Coupling microwave and photonic systems through nanomechanical resonators

Quantum Mechanics III final presentation

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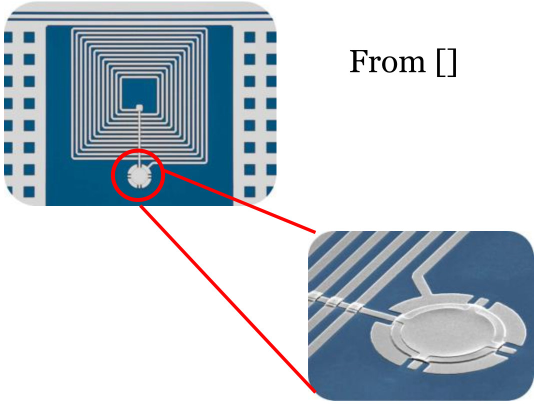
Motivation

- Quantum entanglement normally studied at optical (THz) frequencies
- Entanglement at Microwave (GHz) frequencies opens new areas of study and applications
  - Quantum computing
  - Quantum illumination
- Recent advances in the theory and construction of nanomechanical resonators allow coherent coupling of optical and microwave systems

Example 1: Drum-head capacitor

- Drum-head capacitor coupled to microwave stripline by a planar inductor
- Proposal: mirror coat other surface, put at one end of an optical cavity
- Would result in coupled microwave/optical signals



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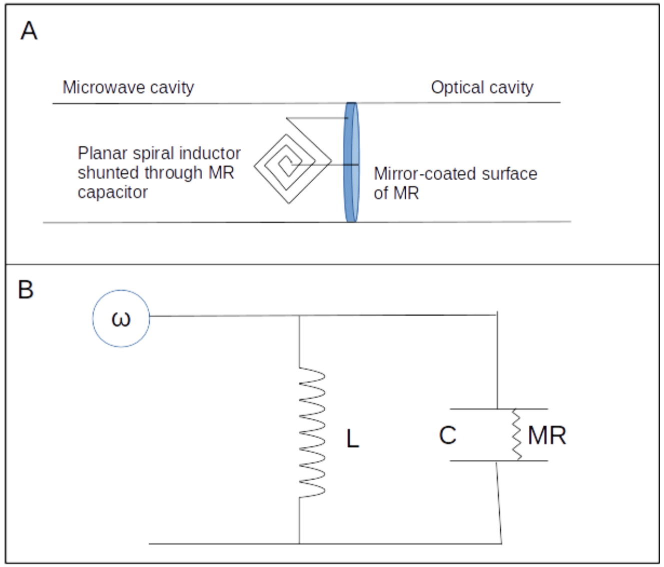
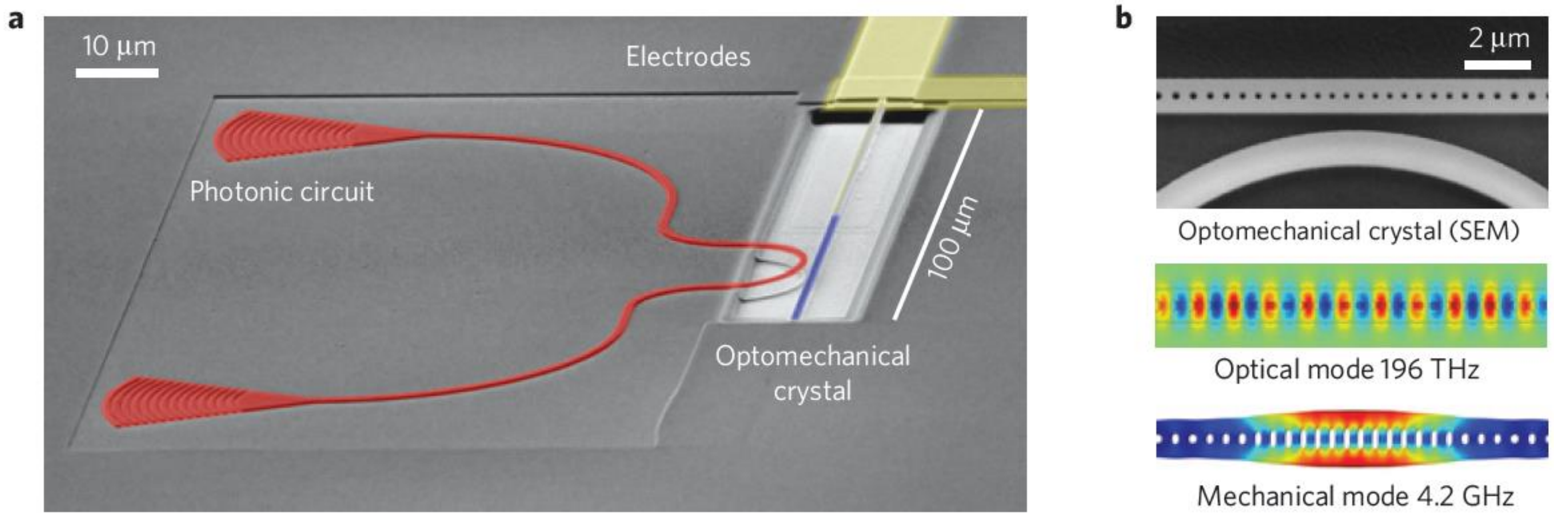


