Observing Longitudinal Modes of a He-Ne Laser with a Fabry-Perot Resonator

Franklin Liou[1]
[1] Department of Physics, Stanford University, Stanford CA

E-mail: fliou@stanford.edu

Abstract. We scan over the spectrum of a He-Ne laser using a Fabry-Perot resonator whose cavity length is modulated by a piezoelectric element. We resolve 4 longitudinal modes from the spectrum and measure their beat frequencies, as well as their linewidths. Direct measurement of the beat frequencies using a fast photodiode and spectrum analyzer also confirms 3 of the modes. However, one mode remains unobservable with this method. From the spectrum linewidth and the free spectral range of our resonator, we determine its finesse and quality factor to be 21.8 ± 1.25 and $(1.38 \pm 0.08) \times 10^7$, respectively.

I. Introduction

Spectral resolution is important for observing quantum phenomenon such as the Zeeman effect and hyperfine structure, since energy level splitting can shift peaks in emission spectra only a few MHz. While the resolution of conventional grating spectrometers is limited by mechanical parts, a Fabry-Perot resonator uses finely-adjustable piezoelectrics to create stringent resonant conditions for selecting particular frequencies.

The Fabry-Perot resonator works by transmitting discrete frequencies of the longitudinal modes of incident light which satisfy its resonant condition. In the case of a confocal configuration, it allows a set of discrete frequencies that satisfy

$$\upsilon_q = \frac{cq}{4L} \tag{1}$$

$$\upsilon_{q+1} = \frac{c(q+1)}{4L} \tag{2}$$

Here, c is the speed of light, L is the length of the resonator, q is the order in one mode and υ_{q+1} and υ_q are two allowed frequencies with successive orders. One can observe that the allowed frequencies are evenly spaced by the free spectral range υ_{FSR}.

$$\upsilon_{FSR} = \upsilon_{q+1} - \upsilon_q = \frac{c}{4L} \tag{3}$$

If a resonant condition starts out at frequency υ_{q0} and we increase L by a small amount ΔL, υ_q decreases linearly with ΔL.

$$\upsilon_q = \upsilon_{q0} + \Delta\upsilon_q = \upsilon_{q0} + \frac{d\upsilon_q}{dL}\Delta L \approx \upsilon_{q0} - \frac{cq\Delta L}{4L^2} \tag{4}$$

Similarly, υ_{q+1} is also shifted linearly. (5)

$$\upsilon_{q+1} = \upsilon_{(q+1)0} + \Delta\upsilon_{q+1} = \upsilon_{q0} + \upsilon_{FSR} + \frac{d\upsilon_q}{dL}\Delta L \approx \upsilon_{q0} + \upsilon_{FSR} - \frac{cq\Delta L}{4L^2}$$

As L changes, the resonant condition selects different frequencies of υ_q, scanning linearly through the spectrum of the light source. However, when the resonant condition shifts a full free spectral range, that is, when $\upsilon_{FSR} = \frac{cq\Delta L}{4L^2}$, υ_{q+1} shifts to the original position υ_{q0}, thus returning the Fabry-Perot resonator to the original resonant conditions. This means that we will obtain a repeating pattern as υ_{q+1} continues to scan beyond υ_{q0}, as shown in figure 2.

This method gives us greater spectral resolution, since the piezo modulates the cavity length by only several wavelengths of the resonant light. The finesse of the resonator is a measure of the spectral resolution, defined as

$$finesse = \frac{\upsilon_{FSR}}{w} \tag{6}$$

where w is the width of the observed spectral peaks. To compare the resolution to conventional grating spectrometers, we can also define the quality Q as

$$Q = \frac{\upsilon_{light}}{w} \tag{7}$$

where υ_{light} is the frequency of the incoming light. In this study, we seek to measure the finesse and quality of our resonator and resolve longitudinal modes of a He-Ne laser using this method.

II. Methods

To vary the length of the Fabry-Perot resonator, we attach one mirror of the resonator to a piezoelectric material, and supply a voltage with a triangular wavegorm to it so that the cavity length expands and contracts linearly with time. As shown in figure 1, we place a reverse biased photodetector behind the cavity and direct a He-Ne laser through the cavity, into the photodetector. We record the voltage signal from the photodetector with an oscilloscope, which is the spectrum of the laser within the free spectral range of the resonator. Since the time axis of the signal is proportional to change in cavity length, by equation (4), it is also proportional to difference in frequency. By identifying the time difference between two repeating features as the free spectral range, as indicated in figure 2, we can measure the frequency difference between all other modes of the laser. With a cavity length of 10.00 ± 0.01 cm, the free spectral range of our resonator is 749.5 ± 7.5 MHz.

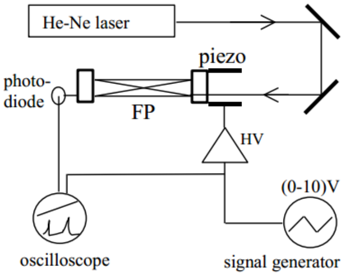

Figure 1: Experimental Setup
We shine a He-Ne laser through a Fabry-Perot resonator while modulating its length with a triangle wave. We place a photodetector behind the cavity and record the transmitted light with an oscilloscope.

Since the difference in frequency of the various peaks in the laser creates a beating signature, we can shine the laser on a fast photodiode and directly observe these beat frequencies with a spectrum analyzer. We compare the two results to confirm observation of different laser modes.

