We report on realization of an efficient triply-resonant coupling between two long lived optical modes and a high frequency surface acoustic wave (SAW) mode of the same monolithic crystalline whispering gallery mode resonator. The coupling results in an opto-mechanical oscillation and generation of a monochromatic SAW. A strong nonlinear interaction of this mechanical mode with other equidistant SAW modes leads to mechanical hyper-parametric oscillation and generation of a SAW pulse train and associated frequency comb in the resonator. We visualized the comb observing the modulation of the modulated light escaping the resonator.

Cavity opto-mechanics has enjoyed intense interest in the research community engaged with investigation of quantum effects in macroscopically large objects, ultra-sensitive measurement of dynamic back action, and cooling thermally excited random motion of mechanical modes of the cavity [1]. The study of the interaction of the optical and mechanical cavity modes has been basically limited to the mechanical oscillations that are localized in the bulk of the cavity. It was pointed out that triply-resonant opto-mechanical interaction with surface acoustic waves (SAWs) is also possible in monolithic whispering gallery mode (WGM) microresonators [2] where SAWs form high-quality (\(Q\)) mechanical WGMs [3]. Feasibility of such interaction was proven experimentally using fused silica microresonators [4]. In this Letter we report on an experimental observation of opto-mechanical oscillation (OMO) [5] involving SAWs localized in crystalline lithium tantalate as well as magnesium fluoride WGM optical microresonators, and show that the monochromatic coherent SAW generated in the OMO process produces SAW pulses and SAW frequency combs. The process is similar to the optical Kerr frequency comb generation in monolithic microresonators [7] and complements the experiments on realization of microresonator based phonon lasers [8].

Two experiments involving different WGM resonators were performed to validate different kinds of the OMO process. In the first experiment we used a Z-cut lithium tantalate (LiTaO\(_3\)) WGM resonator and scanned the relative frequency between its TE and TM WGMs by applying a DC voltage to electrodes on the top and bottom surfaces of the resonator. At at several well defined values of the DC voltage corresponding to specific frequencies fulfilling the resonant condition we observed an OMO in which the SAW wave was coupled to two nearly orthogonally polarized optical modes. In the second experiment we used a magnesium fluoride (MgF\(_2\)) WGM resonator. We tuned the relative frequency between the nearly identically polarized modes (either TE or TM) with temperature and observed much more efficient OMO than in the first experiment.

Schematic of our experiment is shown in Fig. 1. A selected mode of a WGM resonator is pumped with a continuous wave light emitted by a semiconductor laser self-injection locked to the mode [9]. The light is coupled in and out of the resonator using an evanescent field coupler (coupling prism). The coupling efficiency is managed by changing the distance between the coupler and the surface of the resonator, \(d\). The pumping light generates a coherent acoustic wave in a SAW WGM [2] as well as Stokes light in a properly detuned optical WGM if the power of the pump exceeds a certain threshold value.

In the first experiment we used a LiTaO\(_3\) WGM resonator with \(2a = 0.997\) mm diameter and \(0.1\) mm thickness. We sent 2.3 mW of 1550 nm continuous wave light to a TE WGM mode (5 MHz loaded full width at half maximum, \(Q = 4 \times 10^7\)) and observed generation of Stokes sidebands in a TM WGM (4.3 MHz FWHM).

To quantify the observed oscillation frequencies we introduced the light escaping the resonator to a fast photodiode (50 GHz bandwidth U2t) and an RF spectrum analyzer. The resultant spectrum was centered around 880 MHz and is shown in Fig. (2). By measuring the frequency of the individual RF lines we found the free spectral range (FSR) of the acoustic modes to be \(\nu_{\text{FSR}} = 1.05\) MHz and the speed of the waves, given by \(V_{\text{SAW}} = 2\pi a \nu_{\text{FSR}} = 3.3\text{ km/s}\), which corresponds to the
The tabulated speed of surface acoustic waves in LiTaO$_3$.

The SAW WGM is tightly confined by the boundaries of the resonator. We identified the confinement area by touching the surface of the resonator with a polished fused silica plate. The plate did not degrade the Q-factor touching the surface of the resonator with a polished plate. We identified the confinement area by touching the surface of the resonator with a polished fused silica plate. The plate did not degrade the Q-factor of the optical modes since its index of refraction is significantly lower compared with the one of LiTaO$_3$. However, it suppressed the SAW as well as the OMO process, leading to the reduction of the power of the RF signal generated at the photodiode. We quantified the effect using Stokes light emitted by the resonator. The emission is observed when the frequency difference of the TE and TM modes coincide with corresponding harmonic of SAW WGM, and the pump power is strong enough to initialize the OMO. The harmonics (a) are measured using the RF beat note between the pump and Stokes light demodulated with a photodiode and recorded with an RF spectrum analyzer. The spectrum of harmonics is equidistant (b). Three families of lines, belonging to three different SAW WGM families, are observed.

