Fabry-Perot Interferometer

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This article is a description of designing, fabricating, and testing a scanning Fabry-Perot interferometer, and it will be used to determine the mode structure of external cavity diode lasers (ECDLs). The key parameters for designed cavity is calculated, and compared to experimental measurements. The experimental results of free spectrum range, frequency resolution (FWHM), and cavity finesse are $3.2GHz$, $11MHz$, and 300 respectively.

I. INTRODUCTION

Fabry-Perot interferometer(FPI) is useful in the AMO physics lab, such as acting as a high resolution optical spectrum analyzer. One of the function of FPI is to determine whether the continuous wave laser is running with single or multi-mode. The input laser in this experiment is an external cavity diode laser (ECDL). The cavity of the ECDL is formed by one side of the laser diode and the diffraction grating. The diffraction grating can narrow the spectrum of the emitted light from laser diode. However, it does not it does not guarantee a single-mode output. A scanning FPI provides the function that allows one to observe the mode structure. There are many companies that sell commercial scanning FPI. For example, Thorlabs provide commercial scanning FPI for the range of price between $2500 to $3500. However, there is inconvenience when using commercial scanning FPI. First, it does not have a wide range of cavity mirrors for the commercial scanning FPI. It is difficult to replace the cavity mirrors with other mirrors. Second, the length of the cavity is fixed. Therefore, a homemade scanning FPI is a more practical option for the lab. The homemade scanning FPI allows one to replace the cavity mirror at any desire radius of curvature and focal length. It allows one to adjust the length of the cavity. Moreover, a homemade scanning FPI is cheaper than a commercial one. The scanning FPI in this article costs around $ 1000. In this article, it introduces the basic design of a scanning FPI and describe the fabrication and test results.

II. METHODS, RESULTS, AND ANALYSIS

A. Schematic

The schematic diagram of this experiment is shown in Figure 1. The light source is a $780nm$ ECDL laser, and it is coupled to a single mode fiber. The output light goes through two lenses with focal length f_1 and f_2. The cavity consists of two curve mirrors with radius of curvature R_1 and R_2. The non-polarization beam splitter is used for splitting the transmitted beam into two direction. In one direction, the transmitted light is collected by a photodiode, and the photodiode converts the transmitted light into electronic signals. The electronic signals are observed on an oscilloscope. In the other direction,

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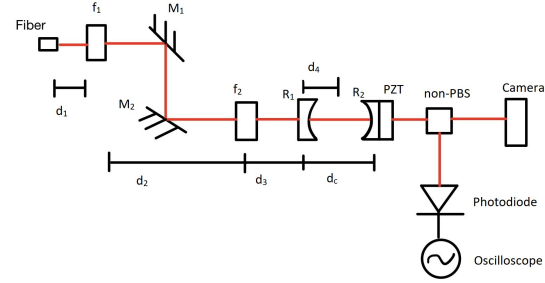[a)]Physics and Astronomy Department, UNLV.

FIG. 1. Schematic diagram of scanning Fabry-Perot interferometer.

the transmitted beam goes to a camera. The camera is used for taking pictures of the beam profile. Another reason of using a non-polarization beam splitter to split the beam is to have the beam profile and the spectrum on the oscilloscope at the same time for mode matching which is discussed later in this article. There are five lengths that are labeled in this diagram. $d1$ is the distance from the fiber to the first lens f_1. $d2$ is the distance from the first lens to the second lens. Note that $d2$ is the path of the light travels from the first lens f_1 to the second lens f_2, and it is shown as a red colored line on the diagram. d_3 is the distance from the second lens f_2 to the first mirror of the cavity R_1. d_4 is the distance from the first mirror of the cavity R_1 to the center of the cavity. d_c is the length of the cavity. The device attached to the second mirror of the cavity R_2 is a piezoelectric transducer (PZT), and it is connected to a function generator and a voltage amplifier. By applying voltage to the PZT, it generates linear motion on the second mirror of the cavity R_2. Thus, the length of the cavity changes and it is used for scanning FPI.