III. Results

From the oscilloscope, we observed a set of 4 repeating peaks, indicating that the laser operates on 4 longitudinal modes. We fitted Gaussians to the peaks to determine their position and width. The free spectral range is identified as the distance between the tallest peak two adjacent set of features, as shown in figure 2.

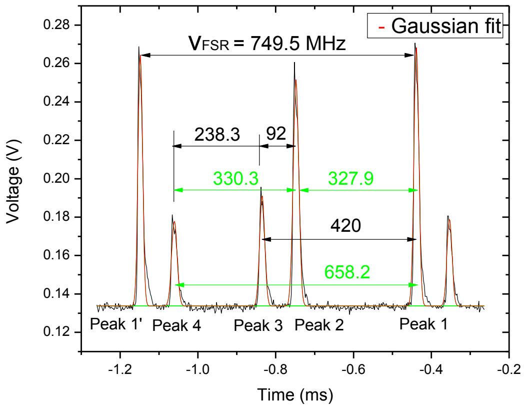

Figure 2: Spectral Features Observed through Fabry-Perot Resonator and Frequency Difference between Peaks
Units of labels in MHz. The observable beat frequencies are highlighted in green.

We measured the distance between various peaks and compare this result to the beat frequencies observed on the spectrum analyzer in table 1. The average widths of the peaks in the spectra were 34.3 ± 2.0 MHz. The finesse of the resonator was determined to be 21.8 ± 1.25, and the quality was $(1.38 \pm 0.08) \times 10^7$.

Table 1: Beat Frequencies of Different Longitudinal Modes

Peak Number	**Frequency Difference (MHz)**	**Standard Error (MHz)**	**Observed on Spectrum Analyzer (MHz)**
1 -> 2	327.90	1.58	328.63
1 -> 3	419.94	2.29	--
1 -> 4	658.20	3.47	657.14
2 -> 3	92.04	1.15	--
2 -> 4	330.30	2.59	328.90
3 -> 4	238.26	2.68	--

Of all the beat frequencies listed in table 1, we only observed three peaks with the spectrum analyzer, as shown in fig 3 and 4. The widths of the 657.14, 328.63, 328.9 MHz peaks were respectively 1.7, 0.43, 0.37 MHz.

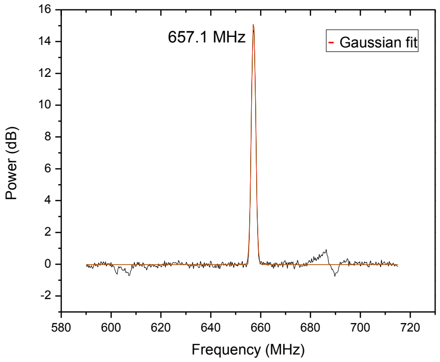

Figure 3: Beat Frequency at 657.14 MHz observed from fast photodiode

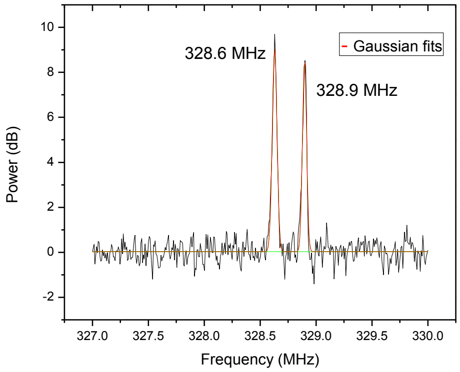

Figure 4: Beat Frequency at 328.63 and 328.90 MHz observed from fast photodiode

IV. Discussion

Although we were able to observe 4 longitudinal modes with the Fabry-Perot resonator, direct observation of the beat frequencies only indicates the existence of 3 modes. No matter how we tried to divide to repeating pattern, it seems impossible not to observe either beating frequency at 420 MHz (peak 1 – peak 3) or 238.3 MHz (peak 3 – peak 4). Since peak 3 and peak 4 are roughly the same in amplitude, our best guess is that peak 3 may not exist in the laser, but is caused by other effects in the resonator induced by the laser. The frequency differences between peaks in the resonator agree with the observed beat frequencies to within 0.3%. However, the frequency difference between peaks have significant error, which may be due to instability of longitudinal modes in the laser, mechanical vibrations in the cavity which may cause υ_q to vary, or the non-Gaussian lineshapes of the spectra. In comparison, the directly observed beat frequencies have much smaller linewidths, due to the fact that the beat frequencies were averaged over 100 traces and the small resolution bandwidth.

Lastly, the quality of the Fabry-Perot resonator, $(1.38 \pm 0.08) \times 10^7$, was around 2000 higher than that of a typical grating spectrometer, which is about 7000 [2]. This is the reason we were able to resolve fine spectral features such as longitudinal modes. One might take advantage of the excellent resolution to observe energy level splitting of atoms under high magnetic field due to the Zeeman effect.

V. Conclusion

In this paper, we have resolved 4 longitudinal modes in a He-Ne laser and measured their respective separation. Beat frequency between 3 of the modes agreed well with the spectrum obtained from the resonator, although some beat frequencies were not observable. The finesse of the Fabry-Perot resonator was 21.8 ± 1.25, which translates to a quality factor of $(1.38 \pm 0.08) \times 10^7$, 2000 times higher than a conventional grating spectrometer.

References

[1] Schleier-Smith, Monika and Pam, Rick. Stanford Physics 107 Lab 4 Handout. (2014)

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