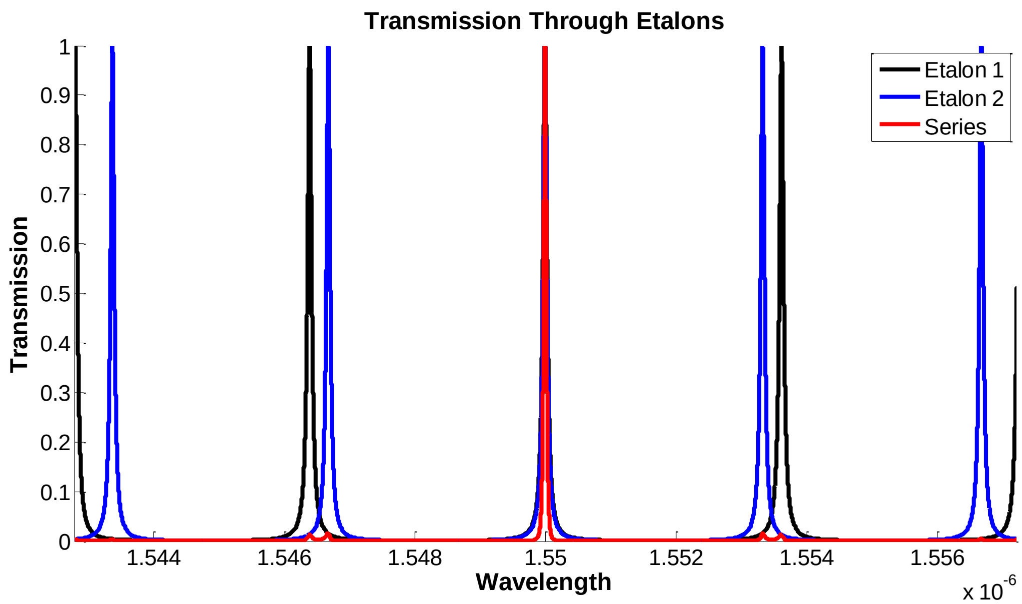

Figure 5.3: Individual Etalon Transmissions and Resulting Dual Etalon System Transmission

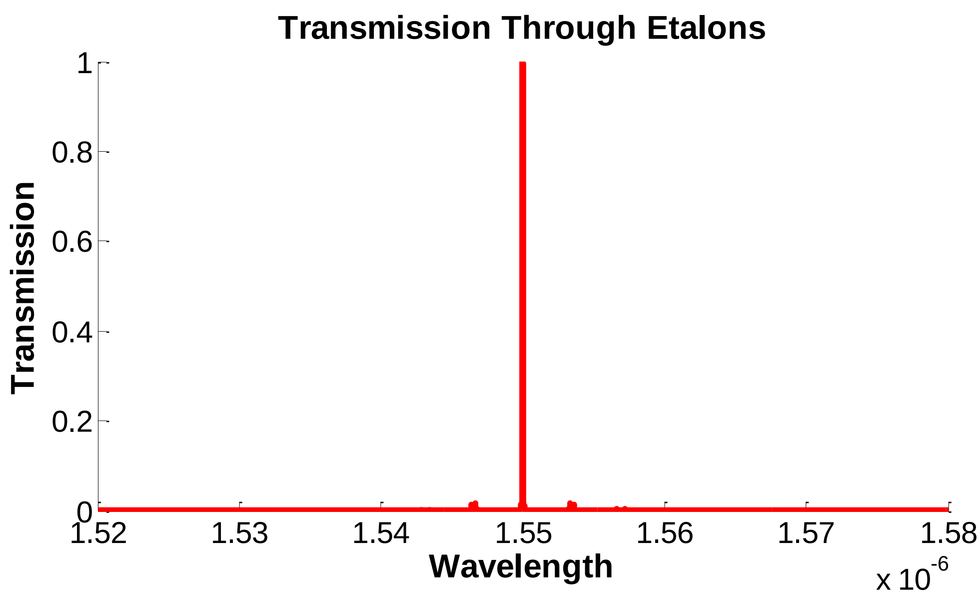

Figure 5.4: Dual Etalon System Transmission

5.4 *Angle Tuning:*

There are two ways to incorporate angle tuning into the model depending on whether the desired relation is wavelength as a function of angle or angle as a function of wavelength. Angle wavelength tuning is a cosine relationship with the internal angle. Snell's Law must be included to consider the incident angle.

Wavelength Shift Relation $$\lambda_0 = \lambda_{shifted}\cos(\Delta\theta)$$ Equation 5.4

One approach to angle tuning is to find the shifted wavelength resulting from tuning an input incident angle.

Shifted Wavelength for Incident Angle Tuning $$\lambda_{shifted} = \frac{\lambda_0}{\cos\left(sin^{-1}\left(\frac{1}{n}sin\,\Delta\theta_0\right)\right)}$$ Equation 5.5

The other approach is to find the internal or incident angle rotation necessary to shift to a specific wavelength.

Internal Angle Tuning for Wavelength Shift $$\Delta\theta = \cos^{-1}\left(\frac{\lambda_0}{\lambda_{shifted}}\right)$$ Equation 5.6

Incident Angle Tuning for Wavelength Shift $$\Delta\theta_0 = \sin^{-1}\left(n\sin\left(\cos^{-1}\left(\frac{\lambda_0}{\lambda_{shifted}}\right)\right)\right)$$ Equation 5.7

In this project, the incident angle tuning has an upper bound so that it can tune over an entire free spectral range, but no more. If the desired wavelength shift is greater than a single free spectral range, the required tuning angle would exceed the limit. Therefore, to tune to that wavelength, an integral number of free spectral ranges must be subtracted from the wavelength shift to get the effective shift to be less than a single free spectral range and the necessary angle tuning to be less than the upper bound. Another term for this is the modulus after division. For example, consider a desired wavelength shift from a center wavelength for an etalon. If the shift is greater than the free spectral range, the modulus after division is found to consider the minimum wavelength shift to put any of the transmission peaks on the desired wavelength. The necessary incident tuning angle is then found from this modulus wavelength shift.

The following steps are taken to center and shift the plot to the desired wavelength:

1. Define center wavelength and center OPL on center wavelength
2. Find initial free spectral range for centered OPL
3. Find modulus of division for wavelength shift using initial free spectral range
4. Find tuning angle to shift to modulus of shifted wavelength
5. Include tuning angle in new OPL
6. Use new OPL to plot transmission

5.5 *Sources of Error:*

There are several sources of error with this approach. First, the free spectral range is a function of the wavelength of the nearest transmission peak. This means that the free spectral range is not truly constant— it changes depending on the considered location in the wavelength domain. With each modulus free spectral range away, the actual free spectral range for the desired wavelength is further from the considered free spectral range around the center wavelength. The greater the wavelength shift, the more error this modeling approach includes.

Additionally, the final optical path length that is used to plot the transmission includes the tuning angle. This OPL is greater than the initial OPL used to find the free spectral range to calculate the shifting modulus. The inherent problem here is that necessary shifting angle modulus is calculated using the free spectral range, but the free spectral range changes with angle. This circular dependence again causes increased error with greater wavelength shift.

These sources of error cause the transmission peaks of the two etalons to be slightly off from the expected single peak. In the transmission plot, this is evident by a slight offset of the peak from the desired location, and a decrease in peak transmission, as shown in Figure 5.5. In theory, these are artifacts of the modeling, but will not be present in the true system.

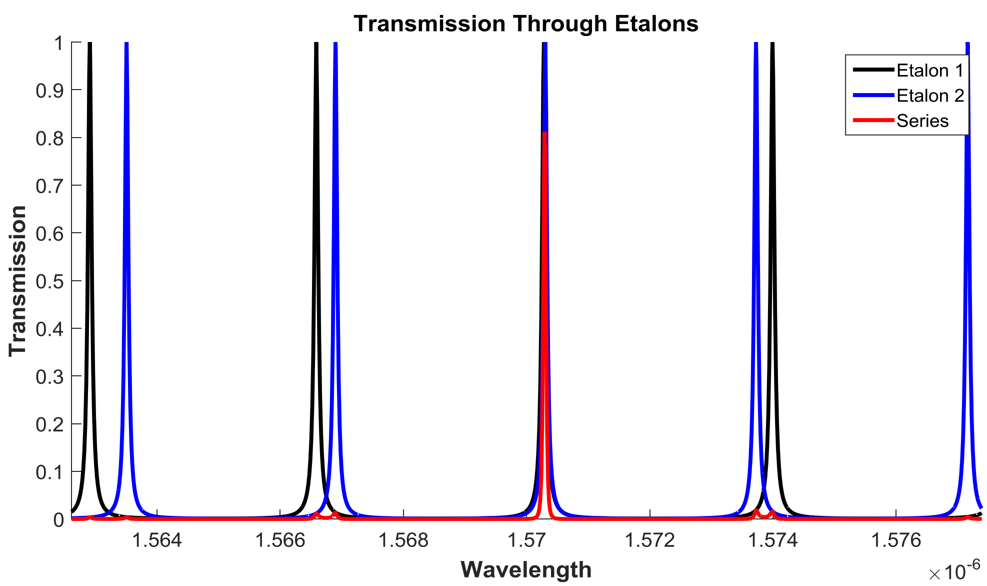

Figure 5.5: Modeling errors evident for 1570nm desired wavelength shifted from 1550nm centered wavelength

5.6 *Sensitivity Calculations:*

In a system that has such narrow bandwidth peaks, wavelength accuracy is important for optimal transmission. It would be helpful to understand how sensitive the transmission peaks are to wavelength offset and angle offset. To do this, locate the wavelength that corresponds to a given percentage of the maximum transmission and the angle offset can then be calculated from this wavelength offset. Sample values are provided in Table 5.2. This analysis can produce plots of wavelength sensitivity and angle sensitivity, as shown in Figure 5.6 and Figure 5.7. To maintain transmission of about 90% of the max, the wavelength accuracy must be about .008nm and the angle accuracy must be about 15 arcminutes. This also gives a better sense of the bandwidth (full width at half max) of the signal through the series of etalons, which is about .044nm.

