Optical combs with a crystalline whispering gallery mode resonator

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We report on the experimental demonstration of a tunable monolithic optical frequency comb generator. The device is based on the four-wave mixing in a crystalline calcium fluoride whispering gallery mode resonator. The frequency spacing of the comb is given by an integer number of the free spectral range of the resonator. We select the desired number by tuning the pumping laser frequency with respect to the corresponding resonator mode. We also observe interacting optical combs and high-frequency hyperparametric oscillation, depending on the experimental conditions. A potential application of the comb for generating narrowband frequency microwave signals is demonstrated.

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Optical combs [1] have become an important tool in a variety of applications, ranging from metrology to spectroscopy. Optical combs are usually realized with modulated light from continuous-wave lasers [2, 3], as well as mode locked lasers [4]. Recently, optical combs produced by the interaction between a continuous-wave pump laser of a known frequency with the modes of a monolithic ultra-high-Q whispering gallery mode (WGM) resonator were demonstrated [5]. The comb generation is based on the four-wave mixing (FWM) process and hyperparametric oscillations occurring in the resonator [6, 7]. The comb generator is physically similar to the additive modulational instability ring laser predicted and demonstrated in the fiber ring resonators [8, 9, 10].

A large intracavity intensity in high finesse WGMs enables four-photon process transforming two pump photons into two sideband (signal and idler) photons. The sum of frequencies of the generated photons is equal to twice the frequency of the pumping light because of the energy conservation law. Increase of the pumping power leads to a cascading the process, generating multiple equidistant signal and idler harmonics (optical comb), and also results in interaction between the harmonics [5]. These optical combs usually have spacing equal to the free spectral range of the resonators. In this Letter we demonstrate for the first time generation of tunable optical combs in CaF$_2$ resonators. We have observed combs with $25 \times m$ GHz ($m$ is an integer number) frequency spacing in the same resonator. The spacing (the number $m$) is changed controllably by selecting the proper detuning of the carrier frequency of the pump laser with respect to a selected WGM frequency.

The demodulation of the optical comb by means of a fast photodiode results in the generation of high frequency microwave signals at comb repetition frequency. This is a consequence, and indeed an indication, that the comb lines are coherent. The spectral purity of the signal increases with increasing Q factor of the WGMs, the optical power of the generated sidebands, and the spectral width of the comb. We have demonstrated generation of 25 GHz signals with less than 40 Hz linewidth and shown that the measured linewidth value is limited by our experimental setup.

We use WGM resonators with a dense mode spectrum. As the result, multiple nonlinear optical phenomena coming from interaction of various mode families have been observed. For instance, some comb envelopes are modulated, and other combs grow asymmetrically. We have observed generation of stand-alone narrowband signal and idler sidebands separated by several THz. We show that some phenomena demonstrated in the overmoded WGM resonators have direct analogies in optical fibers, while some of them are unique to compact resonator systems.

In our experiments light from a pigtailed 1550 nm laser was sent into a CaF$_2$ WGM resonator using one coupling prism, and was retrieved out of the resonator using a second coupling prism. The light escaping the prism was collimated and sent into a single mode fiber. The maximum coupling efficiency was better than 35% and was achieved with overcoupling the resonator. Decoupling the prism resulted in an increase of the quality factor and a decrease of the light transmission through the resonator. The resonator had a conical shape with the rounded and polished rim. It had a 2.55 mm diameter and 0.5 mm thickness. Proper shaping of the resonator allowed reducing the mode crossection area to less than a hundred of square microns. The intrinsic Q-factor has been on the order of $2.5 \times 10^9$. The resonator was packaged into a thermally stabilized box to compensate for external thermal fluctuations.

To achieve a stable comb generation the laser frequency was locked to a mode of the resonator using Pound-Drever-Hall technique [11]. It is important to note that the level and the phase of the lock is different for the oscillating and non-oscillating resonators. Increasing the power of the locked laser above the threshold of the oscillation always resulted in the lock instability. This is expected since the symmetry of the resonance changes at the oscillation threshold [12]. We have manually modified the lock parameters while increasing the laser power that helped us to keep the laser locked. Modifying the lock...
parameters we were able to gradually change the detuning of the laser frequency from the resonance frequency that led to the modification of the comb.

Our resonator had multiple modes families of high Q whispering gallery modes. We found that stimulated Raman scattering (SRS) process has a lower threshold compared with the FWM oscillation process in the case of the direct pumping of the modes belonging to the basic mode sequence. This is an unexpected result because SRS process has somewhat smaller threshold compared with the hyperparametric oscillation in the modes having identical parameters \(^2\). The discrepancy is resolved if we note that different mode families have different quality factors given by the field distribution in the mode and position of the couplers. The setup was arranged in such a way that the basic sequence of the WGMs had lower Q-factor (higher loading) compared with the higher order transverse modes. The SRS process starts in the higher-Q modes even though the modes have larger volume \(\mathcal{V}\). This happens because the SRS threshold power is inversely proportional to \(\mathcal{V}Q^2\).

