Optical filters used in quantum optomechanics

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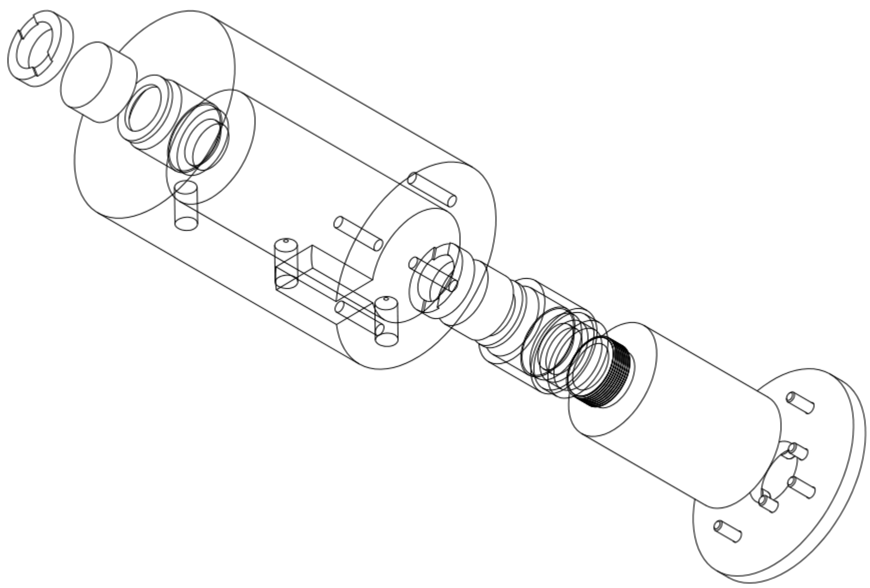


Abstract

Groeblacher Labs, at the TU Delft tries to achieve entanglement using optomechanical resonators like nanobeams. This is done by using the side peaks generated by the optomechanical resonators. These peaks are separated by 5 GHz in relation to the resonance peak of the optomechanical resonator. Because these peaks are of small power compared to the resonance peak of the resonator a filter should be applied to filter out the unwanted peaks. The goal of this project is to develop this filter. The filter is build using two optical cavities, that opperate at the 1556 nm wavelength, of different FSRs (18 GHz and 17 GHz) to have no overlap and to achieve high suppression (-60 dB) of the other peaks. The bandwidth of the filter is determined by the FWHM, which should be within the range of 50 MHz - 60 MHz. A high efficiency of the whole filter setup is also required. The measured FWHM for both cavities are 33.3 MHz for the 18 GHz cavity and 32.3 MHz for the 17 GHz cavity. The total efficiency of the setup is 65%.

Contents

1 Introduction

For years optomechanical resonators have been applied in quantum mechanical applications and as detectors of low-energy scale oscillations. A optomechanical resonator is simply an optical or microwave cavity that contains a mechanical element. This mechanical element is a moving part that can support collective oscillation modes of which the excitation quanta are called phonons. Such a system can simply be described as an optical cavity where one of the mirrors is attached to a spring. In the late 1970s the first well understood mechanical detectors were made. Vladimir Bragnisky, Kip Thorne, Carlton Caves, William Unruh and others have made great contributions to the research on these gravitational wave detectors, which have been built since 1994 and finished in 2002 [5]. These gravitational detectors are basically huge interferometers with arms that were a couple of kilometers long. Each arm had an optical cavity containing mirrors that weight a couple of kilograms. When a gravitational wave occures, the path length of each cavity should change and modulate the resonance frequency. As a result of that a transmission change occurs that can be measured using a photo detector. In September 2015 the first gravitational wave was detected [1].

A property of a optomechanical cavity are its side peaks. For example: An ideal optical cavity (figure 1 (a)) with fixed mirrors has sharp transmission peaks on its resonance frequencies described by [5]

$$\omega_p = \frac{p\pi c}{d}$$

Where d is the cavity length (m), p is an integer (0,1, 2, 3, ...) and c is the speed of light (m/s). The resonance is a result of constructive interference between the partial wave propagating back and forth within the cavity [5].

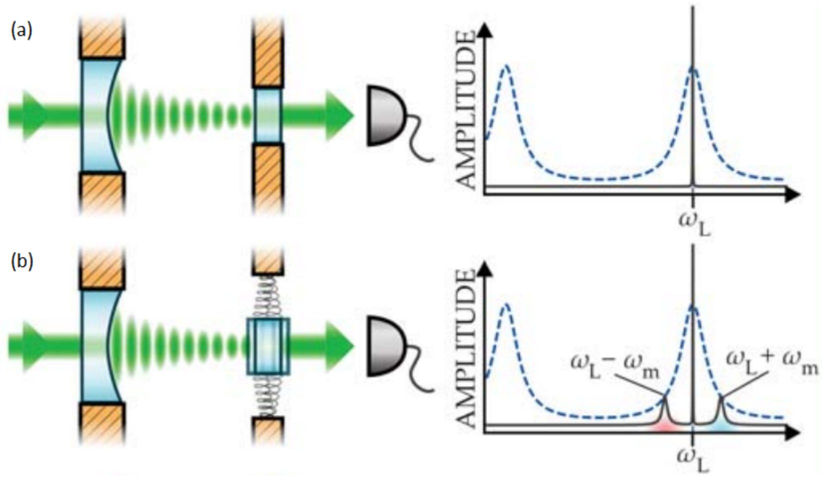


Figure 1: (a) An optical cavity with fixed mirrors and its transmission peaks (left). (b) Optical cavity with a mirror attached to a mechanical resonator with its transmission peaks and created side peaks (left). [5]

When one of the mirrors is attached to a mechanical oscillator like a spring (figure 1 (b)), the laser of frequency ω_L (Hz) will be modulated by the mechanical frequency ω_m (Hz). This results in side peaks with frequencies $\omega_L \pm \omega_m$. The upper side peak is a result of laser photons acquiring energy by annihilation of phonons and the lower side peak is the result of the laser photon depositing phonons while losing energy.

However detecting and exploiting these side peaks however is tricky. The power of these side peaks compared to the resonance peak are multiple times smaller. This resonance peak oversaturates the side peaks, so that detection is nearly impossible. The ability to filter out this peak is key for detecting the side peaks. This can be done using optical cavity filters. The transmission peaks of optical cavities can be seen as band in which certain frequencies get transmitted while the rest gets filtered out. So essentially it can be called a band-pass filter.

Groeblacher labs, a research group situated at the Technical Univeristy of Delft, uses nanobeam optical cavities as optomechanical resonator. The goal of its research is to achieve quantum entanglement by exploiting these side peaks. The frequency of these side peaks is determined by the material of the nanobeam. The nanobeam is made of silicon what results in a mechanical frequency of $\omega_m \approx 5$ GHz with a resonance wavelength of 1556 nm [2]. The goal of this project is to make an optical filters, that opperate at the 1556 nm wavelength, that transmits only one of the side peaks. The bandwidth of the filters is depended on the line width of the (FWHM) of the transmission peak, which should be within a range of 50 MHz - 60 MHz. This is due to a pulsed laser used in the project. The shorter these pulses, the broader the spectrum of frequencies send out by the laser. This is comparable with time space and Fourier space. The smaller the width of a distribution in time space, the broader the distribution in Fourier space. In order not to filter out those frequencies, the linewidth of the filter should be wide enough to fit all those frequencies. If the FWHM is too small to eliminate all other peaks, the FSR of the cavity filter should be above 10GHz. The setup filter consists of two cavities so that enough of the side peaks get suppressed (-60 dB). Two different FSR are chosen for both cavities, so that transmission peaks at other frequencies wont overlap, what results in better suppression. High efficiency of the filter is required to transmit as much power as possible of the chosen side peak. The stability of both cavities is also important, as Piezos commonly have drifts. Because of this, transmission of the cavities will decay after they are locked. The filter is required to stay on resonance for one to two minutes.

2 Theory

2.1 Optical Cavities

An optical cavity in its simplest form can be described as two mirrors that are facing each other, separated by distance d (m). . When light enters the cavity, light will be reflected between the two mirrors, this results in transmission or reflection periodic in wavelength. For example: the simplest cavity is the plane-parallel cavity or Fabry-Perot cavity, named after Charles Fabry and Alfred Perot .This cavity consists of two parralel planar mirrors facing each other. Transmission and reflection solely depends on the distance d between the mirrors and the refractive index n (-)of the medium between the two mirrors. Figure 2 shows how a light beam with incoming angle θ_i (rad) moves within such a cavity.

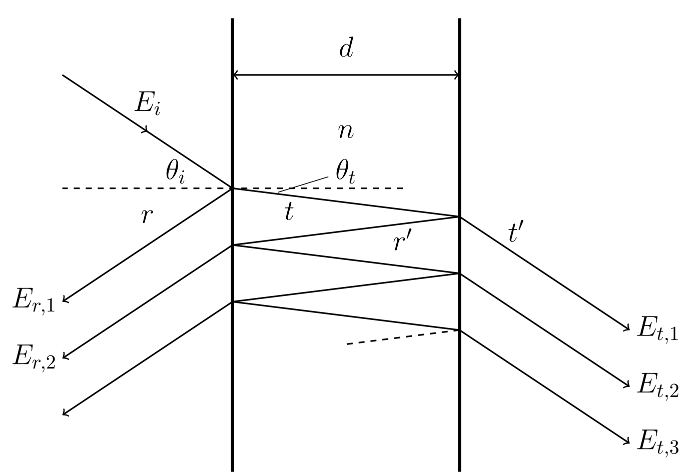


Figure 2: Multiple reflections withing the Fabry-Perot cavity.

An electric field with amplitude E_i hits the first mirror. This results in a reflected amplitude $E_{r,1}$, while the partially transmitted amplitude from the second mirror is given by $E_{t,1}$ with r (-) and t (-) being the coefficients of amplitude of reflection and transmission. The multiple transmitted beams differ in phase due to different path lengths traversed by each of the beams. The optical phase δ (-) acquired by the light on one round trip through the cavity is given by [8]

$$\delta = \frac{4\pi n d}{\lambda} \cos\theta_t \tag{1}$$

With λ being the wavelength of the incoming light (m) and θ_t the angle of the beam within the cavity (rad). The amplitudes of the transmitted waves can be written as [8]

$$E_{t,1} = tt'E_i,\ E_{t,2} = tt'r'^2 e^{i\delta} E_i,\ E_{t,3} = tt'r'^4 e^{2i\delta} E_i, ... \tag{2}$$

Where t and r are the transmission and the reflection coefficients of the first mirror and t' and r' are the transmission and reflection coefficients of the second mirror. Summing up all these amplitudes, you will get the total transmitted amplitude E_t [8]

$$E_t = \sum_{m=1}^{m} E_{t,m} = E_i tt' \left(1 + r'^2 e^{i\delta} + r'^4 e^{2i\delta} + ...\right) = \frac{tt'}{1 - rr'e^{i\delta}} E_i \tag{3}$$

The transmission of an ideal cavity is described by $T = I_t/I_i$, with I_t (W/m$^{\mathbf{2}}$) being the intensity of the transmitted light and I_i (W/m$^{\mathbf{2}}$) the intensity of the incoming light, thus [8]

$$T = \frac{I_t}{I_i} = \frac{|E_t|^2}{|E_i|^2} = \frac{E_t E_t^*}{E_i E_i^*} = \frac{(tt')^2}{(1 - rr')^2 + 4\sqrt{rr'}\sin^2\left(\frac{\delta}{2}\right)} \tag{4}$$

In a loss less system, for identical mirrors, $r = r'$can be considers. So that the transmission function can be described as:

$$T = \frac{(1 - \mathcal{R})^2}{(1 - \mathcal{R})^2 + 4\mathcal{R}\sin^2\left(\frac{\delta}{2}\right)} \tag{5}$$

Where $\mathcal{R}$ (-) is the constant of reflective of the mirror, with $\mathcal{R} = r^2$ and $r^2 + t^2 = 1$ in a loss less system. This is called the Airy function. In figure 3 an example is shown the transmission of a cavity[8].