Transmission Percentage	Wavelength Offset (nm)	Angle Offset (arcmin)
1	0	0
0.98	0.00336	10.33638
0.95	0.00546	13.17636
0.9	0.00792	15.86946
0.75	0.01338	20.62662
0.5	0.02196	26.4252
0.25	0.03408	32.9196
0.1	0.05004	39.89022

Table 5.2: Transmission vs. Wavelength Offset and Corresponding Angle Offset

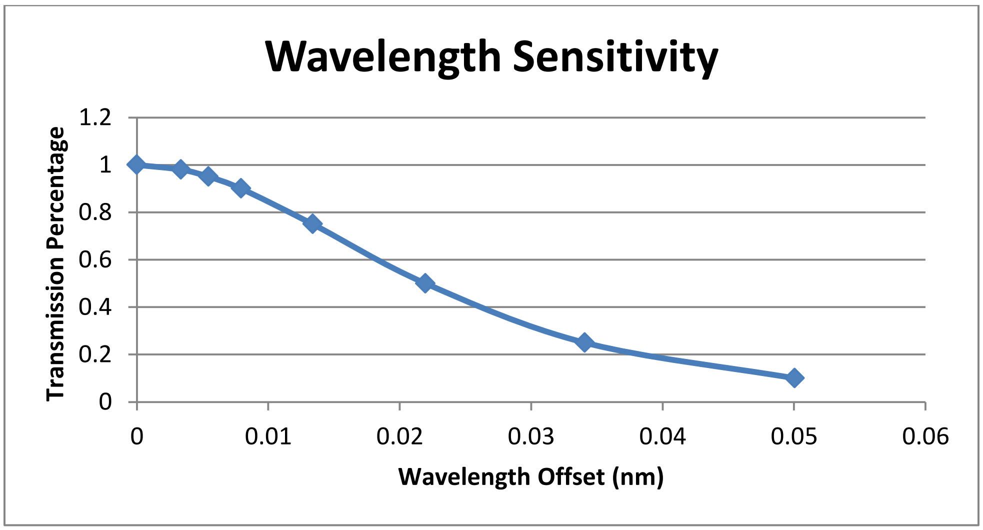

Figure 5.6: Wavelength Sensitivity

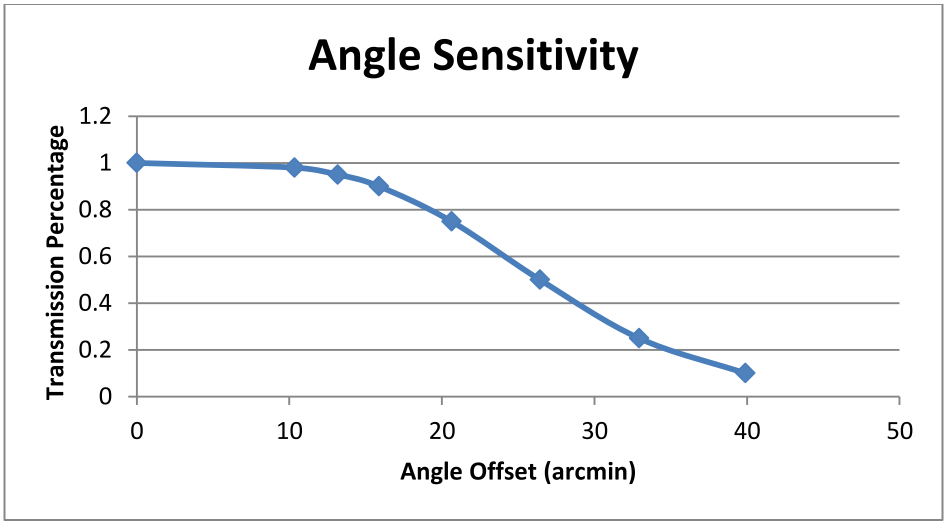

Figure 5.7: Angle Sensitivity

5.7 *Desired Wavelength and Etalon Angle Plots:*

In this process, the incident tuning angle to shift to the modulus of the shifted wavelength is calculated. For a given center wavelength, a vector of desired wavelength values may be used to calculate two vectors for the incident tuning angles of the two etalons to transmit the desired wavelength. These vectors may be used to plot the 2 etalon angles vs. wavelength, as shown in Figure 5.8 for a starting center wavelength of 1530nm.

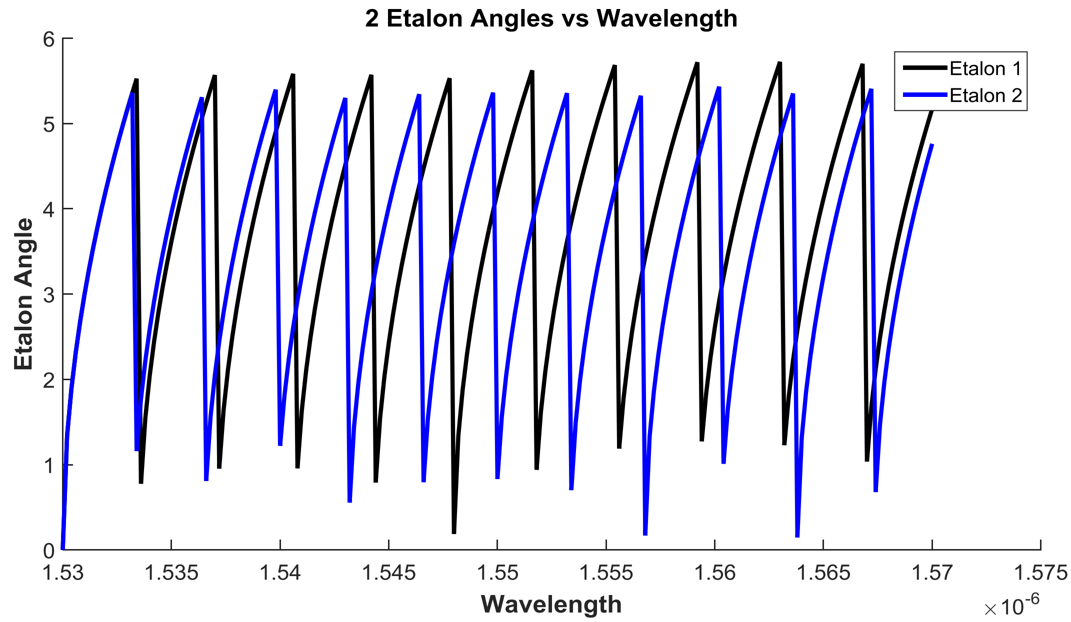

Figure 5.8: 2 Etalon Angles vs. Desired Wavelength starting from 1530nm center wavelength

The two etalon angles follow each other initially, but since they have different free spectral ranges, they return to normal incidence at different wavelengths. Further from the centered wavelength, this effect compounds.

This set of three vectors can also be used to visualize the information in a different way. A 3D plot of wavelength vs. the 2 etalon angles can be produced, as shown in Figure 5.9, Figure 5.10, Figure 5.11, and Figure 5.12.

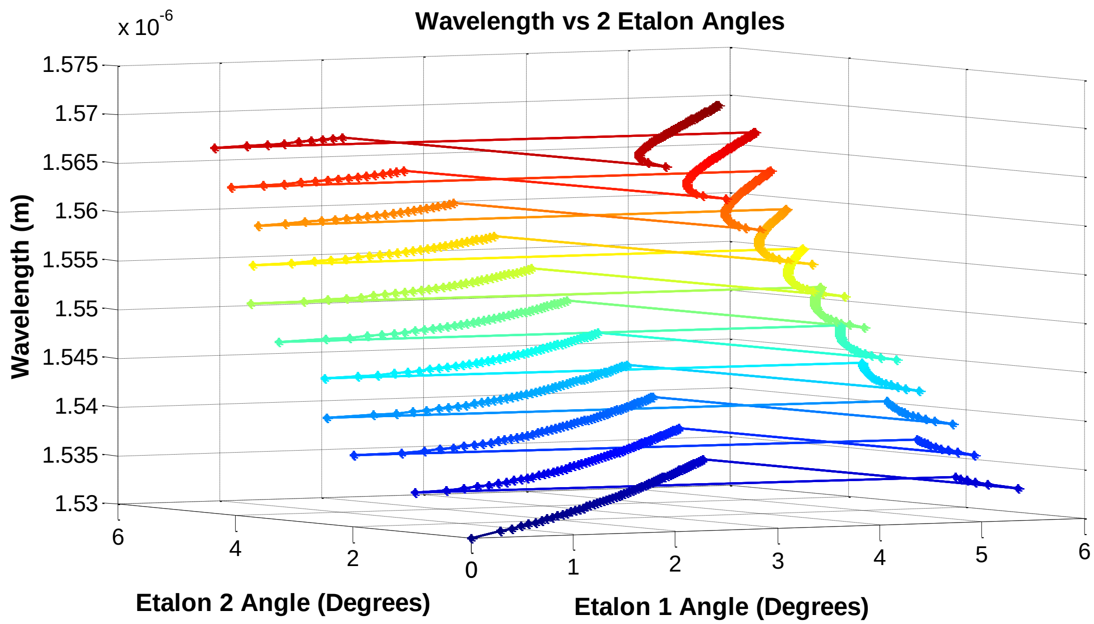

Figure 5.9: Angled View of 3D Plot of Desired Wavelength vs. 2 Etalon Angles starting from 1530nm center wavelength

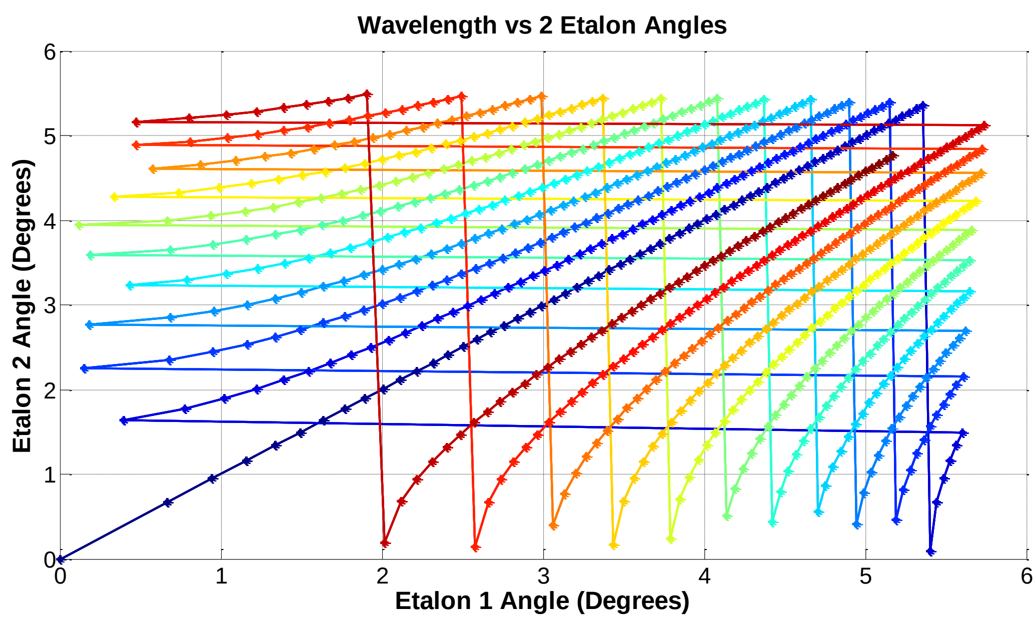

Figure 5.10: Top View of 3D Plot of Desired Wavelength vs. 2 Etalon Angles starting from 1530nm center wavelength

