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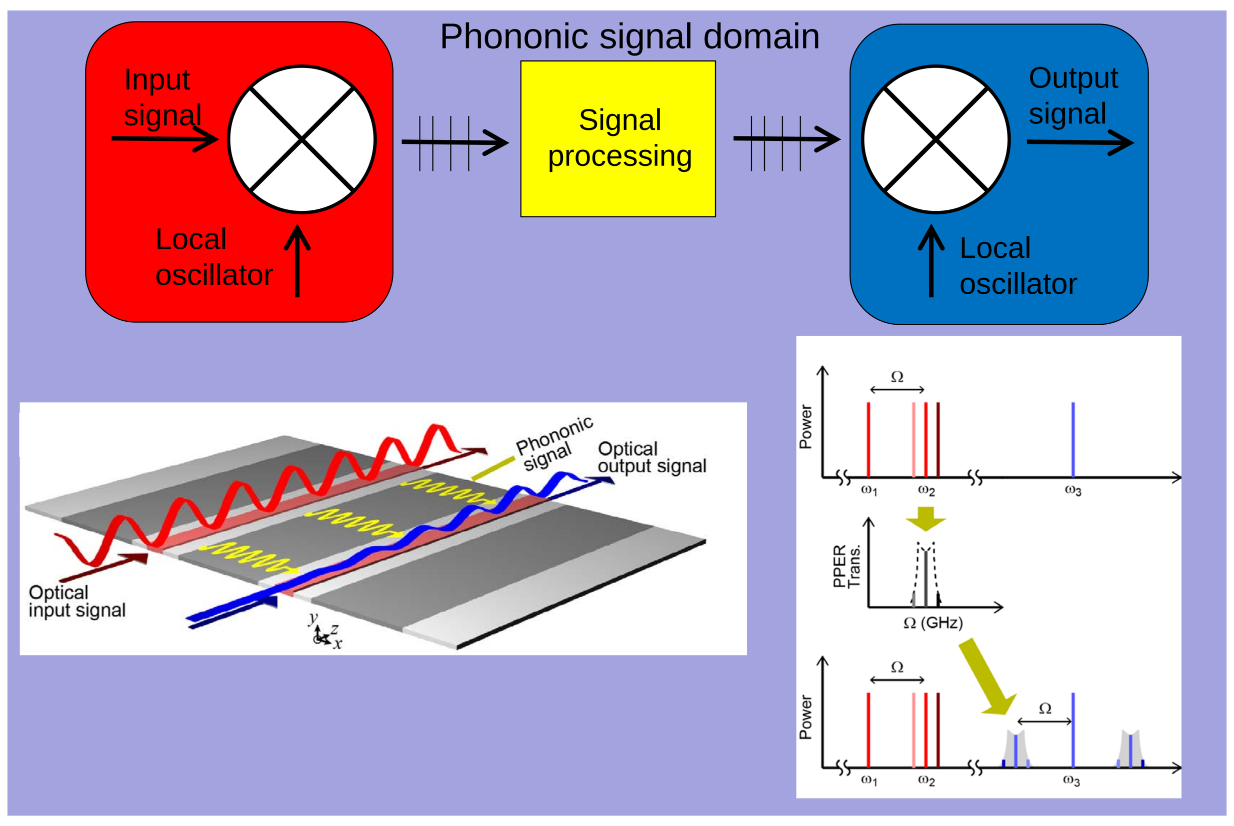
On-chip photonic-phononic emitter-receiver for RF photonic signal processing.

Heedeuk Shin[1], Jonathan A. Cox[2], Robert Jarecki[2], Andrew Starbuck[2], Zheng Wang[3], and Peter T. Rakich[1]

What are the challenges?

- Based on new understanding of light-matter interactions at nanoscales, we seek new applications of photon-phonon interactions as a new form of information transduction from light to sound, etc.
- Engineerable coupling between resonant photonic and phononic modes has been achieved in a variety of chip-scale systems.
- The realization of narrow-band filters that simultaneously achieve high optical power handling, and wavelength insensitivity in silicon to enable new signal processing schemes.