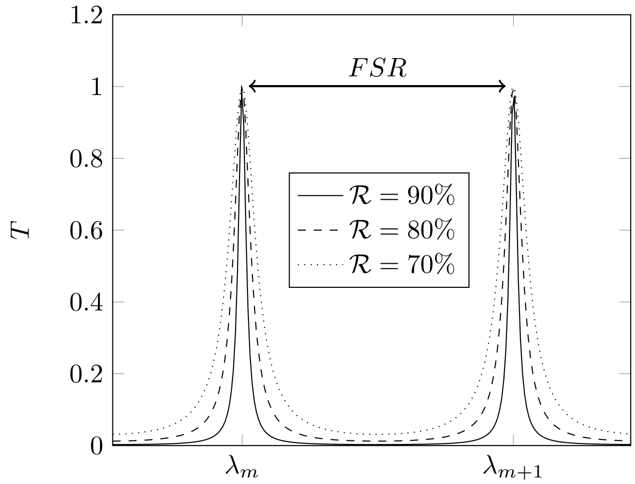


Figure 3: A plotted example of the Airy function.

Considering the incoming beam to be perpendicular to the surface of the mirror, $\theta_i = 0\,\text{rad}$. By Snell's law we know then that $\theta_t = 0\,\text{rad}$. From now on the medium between the two mirrors is considered air, so that $n = 1$. This gives:

$$\delta = \frac{4\pi d}{\lambda} \tag{6}$$

By looking at equation 5, it can be concluded that the phase δ has to be equal to $m2\pi$,with m being an integer $(0, 1, 2, 3, ...)$ in order to have maximum transmission. With condition the fully transmitted wavelengths can be found by:

$$\delta_m = \frac{4\pi d}{\lambda_m} = 2\pi m \rightarrow \lambda_m = \frac{2 \cdot d}{m} \tag{7}$$

The peak to peak separation is called the free spectral range or FSR. Usually the FSR is expressed in frequency $\Delta\nu$ (Hz) instead of wavelength, thus :

$$\Delta\nu = \nu_{m+1} - \nu_m = \frac{c}{\lambda_{m+1}} - \frac{c}{\lambda_m} = \frac{c\,((m+1) - m)}{2d} = \frac{c}{2d} \tag{8}$$

This FSR is a very important parameter in cavity building. Depending on the cavity width will be determined which wavelengths will be transmitted and which will be partly transmitted or not at all. While cavity width determines the peak locations, the reflectivity $\mathcal{R}$ determines the shape of the peaks. The higher the reflectivity of the mirrors, the narrower the FWHM of the peaks. The fraction of the FSR by FWHM is called the finesse $\mathcal{F}$ (-) of the cavity and can be approximately ($\mathcal{R}$¿0.5) calculated using the reflectivity of the mirrors [6] .

$$\mathcal{F} = \frac{\Delta\nu}{FWHM} = \frac{\pi\sqrt{\mathcal{R}}}{1 - \mathcal{R}} \tag{9}$$

In reality planar mirrors are not usable as cavity mirrors. Not only are planar mirrors very sensitive to misalignment and are they unstable if the mirrors are not perfectly parallel to each other, but also only plane waves can be confined within such a cavity, which do not exist in reality. For this reason concave mirrors are used. So called spherical-mirror resonators, where both mirrors are concave, are more stable with confinement of light and are less sensitive to misalignments. In order for a cavity to be stable, it has to satisfy the confinement condition, which is expressed in equation 10, were $g_1 = (1 - d/R_1)$ and $g_2 = (1 - d/R_2)$ with R_1(m) and R_2 (m) being the radii of curvature of each mirror [6].

$$0 \leq g_1 g_2 \leq 1 \tag{10}$$

Commonly, lasers have a Gaussian profile. In this this case Gaussian optics should be used to describe the cavity system. A Gaussian beam is a circular symmetric wave whose energy is confined around its axis (z-axis). For a Gaussian beam the intensity varies in the transverse x-y plane over a distance z (m) and described by [6]

$$I = I_0 \left(\frac{\omega_0}{\omega(z)} \right)^2 \exp\left(-\frac{2\left(x^2 + y^2\right)}{\omega^2(z)} \right) \tag{11}$$

where the radius ω (m) of the beam is described in figure 4 by [6]

$$\omega(z) = \omega_0 \sqrt{1 + \left(\frac{z}{z_0} \right)^2} \tag{12}$$

Where ω increases in relation to the beam waist ω_0 (m) ($z = 0$) and where z_0 is called the Rayleigh range (m). This is the distance at which the beam wave fronts are most curved. The radius R (m) of curvature of these wave fronts is described by [6]

$$R(z) = z\left(1 + \left(\frac{z_0}{z}\right)^2\right) \tag{13}$$

which decreases from∞at the position of the beam waist ($z = 0$), to a minimum radius at ($z = z_0$). The distance of $z_0$in relation to the beam waist is depended on the radius $\omega_0$of the beam waist [6]

$$z_0 = \frac{\pi \omega_0^2}{\lambda} \tag{14}$$

with λbeing the wavelength of the light.

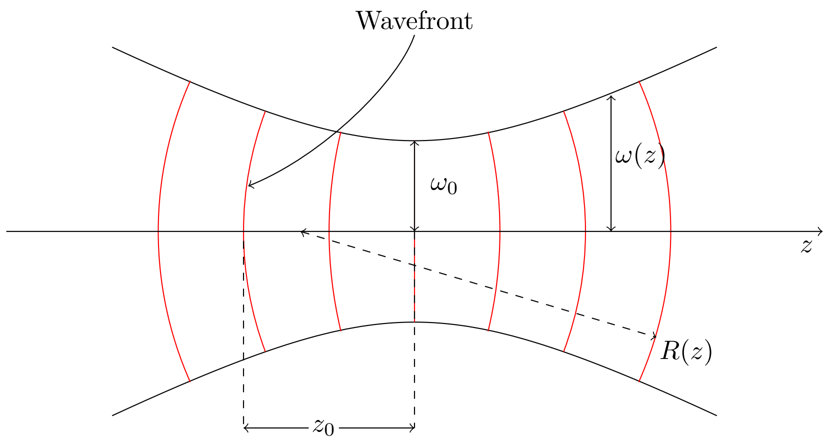


Figure 4: Delineation of a Gaussian beam.

A Gaussian beam reflected from a spherical mirror will retrace if the incoming wave front radius is equal to that of the mirror. So if the two wave fronts separated by a distance d match the same radii of curvature of two mirrors that are also separated by distance d, the Gaussian beam will retrace itself back and forth between the two mirrors. This means that the Gaussian beam exists self-consistently within the cavity [6].

With a symmetric cavity ($R_1 = R_2$)the beam waist of a Gaussian beam lies in the center of the cavity [6]. The radius of the beam waist is described by

$$\omega_0^2 = \frac{\lambda d}{2\pi}\sqrt{2\frac{|R|}{d} - 1} \tag{15}$$

Where $R = R_1 = R_2$ (m). The Rayleigh range is described by [6]

$$z_0 = \frac{d}{2}\sqrt{2\frac{|R|}{d} - 1} \tag{16}$$

A Gaussian beam is not the only solution of the Helmholtz equation that can exist within a spherical cavity. The Hermite-Gaussian beams can also exist. In fact all Hermite-Gaussian modes can match a spherical cavity. However the different mode index values (l, j) give phase shifts compared to the Gaussian Beam $(l = 0, j = 0)$, what results in a shift in resonated frequencies dependable on (l, j). The distribution of resonated frequencies for every mode is described by (with q being a integer) [6]

$$\nu_{qlk} = \Delta\nu \cdot \left[q + \frac{1 + l + j}{\pi} \arccos\left(1 - \frac{d}{R}\right)\right] \tag{17}$$

2.2 Matching A Gaussian Beam

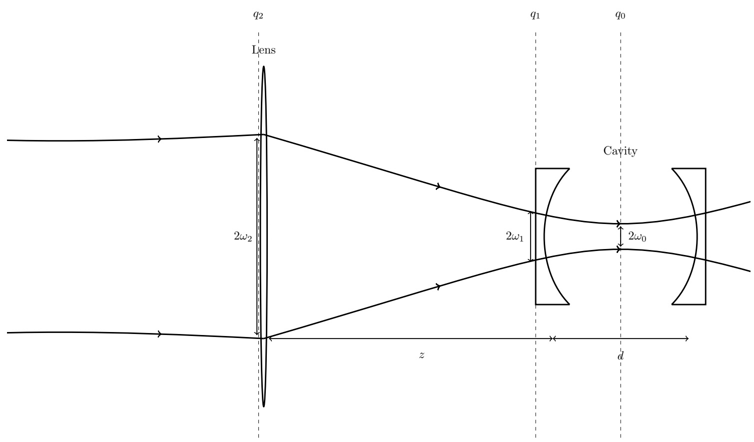


Figure 5: Mode matching of a collimated beam.

