Optical Parametric Metamaterials –
Frequency Mixing, Frequency Combs and Control of Brownian Motion

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Nano-opto-mechanical metamaterials on semiconductor nanomembranes are a perfect platform for parametric optical devices, frequency mixing and optical comb generation, and fundamental studies of coupling between thermal excitations in metamaterials and their optical properties.

A parametric oscillator is one which is driven by varying a parameter of the system, typically at a frequency different from the oscillator's natural frequency. Associated nonlinear phenomenon are readily observed in electronic systems but more difficult to achieve in optics, where very high light intensities are typically required. Here, we demonstrate that photonic metamaterial systems in which structural mechanical resonances at ~MHz frequencies are strongly coupled to near-IR optical resonances offer an ideal, highly adaptable platform for the realization and exploitation of parametric effects at $\mu W/\mu m^2$ intensities.

We employ a metamaterial structure in which high-index dielectric metamolecules – pairs of long/short Si nano-bricks - are supported on neighboring Si_3N_4 nanowires (Fig. 1a), such that the wires' mutual displacement affects the metamolecules' resonant optical properties. Indeed, to the point that the wires' ambient temperature thermal motion (with RMS amplitude ~200 pm) is detectable in transmissivity/reflectivity frequency spectra. On this platform, we perform a series of experiments demonstrating parametric control of said thermomechanical motion, frequency mixing, and tunable phononic frequency comb generation.

For example, when the metamaterial is illuminated with a continuous probe beam at 1540 nm and an electro-optically modulated pump at 1550 nm, with intensity $\sim 2\ \mu W/\mu m^2$, pump absorption (photothermally) modulates the tension in the nanowires, creating an array of Brownian oscillators with time-varying spring constants. The effect of pumping at frequency Ω_p on the thermal motion spectrum of a nanowire with natural oscillation frequency Ω_m is illustrated in Fig. 1b: with increasing pump power, multiple Stokes and anti-Stokes sidebands emerge at $\Omega = \Omega_m \pm N\Omega_p$ (where N is an integer). By then combining parametric pumping at Ω_p with a pondermotive optical driving force at frequency Ω_d close to the mechanical resonance (by modulating pump intensity simultaneously at both frequencies), one may generate tunable phononic frequency combs, as illustrated in Fig. 1c.

This demonstration of optical parametric control over a thermomechanical oscillator, allowing continuous mechanical frequency conversion at low intensities, opens a path towards the realization of time-varying photonic media, in the form of temporal or spatiotemporal nanomechanical metamaterials.

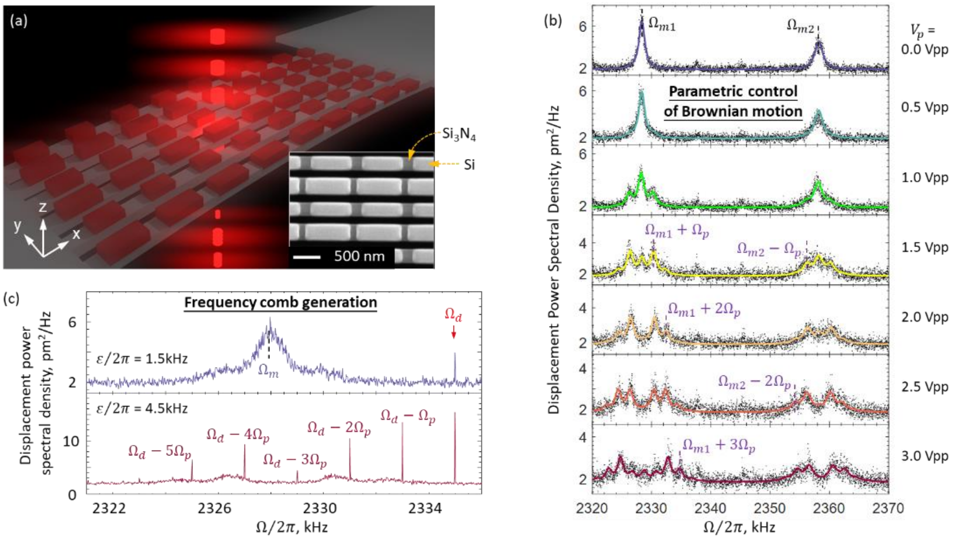

Fig 1 (a) Artistic impression of a metamaterial array of silicon-on-silicon-nitride nanowire oscillators. The inset SEM image shows a portion of the experimental sample. (b) Parametric control of Brownian motion: Spectral density of nanowire displacement as a function of increasing [top to bottom] parametric pumping strength [$\propto Vp$ values of pump EO modulator bias, right]. $\Omega_p/2\pi$ = 2 kHz. Dynamics are described by a Brownian parametric oscillator equation [colored lines]: $\ddot{z}(t) + \gamma\dot{z}(t) + [\Omega_m^2 + 2\varepsilon\Omega_m \cos(\Omega_p t)]z(t) = F_{thermal}(t)/m_{eff}$, where $z(t)$ is nanowire position, m_{eff} effective mass, Ω_m natural frequency, γ mechanical dissipation factor, $F_{thermal}(t)$ a thermal (Langevin) force, and ε the (optically-controlled) parametric pumping strength. (c) Phononic frequency comb generation: signal at the optical driving frequency Ω_d increases with parametric pumping strength ε as a result of parametric gain, and a series of 'teeth' appear at frequencies $\Omega_d \pm N\Omega_p$.