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Background-Free Characterization of Traveling-Wave Optomechanical Devices with Ultrafast Time Domain Spectroscopy

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U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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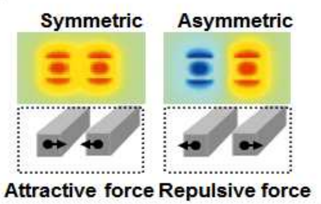
Overview

- Motivation: Non-resonate waveguide device concept
- Prior characterization with CW optical beams
- Investigation of pulsed opto-mechanical transduction with Asynchronous Optical Sampling (ASOPS)
- Conclusion

Motivation

- Optomechanics has been studied extensively with cavity-coupled resonant opto-mechanical devices



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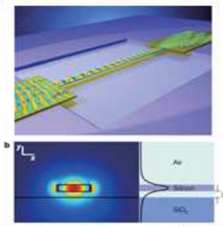
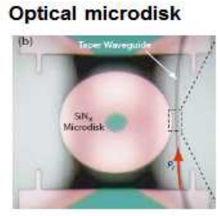

Mo Li *et al.* Nature 1, 480–484 (2008).



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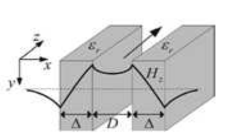
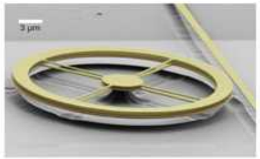

A. Mizrahi & L. Schächter Opt. Lett. 32, (2007), p.692-694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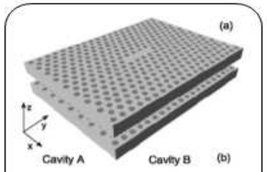

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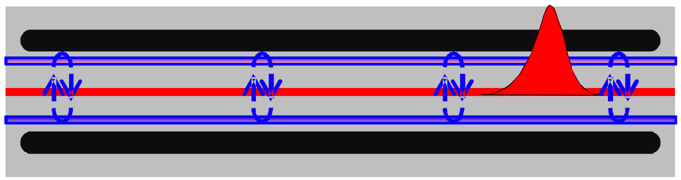
→optical forces & radiation pressure, →quantum ground state cooling,
→ phonon laser,
→ optically induced transparency
→ sensitive motion sensors, etc, . . .

- Non-resonant waveguide devices allow high-frequency, broadband transduction for information processing devices.



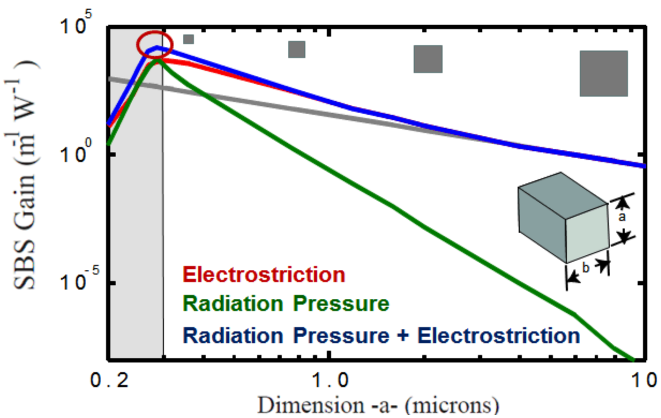
→non-resonant for optical mode allows broadband transduction

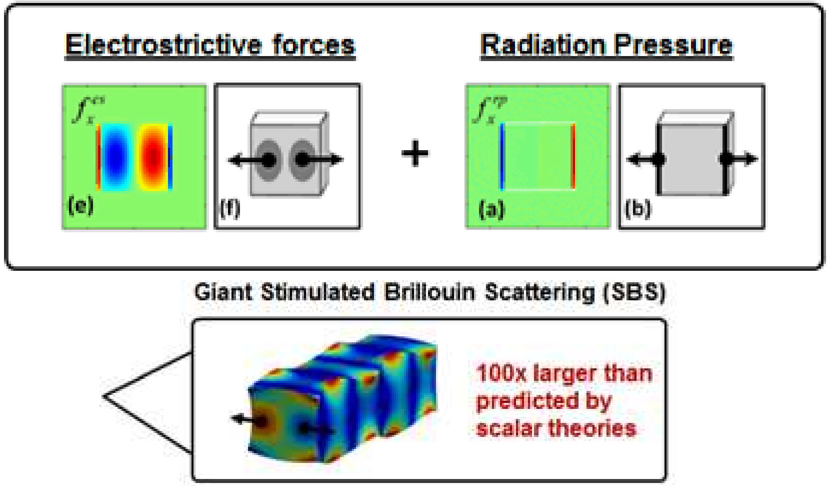
→Previously experimentally and theoretically studied device with CW laser sources.

→In this work, we us pulsed ps-laser sources to study pulsed opto-mechanical transduction to evaluate potential use in information processing applications with phonon pulses.

Traveling-Wave Phonon-Photon Device Concept

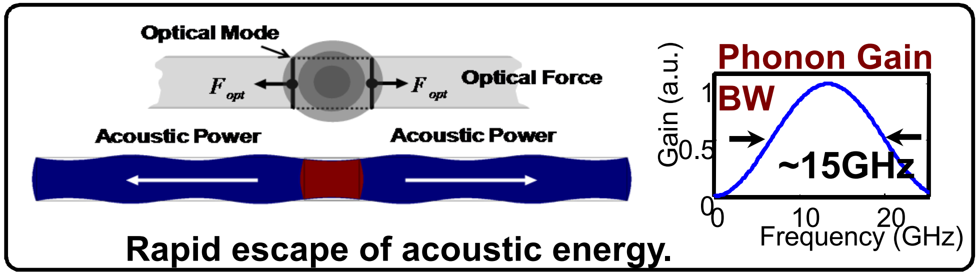
- Practical non-resonant devices require high optomechanical transduction to be viable.
- Previously shown dramatic **enhancement of optomechanical transduction** do to coherent combination of radiation pressure and electrostrication in nanoscale waveguides





- Additionally we have shown **ultra-broadband transduction bandwidth** with transversely oriented phonon modes

