All-Optical Control of an Individual Resonance in a Silicon Microresonator

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We experimentally demonstrate selective control of the $Q$ and transmission of an individual resonance of an optical microcavity by optically controlling its intracavity loss via inverse Raman scattering. A strongly overcoupled resonance is brought into critical coupling with continuous tuning of the on-resonance transmission by $>9$ dB and reduction of the intrinsic $Q$ factor by more than a factor of five. Adjacent resonances experience minimal disturbance and can be selectively controlled by tuning the control beam to the appropriate control resonance. These dynamics are analogous to Zeno effects observed in decoherence-driven atomic ensembles and two-level systems.

On-chip microcavities have attracted significant interest for their ability to confine and manipulate light on a compact, scalable platform [1]. Such microresonators have been applied to modulators [2,3], routers [4], optical delays [5,6], detectors [7] and multiple-wavelength sources [8] for on-chip optical signal processing as well as probes and sensors for optofluidic manipulation [9], biochemical sensing [10,11], and frequency metrology [12,13]. Recent work on cavity-atom interactions offers the promise of ultrasmall optical clocks and on-chip quantum optics [14–17].

Active modulation of on-chip optical cavities is typically achieved via a refractive index shift through free-carrier effects or the Kerr nonlinearity [2,4]. However, the broadband nature of such index-shifts alters all of the resonance wavelengths and does not permit control of individual frequency channels of the cavity. This limits its full functionality as a multichannel router and limits access to other important cavity parameters such as cavity $Q$, linewidth, and on-resonance transmission, which are important for both active operation and postfabrication fine-tuning of the cavity properties [18].

Recently, it was proposed [19] that these previously unaccessible functionalities can be achieved through all-optical control of a narrowband loss in the cavity at the signal wavelength by stimulating Raman loss through the inverse Raman scattering (IRS) process. In silicon, IRS produces a 105-GHz-wide (1-nm) spectral loss at the anti-Stokes wavelength which is blue-detuned by 15.6 THz with respect to the control beam. For a typical microresonator, this stimulated Raman loss (SRL) is spectrally wider than the cavity linewidth but narrower than the free spectral range (FSR), allowing it to alter a single resonance and leaving the adjacent resonances undisturbed. This resonant interaction enhances the coupling of the signal into the cavity making it far more efficient than a direct absorption switch. Furthermore, the coupled signal light continues to circulate in the ring cavity and can be rerouted with an adjoining drop waveguide [20]. Precision control of optical loss in optical cavities has also attracted recent interest for fundamental studies of light-matter interactions as coherent perfect absorption and time-reversed lasing in a Fabry-Perot cavity [21]. Additionally, optical resonators provide an optical analog for the quantum Zeno and anti-Zeno effects wherein the transition between two photonic states can be inhibited or enhanced through decoherence (i.e., optical loss) of the second state [22,23].

Here we present experimental demonstration of selective control of the intracavity loss of individual resonances of an optical cavity. The on-resonance transmission is reduced by 87% and the $Q_i$ is continuously tuned from 82 130 to 15 812 with a 13 pJ control pulse. This is achieved without shifting the resonance wavelength and with minimal disturbance to adjacent resonances. Adjacent signal resonances are controlled with similar efficiencies by tuning the control pulse to the adjacent control resonance. These observations are consistent with the predictions of coupled-mode theory for a loss-modulated cavity which confirms the resonant nature of the effect [19]. Lastly, we observe anti-Zeno and Zeno-like dynamics in the response of the coupling of the waveguide and cavity modes to optical decoherence.