In order to have ideal transmission, the beam of the light source has to be matched to the cavity. As already mentioned, lasers commonly use a Gaussian beam profile. So in order to match the beam to the optical cavity, one should look at Gaussian optics. In order for an optical setup to work over long distance, one would want a beam that diverges slowly over distance. This is called a collimated beam. In the case of a Gaussian beam, all wave fronts will have a radius of $R(z) \approx \infty$. A collimated beam can be matched to an optical cavity by using a lens, as shown in figure 5, this lens is a called the mode matching lens and has a focal length $f_{\text{MM}}(\text{m})$. In order to calculate the right parameters for the collimated beam and the mode matching lens, transfer matrices and complex beam parameters can be used. The beam radius and curvature of a Gaussian beam can be plotted in complex beam parameter $q(z)$ [4].

$$q(z) = z + iz_0 \rightarrow \frac{1}{q\,(z)} = \frac{1}{R\,(z)} - \frac{i\lambda}{\pi\omega(z)^2} \tag{18}$$

Applying a transfer matrix to a $\mathcal{M}$ to a complex beam parameter q_0[4].

$$\mathcal{M} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \tag{19}$$

Which will result in [4]

$$q_1 = \frac{Aq_0 + B}{Cq_0 + D} \tag{20}$$

Typical transfer matrices used in mode matching are the matrix for a beam moving through free space over distance l (m)[4]

$$\mathcal{M}_{free} = \begin{bmatrix} 1 & l \\ 0 & 1 \end{bmatrix} \tag{21}$$

And the matrix for a beam moving through a lens of focal length f (m)[4]

$$\mathcal{M}_{lens} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{bmatrix} \tag{22}$$

In order to calculate the parameters of the collimated beam in relation to the focal length $f_{\mathrm{MM}}$of the mode matching lens that matches a certain optical cavity, you have to consider the cavity width d and curvature R of the mirrors to be chosen, fixed and real. Having these values, calculations can be made by "back-porpagating" the beam from the waist within the cavity q_0 to instance of the collimated beam q_2. By using equation 18 complex parameter q_0 can be calculated at the position of the beam waist within the cavity. Where the waist is determined by equation 15. In figure 4 you can see that the curvature is infinite at the waist, so that

$$q_0 = \frac{i\pi\omega_0^2}{\lambda} \tag{23}$$

To calculate the position of the mode matching lens and radius that the collimated beam should have, you would first want to know what the waist will be at the backside of the mirror. Not only will this make the calculations easier ompared to calculating the whole system at once, but also knowing these parameters can be helpful when designing a cavity. In this case we can consider the mirrors to be lenses with its focal length defined by the lensmaker's equation [3]

$$\frac{1}{f_m} = (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{(n-1)t}{nR_1R_2}\right] \tag{24}$$

Where $f_m$is the focal length of the mirror, n is the refractive index of its material, t the thickness of the lens, and where R_1 and $R_2$are the radius of curvature of its sides. Using the transfer matrices from equations 21 and 22 gives transfer matrix

$$\underset{q_1 \leftarrow q_0}{\mathcal{M}} = \mathcal{M}_{lens} \cdot \mathcal{M}_{free} = \begin{bmatrix} 1 & \frac{d}{2} \\ -\frac{1}{f_m} & 1 - \frac{d}{2 \cdot f_m} \end{bmatrix} \tag{25}$$

With $l = d/2$ where d is the cavity width. Applying matrix $\underset{q_1 \leftarrow q_0}{\mathcal{M}}$ to equation 20 and that to equation 18will give the equation

$$\frac{1}{q_1} = -\frac{d\lambda - 2f_m\lambda + 2i\pi\omega_0^2}{df_m\lambda + 2i\pi f_m\omega_0^2} \tag{26}$$

And using 18 we can define$1/q_1$as

$$\frac{1}{q_1} = \frac{1}{R_1} - \frac{i\lambda}{\pi\omega_1^2} \tag{27}$$

As show in equation 27, two parameters ω_1 and R_1 are divided by a real part and an imaginary part. To calculate R_1,the real part of equation 26 has to be equated to the real of equation 27 and solved. And for ω_1 the same has to be done for the imaginary parts. This will result in

$$R_1 = \frac{f_m\left(d^2\lambda^2 + 4\pi^2\omega_0^4\right)}{-d^2\lambda^2 + 2df_m\lambda^2 - 4\pi^2\omega_0^4} \tag{28}$$

$$\omega_1 = \frac{\sqrt{d^2\lambda^2 + 4\pi^2\omega_0^4}}{2\pi\omega_0} \tag{29}$$

To calculate $1/q_2$ the exact steps can be repeated, but by using q_1. The transfer matrix in this case will be

$$\underset{q_2 \leftarrow q_1}{\mathcal{M}} = \begin{bmatrix} 1 & l \\ -\frac{1}{f_{\mathrm{MM}}} & 1 - \frac{l}{f_{\mathrm{MM}}} \end{bmatrix} \tag{30}$$

With f_{MM}being the focal length of the lens and l being the distance between the lens and the closest mirror. Using equation 20 will then give

$$\frac{1}{q_2} = \frac{\frac{\pi R_1\omega_1^2}{-\pi f_{\mathrm{MM}}\omega_1^2 + i f_{\mathrm{MM}}\lambda R_1} - \frac{l}{f_{\mathrm{MM}}} + 1}{l + \frac{1}{\frac{1}{R_1} - \frac{i\lambda}{\pi\omega_1^2}}} \tag{31}$$

Again by using equation 18 you can also define$1/q_2$. As already stated, at point q_2 we are talking about a collimated beam in which case all wave fronts will have a curvature of $R \approx \infty$. Meaning that

$$\frac{1}{q_2} \approx -\frac{i\lambda}{\pi\omega_2^2} \tag{32}$$

By equating the real parts of equations 31 and 32 you would be able to solve l

$$l = \frac{\sqrt{f_{\mathrm{MM}}^2\left(\lambda^2R_1^2 + \pi^2\omega_1^4\right)^2 - 4\pi^2\lambda^2R_1^4\omega_1^4} + f_{\mathrm{MM}}\lambda^2R_1^2 + \pi^2 f_{\mathrm{MM}}\omega_1^4 - 2\pi^2R_1\omega_1^4}{2\left(\lambda^2R_1^2 + \pi^2\omega_1^4\right)} \tag{33}$$

The distance l between the lens and the mirror should in general be purely real. This means that the value under the square root of the last equation should be equal or above zero. As R_1,$\omega_1$andλ are fixed real values we can find a bound condition that gives the minimum value of f_{MM} .

$$f_{\mathrm{MM}} > \frac{2\pi\lambda R_1^2\omega_1^2}{\sqrt{\lambda^4R_1^4 + 2\pi^2\lambda^2R_1^2\omega_1^4 + \pi^4\omega_1^8}} \tag{34}$$

The beam radius ω_2 of the collimated beam can be calculated equating and solving the imaginary parts of 31 and 32

$$\omega_2 = \frac{\sqrt{R_1^2\left(\pi^2\omega_1^4 + \lambda^2 l^2\right) + 2\pi^2 R_1 \omega_1^4 l + \pi^2\omega_1^4 l^2}}{\pi R_1 \omega_1} \tag{35}$$

3 Parts and Setups

3.1 The Cavity Design

The double cavity setup consists of two cavities, with one having a FSR of 18 GHz and the other 17 GHz. The length of these cavities is defined by equation 8 which are $d_{18GHz} \approx 8.3$ mm and $d_{17GHz} \approx 8.8$ mm. Before designing cavities, important properties have to be considered. For one the cavities should have a FWHM within 50 MHz - 60 MHz range, the mirrors should be able to be fixed without glue so that changing them will not be a problem, no beam clipping should occur and a piezo actuator should be used to change the length of the cavity slightly. The first property is defined by the reflectivity. Reflectivity

defines the finesse of the cavity which is the ratio of FSR and FWHM. Layertec sells mirrors with a reflectivity of 99.0...99.3% by Layertec. According equation 9 this gives a finesse of $\mathcal{F} = 447$. Theoretically this should give the 18 GHz cavity a FWHM of 40 MHz -60 MHz and the 17 GHz cavity a FWHM of 38 MHz - 54 MHz. In order to check if beam clipping occurs, first the design as a whole has to be explained. For both type of cavities it consists of a cylindrical steel enclosure that holds a mirror on the end of it. This mirror is fixed by a polyoxymethylene (POM) screw. Within the enclosure a piezo actuator [Piezomechanik HPSt 150/14-10/12 VS22] is placed which holds the other mirror. The actuator is used to correct the distance between the mirrors needed for the light to resonate. This is needed due to inaccuracies in the length of the cavity and due to errors by thermal expansion and other external causes. The actuator is driven electrical, which is beneficial to make the system work automatically. It is a ring actuator, which means that light can travel through the center. This space has a minimal radius of 4.5 mm. For both cavities, commercial mirrors are used with a reflectivity of ($\mathcal{R}$ = 99.0...99.3%). Clipping may occur when using the wrong radius of curvature for the mirrors. 500 mm [Layertec 108475] mirrors that are made of fused silicon (n=1.444) were available. Before mirrors can even be considered, the mirrors have to satisfy the stability condition described by equation 10. In both cases they do. To check if clipping occurs the beam that fits the cavity is simulated in figure 6. The simulation is calculated and shown in Appendix 1.

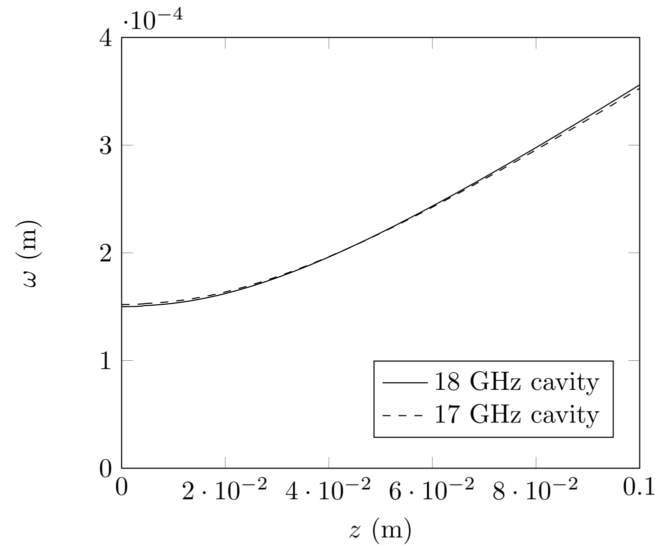


Figure 6: Divergence of the beam in relation to the middle of the cavity.

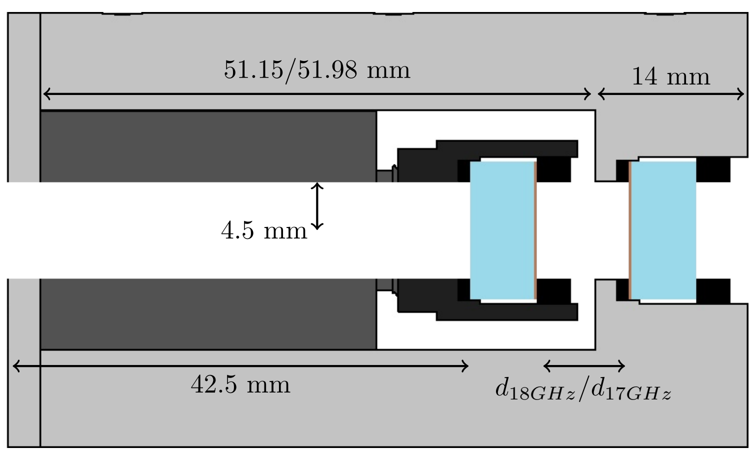
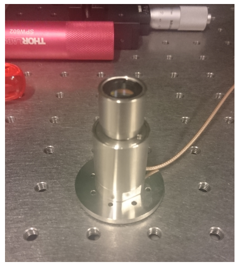
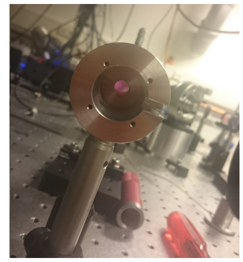


Figure 7: Intersection in length of the cavity (18GHz/17GHz).



(a)



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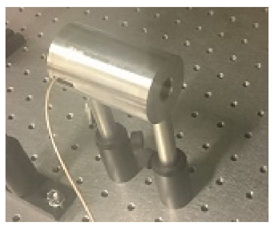
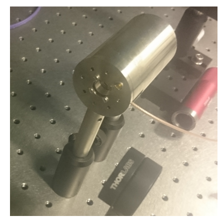


(c)



(d)

Figure 8: (a) The actuator is shown connected to a holder that holds a mirror. The actuator is connected to a voltage generator through a bnc cable. The disk on the end is used to fasten the cavity to the enclosure, with screws. (b) The enclosure without the actuator holding a mirror. At the end the other mirror is fixed using washers and ring screws. (c) The actuator is slided into the enclosure. (d) Back view of the complete design.