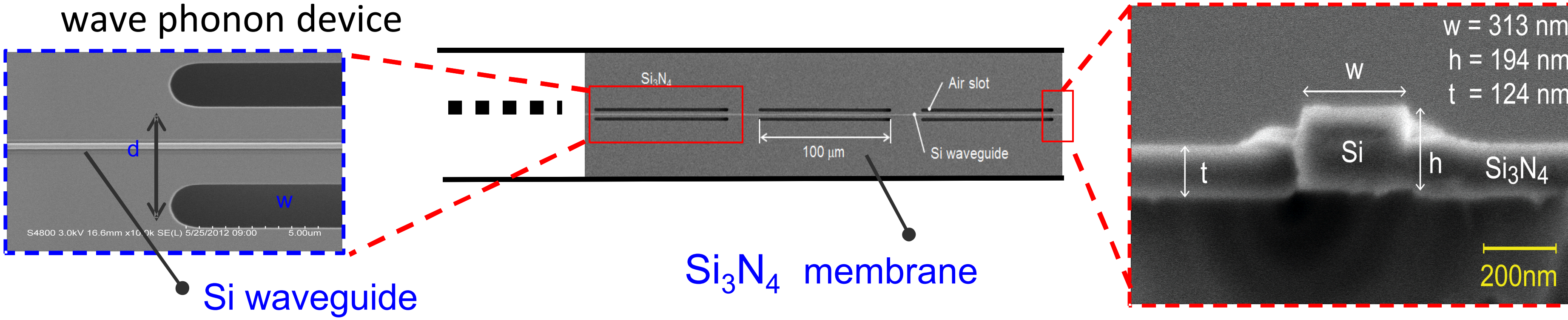
Ultra-Broadband Stimulated Phonon Emission



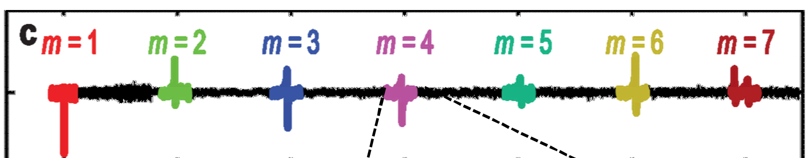
Peter T. Rakich, et. al. " Giant Enhancement of Stimulated Brillouin Scattering in the Sub-Wavelength Limit," Physical Review X Vol 2, No. 1, 011008 (2012)

Previous Device Design and Characterization with CW laser sources in frequency domain

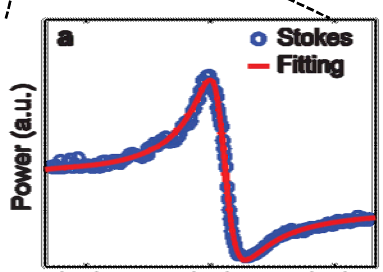
- Previously designed and characterized traveling-wave phonon device

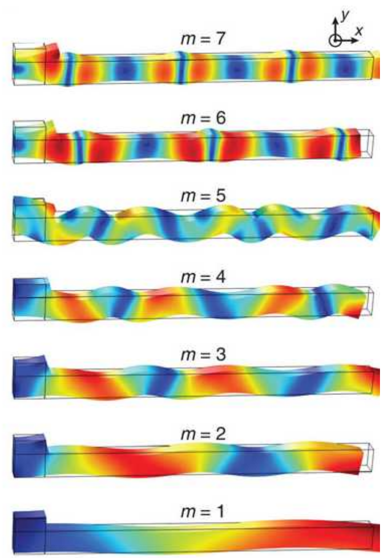


- Optomechanical transduction was characterized with a dual color CW heterodyne setup → mechanical modes linewidths were measured by scanning frequency



Heedeuk. Shin *et al.* "Tailorable stimulated Brillouin scattering in nanoscale silicon waveguides" *Nat. Comm.* 6 June 2013.





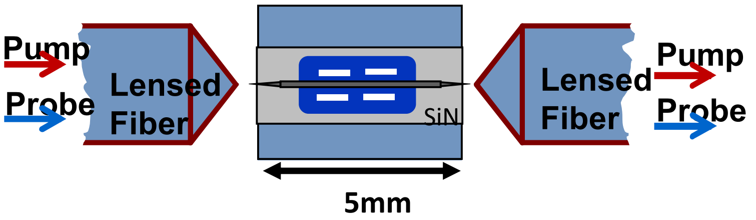
→ Structure supports multiple modes

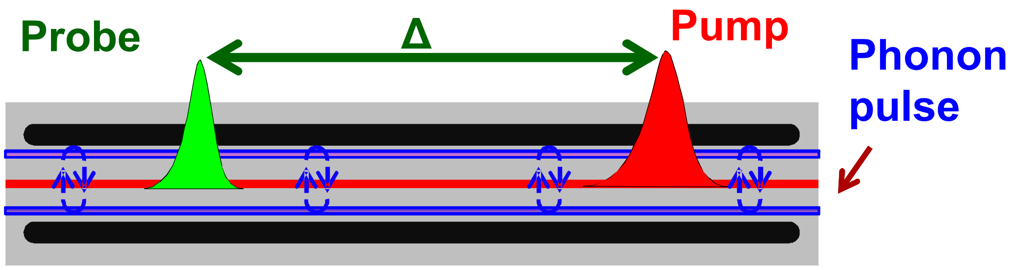
→ Interrogation in frequency domain leads to mixing with intrinsic nonlinearities and limited phase information

