Tunable Optical Frequency Comb 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 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 frequency of the pumping laser with respect to the corresponding resonator mode. We also observe a rich variety of optical combs and high-frequency hyperparametric oscillation, depending on the experimental conditions. A potential application of the comb for generating tunable narrow band frequency microwave signals is demonstrated.

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Introduction.—Optical frequency combs [1] have become an indispensable tool in a variety of applications, ranging from metrology to spectroscopy. Optical combs are usually produced with modulated light from continuous-wave lasers [2,3], and by mode-locked lasers [4]. Recently, optical combs were generated by a continuous-wave pump laser interacting with a fixed frequency with the modes of a monolithic ultrahigh-Q whispering gallery mode (WGM) resonator [5]. In this approach the comb generation is based on four-wave mixing (FWM) and hyperparametric oscillation occurring in the resonator [6,7], where a FWM enabled by the large field intensity in the high finesse WGMs transforms 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. Increasing the pumping power leads to a cascading process, generating multiple equidistant signal and idler harmonics (an optical comb), and also results in interaction between the harmonics [5]. The comb generator produced with the WGM resonator is physically similar to the additive modulational instability ring laser predicted and demonstrated in the fiber ring resonators [8–10].

In this Letter we demonstrate generation of tunable optical combs in CaF_2 resonators. We have observed combs with 25m GHz frequency spacing in the same resonator (m is an integer number). 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. We show that demodulation of the optical comb by means of a fast photodiode results in the generation of high-frequency microwave signals at comb repetition frequency. We demonstrated generation of 25 GHz signals with less than 40 Hz linewidth, a value limited by the resolution of our measurement equipment.

Multiple nonlinear optical phenomena caused by the interaction of various WGM families were observed. For instance, some comb envelopes were modulated, and other combs grew asymmetrically. We also have observed generation of standalone narrow band 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 others are unique to compact resonator systems. We focus on the presentation of our experimental results and provide plausible explanations of the observed phenomena leaving the detailed theoretical discussion to the follow-up works.

Experiment.—In our experiment, 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 another coupling prism. The light escaping the prism was collimated and sent into a single mode fiber. The maximum coupling efficiency was higher than 35%. The resonator had a conical shape with the rounded and polished rim. It had a 2.55 mm diameter and 0.5 mm thickness. The intrinsic Q factor was on the order of 2.5×10^9. The proper shaping of the resonator allowed reducing the mode cross section area to less than a hundred of square microns. The resonator was packaged into a thermally stabilized box to compensate for external thermal fluctuations.

The laser frequency was locked to a mode of the resonator using the Pound-Drever-Hall technique [11]. The level and the phase of the lock is different for the oscillating and nonoscillating resonator. Increasing the power of the locked laser above the threshold of oscillation always resulted in the lock instability. This is expected since the symmetry of the resonance changes at the oscillation threshold [12]. We manually modified the lock parameters while increasing the laser power, which helped us to keep the laser locked. We were able to gradually change the detuning of the laser frequency from the resonance frequency that led to the modification of the comb by modifying the lock parameters.

Low pump power.—Let us discuss the behavior of the optically pumped WGM resonator at low input level when the pumping power approaches the threshold of the hyperparametric oscillations. No optical comb is generated at this point and a competition of stimulated Raman scattering (SRS) and the FWM processes is observed.

Our resonator had multiple mode families of high Q WGMs. We found that SRS has a lower threshold compared with the FWM oscillation process in the case of direct pumping of the modes that belong to the *basic* mode sequence. This is an unexpected result because the SRS process has a somewhat smaller threshold compared with the hyperparametric oscillation in the modes having identical parameters [7]. The discrepancy is resolved if we note that different mode families have different quality factors given by the field distribution in the mode, and positions 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 larger power of light typically leads to hyperparametric oscillation taking place along with the SRS (Fig. 1). We have found that hyperparametric and SRS processes start in the higher Q modes. A study of the signal structure confirms this conclusion. Indeed, the frequency separation between the modes participating in these processes is much less than the FSR of the resonator (see Fig. 1); the modes are apparently of transverse nature. This also explains the absence of FWM between the SRS light and the carrier.

