Kerr Frequency Combs: from Laboratory to Space

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3 November 2015
A “Typical” Space Mission

• On **October 15, 1997**, the Cassini–Huygens spacecraft was launched on an almost 7-year journey to the Saturn system. On its way, Cassini–Huygens passes Venus (twice), Earth, and Jupiter — arriving at the Saturn system on July 1, 2004.

• Cassini made a close flyby of Enceladus on Oct. 28, (2015) in the mission's deepest-ever dive through the moon's active plume of icy material. The spacecraft passed a mere 30 miles (49 kilometers) above the moon's surface.
Microresonators Generating Optical Combs

\[ \lambda = 680 \text{ nm}, 780 \text{ nm}, 800 \text{ nm}, 1060 \text{ nm}, 1550 \text{ nm}, 2500 \text{ nm}, 4500 \text{ nm} \]

Integration, < mm diameter

High Q, > few mm diameter

- Microring
  - Cornell/Columbia
  - GaeCornell/UCLA
  - EPFL
  - Pueduw

- Silica toroid
  - Caltech

- Silica wedge
  - Caltech

- Fused quartz
  - OEwaves
  - JPL
  - EPFL
  - NIST

- Crystalline glass
  - NIST

Slide adopted from NIST
The lightly shaded regions indicate that absorption may be too high for low loss applications.
Choice of Resonator Host Material

Q is ultimately determined by the material absorption $\alpha$:

$$Q = \frac{2\pi n}{\alpha \lambda}$$

$$(2\gamma)^{-1} = n_0(\alpha c)^{-1}$$

For $\alpha \simeq \alpha_{UV} e^{\lambda_{UV}/\lambda} + \alpha_R \lambda^{-4} + \alpha_{IR} e^{-\lambda_{IR}/\lambda}$

<table>
<thead>
<tr>
<th>Material</th>
<th>Transparency $\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaF$_2$</td>
<td>$3 \times 10^{-7}$ cm$^{-1}$</td>
</tr>
<tr>
<td>SiO$_2$ (optical fiber)</td>
<td>$5 \times 10^{-6}$ cm$^{-1}$</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>$1 \times 10^{-5}$ cm$^{-1}$</td>
</tr>
<tr>
<td>SiO$_2$ (quartz)</td>
<td>$1 \times 10^{-5}$ cm$^{-1}$</td>
</tr>
<tr>
<td>LiNbO$_3$/LiTaO$_3$</td>
<td>$1 \times 10^{-4}$ cm$^{-1}$</td>
</tr>
<tr>
<td>Si$_3$N$_4$/Hydex</td>
<td>$1 \times 10^{-2}$ cm$^{-1}$</td>
</tr>
<tr>
<td>Si</td>
<td>$8 \times 10^{-2}$ cm$^{-1}$</td>
</tr>
<tr>
<td>Polymers</td>
<td>$1 \times 10^{-1}$ cm$^{-1}$</td>
</tr>
</tbody>
</table>

* Transparency of most of the optical materials is not well documented in literature and the documented values vary by an order of magnitude.
Spectrally Pure Microwave/mm-wave Oscillators

RF oscillators are needed in a variety of applications including:

- Communications
- Direction finding of signals of interest
- Applications related to coherent operation across multiple segmented platforms
- Radar --- Remote sensing
- Radio science
- Metrology
Hyper-parametric Oscillator

\[ Q = 2 \times 10^{10} \text{ at } \lambda = 1310 \text{ nm} \]

Hamiltonian:

\[ H = -\hbar g \left( b_+^* b_+ a a + a^* a^* b_+ b_+ \right) \]

\[ g = \omega_0 \frac{n_2}{n_0} \frac{\hbar \omega_c}{V n_0} \]

Coupling Schemes

For a resonator with index $n$ surrounded by air, the evanescent height, $h$, is:

$$ h = \frac{1}{k \sqrt{n^2 - 1}} $$

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Where $k$ is the wave number and $n$ is the refractive index.

**Angled Fiber**

- $\theta_{\text{input}} = \frac{\pi}{2} - \arcsin \left( \frac{n}{n_c} \right)$

**Microsphere**

- $\Phi$

- Reflecting surface normal

**Prism Coupling**

- Mechanical Pull
- Clamped End
- SMF28
- Hydrogen Flame

**Fiber taper**
Microresonator Based OEO
Development at OEwaves (2003)

Microresonator – Tool for achieving low vibration sensitivity OEO
Miniature Optical Frequency Comb Oscillator

Optical frequency comb and the corresponding RF signal at 35 GHz.
The First Prototype

X- and Ka-Band Photonic Oscillators

Ka-band RF Signal

SSB Phase Noise, dBc/Hz

Frequency (Hz)