In figure 7 the intersection of both designs is shown. Comparing this picture with figure 6 shows that the beam within the length of the design is multiple times smaller than the minimal radius of 4.5 mm. This means that no clipping should occur. The enclosure and mirror holder are made of steel, because of the low linear thermal expansion ($12 \cdot 10^{-6}$ m/(m K)). In figure 8 photos of the build (18 GHz) are shown. In table theoretical specifications is shown for both cavities. More detailed cavity design drawings can be found in appendix 2.

Cavity/FSR	18 GHz	17 GHz
Cavity Length	8.3 mm	8.8 mm
Reflectivity Mirror 1/2	99.0...99.3%/99.0...99.3%	99.0...99.3%/99.0...99.3%
ROC Mirror 1/2	500 mm/500 mm	500 mm/500 mm
Theoretical Finesse	447	447
Theoretical FWHM	40 MHz -60 MHz	38 MHz - 54 MHz
Max Outer Radius	20 mm	20 mm
Min Inner Radius	4.5 mm	4.5 mm
Total Length	65.48 mm	65.98 mm
Piezo Stroke	0.08 μm/V	0.08 μm/V
Piezo Voltage Range	-30 V - +150 V	-30 V - +150 V

Table 1: Cavity Specifications.

3.2 Single Cavity Setup

Before explaining the way how measurements are done, the parameter of polarization has to be determined. Manipulation of polarization is beneficial to split two counter propagating beams in different directions. This is done by using a polarizing beam splitter. This beam splitter divides the beam in two components: P-polarized (parallel) and S-polarized (perpendicular). For such beam splitters P-polarized light gets transmitted and S-polarized light is reflected under a 90 degree angle. Using a beam splitter efficiently, which means there will be no loss in power for both beams, one of the beams has to be linearly P- and the other S-polarized. This means that the beam polarization out of the laser [Amonics AULLD-PM-1550-02-30] has to be controlled so that is either P- or S-polarized. This is done by a polarization controller [Thor Labs FPC560]. This consists of three levers that can be moved to change polarization. In the case of the single cavity setup and the double cavity setup the beams have to be P-polarized. The cavity can be considered insensitive to polarization.

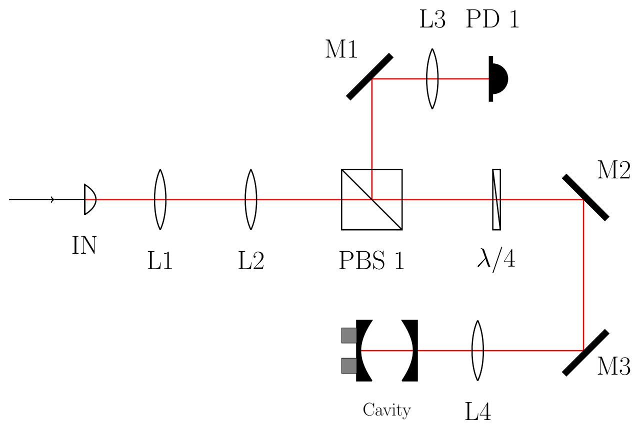


Figure 9: Single cavity filter setup.

The specifications and stability of both cavities have to be determined by measuring them separately. In figure 9 the setup used for these measurements is shown. P-polarized light is coupled into free space using a collimator coupler (IN) [TC18APC-1550]. The beam coming out of the coupler has a radius of $\omega_{col} = 1.665$ mm. After the coupler, the beam propagates through a telescope, which consists of two lenses, L1 and L2. This telescope is used to minimize the radius of the beam to the radius that fits the mode matching lens L4. For both cavities this setup consists of a $f_{\mathrm{MM}} = 250$ mm mode matching lens. Using equation 35 and the calculations of appendix 1, the radius that fits the mode matching lens can be calculated. For the 18 GHz cavity this is$\omega_{2,18GHz} = 0.816$ mm and for the 17 GHz cavity this is $\omega_{2,17GHz} = 0.803$mm. Using the two lens telescope equation, the magnification M can be calculated

$$M = \frac{f_{L2}}{f_{L1}} = \frac{\omega_2}{\omega_{col}} \tag{36}$$

Where f_{L1} and $f_{L2}$are the focal lengths of the lenses used in the telescope. For both cavities

$$M_{18GHz} \approx M_{17GHz} \approx \frac{\omega_{2,18GHz}}{\omega_{col}} \approx \frac{\omega_{2,17GHz}}{\omega_{col}} \approx 0.5$$

Looking at equation 36 can be stated that f_{L1} should be twice as big as f_{L2} to satisfy the equation. In both setups the values $f_{L1} = 100$ mm and $f_{L2} = 50$ mm. In order for the telescope to work properly the lenses have to be separated by the summation of both focal lengths ($f_{L1} + f_{L2}$). The distance between the two lenses is 150 mm. After the telescope the beam travels through a polarizing beam splitter (PBS 1) [Thor labs PBS201]. Because the beam is P-polarized, it will be fully transmitted. To match a Gaussian beam to a cavity, the beam should not only be mode matched but also accurately aligned. After the beam splitter a quarter-wave plate is used to rotate polarization by 45 degrees.

Alignment is done by two beam steering mirrors M2 [Thorlabs BB111-E04] and M3 [Thorlabs BB111-E04. Usage of two mirrors is because of the possibility of changing not only its direction but also the angle in relation to the propagation surface. The beam then enters the mode matching lens L4 which is separated by 23.5 cm in relation to the 18 GHz cavity and 23.4 cm in relation to the 17 GHz cavity. If it's not on resonance, the cavity will reflect the beam full or partly. This light goes back through the mode matching lens, and the steering mirrors. Through the quarter-wave plate the light is rotated again by 45 degrees. Which rotates the polarization 90 degrees in relation to the initial beam. This makes the beam S-polarized and will be fully reflected by the beam splitter PBS 1 at a 90 degree angle. A mirror M2 [Thorlabs BB111-E04] is then used to aim the beam at the photo detector PD 1 [New Focus 1623] and a lens L3 is used to focus the beam. By connecting the photo detector PD 1 to DAQ (Data Aquisition) [NI PCIe-6351] the power of the reflecting beam is measured. The piezo actuator is also connected to the DAQ so that the voltage on the piezo can be controlled by a computer. In order to get the cavity at resonance, software is used that scans the voltage of the piezo while synchronously measures the intensity. The software finds the cavity peak of each scan and locks each run to that while decreeing the scanning range. This is to increase the accuracy each run. When the program gets to its minimal defined scanning range it fixes the voltage to the voltage that represented the resonance peak (minimal reflection). This voltage is fixed for a defined amount of time and after that the whole process starts again. The programming for this process is done with Python and the code is shown in Appendix 3. The voltage can't be fixed endlessly on the same value because transmission decays over time due to instabilities, thermal fluctuations and piezo drift. The time it takes for the transmission to decay a certain amount, gives information about the stability of the cavity. For this project the amount of time measured for the transmission to change by 5% represents the stability of the cavity, the longer the time, the more stable. A specification measured for both cavities, is the efficiency. This is the fraction of transmitted power compared to the power entering the cavity.

3.3 Double Cavity Setup

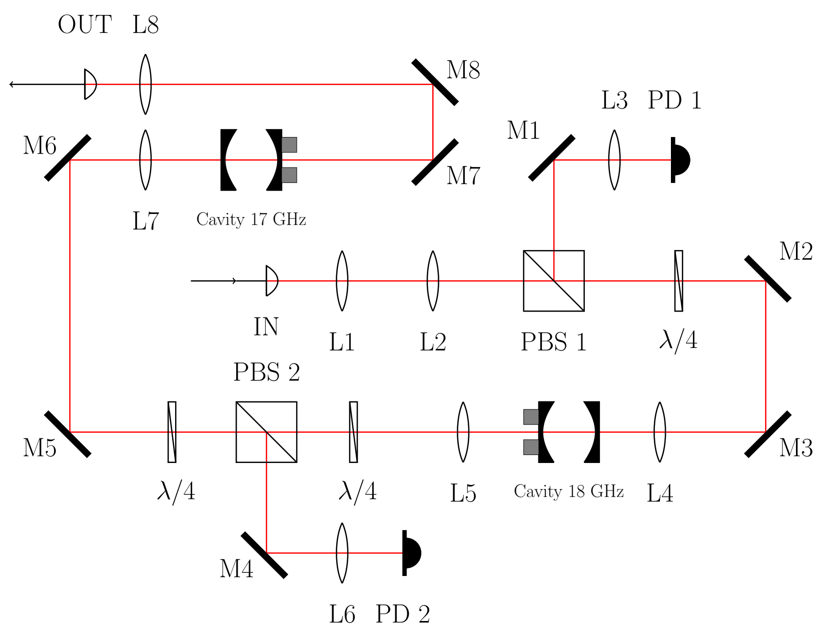


Figure 10: Alignment setup for one cavity.

The double cavity setup is an extension of the single cavity setup. Until the first cavity (18 GHz) it is exactly the same setup. If the first cavity is on resonance the light will be transmitted through a mode matching lens L5 that collimates the beam. The focal length of the lens is 150 mm. The smaller the focal length, the closer it can be placed to the cavity but this also means that aberrations have more of an effect. 150 mm gives a good balance of accuracy and compactness of the whole setup. Because the light is still circularly polarized, the polarization has to be reset to P-polarized in order to apply the second polarizing beam splitter PBS 2 [Thorlabs PBS513] properly. This is done by a quarter-wave plate that rotates the beam by -45 degrees. After the quarter-wave plate the light travels through the second polarizing beam splitter PBS 2 and gets fully transmitted. Just like the single cavity setup, the beam's polarization is rotated by 45 degrees, using a quarter-wave plate. After that the beam moves through two steering mirrors [Thorlabs BB111-E04] in order to align the beam to the second cavity. After that a mode matching lens L7 is used to couple the beam to the second cavity (17 GHz) with a 150 mm focal length. Just like the setup with one cavity the reflection is rotated again by a quarter-wave plate making it S-polarized. The polarizing beam splitter PBS 2 reflects the reflecting beam at a 90 degree angle and that is aimed by a mirror M4 [Thorlabs BB111-E04] into a photo detector PD 2 [New Focus 1623]. Just as PD 1, PD 2 is used with a DAQ and so is the piezo of the second cavity. With the same process the second cavity is put to resonance using programming. The python code for the double cavity setup is shown in appendix 3. If on resonance, the light will be transmitted and will hit two steering mirrors that are used to align the light to the output collimator coupler (OUT) [TC18APC-1550]. Before the light enters the coupler, the light is collimated using a mode matching lens L8. This lens is has a focal length of 500 mm and is placed ∼500 mm in relation to the second cavity. Important for this setup to measure is the stability and efficiency of the whole setup. The efficiency is measured by the fraction of the power coming out of the output coupler (OUT) and the power entering the input coupler (IN) so fiber-fiber. The stability is measured by measuring the decay in the total transmission of both cavities over time. Again the stability is defined by the amount of time it takes in order for the transmission to change 5%.