To explain generation of photon pairs approximately 8 THz apart from the pump frequency (Fig. 1) we recall the results of studies related to phase matching of FWM process in single mode [13] and photonic crystal [14] fibers at 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 light, 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 [15].

The possibility of generating 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 [16]. Moreover, a lossless separation of the narrow band photons with their carrier frequencies several terahertz apart can be readily obtained.

High pump power.—We observed generation of optical combs when the pump power increased far above the oscillation threshold. Stable optical combs were generated when we locked the frequency of the laser to a high Q transverse WGM. In this way, we observed hyperparametric oscillation with a lower threshold compared with the SRS process. Even a significant increase of the optical pump power did not lead to the onset of the SRS process because of the fast growth of the optical comb lines.

The growth of the combs has several peculiarities. In some 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 hyper-

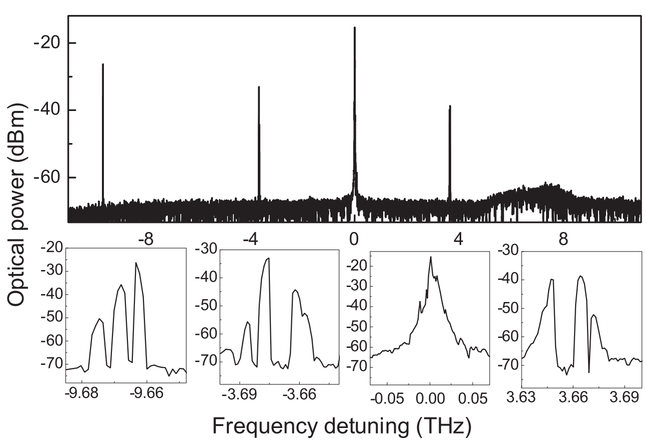

FIG. 1. Frequency spectrum of the SRS (~9.67 THz from the carrier) and hyperparametric oscillations observed in the CaF_2 resonator pumped to a mode belonging to the basic mode sequence. The structure of the lines is shown below the spectrum. The loaded quality factor is $Q = 10^9$; the pump power sent to the modes is 8 mW.

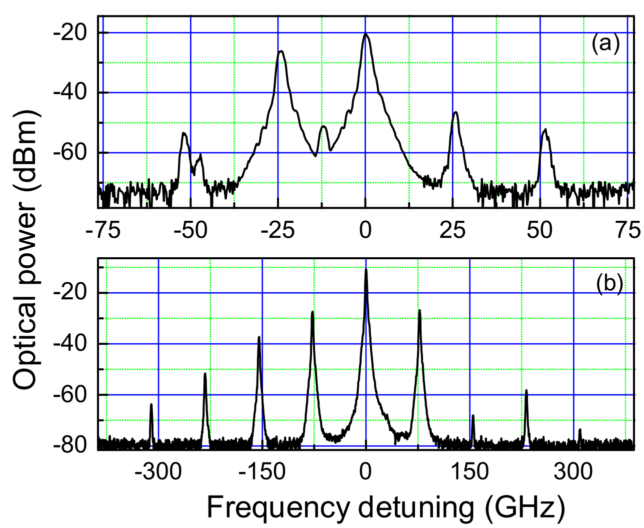

FIG. 2 (color online). Hyperparametric oscillation observed in the resonator pumped with 10 mW of 1550 nm light. Spectra (a) and (b) correspond to different detuning of the pump from the WGM resonant frequency. One can see the result of the photon summation process in (a), when the carrier and the first Stokes sideband, separated by 25 GHz, generate photons at 12.5 GHz frequency. The process is possible because of the high density of the WGMs and is forbidden in the single mode family resonators.

parametric oscillation which predicts generation of symmetric sidebands. We believe the explanation is, again, in the high modal density of the resonator. In the experiment the laser pumps 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 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, and interference results in sideband suppression on either side of the carrier. This results in the "single sideband" oscillations that we observe. It is worth noting that the interfering combs should not be considered as independent because the generated sidebands have a distinct phase dependence, as is shown in the discussion below regarding the generation of microwave signals by comb demodulation. The detailed theoretical discussion of the phenomenon will be presented somewhere else.