What is photonic-phononic emitter-receiver?

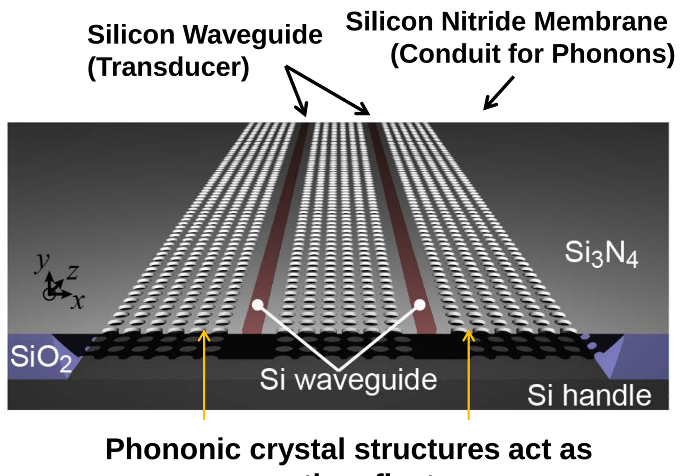


PPER process

- Light-photonic wave-light conversion
- Information on the red wave (emitter)
  - Optical signal
- Information Transduction & signal processing (yellow)
  - Through phononic waves
- Information conversion to the blue wave (receiver)
  - Optical signal
- Phononic information processing
  - Wavelength conversion, isolator, amplifier, RF mixing, and RF photonic filter

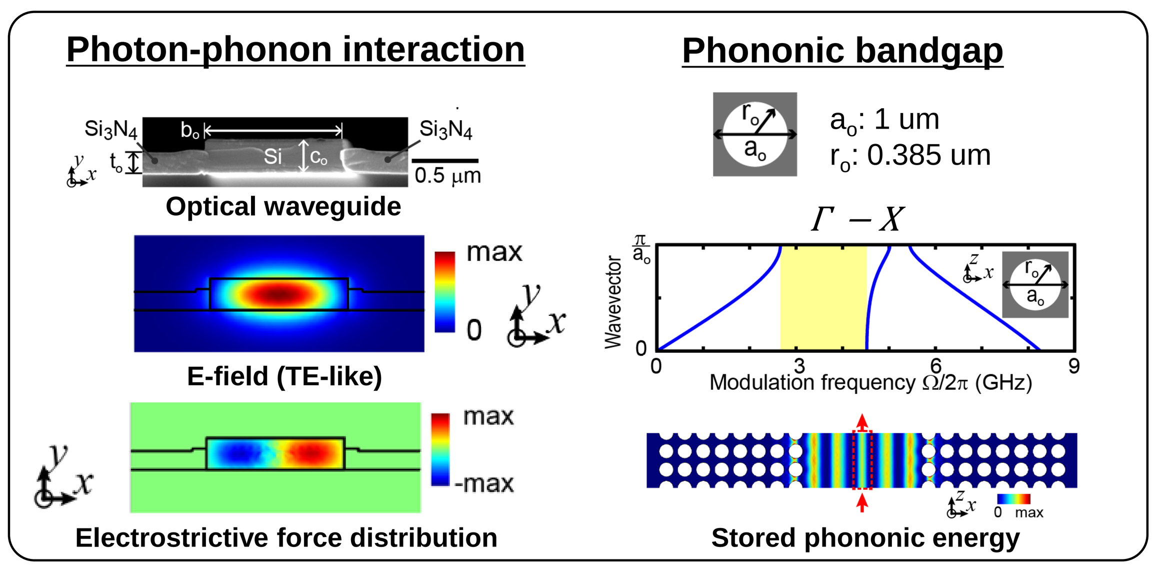
What does a PPER system look like?