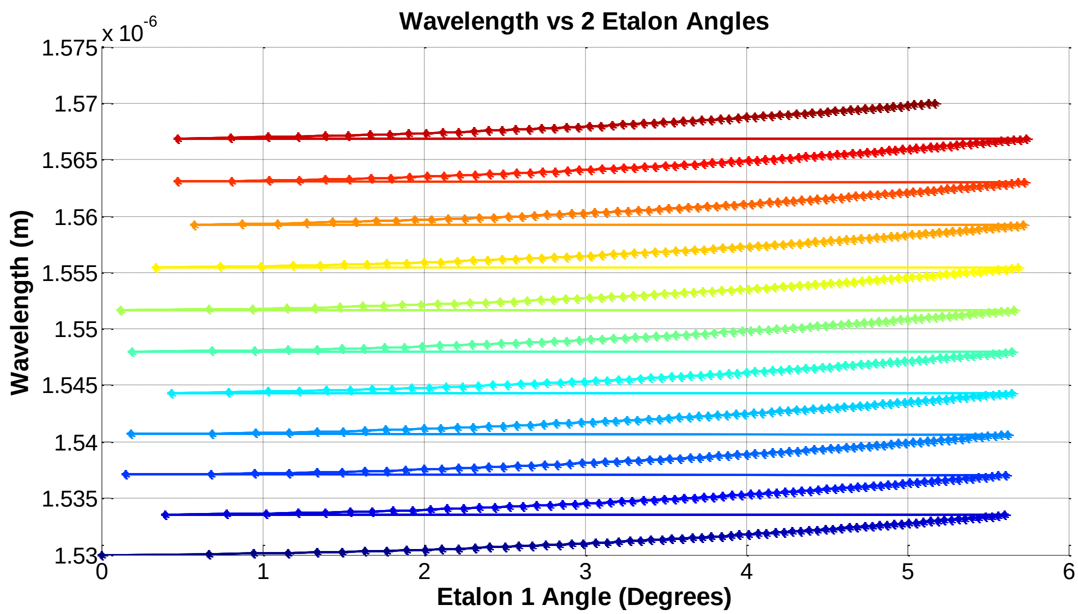

Figure 5.11: Desired Wavelength vs. Etalon 1 Angle starting from 1530nm center wavelength

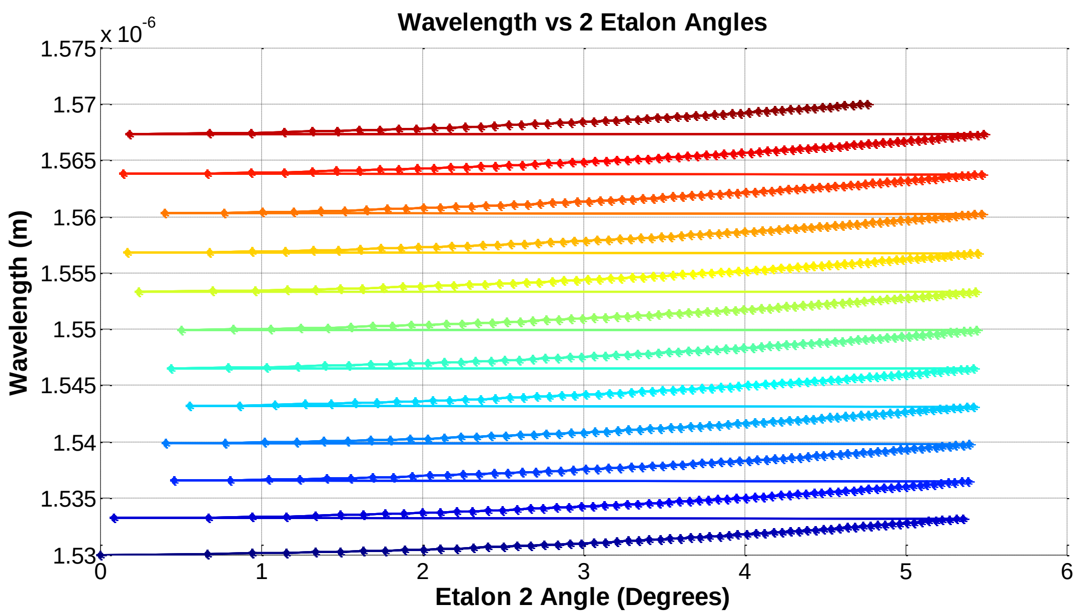

Figure 5.12: Desired Wavelength vs. Etalon 2 Angle starting from 1530nm center wavelength

6. Modes of Operation and System Setup

This system is organized into three main subsystems: Input Beam, Transmission System, and Wavelength Discerning Detector. Some of the components within these subsystems are determined by the mode of operation of the system. The proposed system will have two main modes of operation to simulate different application scenarios.

6.1 *Modes of Operation:*

1. A broadband signal will be input to the filter that spans the entire wavelength range. The program will be told a specific wavelength to transmit, and will tune the filter to pass that signal.

2. A single, known narrow-linewidth signal will be input to the filter. The program will be told at what wavelength the peak is, and will tune the filter to pass that signal.

6.2 *Input System:*

The Input Beam is the only subsystem that is directly affected by the two modes of operation. For mode of operation 1, the input beam will be a fiber-coupled broadband signal that spans the entire wavelength range. Since the source will extend beyond the desired wavelength range, a bandpass filter will be included to isolate the desired region. For mode of operation 2, the input beam will be a narrow-linewidth signal from a tunable, narrow-linewidth, fiber-coupled source plugged directly into the collimator of the transmission system.

Figure 6.1: Narrow-linewidth, fiber-coupled laser source

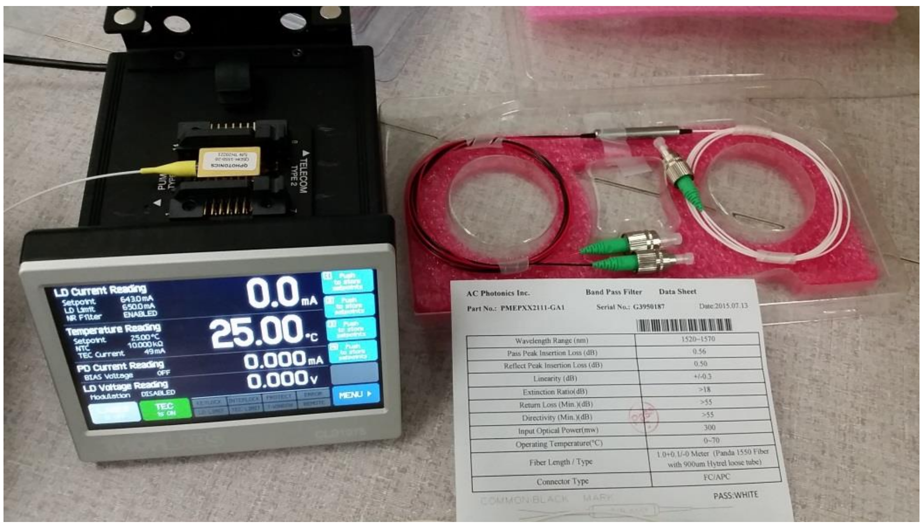

Figure 6.2: Broadband source laser diode, controller, and bandpass filter

Input Beam

Component	Supplier	Part Number	Quantity
Narrow LW Tunable Laser	Agilent	81689B	1
Broadband Source Laser Diode	QPhotonics	QSDM-1550-20	1
Compact Laser Diode and TEC Controller	Thorlabs	CLD1015	1
Fiber-Coupled 1530-1570nm Bandpass Filter	AC Photonics	PMEPXX2111	1
30dBm Er/Yb Fiber Amplifier	Nuphoton	-	1

Table 6.1: Input Beam Bill of Materials

6.3 *Transmission System:*

The transmission system is where the wavelength filtering takes place. It begins by receiving a fiber-coupled signal from the input beam subsystem. This signal is converted from fiber-coupled to free space using a collimator in a 5-axis mount. The light next encounters etalon 1 mounted to a motorized rotation stage. The light proceeds to etalon 2 mounted to a second motorized rotation stage. Transmitting through the pair of etalons, the light is fiber coupled using a second collimator in a 5-axis mount. The fiber-coupled light is passed on to the wavelength discerning detector.

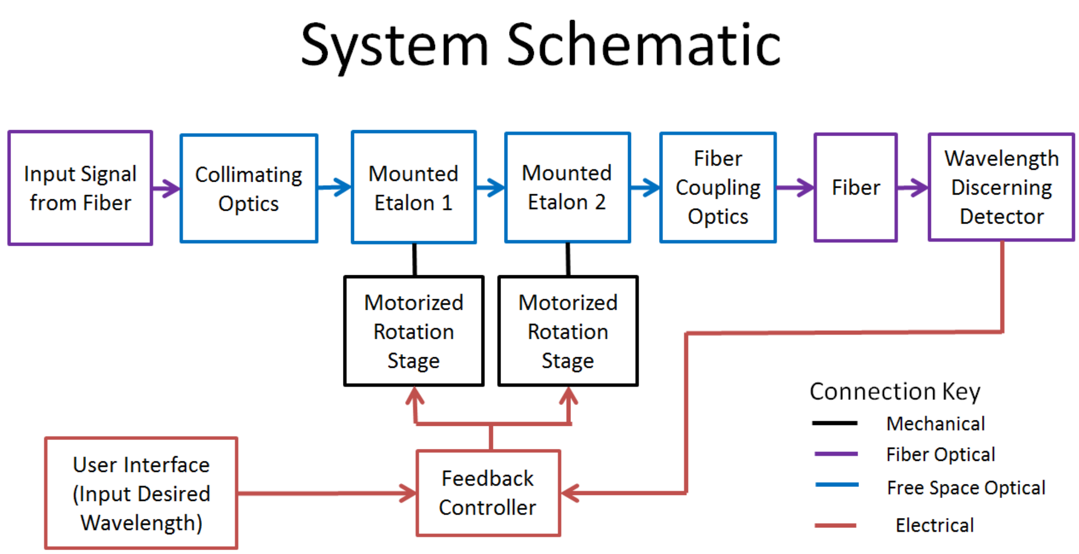

Figure 6.3: Transmission System Schematic

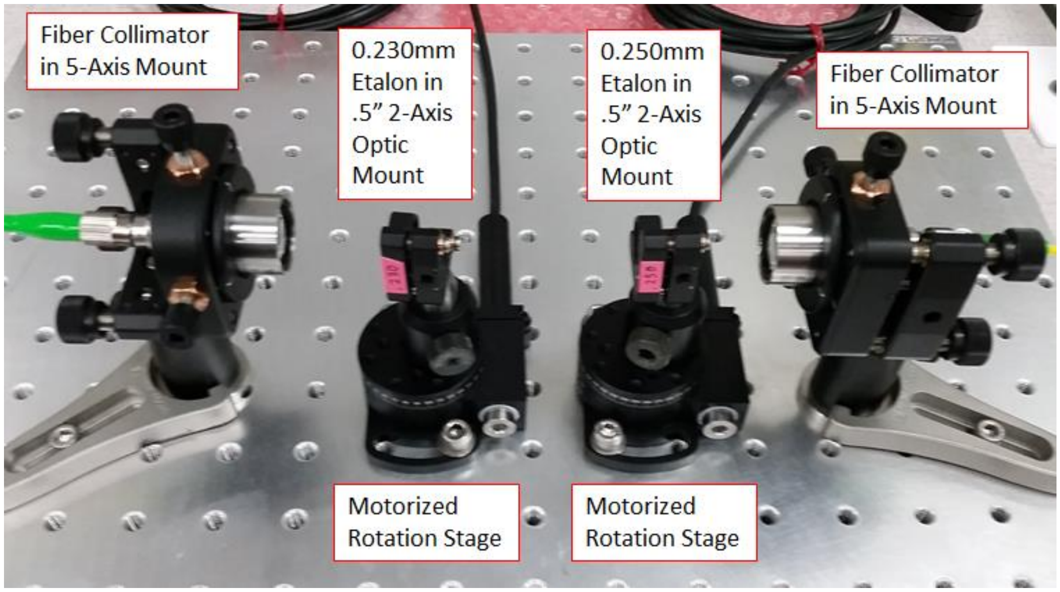

Figure 6.4: Transmission System Architecture

Transmission System

Component	**Supplier**	**Part Number**	**Quantity**
Collimator	Thorlabs	F810APC-1550	2
Collimator Mount to 1" Thread	Thorlabs	AD15F	2
5 Axis Mount	Thorlabs	K5X1	2
Etalon 1	LEO	SE-05-0.23mmT-R94-1560	2
Etalon 2	LEO	SE-05-0.25mmT-R94-1560	2
.5" Optic Mount Threaded	Thorlabs	KM05T	2
Motorized Rotation Stage w/ controller	Thorlabs	CR1-Z7E	2

Table 6.2: Transmission System Bill of Materials

6.4 *Wavelength Discerning Detector:*

The wavelength discerning detector is what allows the system to identify if it is operating properly. It begins by receiving a fiber-coupled signal from the transmission system. First, a 99/1 fiber splitter taps off a small fraction of the signal and directs it to an optical spectrum analyzer (OSA). The OSA is used for operator confirmation purposes as a system check. The majority of the signal is directed to a 50/50 fiber splitter. Half of the signal is sent directly to a photon detector. The other half of the signal is sent through a linear transmission filter (LTF) before getting to the second photon detector. A linear transmission filter attenuates the signal linearly vs. wavelength. The two photon detectors produce analog signals that are sent to an analog-to-digital converter (ADC) via an adapter with a load resistor. The ADC is connected to the feedback control program. If only the signal from the LTF were used, the system would be sensitive to fluctuations in signal power. By comparing the signal through the LTF to the signal directly, the system can be insensitive to signal power.