B. Confocal Cavity

The type of the cavity in this experiment is a confocal cavity. Thus, the radii of curvature is equal to the length of the cavity. The length of the cavity is designed to be $50mm$, so $R_1 = R_2 = d_c = 50mm$

A confocal cavity is a stable cavity. A stable cavity is that the light has the same complex factor q after a round trip. By contrast, an unstable cavity is when the light cannot replicate itself after a round trip. The stability of a cavity can be ex-

pressed in terms of radii of curvatures of the mirrors and the length of the cavity, and it is given by

$$0 \leq g_1 g_2 \leq 1 \tag{1}$$

where $g_1 = 1 - \frac{d_c}{R_1}$ and $g_2 = g_2 = 1 - \frac{d_c}{R_2}$. When the product of g_1 and g_2 is between 0 and 1, the cavity is a stable cavity. If it is not between 0 and 1, then the cavity is an unstable cavity. The stability in this form is useful for designing a cavity. It allows one to check whether the cavity is stable with the designed radii of curvatures and cavity length. For confocal cavity, the length of the cavity d_c is equal to the radii of curvatures, so $g_1 = g_2 = 0$. Thus, confocal cavity is a stable cavity.

C. Characteristic of the Cavity

An optical cavity is essentially a resonator. Only discrete wavelength can fit into the resonator. Therefore, the resonate condition is that only integer multiples of half wavelength can fit into the resonator. Express the resonate condition in terms of frequency

$$\nu_q = q\left(\frac{c}{2L}\right) \tag{2}$$

where q here is the index of longitudinal mode and the parenthesis term is called the free spectrum range (FSR). Evidently, the distance between two adjacent longitudinal mode in frequency domain is one FSR. The FSR of the confocal cavity in this experiment is calculated to be $3GHz$ using the length of the cavity $d_c = 50mm$.

The second parameter of the cavity is cavity finesse. It is defined as the ratio of FSR

$$F = \frac{\pi \sqrt{R}}{1 - R} \tag{3}$$

where R is the reflection of the mirror. Cavity finesse is the total amount of round trips the light has make before it is transmitted. If cavity finesse is large, the interference fringes are sharp. If cavity finesse is small, the interference fringes are broad.

The last parameter of a cavity is full width at half maximum(FWHM) $\Delta \nu_{\frac{1}{2}}$. It is used as the width of the interference fringes. The formula of FWHM is given by

$$\Delta \nu_{\frac{1}{2}} = \frac{FSR}{F} \tag{4}$$

The FWHM is obtained by taking the ratio of the FSR and the cavity finesse. In this experiment, first find the theoretical values of FSR, cavity finesse, and FWHM. Then, taking data from the experiment and calculate the experimental results of these three parameters.

According to the manufacturer, the reflection of the cavity mirrors R is 99%, and these two cavity mirrors are identical. Using equation 3 to calculate the cavity finesse. The result is $F = \frac{\pi \sqrt{0.99}}{1 - 0.99} \approx 313$. Finally, using equation 4 to calculate the FWHM, the result is $\Delta \nu_{\frac{1}{2}} = \frac{3 * 10^9 Hz}{313} \approx 9.6 MHz$.

D. Mode Matching

Laser mode and cavity mode need to be matched for the desire interference pattern. The laser light in this experiment is from a single mode fiber. The cavity has infinite modes, and the desire mode is the lowest Gaussian mode. Mode match condition is met when the laser beam waist and position are the same as the cavity's waist and position. If not matched, higher modes are excited with possible different resonant frequencies.

First, calculate the cavity beam waist. The cavity beam waist is given by $\omega_0 = \sqrt{\frac{\lambda}{n\pi} \sqrt{\frac{d_c R}{2} - \frac{d_c^2}{4}}} * 1000$. n is the index of refraction of air or vacuum. R is the radius of curvature and it is $50mm$. The result of the beam waist ω_0 is $0.079mm$.

