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Coherent Excitation of Multiple Nano-opto-mechanical Modes in Silicon with Ultrafast Time-domain Spectroscopy

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Abstract: We present the first time-domain measurement of a guided-wave nano-opto-mechanical system, resulting in the coherent excitation of multiple mechanical modes. We deconvolved the electronic and mechanical responses to observe the evolution of the coherent superposition.
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Nano-opto-mechanical systems (NOMS) with guided-wave coupling are promising for integrated, chip-scale RF photonic filtering, phononic time-delay lines [1], low-noise stimulated Brillioun scattering oscillators [2] and other applications benefiting from enhanced opto-mechanical forces. The excitation of a guided-wave NOMS devices has, to the best of our knowledge, been confined to observing the steady-state response of individual modes in the frequency domain, with limited mechanical phase information [1], [3]–[6]. However, with time-domain pulsed excitation, multiple modes are simultaneously and coherently excited, with superior efficiency. In this way, we can make direct observation of the transient impulse response with mechanical phase information. Additionally, we separate the electronic and mechanical responses within a single waveguide for much greater sensitivity (>50 dB), to reveal weak mechanical modes. Moreover, this work paves the way for the study of coherent opto-mechanical pulse propagation for high-bandwidth information transduction and for pulsed, multi-mode phonon lasers.

We fabricated an optically non-resonant, mechanically resonant NOMS device consisting of a silicon waveguide suspended in a membrane of silicon nitride, as described elsewhere [1]. The length of the waveguide is surrounded by phononic mirrors which are cut from the silicon nitride membrane. The waveguide is periodically excited by a strong optical pulse, approximately 30 ps in duration, leading to the dispersive propagation of a mechanical pulse in the plane of the membrane. Simultaneously, we record the phase modulation on a probe pulse, at a different wavelength from the pump, using a technique based on asynchronous optical sampling with ultrafast lasers, as shown in Fig. 1 [7]. In this way, we can measure the time-domain response over a long delay of 12.5 ns (3.75 m in vacuum) at speeds impossible with physical delay lines (10 kHz). It is noteworthy, however, that with ASOPS, the picosecond-resolution, 12.5 ns time trace is effectively slowed to 0.1 ms, allowing for very sensitive detection. As a result, we measure the pulse phase directly with a stabilized balanced interferometer that removes fiber fluctuations below 1 kHz. Precision synchronization of the pump laser, probe laser and digital acquisition card allow for long-term averaging for very high signal to noise ratio observation of weak mechanical modes which are otherwise hidden by the electronic Kerr nonlinearity in the waveguide [1].

