NEW FOCUS

Application Note 13

Swept Wavelength Testing:

Characterizing the Tuning Linearity of Tunable Laser Sources

In a swept-wavelength measurement system, the wavelength of a tunable laser source (TLS) is swept continuously at a constant rate throughout the desired tuning range, while the device under test (DUT) is monitored simultaneously for its wavelength-dependent optical properties. Given an ideal continuously tunable laser – one that does not exhibit any discontinuities in wavelength, or sudden changes in direction – you can calculate the instantaneous wavelength and relate each wavelength point to data from the DUT. Because the wavelength is computed by using the sweep speed and elapsed time from the beginning of the sweep, the measured tuning linearity of the laser has a direct impact on the wavelength accuracy.

In this application note, we will first define the tuning linearity, then discuss how to measure the tuning linearity of a TLS, and finally show measured results.

For more information of the swept wavelength technique, please refer to New Focus Application Notes 10 & 11:

> *Application Note 10: Swept Wavelength Testing: Saving Time and Bring Real-Time Process Control to the Manufacturing Environment.*
> *Application Note 11: Swept Wavelength Testing: Insights into Swept-Wavelength Characterization of Passive Fiber-Optic Components.*

Definition of Tuning Linearity

In general, there are two means of expressing spectral-domain information. One is the wavelength, λ, often expressed in [nm] or [µm], and the other is the frequency, ν, commonly denoted in [THz] or [GHz]. The relation between wavelength and frequency is $\lambda = \frac{c}{\nu}$, where c is the speed of light. The principles of tuning linearity described in this application note can be applied to both the wavelength and frequency of the TLS.

The tuning linearity of continuously tunable lasers is a parameter that specifies the error in the tuning speed. It can be defined in two ways: 1) as a function of tuning-speed deviation [nm/s], and 2) as a function of wavelength deviation [pm].

The ***momentary tuning speed deviation (ΔV)*** from the average tuning speed can be expressed as: $\Delta V = V_n - V_{mean}$. The mean or average tuning speed, V_{mean}, is given by: $V_{mean} = \frac{\lambda_{stop} - \lambda_{start}}{t_{stop} - t_{start}}$, and the momentary tuning speed, V_n, is given by: $V_n = \frac{\lambda_n - \lambda_{n-1}}{t_n - t_{n-1}}$, where λ_n - λ_{n-1} represents the local wavelength interval, and t_n - t_{n-1} is the time interval between these two measured points. The tuning linearity error is therefore expressed in percentage as: $\frac{V_n - V_{mean}}{V_{mean}} \times 100\%$.

The tuning speed can also be expressed as a function of optical frequency. In this case, the wavelength λ is exchanged for the frequency ν of the TLS. It is important to note that the tuning linearity in terms of wavelength is not linearly related to the tuning linearity in terms of frequency, because of their inverse relationship: $\lambda = \frac{c}{\nu}$.

Another way to express tuning linearity is as a function of the ***momentary wavelength deviation (Δλ)*** from the expected momentary wavelength, which is derived from the average tuning speed, V_{mean}. The momentary wavelength can be determined by integrating the tuning speed as follows: $\lambda_n = \int V \, \partial t + \lambda_{start}$. Thus, the momentary wavelength deviation is defined as $\Delta\lambda_n = \lambda_n - (t_n - t_0) \times V_{mean}$.

Characterization of the Tuning Linearity

There are two distinct approaches for characterizing the tuning linearity. The first one, the ***etalon method***, is based on time intervals between the peaks of transmitted light from an etalon. This method characterizes the full tuning range, but the resolution depends on the etalon and the interval counter.

The second method, the ***heterodyne method***, is based on heterodyning the tunable laser with another non-tuning (constant-wavelength) laser. The heterodyne technique has the advantage of providing high-resolution measurements, but is limited to only a few GHz tuning range due to the bandwidth limitation of the particular detector used. (Note: a 1-GHz range in laser frequency is equivalent to approximately 8pm in wavelength, if the wavelength is around 1550nm).