→ **Dynamic range limited by Kerr background**

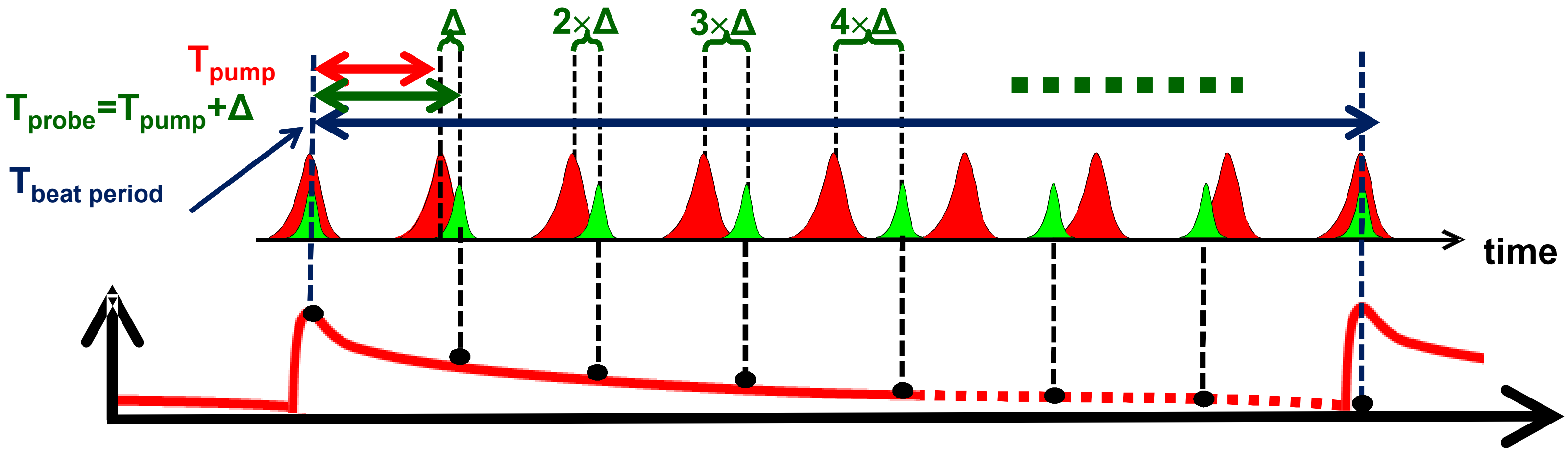
Pulsed Optomechanical Transduction with Asynchronous Optical Sampling (ASOPS)

- Transduction of laser pulses to phonon modes assess the viability of pulsed phonon devices





- In ASOPS, the repetition rate of pulsed pump (f_{pump}) and probe (f_{probe}) lasers are detuned by an offset frequency (f_{offset}) such that the time delay between consecutive pulses is ramped linearly

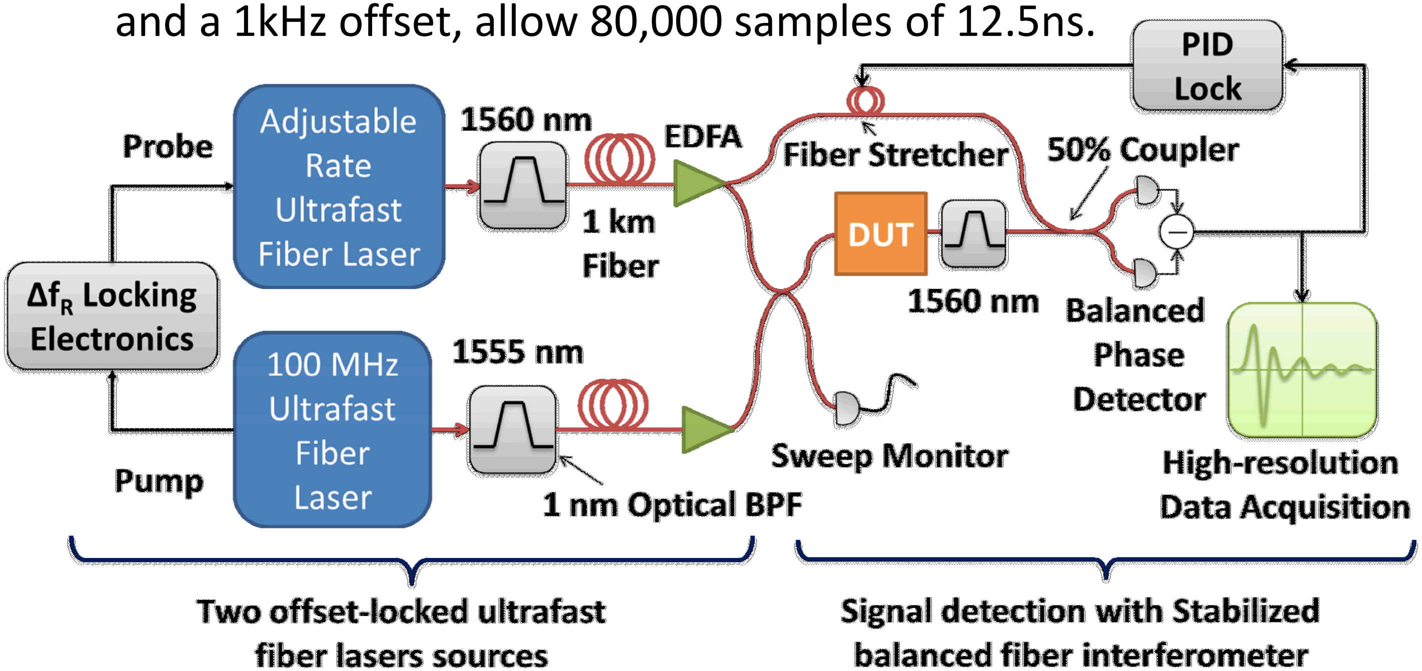


Waveform periodic with T_{beat} and with $N_{sample} = T_{pump}/\Delta$

- 100 MHz laser sources with 10kHz f_{offset} → $f_{optical}$ =1 THz without the need for mechanical delay lines.

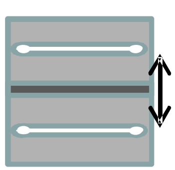
Experimental Setup

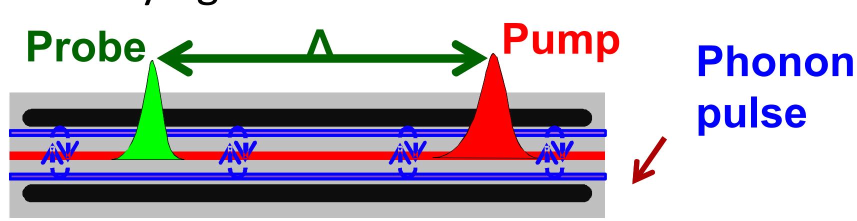
- Two ps-fiber laser sources (pump and probe) locked with an 80MHz repetition rate and a 1kHz offset, allow 80,000 samples of 12.5ns.



