Microresonator-Based Optical Frequency Combs

Prepared by: Alireza Kazemi

Department of Physics & Astronomy

University of New Mexico

Optical frequency combs

An optical frequency comb is an optical spectrum, which consists of equidistant lines. They are been conventionally generated using mode locked lasers [2-3]. Frequency combs work as gear-works that allow linking an optical frequency (oscillating at hundreds of THz) to a radio- or microwave frequency.

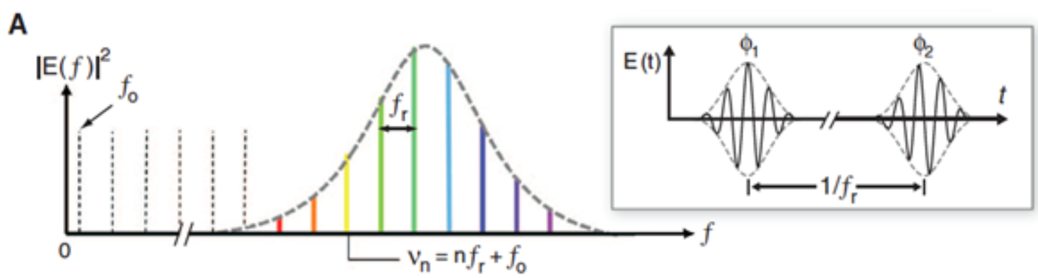

Figure 1: Time and frequency domain representation of a frequency comb. The time domain pulse train (inset) will yield a frequency comb in frequency space. The mode spacing is given by the inverse pulse separation.

Microresonator-Based Optical Frequency Combs

In 2007 a disruptive technology allowed bringing optical frequency comb generation on a chip [4] and in a much more compact setting. The group developed at the Max Planck Institute of Quantum Optics (MPQ) a technique to generate frequency combs [4] using silica micro-resonators [5] (which have approximately the diameter of a human hair).

The underlying process is the nonlinear parametric frequency conversion via the Kerr nonlinearity of silica [6]. The parametric conversion annihilates two pump photons are creates pairs of quantum correlated signal and idler photons (Figure 2).

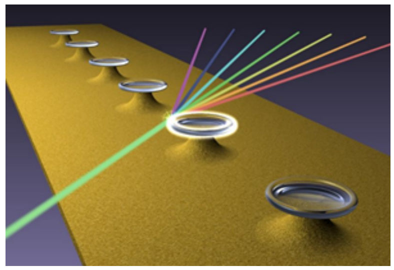

Figure 2. Shows an artistic view of a microtoroid made of silica, which is pumped with a laser of one single wavelength (green line on the left side of the image). Nonlinear processes within the cavity generate light of other colors. Unlike in a normal prism that can generate a continous colorful spectrum from sunlight, the microresonator generates just certain colors (light frequencies) that have exactly the same color difference (frequency difference).

The frequency conversion can be remarkable efficient [7] and enable the generation of octave spanning spectra, i.e. a spectrum that covers a factor of two in frequency. The distance to the sidebands corresponds to the inverse round trip time in the micro-resonator, which are between 10 GHz and 1 THz for different microcavity sizes. It has been verified the equidistance of the frequency comb lines to 1 part in 10^18.

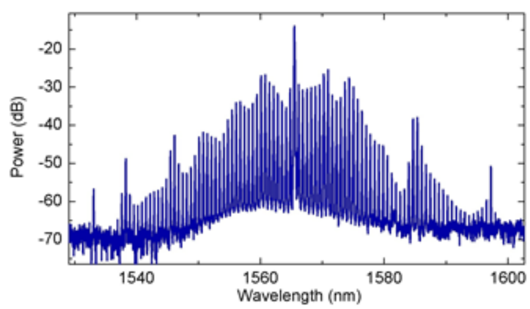

Figure 3. shows the optical spectrum generated from a 375 μm diameter microtoroid. The wavelength that was used for this experiment is in the infrared region, which is invisible for the human eye. The above image shows the 5 mm wide chip with the optical silica microresonators.