Since the results derived from the heterodyne method are limited to a relatively small range of wavelengths — compared to the entire tuning range of the TLS — it is easy to misinterpret the data when it is compared to the data from the etalon method, which covers the full tuning range of TLS. Further information on the heterodyne technique is provided in Appendix A.1.

The Etalon Method

An etalon is a Fabry-Perot interferometer (also known as Fabry-Perot filter), wherein two highly reflective mirrors are placed parallel to each other with a separation L, as shown in Figure 1.

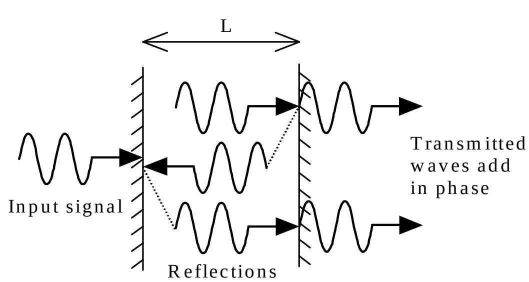


Figure 1. A Fabry-Perot etalon.

The input light beam enters the etalon's first mirror at right angles to its surface. The etalon's output is that part of the beam transmitted through the second mirror. The transmission function of the etalon can be expressed as: $T_{FP}(\nu)=\dfrac{\left(1-\dfrac{A}{1-R}\right)^2}{\left\{1+\left[\dfrac{2\sqrt{R}}{1-R}\sin\left(\dfrac{2n\pi L\nu}{c}\right)\right]^2\right\}}$, where A denotes the absorption loss of each mirror, R denotes the reflectivity of each mirror, and n denotes the refractive index of the material between mirrors. The transmission is shown in Figure 2 as a function of laser frequency ν for various values of R. The transmission function is periodic with respect to laser's frequency (Note: it is not periodic with respect to wavelength), and has an optical frequency interval called Free Spectral Range (FSR), given by: $FSR=\dfrac{c}{2nL}$, expressed in [Hz].

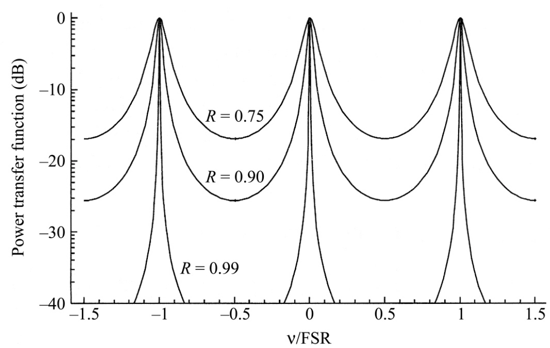


Figure 2. The transmission function of an etalon with *A* = 0 and *n* = 1.

Using the swept-wavelength method, and scanning the laser's wavelength while measuring the transmission output of the etalon, you can measure a time interval corresponding to one FSR of the etalon. Using this time-interval measurement, you can further determine momentary tuning speed in [nm/s] of the laser, simply by converting the known frequency interval to a wavelength interval and then dividing it by the measured time-interval.

A block diagram of a typical tuning linearity measurement using an etalon is shown in Figure 3. The principle is to monitor a periodic signal generated from an etalon by scanning the wavelength (or frequency) of a TLS. In our example, we use a New Focus Model 6528-LN tunable laser, that has an output power of 1 dBm, and scans from 1520 to 1620nm. The etalon can be either a fiber patch cord with flat, PC connectors on each end, or a Mach-Zehnder (MZ) or Michaelson interferometer with Faraday Rotator Mirrors (FRM). Appendix A.2 provides more information on Mach-Zehnder and Michaelson interferometers.

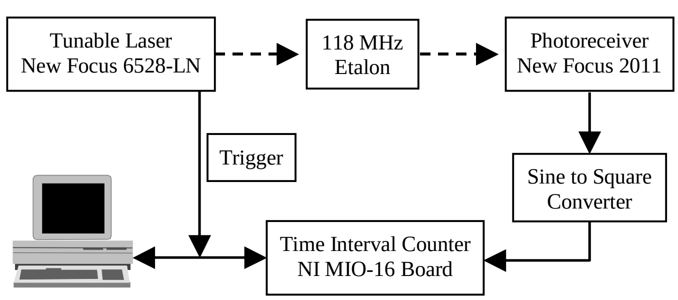


Figure 3. Block diagram for tuning linearity measurement using an etalon.

