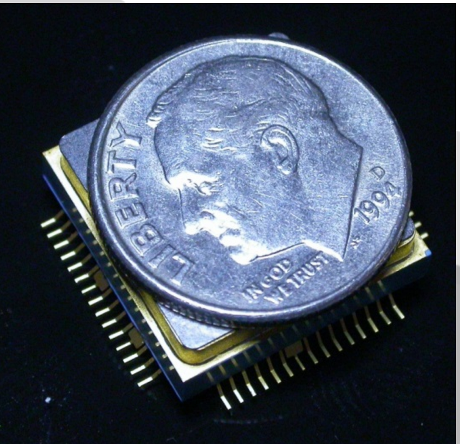
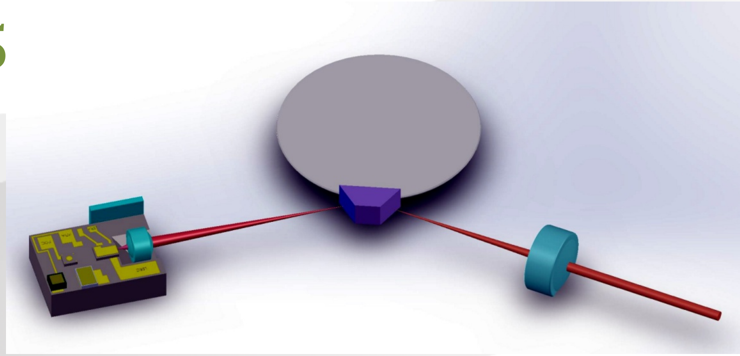
Kerr Frequency Combs: from Laboratory to Space

Lute Maleki

3 November 2015

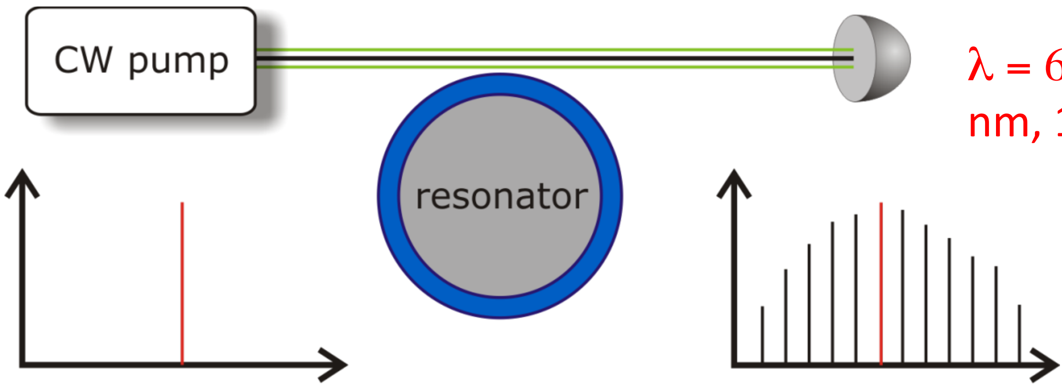




A “Typical” Space Mission

- 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



λ = 680 nm, 780 nm, 800 nm, 1060 nm, 1550 nm, 2500 nm, 4500 nm

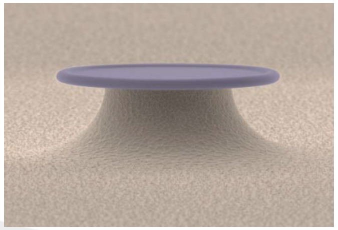
integration, < mm diameter

high Q, > few mm diameter

Microring

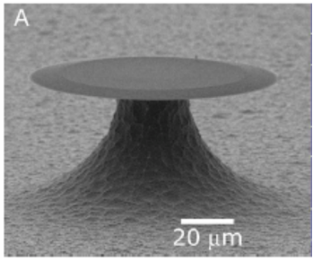
-Cornell/Columbia
-GaeCornell/UCLA
-EPFL
-Pueduw

Silica toroid



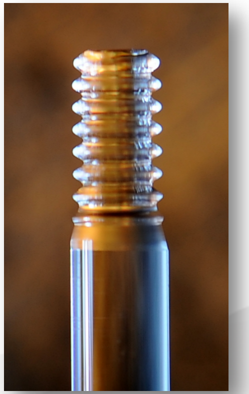
-Caltech
-EPFL

Silica wedge



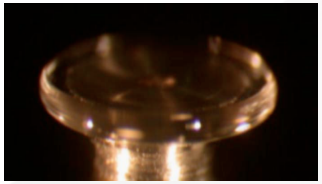
-Caltech

Fused quartz



-NIST

Crystalline glass

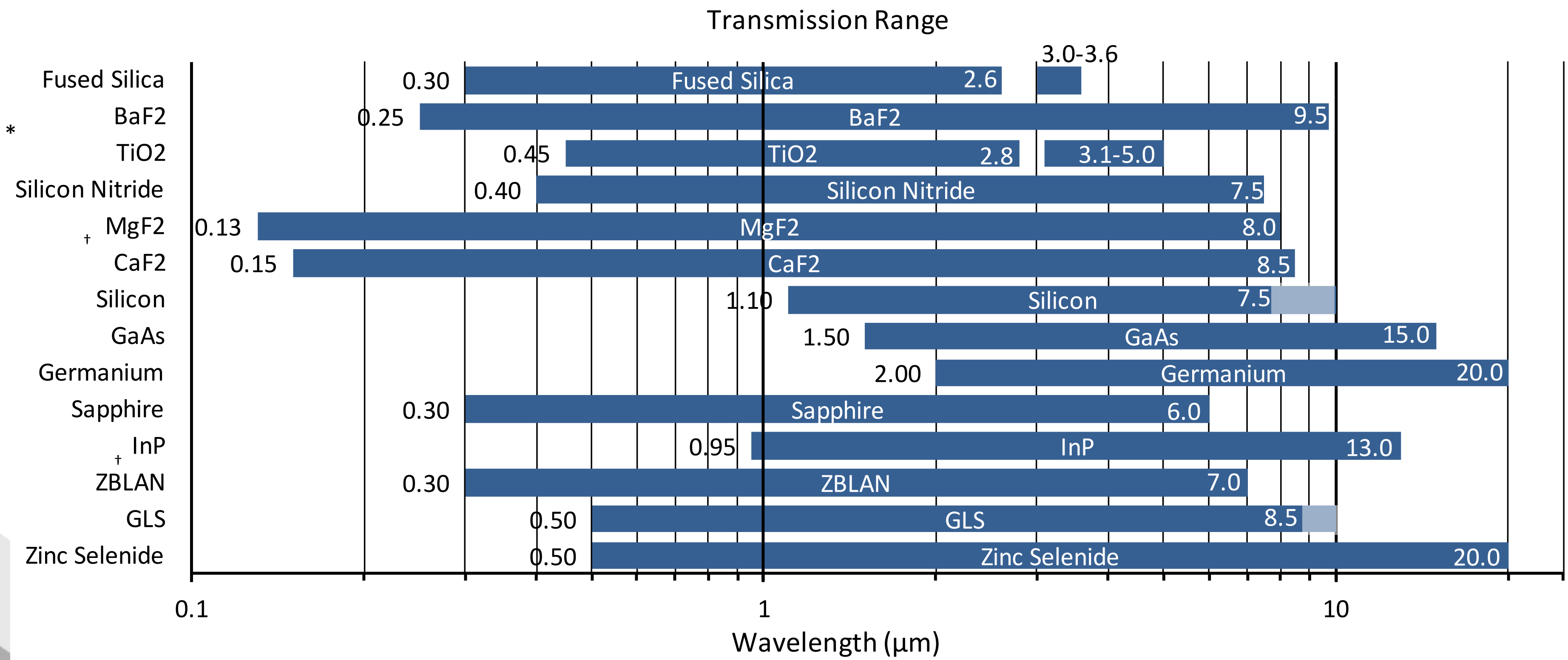


-OEwaves
-JPL
-EPFL
-FEMTO-ST

Slide adopted from NIST

OEwaves

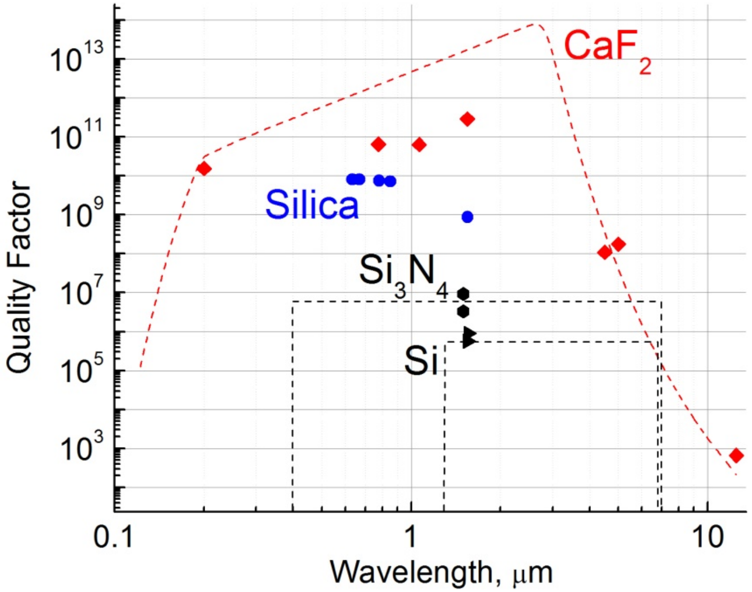
Transmission Range of Selected of Materials



† 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 α:



CaF_2	3×10^{-7} cm^{-1}
SiO_2 (optical fiber)	5×10^{-6} cm^{-1}
Al_2O_3	1×10^{-5} cm^{-1}
SiO_2 (quartz)	1×10^{-5} cm^{-1}
$LiNbO_3/LiTaO_3$	1×10^{-4} cm^{-1}
Si_3N_4/Hydex	1×10^{-2} cm^{-1}
Si	8×10^{-2} cm^{-1}
Polymers	1×10^{-1} cm^{-1}

$$(2\gamma)^{-1} = n_0(\alpha c)^{-1} \qquad Q = \frac{2\pi n}{\alpha \lambda}$$

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

E.D.Palik, "Handbook on optical constants of solids", Academic, NY, 1998

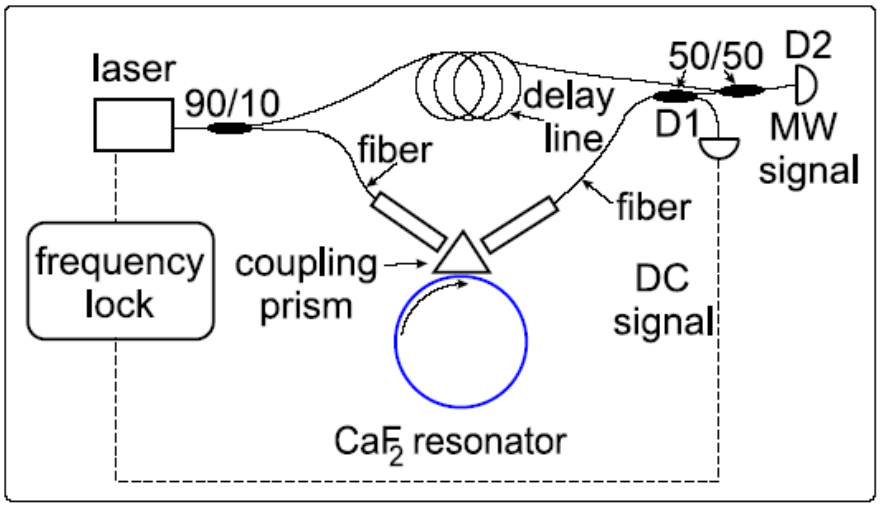
* Transparency of most of the optical materials is not well documented in literature and the documented values vary by an order of magnitude

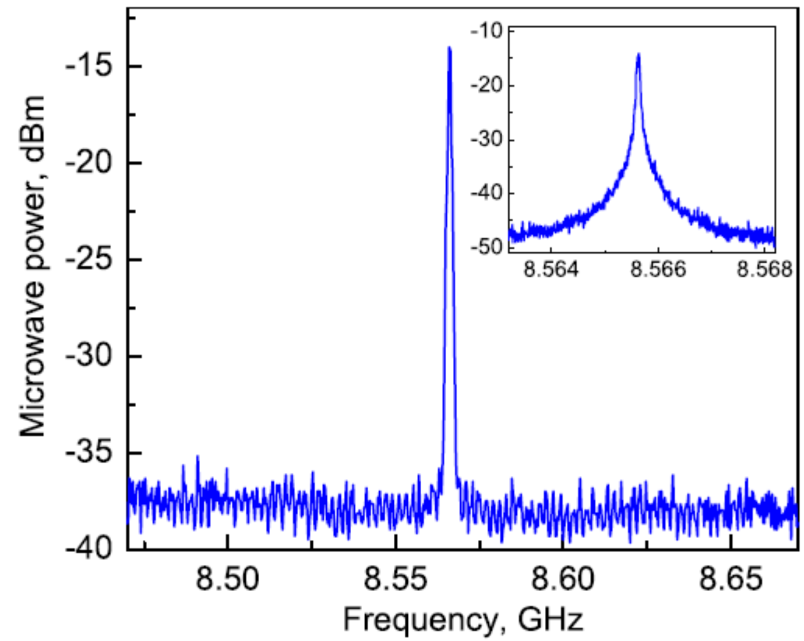
Spectrally Pure Microwave/mm-wave Oscillators

RF oscillators are needed in a variety of applications including:

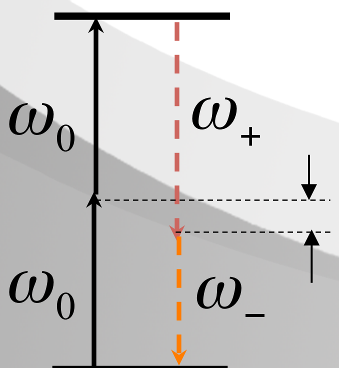
- Communications
- Direction finding of signals of interest
- Applications related to coherent operation across multiple segmented platforms
- Radar --- Remote sensing
- Radio science
- Metrology

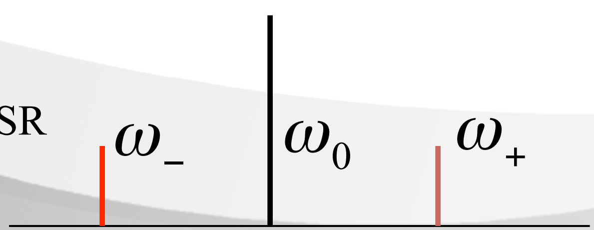
Hyper-parametric Oscillator





$$Q = 2\times10^{10} \ at\ \lambda = 1310\,nm$$





Hamiltonian:

$$H = -\hbar g\left(b_-^+ b_+^+ aa + a^+ a^+ b_+ b_-\right),$$

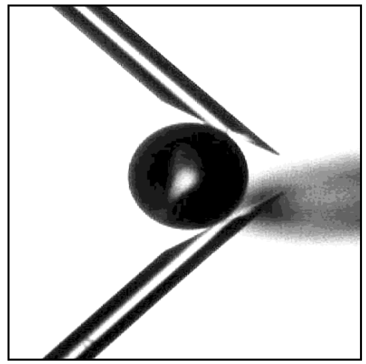
$$g = \omega_0 \frac{n_2}{n_0}\frac{\hbar\omega_0 c}{V n_0}$$

A.A.Savchenkov et al., Phys. Rev. Lett. ***93****, art. no. 243905 (2004)*

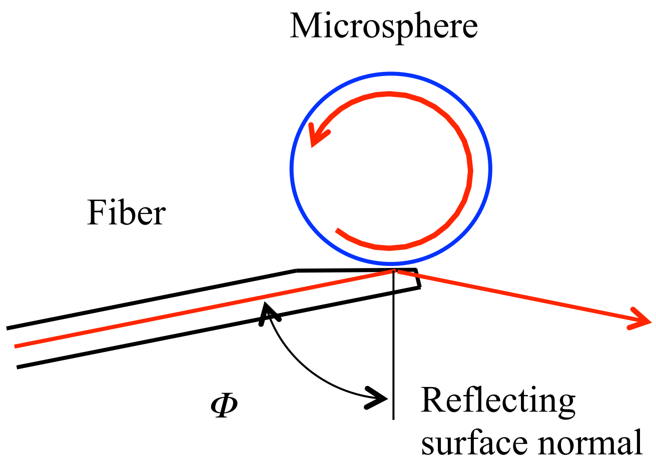
Coupling Schemes

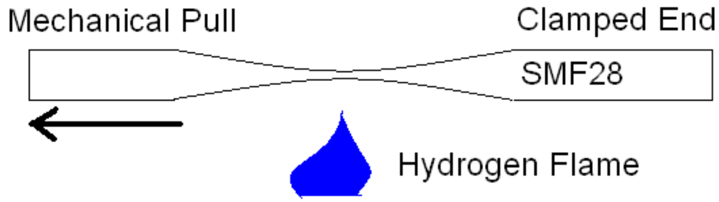
For a resonator with index n surrounded by air, the evanescent height, h, is:

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



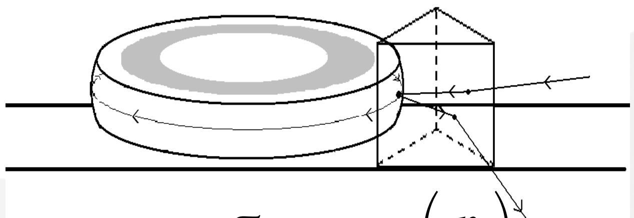
Angled Fiber





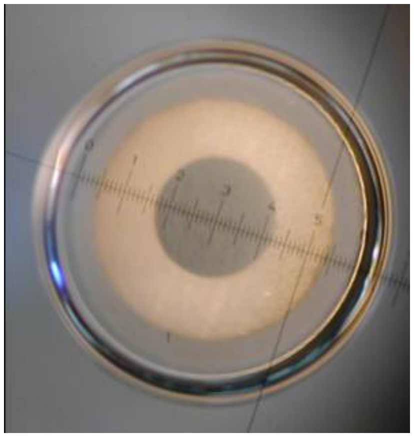
Fiber taper

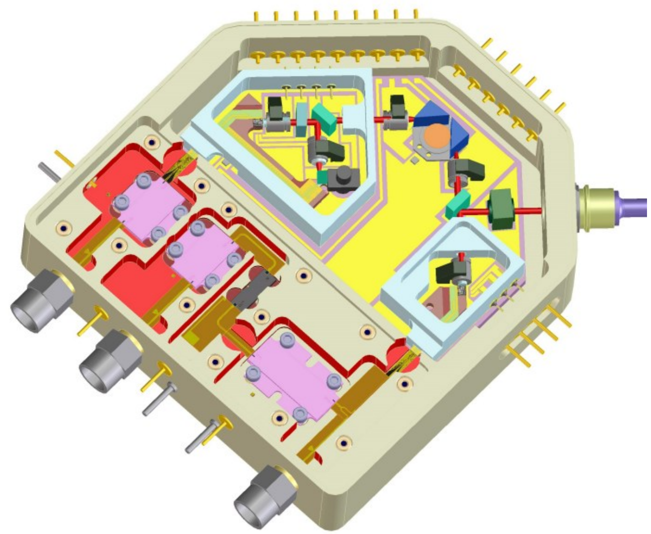
Prism Coupling

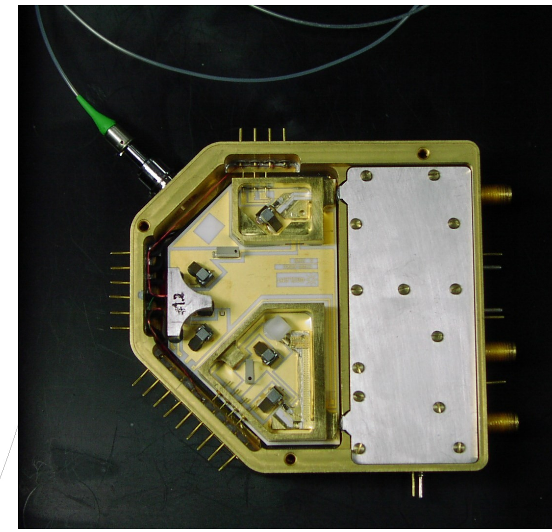


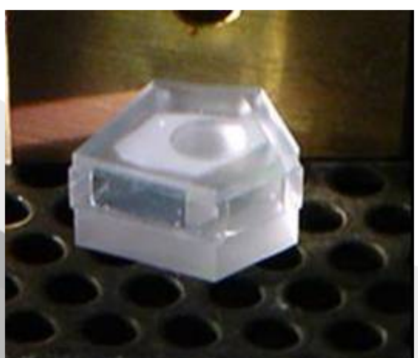
$$\theta_{input} = \frac{\pi}{2} - \arcsin\left(\frac{n}{n_c}\right)$$