The physics of the Kerr frequency combs can be understood as follows. The parametric frequency conversion leads to the generation of symmetrical signal and idler sidebands.

These sidebands itself can interact with each other and the pump light respectively and generate a cascade of new sidebands via the Kerr nonlinearity of glass. The high intensity in the resonators (~GW/cm2) gives rise to a parametric frequency conversion through both degenerate and nondegenerate (i.e., cascaded) Four wave mixing.

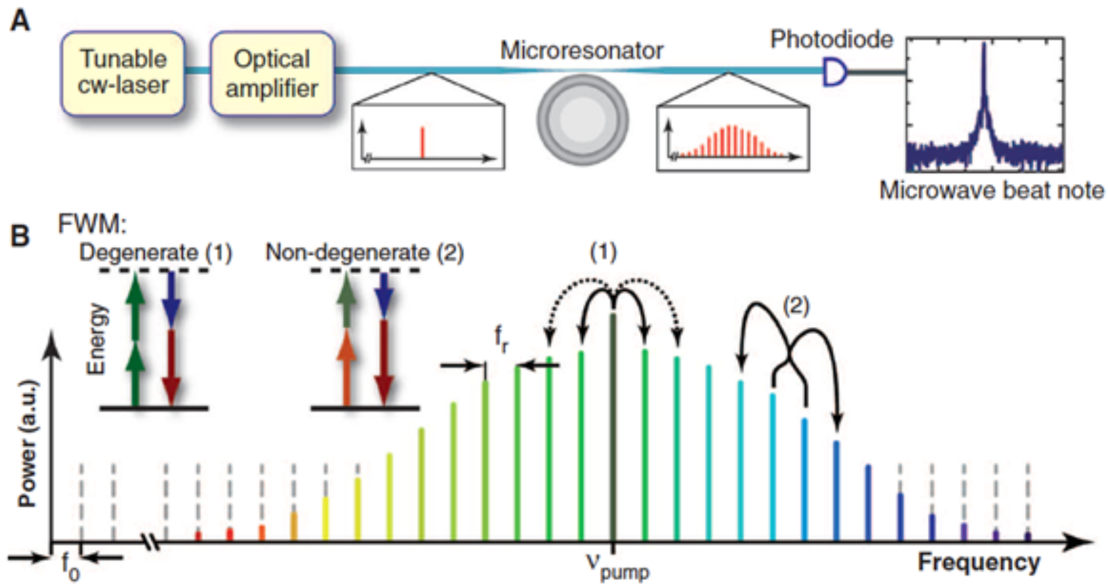

Figure 4. Principle of optical frequency comb generation using optical microresonators. (A) An optical microresonator (here, a silica toroid microresonator) is pumped with a CW laser beam. The high intensity in the resonators (~GW/cm2) gives rise to a parametric frequency conversion through both degenerate and nondegenerate (i.e., cascaded) Four wave mixing. Upon generation of an optical frequency comb, the resulting beat note (given by the inverse cavity round-trip time) can be recorded on a photodiode and used for further stabilization or directly in applications. (B) Optical frequency comb spectrum, which is characterized by the repetition rate (fr) and the carrier envelope frequency (fo). In the case of a micro-resonator based frequency comb, the pump laser is part of the optical comb. The comb is generated by a combination of degenerate FWM (process 1, which converts two photons of the same frequency into a frequency upshifted and downshifted pair of photons) and no degenerate FWM (process 2, in which all four photons have different frequencies). The dotted lines indicate degenerate FWM into resonator modes that differ by more than one mode number.

Since the microcavity exhibits dispersion it is not a priori expected that all the generated sidebands are equidistant. Surprisingly, high precision measurements with a conventional frequency comb as reference revealed that the generated sidebands deviation from the equidistant position is smaller than 0.0014 Hz (!) which corresponds to a relative accuracy in the order of 10-18 when normalized to the optical pump frequency of 200 THz (2x1014 Hz).