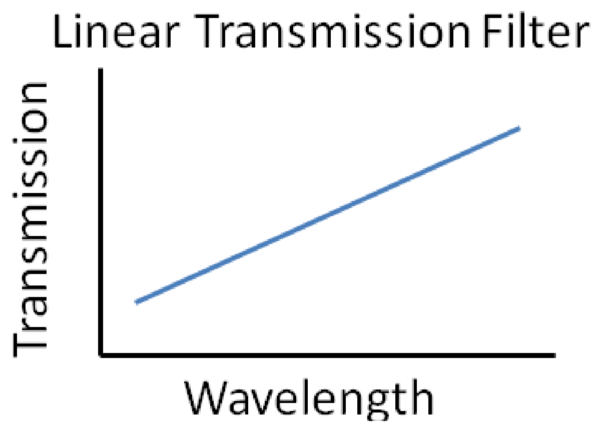

Figure 6.5: Linear Transmission Filter Diagram

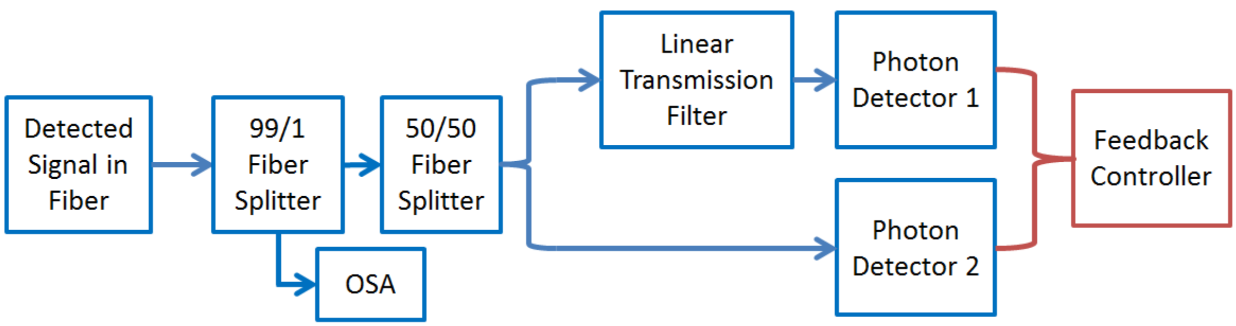

Figure 6.6: Wavelength Discerning Detector Schematic

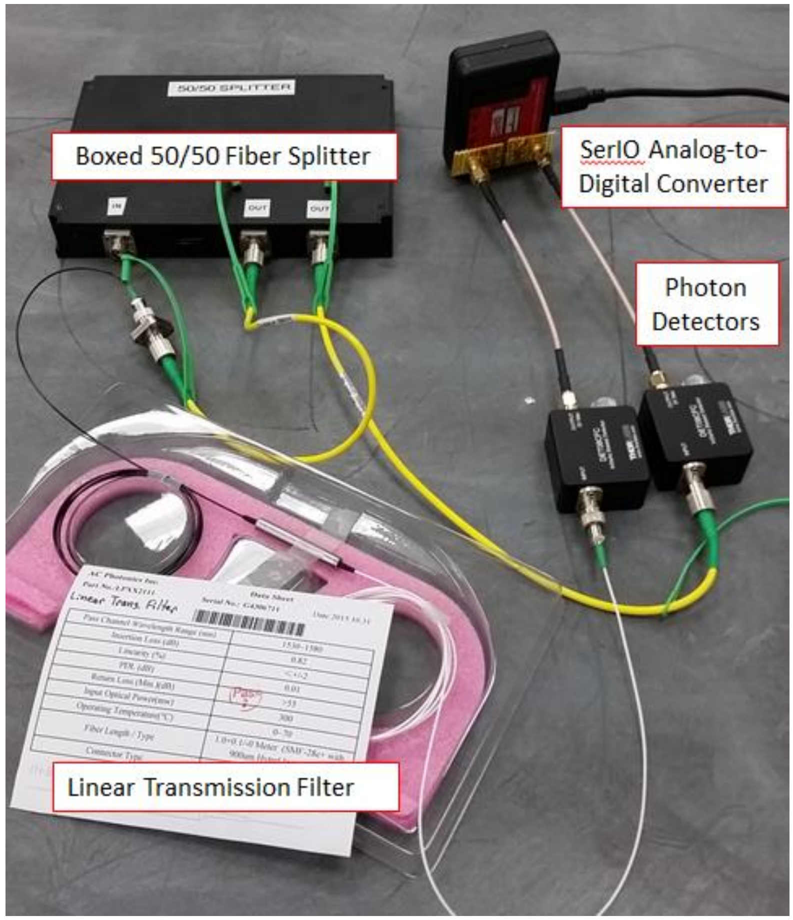

Figure 6.7: Wavelength Discerning Detector Architecture

Wavelength Discerning Detector

Component	**Supplier**	**Part Number**	**Quantity**
99/1 Fiber Splitter	AC Photonics	WP15010202A2011	1
50/50 Fiber Splitter	AC Photonics	LC-2x2-1550-50/50	1
Linear Transmission Filter	AC Photonics	LPXX2111	2
Photon Detector	Thorlabs	DET08CFC	2
Analog to Digital Converter	MicroController Pros LLC	DEV-09521	1
Optical Spectrum Analyzer	Yokogawa	AQ6370C	1

Table 6.3: Wavelength Discerning Detector Bill of Materials

7. Lab Measurements

In order for the system to operate as expected, all components must individually meet their performance specifications. To ensure this is the case, the most critical components, the etalons, were tested to verify their design parameters.

7.1 *Individual Free Spectral Range Measurements:*

Free spectral range was measured for each etalon in two ways. First a broadband source was put through the etalon and observed on the OSA. The wavelengths corresponding to transmission peaks were recorded. The difference between these wavelengths is the free spectral range. A screenshot of the transmission profile on an OSA spanning multiple peaks is shown in Figure 7.1. Second, the free spectral range was verified with power measurements using the narrow-linewidth source at fine increments around adjacent transmission peaks. The measured values are summarized in Table 7.1.

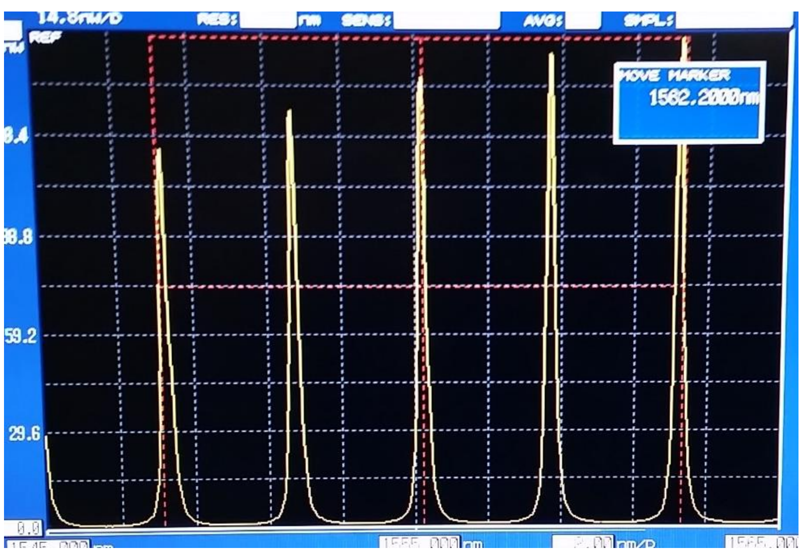

Figure 7.1: Single Etalon Transmission Profile on OSA Spanning Multiple Peaks

Method	.230mm Etalon Free Spectral Range Measurement (nm)	.250mm Etalon Free Spectral Range Measurement (nm)
Broadband Source	3.48	3.18
Narrow-Linewidth Source	3.49	3.184

Table 7.1: Free Spectral Range Measurements

The measured values for free spectral range were relatively close to what was expected for etalons with the specified parameters. The anticipated free spectral range for a 0.230mm thick fused silica etalon is 3.608nm. The measured values are only about 3% off. The anticipated free spectral range for a 0.250mm thick fused silica etalon is 3.320nm. The measured values are about 4% off. In this case, since the actual free spectral ranges are smaller than expected, the incident angle tuning range should be even less than the necessary 6°, increasing the safety factor. However, the harmonic free spectral range will be slightly reduced.

7.2 *Individual Bandwidth Measurements:*

Bandwidth was similarly measured for each etalon in two ways. The first involved putting a broadband source through the etalon and observing the output on the OSA. Zooming in on a single transmission peak, the wavelengths where there was 3dB loss relative to the maximum transmission were used to calculate the full width at half maximum for a given profile. The wavelength difference is the bandwidth. A screenshot of this transmission profile on an OSA is shown in Figure 7.2. To verify this, power measurements were taken with the narrow-linewidth source at fine increments over a single transmission peak. Results are shown in Table 7.2, Figure 7.3, and Figure 7.4.