When the laser light is transmitted though the etalon, the measured optical throughput is periodic with a period corresponding to the FSR of etalon. In this case, the FSR of the etalon is 118 MHz (or 0.94 pm). The FSR of the etalon is constant over the entire tuning range. A New Focus Model 2011 photoreceiver detects this periodic transmission function as the laser is tuned. The electrical sine-to-square converter transforms the sinusoidal signal into a 5V clock signal. The time interval for each FSR of the etalon is collected by a time interval counter, such as a National Instruments MIO-16 board, or by digitizing the data and then analyzing the etalon signal. Figure 4 shows the etalon signal, measured by the photoreceiver, and the squared, clock signal, which drives the time interval counter. The data was taken at both 100nm/s and 1nm/s tuning speeds, shown in the top and bottom plots, respectively.

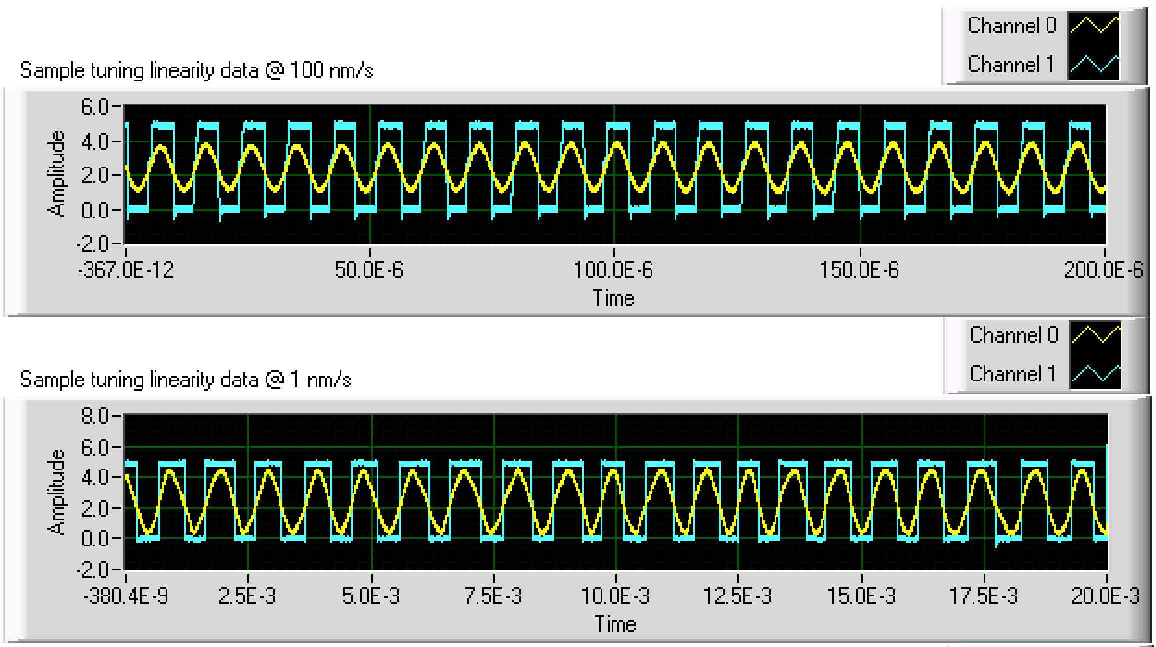


Figure 4. Etalon tuning examples with a New Focus Model 6528-LN tunable laser. These graphs represent the etalon signal and the squared, "clock" signal that drives the time interval counter.

Figure 5 shows four graphs associated with the tuning linearity of the New Focus Model 6528-LN tunable laser. The data is transformed through calculations of both tuning speed and wavelength deviation for their corresponding horizontal and vertical axes. The top two graphs were taken at 100 nm/s tuning speed whereas the bottom two graphs were taken at 1 nm/s tuning speed. The 1st and the 3rd graphs present the momentary tuning speed (V_n). The 2nd and the 4th graphs show the momentary wavelength deviation ($\Delta\lambda$) from the wavelength, as derived from the mean speed.

