Microresonator-Based Frequency Comb Generation

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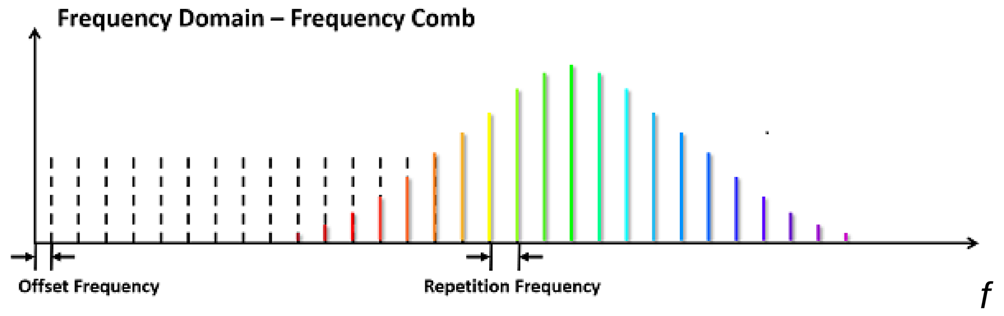
Abstract

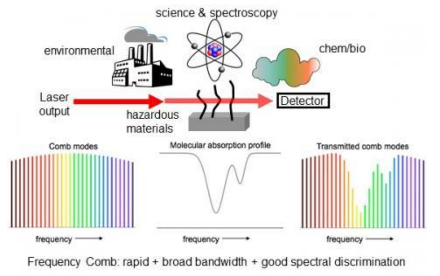
A frequency comb is a set of equidistant spectral lines and works as a ruler in the frequency domain due to the high precision of its frequency spacing. This technology has revolutionized many measurement metrologies such as dual-comb spectroscopy, distance measurement, light detection, ranging (Lidar), and optical atomic clocks. Recent advances made to microresonators have made comb generation from chip-scale devices possible. This is allowing the technology to become much more portable, which in turn gives it more real-world applications. This type of frequency comb generation requires a microresonator with certain characteristics, which are high quality factor (high-*Q*) and anomalous dispersion. The object of this experiment is to optimize geometric parameters of microresonators for these characteristics and to generate frequency combs. The resonances of multiple microresonators were tested by sending laser light through a fiber-coupled photonic waveguide, and the results were fitted and analyzed to determine the quality factor and dispersion of each microresonator. We found a set of optimized microresonators that exhibit high-*Q* and anomalous dispersion, and generated frequency combs from these microresonators. Our research optimized the geometric parameters of microresonators that can efficiently produce frequency comb lines. Our optimized devices are portable and provide a precise frequency spacing, and therefore will have useful applications in many areas such as spectroscopy, bio/chemical sensing, Lidar, and time/frequency metrology.

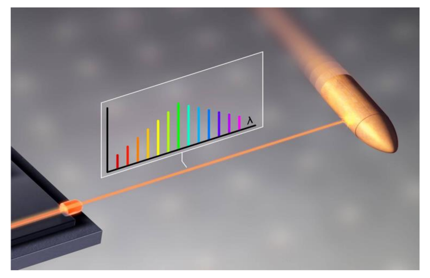
Introduction

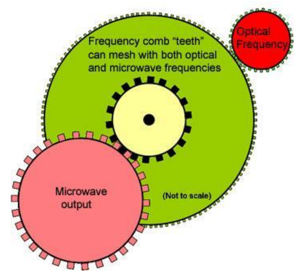
The Nobel prize in physics in the year 2005 went in part to John L. Hall and Theodor W. Hänsch for their development of the first laser-based spectroscopy and the frequency comb technique which they used to figured out how to precisely take readings of the colors of light from atoms and molecules. A frequency comb is a set of equidistant spectral lines that is essentially a tool/ruler for measuring different frequencies of light. In the past, the setups in order to generate these combs were very large and cumbersome. Microresonators are much smaller (in micrometer scale) and portable, making the comb technology more practical in many applications.