Dual-channel PnC-BAM waveguide

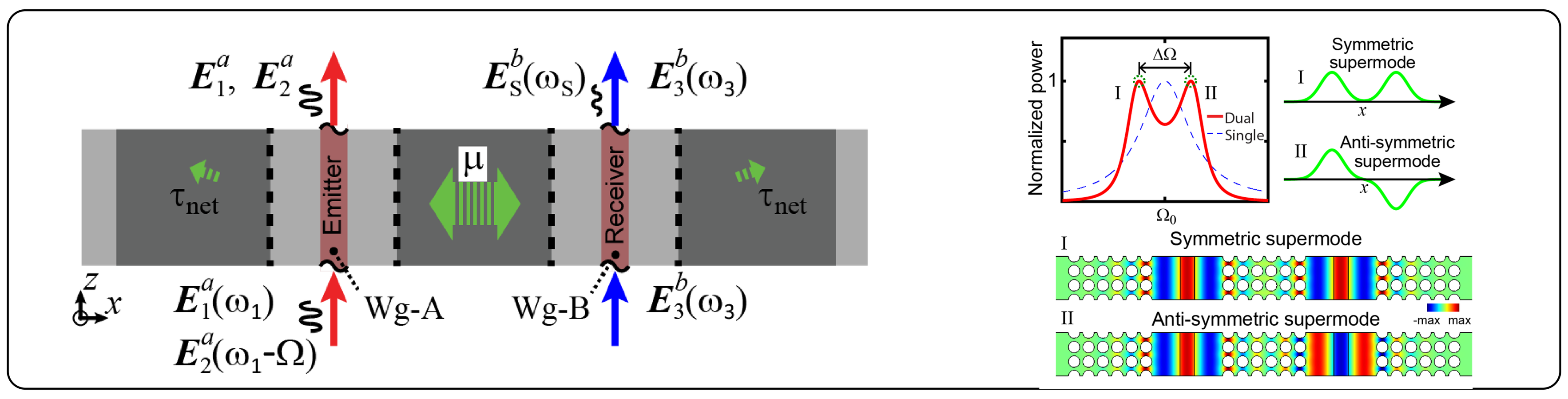


Phononic crystal structures act as acoustic reflectors

Fundamental unit of PPER system



Physics of the PPER system



- Temporal coupled-mode theory of phononic modes

$$\frac{dc_a(t)}{dt} = -\left(i\Omega_0 + \frac{1}{\tau_{net}}\right)c_a(t) + i\mu c_b(t) + \eta(t)A_1A_2^*,$$

$$\frac{dc_b(t)}{dt} = -\left(i\Omega_0 + \frac{1}{\tau_{net}}\right)c_b(t) + i\mu c_a(t),$$