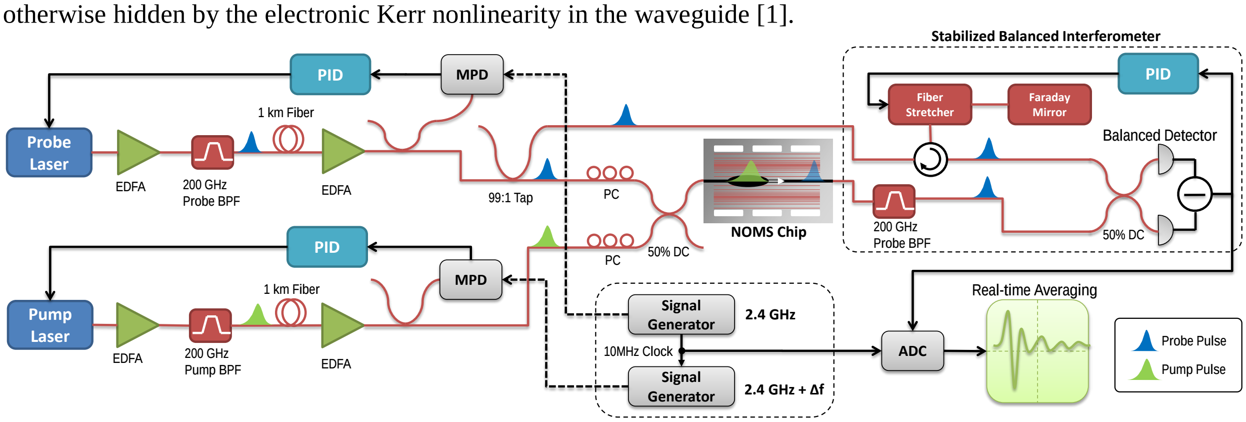

Fig. 1. System diagram of the asynchronous optical sampling (ASOPS) apparatus, stabilized balanced interferometer, synchronization electronics and data acquisition. The pump and probe laser are 80 MHz ultrafast erbium fiber lasers which are filtered at different wavelengths to yield 200 GHz pulses that are stretched to 30 ps in a 1 km fiber spool in order to match the NOMS Brillioun gain bandwidth. An offset lock of the repetition rate (Δf) between the lasers sets the asynchronous sampling rate. **EDFA**: erbium doped fiber amplifier; **BPF**: band-pass filter; **PC**: polarization controller; **MPD**: microwave phase detector; **PID**: loop filter; **DC**: directional coupler; **ADC**: analog-to-digital converter.

To better understand the periodic, pulsed excitation of the waveguide and membrane, we constructed an analytical parametric modal model whereby an optical pulse periodically pumps the waveguide and reflects off the phononic mirrors, separated by 8.5 µm. In this simulation, shown in Fig. 2, we excited 10 mechanical modes and included phononic loss and dispersion. The simulated time-domain ASOPS signal from this model shows periodic features corresponding to the round-trip propagation time of phonons, of multiple modes, within the phononic resonator.

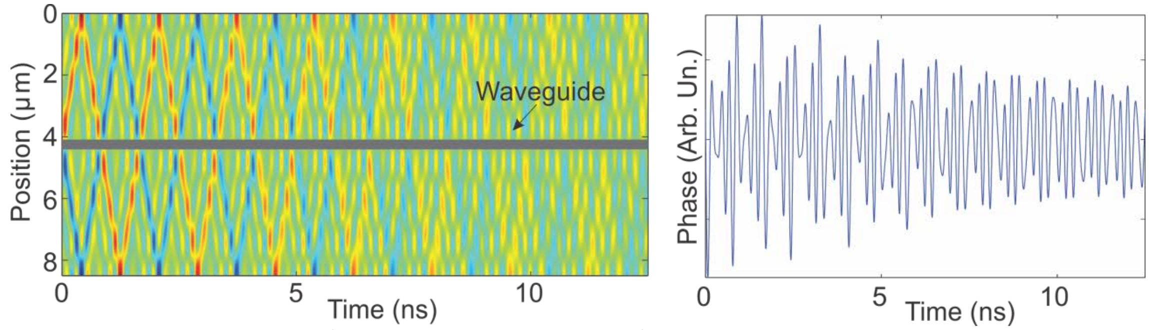

Fig. 2. (a) A parametric modal simulation of the periodic (80 MHz) excitation of the suspended waveguide/membrane structure. Phononic mirrors exist at 0 and 8.5 µm along the membrane. The model includes phononic loss and dispersion. (b) The simulated asynchronous optical sampling signal from the modal simulation at 80 MHz (12.5 ns) rate. The periodic spikes correspond to the round-trip propagation of a dispersive phononic pulse in the membrane.

We also performed, to the best of our knowledge, the first experimental measurements of a guided-wave NOMS device in the time-domain with pulsed coherent excitation of multiple mechanical modes. The time-domain impulse response, shown in Fig. 3, reveals the excitation of 8 and 7 modes with phononic mirror spacing of 8.5 and 6.5 µm, respectively. As in the simulation, periodic structure, corresponding to the superposition of multiple modes, can be seen. The period of the structure is given by the round-trip propagation time of phonons in the membranes. This is suggestive of the propagation of a dispersive phononic pulse, for which we plan to pursue further study.