The tuning linearity for the 100 nm/s tuning speed case (derived from its tuning speed deviation, in graphs 1 and 3 below) is about $\frac{\pm 2}{100} \approx 2\%$, whereas it appears to be around $\frac{\pm 0.3125}{1.0625} \approx 29.4\%$ for the 1 nm/s tuning speed case. Note that the tuning speed (comparing the 1 nm/s and 100 nm/s cases) affects the *tuning-speed deviation* (or tuning speed error), however, the tuning speed seems *not* to significantly affect the *wavelength deviation*.

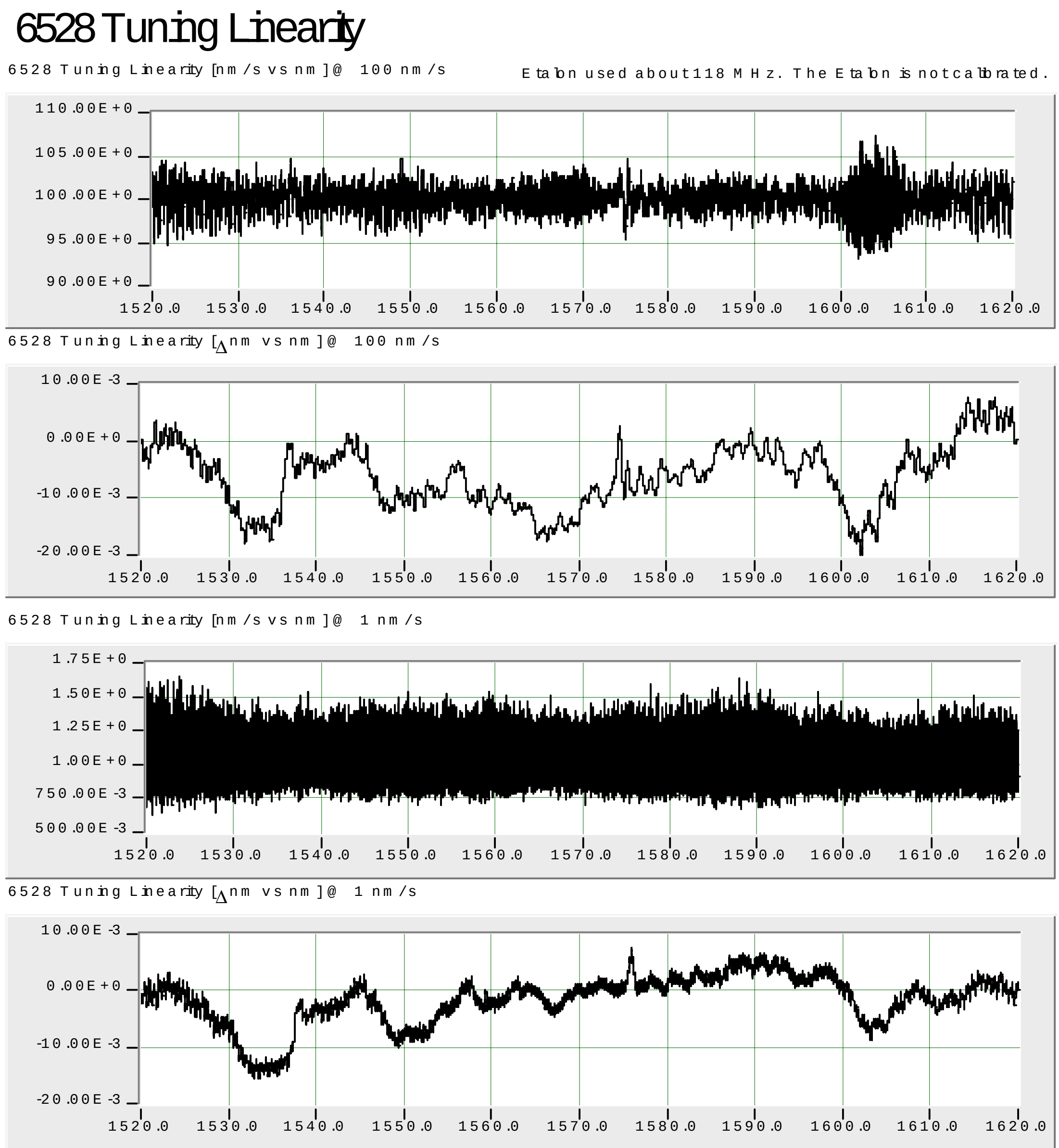


Figure 5. Tuning linearity of the New Focus Model 6528-LN tunable laser. The momentary tuning speed (V_n) is shown in graphs 1 and 3, and the momentary wavelength deviation ($\Delta\lambda$) is shown in graphs 2 and 4.

Tuning Linearity Error and FSR

Figure 6 shows the tuning linearity of the New Focus Model 6528-LN TLS at 100 nm/s, as a function of the FSR of the etalon. In general, momentary tuning speed variations are averaged over the duration (or width) of one FSR. A large FSR (in frequency) may result in too few data points with respect to the tuning speed. This tends to average (or "smooth out") the momentary tuning speed deviations. A small FSR (in frequency) might produce variations caused by fast fluctuations in the natural linewidth of the TLS, which is not related to the tuning linearity. It is suggested that the FSR of an etalon be just adequate to achieve enough resolution for measuring the tuning linearity of TLS. Generally, solid glass etalons are preferred, where FSR > 3GHz is sufficient. Fiber etalons are suggested for shorter FSR's.