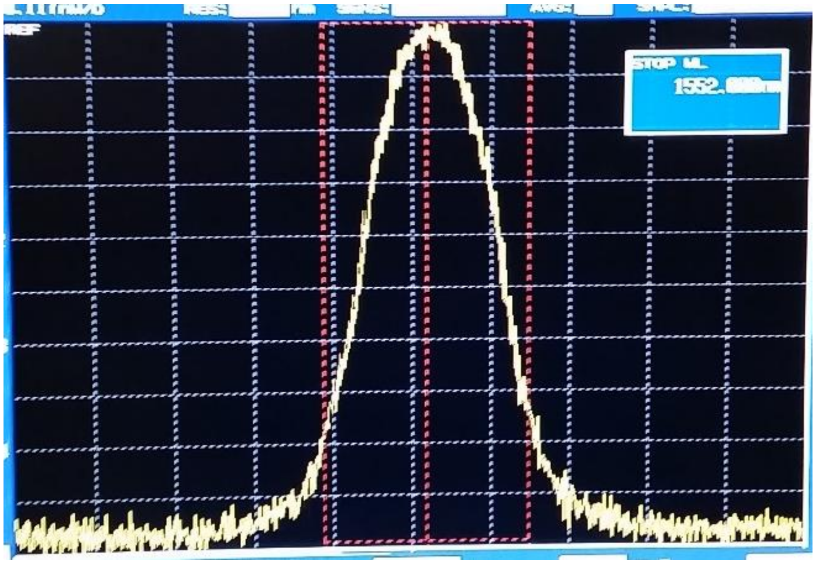

Figure 7.2: Single Etalon Transmission Profile on OSA Zoomed in on a Single Peak

Method	.230mm Etalon Bandwidth Measurement (nm)	.250mm Etalon Bandwidth Measurement (nm)
Broadband Source	.25	.19
Narrow-Linewidth Source	.28	.18

Table 7.2: Bandwidth Measurements

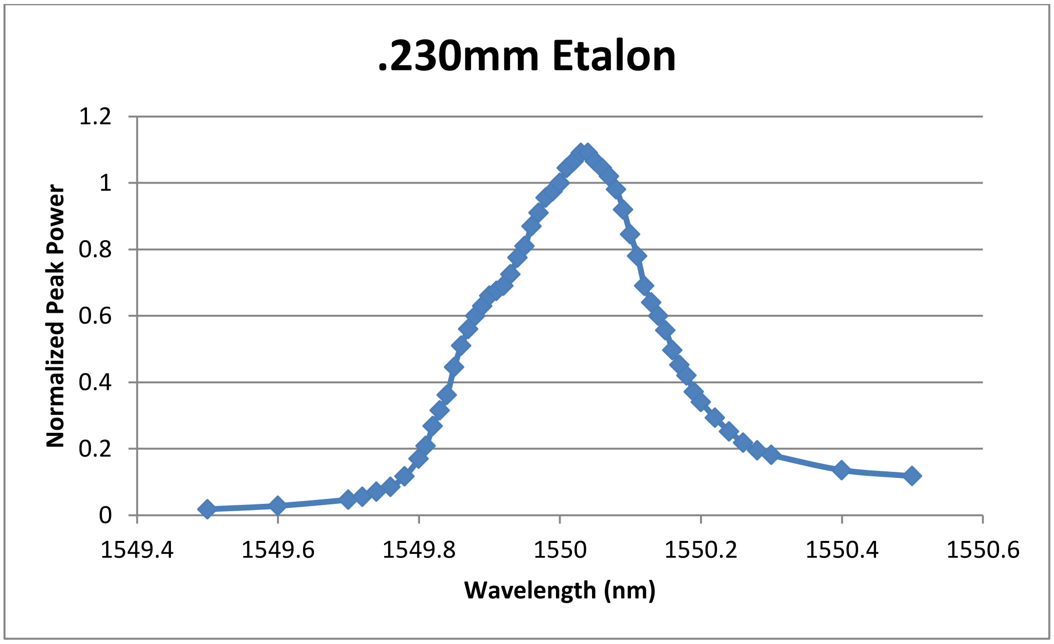

Figure 7.3: Transmission Measurements for .230mm Etalon Transmission Peak

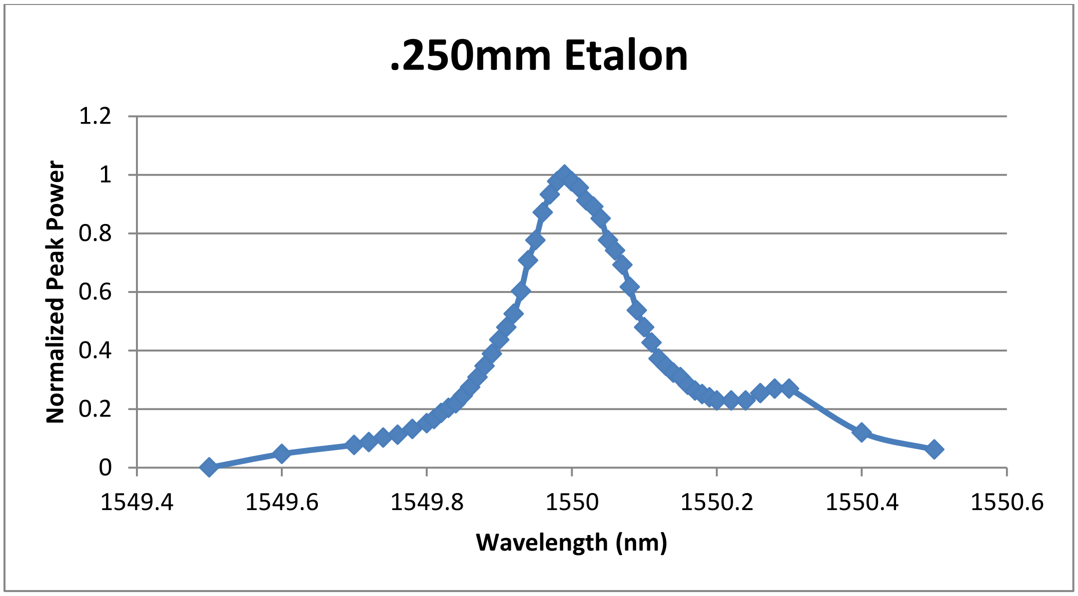

Figure 7.4: Transmission Measurements for .250mm Etalon Transmission Peak

These measured values for bandwidth are significantly different than what is expected for etalons with the specified parameters. The expected bandwidth for an etalon with .230mm thickness and 94% reflectances is 0.071nm. The measured value of about .25nm is over 3 times the expected bandwidth. The expected bandwidth for an etalon with .250mm thickness and 94% reflectances is 0.065nm. The measured value of about .18nm is again nearly 3 times the expected bandwidth. The large discrepancy in bandwidth will have very negative implications on the adjacent line overlap. It is anticipated with these etalons that the dual etalon system will have side bands on either side of the desired transmission peaks.

7.3 *Dual Etalon Measurements:*

To examine the system performance through both etalons, a broadband source was put into the system and the resulting transmission profiles were observed on an OSA. Figure 7.5 shows the transmission profile zoomed in on a single peak. Side bands can be clearly seen in this image, which were measured to be 3.19nm on either side of the main peak. This makes sense, as that is the lesser of the two individual etalon measured free spectral ranges. The bandwidth of the main peak is measured to be 0.19nm. Again, this makes sense as it is the lesser of the two individual etalon measured bandwidths. As shown in Figure 7.6, the span on the OSA can be adjusted to view the harmonic free spectral range of the system. The wavelengths corresponding to each transmission peak were used to measure the HFSR of 39.4nm. These values are summarized in Table 7.3.

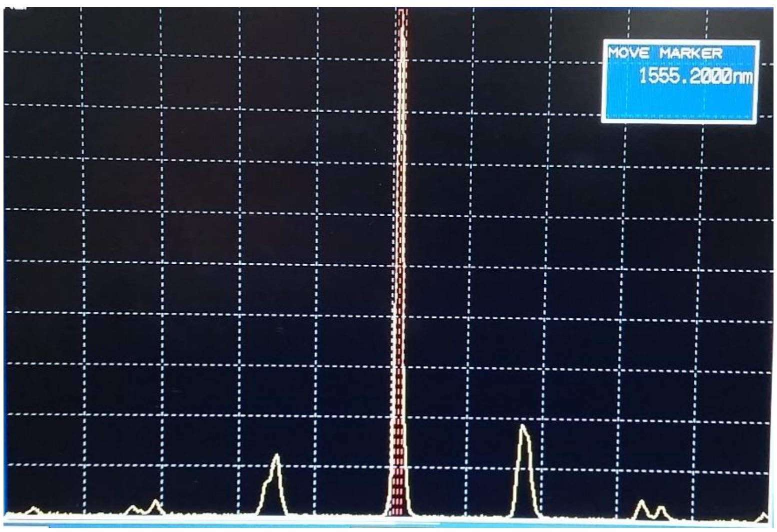

Figure 7.5: Dual Etalon Transmission Profile on OSA Zoomed in on a Single Peak

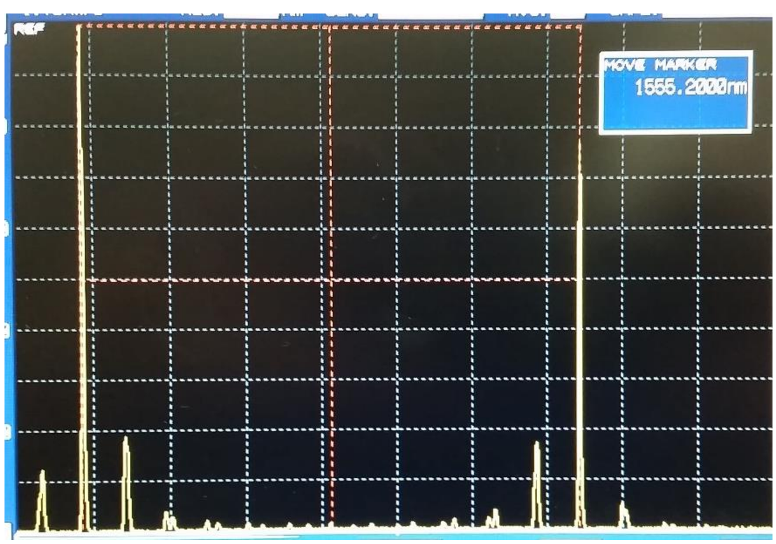

Figure 7.6: Dual Etalon Transmission Profile on OSA Spanning Two Harmonic Free Spectral Ranges

Dual Etalon Effective Design Feature	Value
Harmonic Free Spectral Range, HFSR	39.4nm
Bandwidth	.19nm

Table 7.3: Dual Etalon Measured Design Features

7.4 *Transmission Loss:*

The transmission of the etalons was baselined by first looking at how much light could be detected from light that was collimated into free space, coupled back into fiber, and observed on the OSA. The power at the comb pattern peak was used to quantify transmission loss. This process was performed using both the broadband source and narrow-linewidth source.

Method	.230mm Etalon Transmission (%)	.250mm Etalon Transmission (%)	Both Etalons Transmission (%)
Broadband Source	17.8	10.9	4.3
Narrow-Linewidth Source	21.3	9.2	N/A

Table 7.4: Transmission Measurements

The measured transmissions of the .230mm and .250mm etalons were approximately 20% and 10%, respectively. Ideal etalons would have 100% transmission at the peaks. With the broadband source, the maximum transmission measured through both etalons was about 4%. This is greater than the 2% that would be expected from multiplying the transmissions of the two individual etalons.

7.5 *Explanation:*

The lab measurements are compared to theoretical values based on ideal etalons. Real etalons have limiting factors that reduce the actual transmission and finesse (thus increasing bandwidth), such as surface figure, wedge, spherical error, scatter, and material losses. Surface figure is a root mean square measurement of the surface's deviation from true flatness. Wedge, or tilt, is the deviation from parallel of the two reflecting surfaces, which causes a variation of optical path length and emitted phase across the cross-section of the etalon. Similarly, spherical error causes a variation in phase over the curvature of the etalon. Imperfections in the etalon medium may cause light to scatter or absorb, thus reducing the light transmission.

