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Optical bistability and free carrier dynamics in graphene–silicon photonic crystal cavities

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ABSTRACT

We introduce graphene–silicon hybrid nonlinear devices operating at a few femtojoule cavity circulating energies, including: (1) dual- and single-cavity optical bistability; (2) detailed and broadband switching dynamics, and (3) free-carrier and thermal effects in regenerative oscillations. Sub-wavelength nanostructures confine light in a single mode silicon resonator with high *Q*/*V* ratio, enabling strong light interaction with the graphene cladding layer.

1. Introduction

The unique photonic properties of graphene – optical transparency, broadband dispersionless nature, large carrier mobility, and atomic layer thin structure – make it a unique material for integrated photonic devices. Graphene has been examined for its gate-variable optical transitions [1,2] toward broadband electro-absorption modulators [3] and photoreceivers [4,5] including planar microcavity-enhanced photodetectors [6,7], as well as saturable absorption for mode-locking [8]. Third-order nonlinear susceptibility for graphene is reported as large as $|\chi^{(3)}|\sim 10^{-7}$ esu [9], along with two-photon absorption (TPA) rate five orders of magnitude higher than silicon [10] and large nonlinearities in the terahertz [11]. Coupled with TPA-generated free carrier and consequently thermal dynamics, a wavelength-scale localized photonic crystal cavity enables ultralow power optical bistable switching and self-induced regenerative oscillations at femtojoule cavity energies on the semiconductor chip platform [12]. Here we transfer single layer graphene on suspended silicon photonic crystal membranes and examine the optical bistability and the carrier/thermal-nonlinearity-induced regenerative oscillations on-chip. The refractive index change for the hybrid media, induced by TPA generated free carriers, is twenty times larger than the monolithic sample, and thus significantly reduces the optical pump power [27].

2. Effective two photon absorption in graphene–Si system

The two-photon absorption coefficient β_2 in monolayer graphene is estimated through the second-order interband transition probability rate per unit area as [10]

$$\beta = \frac{4\pi^2}{\varepsilon_\omega \omega^4 \hbar^3}\left(\frac{v_F e^2}{c}\right)^2, \quad (1)$$

where ν_F is the Fermi velocity, $\hbar$ is reduced Planck's constant, e is the electron charge, and ε_ω is the permittivity of graphene at the drive frequency. For our 1550 nm wavelengths, β_2 for single layer graphene is determined through *z*-scan measurements and first-principle calculations to be in the range of $\sim$3000 cm/GW [10], compared to 0.8 cm/GW in silicon.

In the hybrid photonic crystal–graphene structure, most of light is confined in the 250 nm silicon membrane, and evanescently coupled to the $\sim$1 nm graphene cladding layer (Fig. 1). The effective TPA coefficient is a balance between graphene and silicon, weighted by the optical filed distributions. The effective two-photon absorption coefficient of graphene on silicon is

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defined as

$$\bar{\beta}_2=\left(\frac{\lambda_0}{2\pi}\right)^d \frac{\int n^2(r)\beta_2(r)(|E(r)\times E(r)|^2+2|E(r)\times E(r)^*|^2)d^d r}{\left(\int n^2(r)|E(r)|^2 d^d r\right)^2} \tag{2}$$

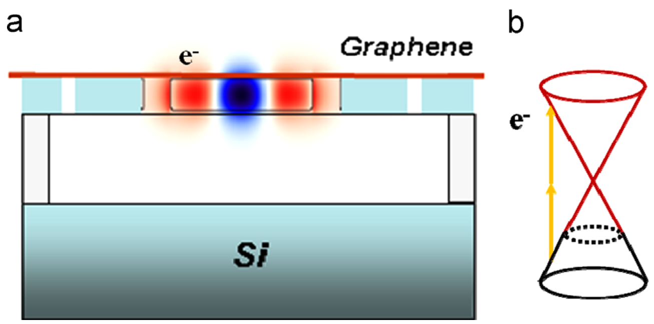

Fig. 1. Graphene-cladded silicon photonic crystal cavity. (a) Cross section of the graphene cladded silicon photonic crystal membrane. The light blue part is silicon. Silicon oxide (grey part) is released under the photonic crystal part. Graphene (red) is transferred on the TE polarized light confined in the resonator. (b) Band diagram of graphene and two photon absorption of the near-infrared light. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

where $E(r)$ is the complex fields in the cavity and $n(r)$ is the local refractive index. λ_0 is the wavelength in vacuum, and $d=3$ is the number of dimensions. The complex electric field $E(r)$ is obtained from the three-dimensional finite-difference time-domain computations of the optical cavity [13]. The local two photon absorption rate is 1.5 cm/GW in the silicon membrane and ~3000 cm/GW for graphene, and the effective n^2 can be analogously calculated.