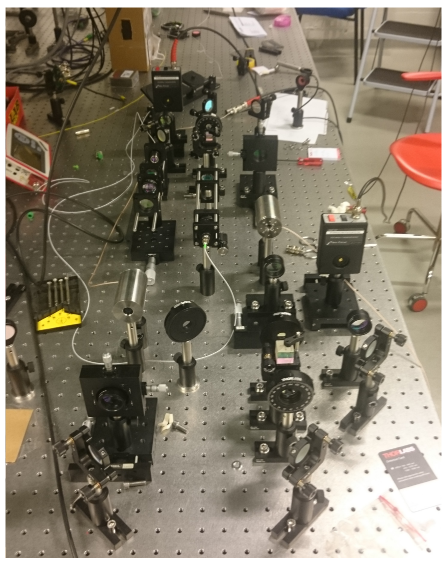


Figure 11: The double cavity setup build.

4 Measurements

4.1 Cavity Specifications

Some important properties of an optical cavity are not only its FSR but also its finesse and FWHM. These values can be measured relatively easy. When a cavity is placed in the "Single Cavity Setup"' (3.2) a full FSR can be measured by connecting the piezo to a function generator. This function generator scans the piezo with a triangle wave. To measure a full FSR the piezo has to scan with a high enough range, so that a second transmission peak can be measured. The change of distance between the mirrors in order to generate the neighboring peaks can be calculated using equation 7.

$$\frac{4\pi d}{1556\,\mathrm{nm}} = 2\pi\,(2-1) \rightarrow d = \frac{1556\,\mathrm{nm}}{2} = 778\,\mathrm{nm}$$

Table 2 shows that, for both cavities, in order to achieve a full FSR at least 9.75 V voltage difference has to applied compared to the main peak. Because the function generator can apply a voltage from -10 V up to 10 V at least one FSR should be detectable. The photo detector is connected to a oscilloscope which measures the reflected power of the cavity. If scanning from -10 V to 10 V reflection dips will appear. Meaning that at points where the power of the reflection is the lowest, you will get the highest transmission (points of resonance). In the next two images the scans for both cavities are shown. With on the y-axis the percentage of reflection by the cavity. On the x-axis the measurement time is shown of the oscilloscope. The scan rate of the piezo is 100 Hz from -10 V to 10 V.

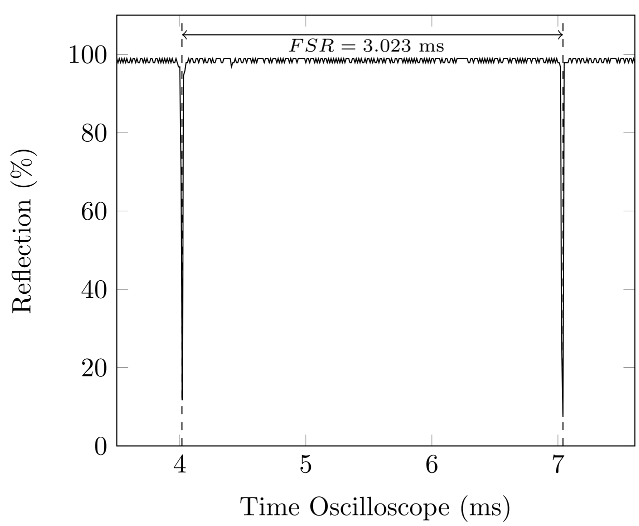


Figure 12: FSR scan of the 18 GHz cavity.

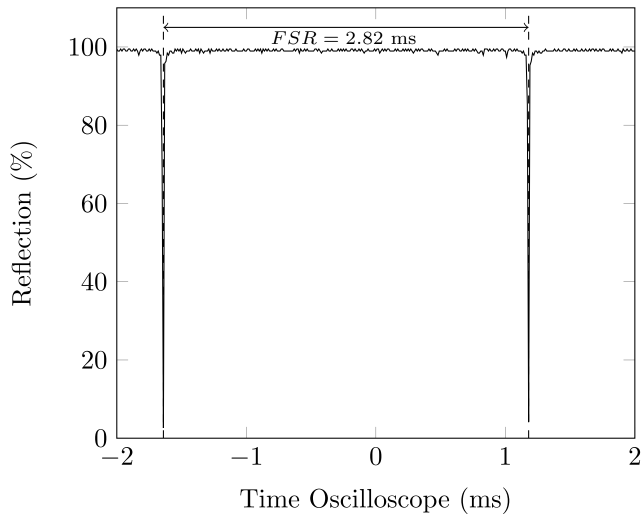


Figure 13: FSR scan of the 17GHz cavity.

Because the oscilloscope does not read out frequency, FSR is expressed in ms. Zooming in on one of the peaks gives a clear image of the shape of the peaks. These peak are Lorentzian distributions. The equation for a Lorentzian is [9]

$$f(x, x_0, \gamma, I) = \frac{I}{\left(1 + \left(\frac{x - x_0}{\gamma}\right)^2\right)} \tag{37}$$

Where x is the changing variable, I the normalization factor, x_0 the position of the peak and γ the scale parameter. By fitting a Lorentzian function over the measured peaks, the FWHM can be calculated using [9]

$$FWHM = 2\gamma \tag{38}$$

The measurement and fit for both cavities are shown in the next two images.

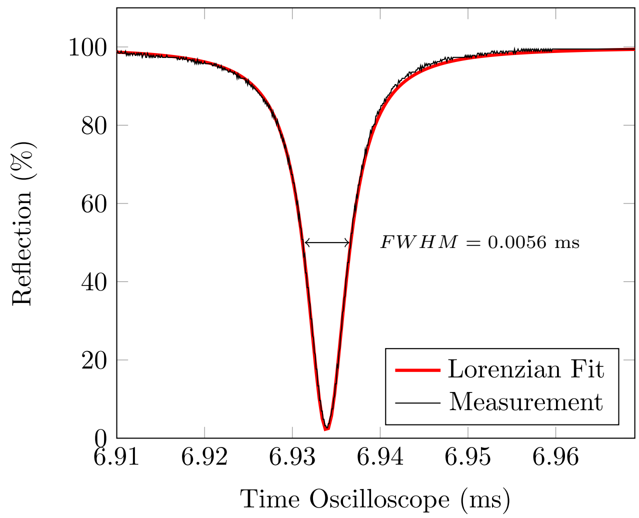


Figure 14: Resonance peak fit for the 18 GHz cavity.

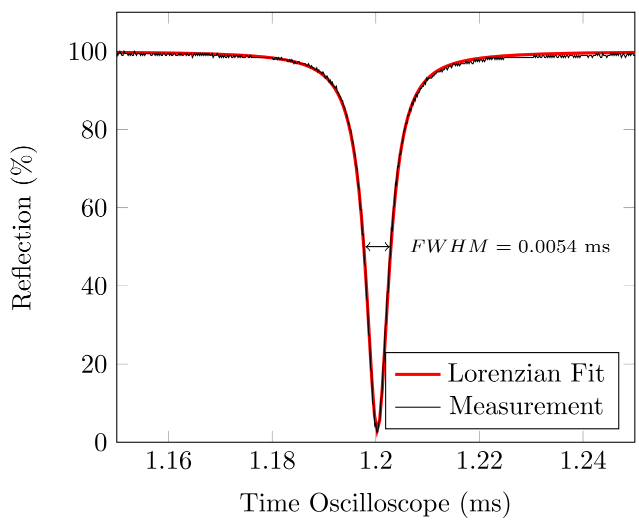


Figure 15: Resonance peak fit for the 18 GHz cavity.

For the 18 GHz cavity a FSR was measured of 3.023 ms and a FWHM of 0.0056 ms and for the 17 GHz cavity this was 2.82 ms and 0.0054 ms. As these measurements are linear with frequency, equation9 can be used to calculate the finesse of the cavities.

$$\mathcal{F}_{18GHz} = \frac{3.023}{0.0056} = 539$$

and

$$\mathcal{F}_{17GHz} = \frac{2.82}{0.0054} = 522$$

Using equation 9 again, the FWHM in frequency can be calculated for both cavities by using the finesse and the FSR in GHz.

$$FWHM_{18GHz} = \frac{18\,\text{GHz}}{539} = 33.3\,\text{MHz}$$

and

$$FWHM_{17GHz} = \frac{17\,\text{GHz}}{522} = 32.2\,\text{MHz}$$

In order determine the efficiency of both cavities, they were locked on resonance using a DAQ controller and a script written in Python [Appendix 3]. Then the power was measured, using the a power meter [Product], in front of the cavity and after it. The efficiency and the other properties are shown in table 2.

Cavity/FSR	18 GHz	17 GHz
Finesse	539	522
FWHM	33.3 MHz	32.2 MHz
Cavity Efficiency	95%	98%

Table 2: Cavity Specifications.

In the actual project the filters will be applied in, the procedure goes as followed.

1. Cavities get locked by a locking laser.
2. A fixed voltage is applied to the cavity piezo in order to keep the cavity on resonance
3. Locking laser is turned off.
4. Side peak filtering is done
5. Transmission cavities decay because of thermal and electrical drifts
6. Measurements stops and locking laser is turned on again
7. Back to the start of the procedure

This procedure will be rerun multiple times. In order to have long measurement times, the cavities have to be stable for a certain time, like a couple of seconds and preferably a couple of minutes. In order to measure this stability, the procedure is simulated. With software appendix 3 the cavity is locked using the laser. After that the voltage is fixed on resonance. The photo detector PD 1 then measures the decay in transmission over time. This procedure has been rerun 18 times for each cavity. The stability measure is the time needed for the original transmission to change by 5 %. The results of those measurements are shown in figure 16

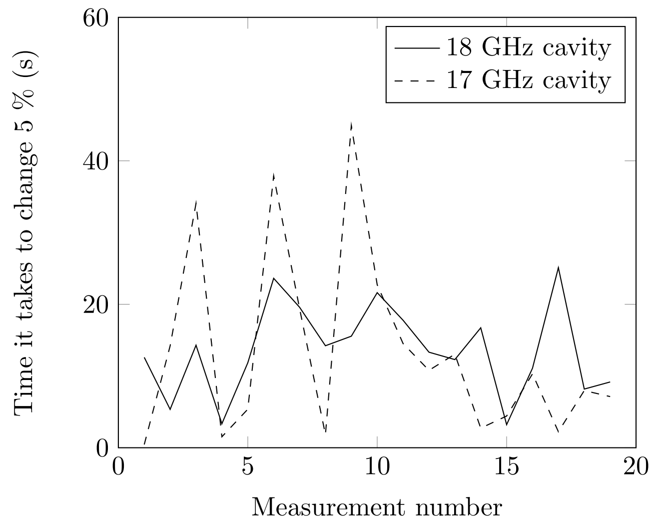


Figure 16: Stability of both cavities.

Each run took 90 seconds, with a locking sample rate of 10 kHz and a measurement sample rate of 60 Hz.

4.2 Double Cavity Filter

While both cavities are locked, all the losses over the setup are measured. The losses shown in figure 17 are mapped with red values. Each loss defines the loss between the position of two red values. For example the values shown after the first water-waveplate is the loss between in front of L2 and after $\lambda/4$.