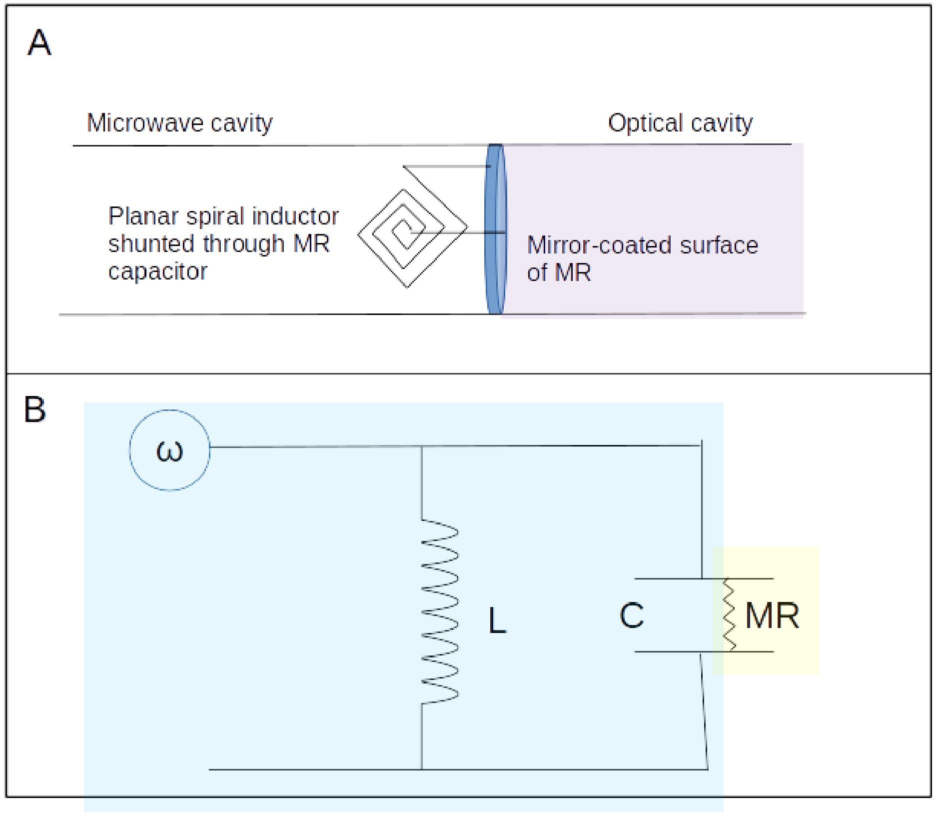
Example 2: Opto-mechanical crystal[2]

- Optical crystal made from piezoelectric material
- Microwave and optical resonances
- Experimental measurement of phase/amplitude fidelity and optical transparency controlled by microwave signal



System dynamics [3]

$$
\begin{aligned}
H = &\frac{p_x^2}{2m} + \frac{m\omega_m^2 x^2}{2} \\
&+ \frac{\Phi^2}{2L} + \frac{Q^2}{2(C + C_0(x))} - e(t)Q \\
&+ \hbar\omega_c a^\dagger a - \hbar G_{0c} a^\dagger a x \\
&+ i\hbar E_c \left(a^\dagger e^{-i\omega_{0c}t} - a e^{i\omega_{0c}t}\right)
\end{aligned}
$$



Quantum Langevin equations [3]

- Thermal noise is important in microwave regime
- QLEs: differential equations for system evolution (“slow” system plus “fast” noise terms)