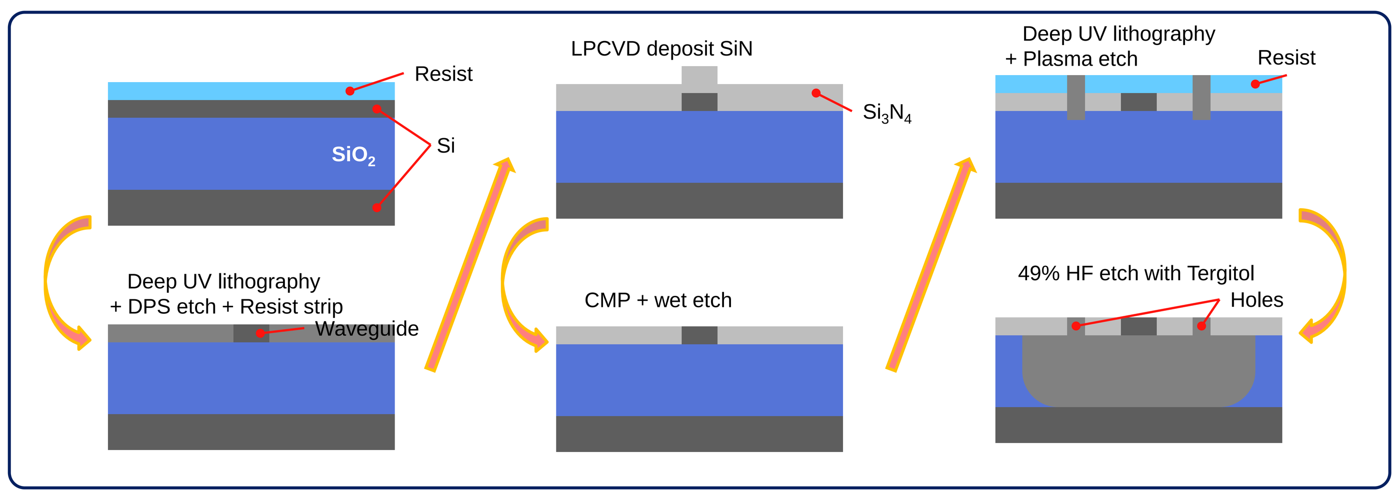
$c_a(t)$, $c_b(t)$: phononic mode at Wg-A and Wg-B
Ω_0: angular resonant frequency
τ_{net}: phonon lifetime
μ: modal coupling rate of phonon between Wg-A and Wg-B
$\eta(t) = \eta_0 \exp(-i\Omega t)$, and $\eta(t)A_1A_2^*$ is the driving term.

- Analytical expression of the PPER functionalities

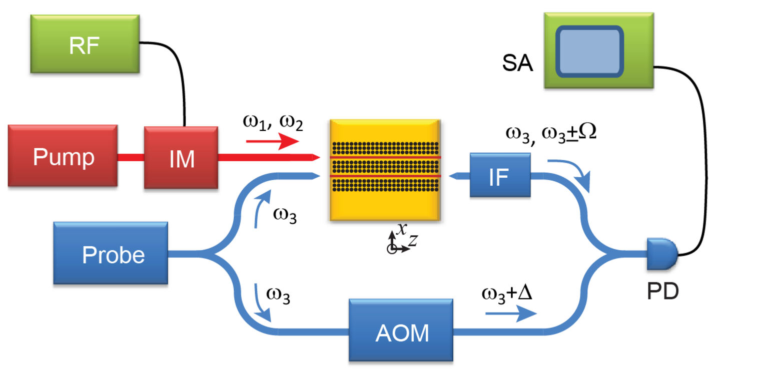
$$\gamma_{a\to b}(\Omega) = \left[\frac{\omega_3 \tau_{net}}{2\Omega_0}\frac{\langle \mathbf{f}_n^a, \boldsymbol{e}_a\rangle \langle \boldsymbol{e}_b, \mathbf{f}_n^b\rangle}{\langle \boldsymbol{e}_a, \rho \boldsymbol{e}_a\rangle}\frac{2\mu/\tau_{net}}{\left[\Omega - \Omega_0 - \sqrt{\mu^2 - 1/\tau_{net}^2}\right]\left[\Omega - \Omega_0 + \sqrt{\mu^2 - 1/\tau_{net}^2}\right]}\right].$$