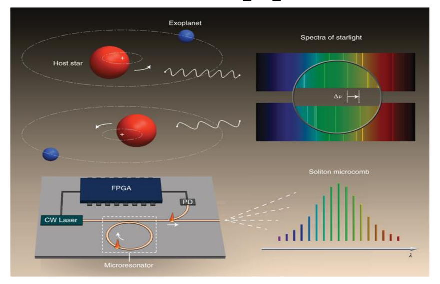


Frequency comb spectra in the frequency-domain [1]


Spectroscopy [2]


Lidar [3]

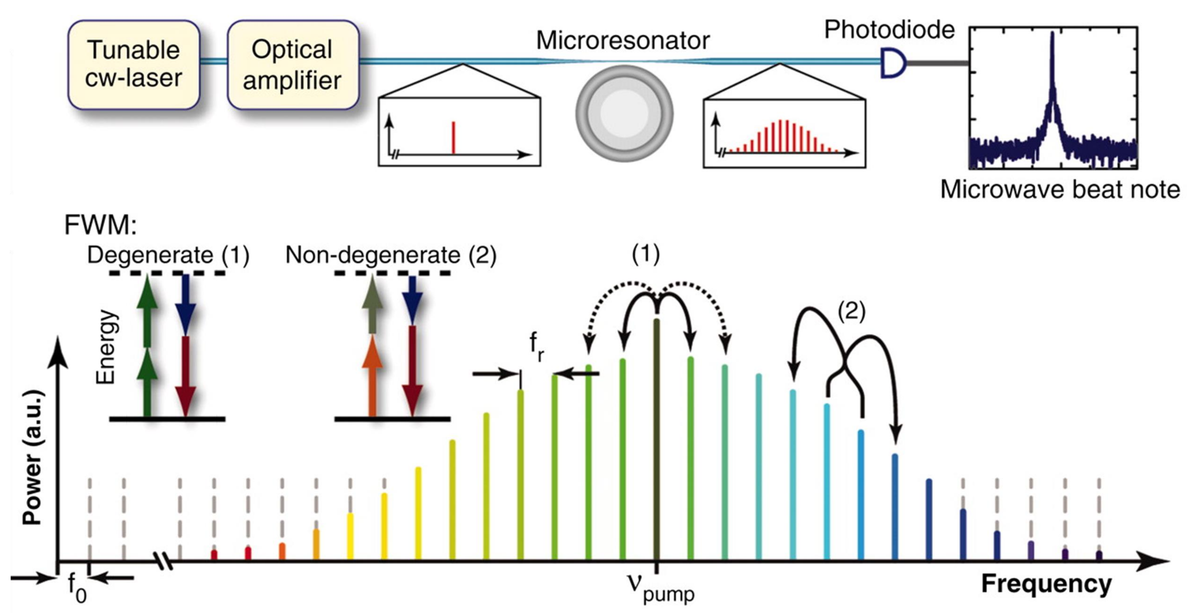

Atomic Clock [4]


Astrocomb [5]

Applications of frequency combs

Theory Behind Frequency Comb Generation

- Monochromatic light enters the microresonator and circles around inside.
- Light resonates at certain frequencies when the waves are in phase. The number of standing waves around the microresonator's perimeter correspond to modes. This number changes as the frequency changes. One comb produced corresponds to these modes.
- Another comb is produced by parametric frequency conversion through four wave mixing. The initial energy is split and redistributed, which then happens again and again, cascading down to create the bell curve shape as energy is lost in the process each time.
- The quality (*Q*) factor is the ratio of the energy lost per cycle and is important because of power buildup. A high-*Q* means a more useful frequency comb.

