Optical frequency comb generation and stabilization in a monolithic microcavity

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Abstract

In previous work we have shown the generation of optical frequency combs in monolithic fused silica microcavities for the first time. The equidistance of the comb modes has been proved down to a level of 7.3×10^{-18} relative to the pump laser. Here, we demonstrate independent control and full stabilization of the offset frequency and mode spacing of the frequency comb.

1. Introduction

Recently our group has shown a novel, monolithic approach to generate phase coherent frequency combs [1]. The frequency comb is induced by degenerate and non-degenerate four-wave mixing in a monolithic ultra-high-Q silica microresonator [2], and their mode spacing corresponds to the microresonators free spectral range. Owing to their ultra-high quality factors and small mode volumes (which yield extremely high circulating intensities) microresonators [2,3] are ideally suited for parametric frequency conversions. The deviation from equidistance of the generated comb lines has been shown to be less than 1.4 mHz which leads to a relative accuracy of 7×10^{-18} when normalized to the optical carrier frequency of around 200 THz [1]. Figure 1 (left panel) shows a typical optical spectrum obtained by optically pumping a 180-micron-diameter toroidal microcavity with an amplified 1550-nm external cavity laser. Highly efficient evanescent coupling from a tapered optical fiber is used to excite the whispering-gallery modes of the microtoroid, yielding comb generation at threshold powers typically in the range of tenth of microwatt. Frequency combs up to 500 nm bandwidth could be observed by pumping the cavities at higher pump power.

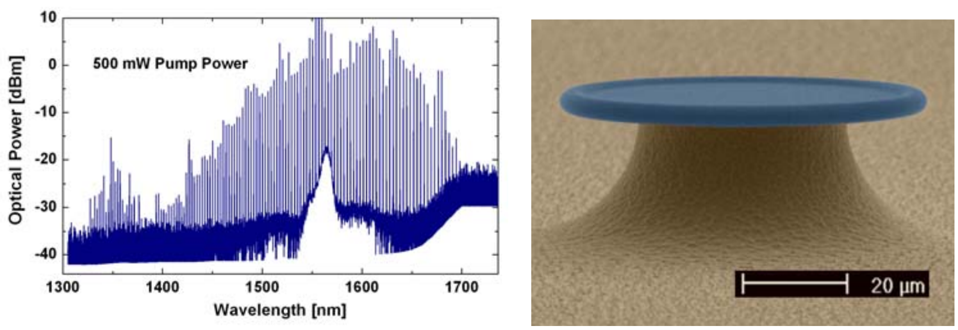

Figure 1. Left panel: Frequency comb generated in a 180-µm diameter toroid. The free spectral range is 3 nm which corresponds to a mode spacing of 375 GHz. The spectrum consists of more than 134 individual modes. Right panel: False-colored scanning electron microscope image of a toroidal microcavity, blue: silica toroid, brown: silicon support.

2. Frequency comb stabilization

An important prerequisite to use a frequency comb as a measurement tool for spectroscopy [5] is the stabilization of the frequency of each comb line. In particular it is necessary to access two linearly independent control parameters such as the carrier envelope offset frequency and mode spacing of the comb [6]. Here we report experimental results which demonstrate that it is indeed possible to control two independent parameters of a frequency comb generated in a monolithic microcavity and lock them to a reference comb. A central difference of a monolithic microcavity as a frequency comb generator compared to conventional mode locked lasers is that the pump laser itself defines one of the comb lines. Thus one degree of freedom of the frequency comb can be simply controlled by adjusting the frequency of the pump laser or locking it to a known reference like an atomic transition. The second control parameter for a microcavity frequency comb is the mode spacing which depends on the optical pathlength of the resonator. In a conventional frequency comb this parameter can be influenced by changing the cavity size for example with a piezo-mounted mirror. For a microcavity the access to this control parameter is less evident, however it could be shown that the mode spacing can be controlled by changing the pump power of the microcavity. Since the refractive index of the silica microcavity depends on the temperature of the resonator ($dn/dT=1.28 \times 10\text{-}5\ K^{-1}$) it is possible to control the mode spacing (the thermal expansion of the resonator also leads to a change of the mode spacing, however this contribution is smaller). The left panel of figure 2 shows the measured dependence of the mode spacing on the optical pump power yielding a linear dependence of approximately 200 kHz per milliwatt pump power. A schematic setup used for locking the frequency comb is depicted in the right panel of figure 2.