Then, use the ABCD matrix method to calculate the laser mode in the cavity. There are several optical components in this round trip. The ABCD matrices of these optical components can be found on textbook[1]. The total ABCD matrix is the product of the ABCD matrices of these individual optical components. Note that free space also has an ABCD matrix. For example, the input laser beam travels from the fiber to the first lens f_1 has an ABCD matrix. The flat mirrors M_1 and M_2 also have ABCD matrices. However, these mirrors are flat mirrors, so their radii of curvatures are infinity. An off-diagonal element of the ABCD matrix goes to zero as the radius of curvatures goes to infinity. Thus, the ABCD matrices of the flat mirrors are essentially identity matrices. The calculation of the ABCD matrix is shown below

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & d_4 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{1}{f_3} & 1 \end{pmatrix} \begin{pmatrix} 1 & d_3 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{1}{f_2} & 1 \end{pmatrix} \\ \begin{pmatrix} 1 & d_2 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{1}{f_1} & 1 \end{pmatrix} \begin{pmatrix} 1 & d_1 \\ 0 & 1 \end{pmatrix} \tag{5}$$

where f_3 is the focal length of the cavity mirror R_1. Since the ABCD matrices of the flat mirrors are identity matrices, they are not shown in equation 5.

The final step is to calculate the beam waist of the transmitted beam after it goes through the first cavity mirror R_1. There are several more calculations. First, calculate the q factor of the input beam after the fiber at its beam waist. The beam waist of the input beam ω_1 is $2.5 * 10^{-6} m$, and the wavelength of the input beam is $780nm$. The q factor of the input beam is then $q_1 = i\frac{n\pi\omega_0^2}{\lambda} = 0.000025i$. Next, calculate the q factor q_2 of the beam after it goes through the ABCD matrix in equation 5, and it is given by $q_2 = \frac{Aq_1 + B}{Cq_1 + D}$. Lastly, the beam waist ω_2 after goes through the ABCD matrix in equation 5 is

$\omega_2 = \sqrt{\frac{-\lambda}{\pi Im[q_2^{-1}]}} * 1000$, and the position of the beam waist is given by $-\frac{Re[q_2^{-1}]}{(|q_2^{-1}|)^2} * 1000$. The goal is to have the output beam waist ω_2 matches the cavity waist ω_0, and also have the position of the output beam waist $\omega_2$near 0. If the position of the output beam waist is not near 0, that implies the beam waist is away from the cavity waist ω_0.

The focal lengths are $f_1 = 4.05 * 10^{-3}m$, $f_2 = 75 * 10^{-3}m$ and $f_3 = -100 * 10^{-3}m$. The distance is $d_1 = 4.085 * 10^{-3}m$, $d_2 = 200 * 10^{-3}m$, $d_3 = 39.7 * 10^{-3}m$, and $d_4 = 25 * 10^{-3}m$. Putting these value into equation 5 to get

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} -30.76 & -0.00004 \\ 72.44 & -0.03 \end{pmatrix} \qquad (6)$$

Using the elements of the ABCD matrix in equation 6 to calculate the required parameters. The output beam q factor is $q_2 = 0.000012 + 0.024i$. The output beam waist is $\omega_2 = 0.077mm$, and its position is $-0.012mm$ that shows deviation from the center of the cavity. Thus, the design of the optical system with mode-match condition is finished.

E. Laser Alignment

The next step is to align the laser into the cavity. The technique of aligning the laser is called walking the beam. This technique requires two adjustable mirrors, so mirrors M_1 and M_2 are used to align the laser. Both mirrors have adjustments for horizontal and vertical directions. The goal of the alignment is that the laser goes into the cavity at the center of mirror R_1, and it comes out of the cavity at the center of mirror R_2. Moreover, the cavity in this experiment is a closed cavity, so it is difficult to see whether the laser comes out of the cavity at the center of mirror R_2 for this alignment. The length of the cavity is set to be 50 mm roughly. A small deviation of d_c changes the resonant frequency. Thus, the output beam might not be resonant for one to see.