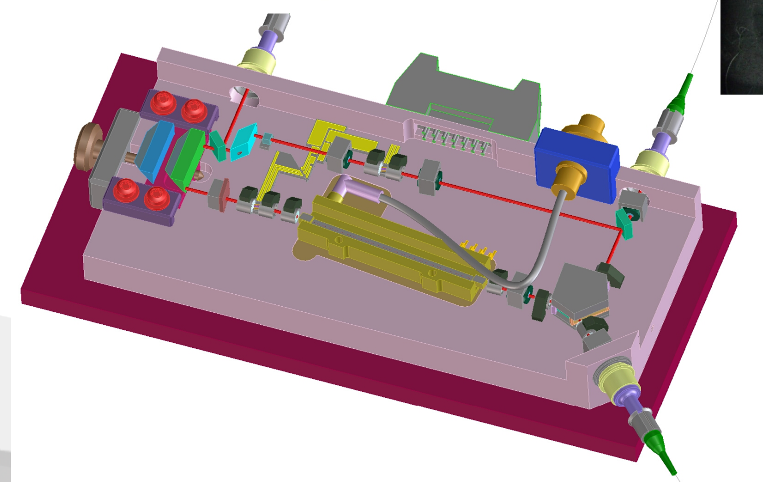
Microresonator Based OEO Development at OEwaves (2003)





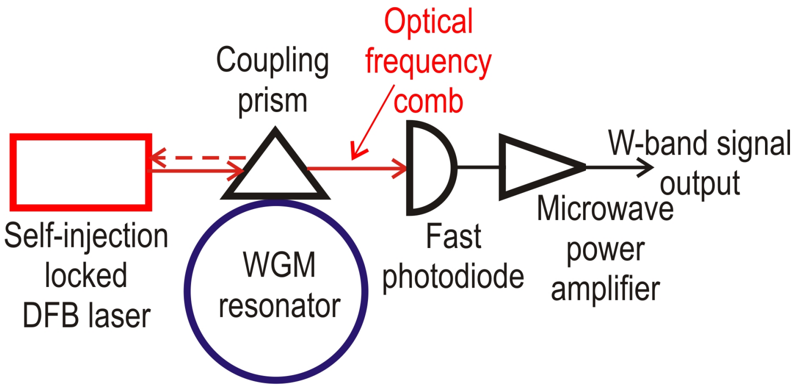


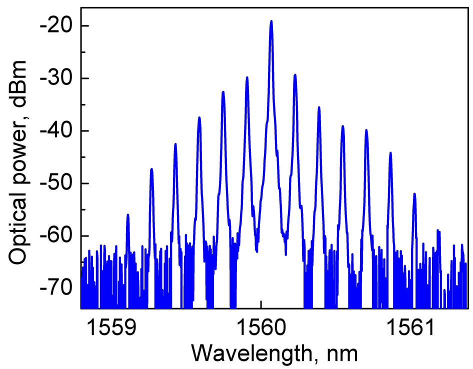


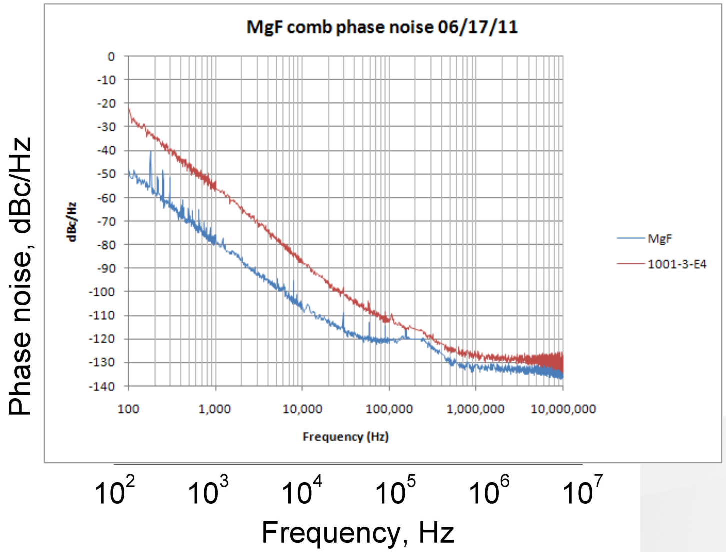


Microresonator – Tool for achieving low vibration sensitivity OEO

Miniature Optical Frequency Comb Oscillator



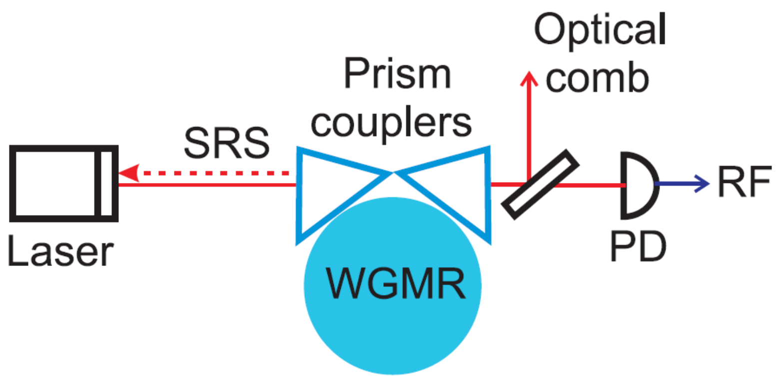


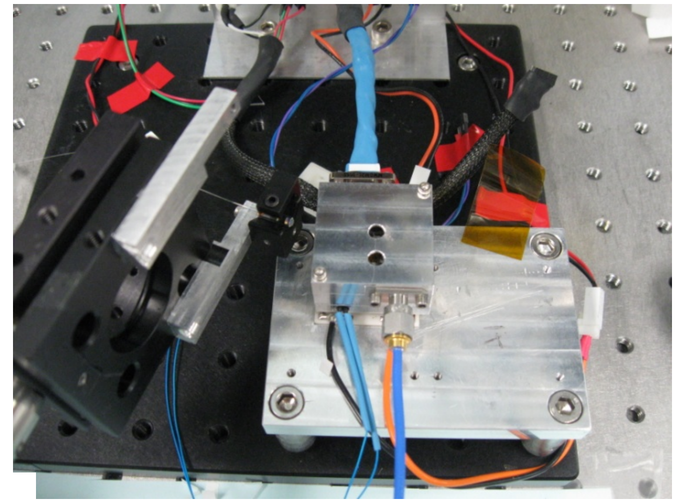


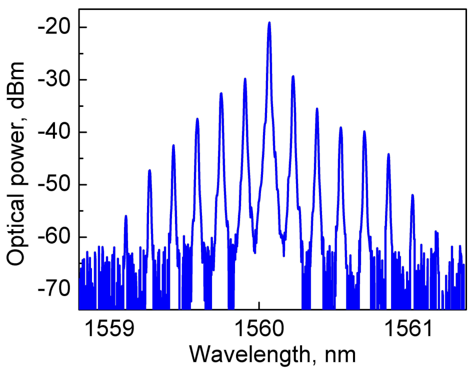
Optical frequency comb and the corresponding RF signal at 35 GHz.

