Ultimate fast optical switching of a planar microcavity in the telecom wavelength range

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We have studied a GaAs–AlAs planar microcavity with a resonance near 1300 nm in the telecom range by ultrafast pump-probe reflectivity. By the judicious choice of pump frequency, we observe an ultimate fast and reversible decrease in the resonance frequency by more than half a linewidth due to the instantaneous electronic Kerr effect. The switch-on and switch-off of the cavity is only limited by the cavity storage time of $\tau_{cav}=0.3$ ps and not by intrinsic material parameters. Our results pave the way to supraterahertz switching rates for on-chip data modulation and real-time cavity quantum electrodynamics. © *2011 American Institute of Physics*. [doi:10.1063/1.3580615]

Switches are widely applied and necessary ingredients in modulation and computing schemes.[1] The recent progress on photonic integrated circuits[2,3] promises to overtake boundaries set by conventional switching technology. To do so, ultrafast switching of photonic cavities is crucial as it allows the capture or release on demand of photons,[4–6] which is relevant to on-chip communication with light as information carrier,[7] and to high-speed miniature lasers.[8] Ultrafast switching would also permit the quantum electrodynamical manipulation of coupled cavity-emitter systems[9] in real time. Switching the optical properties of photonic nanostructures is achieved by changing the refractive index of the constituent materials. To date, however, the switching speed has been limited by material properties[10–13] but not by optical considerations. To achieve ultimate fast switching of a cavity two challenges arise. First, both the switch-on and switch-off times τ_{on} and τ_{off} must be shorter than all other relevant time scales for the system, i.e., the cavity storage time in photon capture/release experiments τ_{cav}, or the vacuum Rabi period τ_{Rabi} for a strongly coupled emitter-cavity system.[14] Second, the refractive index change must be large enough to switch the cavity resonance by at least half a linewidth.

Here, we demonstrate the ultimate fast switching of the resonance of a planar cavity in the well-known GaAs/AlAs system in the telecom wavelength range. We exploit the instantaneously fast electronic Kerr effect by the judicious tuning of the pump and probe frequencies relative to the semiconductor band gap. We observe that the speed of the switching is then only limited by the dynamics of the light in our cavity ($\tau_{cav}=0.3$ ps), but not by the intrinsic material parameters.

Instantaneous on- and off-switching with vanishing τ_{on} and τ_{off} is feasible with the well-known nonlinear refractive index from nonlinear optics.[15] Physically the electronic Kerr effect is the fastest Kerr phenomenon on account of the small electron mass. In many practical situations, however, nondegenerate two-photon absorption overwhelms any instantaneous effect and therefore also the dispersive electronic Kerr effect.[12,15] In order to avoid two-photon absorption and to access the electronic Kerr switching regime, we designed our experiment to operate with low energy pump photons, see Fig. 1(a). First of all, the energy of the pump photons is chosen below half the semiconductor band gap energy ($E_{pump}<1/2E_{gap}$). Second, the energies of the pump and probe photons are chosen so that their sum does not exceed the band gap energy of the semiconductor ($E_{probe}+E_{pump} \leq E_{gap}$).[16] These conditions serve to suppress instantaneous two-photon generation of free carriers and to perform electronic Kerr switching at elevated frequencies ($E_{probe} > 1/2E_{gap}$), including the telecom band, with a broad range of semiconductors.

We have performed our experiments on a planar microcavity grown by means of molecular-beam epitaxy. The sample consists of a λ-thick GaAs layer (d=376 nm) sandwiched between two Bragg stacks consisting of 7 and 19 pairs of λ/4 thick layers of nominally pure GaAs (d_{GaAs}

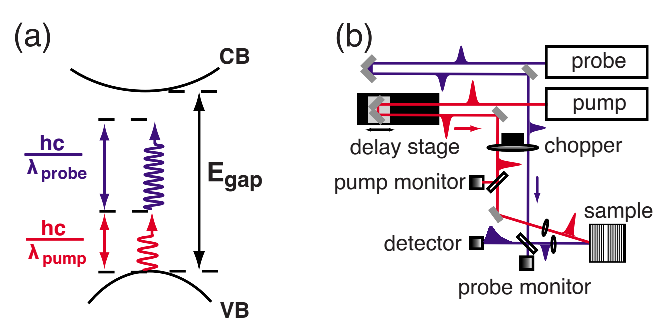

FIG. 1. (Color online) (a) Schematic energy diagram. The frequency of the probe beam is resonant with the cavity. The pump frequency is tuned such that the sum of pump and probe energies are less than the energy gap of GaAs to avoid two-photon absorption. (b) Schematic of the setup. The probe-beam path is shown in dark, the pump-beam path in light color.

