Optical Cavities: Confocal vs Concentric

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Optical Cavities: What are They?

Also known as Optical resonators, these cavities consist of two mirrors coated with partially reflective coating. Depending on the type of resonator, the length of the cavity will vary, but in all scenarios, the rough setup is the same. The result is an output of greater intensity than the original beam and of a single frequency.
• There are many configurations for optical cavities.
• Each configuration has specific requirements that make it either stable or unstable.
• The ones pictured to the left are all stable configurations.
What is an OC Used for?

- Lasers
- Frequency modulation and laser locking
- Frequency reference
- Interferometers (Fabry-Perot)

![Spherical-plane resonator for a HeNe laser.](image.png)
Definition of Stability

• Light is completely contained within the cavity and retraces its path after one round trip through the cavity.

\[ g = 1 - \frac{L}{r} \]

Where \( L \) is the cavity length and \( r \) is the radius of curvature for the mirror.

\[ 0 \leq g_1 g_2 \leq 1 \]

This expression implies stability. The blue area is considered stable.
How do Stable OC Work?

• The cavity employs the powers of constructive interference in order to create a standing wave within the confines of the cavity.

The conditions for a standing wave in a cavity are:

Where $m$ - integer, $\lambda$ – wavelength, $L$ – cavity length

$$m \frac{\lambda}{2} = L$$
Longitudinal Modes

A longitudinal mode occurs every time a standing wave is formed in the cavity. The distance between the modes, in terms of frequency (hertz), is called the Free Spectral Range:

$$\Delta \nu = m \frac{c}{2L}$$

The spectral width (FWHM) of the peaks is determined by the frequency of the first mode over the finesse of the cavity.

$$\delta = \frac{\nu_f}{F}$$
What is Finesse?

A characteristic of the cavity defined as a function of the total reflectivity of the cavity mirrors ($R = R_1 R_2$).

The higher the reflectivity, the higher the finesse, which implies a narrower emission peak.

\[ F = \frac{\pi \sqrt{R}}{1 - R} \]
Transverse Modes

Transverse modes are just as the title suggests, modes of the cavity that originate from standing waves in the transverse direction.

The purest form of output from an optical cavity is Gaussian. This mode is deemed $\text{TEM}_{00}$, zero transverse modes, and is one reason why stable cavities are so favorable.

![Figure 6.8.2 Gaussian beam inside a laser cavity.](image)

Side Note: An unstable resonator never produces a Gaussian beam, but can handle much higher power than a stable resonator because of the lack of need for partially reflective optics, which can be burned through at high power.

\[ w_0 = \left( \frac{\lambda L}{2\pi} \right)^{1/2} \]
Laguerre – Gaussian beams are the result of transverse modes. Transverse modes are generally not wanted in applications of an optical cavity, however, in laser cavities, the modes indicate that more of the lasing medium is being utilized, so the resulting output is more intense. The center of the pattern for $\text{TEM}_{p_0}$ remains Gaussian, so only that is used.
Summer REU Project

• Investigate the difference between a confocal cavity, something the lab is rather familiar with, and a concentric cavity.
  • Visually
  • Quantitatively
• Is a concentric cavity realistic to use in a future experiment?
Confocal vs Concentric

• Using 20cm radius of curvature, 90% reflective mirrors with 1064nm light
• Major difference in setup:
  Cf – 20cm cavity length
    Collimated beam through first journey across the cavity length
  Cc – 40cm cavity length
    Light is focused to the center of the cavity
Visual Results

• When properly aligned, the concentric output was identical to the confocal output. i.e. transverse modes and then eventual constant TEM$_{00}$ output.

• The difference was really in how each output looked prior to being aligned correctly.

Confocal:
-- Misaligned
-- Almost aligned

Concentric:
-- Misaligned with center focus
-- w/o center focus
Finding Emission Peaks

• Creating the piezo controlled mirror mount
• Supplies:
  - 1 mirror
  - 2 homemade 1in. washers
  - Kepton foil
  - 3 Piezo Chip Actuators
  - 1in diameter lens holder
  - Spring ~1in diameter
Putting it all Together
Seeing the Peaks

• In order to see a peak, one must sweep the laser.
• Swept the cavity length with the Piezos hooked to a function generator outputting a saw-tooth function.
• -10 – 1000 V @ 2.2 microns per 100V
• This is enough for many FSR and thus many peaks.
The voltage ramp was about 300V.

As you can see, the middle two peaks are closer together. This is because the piezo changes direction at \( T = \text{zero} \). This produces a mirror image effect on the scope.

Due to scope constraints, we see only one FSR (2 peaks), but as the voltage ramp indicates, there could easily be 2 or 3.
Calculations

• Concentric cavity of L = 40 cm implies an FSR of 375 MHz (refer to slide 8)
• Two 90% reflective mirrors gives a total reflectivity of 81% which implies a Finesse of 14.88 (refer to slide 9)
• These two factors give a peak FWHM of about 25 MHz (refer to slide 8)
• All of these characteristics are roughly realized in the following graphs, which are all of oscilloscope data of cavity behavior while testing was performed
For quick comparison, this is a graph of confocal peaks that were created by the cavity in a very rough confocal setup. Note the lack of extra modes, so although it is a rough setup, it is relatively close to the correct cavity distance, and if it were more carefully aligned, the peaks would be slightly more narrow.
First attempt at concentric setup. Length was misjudged and was actually ~38 cm, for this diagram. Note the cavity is still stable, but there are additional smaller peaks. These small peaks are caused by higher order modes. Recall, the desired mode is TEM\textsubscript{00} only, and can be achieved by honing in on the correct cavity length (in this case, 40 cm).
After many rounds of tweaking the length of the cavity, the peaks become slightly more narrow and the extra modes almost completely disappear.
Going from Unstable to Stable, it is apparent how close to the edge of the stability area (refer to slide 5) the concentric setup is. Cavity length changed was < 0.5 cm.
Future Investigation

- Seeing if the Pound Drever Hall locking technique is applicable to this type of cavity.
- How does it compare to other PDH locking setups around the lab?
- Converting the entire setup to UHV and integrating it into the master plan for a future experiment.
Sources

• Laser Fundamentals by William Thomas Silfvast
• Fundamentals of Light Sources and Lasers by Mark Csele
• Experiment 3 Fabry Perot Resonator by Dr. –Ing Dickmann
• Some pictures came from either Wikipedia or Csele.
• All data, animations, and photographs were original
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Other Lab Creations

• Wired a PID lock box
• Constructed a BNC Connection box
• Helped build a fan stand
• Random setup for the High B (i.e. coupling the lasers)
• Shop class saw (mine is totally better than Sarah’s, or so I have heard from a nonbiased source)