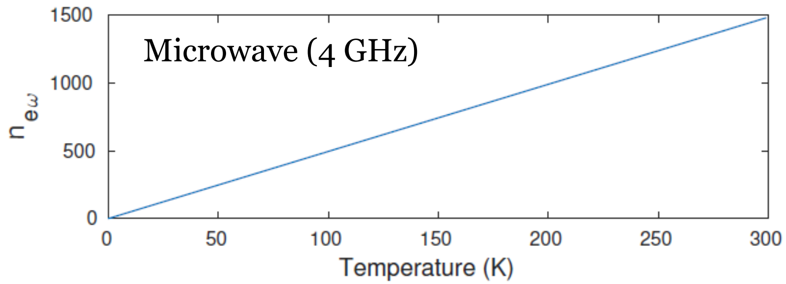
$$\langle n \rangle_e = \frac{1}{z^{-1}e^{\beta\hbar\omega} - 1}$$

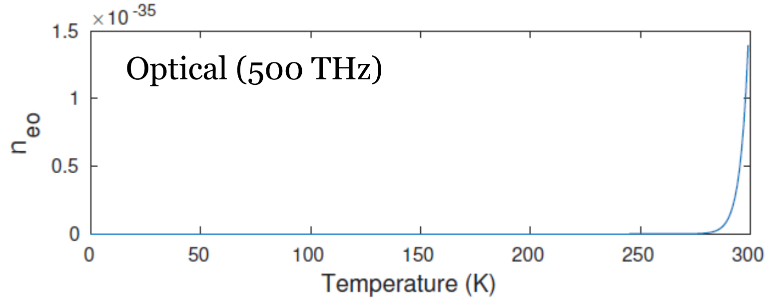
$$\dot q = \omega_m p \tag{3.5}$$

$$\dot p - -\omega_m q - \gamma_m p + G_{0c}a^\dagger a + G_{0w}b^\dagger b + \xi \tag{3.6}$$

$$\dot a = -(\kappa_c + i\Delta_{0c})a + iG_{0c}qa + E_c \tag{3.7}$$

$$\dot b = -(\kappa_w + i\Delta_{0w})b + iG_{0w}qb + E_w + \sqrt{2\kappa_w}b_{in} \tag{3.8}$$





Entanglement metrics

- Systems are separable (not entangled) if we can write state as a tensor product $$\rho^{ab} = \sum_i c_i \rho_i^a \otimes \rho_i^b$$
- If the entangled systems are in a pure state, can use reduced density matrix

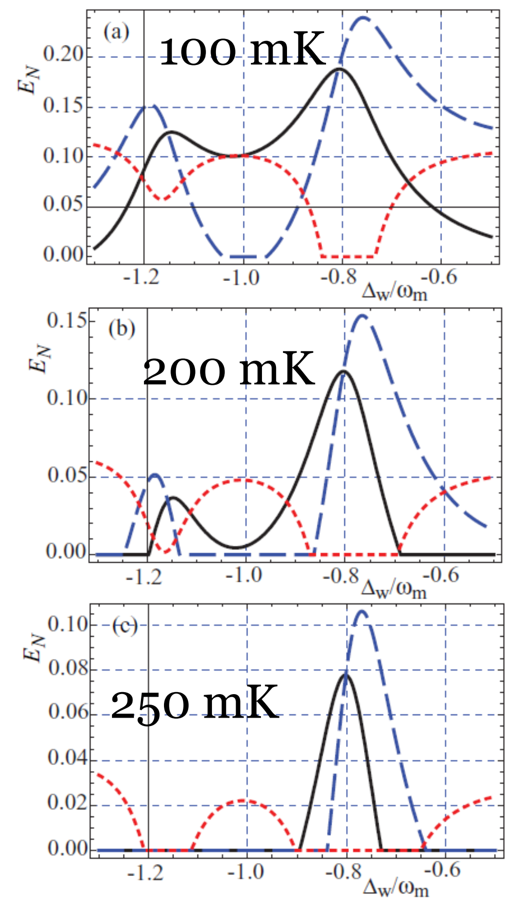
$$\rho^a \equiv Tr_b(\rho^{ab})$$
$$S = -Tr(\rho^a \ln \rho^a)$$

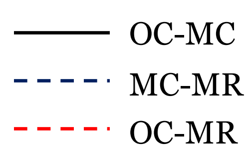
- For a general mixed state it's more complicated
- One computable metric is the negativity [6]

$$N(\rho) \equiv \frac{\|\rho^{T_a}\|_1}{2}$$

Entanglement results [3]