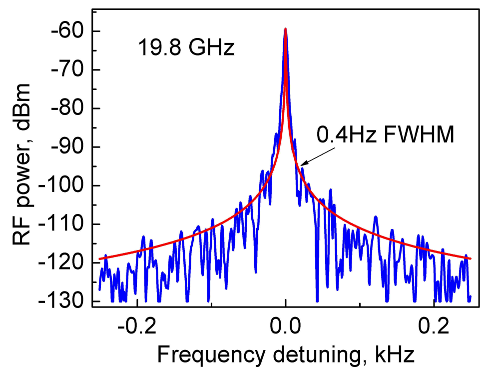
OEwaves

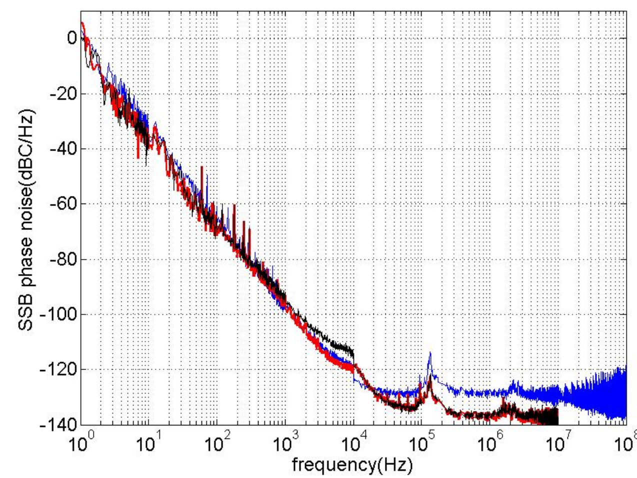
The First Prototype





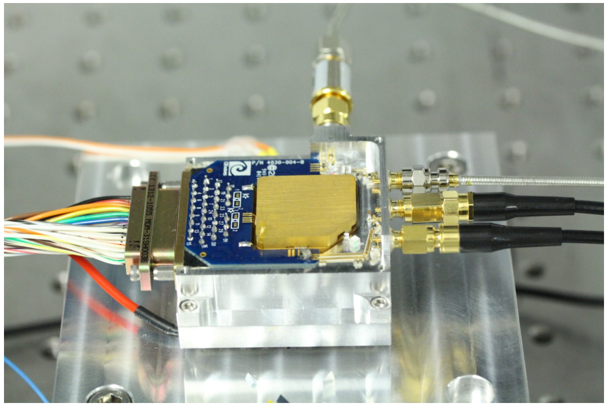


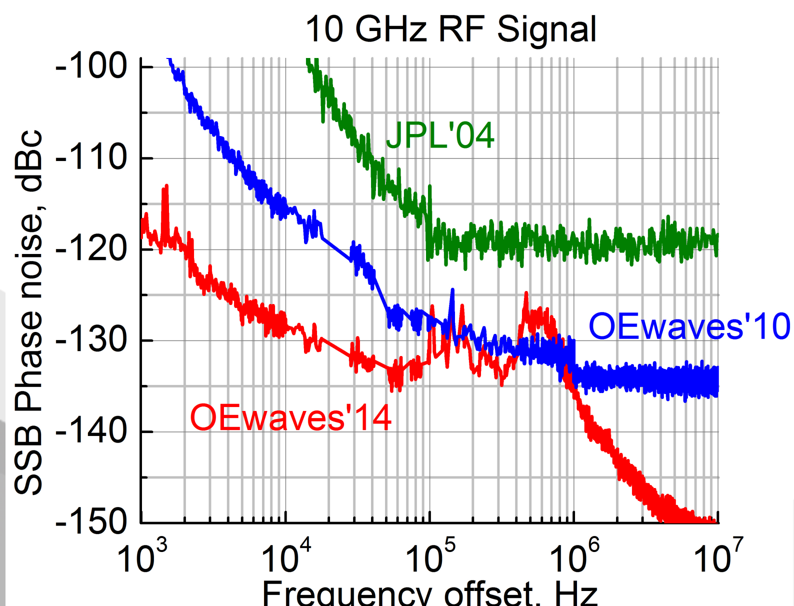


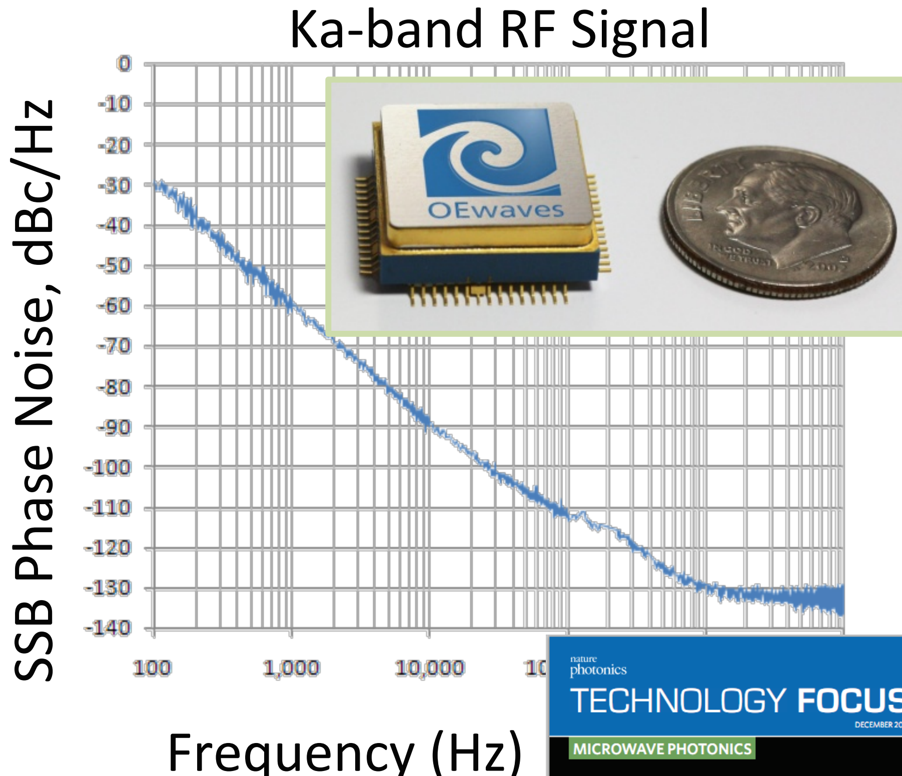


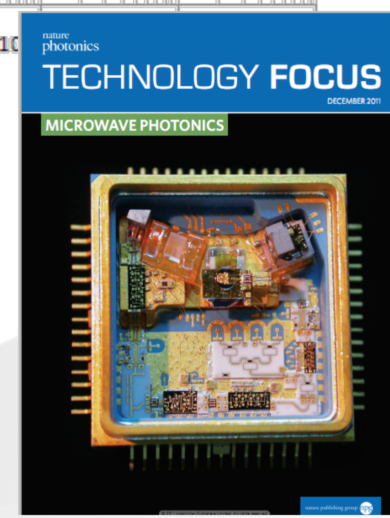
L. Maleki et al., 2010 IEEE International Frequency Control Symposium (FCS), pp.119-124, 1-4 June 2010.

X- and Ka-Band Photonic Oscillators





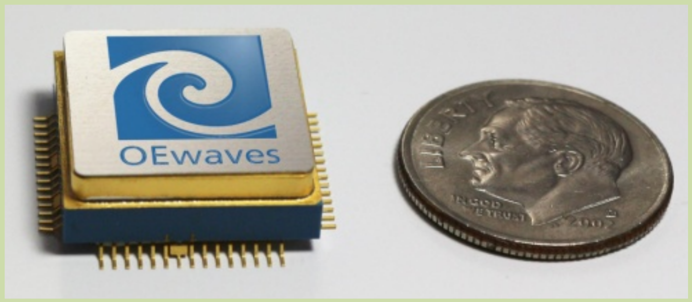




SPIE PRISM AWARDS WINNER

OEwaves

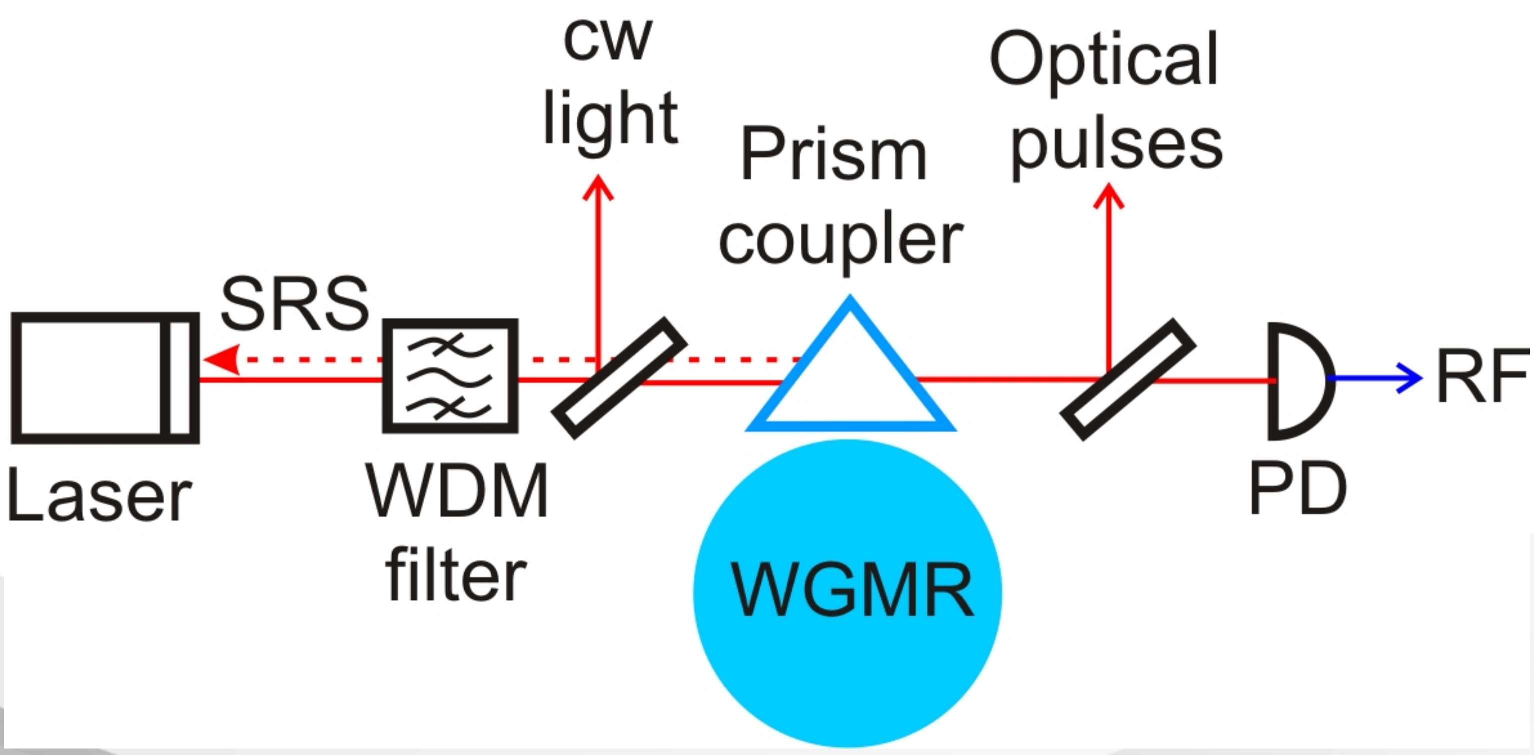
Field Operation



Participated in a controlled flight. Remained operational during the entire duration of the mission.