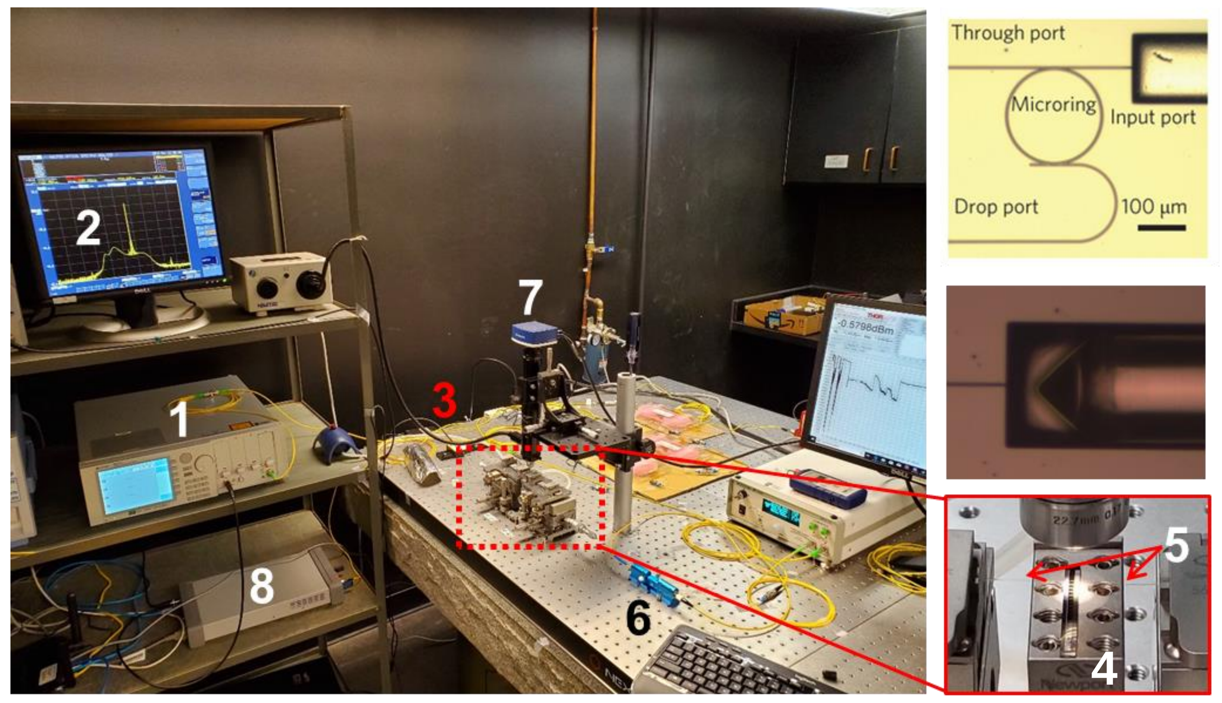


Principles of frequency comb generation with a microresonator [1]

Research Goals (Questions)

- Identify microresonators with high quality factors
- Generate frequency combs by pumping a high power continuous-wave laser (single frequency) into the resonance frequency
- Generate multiple frequency combs with different frequency spacing (different grid-size)

Experimental Setup & Methods



1. Laser
2. Optical Spectrum Analyzer
3. Fiber-to-Chip Coupling Stage
4. Microresonator Chip
5. Lensed Fiber
6. Polarizer
7. Microscope
8. Power Meter