A ring resonator coupled to a single bus waveguide [Fig. 1(c)] has a coupling region modeled by a coupling matrix given in Fig. 1(d), with field coupling rate of $r = i\sqrt{1 - t^2}$ and a field transmittance $t$, which is close to unity for a weakly coupled cavity. The on-resonance transmission at the through-port is given by,

$$T_N(\lambda_{res}) = \left[\frac{t - \alpha}{1 - \alpha t}\right]^2,$$

(1)
where $a(\lambda) = e^{-a(\lambda)L/2}$ is the round-trip field transmission of a ring cavity of circumference $L$, and $a(\lambda)$ is the intrinsic loss coefficient [19,24]. The related $Q$ factors provide an equivalent analysis of the system where $Q_{\lambda} = \lambda / (a(\lambda)\text{FSR}_R)$, FSR is the free-spectral-range, and $\text{FSR}_R$ is the ring radius. We define the loaded loss coefficient $a(\lambda) = a(\lambda) - 2\ln(\tau)/L$, where the out coupling is included as a loss process in the cavity. The on-resonance transmission in terms of the $Q$ factors is $T_N(\lambda_{\text{res}}) = (1 - 2Q/\lambda)^2$. However, the $a(\lambda) - \tau$ picture is the more natural basis with which to analyze the performance of the system since $a(\lambda)$ and $\tau$ correspond directly to the controllable parameters of intracavity loss and coupling gap, respectively.

Figure 2 (inset) plots Eq. (1) as a function of $\alpha$ for $t = 0.93$ and shows that the transmission is most sensitive for values of $\alpha$ in the overcoupled regime, where the round-trip intracavity loss is less than the waveguide-cavity coupling rate [i.e., $a(\lambda) < |\alpha|$. Without the control beam, only the linear loss contributes to the loss coefficient (i.e. $a(\lambda) = a_L$). The control beam stimulates Raman loss $a_R(\lambda, I)$ and generates several undesirable broadband nonlinear effects. Degenerate two-photon absorption (D-TPA) of the control grows quadratically with control power and generates free-carriers which causes free-carrier absorption (FCA). Nondegenerate TPA from control plus anti-Stokes photons adds to broadband loss of the signal, which grows linearly with control power. These two losses are represented as a lumped broadband loss $a_{\text{NL}}(I, I^2)$ such that $a(\lambda, I) = a_L + a_R(\lambda, I) + a_{\text{NL}}(I, I^2)$, where $I = \mathcal{F}_\text{eff} E_c/(\pi\tau \alpha_{\text{eff}})$ is the intracavity intensity, $\mathcal{F}_\text{eff}$ is the effective finesse at the control wavelength, $E_c$ is the control pulse energy, $\tau$ is the control pulse width and $\alpha_{\text{eff}}$ is the effective mode area of the waveguide. D-TPA of the signal is negligible due to the low signal powers in use. The broadband nonlinear losses and the associated refractive effects become a limiting process on the overall control efficiency and wavelength selectivity.

Inverse Raman scattering is a stimulated stokes scattering process wherein an anti-Stokes photon is scattered into a pump photon and the energy difference is deposited as an optical phonon in the material. Previously measured IRS in silicon nanowaveguides is consistent with the known Raman gain coefficient of $g_R = 7$ cm/GW at the control wavelength 1550 nm [25]. The SRL near the anti-Stokes frequency $\omega_a$ is given by

$$a_R(\omega, I) = \frac{g_R \Gamma_R^2}{(\omega - \omega_a)^2 + \Gamma_R^2} I,$$

where $\Gamma_R = 105$ GHz is the Raman loss linewidth for silicon. The FSR is chosen to be an integer fraction of $\Omega_k = 15.6$ THz such that the transverse electric (TE) control beam at 1556.1 nm and the transverse magnetic (TM) anti-Stokes signal beam at 1439.5 nm are simultaneously resonant with the ring. Figure 2 shows the

FIG. 1 (color online). (a) Schematic for all-optical control of a single resonance. 200 ps control pulses at 1556.1 nm are generated at the rep-rate of the optical parametric amplifier (OPO) which generates the broadband signal pulses near 1440 nm. The low power signal pulse does not cause nonlinear effects. The two pulses are combined and synchronized in time and injected into the silicon waveguide using a free-space objective. The through-pulses are combined and synchronized in time and injected into the silicon waveguide using a free-space objective. The throughput transmission for a cavity as a function of the intracavity field transmission.