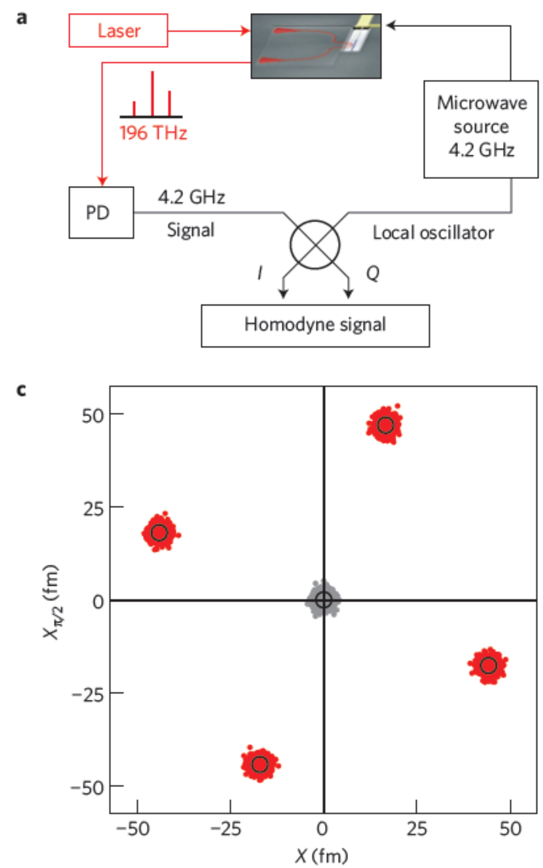
- Correlation analysis from QLEs (fluctuations about steady state)
- Log-negativity shows substantial entanglement between optical and microwave modes
- Enhancing OC-MC entanglement
  - Minimize resonator mass
  - Low temperature

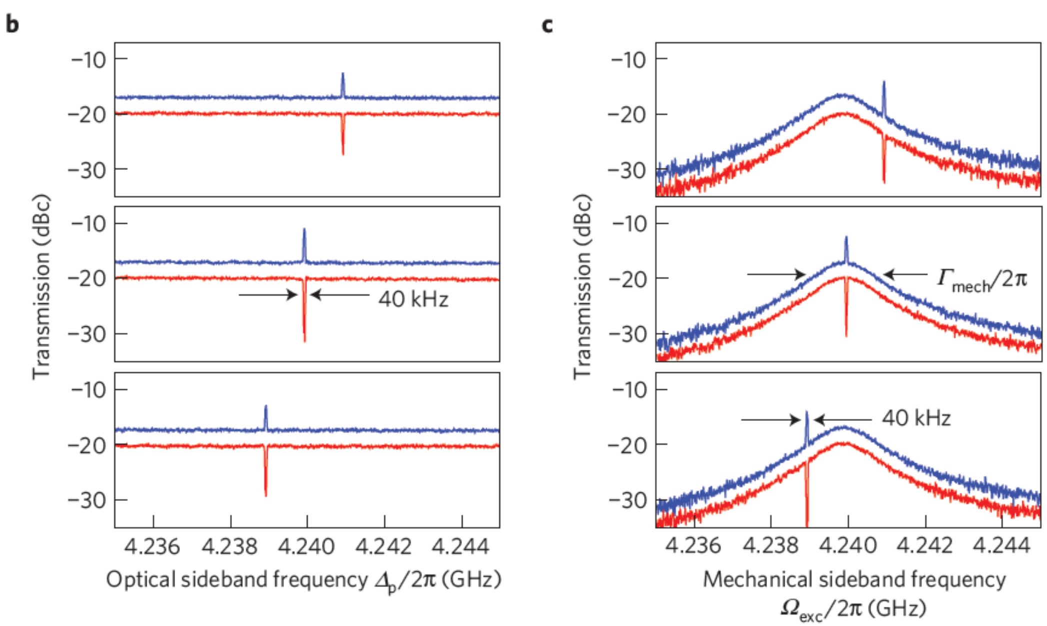




Photonic crystal result [2]

- Experimentally showed phase/amplitude transfer from microwave to optical carriers
- Also showed microwave-controlled optical sideband transparency