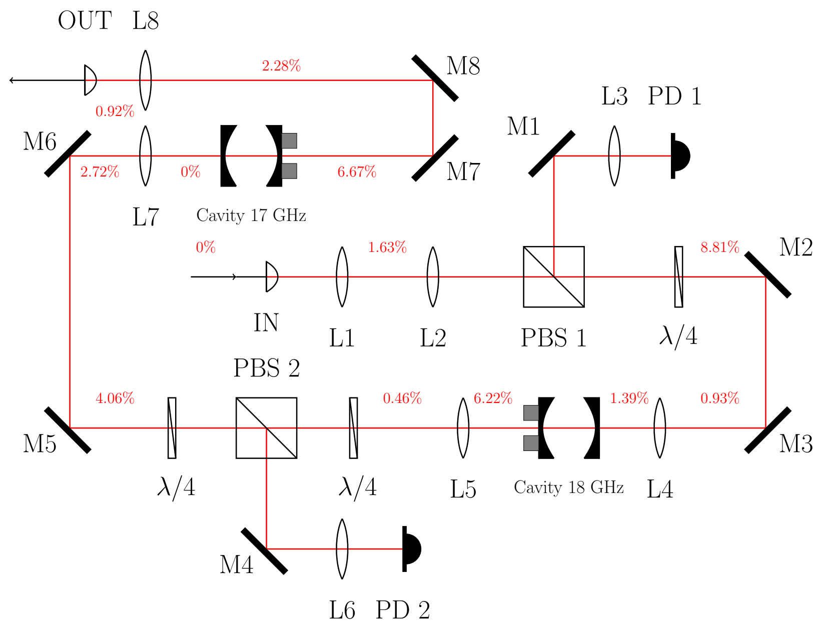


Figure 17: Map of losses in the system per part.

There is no loss measured after the coupler (OUT) because there was no time left to properly align it. But the efficiency the total loss between IN and right before OUT is 35%. Meaning the efficiency for the whole setup is 65%. The stability of the double cavity is measured and shown in figure 18. Again like the previous stability measurement of each cavity, the stability is determined by the amount of time it takes in order for the measured signal to change by 5 %.

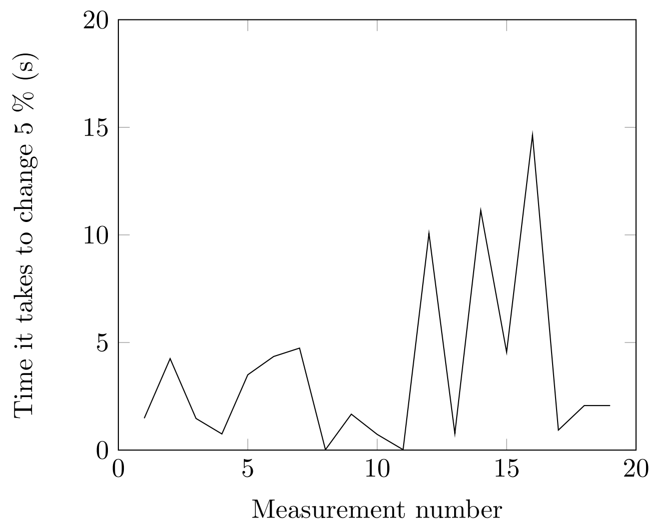


Figure 18: Stability of the double cavity setup.

4.3 Suppression

An important parameter to know is the suppression acted upon the neighboring 5 GHz peaks. For this thesis this measurement has not been done. But, discussing how this should be done is important, as this is a key parameter to know. Measuring this parameter is done by using two lasers. One locking laser and one detuning laser. The function of the locking laser is to hold both cavities on resonance using a PID controller. The detuning laser detunes 5 GHz. Both lasers have to be combined using a beam splitter and are both propagating through the whole setup. At the end of the setup a photo detector is placed to measure the total power. In order to measure the suppression of the 5 GHz side peaks, both laser are first set to the same frequencies. The cavities are then locked on that frequency. The photo detector now measures the max transmitted power. If the detuning laser is now detuned by 5 GHz, a power loss should occur. The loss can then be translated to a suppression.

5 Conclusion

The individual specification of the both cavities measured a 95% efficiency for the 18 GHz cavity and 98% for the 17 GHz cavity. The values for the 18 GHz cavity could be increased by better mode matching. As shown in figure 12 some higher order modes still existed. Both cavities failed having a FWHM within the 50 MHz - 60 MHz. In order to fix this the mirrors should be changed to lower reflectivity mirrors. Mirrors with a reflectivity of 99% should give a FWHM for both cavities within the required range. Also in order for the current cavities to work the pulse speed could be slowed down a bit. Both cavities do not have the required stability. This could be a software issue. The code used to lock the cavities is very simple, but an algorithm that guesses the drift by using data of previous runs could increase the stability because scan ranges could be reduced. Enclosing the whole setup could also increase stability. Changing the material of the cavity enclosure to a material with a smaller thermal expansion could improve stability.

For the double cavity setup a total efficiency of 65% was measured. Some of this could be improved by better mode matching, but looking at the loss map in figure 17 a power loss of % and 4.06% can be seen at the polarizing beam splitters. On the data sheet [7] transmission should lose 10% and reflection 0.5%. Changing the setup so that the reflection instead of transmission of the beam splitters is used could increase overall efficiency. The stability, shown in figure 18, is worse for the double cavity setup. This stability could be improved doing the same things as stated for the single cavity setup. Improve code and enclosing the setup.

In order for the cavities to work as filters in the Groeblacher Labs project, things should be changed in the setup. Mirrors with a lower reflectivity should be used in the cavities in order to get a bigger FWHM. Stability should be increased by writing a better working code, using different materials for the cavities and by enclosing the setup so that air movement and pressure changes have less effect on the setup. An important parameter that has to be measured is the suppression of neighbouring side peaks. This process is explained in section 4.3.

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6 APPENDIX 1: Calculations

6.1 Focal length mirrors

Both cavities use the same mirrors. These mirrors have a refractive index of$n = 1.444$. The mirrors are planar-concave, meaning that one side of the mirror is curved with a radius of curvature of $R = 0.5$ m, and the other side is planar meaning that its radius is infinite. The focal length of the mirrors can be calculated using the lens makers formula shown in equation 24. B

$$\frac{1}{f_m} = (1.444 - 1)\left[\frac{1}{0.5} - \frac{1}{\infty} + \frac{(1.444-1)t}{n \cdot 0.5 \cdot \infty}\right] = \frac{0.444}{0.5} = 0.888 \rightarrow f_m = 1.126\text{m}.$$

6.2 Beam waist of the cavities

Using equation 15 the waist of the confined beam is calculated for both cavities

$$\omega_{0,18GHz} = \sqrt{\tfrac{1.556 \cdot 10^{-6} \cdot 0.0083}{2\pi}\sqrt{2\tfrac{|0.5|}{0.0083} - 1}} \approx 150\mu\text{m}$$

and

$$\omega_{0,17GHz} = \sqrt{\frac{1.556 \cdot 10^{-6} \cdot 0.0088}{2\pi} \sqrt{2\frac{|0.5|}{0.0088} - 1}} \approx 152\mu\text{m}.$$

6.3 Beam radius and ROC passing the cavity mirror

Now for both cavities we calculate $R_1$and $\omega_1$for both cavities using equations 28 and 29

$$R_{1,18GHz} = \frac{1.126\left(0.0083^2 \cdot \left(1.556 \cdot 10^{-6}\right)^2 + 4\pi^2\left(150 \cdot 10^{-6}\right)^4\right)}{-0.0083^2\left(1.556 \cdot 10^{-6}\right)^2 + 2 \cdot 0.0083 \cdot 1.126 \cdot \left(1.556 \cdot 10^{-6}\right)^2 - 4\pi^2 \cdot \left(150 \cdot 10^{-6}\right)^4} = 0.90399$$

and

$$R_{1,17GHz} = \frac{1.126\left(0.0088^2 \cdot \left(1.556 \cdot 10^{-6}\right)^2 + 4\pi^2\left(152 \cdot 10^{-6}\right)^4\right)}{-0.0088^2\left(1.556 \cdot 10^{-6}\right)^2 + 2 \cdot 0.0088 \cdot 1.126 \cdot \left(1.556 \cdot 10^{-6}\right)^2 - 4\pi^2 \cdot \left(152 \cdot 10^{-6}\right)^4} = 0.89594$$

And for calculating ω_1

$$\omega_{1,18GHz} = \frac{\sqrt{0.0083^2(1.556 \cdot 10^{-6})^2 + 4\pi^2(150 \cdot 10^{-6})^4}}{2\pi \cdot 150 \cdot 10^{-6}} \approx 151\mu\text{m}$$

and

$$\omega_{1,17GHz} = \frac{\sqrt{0.0088^2(1.556 \cdot 10^{-6})^2 + 4\pi^2(152 \cdot 10^{-6})^4}}{2\pi \cdot 152 \cdot 10^{-6}} \approx 153\mu\text{m}$$

6.4 Divergence of beam radius after mirror

Using $R_{1,18GHz}$, $R_{1,17GHz}$, $\omega_{1,18GHz}$ and $\omega_{1,17GHz}$, which are values right after the cavity mirror, we can calculate the divergence of the beam for both cavities. This is done by using complex q parameters and the transfer matrix 21.

$$q_{free}(z) = \frac{1}{\frac{1}{R_{free}} - \frac{i\lambda}{\pi\omega_{free}^2}} = q_{in} + z \tag{39}$$

The complex q parameter right after the mirror for both cavities are calculated using equation 18. What results in

$$q_{in,18GHz} = 0.002338 + i0.045917$$

and

$$q_{in,17GHz} = 0.002486 + i0.047132$$

Equating the imaginary parts of equation 39 we should now be able to solve the beam radius $\omega_{free,18GHz}(z)$ and $\omega_{free,17GHz}(z)$ for both designs

$$\omega_{free,18GHz} = 2.25537 \cdot 10^{-13}\sqrt{2.12056 \times 10^{20} z^2 + 9.91576 \times 10^{17} z + 4.48253 \times 10^{17}}$$

$$\omega_{free,17GHz} = 4.64224 \cdot 10^{-18}\sqrt{4.87627 \times 10^{29} z^2 + 2.42481 \times 10^{27} z + 1.08624 \times 10^{27}}$$

7 APPENDIX 2: Drawings Cavity

7.1 Washer and Screws

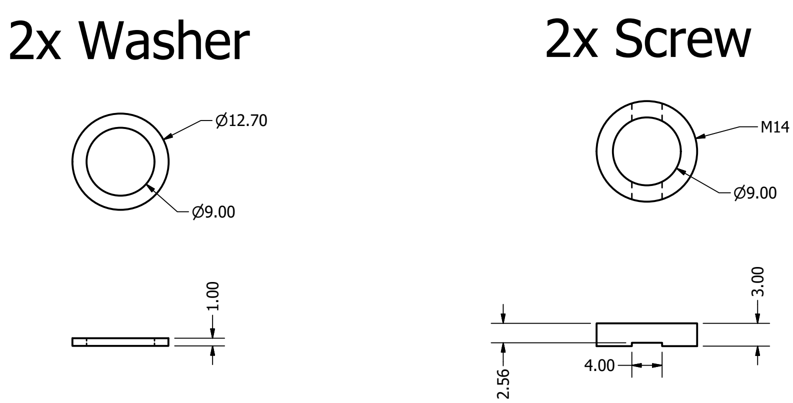

Figure 19: Drawing of the screws and washers made of POM. Per cavity 2 of each part are used.