Modes belonging to, say, the TE mode family have a slight deviation in the direction of their polarization depending on the mode numbers. The crystal is anisotropic and, hence, the modes have different thermal sensitivity. It is possible to reconfigure the entire spectrum of the resonator by changing its temperature. The process is less controllable compared with the electro-optical tuning of TE and TM modes in LiTaO$_3$ resonator, yet it allows finding two optical and a SAW WGM for the OMO.

The MgF$_2$ resonator had $Q = 3 \times 10^9$ (67 kHz FWHM) loaded Q-factor, which ensured high efficiency of the interaction. The resonator was glued to the substrate to suppress the volumetric mechanical vibrations; only SAW WGMs survive in such a structure. We pumped the resonator with 1.7 mW of 1543 nm cw light. The laser was self-injection locked to a selected optical WGM.

We observed generation of optical pulses shown in Fig. 4 by sending the light escaping the resonator to a fast photodiode directly connected to the 50 Ohm input of a fast oscilloscope (Tektronix 300 MHz). The value of the optical power at the input of the photodiode was 0.11 mW, which is far from its saturation power of 20 mW. Also, the frequency of the generated RF signal (67 MHz) was much smaller than the 50 GHz bandwidth of the photodiode. Therefore, the measurement system operated in a linear regime and the observed pulses were originated by the resonator, not the measurement system. The signal disappeared if the laser was detuned from the optical WGM or the temperature of the resonator changed by about two degrees.

The Fourier transform of the generated pulse train reveals a number of equidistant harmonics separated by 67 MHz. The spectrum is significantly wider than the bandwidth of the optical WGMs and scales up to 1 GHz.

Fig. 2. Measurement of the FSR of the SAW WGMs using Stokes light emitted by the resonator. The emission is observed when the frequency difference of the TE and TM modes coincide with corresponding harmonic of SAW WGM, and the pump power is strong enough to initialize the OMO. The harmonics (a) are measured using the RF beat note between the pump and Stokes light demodulated with a photodiode and recorded with an RF spectrum analyzer. The spectrum of harmonics is equidistant (b). Three families of lines, belonging to three different SAW WGM families, are observed.

Fig. 3. Dependence of the RF signal produced by the modulated light escaping the resonator on a fast photodiode, on the position of the fused silica plate touching the resonator. The signal disappears when the angle is less than 20 degrees. This confirms that the SAW WGM is localized between $\alpha = \pm 20^\circ$ at the resonator surface.
The spectrum certainly cannot be generated within the optical WGM. Instead, it is generated due to the modulation of the coupling occurring when the SAW pulse passes by the evanescent field coupler (Figure 1). The quality factor $Q_c$ describing the loading efficiency of the fundamental WGM family depends on the gap between the resonator surface and the coupling prism, \(d\), as

\[ Q_c \approx \frac{\pi(n_r^2 - 1)^{3/2}}{2n_r \sqrt{n_c^2 - n_r^2}} \exp\left[\frac{4\pi d}{\lambda} \sqrt{n_c^2 - 1}\right] \]  

(1)

where \(n_r\) and \(n_c\) the refractive indices of the resonator and the coupling prism, and \(\lambda\) and \(l\) are the wavelength and the number of the mode. Therefore, modulation of the gap \(d\) results in the modulation of the power of the light reflected from the prism coupler. Our observation supports the conclusion that resonant modulators with high Q-factors can operate at frequencies much larger than the resonator linewidth if the modulation of light is realized via control of the coupling efficiency [10].

A monochromatic SAW cannot generate the observed wide spectrum, even if we take into account the nonlinear dependence of the coupling efficiency on \(d\). The only possibility is that the acoustic pulses are formed at the surface of the resonator. This is a consistent picture since the SAW WGMs have equidistant spectra, and also are characterized with cubic nonlinearity [6]. A monochromatic SAW is generated due to the opto-mechanical effect, and then becomes strong enough to generate an acoustic frequency comb similarly to the generation of the optical Kerr frequency comb in a nonlinear WGM resonator pumped with cw light [7].

We performed a direct demonstration of the broad RF spectrum by selecting another optical mode and a different temperature for the resonator. The light exiting the optically pumped resonator was sent to the fast photodiode connected to a 26.5 GHz Agilent RF spectrum analyzer. The observed RF spectrum (Figure 5) was much wider than the full width at half maximum of any of the optical WGMs. The Q-switching mechanism explains such a broad spectrum [10].

To conclude, we have demonstrated a triply-resonant opto-mechanical interaction between two optical and one SAW WGMs. The process takes place when the optical modes have either the same or orthogonal polarizations. The large magnitude of the surface acoustic wave excited in the OMO results in nonlinear generation of SAW frequency combs, leading to a Q-switching phenomenon at the output coupling port of the resonator, and in the generation of much shorter optical pulses than allowed by the intrinsic quality factor of the optical modes. The observed phenomena are promising for creation of extremely efficient novel opto-mechanical systems for the study of, for example, efficient optical cooling of acoustic modes down to the zero phonon level.

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