A Micromechanical Red-Shifting Tunable Vertical Cavity Filter

by

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Introduction

With the demand for telecommunications bandwidth increasing every year, much research and development is going into the devices necessary to expand a fiber’s information carrying capacity. One method of performing this task, using wavelength division multiplexing, is already being implemented on quite a broad scale. Naturally, this approach requires sources, detectors, and filters which can be used to pick precisely the proper wavelength, and so the demand for these devices continues to increase at a rapid rate.

Until recently, most of the tunable devices available were made of bulk optics, and so tended to be expensive and unwieldy. Semiconductor micro-electrical mechanical structures (MEMS), however, offer a low cost and low power solution. Vertical cavity structures in particular offer the advantages of single longitudinal mode operation, batch processing, 2D array integrability and cylindrical symmetry. Also, since the cavity length of a vertical cavity structure is so small, it can offer continuous tuning rather than discrete mode hopping.

Blue-shifting tunable vertical cavity structures using electrostatic attraction for mirror actuation have been studied rather extensively.\textsuperscript{[1]-[5]} Tunable cavities using thermal expansion for actuation were considered in our studies, but were discarded as not being accurate enough for our purposes.\textsuperscript{[6]-[7]} This thesis will describe a red-shifting
tunable vertical cavity filter using electrostatic attraction. In the theory section, the principles of operation will be discussed and models of the mechanical and optical operation of such a device will be presented. The testing section will describe the wafer structure, processing, measurements and results. Finally, the results will be summarized and future work will be discussed in the conclusion.

Theory

1) Principle of Operation

In the vertical cavity structure, optical filtering is most often achieved using a Fabry-Perot cavity formed by two Distributed Bragg Reflectors (DBRs) grown into the crystal. This can be accomplished by alternating high and low refractive index materials, each grown to a thickness of one quarter of the wavelength of the light at the center of the filter design. Varying compositions of Al$_x$Ga$_{1-x}$As work well for this purpose, as the refractive index can vary over a range of 3.54 (x=0) to 2.96 (x=1) (at 950nm) while the lattice constant of the material remains nearly constant, allowing for single crystal growth. Figures 1 and 2 show a typical DBR structure as well as the expected reflective properties of such a mirror. The expected reflectivity was calculated using a program written by two members of our group, G.S. Li and S.F. Lim. This program accepts as input the layer compositions and thicknesses, calculates the proper refractive indices, and uses the matrix method to calculate reflectivity.\[8\]
Fig. 1 - A common DBR structure. This one consists of alternating GaAs/AlAs layers, each designed to be \( \frac{1}{4} \) wavelength thick at 950nm. It consists of 12.5 pairs.
Fig. 2 – A graph of the reflectivity of the above structure as a function of input wavelength. Values for air were used for the surrounding media.

Fig. 3 – A graph of the reflectivity of a Fabry-Perot cavity formed by two of the above mirrors separated by 950nm of air. There is now a very narrow transmission peak at 950nm.

Figure 3 shows the effects of adding a second DBR to the first, separated by 950nm of air and thus creating a Fabry-Perot cavity. For our structures, the material separating the two DBRs can be removed using a selective plasma etch, creating an air gap between the two mirrors. This leaves the top mirror as an overhanging cantilever-type structure. If one of the DBRs is made of highly doped n-type material and the other is formed of highly doped p-type material, the whole structure can be reverse biased, creating a depletion layer formed by the charged doping ions. These ions will attract each other, bending the cantilever structure towards the bottom plane and actuating the mirror. As the distance between two Fabry-Perot mirrors changes, the transmitting
wavelength will also change, allowing for continuous tuning over the free spectral range of the mirrors. Figure 4 shows the predicted Fabry-Perot wavelength versus mirror spacing of the mirrors shown in figure 1. This was calculated using an addition to the program mentioned above. The addition was written by M.Y. Li, and iterates through the reflectivity program while changing the thickness of the air gap layer.

Fig. 4 – A graph of the Fabry-Perot mode of a cavity formed by two of the above mirrors as a function of mirror spacing. Modes outside of the range 900nm-1µm are ignored.