The etalons purchased for this experiment specified thickness and surface reflectances. The truly desired design features, free spectral range, bandwidth, and finesse, should have been specified instead. By not specifying required finesse and transmission, this allowed for uninspected performance-limiting imperfections.

One possible laboratory solution to increase the finesse is to decrease the spot size incident on the etalons. By having the light incident on a smaller area, there is a higher likelihood of the surface figure being more uniform, resulting in a cleaner interference pattern. There are two ways to achieve a smaller spot. One method is to use an aperture to stop down the beam diameter. The disadvantage to this is that it cuts out some of the power in the beam. Reducing transmission losses is critical for the detection system of this project, so this is not a desired solution. The other solution is to use different fiber couplers that produce a smaller beam diameter. The trade-off with this approach is that it increases the divergence of the beam, which, as shown earlier, also reduces the finesse. A balance may be found between the two sources of finesse reduction, which is an investigation that may be performed outside of the scope of this project.

7.6 *Implications on Modeled Effective System:*

Using the measured free spectral range and bandwidth, the effective finesses of these etalons are about 13 and 17, respectively. These are both significantly less than the expected finesses, both of which should be about 50. To model the new expected results based off of these measured values, effective etalon parameters will be used. To simulate the measured free spectral range and bandwidth, the effective parameters for the two etalons are shown in Table 5.2.

Effective Parameter	Etalon 1	Etalon 2
Effective Thickness (mm)	.238	.260
Effective Finesse	13	17
Effective Surface Reflectances	79%	83%

Table 7.5: Effective Parameters

Using these effective parameters in the model produces the system design features shown in Table 7.6 and the expected effective dual etalon system performance plotted in Figure 4.2 and Figure 4.3. The marginally changed effective etalon thicknesses cause a slightly reduced modeled harmonic free spectral range. It now dips just below the desired design guideline of 40nm, but only by about 5%. It is interesting to note that although the modeled and measured HFSRs are very similar, the modeled one is just less than the measured value. The significantly reduced effective surface reflectances yield a greatly reduced adjacent line overlap factor. As can be seen, this produces unwanted power in the transmission peaks on either side of the desired peak. Because the detection scheme for this project is looking for a single transmission peak from a broadband source, this may cause inaccurate results.

Dual Etalon Effective Design Feature	Value
Harmonic Free Spectral Range, HFSR	37.8nm ≈ 4717.4GHz
Adjacent Line Overlap Factor, ALOF	1.12

Table 7.6: Modeled Dual Etalon System Effective Design Features

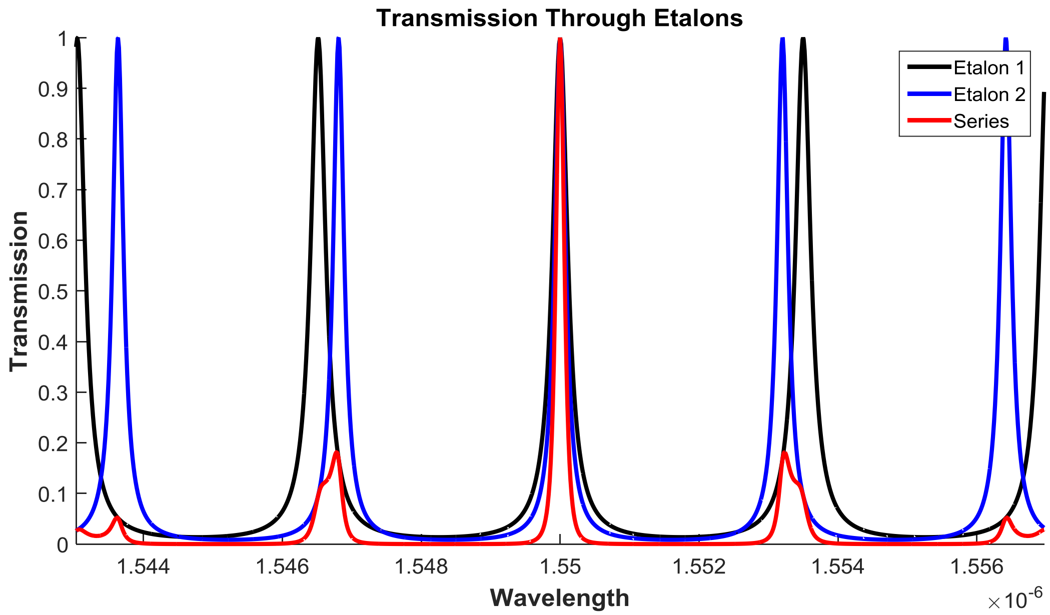

Figure 7.7: Individual Etalon Transmissions and Resulting Dual Etalon System Transmission Modeled using Effective Etalon Parameters

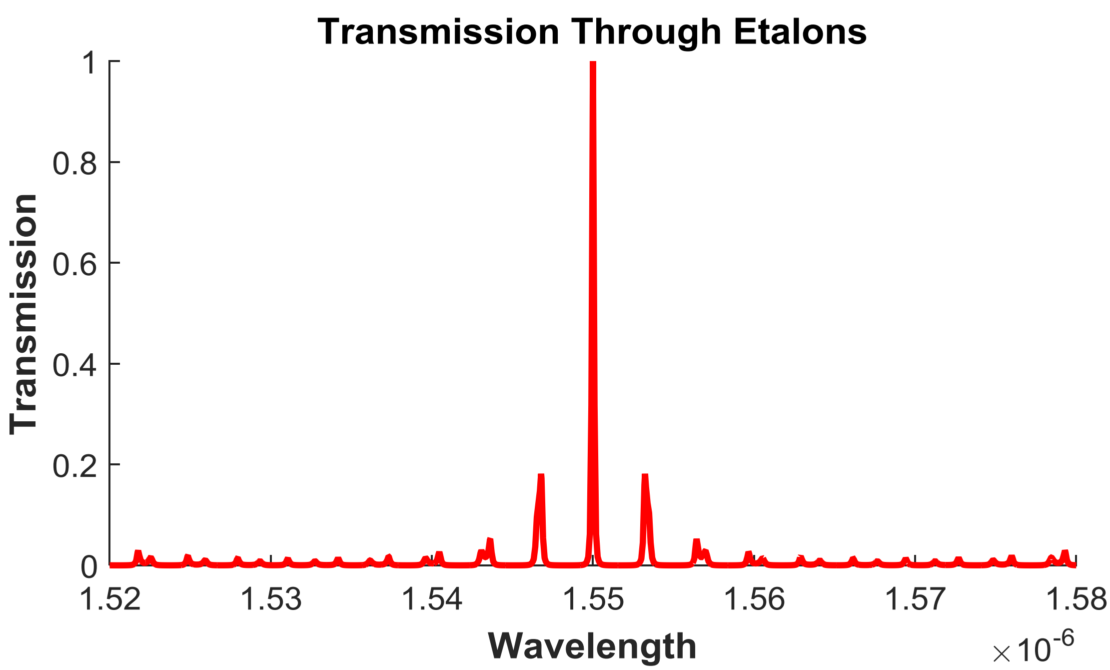

Figure 7.8: Dual Etalon System Transmission Modeled using Effective Etalon Parameters

Broadband light was put through the series of etalons and detected on the OSA, as shown in Figure 7.9. This profile matches very closely to the modeled effective system in Figure 4.3.

During testing, the etalons were rotated to observe the behavior on the OSA. When a single etalon was rotated, the transmission jumped from the current peak to the adjacent peak. When the two etalons were rotated equally together, the entire pattern shifted laterally, slowly moving the peak of the transmission along wavelength.   Both of these behaviors are as expected, and lend themselves to successful control operation.

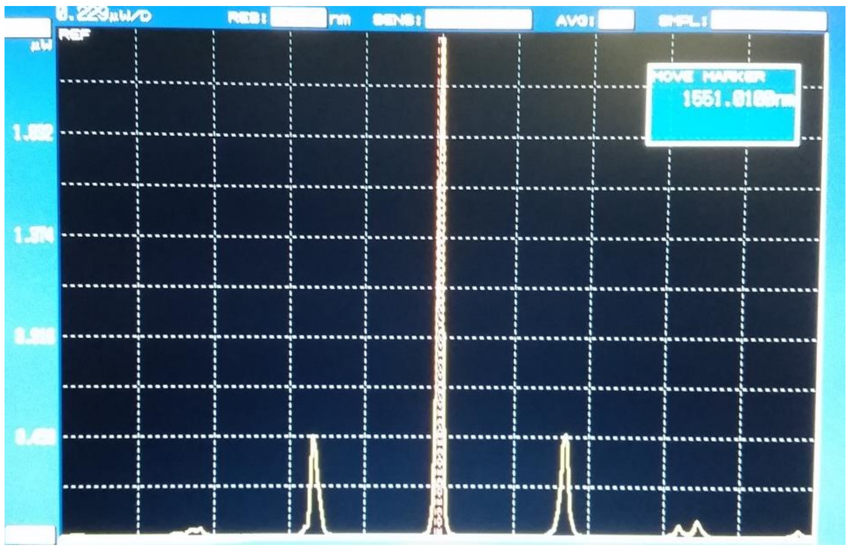

Figure 7.9: Dual Etalon System Observed Transmission

New sensitivities for the effective system can also be calculated to give a better understanding of the wavelength and angle accuracies necessary for the provided etalons. Updated plots of wavelength sensitivity and angle sensitivity are shown in Figure 5.6 and Figure 5.7. To maintain transmission of about 90% of the max, the wavelength accuracy must be about .025nm and the angle accuracy must be about 28 arcminutes. These sensitivities are about 3 times and 2 times the designed system, respectively. The effective bandwidth (full width at half max) of the signal through the series of etalons is about .14nm, which is about 3 times the designed system.