Pumping of the basic mode sequence with the light having larger power leads to hyperparametric oscillations taking place along with the Raman process (Fig. 1). Interestingly, the oscillation occurs at several terahertz detuning from the pump carrier frequency. Neither hyperparametric oscillation nor FWM process between the Raman mode and the carrier are observed in the vicinity of the carrier. Again, this is an unexpected result that intuitively contradicts the earlier studies demonstrating generation of the sidebands in the direct vicinity of the pump frequency (an FSR away from the pump frequency).

The contradiction can be removed if we note that the hyperparametric process as well as the SRS process start in the higher Q modes. A study of the signal structure confirms the conclusion. Indeed, the frequency separation between the modes participating in the processes is much less than the FSR of the resonator (see Fig. 1). The modes are apparently of the transverse nature. This also explains the absence of the four wave mixing between the SRS light and the carrier. Nonlinear mixing of the pump and generated light do not create signals an FSR away from the pump carrier frequency.

Generation of photon pairs approximately 8 THz apart from the pump frequency (Fig. 1) is also intriguing. It seems to be unclear why such an oscillation frequency is selected by the system. The question can be answered if we recall the results of the studies related to phase matching of the FWM process in single mode as well as photonic crystal fibers in the minimum of the chromatic dispersion region. The dispersion of the fiber results in unique phase matching conditions for generation of highly detuned signal and idler if the pumping light frequency is tuned near zero-dispersion wavelength of the fiber. The same conditions are valid for our resonators since CaF\(_2\) has its zero dispersion point in the vicinity of 1550 nm.

The possibility of generation of photon pairs far away from the pump makes the WGM resonator-based hyperparametric oscillator well suited for quantum communication and quantum cryptography networks. The oscillator avoids large coupling losses occurring when the photon pairs are launched into communication fibers, in contrast with the traditional twin-photon sources, based on the \(\chi^{(2)}\) down-conversion process. Moreover, there is no problem in lossless separation of the narrow band photons having carrier frequencies several terahertz apart.

To observe generation of optical combs we locked the frequency of our laser to a transverse WGM. As a result, we observed hyperparametric oscillation with lower threshold compared with the SRS process. Even a significant increase of the optical pump power did not lead to the SRS process because of the fast growth of the optical combs.

In several cases we observed a significant asymmetry in the growth of the signal and idler sidebands (see Fig. 2). This asymmetry is not explained with the usual theory of the hyperparametric oscillation which predicts generation of symmetric sidebands. We see the explanation in the high modal density in our resonator. We pump not a single mode, but a nearly degenerate mode cluster. The transverse mode families have slightly different geometrical dispersion so the shape of the cluster changes with the frequency and each mode family results in its own hyperparametric oscillation. The signal and idler modes of those oscillations are nearly degenerate so they can interfere. The interference results in sideband suppression on either side of the carrier. This results in the "single sideband" oscillations we observe. It is worth noting,
though, that the interfering combs should not be considered as independent because the generated sidebands have a distinct phase dependence, as is shown in the later discussion devoted to the generation of microwave signals by the comb demodulation.

The interaction of the signal and idler harmonics becomes even more pronounced when we increase the pump power to generate optical combs. We have observed more than 30 THz wide combs in the resonator (Figs. 3 and 4). The envelopes of the combs are modulated and the reason for the modulation can be deduced from the Fig. (4b). One can see that the comb is generated over a mode cluster that changes its shape with frequency.

Another and probably the most important funding is related to the possibility of controllable tuning of the comb repetition frequency by changing the frequency of the pump laser. Keeping the all experimental conditions the same we changed the level and the phase of the laser lock. This modification of the experimental conditions resulted in the change of the comb. Examples are presented in Figs. 3-4.

To demonstrate the coherent properties of the comb we have sent a comb having primarily 25 GHz frequency to a fast (40 GHz) photodiode (optical band 1480-1640 nm) and recorded the microwave signal. The result of the measurement is shown in Fig. 5. Our microwave spectrum analyzer (Agilent 8564A) has a 10 Hz video bandwidth, no averaging, and the internal microwave attenuation is 10 dB (the real microwave noise floor is an order of magnitude lower). No optical post-filtering of the optical signal was involved.

It can be seen that the microwave signal is inhomogeneously broadened to 40 Hz, however the noise floor corresponds to the measurement bandwidth (is approximately 4 Hz). The broadening comes from the thermorefractive jitter of the WGM frequency with respect the pump laser carrier frequency. Our lock is not fast enough (we use 8 kHz modulation) to compensate for this jitter. We expect that a better and faster (e. g. 10 MHz) lock will allow measuring much narrower bandwidth of the microwave signal. However, even a 40 Hz linewidth already shows the high coherence of the comb.

It worth to highlight the asymmetric shape of the comb we used in the microwave experiment Fig. 5c. Unlike the nearly symmetric combs (see Figs. 3 and 4), this
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