→ Sampling card and laser systems tightly synchronized enabling long-term averaging

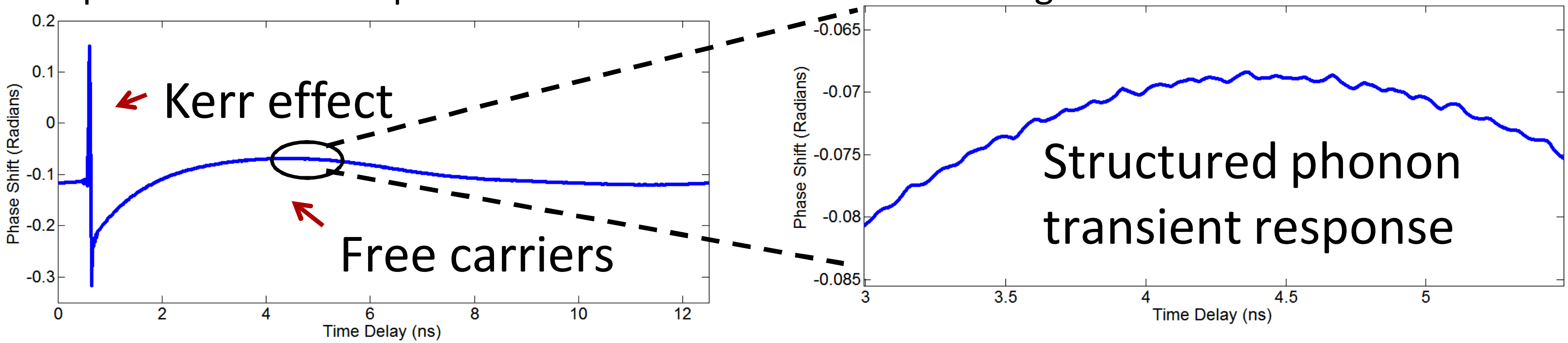
- The pump pulse generates a phonon-pulse via optical transduction which imparts a phase shift on the signal pulse that is measured in an interferometer having shot-noise-limited detection of a few µ-rad phase.
- “Slot” waveguide devices with varying widths were measured



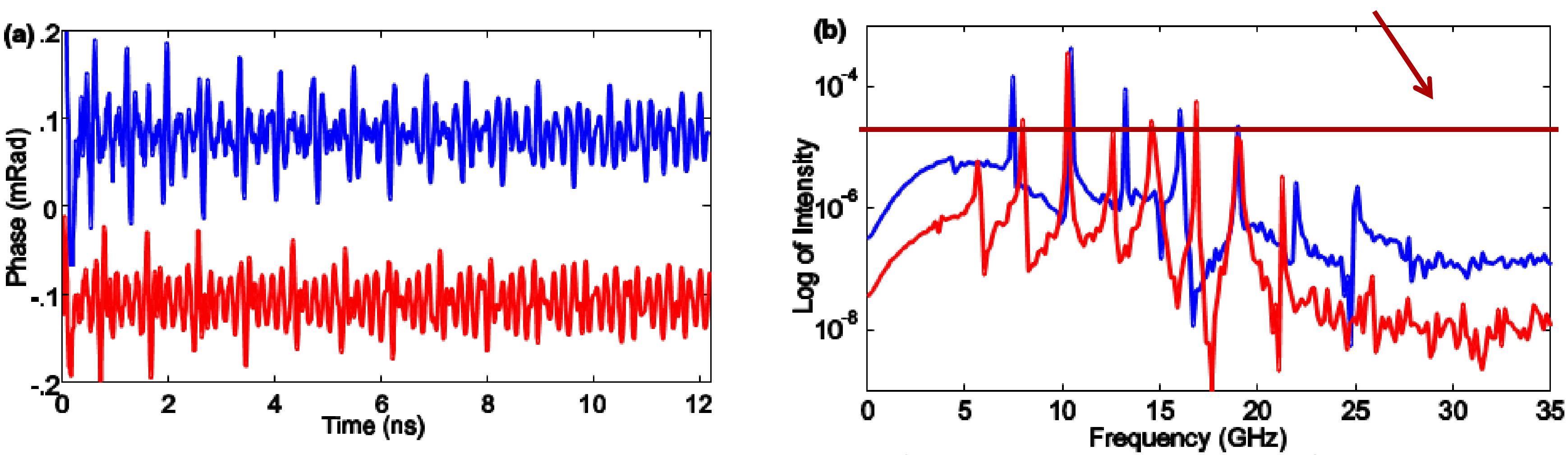


Time-domain signals allow separation of nonlinearities

- Experimental data captures Kerr effect and free carrier background



- Convergence after 100,000 averages
- In prior work, Kerr and free carrier response dramtically limited dynamic range

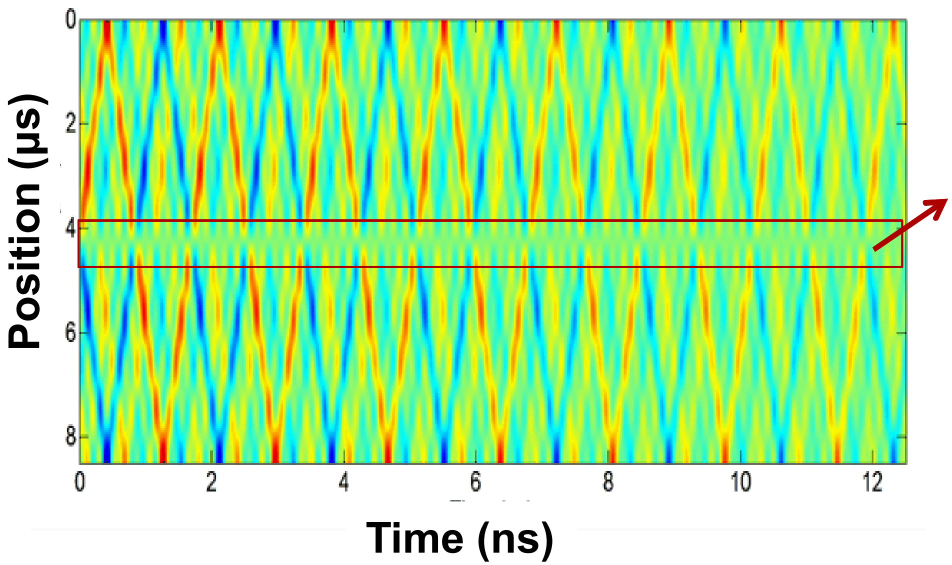


- Here we can use signal processing to separate fast phonon oscillation from slow transients and the instantaneous Kerr effect

