Characterising a Planar-Spherical Optical Resonator

How the length of the cavity changes the Finesse, Line Width and Quality Factor.

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1 Abstract

Optical cavities can be used for a variety of applications, such as for optical spectrum analysers. The behaviour of optical cavities can be described by a number of parameters, such as the finesse. In this report, we characterise a planar-spherical optical cavity by determining the finesse, quality, and linewidth at a range of lengths. It was found that the finesse of the cavity decreased at larger cavity lengths, contrary to our expectations.

2 Discussion

For this experiment we wanted to analyse properties of a given optical cavity. When analysing an optical cavity, the most important quantities are the Finesse and Free Spectral Range (FSR). Using the Finesse we can determine the efficiency of our cavity. When a cavity is operating at a multiple of the FSR frequency, the cavity is said to be in resonance and the intensity of the system is maximised.

2.1 Background

For this experiment we analysed an optical resonator consisting of one planar mirror and one spherical mirror. Many optical cavities are design to be confocal, a cavity consisting of two symmetric spherical mirrors. The benefit of using a confocal cavity is that the modes are degenerate. In the case of cavity we need to make sure that proper mode matching occurs through the use of a lens as the modes are non-degenerate. Figure 1 shows the configuration of the cavity we used in this experiment. The mode is properly matched when the beam waist is smallest at the M1 mirror. From our analysis we determine that a lens with a focal length of around $45cm$ at a cavity length of $15cm$ would provide us with optimal mode matching. Refer to the lab book for a detailed description of the calculations.

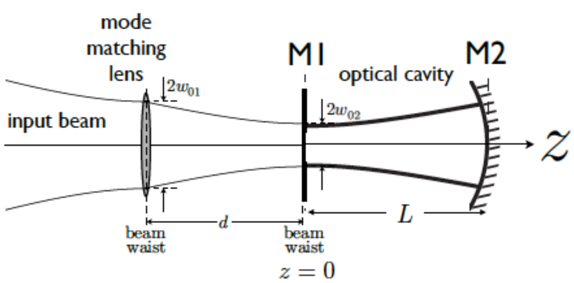

Figure 1: This image illustrate the design of this specific cavity. Since this is not a confocal cavity, mode matching is important to create an optimal resonator. Image from Physics 458/408 Lab Manual by David Jones

The finesse of a cavity characterises the losses within the cavity. A higher finesse means that a photon spends more time inside the cavity. If the frequency of the photon isn't exactly an integer multiple of the FSR, the phase will precess with each trip inside the cavity. If the finesse of the cavity is high, the photon will eventually interfere destructively; conversely if the finesse is low, the photon will likely have exited the cavity before the phase has precessed too drastically. This explains why the resonances narrow with an increase in finesse and broaden with a decrease, since a lower finesse cavity will experience a smaller effect due to small variations in frequency.

The FSR can be calculated given the following equation where d is the cavity length. It is important to note that the distance the optical cavity needs to increase to excite the next mode is given as $\frac{\lambda}{2}$.

$$FSR = \frac{c}{2d}$$

The finesse can be calculated in multiple ways, the most important is given below where f_{FWHM} is the cavity line width (calculated at full width half max, or FWHM).

$$F = \frac{FSR}{f_{FWHM}}$$

The quality factor is also closely related to the Finesse and it represents how much energy is stored with the cavity. Note, q is an integer multiple of the wavelength and represents the mode that the cavity is in.

$$Q = qF = \frac{2d}{\lambda}F$$

2.2 Procedure

The experimental setup for this lab can be seen in Figure 2. M2 has a voltage controlled piezo that can be used to move the mirror small distances.

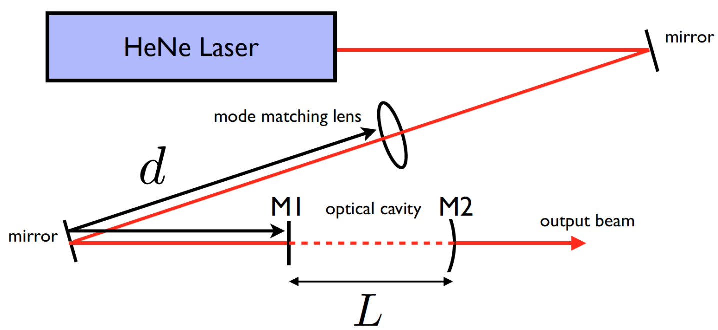

Figure 2: Experimental setup of the optical cavity. Image provided by Mark Halpern from PHYS 408 Lab Manual.