10 GHz RF Signal

-150
-140
-130
-120
-110
-100

JPL'04
OEvwaves'10
OEvwaves'14

Frequency offset, Hz

10^3 10^4 10^5 10^6 10^7

SPIE PRISM AWARDS WINNER

INVENT • DEVELOP • DELIVER
Field Operation

Participated in a controlled flight. Remained operational during the entire duration of the mission.
The “Triple Oscillator”
Integrated Prototypes with Improved Thermal Isolation
Mode Locked Comb Oscillator

![Graph showing relative optical power and wavelength]

- Relative RF power, dB
- Frequency detuning from 9.9 GHz, Hz

- Relative optical power, dB
- Wavelength, nm

![Diagram of Mode Locked Comb Oscillator]

INVENT • DEVELOP • DELIVER
Impact of Mode Crossing

Interaction among mode families limits growth of the mode locked frequency combs
Self-Injection Locked Laser Performance

W. Liang et al., Nature Communications 6, Article no: 7371 (2015)
Close-in Noise Comes From the Laser (via the Resonator)

Blue line: laser noise
Red line: comb noise
Ratio is $20\log(\nu_{\text{opt}}/\nu_{\text{RF}})$: it results from the common noise source, e.g. temperature fluctuations in the resonator mode resulting from the laser noise.

Two lasers are locked to modes of the same resonator (another, test, build was created)
Blue line: laser on reflection
Red line: laser on transmission
Magenta line: beat between the lasers. Common noise is rejected.
10 GHz Coherent Frequency Combs With Crystalline Resonators at OEwaves

That’s the 4th mode
FSR is ~0.02nm
~1nm

795 nm

1550 nm

4550 nm

-106dBc/Hz @ 10kHz
KOEO Assembly Overview

Optical shim consisting of:
• Semiconductor Laser
• Resonator for Kerr-Comb Generation
• High speed photo-diode for RF generation
• Amplification
• Thermo-electric coolers for stabilization
• Various passive optics

• Optical shim
• Additional amplification
• Various RF and DC components
Process Flow for Photonic Front End manufacturing

1. Manufacture and Test Resonator
2. Resonator, prism, and flex arm
3. Alignment of laser to resonator
4. Alignment of focusing lens
5. Wirebond
6. Performance Tests
Challenges for Space Instruments

- Size, weight, and power (SWaP) and cost
  - In deep space missions, these parameters “sum to a fixed value”
- Space qualification
- Rad hardening
- Other environmental perturbations (launch and vibration, temperature, magnetic fields, vacuum, ...)
- Reliability
- Redundancy
Kerr Comb Operation

- Recall that Kerr combs depend on a balance between nonlinearity and group velocity dispersion in the resonator
  - Nonlinearity $\rightarrow$ Optical power
  - GVD $\rightarrow$ Resonator dispersion (material and geometric)

Both laser characteristics and resonator material must survive in the radiation environment of space
Induced Absorption

<table>
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<tr>
<th>Treatment</th>
<th>Samples</th>
</tr>
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<tbody>
<tr>
<td>p^+ 90 krad</td>
<td>BK7, BK7, K5, K5G20, LaK9, LF5, KzFsN4, SK5, SF6, SFL6, SFL6 G05</td>
</tr>
<tr>
<td>p^+ 350 krad</td>
<td></td>
</tr>
<tr>
<td>p^+ 900 krad</td>
<td></td>
</tr>
<tr>
<td>γ 100 krad</td>
<td></td>
</tr>
<tr>
<td>γ 400 krad</td>
<td></td>
</tr>
</tbody>
</table>

European Space Agency
Space radiation testing of radiation resistant glasses and crystals

Tammy D. Henson and Geoffrey K. Torrington
Sandia National Laboratories, P.O Box 5800, Albuquerque, NM 87185-0972

Figure 23. Transmission measurements of a Schott 157 nm eximer grade synthetic monocrystalline CaF₂ window after exposure to gamma radiation (t = 7.065 mm).

Figure 24. Transmission measurements of a Schott 193 nm eximer grade synthetic monocrystalline CaF₂ window after exposure to gamma radiation (t = 9.94 mm).

Beware Lead Contamination!
Lasers for Space

• First laser in space for Appolo 15 LIDAR in 1971, a flashlamp pumped ruby laser
• Mars Orbiter Laser Altimeter (MOLA) laser transmitter launched in 1995
• Geoscience Laser Altimeter System (GLAS) in 2003
• A laser diode space module qualification and certification program was initiated by NASA in 2013 for ICEsat-2 mission
  – Lifetime goal, 27,000 hours
Parting Thoughts

- Chip scale Kerr combs based on crystalline resonators are now in use as oscillators in actual field operation (TRL-7).
- Generation of Kerr combs from visible to mid-IR has been demonstrated.
- These devices could be considered for space applications, for example in cubesat/nanosat, in both optical and microwave/mm-wave applications.
- Space qualification of semiconductor lasers and detectors will enable chips scale Kerr combs for deep Space applications.