2) The One-Third Rule

One of the problems associated with blue-shifting cantilever structures, such as that shown in Figure 5, is that the cantilever can only reversibly tune over one third of the gap distance. This is called the one-third rule and can be derived with some simple calculations. First, we approximate the electrical properties of the cantilever as being much like a parallel plate capacitor. The requirement for this is that the longitudinal dimensions be much larger than the gap distance. Cantilevers are usually on the order of
100µm long by 5µm wide, and the gap distance is usually on the order of 1µm. So we are on the edge of the valid range for this approximation, though it is close enough to suit our purposes. The potential energy of such a structure, $U_{cap}$, is given by the equation:

$$U_{cap} = -\frac{\varepsilon AV^2}{2z}$$  \hspace{1cm} \text{(Eqn. 1)}

where $A$ is the area of the capacitor, $V$ is the voltage between the plates, $z$ is the separation of the plates, and $\varepsilon$ is the dielectric constant (which for us is $\varepsilon_0$, that of air, or vacuum). The negative sign ensures that the minimum potential energy occurs when the two plates come together. Naturally, this approximation breaks down when $z \to 0$, but in this limit, we know the two plates discharge and stick together due to Van der Waals interactions. The cantilever itself can be modeled to first order as having a spring-like return force. The energy of this is given by the equation:

$$U_{spring} = \frac{k(z - g)^2}{2}$$  \hspace{1cm} \text{(Eqn. 2)}

Here, $k$ is the spring constant, $g$ is the equilibrium gap distance (at 0 volts), and $z$ is again the separation of the cantilever and ground plane. We note that the minimum potential energy occurs at the equilibrium point, rising equally in both directions. The total potential energy of the system is simply the sum of $U_{cap}$ and $U_{spring}$, and the equilibrium $z$ position for a certain voltage can be found by solving for the minimum potential energy at that voltage. This can be accomplished by taking the derivative of the potential energy with respect to the displacement distance $z$, setting it equal to zero, and verifying whether or not it is a minimum at this point:

$$\frac{\partial U_{total}}{\partial z} = k(z - g) + \frac{\varepsilon AV^2}{2z^2} = 0$$
This equation admits the solutions for $z$ which satisfy:

\[ z^2(g - z) = \frac{\varepsilon AV^2}{2k} \]  

(Eqn. 4)

The graph of this equation can be found in Figure 6. We see that it is a cubic equation and has a negative slope for $z>2g/3$ and $z<0$. The solutions for $z<0$ are non-physical (they represent a cantilever displacement below the ground plane), so we will ignore them. The second derivative of the potential energy equation will tell us whether we are at an energy minimum, maximum, or saddle point:

\[ \frac{\partial^2 U_{\text{tot}}}{\partial z^2} = k - \frac{\varepsilon AV^2}{z^3} \]  

(Eqn. 5)

We can substitute in for $k$ due to our requirement that the first derivative be zero.

Rearranging equation 4 gives:

\[ k = \frac{\varepsilon AV^2}{2z^2(g - z)} \]  

(Eqn. 6)

Substitution yields:

\[ \frac{\partial^2 U_{\text{tot}}}{\partial z^2} = \frac{\varepsilon AV^2}{2z^2(g - z)} - \frac{\varepsilon AV^2}{z^3} = \left( \frac{z - 2(g - z)}{2z^3(g - z)} \right) \varepsilon AV^2 = \left( \frac{3z - 2g}{2z^3(g - z)} \right) \varepsilon AV^2 \]  

(Eqn. 7)
An energy minimum is found when the second derivative is positive, which happens for $z>0$ only when $g>z>2g/3$. Thus, we have proven that the only stable positions for our cantilever are in the upper third of the gap. For larger voltages, the electrostatic force overwhelms the spring return force and the cantilever slams into the ground plane.

Further discussion of the one-third rule can be found in [2, 3].

Fig. 6 – A graph of equation 4 showing the cubic nature of the allowed solutions for $z$ when the energy derivative is forced to be zero.