To determine the finesse of the cavity we need to measure the cavity line width experimentally. By directing the output beam into a photodiode and applying a triangular wave to the piezo we can generate a transmission signal. By moving the M2 we are adjusting the cavity length so the cavity will move from one mode to the next. Peaks are only present when the distance is close to an integer multiple of the FSR. From these peaks we can determine the line width (width measured at half the peak). Note, we convert to a distance scale because we know that the distance the mirror must move between two peaks is $\frac{\lambda}{2}$. Figure 3 illustrates a transmission signal generated for a given cavity length.

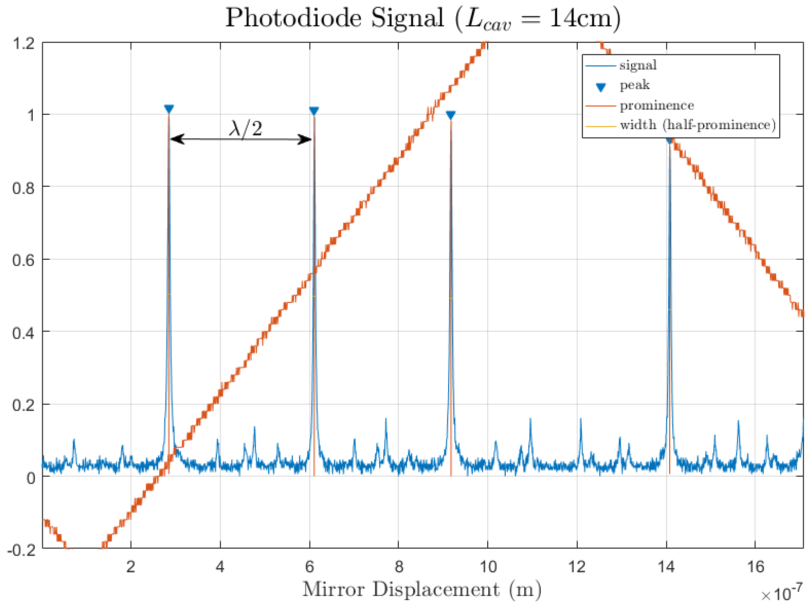

Figure 3: A triangular waveform was applied to the piezoelectric actuator causing the cavity length to be linearly swept. Large resonances occur as the cavity length sweeps through integer multiples of $\lambda/2$. The spacing and width of these peaks was measured to determine the finesse of the cavity.

2.3 Results

The results are summarised in Table 1. Figures 4, 5 and 6 illustrate the change in finesse, line width and quality with cavity length.

Table 1: Measured cavity parameters at a range of cavity lengths

Cavity Length	Finesse	Line Width	Quality
3 ± 0.5 cm	75 ± 4	67 ± 4MHz	$7.1 \pm 0.4 \cdot 10^6$
14 ± 0.5cm	53 ± 5	20 ± 2MHz	$24 \pm 2 \cdot 10^6$
23 ± 0.5 cm	44 ± 9	15 ± 3MHz	$32 \pm 6 \cdot 10^6$
28 ± 0.5 cm	38 ± 8	14 ± 3MHz	$33 \pm 7 \cdot 10^6$

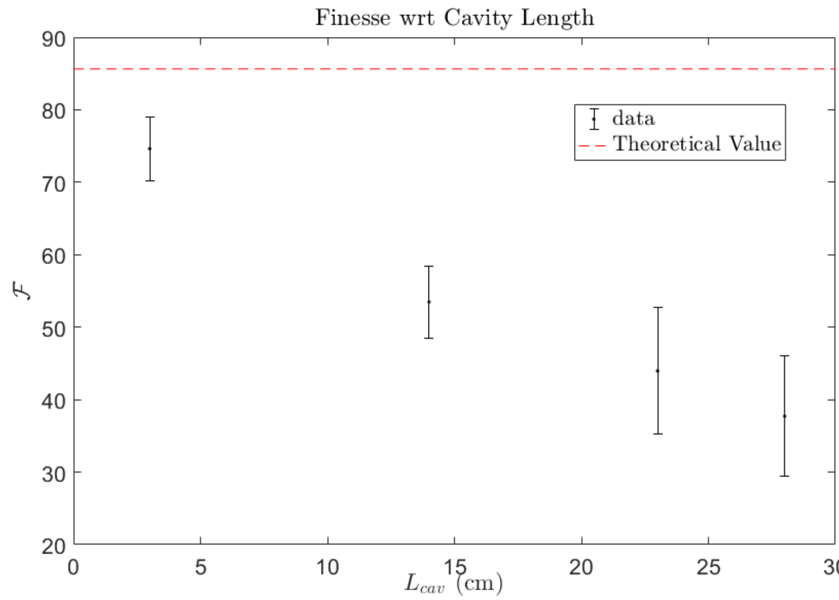

Figure 4:

We found that the finesse fell off with an increase in cavity length even though the theoretical expression for finesse is independent of cavity length. This is hypothesised to be due to an increase in losses at longer cavity lengths due to mirrors only having finite extent. When the cavity length is increased the beam is wider and more of the beam misses the mirror, increasing the losses and decreasing the finesse. Mode matching is important for this type of resonator as well. To work as close to ideal, the cavity must be properly mode matched. As we increase the length of the cavity, we tend to move away from the optimal mode matched configuration. If there was some misalignment in our cavity

Our line width data also agrees with the theoretical value. The reason for the difference is that the finesse values decreases with cavity length, which is an undesired result. Figure 5 illustrates the change in line width with cavity length.