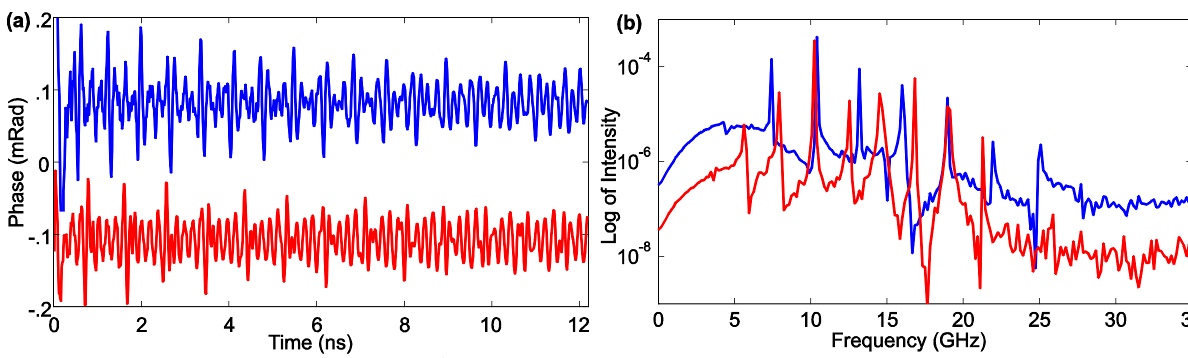

Fig. 3. (a) Experimental time-domain measurement of the NOMS device with asynchronous optical sampling. Phononic mirror spacing is 8.5 and 6.5 µm, for red and blue signals, respectively. The periodic structure corresponds to the round-trip propagation time of phonons of multiple modes in the membrane. (b) The corresponding fourier transform of the time-domain impulse response, showing the simultaneous excitation of 8 and 7 modes in the 8.5 and 6.5 µm cavities. Note, the electronic Kerr response is removed in the time-domain with post-processing to give a background-free signal that reveals mechanical modes in the frequency domain with very high signal-to-noise ratio.

In conclusion, we have theoretically and experimentally demonstrated the picosecond pulsed excitation of multiple, coherent phonic modes in a guided-wave NOMS device. Observation of the time-domain impulse response with ultrafast asynchronous optical sampling allows us to remove the electronic Kerr effect which otherwise obscures the mechanical modes in the frequency domain. Simulations and experiments suggest the propagation of a dispersive phononic pulse, for which we plan to present further results at the conference.

Acknowledgements

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References

[1] H. Shin, et al., "Tailorable stimulated Brillouin scattering in nanoscale silicon waveguides," *Nat. Comm.*, vol. 4, 2013.
[2] J. Li, H. Lee, and K. J. Vahala, "Low-noise Brillouin laser on a chip at 1064 nm," *Opt. Lett.*, vol. 39, no. 2, p. 287, 2014.
[3] M. R. Vanner, et al., "Cooling-by-measurement and mechanical state tomography via pulsed optomechanics," *Nat. Comm.*, vol. 4, 2013.
[4] M. Li, W. H. P. Pernice, and H. X. Tang, "Broadband all-photonic transduction of nanocantilevers," *Nat. Nanotech.*, vol. 4, no. 6, 2009.
[5] M. Eichenfield, et al., "A picogram- and nanometre-scale photonic-crystal optomechanical cavity," *Nature*, vol. 459, no. 7246, 2009.
[6] M. S. Kang, A. Brenn, G. S. Wiederhecker, and P. S. J. Russell, *Appl. Phys. Lett.*, vol. 93, no. 13, 2008.
[7] P. A. Elzinga, R. J. Kneisler, F. E. Lytle, Y. Jiang, G. B. King, and N. M. Laurendeau, *Appl. Optics*, vol. 26, no. 19, p. 4303, Oct. 1987.