7.2 Mirror Holder

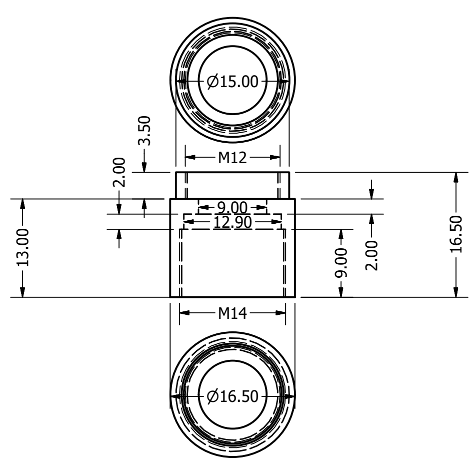

Figure 20: Holder that houses one mirror which is connected to the actuator.

7.3 17 GHz enclosure

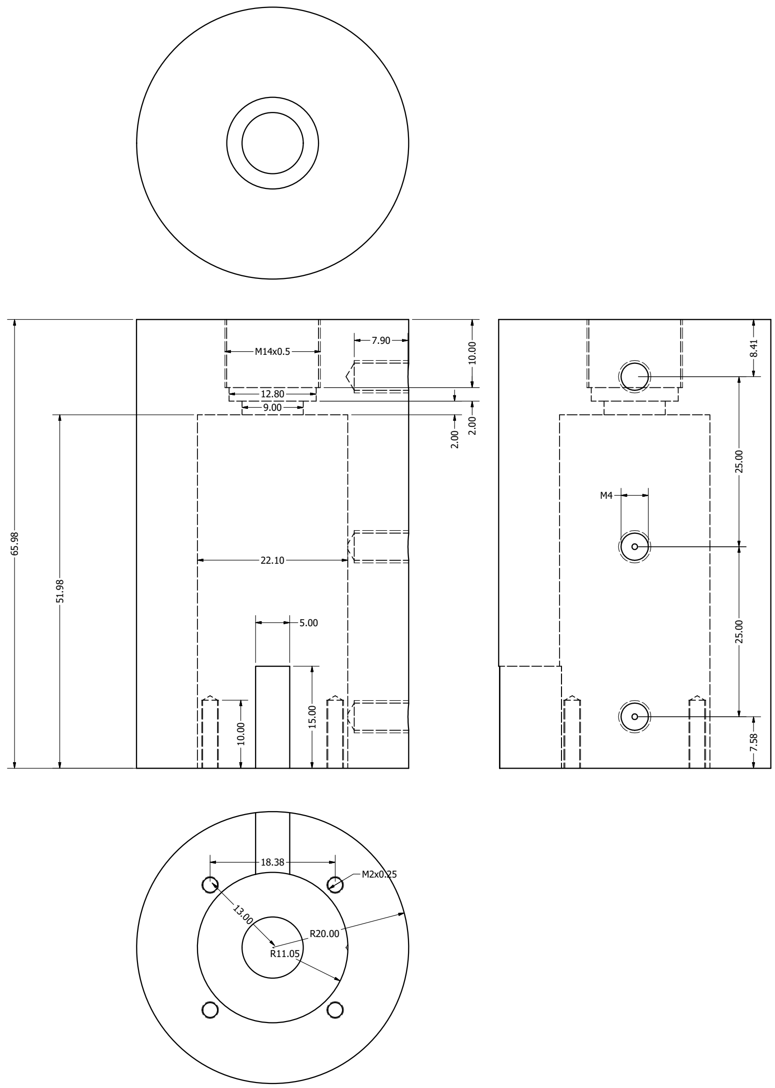

Figure 21: Cavity enclosure drawing for the 17 GHz cavity.

7.4 18 GHz enclosure

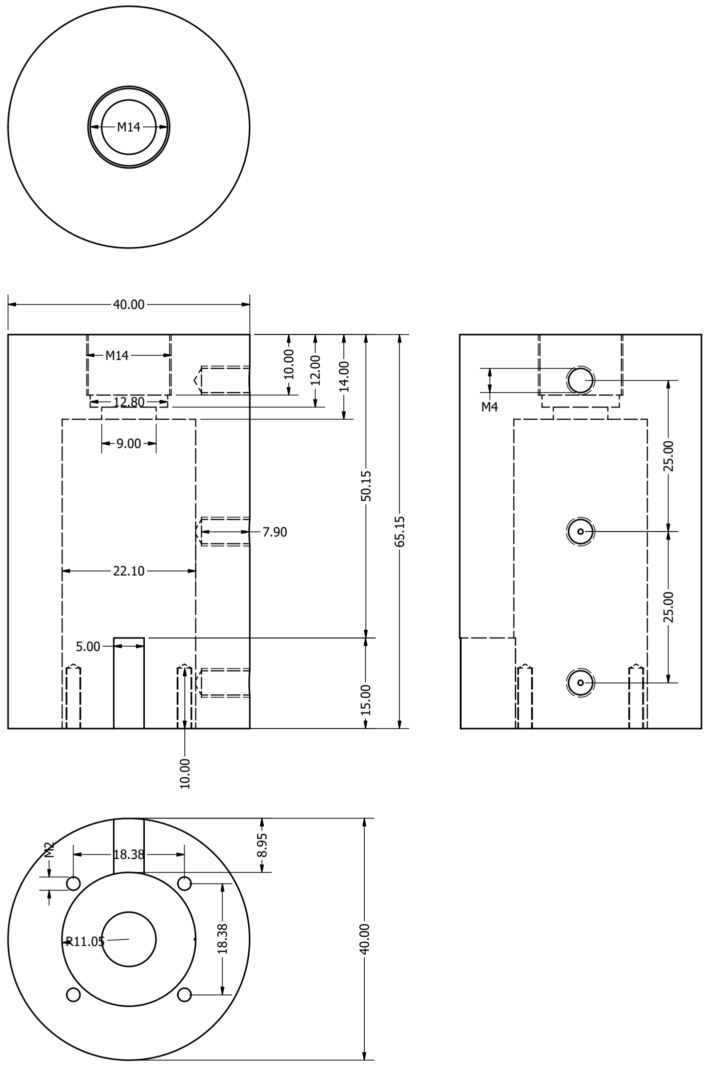

Figure 22: Cavity enclosure drawing for the 18 GHz cavity.

7.5 Back of the Cavity

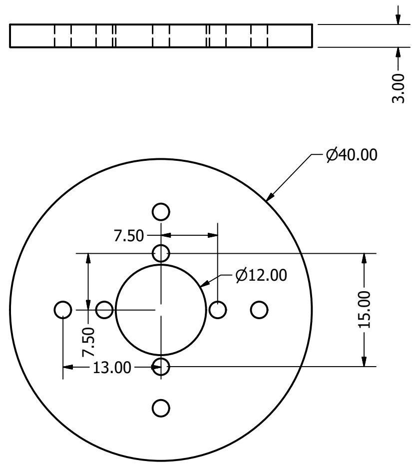

Figure 23: Cavity enclosure drawing for the 18 GHz cavity.

8 APPENDIX 3: Python Programming Code

8.1 Cavity locking

```
from nidaqmx import AnalogInputTask
from nidaqmx import AnalogOutputTask
from scipy import signal
import numpy as np
import matplotlib.pyplot as plt




#######SETTINGS########
chanin= 'Dev1/ai1' #input channel#
chanout= 'Dev1/ao1' #input channel#
sratescan = 100000.0 #Sample rate in Hz of the scanning procedure#
scanrate = 10 #Scanning rate in Hz of the scanning procedure#
mrate = 1 #sample rate Hz of measurement#
mtime = 0 #measurement time (s)#
msamples = mrate*mtime
minpeak=0.12
maxvoltage=9 #max or min voltage generated or applied to the daq
    (+9V,-9V)#
#######STARTING VALUES########
offset=0 #Offset triangle wave#
A=float(9) #Amplitude of the triangle wave#
amount=2000
```

```python
########PREPARING TRIANGLE WAVE#########
time=float(1)/float(scanrate) #time for each scan#
samples=sratescan*time
t = np.linspace(0, time, samples) #time array#
mt=np.linspace(0, mtime, msamples)
meas = np.zeros((amount+1,len(mt)))
meas[0]= np.linspace(0, mtime, msamples)
########CREATING TASKS#########
piezo = AnalogOutputTask() #Creating Output task to supply the piezo#
piezo.create_voltage_channel('Dev1/ao1', min_val=-10.0, max_val=10.0) #Creating virual channel for the output task#
piezo.configure_timing_sample_clock(sample_mode = 'continuous',rate = sratescan) #Setting up sample clock for output#
pd = AnalogInputTask() #Creating Input task to receive PD data#
pd.create_voltage_channel('Dev1/ai1', terminal = 'rse', min_val=-10.0, max_val=10.0) #Creating virual channel for the input task#


########STARTING TASKS#########
 #Starting Supply task#
k=1
piezo.start()
n=0 #setting up loop counter#
#####

pd.configure_timing_sample_clock(source='/Dev1/ao/SampleClock', sample_mode = 'continuous',rate = sratescan) #Setting up sample clock for the input to be equal to that of the output#
pd.start() #Starting Receiving task#

while True:


########SCANNING LOOP#########
    try:
        while True:
            triangle=offset+A*signal.sawtooth(2 * np.pi * scanrate * t) #Generating triangle wave#
            piezo.write(triangle) #Writing data to piezo#
            data = pd.read(len(triangle), fill_mode='group_by_scan_number') #Reading data of PD#
            Max=np.argmin(data)
            offset=triangle[Max]  #moving the peak to the middle of the scan
            if (data[Max]>minpeak):
                n=n-1
                A=float(pow(10,(-n+1)*0.25))
                if (A+offset>maxvoltage):
                    A=maxvoltage-np.absolute(offset)
                elif (offset-A<-maxvoltage):
                    A=maxvoltage-np.absolute(offset)
                elif (A<=0.001):
        break


```

```
            else:
                n=n+1
                A=float(pow(10,(-n+1)*0.25) )#Reducing the scanning range#
                if (A+offset>maxvoltage):
                    A=maxvoltage-np.absolute(offset)
                elif (offset-A<-maxvoltage):
                    A=maxvoltage-np.absolute(offset)
                elif (A<=0.001):
        break
        n=12
        ###piezo.write(offset) #writing the resonance voltage#




    except KeyboardInterrupt:
        break  # The answer was in the question!




 #######DONE#########
print "done"
measT=meas.T
plt.plot(measT[:,0], measT[:,1], 'ro')
plt.axis([0, mtime, 0, 1.2])
plt.show()
np.save(meas, measT, allow_pickle=True, fix_imports=True)
pd.clear(libnidaqmx=None)
piezo.clear(libnidaqmx=None)
reload(AnalogInputTask)
reload(AnalogOutputTask)
```