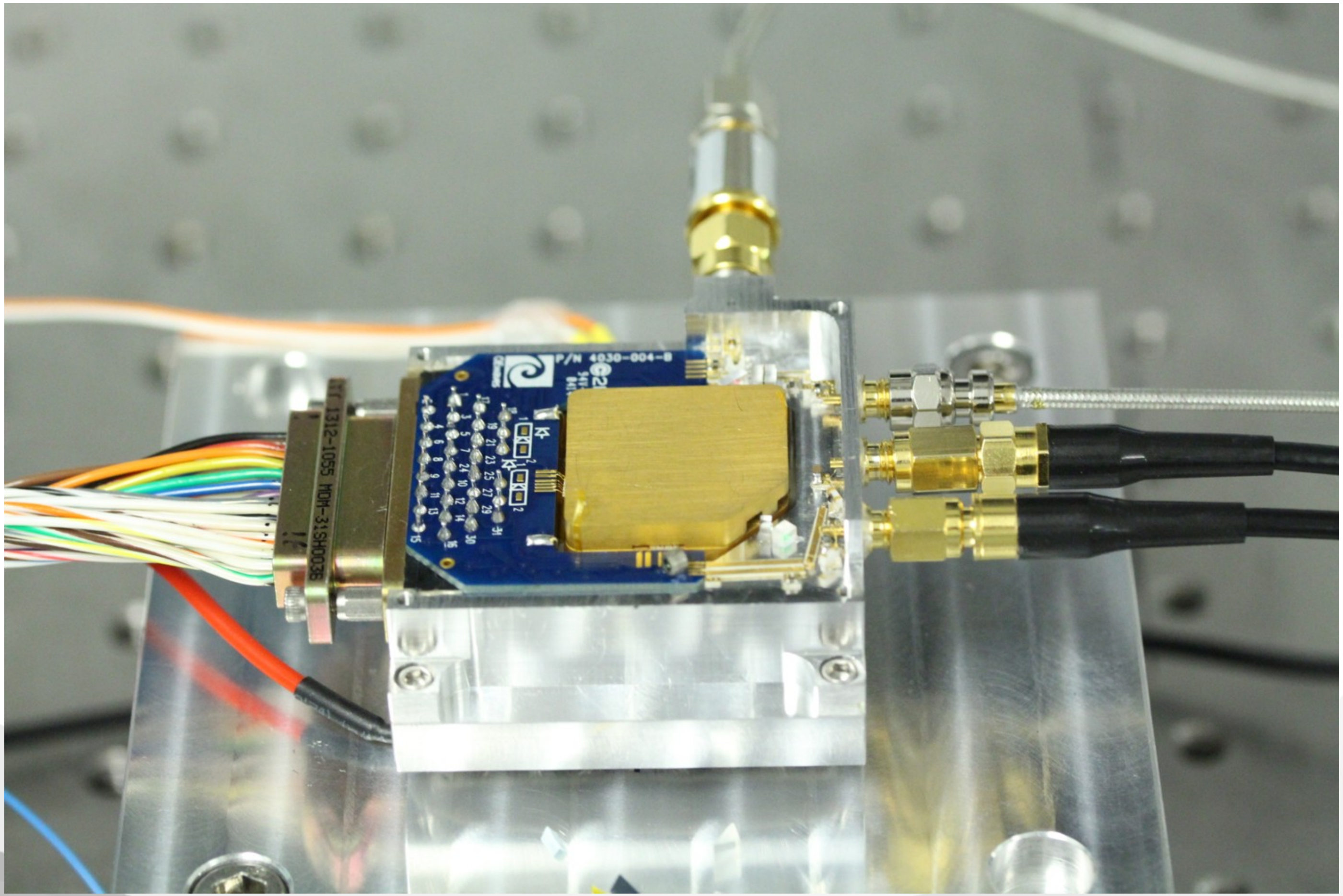
OEwaves

The “Triple Oscillator”



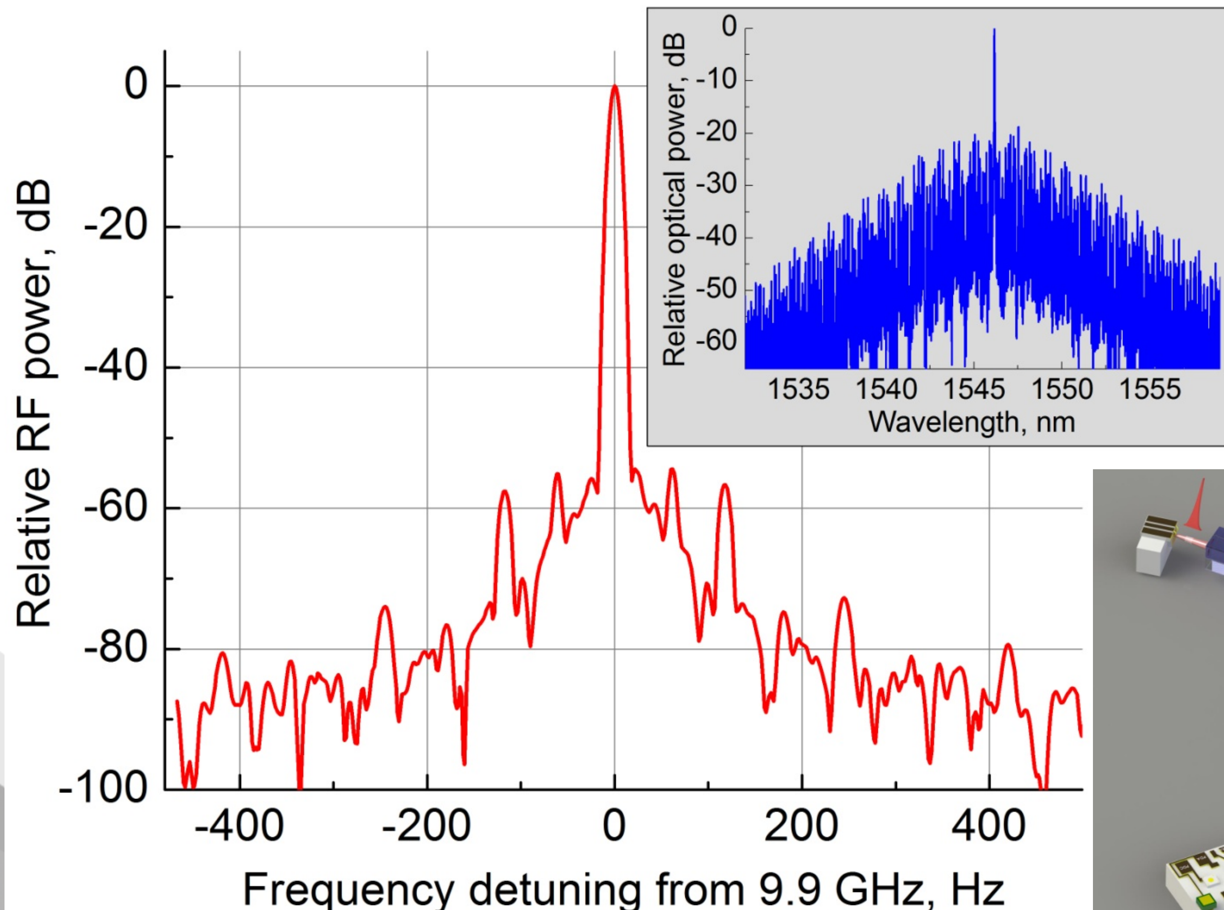
OEwaves

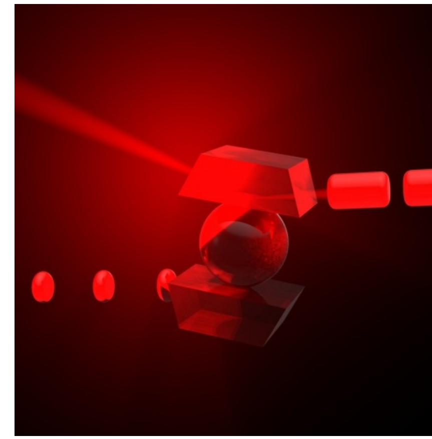
Integrated Prototypes with Improved Thermal Isolation