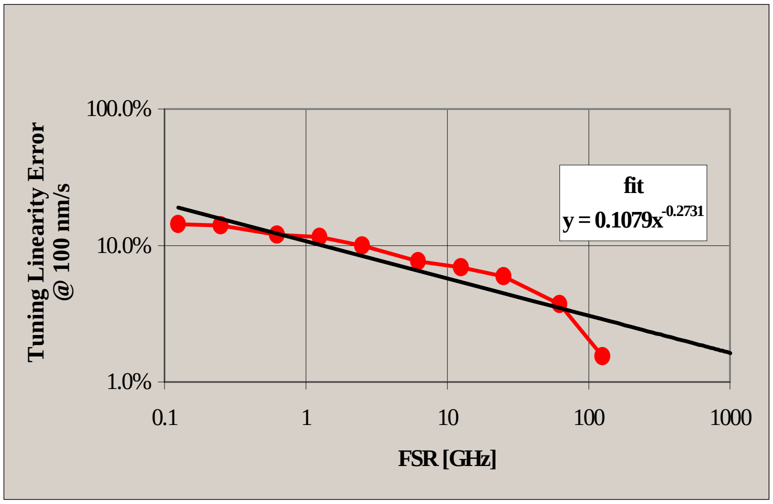


Figure 6. Tuning linearity error versus the FSR of the etalon.

Summary:

In this application note, we discussed the tuning linearity of swept-wavelength lasers. Measuring the tuning linearity of a TLS in a swept-wavelength system is very important since it determines the wavelength accuracy, and therefore, the accuracy associated with the measured wavelength-dependent properties of the DUT. The etalon approach was discussed in detail and an example was presented using the New Focus Model 6528-LN TLS and an etalon with a FSR of 118 MHz. Some items to keep in mind are:

1) The etalon method has the advantage of measuring the full tuning range. The resolution depends on the size of the FSR, which should be two times the linewidth of the TLS. A practical limitation is the processing power of the data acquisition and analysis system.

2) The heterodyne method has the advantage of inherently high resolution, which is limited by the combined linewidths of the two lasers. Practical limitations of the detector bandwidth limit the tuning range to only a few GHz in frequency.

3) The proper expression for tuning linearity depends on the application. The expression in terms of wavelength is desirable if it is intended to describe the wavelength at any given time.

4) The tuning linearity in terms of wavelength deviation is not typically dependent upon the tuning speed. However, the tuning linearity in terms of tuning-speed deviation does vary with the TLS's tuning speed (shown in Figure 5).