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

Tunability of the comb.—Another, and probably the most important, finding is related to the controllable tuning of the comb repetition frequency by changing the frequency of the pump laser. Keeping the experimental conditions the same, we changed the level and the phase of the laser lock. This modification of the experimental conditions resulted in a change of the comb frequency spacing. Examples are presented in Figs. 2–4). This is a major advantage of WGM based comb generators, and is a feature not directly achieved with the conventional frequency combs.

Generation of microwaves.—To demonstrate the coherent properties of the comb we sent a comb with the primary frequency spacing of 25 GHz to a fast (40 GHz) photodiode (optical band 1480–1640 nm) and recorded the microwave beat signal. The result of the measurement is shown in Fig. 5. The microwave spectrum analyzer (Agilent 8564A) used in this experiment has a 10 Hz video bandwidth, no averaging, and the internal microwave attenuation is 10 dB (the actual microwave noise floor is an order of magnitude lower). No optical postfiltering 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 (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 is worthwhile to highlight the asymmetric shape of the comb used in the microwave generation experiment Fig. 5 (c). Unlike the nearly symmetric combs (see Figs. 3 and 4), this comb is shifted to the blue side of the carrier (cf. [5]). To produce the comb in Fig. 5(c) we locked the laser to one of the modes belonging to the basic mode sequence. We observed the two mode oscillation process as in Fig. 1 for lower pump power that finally transformed to the equidis-

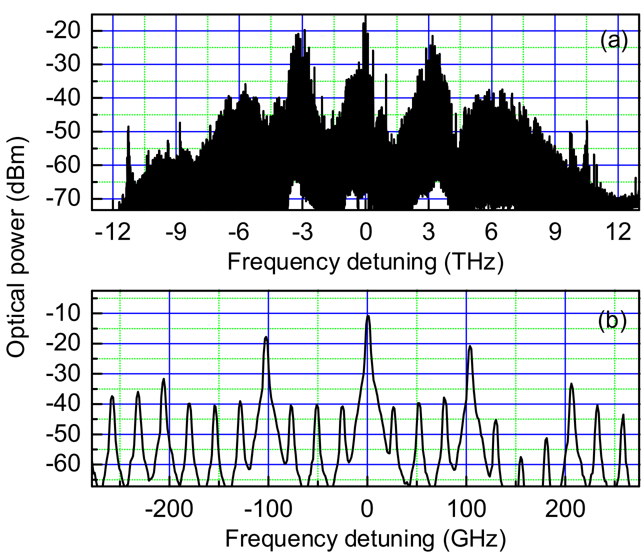

FIG. 3 (color online). (a) Optical comb generated by the laser with 50 mW power (b) represents the central part of (a). The comb has two definite repetition frequencies equal to one and four FSRs of the resonator.

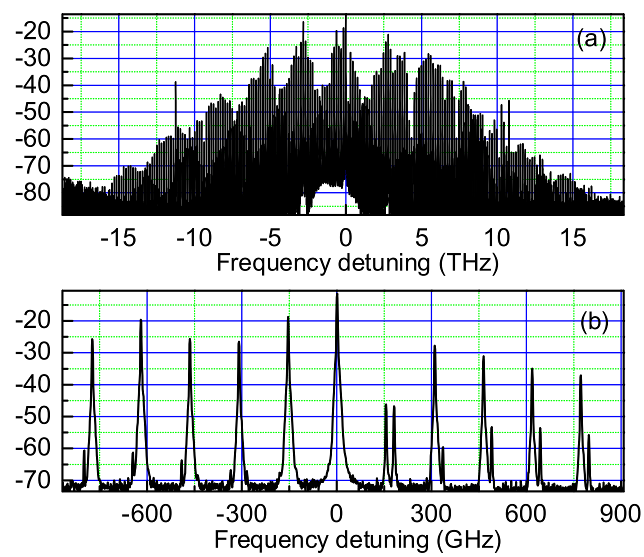

FIG. 4 (color online). Modification of the comb shown in Fig. 3 when one changes the level and the phase of the lock.