Fig. 7 – A simple cantilever structure, top and side view.
3) The Torsional Cantilever

For simple cantilever structures, like the one shown in Figure 7, the unbiased (zero voltage) gap distance is larger than the biased (reverse voltage > 0) gap distance because as the reverse bias is increased, the cantilever is attracted to the bottom plane. This causes the Fabry-Perot wavelength to shift from longer wavelengths to shorter wavelengths, a phenomenon known as blue-shifting. The filter structure we have designed, shown in figure 8, instead works like a seesaw. Everything but the support base is freely suspended. The counterweight, having a larger area than the head, has a greater electrostatic attraction and is attracted towards the bottom plane. This causes a rotation around the torsional beams, resulting in the head (where the light is coupled) being forced upwards. The result is a red-shifting filter structure, or one that passes longer wavelengths of light with increased reverse bias.

One of the advantages of such a structure is that the head is no longer subject to the one-third rule. While the counterweight can only tune over one third of the gap, the mirror beam acts as a lever to translate that motion into a longer travelling distance for the head. With this improvement, the limitation on how far a mirror can be actuated for a given gap size is only restricted by the geometrical design of the cantilever.

Using simple beam mechanics, one can derive the maximum deflection of a simple cantilever beam supported at both ends with a point force in the middle. For us, this point force can be modeled as that of a parallel plate capacitor, and would represent
Fig. 8 – Top and 3D views of the torsional cantilever structure. Note that in operation, everything except the support bases is freely suspended.

the combined electrostatic force pulling both the counterweight and the mirror head. For a beam of length $2L$, width $b$, thickness $t$, gap distance $g$, Young’s Modulus $E$ and combined area (of counterweight and mirror head) $A$, the maximum deflection (called sag) can be derived\cite{9}:

$$sag = \frac{2L^3}{t^3 \varepsilon E} \left( \frac{\varepsilon AV^2}{2g^2} \right)$$  \hspace{1cm} (Eqn. 8)

In this derivation, it is assumed that the gap size does not change much over the length of the cantilever, and the effects of attraction of the beam itself are neglected. The effects of sag are shown pictorially in Figure 9(a). I present the equation here only to get a feel for
how the deflection scales with such parameters as thickness, length, and width. A similar
equation can be found for the angular deflection of a rectangular shaft under an applied
twisting moment, as is shown in the mechanics text by Crandall, Dahl, and Lardner.\[10]\]

They state that the angular deflection $\phi$ of a rectangular shaft of length $2L$, transverse
dimensions $a$ and $b$ ($a \geq b$), and shear modulus $G$ can be expressed in the form:

$$\phi = \frac{M_t L}{c_2 G ab^3}$$  \hspace{1cm} (Eqn. 9)

where $c_2$ depends on the ratio $a/b$ and can range from 0.141 to 0.312 for a ratio from 1 to
10. Here, $M_t$ is the twisting moment, which is just the applied force $\varepsilon AV^2/2g^2$ times the
distance of the lever arm. Since the mirror and counterweight moments counteract each
other, we must subtract the mirror twisting moment from the counterweight twisting
moment to get the total moment. For our case, where the torsional beams are fixed at
both ends and a twisting moment is applied in the center, this can be approximately
rewritten as:

$$\phi = \frac{L_{beam}}{c_2 G ab^3 g^2} \left( A_{cw} w_{cw} - 2 A_{head} L_{head} \right)$$  \hspace{1cm} (Eqn. 10)

where $w_{cw}$ is the width of the counterweight, $L_{head}$ is the length of the mirror beam, and
$L_{beam}$ is the length of the torsional beams. The twist is shown pictorially in Figure 9(b).