Appendix

A.1 The Heterodyne Method

The heterodyne method, as a special case of coherent detection, has been used in industry for improving receiver sensitivity by mixing the incoming signal with another “local oscillator” signal. In this example, a New Focus Model 6328 laser with wavelength fixed at 1550 nm was used as the so-called local oscillator laser. The Model 6328 laser has a known linewidth of 15MHz over 50 ms interval. This laser was mixed through a 50/50 fiber splitter with a New Focus Model 6528 tunable laser, which was swept at 1 nm/s tuning speed. The mixed signal (or beat) was detected by a New Focus 12-GHz photoreceiver (Model 1544). The resulting frequency was analyzed with an Agilent 53310A Modulation Domain Analyzer. A block diagram of the heterodyne method for measuring tuning linearity is shown in Figure A-1.

In general, the beat signal is the difference between the momentary frequencies of the two lasers. The beat frequency variation is a direct representation of the tuning speed. The advantage of this method is its high resolution, which is limited by the linewidth of the lasers. The disadvantages are 1) it requires an accurate time interval analyzer such as an Agilent 53310A and 2) it can only measure a very small section of the laser’s tuning range, which is limited by the bandwidth of the detector. In this case, the tuning range of the New Focus 6528 TLS was limited to 2.5GHz (or 20pm in wavelength) of the Agilent 53310A Modulation Domain Analyzer.

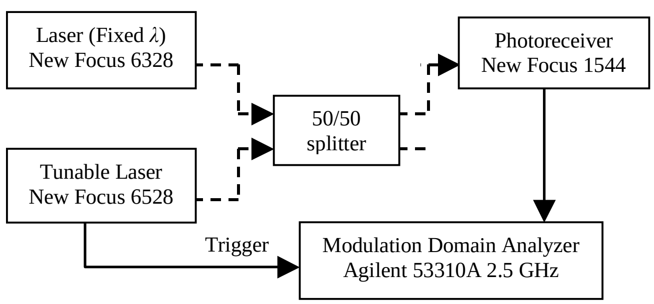


Figure A-1. Block diagram of heterodyning measurement setup.

Figure A-2 represents the tuning speed as a function of wavelength. The wavelength range of the New Focus 6528 TLS was set to be about 15pm. The mean tuning speed was about 0.7nm/s, and the maximum variation was approximately $\frac{\pm 0.3}{0.7} = 43\%$, as shown in Figure A-2.

Figure A-3 shows the wavelength deviation between the momentary wavelength and the wavelength derived from the mean tuning speed of New Focus 6528 laser. The maximum deviation in wavelength was approximately ±0.25 pm or approximately 31 MHz.

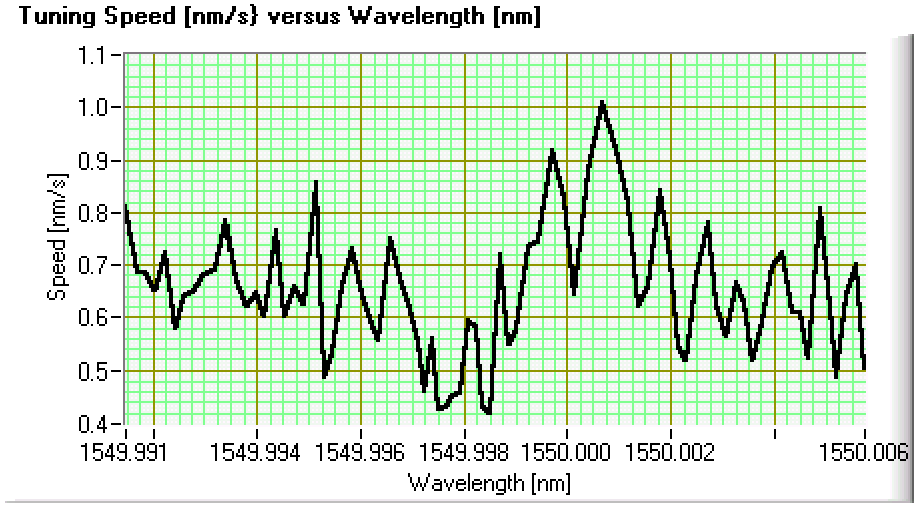


Figure A-2. Tuning-speed deviation measured with the heterodyne method.