The solution for this problem is that make two optical components that can be used to point at the center of the mirrors R_1 and R_2 and remove the cavity from the optic table. These two optical components have the same function as iris. They consist of a knob, washers, and a hexagon wrench. Washers are used to adjust the vertical height. The knob is used as the base. The hexagon wrench is used as a pointer. Place these two optical components and point them at the center of the mirrors R_1 and R_2. Then, remove the cavity from the optic table while keeping the two optical components in the same position. Use the technique walking the beam to align the laser at both tips of the components.

First, adjust first mirror M_1 with the horizontal and vertical direction knobs so that the laser goes on the tip of the first component. Then, adjust the second mirror M_2 so that the laser goes on the tip of the second component. Since the second mirror is adjusted, the laser is no longer pointing at the tip of the first component. Repeat the process so that the laser goes through both tips of the components. After the alignment is finished, put the cavity back on the optic table and ensure that the centers of the mirrors R_1 and R_2 are roughly the same position as the tips of the two components.

The coarse alignment ensures that the laser goes through the center of the cavity roughly. Turn on the PZT and observe the spectrum shown on the oscilloscope. Use the same technique walking the beam discussed previously to fine adjust the alignment. While walking the beam using the two mirrors M_1 and M_2, the amplitudes of the modes shown on the spectrum change. For a perfect alignment, only longitudinal modes are shown on the spectrum. By contrast, some transverse modes are shown on the spectrum when it has misalignment. Moreover, the beam profile image taken by the camera changes as one walking the beam. Two concentrated spots are shown in figure 2 on the bottom right image. When adjusting the two mirrors M_1 and M_2, the position of the two concentrated spots change. If using the beam profile as a reference to walk the beam, the goal is to merge the two concentrated spots into a single spot. However, when two concentrated spots are merged into a single spot, it is difficult to tell whether it is perfect mode matched. Therefore, the spectrum on the oscilloscope is useful for fine adjustment to perfect mode matched. The focus of the fine alignment is to eliminate the transverse modes. It is difficult to walk the beam using only the spectrum on the oscilloscope, because the transverse peak is a superposition of many different transverse modes. When adjusting the mirrors M_1 and M_2, the amplitude of the transverse modes often does not change at all unless the laser and cavity mode are close to a perfect mode matched. Thus, the goal of the laser alignment is to eliminate the transverse mode on the spectrum.

III. INTERPRETATION AND CONCLUSIONS

A. Results

The result after finished the laser alignment is shown in figure 2. The top left graph is the the original spectrum on the oscilloscope. The waveform of the PZT is a triangle wave, and it is shown as the orange triangle wave on the top left graph. The driving frequency of the PZT is 10 Hz, and the amplitude of the signal is 60V. According to the manufacturer, the travel range of the PZT is 2 μm when applies 100V signals. The estimated travel range is $\frac{60V}{100V} * 2\mu m = 1.2\mu m$. The change in cavity length to travels from one cavity mode to the adjacent mode is half wavelength of the laser 390nm. The ratio of 1.2μm and 390nm tells one that how many modes have scanned when the PZT travels 1.2μm, and the result of the ratio is $\frac{1.2\mu m}{390nm} = 3.08$. The estimated FSR is 3 GHz as discussed before. The product of the estimated FSR and 3.08 gives the range of the spectrum in frequency domain, and the range is 9.2 GHz. In the time domain, the driving frequency is 10 Hz, so the period of the PZT is $\frac{1}{10s} = 100ms$. The symmetry is set to be 90%. The reason is that the spectrum is the same but opposite direction when the PZT travels back and forth. Therefore, 90% symmetry shows the wider spectrum when the PZT travels in one direction. On the top left graph, the time for the PZT to travels 1.2μm is 90 ms then it takes 10 ms to travels
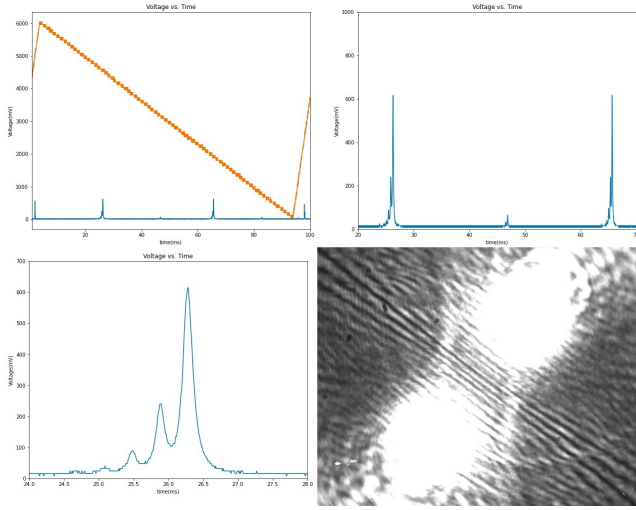
FIG. 2. Graphs of the output beam spectrum on the oscilloscope and the beam profile. Top left graph is the entire spectrum on the oscilloscope. Top right is magnified on two longitudinal modes. Bottom left is magnified on one longitudinal mode. Bottom right is the output beam profile taken by a camera.