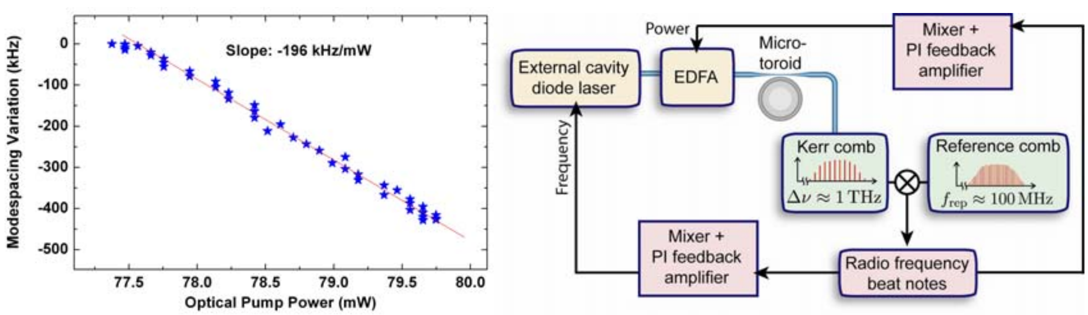

Figure 2. Left panel: Dependence of the microresonator mode spacing on the optical pump power. Right panel: Schematic diagram of the setup that was employed to lock the frequency comb from a monolithic microresonator to a reference frequency comb. (EDFA = Erbium doped fiber amplifier; PI = proportional integral)

The left panel of figure 3 shows the drift of the mode spacing of a microcavity frequency comb. The mode spacing exhibits a thermal drift of approximately 60 kHz per hour and faster fluctuations in a timescale of several seconds with a root mean square of ~30 kHz. The right panel of figure 3 shows the variation of both mode spacing and pump frequency of a locked frequency comb from a monolithic microcavity.

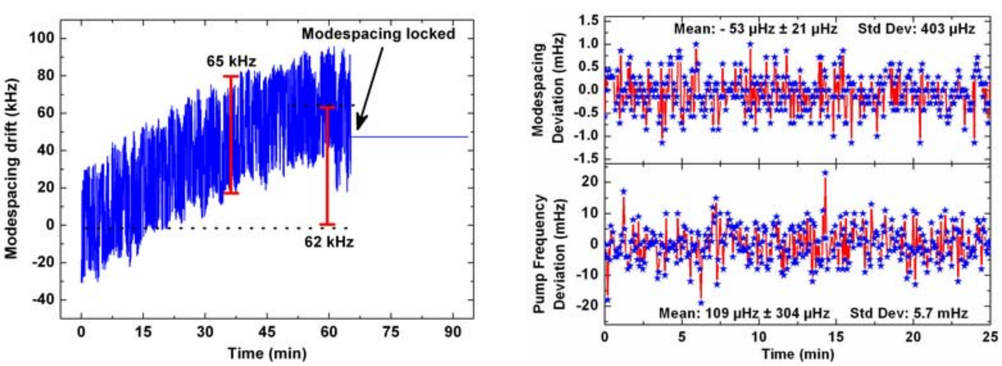

Figure 3. Left panel: Thermal drift of the mode spacing of frequency comb from a monolithic microcavity. In the right part of the graph the mode spacing has been locked to a reference. Right panel: Mode spacing and pump frequency fluctuations of a fully stabilized microcavity frequency comb around a certain setpoint. The gate time for this measurement is 1 second.

Summarizing, we have demonstrated locking of a frequency comb that is generated in a monolithic microcavity, which is an important pre-condition to use a frequency comb for metrology applications. The low threshold powers for the comb generation, the large mode spacing and the high power per comb component make this frequency comb ideally suited for telecom applications where high power per comb mode is required. Finally, it is noted that it was also possible to reduce the mode spacing of a microcavity frequency comb to less than 100 GHz by increasing the size of the microresonator, enabling direct measurement of the mode spacing in time domain with fast photodiodes, making the toroidal frequency comb generator independent of a reference frequency comb.

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