$$P_s^b = |\gamma_{a\to b}(\Omega)|^2 P_1^a \, P_2^a \, P_3^b \, L^2$$

Fabrication

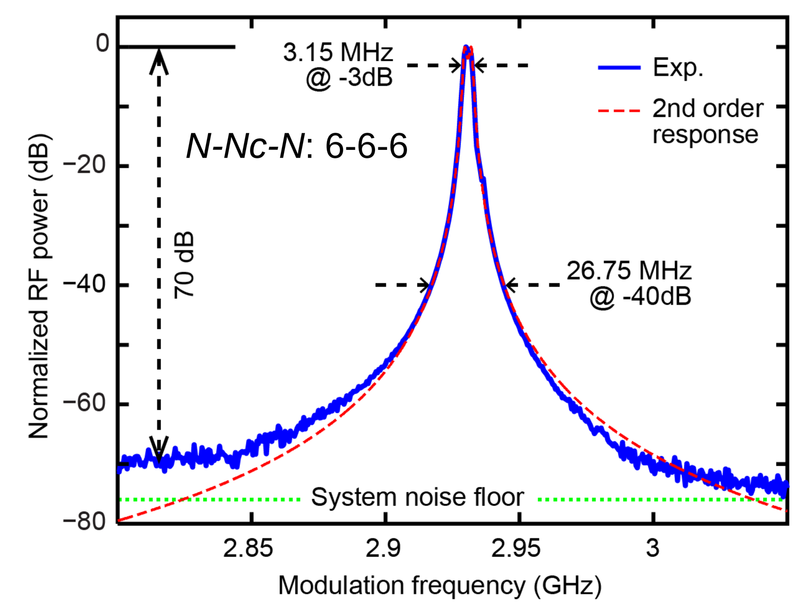


How to measure the PPER response?



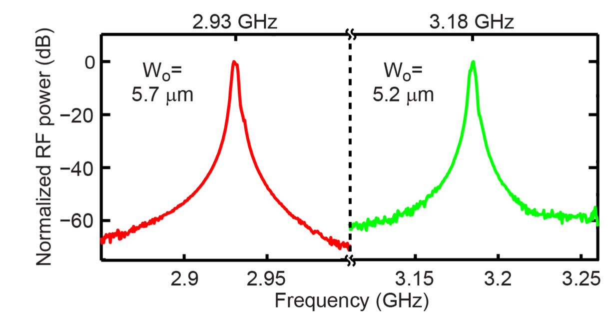
Pump: pump laser at 1547 nm
Probe: probe laser at 1536 nm
IM: intensity modulator
RF: RF signal generator with bias controller
AOM: acousto-optic modulator frequency shifter by 40 MHz
IF: interference filter
PD: receiver
SA: signal analyzer

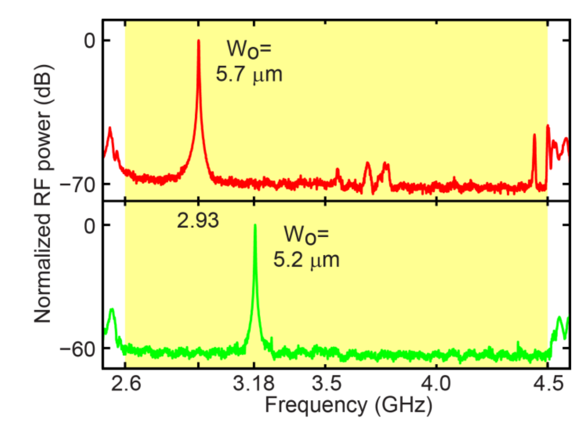
Experimental results



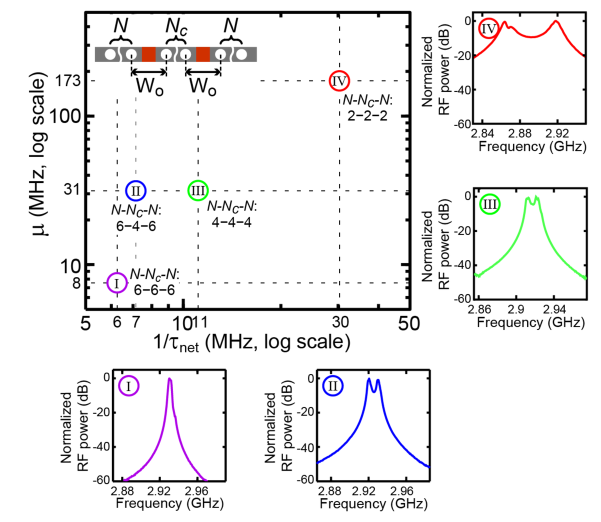
- Narrow band (3.15 MHz) at GHz range
- High instrinsic Q-factor (~ 2000)
- High dynamic range (> 70 dB)
  - limited by the system noise floor
- Second order response
  - fast drop & high selectivity
- High power handling (7-mW pump power)
- Peak signal generation efficiency of ~ 10^{-4}