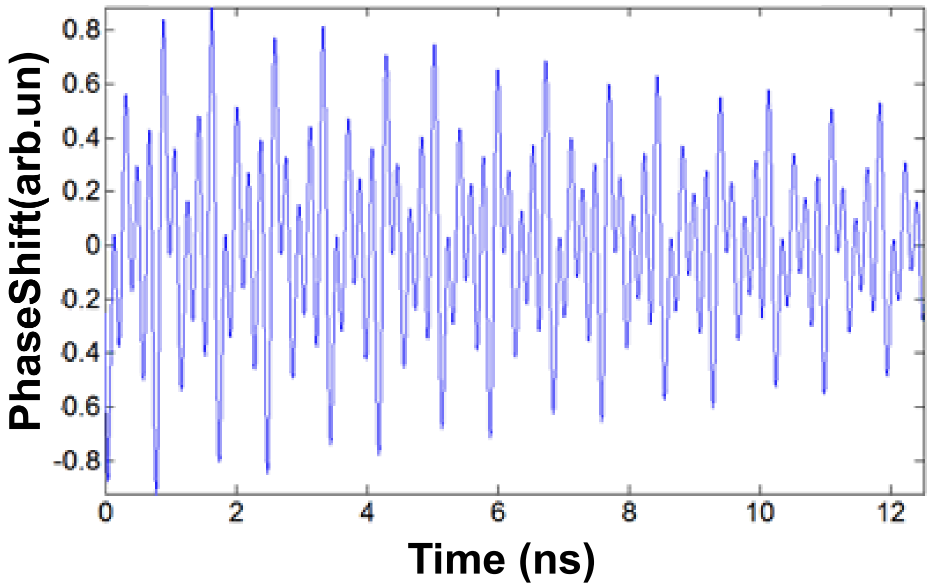
Simulation of System

- Simulated parametric pumping with side-wall reflections

Steady state Displacement Amplitude



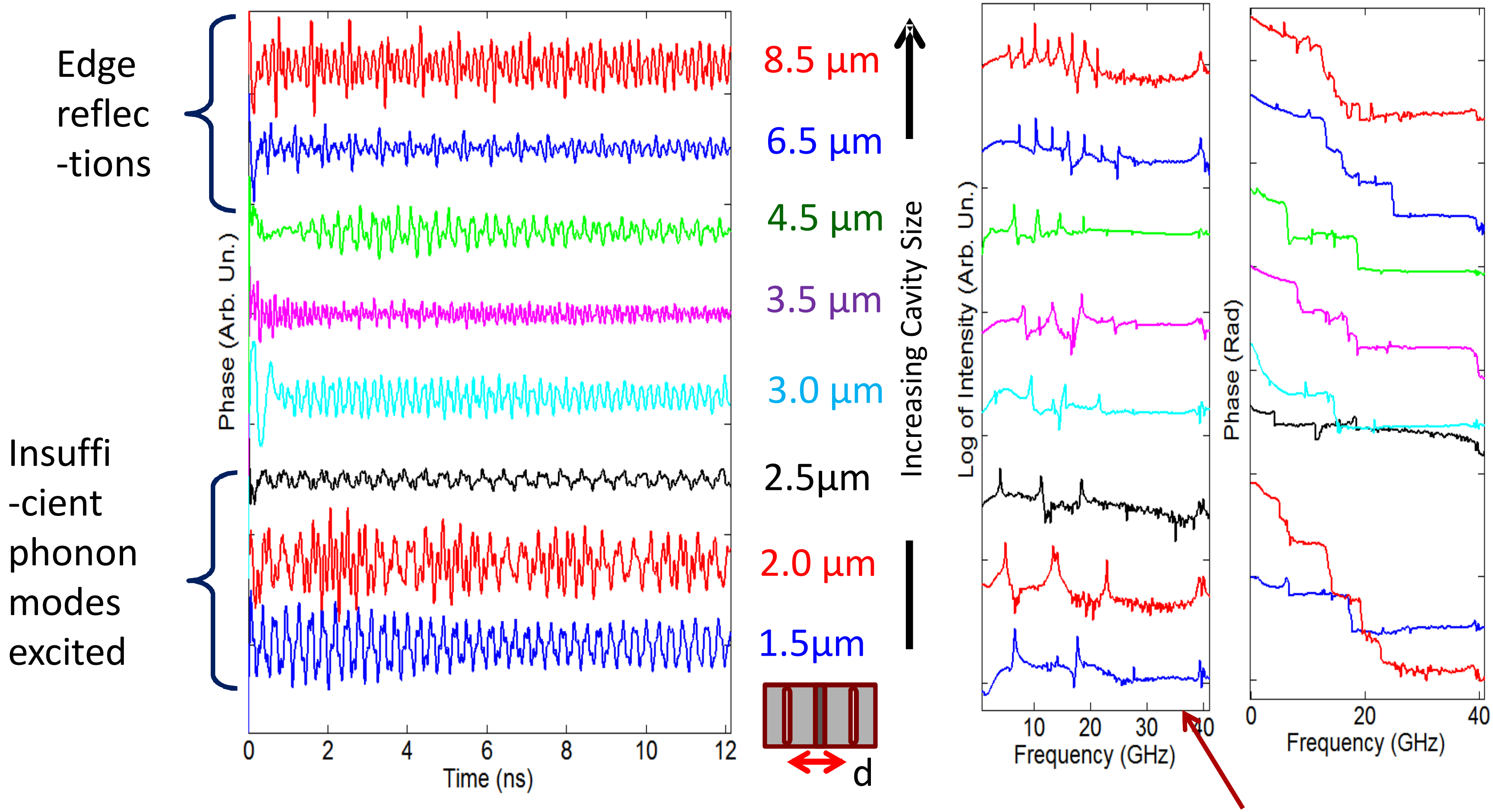
Phase Shift Imparted onto Waveguide



- Parametric pumping do to limited measurement window
- Large side-wall reflections indicate that optical delay with dual waveguide devices are feasible.