Transmission Percentage	Wavelength Offset (nm)	Angle Offset (arcmin)
1	0	0
0.98	0.01086	18.58296
0.95	0.01746	23.5626
0.9	0.02532	28.3749
0.75	0.0429	36.93474
0.5	0.07056	47.36874
0.25	0.11025	59.21208
0.1	0.16314	72.03

Table 7.7: Effective System Transmission vs. Wavelength Offset and Corresponding Angle Offset

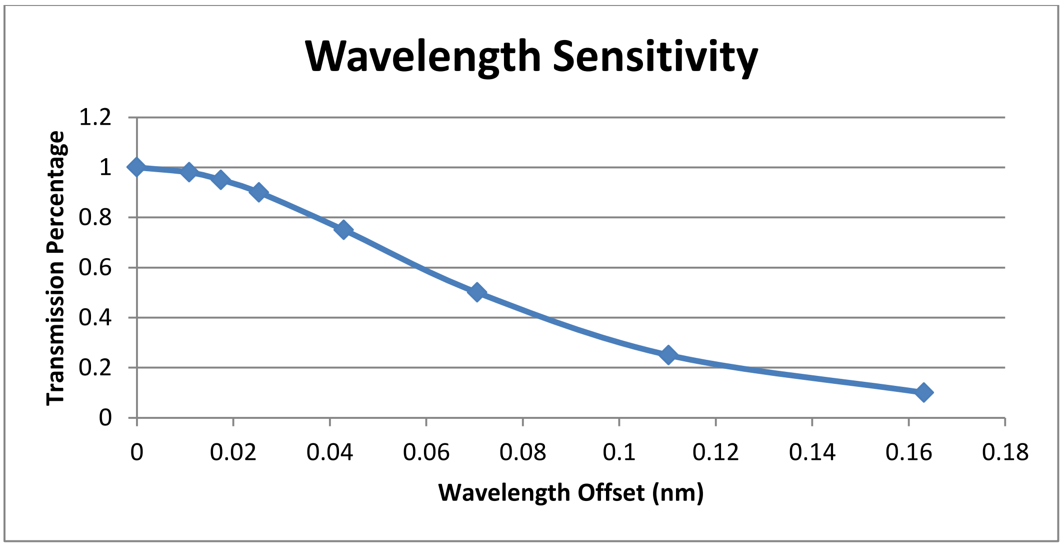

Figure 7.10: Wavelength Sensitivity Modeled using Effective Etalon Parameters

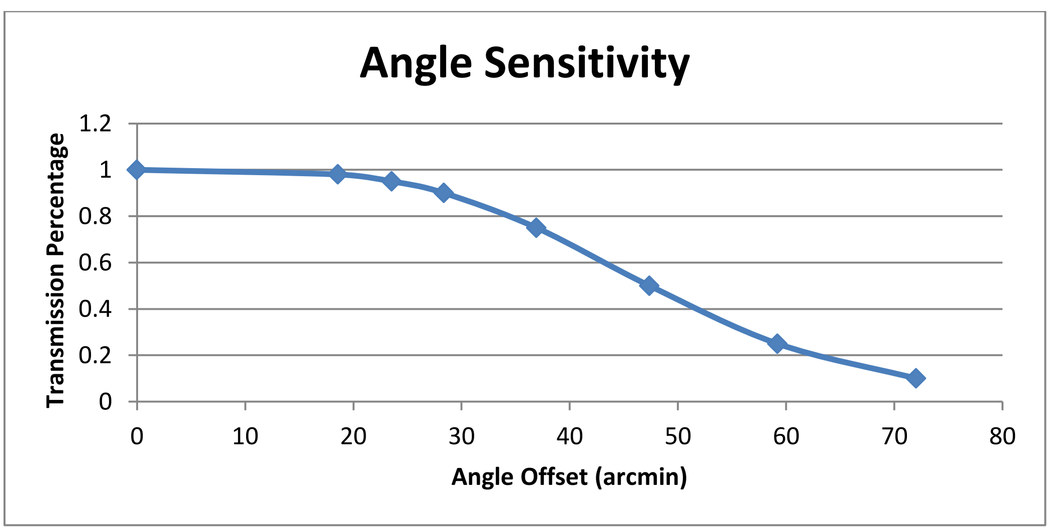

Figure 7.11: Angle Sensitivity Modeled using Effective Etalon Parameters

8. Link Budget

8.1 *Detectable Power Range:*

The theory of this system is continuous, but the application in order to detect and provide feedback is discrete. The detectors sense optical power and provide an analog signal via an adapter to an analog-to-digital converter (ADC), which discretizes the signal. The detectors perceive input optical power and produce an output analog current correlating to the sensor's spectral responsivity. In the target wavelength range of 1530-1570nm, the responsivity is approximately flat at 1.04 A/W.

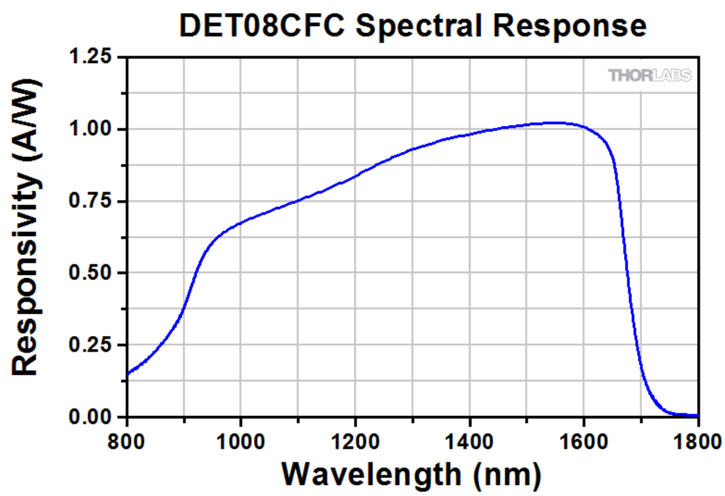

Figure 8.1: Detector Responsivity

The detectors produce a current (I), but the ADC responds to voltage (V), so an adapter must convert current to voltage via a resistor (R) using Ohm's Law. A 1kΩ resistor is used in this adapter.

The SerIO ADC is 10 bit and has a maximum input voltage of 3.3V, so it can divide the analog signal into 1024 individual bins with resolution of about 3.2mV/bin.

Stringing these values together simplifies the detection system to a simple relation of incident optical power to digital readout of 3.1μW/bin. If the full 1024 bins are used, this allows a detectable power range of 3.17mW.

$$\left(\frac{1}{1.04}\frac{\mathrm{W}}{\mathrm{A}}\right)\left(\frac{1}{1000}\frac{\mathrm{A}}{\mathrm{V}}\right)\left(\frac{3.3V}{1024\,bins}\right)=\sim\frac{3.1\mu W}{bin}$$

The Linear Transmission Filter (LTF) has a detection attenuation of about .06mW/nm. Over the full 40nm operation range, the power range is 2.4mW. This is approximately 76% of the 3.17mW available range, which equates to using about 775 of the 1024 bins. Factoring the LTF into the link budget translates to a detectable wavelength resolution of about .05nm. The model for the designed system predicted a 90% transmission wavelength resolution of .008nm. The model of the effective system for the measured etalon parameters predicts a 90% transmission wavelength resolution of .025nm. This implies that the detectable wavelength resolution is not sufficient for 90% transmission accuracy. The way to improve detectable resolution below .05nm would be to use an ADC with more than 10 bits, allowing for more than 1024 bins.

$$\left(\frac{1}{.06}\frac{nm}{mW}\right)\left(\frac{1000mW}{W}\right)\left(\frac{1}{1.04}\frac{\mathrm{W}}{\mathrm{A}}\right)\left(\frac{1}{1000}\frac{\mathrm{A}}{\mathrm{V}}\right)\left(\frac{3.3V}{1024\,bins}\right)=\frac{.0516nm}{bin}$$

Having the LTF power range match the detectable power range well allows for better resolution, but it tightens the sensitivity on input power. The power incident on the detectors for 1070nm light must be between 2.4mW and 3.17mW to detect wavelength variations over the entire range.

8.2 *Transmission Losses:*

An ideal system would have no transmission losses throughout the system. A zero transmission loss system, however, is not an expected reality. Minor losses occur at fiber connections and through fiber components, such as at splitters and filters. Major sources of loss are from free space collimation and coupling, and transmission through the etalons. These all need to be factored in to predict the performance of the system.

The linear transmission filter has a variable transmission loss over the wavelength range. The maximum transmission will be at the top of its range at 1570nm. At 1570nm the transmission through the LTF is measured to be about 70%.

The 50/50 splitter divides the incident light equally among its two outputs, but there is still loss in the device. The transmission through each leg of the splitter is measured to be about 40% of the incident light.

The process of collimating light from a fiber into free space, then re-coupling the light into fiber comes with a great deal of loss and is heavily dependent on fine alignment of the system. With this setup, the best alignment achieved a transmission of about 25%.

In free space, the light passes through the two etalons. As stated earlier, a theoretical ideal etalon will have no transmission loss at its peaks. However, the etalons used in this setup are measured to be well less than ideal. Individually, the etalons measured transmissions of about 20% and 10%. Mathematically, this translates to a series transmission of 2%. However, the transmission of the etalons in series was measured to be about 4%, which is twice as much as expected. To be conservative, the individual transmissions will be factored into the link budget.

Using the train of transmission percentages as outlined in Figure 3.8, detector 1 will receive 1.4% of the light that is input to the system through the collimator. To achieve this power level, an optical amplifier is inserted into the system after the bandpass filter. Conservatively, about 1.7 W is required into the collimator to get 2.4mW of 1070nm light to detector 1 and allow the system to detect wavelength variations over the entire 40nm range.

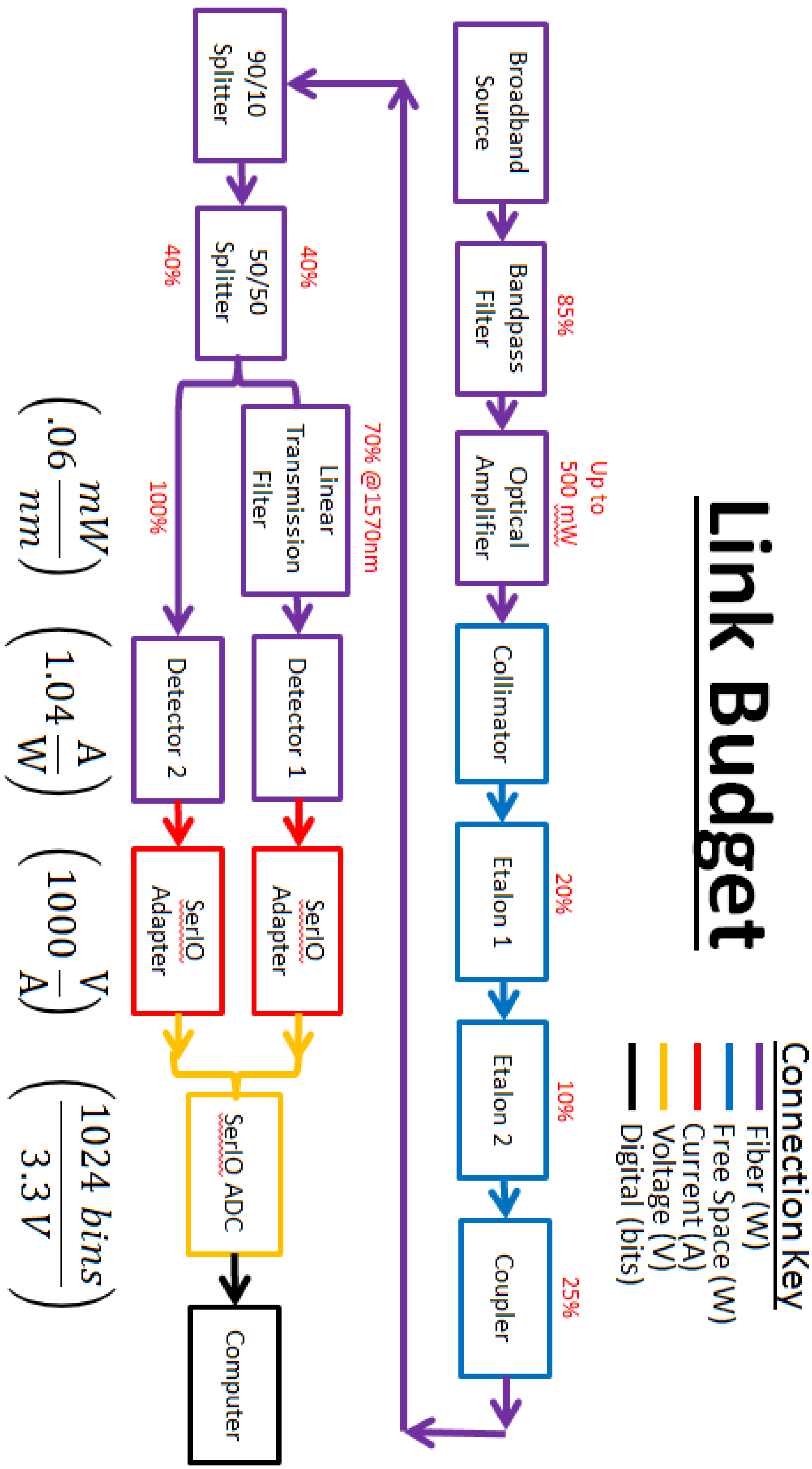

Figure 8.2: System Link Budget with Transmission Percentages

8.3 *Rotation Stage Selection:*

The model for the designed system predicted a 90% transmission angle resolution of 15 arcminutes. The model of the effective system for the measured etalon parameters predicts a 90% transmission angle resolution of 28 arcminutes. The rotation stage specifications provided in Figure 8.3 show a resolution of 2.16 arcseconds and repeatability of <1 arcminute. These specifications are more than sufficient to meet the required angle resolution.