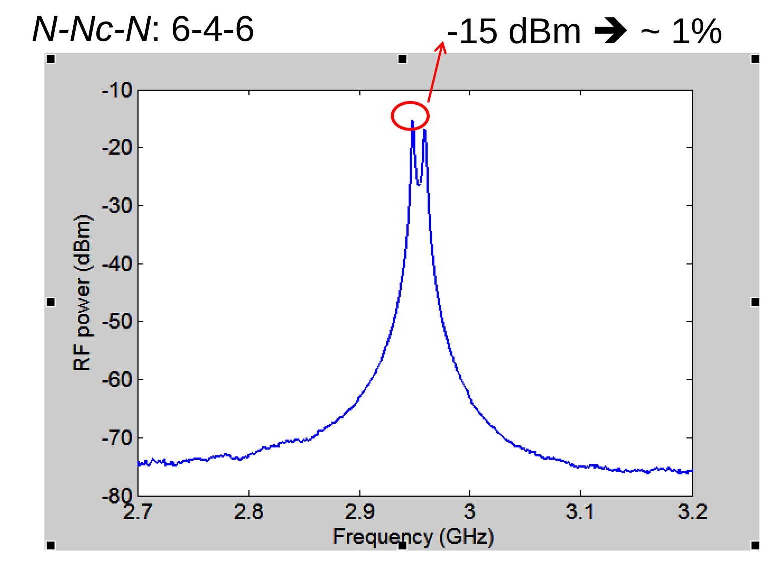
- Lithographically engineerable PPER functionalities
  - Phononic defect size (resonant frequency shift)
  - Number of hole layers (*N-N$_c$-N*)
  - PnC structure





- Wide stopband (2.6 – 4.5 GHz)





- Peak signal generation efficiency was ~ 10^{-4} for 7-mW pump power.
- Factor of 100 enhancement of efficiency (~1%) was achieved for 70-mW pump power.

$$P_s^b = |\gamma_{a\to b}(\Omega)|^2 P_1^a \, P_2^a \, P_3^b \, L^2$$

- High power handling with no shape distortion
- >10% efficiency is readily achievable with longer length (L^2) and better photon-phonon coupling ($|\gamma(\Omega)|^2$)

Why is this important?

- First demonstration of the traveling-wave Photonic-Phononic Emitter-Receiver system.
- Realization of narrow-band RF photonic filters with the second order response
- High optical power handling (~70 mW) with no shape distortion
- Wavelength insensitive narrow-band filter
  - Wavelength converter for any wavelength
  - No optical cavity
- Laser linewidth insensitivity
  - No need to have frequency stabilization or frequency locking
  - LED can be used.
- Excellent performance: High dynamic range attenuation (70 dB), high Q-factor, wide rejection bandwidth (1.8 GHz), and high selectivity (bandwidth of 3 MHz, low shape factor of 5, and slope of 20/3 [dB/MHz]).
- No optical cross-talk
- Potential application in quantum information processing
- Reflectionless geometry negates the need for optical isolators.
- Directional preference through interband transition.
- Large design space for hybrid photonic-phononic design: Lithographically engineerable responses

This PPER system can be the impetus for numerous powerful new coherent information signal processing schemes including wavelength conversion, amplifier, RF mixing, isolator, and RF photonic filter.

[1] Department of Applied Physics, Yale University, New Haven, CT 06520, USA
[2] Sandia National Laboratories, PO Box 5800, Albuquerque, NM 87185, USA
[3] Department of Electrical and Computer Engineering, University of Texas at Austin, Austin, TX 78758, USA

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