Measurement of impulsive phonon response vs device width

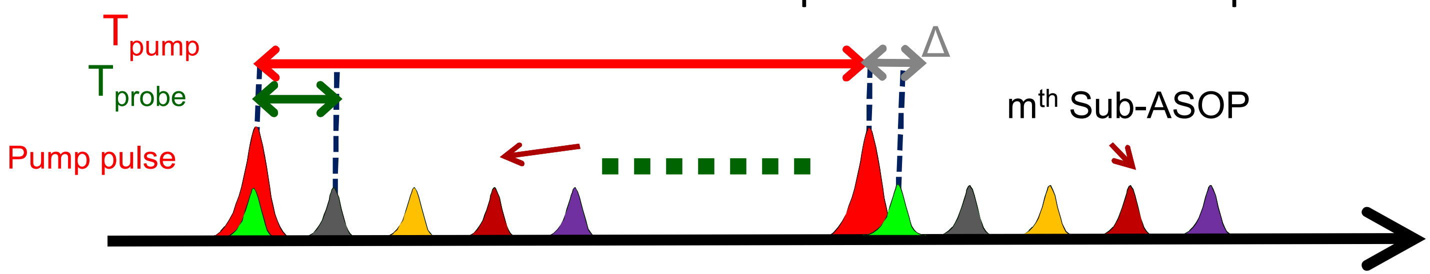
- Frequency domain (magnitude and phase) shows phonon spectrum.



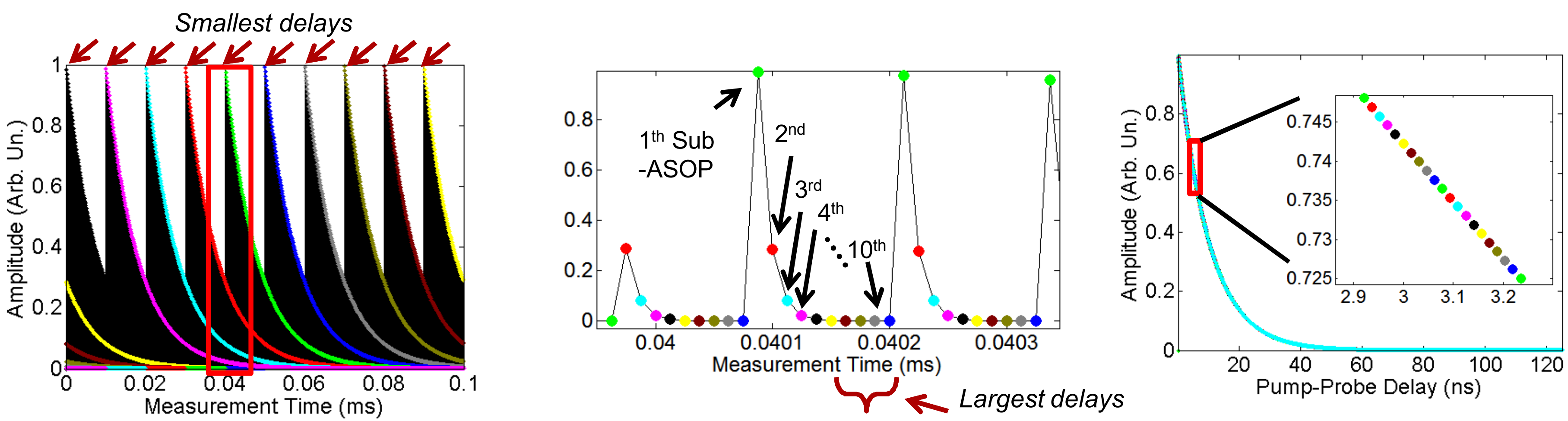
Frequency limitation from ps optical pulse duration

I-ASOPS: Signal Re-ordering

- I-ASOPS is consists of N sub-ASOP measurements each phase shifted with respect to the pump



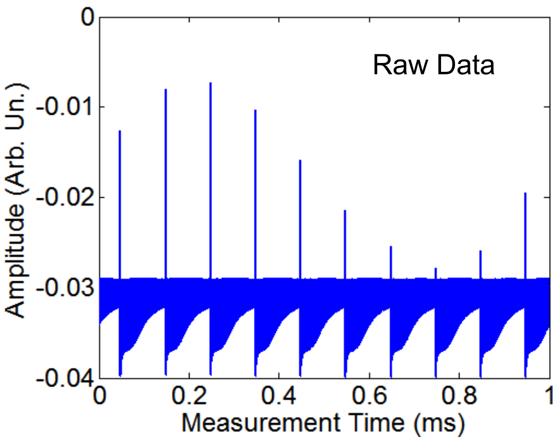
- Sequential probe pulses delayed by $m \times T_{probe}$, so later pulses correspond to longer delays. However, each sub-ASOPs by itself is properly ordered.

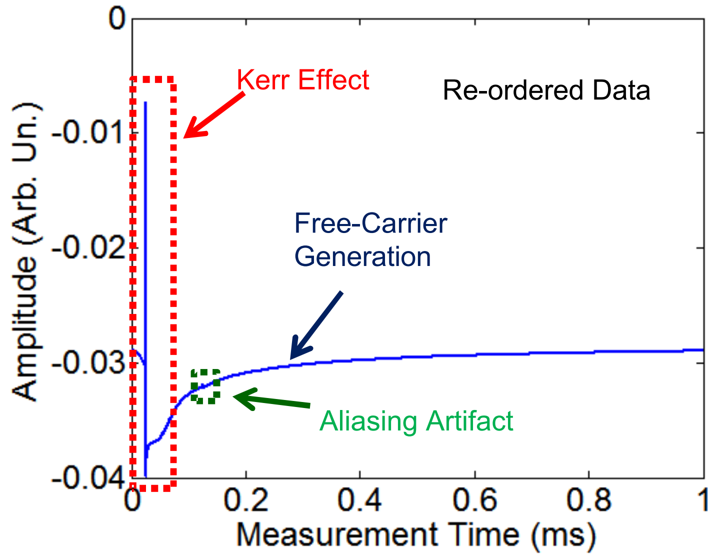


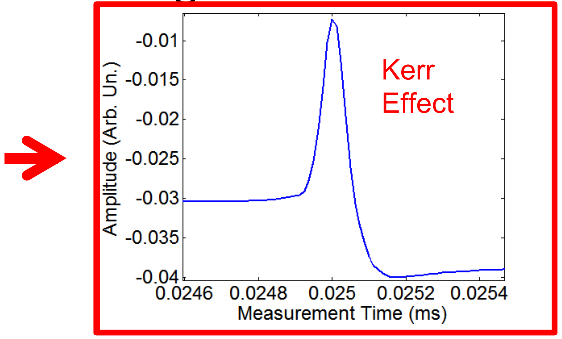
- The m^{th} sub-ASOP group needs to be circularly shifted in place m-1 times for proper ordering
- Adequate bandwidth needed to avoid aliasing in time.