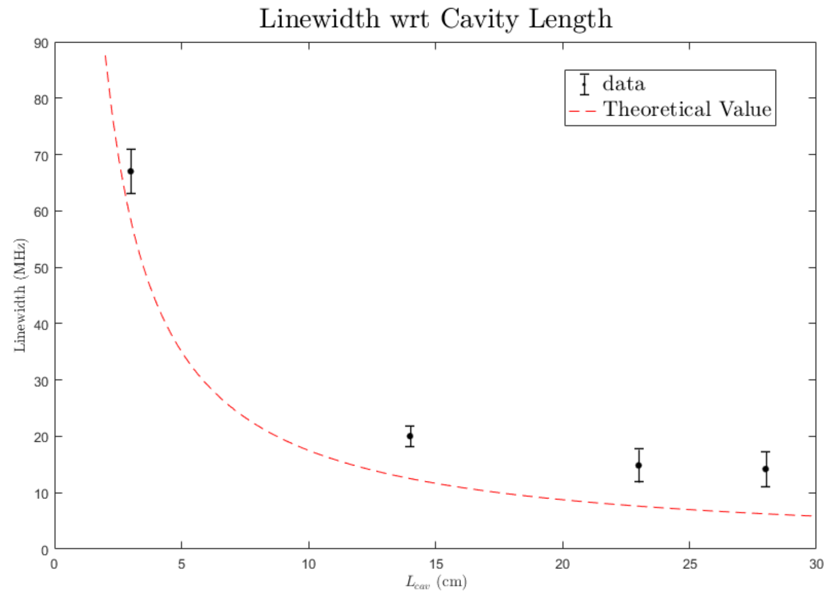

Figure 5:

The quality factor is closely related to finesse, so it's value also falls off from the predicted value for the same reason as the line width. Figure 6 illustrates the change in line width with cavity length.

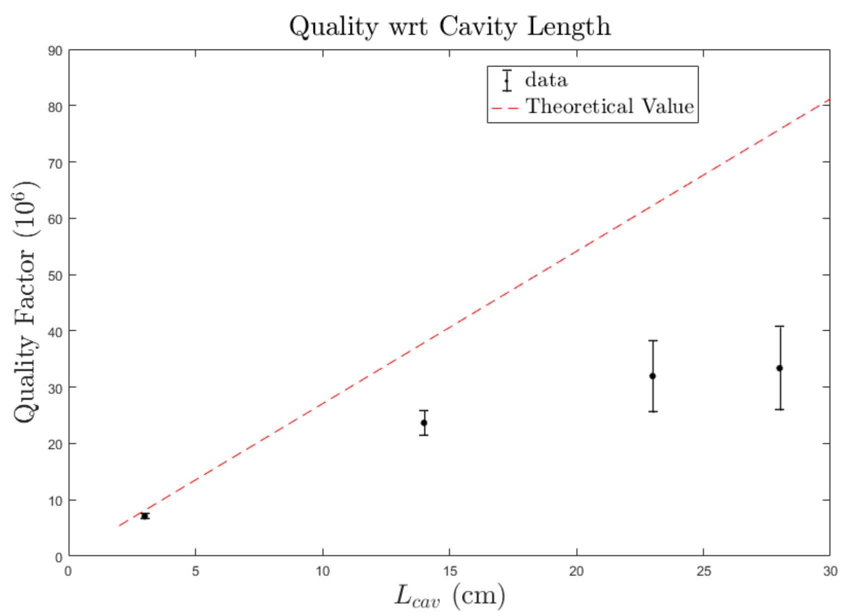

Figure 6:

3 Conclusion

The finesse, linewidth, and quality of a Fabry-Perot optical cavity was determined for multiple cavity lengths. It was found that the length of the cavity affected the measure value of finesse, contrary to theoretical expectations, likely due to unaccounted for losses being magnified at larger cavity lengths. Since the cavity is sensitive to mode matching an alignment, any deviation from the ideal case when exaggerate any errors. The linewidth decreases expected in relation to the theory. The only discrepancies are found at higher lengths where we found a decreasing finesse. It was found that the quality of optical cavities is extremely high when compared to that of mechanical resonators (for example, a tuning fork with a similar quality factor would ring for over 2 hours!).