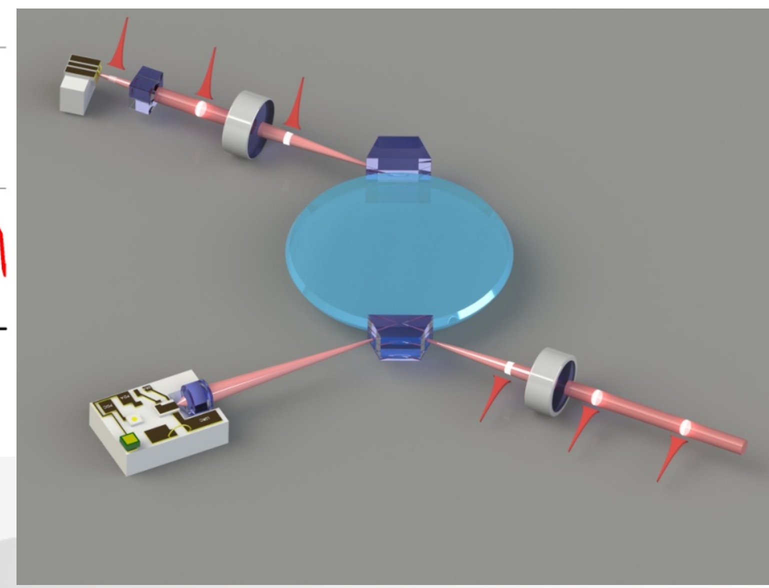


OEwaves

Mode Locked Comb Oscillator

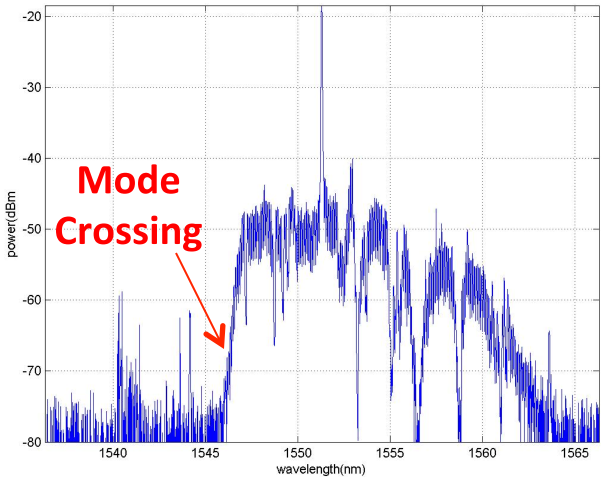


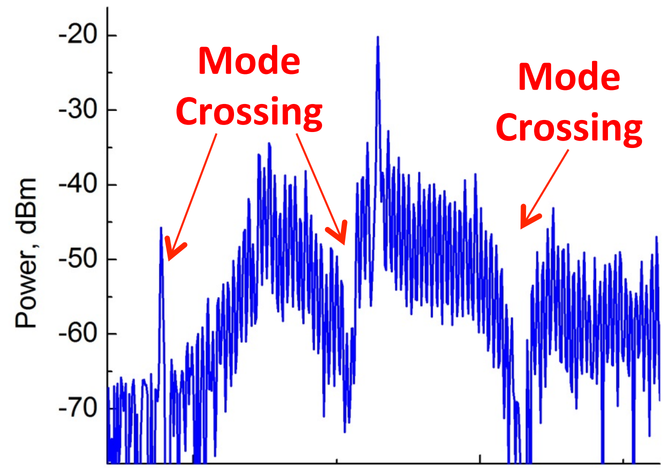


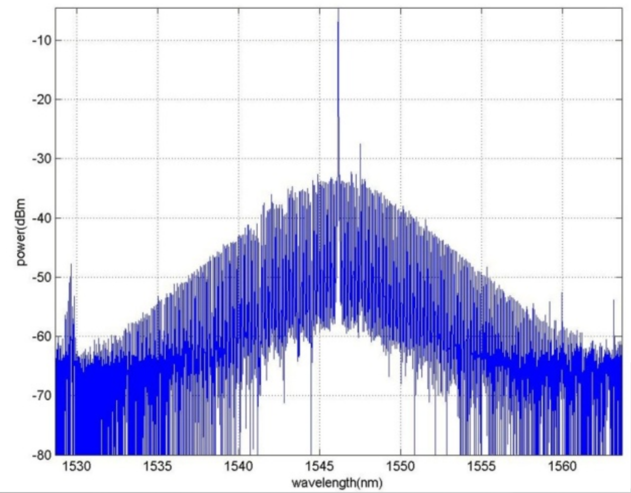


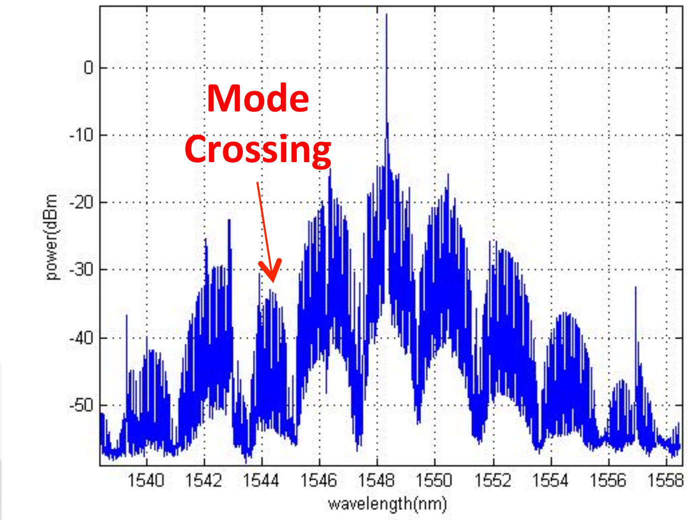
Impact of Mode Crossing

Interaction among mode families limits growth of the mode locked frequency combs



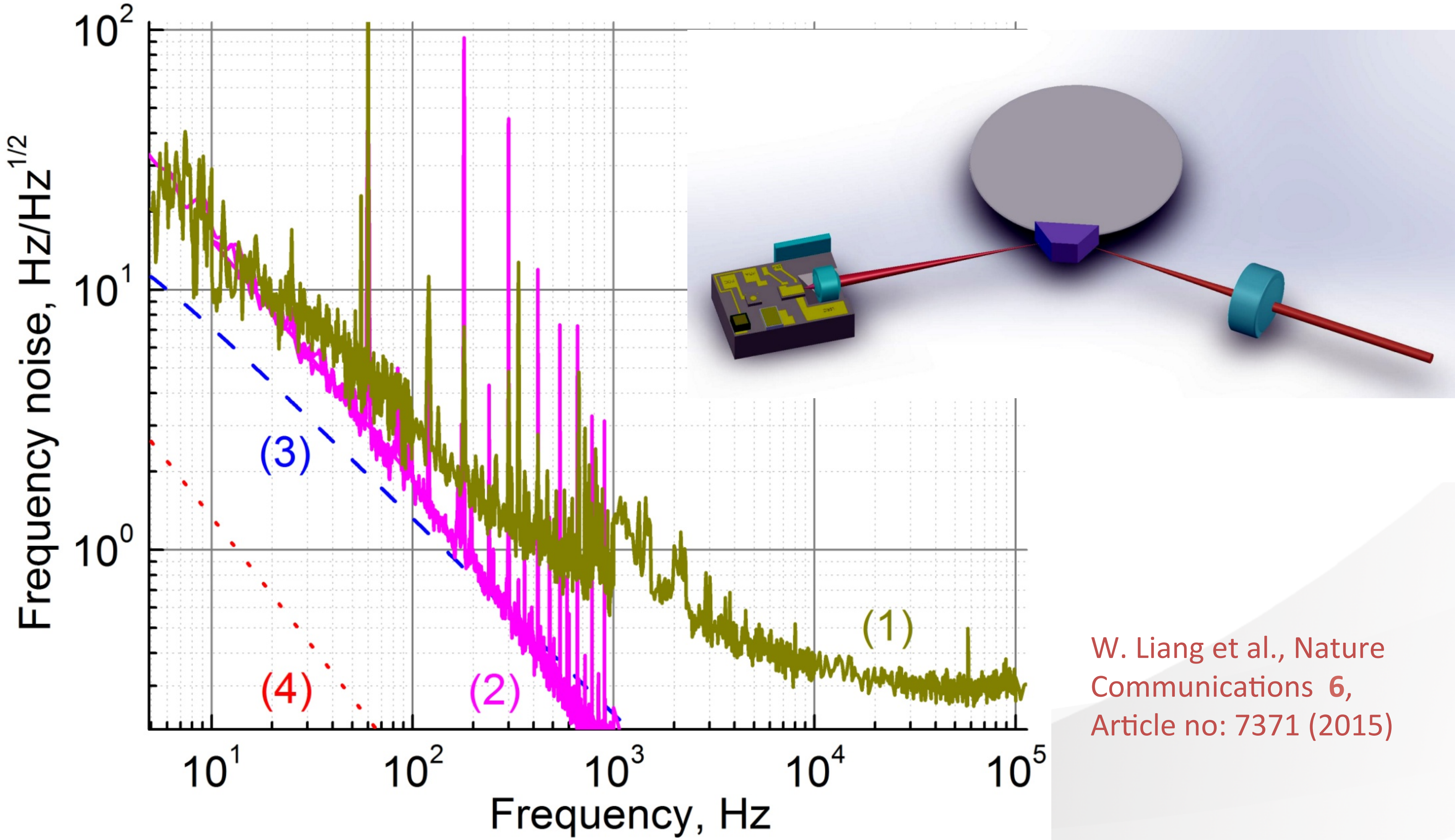






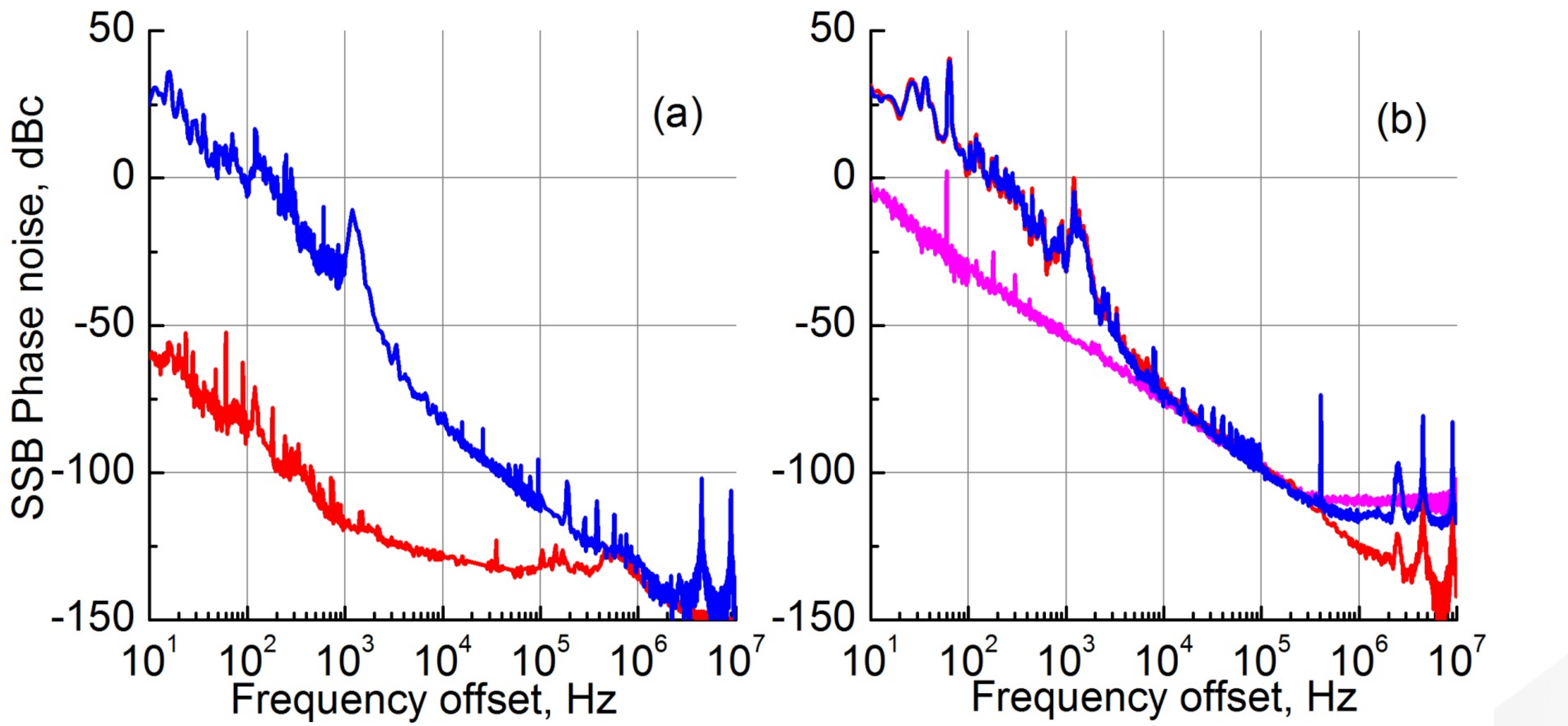
OEwaves

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)

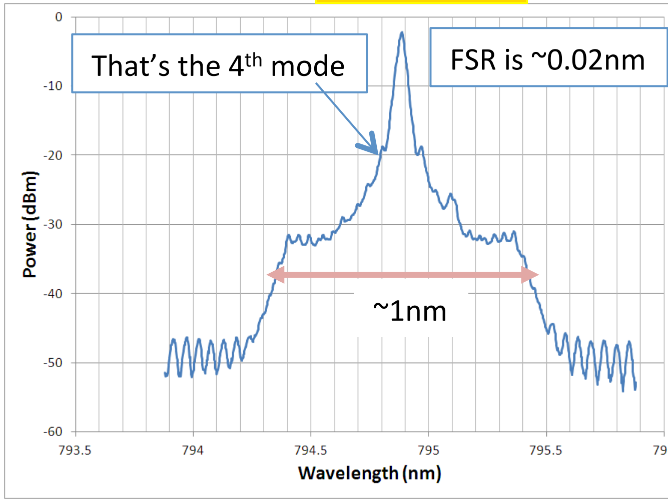


Blue line: laser noise
Red line: comb noise
Ratio is $20\log(\nu_{opt}/\nu_{RF})$: it results from the common noise source, e.g. temperature fluctuations in the resonator mode resulting from the laser noise.