Here, I have assumed that the radius of the head is much smaller than the length of the
mirror beam, and I have ignored the contribution of the mirror beam to the mirror
twisting moment. Again, the most important thing is to realize how the scaling laws
apply. The sag of the torsional rods will work against the twisting deflection, minimizing
the overall amount of deflection one will be able to generate. If the torsional beam is
wider than it is thick, than the scaling of $\phi$ and and sag are nearly identical in length,
width, and thickness (\( \phi \propto \frac{L}{wt^3}, \) sag \( \propto \frac{L}{wt^3} \)). Obviously, this is not ideal, as it would be difficult to generate much overall deflection in this manner. If, on the other hand, the thickness is greater than the width, the scaling is not the same. Recall that in our original equation for angular deflection, it is the smaller of the two transverse beam dimensions which is cubed. Thus, the scaling would be \( \phi \propto \frac{L}{tw^3} \) and \( \text{sag} \propto \frac{L}{wt^3} \). With careful choices of \( t \) and \( w \) for the mirror beam and torsional beam, it is now possible to make a significant improvement over normal deflections. That is, it is now possible to make twist deflection \( \gg \) sag.

\[
\text{Force} = \frac{\varepsilon AV^2}{2g^2}
\]

For more exact calculations, the equations become too difficult to solve without a computer. Modeling of the mechanical motion of the torsional cantilever was accomplished with Parametric Technology Corporation’s (PTC’s) Pro/MECHANICA™ software, release 20.0. The only constraints to the deflection range are imposed by the wafer growth and device fabrication process. For example, wafer thickness is limited by the length of time that the growth chamber can remain calibrated. The counterweight
size is constrained by the etching process that selectively removes the mirror gap material and leaves the cantilever freely suspended. If the counterweight is too large, this etch will not remove all of the underlying material (eventually, the sacrificial layer becomes passivated and un-etchable), and the device will be useless. The selective etch will be described in more detail in the next section. The head diameter should be small to minimize its twisting moment, but needs to be large enough for coupling of light from a fiber. Limits on these devices were chosen as a balance of maximizing device performance and minimizing fabrication difficulty. Once the dimensions for everything but mirror beam length and torsional beam length were chosen I used the PTC software to find the optimal solutions for these two variables. An optimal solution was defined as the dimensions allowing the largest twist ratio, where twist ratio is given by the equation:

\[
TwistRatio = \frac{|MaxHeadDeflection|}{MaxCounterweightDeflection}
\]  \hspace{1cm} (Eqn. 11)

Below is a table of device dimensions, with the twist ratio for each calculated using the Pro/Mechanica™ software.
Calculated Performance of Various Devices

<table>
<thead>
<tr>
<th>Various dimensions [µms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>cantilever width</td>
</tr>
<tr>
<td>mirror beam width</td>
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<tr>
<td>cantilever length</td>
</tr>
<tr>
<td>mirror beam length</td>
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<tr>
<td>counterweight width</td>
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<td>counterweight length</td>
</tr>
<tr>
<td>connector width</td>
</tr>
<tr>
<td>connector length</td>
</tr>
<tr>
<td><strong>Twist Ratio</strong></td>
</tr>
</tbody>
</table>

Table 1 – Twist ratios of various torsional cantilever structures. Assumes a gap size of 0.8 µm

Fig. 10 – Actual growth structure of wafer used.
Test and Measurement

Design

The structure of the wafer used is shown in Figure 10. It was grown by Molecular Beam Epitaxy using Be for p-doping and Si for n-doping. Grown on an n-doped GaAs substrate, it is composed of 12 pairs of n-doped ¼ wavelength thick AlAs/GaAs layers followed by one AlAs/Al$_{0.2}$Ga$_{0.8}$As layer pair. The designed center filter wavelength is 950nm. On top of this bottom DBR was grown an undoped 0.8µm thick GaAs sacrificial layer, which is selectively removed to form the air gap. The top DBR is composed of 18.5 pairs of ¼ wavelength thick p-doped Al$_{0.2}$Ga$_{0.8}$As/Al$_{0.7}$Ga$_{0.3}$As layers, followed by a ½ wavelength thick layer of p-doped Al$_{0.7}$Ga$_{0.3}$As, and then finally a 1.4µm thick p-doped cap layer of Al$_{0.2}$Ga$_{0.8}$As on top of the whole structure. This cap layer was included to make the cantilever thicker than wide, as described in the theory section. The n-doping was set at 1e18cc$^{-1}$, while the p-doping was also set at 1e18 cc$^{-1}$, with the exception of the last 0.1µm of the capping layer, which was highly doped to 1e19cc$^{-1}$ to lower contact resistance. Figures 11 and 12 respectively show the calculated and measured reflectometry scans for this wafer. As one can see, the wafer matches quite well with expectations.

