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Ultrafast all-optical modulation in GaAs photonic crystal cavities

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We demonstrate all-optical modulation based on ultrafast optical carrier injection in a GaAs photonic crystal cavity using a degenerate pump-probe technique. The observations agree well with a coupled-mode model incorporating all relevant nonlinearities. The low switching energy (~120 fJ), small energy absorption (~10 fJ), fast on-off response (~15 ps), limited only by carrier lifetime, and a minimum 10 dB modulation depth suggest practical all-optical switching applications at high repetition rates. © *2009 American Institute of Physics.*
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On-chip all-optical semiconductor switching has attracted a significant amount of attention in recent years. Various approaches to high-speed devices have been investigated involving the plasma dispersion effect in silicon photonic crystal (PhC) cavities[1] and optically pumped silicon microrings.[2] The free carriers that cause the plasma effect and consequent refractive index shift are generated from two-photon absorption (TPA). All-optical modulation has also been achieved in III-V microrings.[3] In each of these experiments, the fundamental limit of the switching speed is the *effective* carrier lifetime τ_{eff}. Advanced semiconductor processing techniques such as ion implantation[4] and *p-i-n* diodes[2] have reduced τ_{eff} to 70 and 50 ps, respectively, in crystalline silicon, though at the cost of increased optical loss or power threshold. Designs incorporating two-color switching mechanisms have achieved faster speeds than their single color counterparts but have decidedly more challenging fabrication processing involving the following: (a) selective area growth of highly homogeneous self-assembled quantum dots[5] (2 ps), (b) three-dimensional polysilicon PhCs (Ref. 6) (18 ps), or (c) a silicon and Kerr-polymer hybrid waveguide (WG) Mach–Zender[7] (10 GHz). Despite the variety of approaches, due to their ability to strongly confine light,[8,9] reduced τ_{eff}, and enhanced light-matter interaction,[10–12] we believe PhC cavities are the most promising approach for achieving high-speed, low-power, switches and memory. In this letter, we demonstrate a single color, ultrafast nonlinear response due to the plasma dispersion effect in a GaAs PhC cavity with a recovery time less than 10 ps.

An approach for an all-optical switch is to modulate the refractive index of the material. Instead of near-instantaneous all-optical Kerr, we suggest that an efficient TPA induced plasma effect coupled with fast carrier recovery is also a viable option.[13] In this respect, we performed degenerate pump-probe experiments on PhC cavities fabricated in GaAs, a material known for its large TPA coefficient β and elevated electron mobility. The combination of high mobility and enhanced surface to volume ratio S/V of the GaAs PhC nanocavity greatly reduce τ_{eff},[4] reaching values as low as 8 ps in AlGaAs PhC lattices without resonant cavities.[14] An additional advantage of GaAs is the ability to embed active materials, such as quantum wells or dots.[5,15,16]

The PhC structure studied here is an in-line, overcoupled H0 cavity in an air slab structure with a thickness of 250 nm based on a triangular lattice (period $a=430$ nm) of holes with radius $r=0.22a$. We used the design proposed in Ref. 14 providing ultrasmall mode volume of $0.24(\lambda/n)^3$. The cavity is formed from two air holes shifted by $s=0.16a$ three rows above the WG. The holes nearest the PhC WG are enlarged to $r_{wg}=0.34a$ in order to couple light to the cavity mode. All quoted distances are nominal. The fabrication process and the detailed linear characterization of similar structures have been described elsewhere.[17] The cavity resonant wavelength is measured to be 1540.05 nm with a full width at half maximum (FWHM) of 1.2 nm, as shown in Fig. 1. The coupling loss into the WG, here ~−5 dB/facet, is estimated after accounting for the losses due to the microscope objectives, as well as the mode adaptation of the free-space beam coupled into the PhC.[13] The small insertion loss here is due to a mode adapter, the details of which will be published elsewhere. The linear transmission of the PhC sample was therefore estimated to be 90% with the cavity on-resonance. The FWHM and transmission data yield loaded and intrinsic *Q*-factors of $Q_L=\lambda_0/\Delta\lambda=1, 200$ and $Q_i=2.5\times10^4$, respectively.[18] The cavity photon lifetime is $\tau_{ph}=Q_L\lambda_0/2\pi c$ ≈ 1 ps, thereby intentionally ensuring that the switching

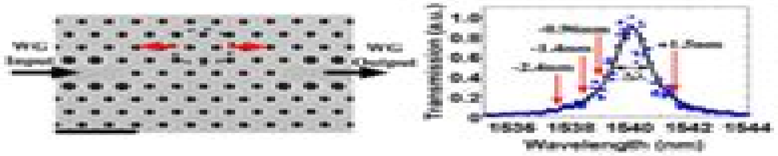

FIG. 1. (Color online) Left: SEM of cavity region. The innermost holes were shifted $s=0.16a$. Scale bar: 1 μm. Right: Cavity resonance with arrows indicating various detuning regions where pump-probe measurements were carried out.

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