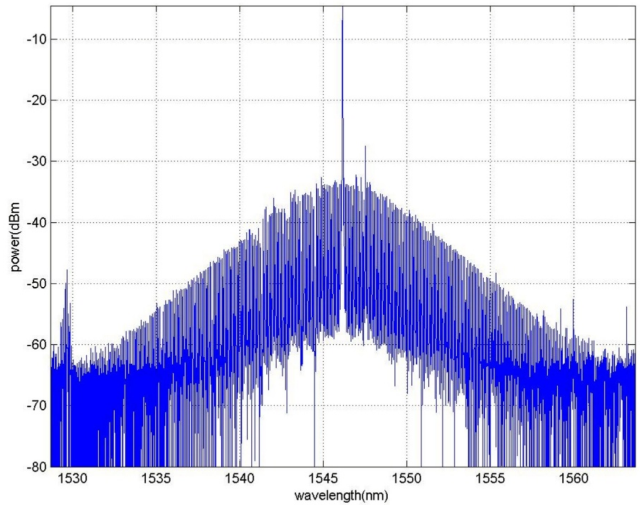
Two lasers are locked to modes of the same resonator (another, test, build was created)
Blue line: laser on reflection
Red line: laser on transmission
Magenta line: beat between the lasers. Common noise is rejected.

10 GHz Coherent Frequency Combs With Crystalline Resonators at OEwaves

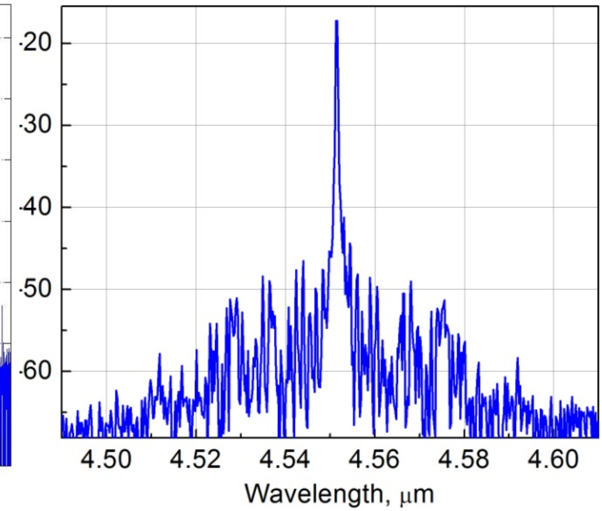
795 nm

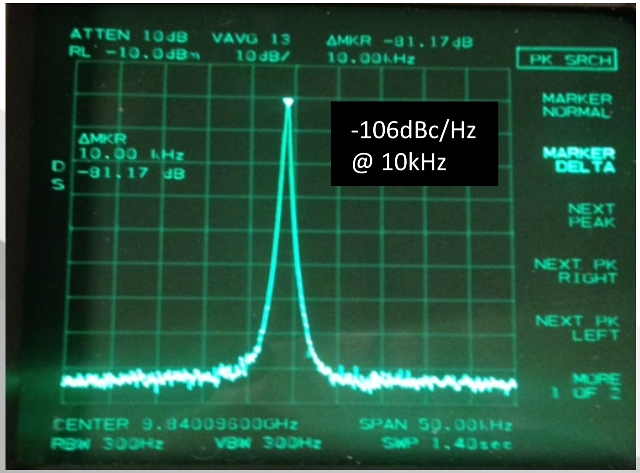


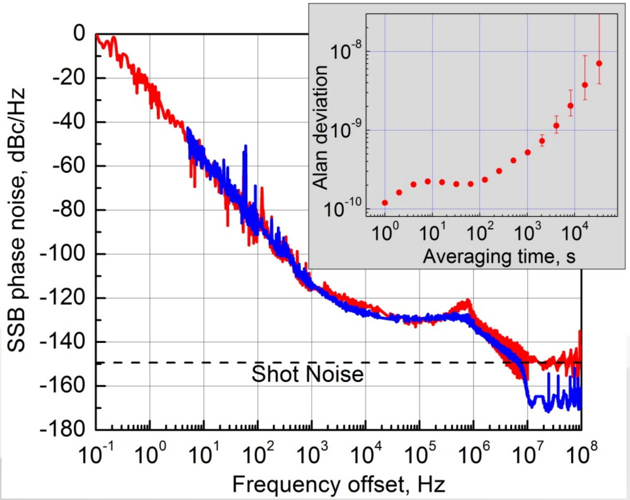
1550 nm

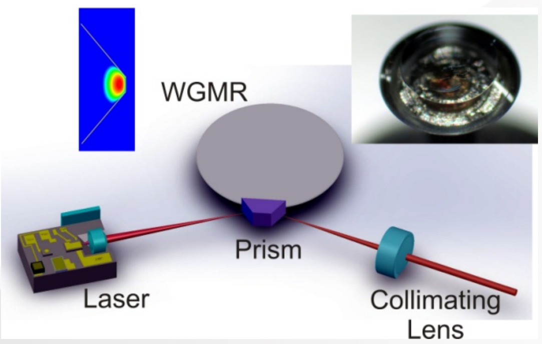


4550 nm





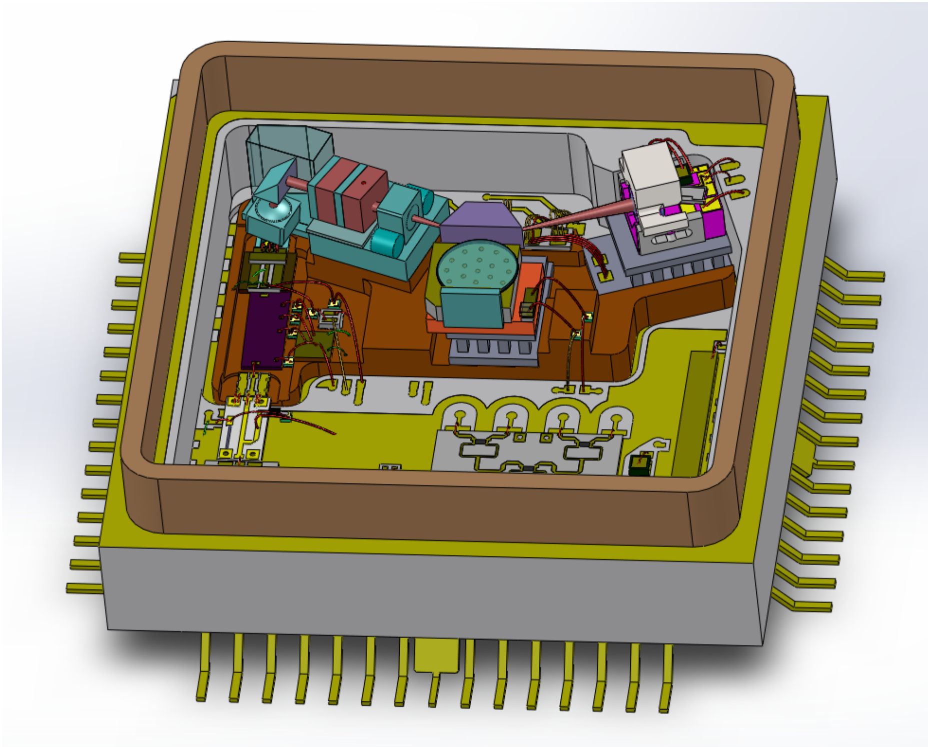




KOEO Assembly Overview

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

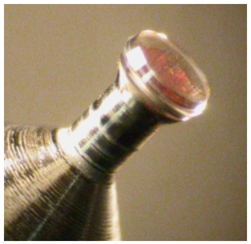


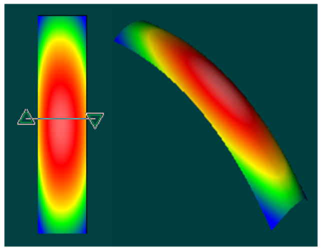
- Optical shim
- Additional amplification
- Various RF and DC components

OEwaves

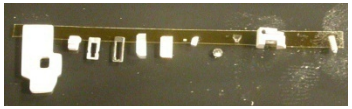
Process Flow for Photonic Front End manufacturing

