Optical disk resonators with micro-wave free spectral range for optoelectronic oscillators

Hervé Tavernier, Ngan Ti Kim Nguyen, Patrice Féron, Patrice Salzenstein, Laurent Larger, Enrico Rubiola

Outline

• Choice of the material
• Resonator fabrication
• Experiments
• Results
• Conclusion
Optical materials

- \( Q = 6 \times 10^{10} \) demonstrated with CaF\(_2\) disk (I. Grudinin).

<table>
<thead>
<tr>
<th></th>
<th>MgF2</th>
<th>CaF2</th>
<th>Fused silica</th>
<th>Quartz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transparency range</td>
<td>0.12 to 8.5 µm</td>
<td>0.2 to 9 µm</td>
<td>0.18 to 2.5 µm</td>
<td>0.19 to 2.9 µm</td>
</tr>
<tr>
<td>Refractive index @ 1550 nm</td>
<td>no = 1.37, ne = 1.38</td>
<td>n = 1.42</td>
<td>n = 1.44</td>
<td>no = 1.54, ne = 1.53</td>
</tr>
<tr>
<td>Hardness (Mohs)</td>
<td>6</td>
<td>4</td>
<td>6-7</td>
<td>7</td>
</tr>
<tr>
<td>Crystal Class</td>
<td>Tetragonal</td>
<td>Cubic</td>
<td>noncrystalline</td>
<td>Hexagonal</td>
</tr>
<tr>
<td>H2O pollution</td>
<td>Good</td>
<td>Good</td>
<td>Bad</td>
<td>Bad</td>
</tr>
<tr>
<td>Mechanical shock</td>
<td>Good</td>
<td>Bad</td>
<td>Good</td>
<td>good</td>
</tr>
</tbody>
</table>

MgF2 inversion point relates to Pound stabilization

Whispering-gallery-mode resonators as frequency references. II. Stabilization


Anatoliy A. Savchenkov, Andrey B. Matsko,* Vladimir S. Ilchenko, Nan Yu, and Lute Maleki
Dedicated lathe

- Brushless motor.
- Air-bearing to guarantee low vibrations.
- Small eccentricity error (200 nm).
- Precision collet to position the resonator holder.

Derives from hard-disk test equipment
Can you figure out what a hard disk is?
3.5” & 7200 rpm => ~ 200 km/h
1 (μm)^2 bit area, 50 nm head–disk distance
Resonators preforming

• Stick a 6 mm MgF2 optical window on a metal holder (0.5 - 1 mm thick).

• Correct for the centering error by grinding with several diamond grains size (40 - 20 \( \mu m \)).

• Create two 20° bevels to get a thin edge (about 30 \( \mu m \), depending on crystal splinters).
Manual polishing step

- Several polishing powders in decreasing grains size (diamond, colloidal silica, cerium oxide, alumina) diluted in distilled water (6 µm to 30 nm).

- Polishing baize used as powder holder.

- Rotation speed depends on grain size.
Newton rings

- White light phase-shifting microscope with 1 nm of resolution.
  (FEMTO-ST instrument, based on the idea of phase-contrast microscope)

- Interference fringes as contour curves. Smooth contour curves indicates roughness less than 20 nm.
Roughness measurement

White light phase-shifting microscope with piezo control, after scan and image processing

3D surface of the disk

Roughness: **6 nm** peak-to-peak, **0.92 nm** rms.
Taper coupling

- Tapered SMF28 fiber glued on the holder. Manufactured by LASEO (Lannion, FR)
- For lowest stress, holder geometry and alloy match the thermal expansion of glass.
- Waist $< 3 \mu m$.
- 3-axis nano-positioning with 20 nm resolution.

Advantages vs. prism-shaped fiber:
+ higher modal selectivity
+ clean mechanical design
+ one coupler serves as in/out
Resonance measurement

- 1550 nm erbium laser (3 mW power).
- 50 pm wavelength sweep (6 GHz).
- High resolution oscilloscope to analyze very sharp phenomena as peak resonance.
Detection of the resonance peak

- Single mode excitation:
  - Small taper size selects a thin excitation region.
  - Needs polarization controller.
- Wavelength span too small to scan a full FSR.
- Scan rate 50 Hz
Q factor measurement

- Self-homodyne method.
- Increasing wavelength triangle scan.
- 400 Hz scan rate.
- Oscillation damping gives: \( Q = 3.4 \times 10^8 \)

• Asymmetric shape.
• Positive TC ($\lambda$) of the resonance.
• Triangle sweep.
• First half of resonance shape: the carrier increasingly heats the energy region.
  The resonance tracks the carrier.
• Second half: heating decreases.
  The resonance steps back
Thermal effects
example of CaF2 resonator

- cross section of the field region 1 μm²
- CaF₂ thermal conductivity 9.5 W/mK
- dissipated power 300 μW
- wavelength 1.56 μm
- air temperature 300 K
- still air thermal conductivity 10 W/m²K
- simplification: the heat flows from the mode region is uniform

finite-element simulation and data refer to another resonator because with a single taper we can’t measure the resonator dissipated power
Thermal effects: CaF2 example

Thermal expansion yields a frequency change

\[ \frac{\Delta \nu}{\nu_0} \simeq \frac{dL}{L \, dT} \Delta T \]

The thermal expansion coefficient of CaF2 is

\[ \frac{dL}{L \, dT} \simeq 1.85 \times 10^{-5} \]

Take a frequency change of 1.13 MHz at 192 THz (1560 nm)

\[ \Delta T \simeq 3.2 \times 10^{-4} \text{ K} \]

A factor 10 is missing, vs. finite-element calculus.

Of course, the mode ring is constrained by the cold crystal around.

High temperature gradient
Conclusion

- Design and implementation of a dedicated lathe with 200 nm eccentricity error and low vibrations.

- A few 5.5 mm MgF2 resonator implemented.

- Preforming and polishing process gives surface roughness of 0.92 nm rms on the 60 µm polished edge.

- First demonstration of the microwave-FSR resonator with taper coupling.

- Stable coupling over > 1 week.

- Preliminary result: Q = 3.4 x 10^8.

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