FIG. 2 (color online). Theoretical transmission of the TE (red, right branch) and TM (blue, left branch) modes across the relevant spectral range. Control (TE at 1556.1 nm) is near critical-coupling, anti-Stokes signal (TM at 1439.5 nm) is strongly overcoupled. The two are separated by exactly $\Omega_k$ of silicon and are both resonant with the cavity. (Inset) Throughport transmission for a cavity as a function of the intracavity field transmission.
theoretical transmission spectra of the TE (red, right branch) and TM (blue, left branch) modes and the spectral placement of the control and signal.

Simulations reveal that the cross-sectional dimensions of TE mode at 1439 nm is 15% shorter and 20% narrower than that of the TE mode at 1556 nm. This mode size difference leads to a significant difference in coupling rates for the control and signal. Using the more delocalized TM mode for the shorter anti-Stokes wavelength alleviates this difference for the disparate wavelengths. The Raman interaction in silicon is also stronger for orthogonally polarized control and signal beams. For waveguides fabricated on a wafer grown in the [001] direction and traveling in the [110] direction, the Raman interaction for TE-TM or TM-TE control-signal combination is enhanced by a factor of 3 over the TE-TE combination. In a circular ring cavity the control and signal fields sample all $2\pi$ of lattice directions which reduces the enhancement to a factor of 1.5 for the TE-TM combination over the TE-TE combination [26,27]. This suggests that the Raman interaction can be increased by using racetrack cavities that extend the portions of waveguide which prefer the TE-TM combination.

The ring-resonators are fabricated on a 250-nm SOI wafer with 3 μm of buried oxide using standard CMOS fabrication processes. The rings have a radius of 50 μm, and are coupled to a straight waveguide separated by a gap of 230 nm. All waveguides have a cross section of 450-nm wide by 250-nm tall and have an effective mode area $A_{eff} = 0.25 \mu m^2$. The anti-Stokes wavelength of the field coupling rate is estimated to be $r = 0.55$ ($t = 0.83$) with an intrinsic loss of $\alpha_L = 10.77 \text{ dB/cm}$, which results in cavity resonances with an intrinsic $Q_j = 82,130$ but a loaded $Q_j = 12,613$. The large linear loss is due to the delocalized nature of the TM polarized mode and the large field coupling rate achieves initial overcoupling for the signal resonance. The control pulses are 200 ps which is close to the lifetime of the cavity. This reduces the effective finesse ($F_{eff}$) from the steady-state value of 63 to 36. The optical transmission of the cavity was characterized using a low-power broadband pulse near the anti-Stokes wavelength (Fig. 1).

Figure 3 shows the narrowband SRL acting on single resonances. The affected resonance is exactly 15.6 THz blue-shifted from the control wavelength. The adjacent signal resonances can likewise be controlled by tuning the control wavelength to an adjacent control resonance such that the anti-Stokes loss shifts to the corresponding signal resonance [Figs. 3(b) and 3(c)]. This indicates that Raman loss is the dominant process affecting the resonances. The non-anti-Stokes resonances are not affected by the Raman loss; however, the broadband TPA and FCA loss does result in modulation of their transmission by 1–2 dB for a 13-pJ control pulse. The contribution of the nonlinear losses to the system is further discussed in

![Image](223907-3)
resonance (Fig. 4 right inset) and by the broadened line-
widths of both resonances. Both observations indicate that
the spectra for 19.5 pJ control pulse corresponds to greater
loss, and hence greater power, inside the cavity. The signal
loss due to SRL in the straight waveguide is less than
0.1 dB. An off-resonant measurement of the Raman
absorption at the anti-Stokes frequency in the straight
waveguide reveals 0.25 dB of loss for a 20-pJ control pulse,
but the loss is much less for resonant control and signal
since the signal experiences Raman absorption for only 5%
of the entire length of the straight waveguide.