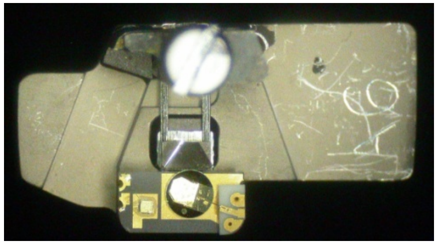
Manufacture and Test Resonator



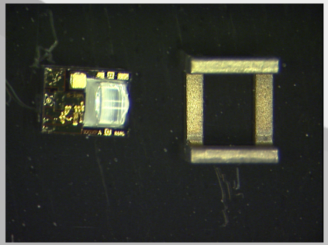


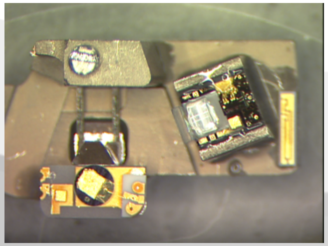
Resonator, prism, and flex arm



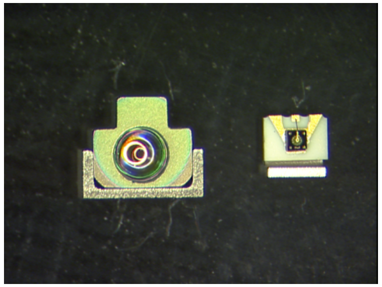


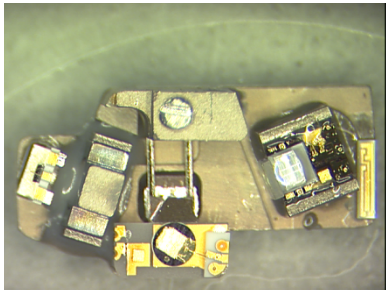
Alignment of laser to resonator



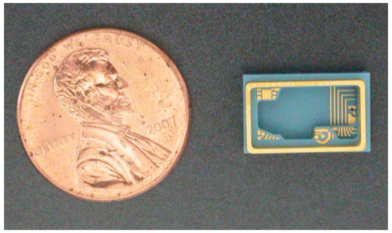


Alignment of focusing lens

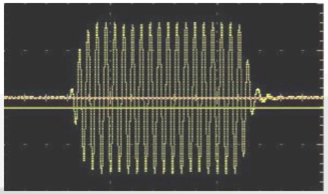


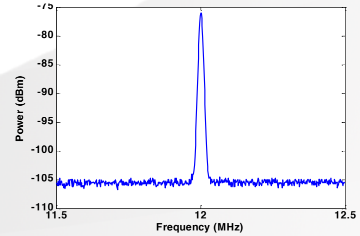


Wirebond



Performance Tests





OEwaves

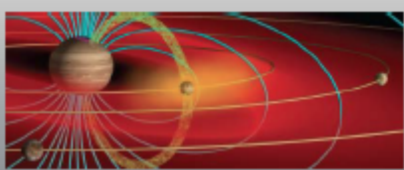
Challenges for Space Instruments

- 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

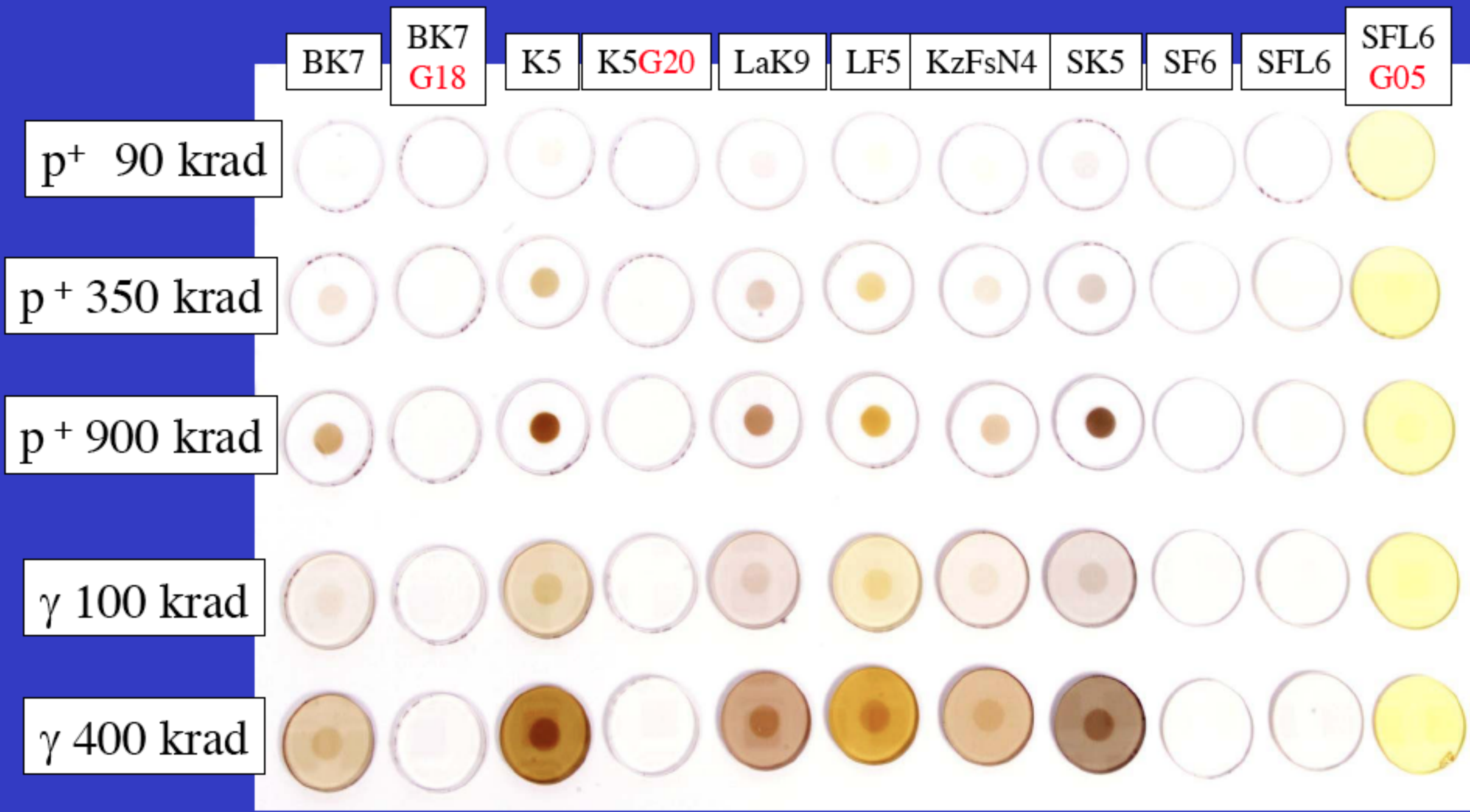
Kerr Comb Operation

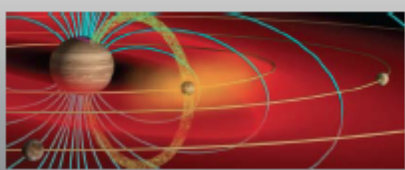
- Recall that Kerr combs depend on a balance between nonlinearity and group velocity dispersion in the resonator
  - Nonlinearity → Optical power
  - GVD → Resonator dispersion (material and geometric)

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



Induced Absorption





CaF2 @ 10 Mrad

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

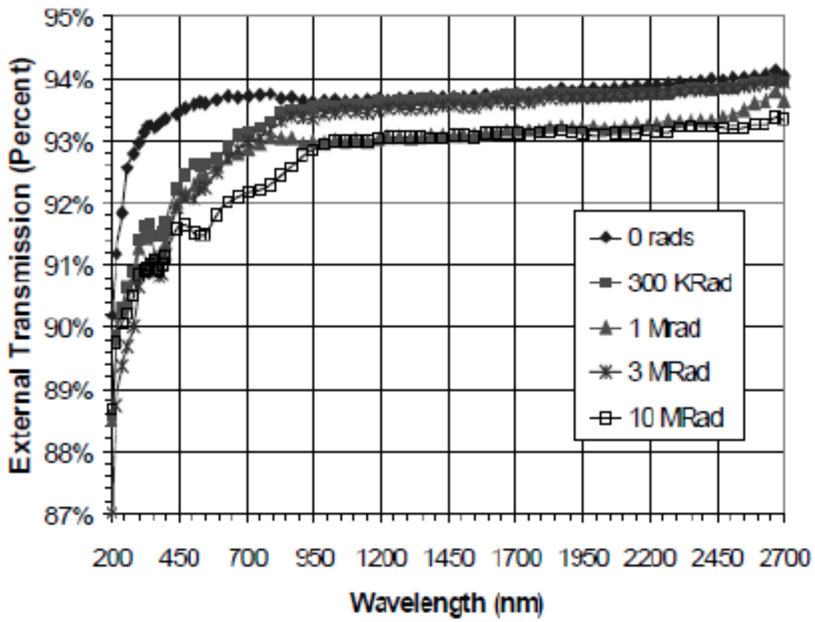


Figure 23. Transmission measurements of a Schott 157 nm eximer grade synthetic monocrystalline CaF_2 window after exposure to gamma radiation (t = 7.065 mm).

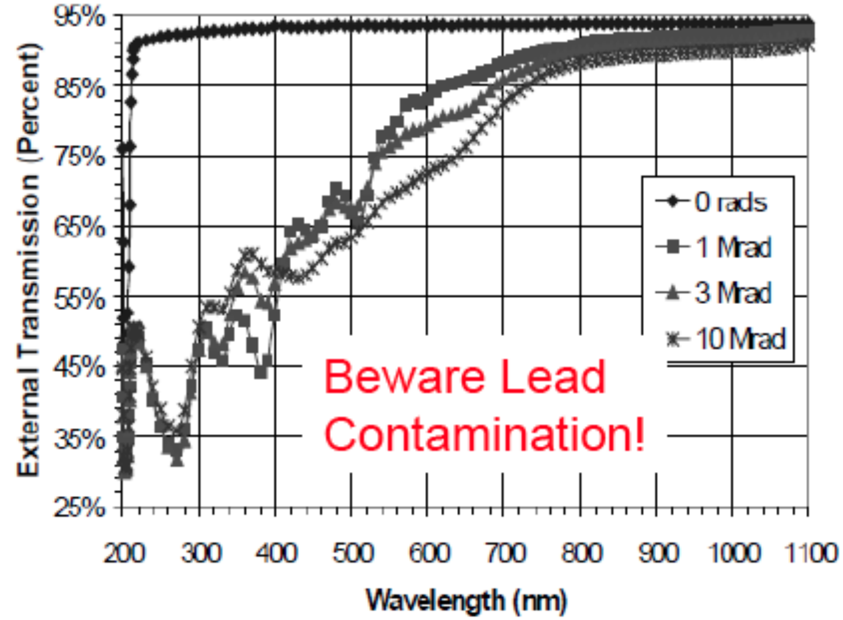


Figure 24. Transmission measurements of a Schott 193 nm eximer grade synthetic monocrystalline CaF_2 window after exposure to gamma radiation (t = 9.94 mm).

Inorganic Optical Materials III, Alexander J. Marker III, Mark J. Davis, Editors, Proceedings of SPIE Vol. 4452 (2001) © 2001 SPIE · 0277-786X/01/$15.00

OEwaves

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

OEwaves

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