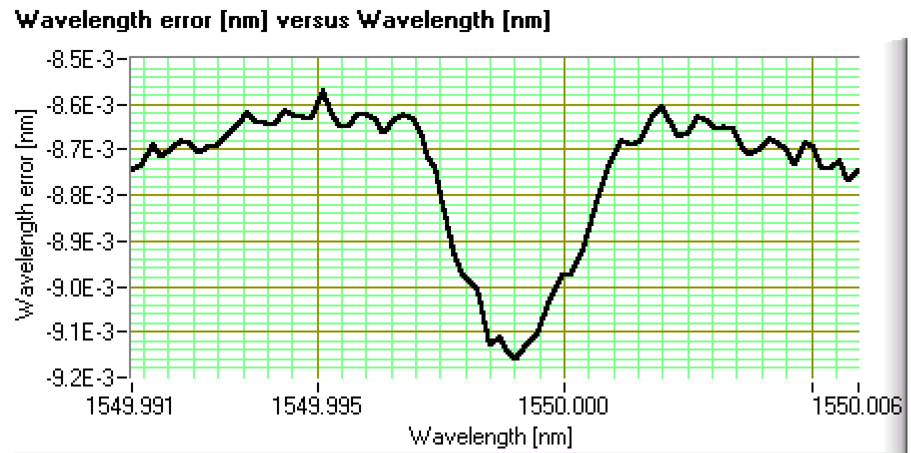
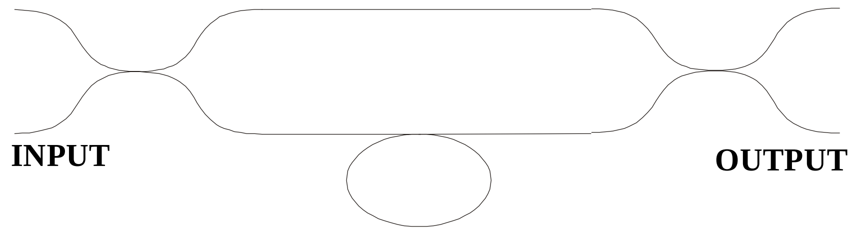


Figure A-3. Wavelength deviation measured with the heterodyne method.

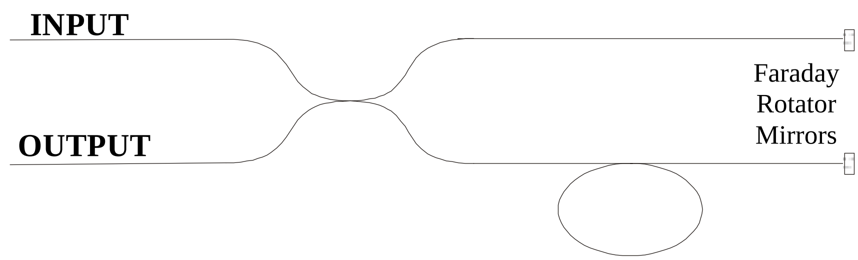
A.2 Michaelson and Mach-Zehnder interferometers

Etalon references are easily made in a Mach-Zehnder configuration with two 2x1 splitters and a polarization controller in one of the delay lines, or in a Michaelson configuration with one 2x2 splitter and two Faraday rotator mirrors (as shown in Figure A-4). The latter does not need a polarization controller. The path-length difference defines the Free Spectral Range (FSR). As a rule of thumb, a path difference of 1 meter has a FSR of 0.8pm for a Mach-Zehnder, or 0.4pm for a Michaelson configuration. A FSR larger than 20pm is difficult to set up due to the requirement of an accurate path-length difference (implying a fiber length difference of less than 70mm). Solid or air-spaced etalons are preferred in these cases.

It is important to use APC connectors to eliminate etalon effects for both Mach-Zehnder and Michaelson interferometers. Note that etalon effects can add up to 0.2dB of amplitude uncertainty.



Mach-Zehnder fiber interferometer



Michaelson fiber interferometer

Fig A-4. Examples of fiber interferometers.