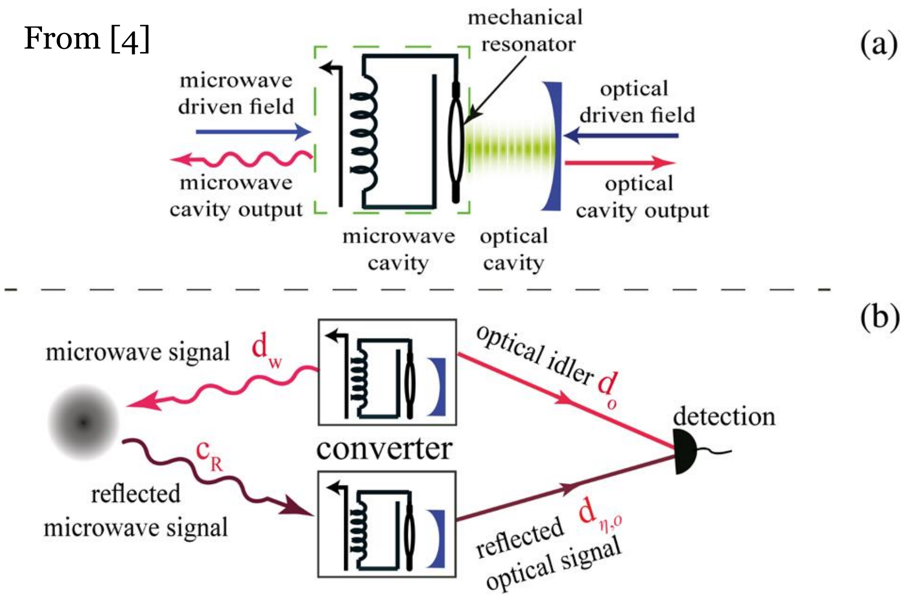




Quantum illumination

- Uses entangled photons for enhanced sensing
- Create entangled pair, retain one "idler", correlate with received signal

From [4]



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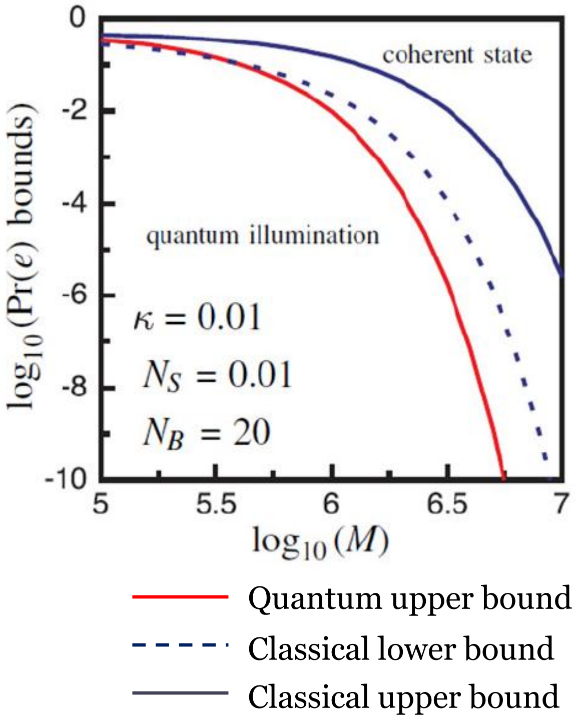
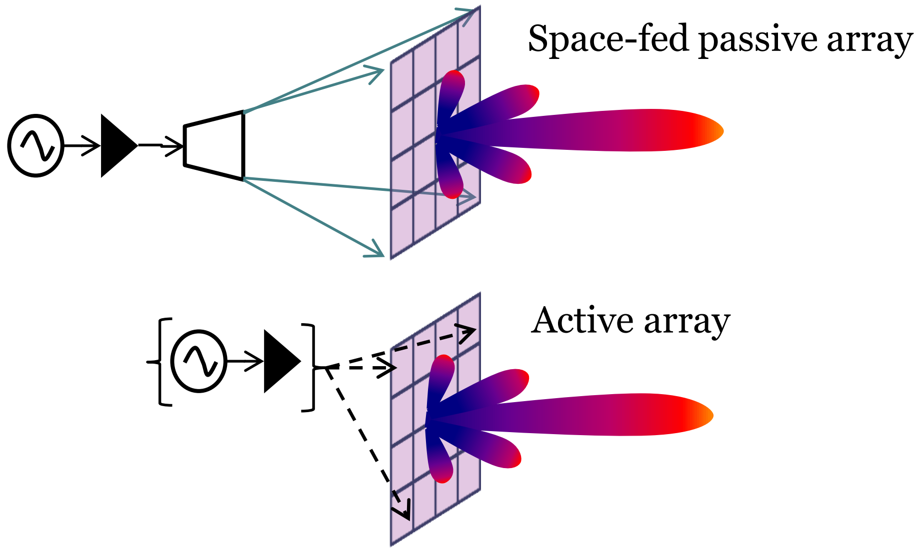


Application to radar systems

- Current analyses focus on thermal noise, but radar systems usually limited by unwanted reflections ("clutter")
  - Space sensing might be an exception
- Not clear how to use single idler to search multiple range gates
- Not clear how to apply to electronically steered arrays



References

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