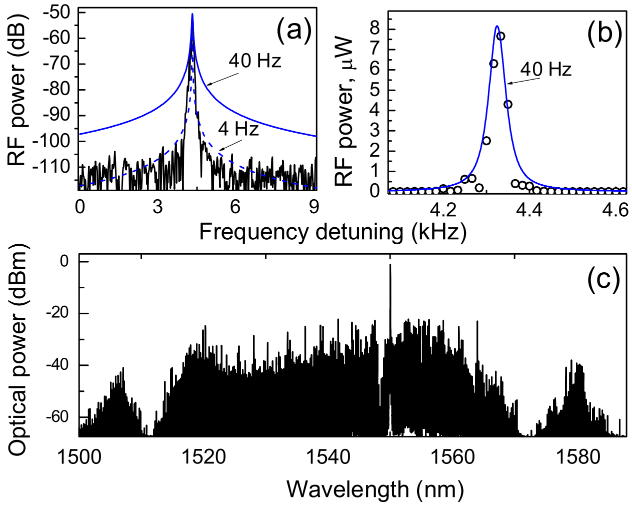

FIG. 5 (color online). Microwave signal generated by demodulating the comb with high-frequency photodiode. (a) The signal in the logarithmic scale; (b) the same signal in the linear scale; (c) optical comb used in the experiment. Linear fit of the microwave line gives a 40 Hz linewidth; however, evaluation of the logarithmic scale shows that the signal bandwidth is much smaller.

tant comb as the power was increased. The SRS process was suppressed. We expect that the blue shift of the spectrum is explained by the soliton fission process [17]. We also observed short pulses going out of the oscillator, but our equipment does not allow resolving pulses shorter than 10 ps. This issue requires additional study.

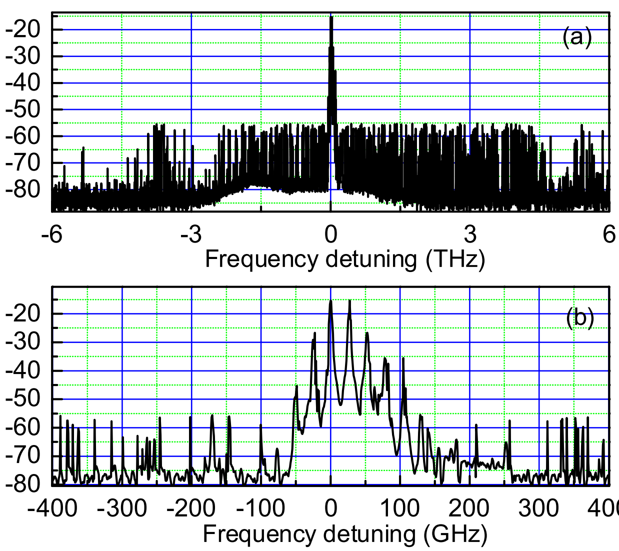

FIG. 6 (color online). Harmonics generated by the externally modulated light. We have pumped the resonator with light 1550 nm light modulated at 25 786 kHz and having 50 mW power. The generated spectrum is not broader than the spectrum that was produced with a cw pumped resonator and the modes are not equidistant.

Chaotic behavior.—Finally, we sent externally modulated light to the resonator expecting generation of even broader combs because of the low dispersion and high nonlinearity of the resonator (cf. the continuum generation in microstructured fibers [18]). Instead, we observed chaotic oscillations (Fig. 6). Though the spectrum looked flat and nice, the generated modes are completely unequidistant. Additional study is required to explain this behavior of the system.

Conclusion.—We have studied experimentally generation of optical frequency combs in a WGM crystalline resonator, and observed a rich variety of nonlinear phenomena including generation of a comb with tunable frequency spacing corresponding to the FSR of the resonator. The combs have spectral widths exceeding 30 THz, as well as outstanding relative coherence of the modes. The coherence was verified by studying the linewidth of the microwave beat note produced by demodulation of the comb on a fast photodiode. We have shown that the properties of the generated combs depend significantly on the selection of the optically pumped mode, and the level and the phase of the lock of the laser to the resonator. We succeeded in locking the pump laser to the WGM to achieve the stable oscillations in the system.

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