Fabrication

Device fabrication involved two mask steps. To begin, the top electrical contact area was defined by photolithography using positive resist and a dark-field mask. 150A of titanium was then deposited using an Ultek e-beam evaporator, followed by 1500A of gold. The photoresist was then stripped with acetone, and ~2000A of nitride was
Fig. 11 – Calculated reflectometry scan of the actual wafer structure.

Fig. 12 – Measured reflectometry scan from the actual wafer used. The x-axis is wavelength [μm], and the y-axis is reflectivity [au], normalized to the gold.
deposited over the whole wafer. Photolithography with the second mask was performed on top of the nitride to define the devices, and the nitride was then stripped using a CF$_4$ plasma etch to ensure straight sidewalls. The photoresist was again stripped, and the devices were etched in an Oxford RIE 100 using an SiCl$_4$ plasma until the sacrificial layer was exposed. We used nitride because we found a photoresist mask in this step would react with the etch gasses and contaminate the machine. The end point of this etch was determined by a laser reflectometry scan of the wafer while it was being etched. This scan takes advantage of the difference in indices of refraction of the various layers in the wafer structure due to the varying aluminum concentration. A typical scan is shown in Figure 13. Finally, undercut was achieved using the Oxford RIE 100, running a selective etch recipe consisting of 20sccm of SiCl$_4$ and 10sccm of SF$_6$ at 75mTorr, 35W, and 60°C for ~25 minutes. The SF$_6$ ions react with the aluminum in the crystal to form AlF$_3$, which is not etched by these gasses. This passivates all layers with aluminum, and allows the GaAs layer of the mirror gap to be selectively etched.$^{[11]-[16]}$ The nitride was

![Fig. 13 – The reflectometry trace for the vertical etch of this wafer. Vertical etching performed in an Oxford 100 RIE, using a SiCl$_4$ plasma.](image)
First, gold contact pads are deposited.

Next, the device is defined by etching down to the GaAs sacrificial layer.

Finally, the device is released and suspended by removing the selective etch layer.

Fig. 13 – Summary of the major processing steps involved in device fabrication.
removed by washing the wafer in 5:1 BOE, and the devices were released with a critical point dryer to keep them from being drawn down to the substrate by liquid surface tension. A summary of the major processing steps is presented in Figure 14.

Results

Figure 15 shows an SEM photo of a typical device. The contact pads are 180\(\mu\)m on a side, and the bases are 200\(\mu\)m on a side. Figure 16 shows a close-up of the head of this device. Notice that the sidewalls of the device are quite a bit over-etched. The mirror beam is supposed to be 5\(\mu\)m wide and 4.25\(\mu\)m thick, but in this picture the device is considerable thinner than it is tall, suggesting quite a bit of discrepancy between photolithography mask dimensions and actual dimensions. In truth, these differences are only noticeable on small dimension structures such as the mirror beams and the torsional beams; in the other features, the percentage error is much smaller because the dimensions are larger. We believe this overetching is due to the Oxford’s RIE chamber being dirty during the vertical etch. Vertical etches with a clean chamber produced cantilever heads like the one shown in Figure 17. As you can see in this figure, the sidewalls are quite straight. In both pictures, you will notice significant structure on the ground plane. This occurs because the selective etch is over-aggressive; the aluminum layer beneath the sacrificial layer is not being passivated. Unfortunately, at this time we have not found a selective etch recipe which both gives the required amount of undercut to release the structures and leaves a clean ground plane. This will be discussed further in the conclusions section.
Fig. 15 – An SEM photo of an actual device. On the right hand side, you can see the thin aluminum wire used to wire bond the device.