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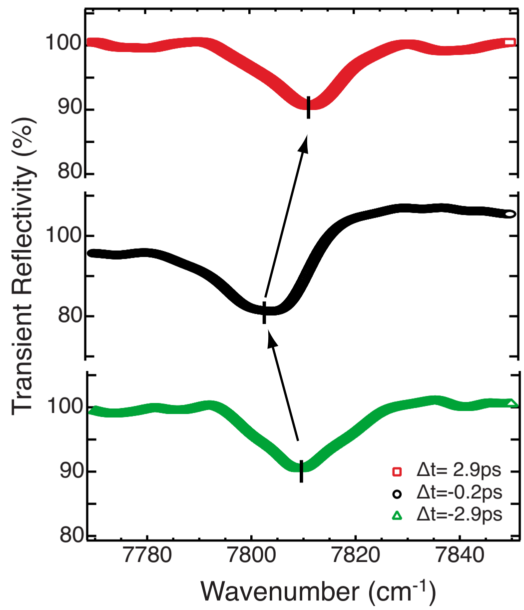

FIG. 2. (Color online) Transient reflectivity vs frequency spectra for three different delay times, $\Delta t = -2.9$ ps (triangles), $\Delta t = -0.2$ ps (circles), and $\Delta t = +2.9$ ps (squares). We observe an ultrafast shift in the cavity resonance (ticks) to lower frequencies and back to its original frequency.

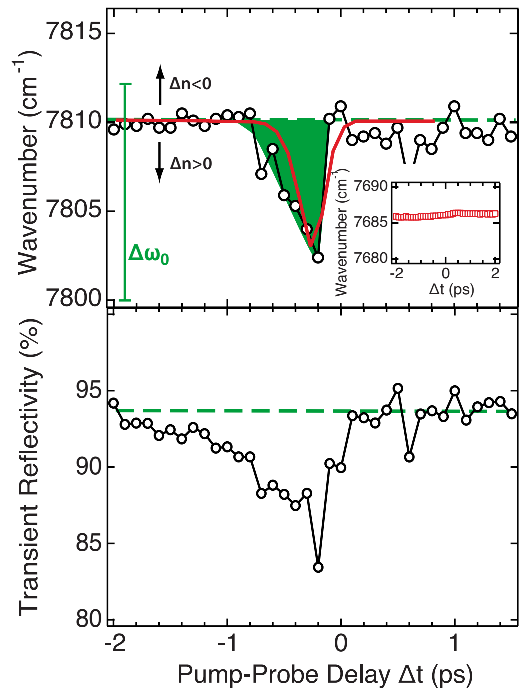

FIG. 3. (Color online) (Upper panel) Measured (open symbols) and modeled (line) resonance frequency vs pump-probe delay. The pump frequency is at 4166 cm^{-1}. The resonance frequency reaches its maximum shift at -0.2 ps and quickly returns to its unswitched value. The model matches the experiment well. The inset shows no switch when the pump frequency is at 5000 cm^{-1} for comparison. (Lower panel) Transient reflectivity vs pump-probe delay at the cold cavity resonance frequency. The transient reflectivity shows similar reversible behavior as the resonance.

$=94$ nm) or AlAs ($d_{AlAs}=110$ nm). The cavity was designed such that the resonance occurs at $\lambda_0=1280$ nm in the Original (O) telecom band. Measuring the linewidth of the cavity resonance we obtained a quality factor $Q=320\pm 30$ corresponding to a cavity storage time of $\tau_{cav}=0.3$ ps.