Specification	Value
Travel</td>	Continuous 360°
Max Load (Horizontal)	25 lbs (11.3 kg)
Maximum Torque in Vertical Configuration	6.25 lbF-in.
Gear Type	Back Lash Reduction Worm Gear
Motor Type	DC Servo
Motor Drive Voltage	12 V
Max. Recommended Current	80 mA
Backlash	<1 arcmin
Calculated Resolution	2.16 arcsec
Wobble	<2 arcsec
Repeatability	<1 arcmin
Feedback	Hall Effect Encoder
Encoder Counts per Revolution of the Leadscrew	12,288
Planetary Gearhead Ratio	256:1
Speed Range	0.006 to 4.8 °/sec
Index Signal	None
Cable Length	9.0' (2.743 m)
Compatible Controllers	TDC001

Figure 8.3: Rotation Stage Specifications

9. Control System

The goal of this project is to have a GUI-operated system with motorized control and active feedback. To initiate the measurements, however, a calibration process is necessary to baseline the detection system linear transmission filter slope and link budget conversion. The steps involved in this calibration process are outlined in the pseudo code below. After calibration, the wavelength detection system will be able to accurately test and report the wavelength incident on the detectors. Screenshots of the GUI for this process are shown in Figure 9.1 and Figure 9.2.

Detection System Calibration: (Not through etalons)

1. Input narrow-linewidth source at wavelength 1. Detect ADC values from Detector 1 (D1) through the linear transmission filter (LTF), and Detector 2 (D2) direct from the splitter. Calculate detection ratio.
2. Input narrow-linewidth source at wavelength 2 far from wavelength 1. Calculate detection ratio.
3. Calculate the line equation slope (m) and intercept (b) of the LTF from wavelength 1, wavelength 2, detection ratio 1, and detection ratio 2.

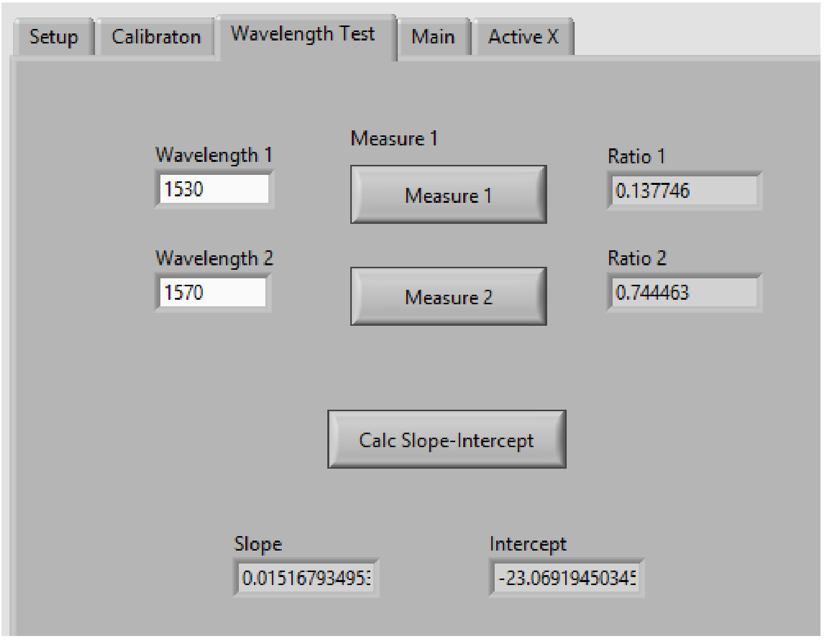

Figure 9.1: Linear Transmission Filter Line Equation Calibration GUI

Figure 9.2: Wavelength Test GUI

The system has two modes of operation that require slightly different feedback control processes. In either case, the system will need to be calibrated with a "center wavelength" test using broadband light for the etalons' initial positions. The user may input the desired wavelength into the GUI, and the program will calculate the necessary angle rotations to shift from the "center wavelength" to the "desired wavelength." When the etalons have rotated, the wavelength detection system will test the transmitted signal.

The detection correction system is what differs for the two modes of operation. With broadband light through the system, there should always be a transmitted peak, it just may not be correct. The feedback system here is to adjust the etalon angles in the direction of the desired wavelength until it is achieved. With narrow-linewidth light, the input wavelength may be offset from the dual etalon transmission peak, in which case no light is transmitted and detected. In this case, the feedback system has to blindly adjust forward and backward to see if the desired wavelength is found. The steps involved in the two modes of operation processes are outlined in the pseudo code below. Additionally, the calculations necessary to determine the angle changes to tune to the desired wavelength are provided in the Math Block.

System Mode of Operation 1: (Through etalons)

1. **(Calibration)** Input broadband source through the etalons at normal incidence. Detect wavelength of the transmitted peak. Define this wavelength as "Center Wavelength," which will be an input to the math block.
2. Input "Desired Wavelength" into program, which will be an input to the math block.
3. Use center wavelength and desired wavelength as inputs to the math block to calculate "delta angle 1" and "delta angle 2" to transmit desired wavelength.
4. Move motors by delta angle 1 and delta angle 2 to the approximate desired wavelength location.
5. Detect the "observed wavelength." The observed wavelength should be within a free spectral range of the desired wavelength. If the observed wavelength is within tolerance of the desired wavelength, operation is complete.
6. If the observed wavelength is outside the tolerance of the desired wavelength, more angle movement is necessary, but it should be minimal. Incrementally move the etalons equally in the direction of the desired wavelength and detect the observed wavelength until it is within tolerance. When the observed wavelength is within tolerance of the desired wavelength, operation is complete.
    a. Alternatively, use the observed wavelength as the new center wavelength and re-calculate the necessary delta angles to reach the desired wavelength.

System Mode of Operation 2: (Through etalons)

1. **(Calibration)** Input broadband source through the etalons at normal incidence. Detect wavelength of the transmitted peak. Define this wavelength as "Center Wavelength," which will be an input to the math block.

2. Input known, narrow-linewidth wavelength through etalons. Define known wavelength as "Desired Wavelength" into program, which will be an input to the math block.
3. Use center wavelength and desired wavelength as inputs to the math block to calculate "delta angle 1" and "delta angle 2" to transmit desired wavelength.
4. Move motors by delta angle 1 and delta angle 2 to the approximate desired wavelength location.
5. Detect if there is an "observed wavelength." If there is an observed wavelength detected, it is the desired wavelength and operation is complete.
6. If there is no observed wavelength, then the transmitting wavelength is outside of the desired wavelength. More angle movement is necessary, but it should be minimal. Incrementally move the etalons equally in one direction and detect if there is an observed wavelength. If there is an observed wavelength detected, it is the desired wavelength and operation is complete.
7. When a finite angle limit is reached and there is no observed wavelength, incrementally move the etalons equally in the opposite direction and detect if there is an observed wavelength. If there is an observed wavelength detected, it is the desired wavelength and operation is complete.
8. When a finite angle limit is reached and there is no observed wavelength, operation has failed.

Math Block:

Inputs:
λ_D = Desired Wavelength
λ_0 = Center Wavelength (Detected)

Constants:
n = 1.444
t_1 = 0.230mm, Etalon thickness 1
t_2 = 0.250mm, Etalon thickness 2

Math: (Make sure units match. Put all in meters)

Free Spectral Range 1: $\Delta\lambda_1 = \frac{\lambda_D^2}{2\,n\,t_1 + \lambda_D}$

Free Spectral Range 2: $\Delta\lambda_2 = \frac{\lambda_D^2}{2\,n\,t_2 + \lambda_D}$

Wavelength Shift: $\lambda_{shift} = \lambda_D - \lambda_0$

Modulus Wavelength Shift 1: $\lambda_{shiftMOD1} = mod(\lambda_{shift}, \Delta\lambda_1)$

Etalon Rotation Angle 1: $\Delta\theta_1 = \sin^{-1}(n \sin(\cos^{-1}(\frac{\lambda_0}{\lambda_0 - \lambda_{shiftMOD1}})))$

Modulus Wavelength Shift 2: $\lambda_{shiftMOD2} = mod(\lambda_{shift}, \Delta\lambda_2)$

Etalon Rotation Angle 2: $\Delta\theta_2 = \sin^{-1}(n \sin(\cos^{-1}(\frac{\lambda_0}{\lambda_0 - \lambda_{shiftMOD2}})))$

Outputs:
$\Delta\theta_1$= delta angle 1
$\Delta\theta_2$= delta angle 2

10. Conclusion

A method of modeling the performance of a dual etalon angle-tunable filtering system was successfully generated. By entering a few basic etalon parameters, the corresponding design features are produced and the expected transmission pattern is plotted.

For the given set of system constraints, a corresponding dual etalon tunable filter was successfully constructed in a lab environment. The etalon parameters were measured to get a complete understanding of operation conditions. An effective system was considered from measured parameters, and modeled to predict the dual-etalon performance. Lab measurements successfully confirmed the expected filtering performance of the system.

The development of a complete feedback control for the tunable dual etalon filter was unsuccessful, but is certainly believed to be realizable with some next steps. The operation of the wavelength discerning detection system utilizing a linear transmission filter was successfully validated in lab use. However, the inhibiting factor to complete success was the power loss from generation to detection, as outlined in the link budget. If more optical power were able to be attained on the detectors, the feedback control would have a reading to correct. One attempted solution to this issue was to use an electrical pre-amplifier between the SerIO adapters and the SerIO ADC. Unfortunately, the device amplified the noise of the system too much causing inconsistent digital readings and inaccurate wavelength identification. There are a number of other paths forward to improve this power limitation. One option is to increase the power injected into the transmission system. This could be achieved with a higher output power optical amplifier. Another possibility is to reduce the losses in transmission. This would involve obtaining higher quality etalons with stricter specifications. A third route is to obtain detectors that are more sensitive at lower power levels without introducing more noise.

Independent of the power limitation, there are other means of improving the success of this system. The primary enhancement would be the quality of the etalons. Only the reflection of the ordered etalons was specified, but not the finesse or transmission. This allowed for imperfections in the etalon, such as wedge or surface figure, which caused decreased performance. An additional improvement could be made by increasing the resolution of the ADC. The utilized ADC only had 1024 bits. If a higher bit ADC were used, the wavelength detection resolution would be vastly improved.

Overall, the demonstration of the dual etalon tunable filter was successful, and through execution of the outlined path forward to finalize an operational feedback control system, a complete system is realizable.

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