8.2 Single cavity scanning code (Python)

```
from nidaqmx import AnalogInputTask
from nidaqmx import AnalogOutputTask
from scipy import signal
import numpy as np
import matplotlib.pyplot as plt




#######SETTINGS#########
chanin= 'Dev1/ai1' #input channel#
chanout= 'Dev1/ao1' #input channel#
sratescan = 100000.0 #Sample rate in Hz of the scanning procedure#
scanrate = 10 #Scanning rate in Hz of the scanning procedure#
mrate = 1 #sample rate Hz of measurement#
mtime = 0 #measurement time (s)#
msamples = mrate*mtime
minpeak=0.05
maxvoltage=9 #max or min voltage generated or applied to the daq (+9V,-9V)#
#######STARTING VALUES########
```

```
offset=0 #Offset triangle wave#
A=float(9) #Amplitude of the triangle wave#
amount=2000
########PREPARING TRIANGLE WAVE#########
time=float(1)/float(scanrate) #time for each scan#
samples=sratescan*time
t = np.linspace(0, time, samples) #time array#
mt=np.linspace(0, mtime, msamples)
meas = np.zeros((amount+1,len(mt)))
meas[0]= np.linspace(0, mtime, msamples)
########CREATING TASKS#########
piezo = AnalogOutputTask() #Creating Output task to supply the piezo#
piezo.create_voltage_channel('Dev1/ao1', min_val=-10.0, max_val=10.0) #Creating virual channel for the output task#
piezo.configure_timing_sample_clock(sample_mode = 'continuous',rate = sratescan) #Setting up sample clock for output#
pd = AnalogInputTask() #Creating Input task to receive PD data#
pd.create_voltage_channel('Dev1/ai1', terminal = 'rse', min_val=-10.0, max_val=10.0) #Creating virual channel for the input task#


########STARTING TASKS#########
 #Starting Supply task#
k=1
piezo.start()
n=0 #setting up loop counter#
#####

while True:
    pd.configure_timing_sample_clock(source='/Dev1/ao/SampleClock', sample_mode = 'continuous',rate = sratescan) #Setting up sample clock for the input to be equal to that of the output#
    pd.start() #Starting Receiving task#

########SCANNING LOOP#########
    try:
        while True:
            triangle=offset+A*signal.sawtooth(2 * np.pi * scanrate * t) #Generating triangle wave#
            piezo.write(triangle) #Writing data to piezo#
            data = pd.read(len(triangle), fill_mode='group_by_scan_number') #Reading data of PD#
            Max=np.argmin(data)
            offset=triangle[Max]  #moving the peak to the middle of the scan
            if (data[Max]>minpeak):
                n=n-1
                A=float(pow(10,-n+1))
                if (A+offset>maxvoltage):
                    A=maxvoltage-np.absolute(offset)
                elif (offset-A<-maxvoltage):
                    A=maxvoltage-np.absolute(offset)



```

```
            else:
                n=n+1
                A=float(pow(10,-n+1)) #Reducing the scanning range#
                if (A+offset>maxvoltage):
                    A=maxvoltage-np.absolute(offset)
                elif (offset-A<-maxvoltage):
                    A=maxvoltage-np.absolute(offset)
                elif (A<=0.001):
        break
        n=3
        pd.stop()
        ###piezo.write(offset) #writing the resonance voltage#
        pd.configure_timing_sample_clock(source='OnboardClock', sample_mode = 'continuous',rate = mrate) #Setting up sample clock for the input to be equal to that of the output#
        pd.start()
        out=pd.read(timeout=1+mtime,fill_mode='group_by_scan_number',samples_per_channel=msamples)
        meas[k] = np.append([], out)
        pd.stop()
        k=k+1


    except KeyboardInterrupt:
        break  # The answer was in the question!

    if (k>amount):
         break


 ########DONE#########
print "done"
measT=meas.T
plt.plot(measT[:,0], measT[:,1], 'ro')
plt.axis([0, mtime, 0, 1.2])
plt.show()
np.save(meas, measT, allow_pickle=True, fix_imports=True)
pd.clear(libnidaqmx=None)
piezo.clear(libnidaqmx=None)
reload(AnalogInputTask)
reload(AnalogOutputTask)
```

8.3 Double cavity scanning code (Python)

```
from nidaqmx import AnalogInputTask
from nidaqmx import AnalogOutputTask
from scipy import signal
import numpy as np




########SETTINGS#########
chanin= 'Dev1/ai1' #input channel#
chanout= 'Dev1/ao1' #input channel#
sratescan = 10000.0 #Sample rate in Hz of the scanning procedure#
scanrate = 10 #Scanning rate in Hz of the scanning procedure#
```

```
mrate = 60 #sample rate Hz of measurement#
mtime = 45 #measurement time (s)#
msamples = mrate*mtime
minpeak=0.09
minpeak2=1
maxvoltage=9 #max or min voltage generated or applied to the daq
    (+9V,-9V)#
########STARTING VALUES##########
offset=0 #Offset triangle wave#
offset2=0
A=float(9) #Amplitude of the triangle wave#
B=float(9) #Amplitude of the triangle wave#
amount=20
########PREPARING TRIANGLE WAVE##########
time=float(1)/float(scanrate) #time for each scan#
samples=sratescan*time
t = np.linspace(0, time, samples) #time array#
mt=np.linspace(0, mtime, msamples)
meas = np.zeros((amount+1,len(mt)))
meas[0]= np.linspace(0, mtime, msamples)
########CREATING TASKS##########
piezo1 = AnalogOutputTask() #Creating Output task to supply the
    piezo#
piezo1.create_voltage_channel('Dev1/ao1', min_val=-10.0, max_val
    =10.0) #Creating virual channel for the output task#
piezo1.configure_timing_sample_clock(sample_mode = 'continuous',
    rate = sratescan) #Setting up sample clock for output#
piezo2 = AnalogOutputTask() #Creating Output task to supply the
    piezo#
piezo2.create_voltage_channel('Dev1/ao0', min_val=-10.0, max_val
    =10.0) #Creating virual channel for the output task#
piezo2.configure_timing_sample_clock(sample_mode = 'continuous',
    rate = 1000) #Setting up sample clock for output#
pd1 = AnalogInputTask() #Creating Input task to receive PD data#
pd1.create_voltage_channel('Dev1/ai1', terminal = 'rse', min_val=0,
     max_val=7.0) #Creating virual channel for the input task#
pd2 = AnalogInputTask() #Creating Input task to receive PD data#
pd2.create_voltage_channel('Dev1/ai0', terminal = 'rse', min_val=0,
     max_val=7.0) #Creating virual channel for the input task#



########STARTING TASKS##########
 #Starting Supply task#
k=1
n=0 #setting up loop counter#
j=0

piezo1.start()
pd1.configure_timing_sample_clock(source='/Dev1/ao/SampleClock',
    sample_mode = 'continuous',rate = sratescan) #Setting up sample
     clock for the input to be equal to that of the output#
pd1.start() #Starting Receiving task#

while True:
    kk = 1
    triangle=offset+A*signal.sawtooth(2 * np.pi * scanrate * t) #
```

```
    Generating triangle wave#
    piezo1.write(triangle) #Writing data to piezo#
    data = pd1.read(len(triangle), fill_mode='group_by_scan_number') #Reading data of PD#
    Max=np.argmin(data)
    offset=triangle[Max]  #moving the peak to the middle of the scan

    if (data[Max]>minpeak):
        n=n-1
        A=float(pow(10,(-n+1)*0.25))
        if (A+offset>maxvoltage):
            A=maxvoltage-np.absolute(offset)
        elif (offset-A<-maxvoltage):
            A=maxvoltage-np.absolute(offset)



    else:
        n=n+1
        A=float(pow(10,(-n+1)*0.25)) #Reducing the scanning range#
        if (A+offset>maxvoltage):
            A=maxvoltage-np.absolute(offset)
        elif (offset-A<-maxvoltage):
            A=maxvoltage-np.absolute(offset)
        elif (A<=0.01):
            break

#####
piezo1.stop()
pd1.stop()
datasave =0
while True:
    piezo1.start()
    pd1.configure_timing_sample_clock(source='/Dev1/ao/SampleClock',sample_mode = 'continuous',rate = sratescan) #Setting up sample clock for the input to be equal to that of the output#
    pd1.start() #Starting Receiving task#

#######SCANNING LOOP#########
    try:
        while True:
            kk = 1
            triangle=offset+A*signal.sawtooth(2 * np.pi * scanrate * t) #Generating triangle wave#
            piezo1.write(triangle) #Writing data to piezo#
            data = pd1.read(len(triangle), fill_mode='group_by_scan_number') #Reading data of PD#
            Max=np.argmin(data)
            offset=triangle[Max]  #moving the peak to the middle of the scan

            if (data[Max]>minpeak):
                n=n-1
                A=float(pow(10,(-n+1)*0.25))
                if (A+offset>maxvoltage):
```

```
                A=maxvoltage-np.absolute(offset)
            elif (offset-A<-maxvoltage):
                A=maxvoltage-np.absolute(offset)



        else:
            n=n+1
            A=float(pow(10,(-n+1)*0.25)) #Reducing the scanning range#
            if (A+offset>maxvoltage):
                A=maxvoltage-np.absolute(offset)
            elif (offset-A<-maxvoltage):
                A=maxvoltage-np.absolute(offset)
            elif (A<=0.01):
    break
    n=1
    pd1.stop()
    piezo1.write(offset) #writing the resonance voltage#
    piezo1.stop()

    print('locked cavity 1')
    #plt.plot(data)

    piezo2.start()
    pd2.configure_timing_sample_clock(source='/Dev1/ao/SampleClock',sample_mode = 'continuous',rate = sratescan) #Setting up sample clock for the input to be equal to that of the output#
    pd2.start() #Starting Receiving task#
    kk = 1
    while True:
        triangle2=offset2+B*signal.sawtooth(2 * np.pi * scanrate * t) #Generating triangle wave#
        piezo2.write(triangle2) #Writing data to piezo#
        data2 = pd2.read(len(triangle2), fill_mode='group_by_scan_number') #Reading data of PD#
        Max2=np.argmin(data2)
        offset2=triangle2[Max2]  #moving the peak to the middle of the scan


        if (data[Max2]>minpeak2):
            j=j-1
            B=float(pow(10,(-j+1)*0.25))
            if (B+offset2>maxvoltage):
                B=maxvoltage-np.absolute(offset2)
            elif (offset2-B<-maxvoltage):
                B=maxvoltage-np.absolute(offset2)



        else:
            j=j+1
            B=float(pow(10,(-j+1)*0.25)) #Reducing the scanning range#
            if (B+offset2>maxvoltage):
```

```
                    B=maxvoltage-np.absolute(offset2)
                elif (offset2-B<-maxvoltage):
                    B=maxvoltage-np.absolute(offset2)
                elif (B<=0.01):
        break
        j=10
        pd2.stop()
        piezo2.write(offset2) #writing the resonance voltage#
        print('locked cavity 2')
        pd2.configure_timing_sample_clock(sample_mode = 'continuous',rate = mrate)
        pd2.start()
        out=pd2.read(timeout=1+mtime,fill_mode='group_by_scan_number',samples_per_channel=msamples)
        meas[k] = np.append([], out)
        pd2.stop()
        piezo2.stop()
        k=k+1





    except KeyboardInterrupt:
        pd2.stop()
        piezo2.stop()
        break  # The answer was in the question!

    if (k>amount):
         break


 #######DONE#########
print "done"
measT=meas.T
np.savetxt('D:\meas', measT)
```