Fig. 16 – A close-up of the head of the cantilever shown above.
Unless otherwise noted, the rest of the data shown will be on a device with the following parameters: torsional beam length 70µm, head diameter 15µm, mirror beam length 100µm, counterweight length 250µm, counterweight width 30µm, torsional and mirror beam widths 5µm, and connector 5µs wide by 10µs long. The thickness of the cantilever, determined by the wafer structure, is 4.25µm. Again, recall that actual dimensions can vary slightly due to over-aggressive vertical etching.

![Fig. 17 – A close-up of the head of a cantilever with straight sidewalls.](image)

**Proof of Concept**

To test the movement properties of these cantilevers, certain devices were wire-bonded to gold contact pads on a glass slide. These contact pads were then soldered to wire feed-throughs on a scanning electron microscope so that the device could be reverse biased while inside the SEM. Figures 18 and 19 show a close up of the head of the
Fig. 18 – An extreme close-up of the head of the device shown in figure 15 with no reverse bias applied. A white mark was inserted to aid viewing.

Fig. 19 – A close up of the head of the device in figure 15, reverse biased to 10 volts. Note that this is the same magnification and working distance as that of figure 18. By looking at the head relative to the structure on the ground plane, it is clear that the head moves upwards under reverse bias.
Fig. 20 – A close up of the corner of the counterweight shown in figure 15, with no reverse bias applied. A white arrow was inserted to aid viewing.

Fig. 21 – The same picture as above, with 10 V reverse bias applied. By again looking at the counterweight relative to the structure on the ground plane one can see that the counterweight deflects downwards. Device shown in figure 15, reverse biased at 0 and 10 Volts, respectively. One can see by looking at the device relative to the structure on the ground plane that the head clearly
moves upwards. Looking at the close ups of the back corner of the counterweight of the same device in Figures 20 and 21, also biased at 0 and 10 Volts, it is clear that the counterweight moves downwards. Thus, the whole device must be twisting about the torsional beams. To our knowledge, this is the first optical semiconductor device to use electrostatic attraction to produce deflections away from the ground plane.

Filter Characteristics

The optical test setup is shown in Figure 22. With this setup, it is possible to obtain a graph of filter transmission as a function of input wavelength. The filter transmission is normalized to the laser power by splitting the input beam and measuring the input power at the same time that the filter transmission power is measured. The Spectra Physics brand Model 3900 tunable Ti-sapphire laser allows us to reliably reach wavelengths from 850nm to 970nm. Figure 23 shows a graph of filter transmission as a function of wavelength for a device at several different reverse bias conditions. This light was coupled through the counterweight of the filter, so we would expect it to blue-shift, as we indeed see. The presence of partially etched material underneath the head of the cantilever, which can be seen in the SEM photos, prevented an adequate signal from being transmitted. The fact that the counterweight transmission peak blue-shifts, however, is further proof that the counterweight is being attracted to the bottom plane.
Fig. 22 – The test measurement setup.
Fig. 23 – Filter transmission as a function of wavelength. In this graph, the light is being coupled through the counterweight, explaining the blue-shifting with increasing reverse bias.

Conclusion

We have designed a red-shifting tunable vertical cavity filter that uses electrostatic attraction for mirror actuation, twisting around a set of torsional beams. To our knowledge, this thesis comprises the first demonstration of an optical MEMS device to use electrostatic attraction to produce a torque on a cantilever structure, creating a red-shifting cavity. This has important implications in achieving widely tunable optoelectronic devices such as lasers, detectors, and filters beyond the 1/3 rule set by electrostatics. Extension of the tuning ranges of these devices can have important
implications for any fiber optic communications network by ultimately increasing the bandwidth of these networks and reducing the cost of the components involved. We have demonstrated that the device moves as expected by applying a reverse bias while observing with an SEM, and have measured the optical filter properties through the counterweight of the device. We were not able to obtain optical filter data for the head of the device because our selective etch recipe is not quite selective enough for the amount of undercut we require. Further work needs to be done to fully characterize this selective etch. Another item to work on in the future would be to incorporate another p-n junction within the mirrors. When reverse biased, this would create a tunable detector, and when forward biased it would create a tunable laser.
References