To perform Kerr-switching on a semiconductor microcavity, we have built a set-up illustrated in Fig. 1(b), consisting of two independently tunable optical parametric amplifiers (OPA, Topas) that are the sources of the pump and probe beams. The pump beam can be tuned down to 4200 cm^{-1} (2400 nm) and the probe beam is tuned to cavity resonance at 7810 cm^{-1} (1280 nm). Under these conditions, we solely pump GaAs (the refractive index change in AlAs is much smaller and can be neglected here). The pump beam has a larger Gaussian focus (75 μm full width at half maximum) than the probe beam (28 μm), to ensure that only the central flat part of the pump focus is probed and that the probed region is homogeneously pumped. The OPAs have pulse durations $\tau_P=0.12\pm 0.01$ ps. The delay Δt between pump and probe pulse is set by a delay stage with a resolution of 0.01 ps. A versatile measurement scheme was developed to compensate for possible pulse-to-pulse variations in the output of our laser.[17]

Figure 2 shows transient reflectivity versus frequency spectra for three different pump-probe delay times. One can see that the cavity resonance redshifts when approaching pump-probe overlap. Afterwards, at positive delay times, the cavity resonance blueshifts back to its original frequency. By modeling the transient reflectivity trough with a Lorentzian, both the resonance frequency ω_0 and the width of the resonance Γ are obtained for every time delay Δt. The unswitched cavity resonance frequency ($\omega_0=7810$ cm^{-1}) and width ($\Gamma=12$ cm^{-1}) are obtained at a delay of $\Delta t=-5$ ps, confirming a cavity quality factor of $Q=320$.

Figure 3(a) shows the switching of the cavity resonance due to the electronic Kerr effect. The resonance frequency as a function of delay near pump and probe coincidence is obtained from spectra similar to those shown in Fig. 2. The dashed horizontal line denotes the unswitched resonance frequency ω_0. The measured resonance frequency shifts to a lower frequency starting at -0.8 ps and reaching its maximum shift at -0.2 ps. Subsequently, the resonance frequency shifts back to its original frequency ω_0. The dynamic frequency shift $\Delta\omega=7$ cm^{-1} clearly exceeds one half of the cold cavity linewidth. We conclude from the shift to a lower frequency that the refractive index is increased by 0.1%, which corresponds to a positive Kerr coefficient for GaAs.[16] To confirm our interpretation we performed calculations with a dynamic Fabry–Pérot model,[18,19] taking solely into account the refractive index change of GaAs due to the electronic Kerr effect. We observe an excellent quantitative agreement between the measured and calculated shifts for the amplitude and the temporal evolution. Our results furthermore demonstrate that our method serves to truly inhibit excitation of free carriers since there is no blueshift of the resonance at $\Delta t>0$ ps. For comparison, the inset shows the result when the pump frequency is increased to 5000 cm^{-1} in the free carrier regime. There is no instantaneous shift in the resonance in the given range as expected; the free-carrier excitation leads to a blueshift after a time of 3 ps.[12] The very good agreement between the calculation and our experimental results firmly confirm the ultimate fast electronic Kerr switching of our photonic microcavity.

Figure 3(b) shows the transient reflectivity of the unswitched resonance frequency as a function of pump-probe delay. The relatively high reflectivity of the trough ($R_{trough}=90\%$) is a result of the asymmetric cavity design. One can see that the transient reflectivity quickly changes from high to low (at pump-probe overlap) and back to high, within 1.5 ps. This decrease is a result of the change in the refractive index of GaAs not only in the cavity but also in the mirrors, which leads to a higher contrast in the Bragg stack.

The shape of the resonance shift in Fig. 3(a) is strikingly asymmetric. The asymmetry is a direct result of the light dynamics in the cavity. In our experiment we are probing the change in the dielectric function $\Delta\varepsilon$ of the material induced by $\mathbf{P}^{(3)}$.[15] The magnitude of the observed frequency shift $\Delta\omega$ is given by the overlap integral of the pump and probe, the latter has been stored in the cavity and subsequently escaped, at a certain delay time Δt,

$$\frac{\Delta\omega(\Delta t)}{\omega_0(0)} = \frac{\Delta\varepsilon(\Delta t)}{\varepsilon(0)} = \frac{\chi^{(3)}}{\varepsilon(0)}\int E(\omega_0, t' - \Delta t)E(\omega_2, t')dt' . \tag{1}$$

Hence, we tomographically sample the probe with the shorter pump. Thus, while scanning Δt, we obtain a shift that follows the cavity envelope. The shift is maximal at -0.2 ps when the cavity field is also maximum.