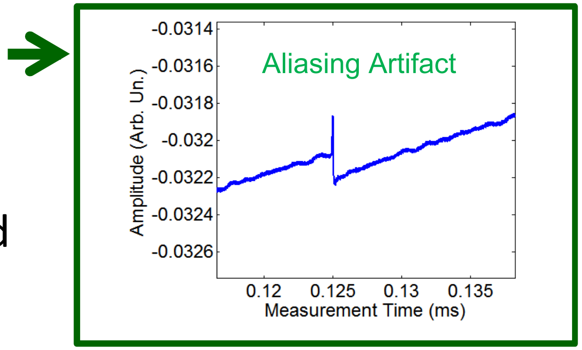
Measured Transient Responses

- Transient response dominated by optical kerr effect and free carrier generation.

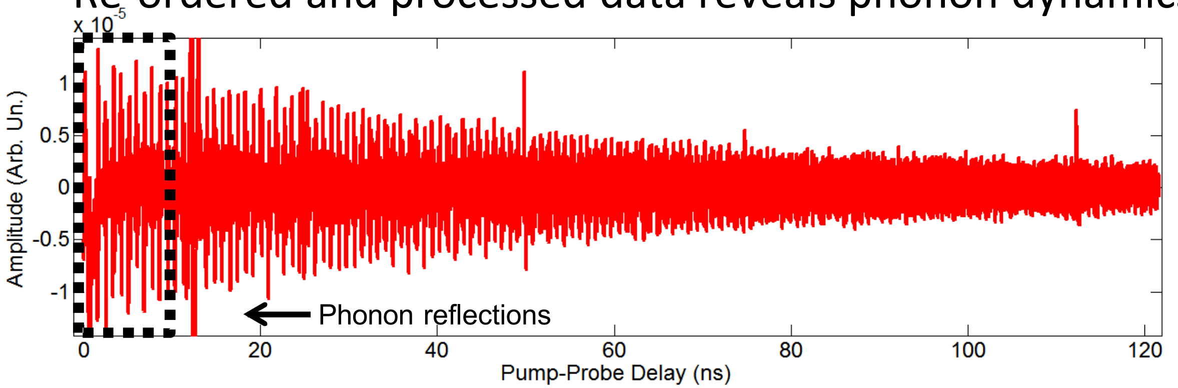


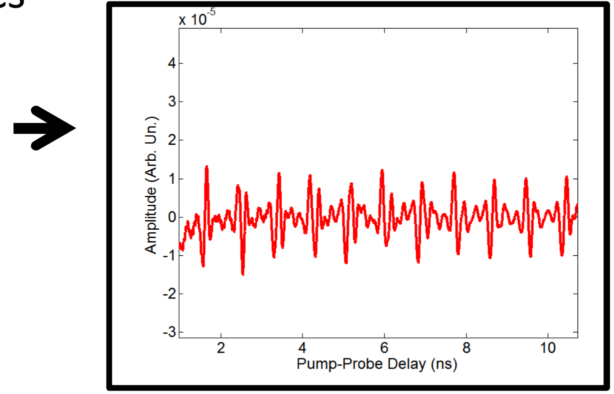






- Artifact reduced by 1/200 from Kerr Effect which is localized in time only effecting discrete regions
- Re-ordered and processed data reveals phonon dynamics