in the other direction. There are two peaks when the triangle wave travels downward and upward. Since the triangle wave takes 10*ms* to travel upward, the two peaks are close to each other. Nonetheless, the focus is when the triangle wave travels downward.

The top right graph in figure 2 is the magnified two peaks when the triangle wave travels downward. These two peaks are the longitudinal modes of the cavity. The distance between them is one FSR. Notice that there is a small peaks in between the two longitudinal modes, and this small peak is the transverse mode. Perfect laser alignment can eliminate the transverse mode. A small misalignment causes the appearance of the transverse mode in the spectrum. Although eliminating the transverse mode halfway between the longitudinal can be done by walking the beam, there are more transverse modes on the peaks of the longitudinal modes and they are shown in the bottom left graph.

The bottom left graph in figure 2 is a magnified longitudinal mode. The highest peak on the right is the longitudinal mode. There are some small peaks on the left side of the longitudinal mode, and they are the transverse modes. Laser alignment is not able to eliminate these transverse modes. For example, before adjusting mirrors M_1 and M_2, there are five peaks on the left side of the longitudinal mode. After laser alignment is finished, there are three obvious peaks on the left side of the longitudinal modes. Several readjustments of laser alignment are done, but the small peaks on the left side of the longitudinal modes are still appeared.

The bottom right graph in figure 3 is the beam profile taken by a camera. The laser power is concentrated in the two spots. This picture is not related to other graphs on figure 2, but it is used for showing the beam profile when there is misalignment. In the desire Gaussian mode, the beam has only one concentrated spot. In higher order modes, multiple concen-

trated spots exist.

The next step is to eliminate the small peaks on the left side of the longitudinal modes. The following section discuss the method tested for eliminate the small peaks. First, replace a different resistor on the photodiode. The effect of changing resistors is the magnitude of the output voltage. The shape of the spectrum does not change. The small peaks are still appeared. Second, change the driving frequency of the PZT. If the driving frequency is higher, the widths of the peaks are smaller. If the driving frequency is lower, the widths are larger. Thus, changing the driving frequency has no effect on the shape of the spectrum. Third, change the mode of the input laser by adjusting the current. The desire input laser mode is Gaussian mode. If the input laser mode has higher order mode, the spectrum of the transmitted beam is completely different, and it does not eliminate the small peaks with the desire mode.

