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Electromagnetically induced transparency and slow light with optomechanics

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Electromagnetically Induced Transparency and Slow Light with Optomechanics

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Abstract: We demonstrate electromagnetically induced transparency and slow light in an optomechanical cavity, at cryogenic and ambient conditions, and show effects analogous to electromagnetically induced absorption.

Controlling the interaction between localized optical and mechanical excitations is now possible following advances in micro- and nano-fabrication techniques [1]. To date, most experimental studies of optomechanics have focused on measurement and control of the mechanical subsystem through its interaction with optics, and have led to the experimental demonstration of dynamical back-action and mechanical mode-mixing [2]. However, the optical response of these systems is conversely modified in the presence of mechanical interactions, leading to effects such as Electromagnetically Induced Transparency (EIT) [3], parametric normal-mode splitting [4], and thus a platform for strongly nonlinear optics. Using the optomechanical nonlinearity, we propose and demonstrate a new way of control-

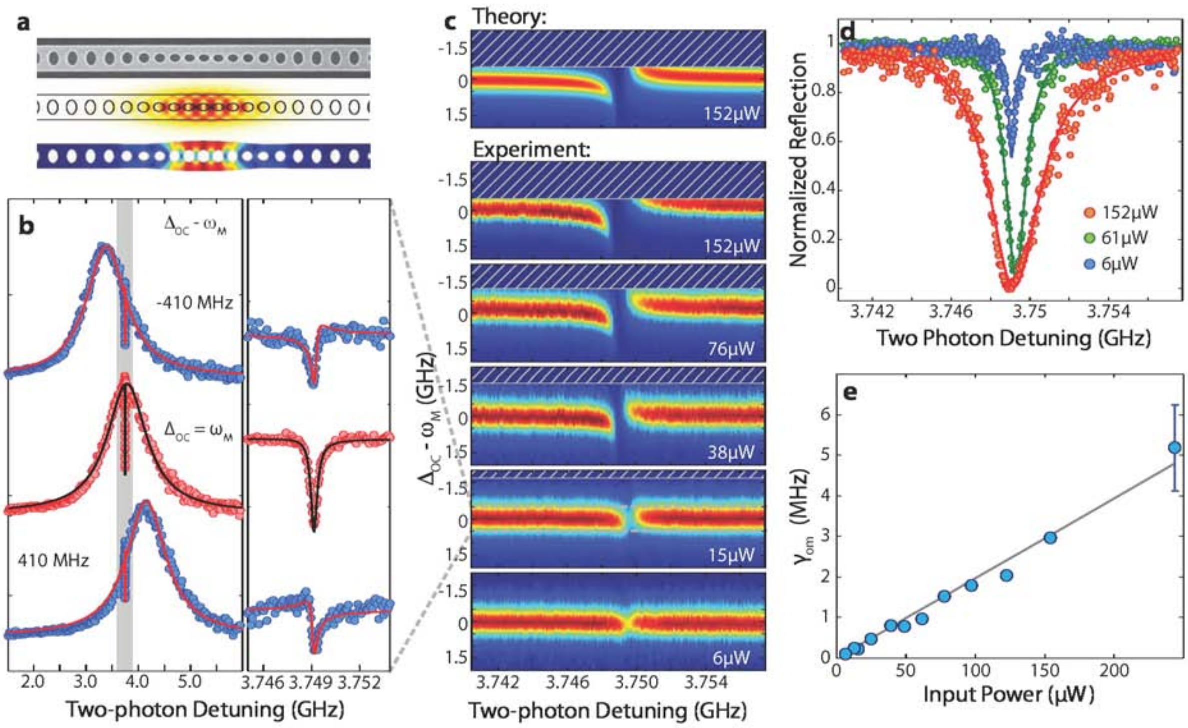

Fig. 1. (a) Fabricated optomechanical device with E_y and $|\mathbf{Q}|$ fields for the modes of interest. (b) Reflection spectra for various pump frequencies, along with (c) color plots of reflection as a function of both the pump, and the two-photon detuning. (d) Detailed view of transparency region, at different pump powers. (e) Inferred optomechanical damping as a function of input power.

ling the velocity of light via engineered photon-phonon interactions. Our results demonstrate EIT and tunable optical delays on a nanoscale optomechanical crystal device, fabricated by simply etching holes into a thin film of Silicon. At low temperature (8.7 K), we show an optically-tunable delay, of 50 ns, with near-perfect transmission, and superluminal light with a 1.4 μs signal advance. These results, while indicating significant progress towards an integrated quantum optomechanical memory [5], are also relevant to classical signal processing applications.