Additionally, the linewidth, and therefore the $Q$, can
be continuously tuned with increasing control energy.
Figure 5 shows the single resonance intracavity loss and $Q$
extracted from the resonance linewidth and extinction
[28]. The initial $Q_i$ is 6.5 times smaller than the initial $Q_i$
of the cavity but should be exactly 2 times smaller for a
critically coupled cavity. This ratio drops to 2.3 for a
13-pJ control pulse, indicating that the cavity is tuned
close to critical coupling. For a 19.5 pJ control pulse, the
$Q_i$ decreases by a factor of 5.19, from 82,130 to 15,1812.
Correspondingly, the intracavity loss increases by
45.2 dB/cm. Comparing the intracavity loss of the anti-
Stokes resonance (Fig. 5, blue circle) with that of an
adjacent resonance (green diamond) indicates that TPA
and FCA contributes 16% (7.24 dB/cm) of the total loss
of the anti-Stokes cavity; the other 84% (38.0 dB/cm) is
due to Raman loss. TPA and FCA makes an appreciable
contribution at high control powers due to its quadratic
growth with control intensity. The sub-linear increase of
the intracavity loss with the control pulse energy is con-
sistent with broadband TPA and FCA reducing the $Q$
factors for the control wavelength. The nonlinear losses
measured from the adjacent resonance corresponds to a
45% decrease in both $Q_i$ and $F_{\text{eff}}$ at the control wave-
length, in agreement with theoretical predictions (Fig. 5).

In the current scheme, the passive signal transmission
can be increased to greater than $-0.2$ dB (95%) by using
a more overcoupled cavity. Routing applications require
a drop waveguide to couple out the signal from the cavity
where it would be advantageous to use an initially
critically coupled cavity and use the loss to push the cavity
into undercoupled regime as described in [19].
The undercoupled regime allows complete isolation of
the bus and drop waveguide in the on-state, which is not
possible for the overcoupled cavity. For high-$Q$ cavities
($Q_i > 200,000$), signal routing can be achieved with
$\leq 0.1$ signal loss ($\geq 97$% transmission) for picojoule
control energies. Selective routing of single channels
dramatically increases the degrees-of-freedom and data
density of the system. Networks of such devices with
multiplicative degrees-of-freedom can easily be envi-
sioned [29].

The dynamics shown here are also the optical analogue
of Zeno effects observed in decoherence-driven atomic
ensembles and quantum two-level systems where the
natural evolution of the system is strongly perturbed by
frequent measurement or decoherence on the upper state
[23,30]. This relation has been well established and is a
current topic investigation by several groups [15,22,31].
In atomic systems [23,30], measurement-induced deco-
herence enhances (anti-Zeno) the transition between two
states for infrequent measurement and inhibits (Zeno) the
transition for more frequent measurement. Here, the mode
of the bus waveguide and the resonant mode of the cavity
at the anti-Stokes wavelength represent the two photonic
states, and the stimulated Raman absorption of anti-
Stokes photons constitutes the measurements of the
“upper” cavity state by coupling it to the phonon bath of
the waveguide. The strength of the induced decoher-
ence is directly (inversely) proportional to the frequency
of (delay between) the loss events. For control pulses
below 13 pJ, the cavity experiences anti-Zeno enhance-
ment of the photonic transition but for higher control
energies the cavity experiences Zeno inhibition of the
transition. The current scheme provides a robust and
sensitive platform for exploring the effects of loss on
the thermodynamics of classical and quantum photonic
states.

Stimulated Raman loss in silicon allows the manipula-
tion of single cavity resonances in silicon microreson-
ators. This system enables on-chip optical microcavities
to achieve their full potential as multichannel all-optical
routers on a monolithic, CMOS compatible platform.
This dramatically increases the degrees-of-freedom for
design of both hardware and software for on-chip optical
processing. Finally, it also demonstrates the universality
of the effects of decoherence on resonant systems and
their usefulness in controlling the system’s dynamics.
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