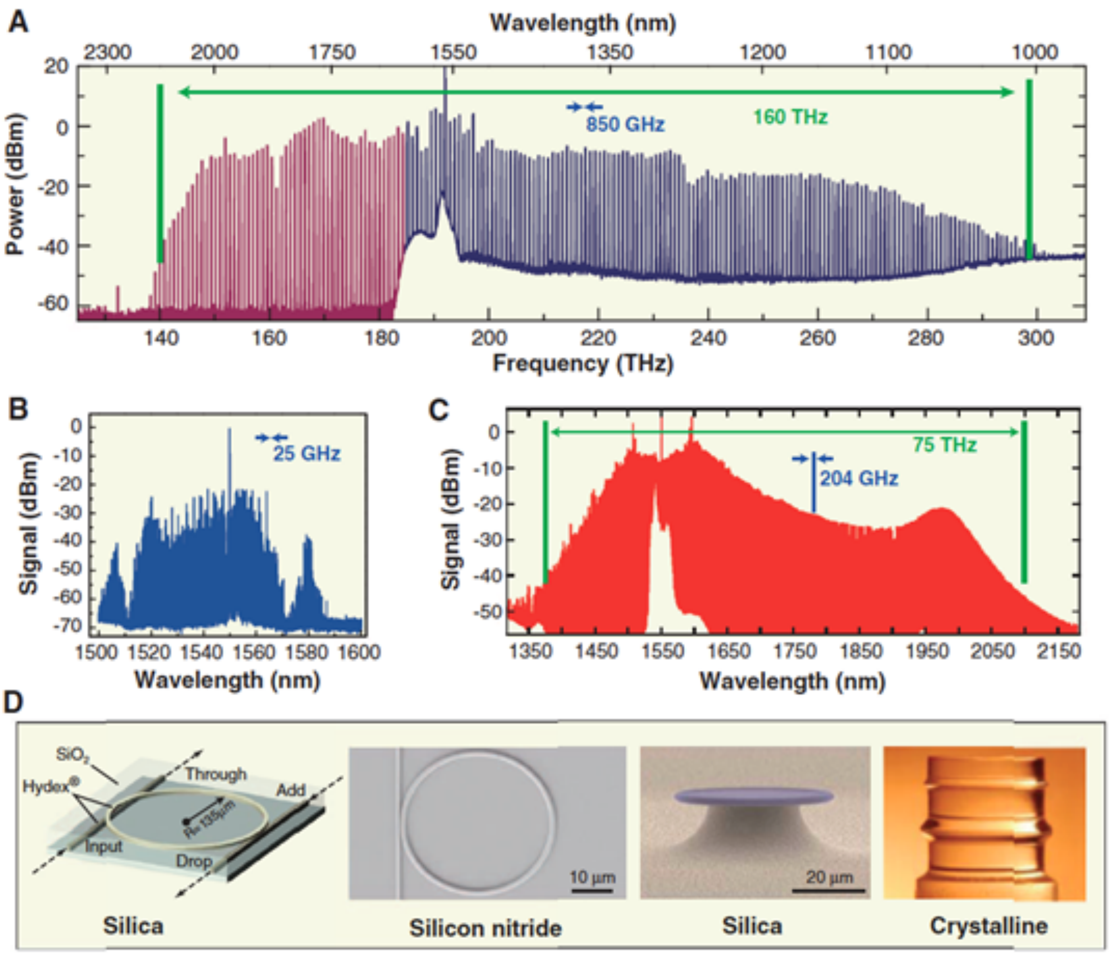

Figure 5. The figure gallery shows different optical Kerr frequency comb generation platforms. Also shown are typical frequency comb spectra. The widest spectrum that has been achieved to date convers a full optical octave10, i.e. a factor of two in frequency.

Refrences

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