The nanobeam OMC cavity used in this study, utilizes a periodic free-standing Si structure to create high-Q co-localized optical and mechanical resonances [6], shown in Fig. 1a. These devices are designed to operate optically in the telecom band ($\lambda_o = 1550$ nm) and acoustically at microwave frequencies ($\omega_m/2\pi = 3.75$ GHz). By optimizing both the defect and crystal structure, an intrinsic optical decay rate of $\kappa_i/2\pi \approx 290$ MHz was obtained for the optical mode, coupled at a rate $g/2\pi \approx 800$ kHz to a mechanical mode with an intrinsic dissipation rate $\gamma_i/2\pi \approx 250$ kHz (1.9 MHz) at a temperature of 8.7 K (300 K).

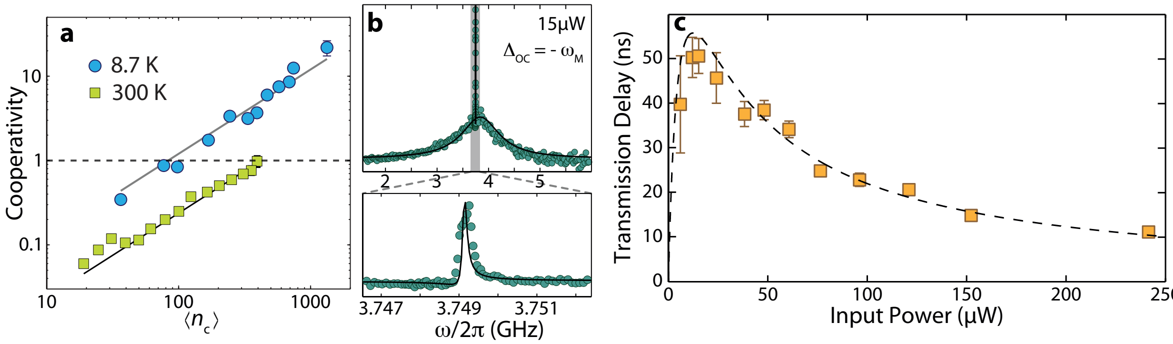

Fig. 2. (a) Measured cooperativities, as a function of mean intracavity photon number. (b) Optomechanical EIA spectra. (c) Transmission delay (yellow squares) inferred from phase lag of a modulated probe at different powers, along with the expected theoretical curve from equation (1) taking into account the independently measured system parameters.

When the system is driven with an intense red-detuned optical "control" beam at frequency ω_c, the form of the effective interaction is given by that of a beam-splitter-like (linear) Hamiltonian $H_{\text{int}} = \hbar G(\hat{a}^\dagger \hat{b} + \hat{a}\hat{b}^\dagger)$. With the control beam detuning set to $\Delta_{\text{OC}} \equiv \omega_o - \omega_c \cong \omega_m$, the optical and mechanical modes $\hat{a}$ and $\hat{b}$ become coupled at a rate $G = g\sqrt{\langle n_c \rangle}$. The dressed mechanical mode then takes on a weakly photonic nature, coupling it to the optical loss channels at a rate $\gamma_{\text{om}} \equiv C\gamma_i$, where the optomechanical cooperativity is defined as $C \equiv 4G^2/\kappa\gamma_i$. The drive-dependent loss rate γ_{om} has been viewed in most previous studies as an incoherent, quantum-limited loss channel, and was used in recent experiments to cool the mechanical motion. We show that the coherent cancellation of the loss channels in the dressed optical and mechanical modes can be used to switch the system from absorptive to transmittive, creating a narrowband transparency window for probe light around the cavity resonance. Much as in atomic EIT, this effect causes an extremely steep dispersion for the transmitted probe photons, with a group delay on resonance of

$$\tau^{(\text{T})}|_{\Delta_{\text{SC}}=\omega_m} = \frac{2}{\gamma_i} \frac{(\kappa_e/\kappa)C}{(1+C)(1-(\kappa_e/\kappa)+C)}, \tag{1}$$

which itself can be dynamically adjusted via the control beam intensity. By measuring the phase shift imparted on a probe signal modulated at a low frequency, we measure directly the group delay on reflection, and infer the group delay on transmission which is plotted in Fig. 2c. Measurements at room temperature (Fig. 2a) and in the analogous regime of Electromagnetically Induced Absorption (EIA) (Fig. 2b) show the utility of these chip-scale optomechanical systems for optical buffering, amplification, and filtering of microwave-over-optical signals.

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