3. Steady-state bistable switching

We measure and model the nonlinear cavity transmissions with time-domain nonlinear coupled-mode theory [14] for the temporal evolution of the cavity amplitude, carrier densities, and effective cavity temperature as described by

$$\frac{da}{dt}=\left(i(\omega_L-\omega_0+\Delta\omega)-\frac{1}{2\tau_t}\right)a+k\sqrt{P_{in}}, \tag{3}$$

$$\frac{dN}{dt}=\frac{1}{2\hbar\omega_0\tau_{TPA}}\frac{V_{TPA}}{V_{FCA}}|a|^4-\frac{N}{\tau_{fc}}, \tag{4}$$

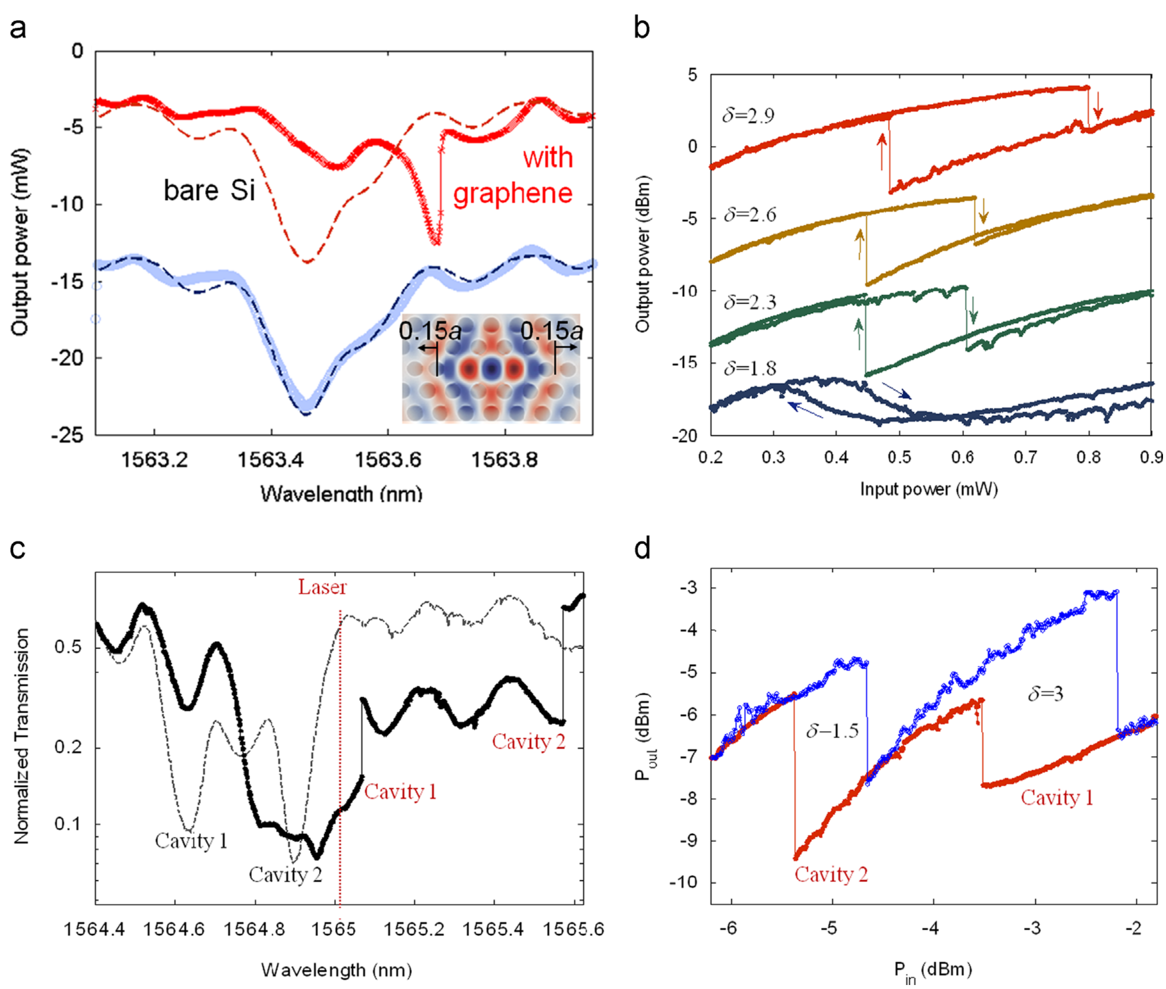

Fig. 2. Bistable switching in graphene-clad nanocavities. (a) Measured graphene-cladded cavity transmission with asymmetric Fano-like lineshapes at high power $P_{in}=0.6$ mW (red dotted line) and low power $P_{in}=0.1$ mW (blue dotted line). The blue dashed line is coupled mode theory curve fitting in the linear region, with Fano-like interference induced asymmetry. Red dashed line is the coupled mode theory expected transmission lineshape for the same resonance without graphene. Inset: example E_z-field from finite-difference time-domain computations. (b) Measured steady-state bistability at different detunings set at 0.18, 0.23, 0.26, 0.29 nm (from bottom to top), corresponding to $\delta=1.8$, 2.3, 2.6 and 2.9 ($\delta=(\lambda_{laser}-\lambda_{cavity})/\Delta\lambda_{cavity}$). The plots are offset for clarity: green (offset 2 dB), brown (offset 8 dB) and red lines (offset 15 dB). (c) Normalized transmission of two cavities with resonance separation of $\delta=3$. The grey dashed line is measured at −16 dBm input power, and the solid black line is for 0 dBm input. (d) The measured transmission for optical bistability in a two-cavity system as from (c). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)