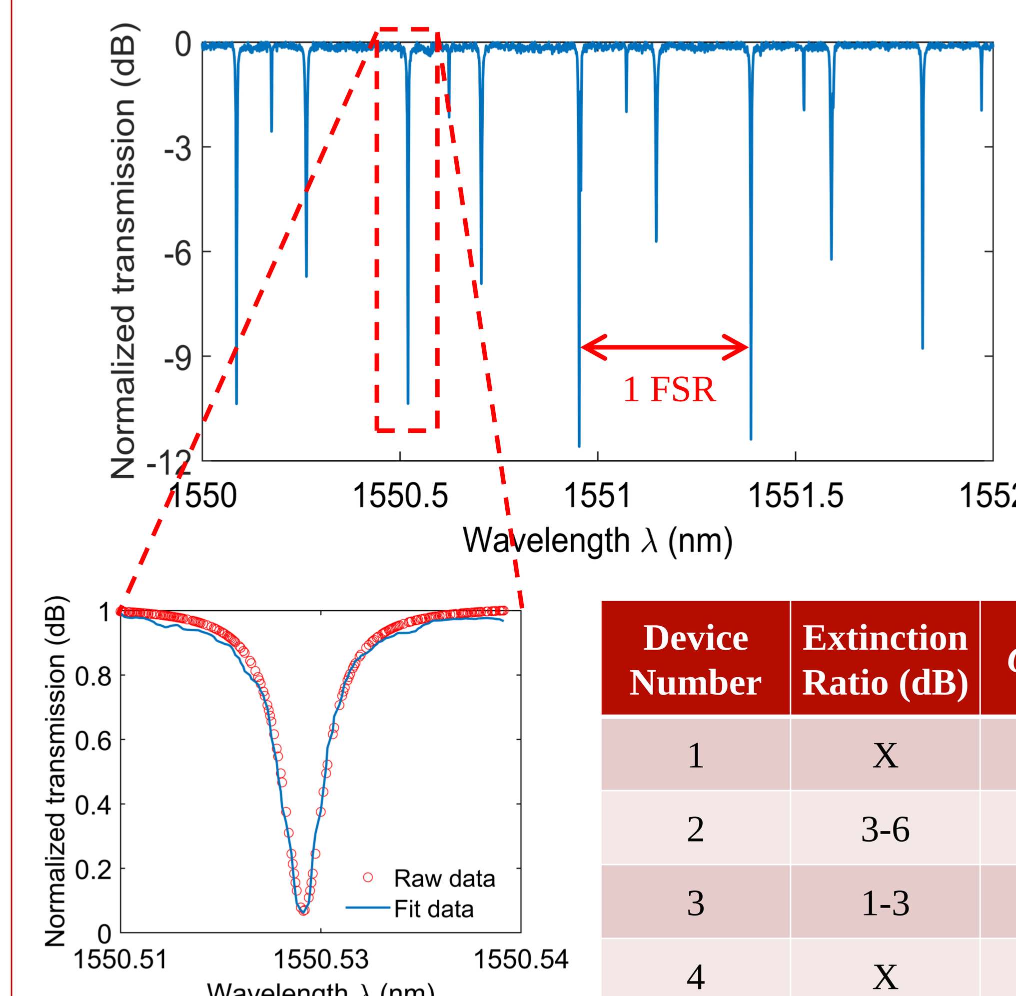
•**Step 1:** Fiber-to-chip coupling through lensed fiber and inverse coupler

•**Step 2:** Measure the linear transmission spectra of the microresonators

•**Step 3:** Fit the data and characterize the quality factors (*Q*) to identify the devices that can generate frequency combs

•**Step 4:** Pump the high power CW laser into the resonator to generate the frequency combs