The solution is found when adjusting the cavity mirror R_2, there are more small peaks. The problem is that the length of the cavity is approximately 50 mm. However, 1 mm deviation can cause the small peaks on the left side of the longitudinal modes. The frequencies of longitudinal and transverse modes are given by

$$\nu_{nmq} = [q + (n+m+1)\frac{cos^{-1}(\pm\sqrt{g_1 g_2})}{\pi}]\frac{c}{2d_c} \qquad (7)$$

where q, n, and m are the index of the longitudinal and transverse modes. The term $\frac{cos^{-1}(\pm\sqrt{g_1 g_2})}{\pi}$ is called the Gouy phase term. When the cavity is confocal, the spacing between two adjacent modes is half of FSR. If the cavity is not exactly confocal, the side peaks are not exactly overlapped with the longitudinal modes.

The next step is to adjust the length of the cavity so that the cavity is confocal. Suppose the laser alignment for the result shown on figure 2 is nearly perfect, adjust the cavity mirror R_1 and observe the spectrum on the oscilloscope. The goal is to eliminate the small peaks on the longitudinal modes while the transverse mode between the longitudinal might appear with greater amplitude. Once the small peaks disappeared, tighten the screws on the cavity mirror R_1.

Use walk the beam technique to adjust laser alignment so that the mode of the input laser and the cavity mode are matched. The results are shown in figure 3. The driving frequency of the PZT is 60 Hz, and the amplitude of the triangle is 60V. The top left graph is the entire spectrum on the oscilloscope. The top right graph is the magnified spectrum on the two longitudinal modes. The bottom left graph is the magnified spectrum on a longitudinal mode. The bottom right graph is the beam profile taken by a camera.

Calculate the FSR and the cavity finesse using the result on figure 3. The FSRs on figure 3 are 6*ms*. The FWHM is 0.02*ms*. The cavity finesse is $F = \frac{6}{0.02} = 300$. Convert the FSR from time domain to frequency domain. The maximum travel range of the PZT is 2μm at 100V. The travel range with 60V is $60 * 2\mu m\frac{1}{100V} = 1.2\mu m$. From one longitudinal mode to the adjacent mode requires the length of the cavity changes by $\frac{\lambda}{2} = 390nm$. Thus, the scanning range in frequency domain
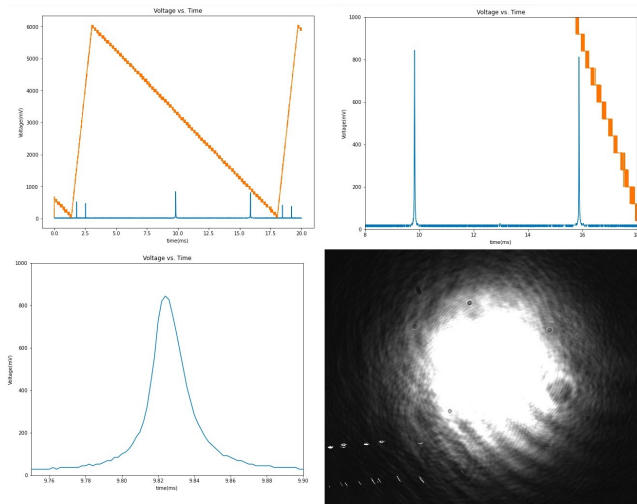
FIG. 3. Graphs of the spectrum and a picture of the beam profile.

is $\frac{1.2\mu m}{390nm} * FSR = 9.2GHz$. Since the driving frequency is 60 Hz, the period is now $\frac{1}{60s} = 17ms$ The FSR from the measurement on figure 3 then is $\frac{9.2GHz}{17ms} * 6ms = 3.2GHz$. The FWHM is $\frac{9.2GHz}{17ms} * 0.02 = 0.012GHz = 1.1 * 10^7 Hz$. The experimental results of these parameters are close to the theoretical calculation. Thus, the laser and cavity are mode matched.

[1] W. Nagourney, *Quantum electronics for atomic physics and telecommunication* (OUP Oxford, 2014).

[2] J. T. Verdeyen, "Laser electronics," Laser electronics/2nd edition (1989).

[3] G. R. Fowles, *Introduction to modern optics* (Courier Corporation, 1989).