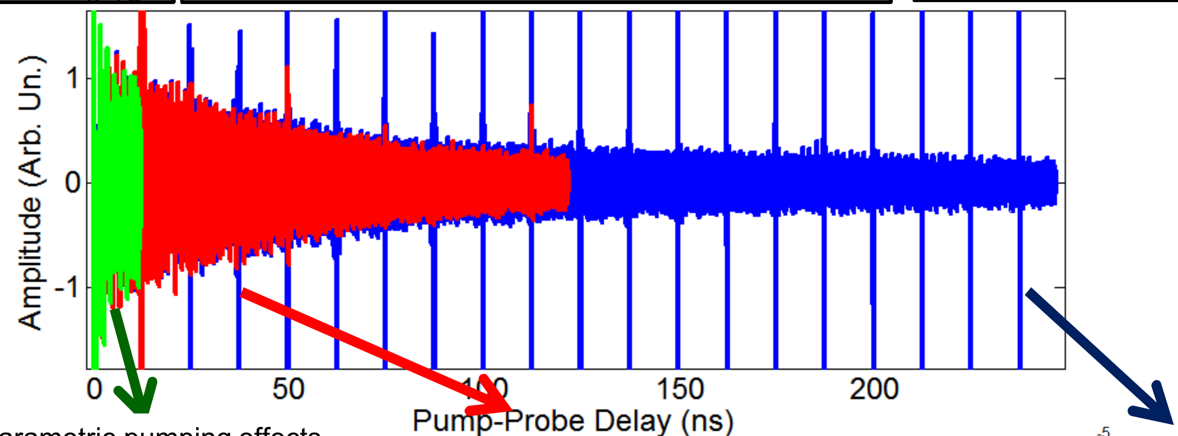


Comparison to ASOP

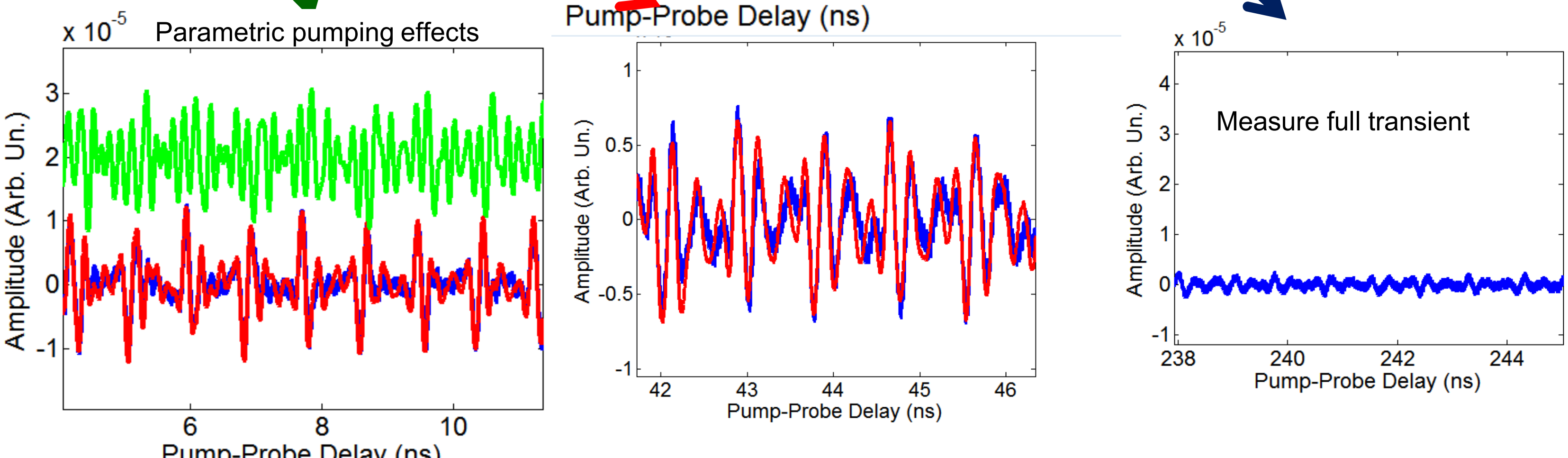
- Measurement conditions with f_{offset} =10kHz:

1. f_{pump} = 80MHz, f_{probe} = 80MHz, N=1
2. f_{pump} = 8MHz , f_{probe} = 80MHz, N=10
3. f_{pump} = 4MHz , f_{probe} = 80MHz, N=20

	I-ASOPS	ASOPS
1.		$f_{optical}$ = 0.64THz
2.	$f_{optical}$ = 0.64THz	$f_{optical}$ = 0.064THz
3.	$f_{optical}$ = 0.64THz	$f_{optical}$ = 0.032THz

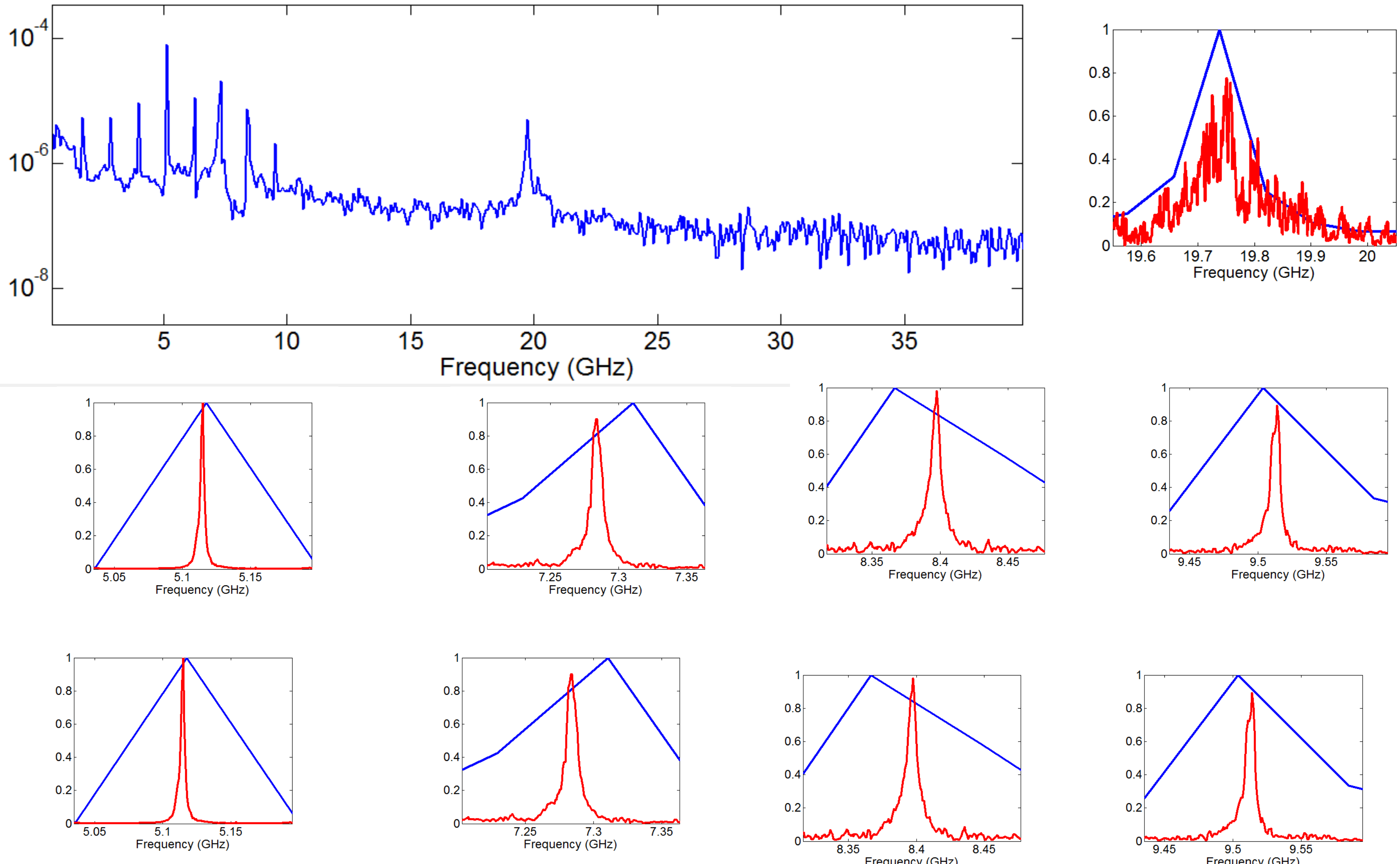


- 150ns lifetime



- Longer measurement window afforded by I-ASOPS enables full measurement of transient without parametric pump.→ Preserves timing resolution while increasing resolution bandwidth

Dramatically Enhanced Spectral Resolution



Summary and Conclusion

- Developed an ASOPS system enabling rapid time domain acquisition over long durations (ns-µs) with high (ps) temporal resolution and µ-radian sensitivity.

- Measured pulsed optical-phonon transduction in a traveling wave devices, and have ample sensitivity to measured the influence of phonon reflection from sidewalls.

- The number of modes excited and the degree of broadening due to phonon dispersion is sufficient for wide devices to allow for pulsed transduction.