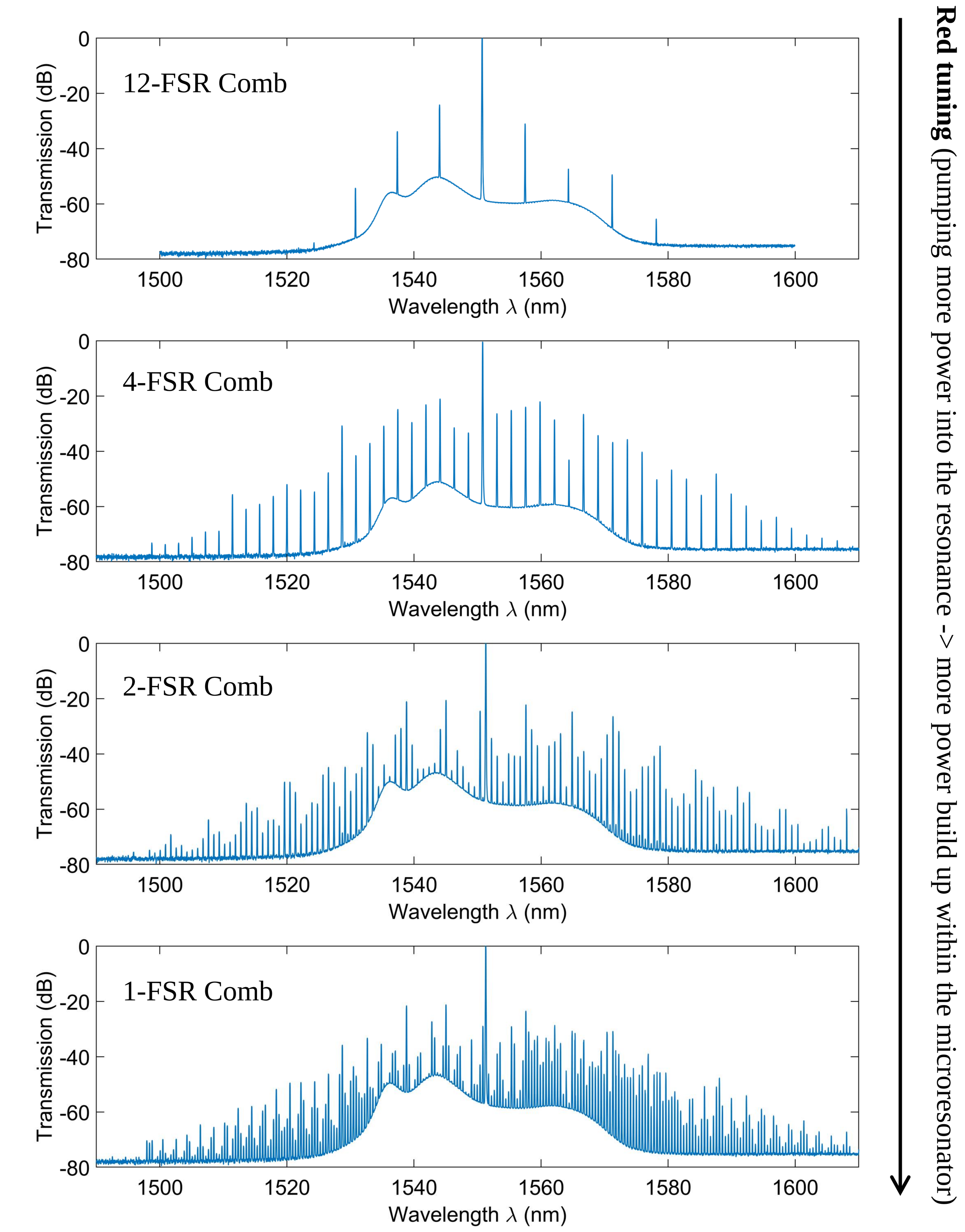
Result 1 – Transmission Measurements



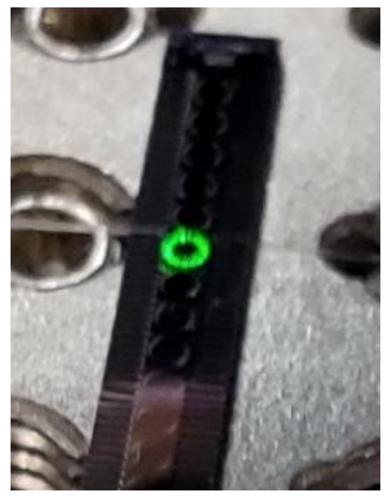
- $Q_t = \frac{f_0}{\Delta f}$
- $Q_i = \frac{2Q_t}{1+\sqrt{T_{\min}}}$

Device Number	Extinction Ratio (dB)	Q_i (x10^6)
1	X	X
2	3-6	0.5-1.5
3	1-3	0.1-1.5
4	X	X
5	4-6	1.4-1.8
6	5-8	1.2-2.1
7	12	0.8-2.0

Result 2 – Frequency Comb Generation



- By pumping the high-*Q* resonance with a high power CW laser, we have generated frequency combs.
- The initial comb had 12-FSR comb lines.
- As we red-tuned the pumping wavelength, more comb lines appeared due to the high power build-up within the microresonator.
- Each comb line works as a grid in the frequency-ruler, and we have generated frequency-rulers with different grid sizes.
- During the comb generation, the third harmonic generation (THG) was observed (the green circle in the picture to the right. 1.55μm/3≈ 516nm).



Third harmonic generation (THG)

Conclusion

•Approximately 50 devices are tested and their linear transmission data were obtained.

•Microresonators with high quality factors were identified (devices 5-7). These have waveguide-resonator gap sizes of 300-400 nm.

•Frequency combs were generated out of the microresonator (device 6) by pumping with CW lasers.

•Multiple frequency combs with different frequency spacing have been generated.

•Third harmonic generation (THG) was also observed.

•The frequency comb lines obtained here can be used as a very precise frequency ruler for high-precision spectroscopy, distance measurement (Lidar), atomic clock, etc.

•For future work, we will generate a cavity single soliton, which is a more stable stage of a frequency comb.

References

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