We have demonstrated for the first time the switching of a semiconductor microcavity at telecom wavelengths using the electronic Kerr effect. Our system also serves as a model system, since the nature of the switch process can be employed in any realization of a semiconductor cavity. We observed that the switching speed is limited by the cavity storage time and not by material properties. The 0.3 ps storage time in our work paves the way to subpicosecond real-time data modulation. Since switching using the electronic Kerr effect is repeatable, on-chip supraterahertz switching rates are feasible. Our results also open an avenue toward ultrafast control of all solid-state cavity quantum electrodynamical systems that exploit the strong coupling regime of quantum wells or quantum dots in optical microcavities.[14]

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Slippery when hot

Phys. Rev. Lett. (in the press)

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When a liquid comes into contact with an object that is significantly hotter than the liquid's boiling point, several unusual effects arise. The rapid evaporation of the liquid at the point of contact forms a layer of gas that insulates it from the solid and slows the rate of subsequent evaporation, compared with the situation in which the solid is only just above the liquid's boiling point. This layer also acts as a cushion beneath a liquid droplet that levitates and allows it to glide almost effortlessly across a hot surface. Such behaviour, known as the Leidenfrost effect, is familiar to anyone who has dropped water into a hot frying pan.

Ivan Vakarelski and colleagues show that similarly dramatic effects occur when a hot steel ball is dropped into a low-boiling-point liquid. At temperatures just above the liquid's boiling point, the ball generates a chaotic stream of gas bubbles. But at around three times the boiling point and above, a smooth continuous layer of gas forms around the ball. This drastically reduces the drag on the ball as it falls through the liquid, more than doubling its terminal velocity when compared with a cold ball.

Far from ideal

Phys. Rev. Lett. (in the press); preprint at http://arxiv.org/abs/1103.2896 (2011)

Compared with all other phase transitions, Bose–Einstein condensation is unique in that it is a purely quantum-statistical phenomenon. Naaman Tammuz and colleagues have now experimentally confirmed the theoretical picture that Albert Einstein used to explain the effect. But they also show that even weak interparticle interaction leads to substantial deviations from the ideal, non-interacting case considered by Einstein.

Einstein's saturation picture is based on the theoretical observation that once the total number of particles in a bosonic system exceeds the critical value of particles that can be accommodated in the excited states, then the addition of any more particles leads to a macroscopic occupation of the ground state — a Bose–Einstein condensate forms.

Such saturation-driven condensation does not require any interaction between the particles. But in experiments there will always be some interaction, even if it is, as in the case of dilute atomic gases, fairly weak. Tammuz *et al.* now demonstrate that with the amount of interaction present in typical ultra-cold gas experiments, the purely statistical picture clearly does not hold. However, measurements at different interaction strengths enabled them to extrapolate to the non-interacting case, where they indeed recovered Einstein's predictions.

A switch in time

Appl. Phys. Lett. **98,** 161114 (2011)

Photonics, using light as a carrier of information much as electrons are used in electronics, promises communication and computation at speeds much higher than current systems. Just as tiny electrical switches — transistors — revolutionized electronics, optical switches are needed for the full implementation of photonic circuits. Georgios Ctistis and colleagues have now developed the fastest optical switch so far.

Optical switches are generally based on effects that change the refractive index of a material. However, the switching speed is limited by the response time of the medium, which is typically much slower than the full potential offered by optical signal processing. Ctistis *et al.* have circumvented this problem and achieved an optical switching time of as little as 0.3 picoseconds using a semiconductor microcavity.

Strong laser pulses change the optical properties of the microcavity and thereby control when probe light at a specific wavelength is transmitted. The key to the advance in speed was to ensure that the sum energy of the control and probe photon was smaller than the semiconductor bandgap. This suppressed two-photon-absorption processes that would otherwise overwhelm the switching effect.

Exoplanets unbound

Nature **473,** 349–352 (2011)

Gravitational lensing — whereby gravity can bend light — was originally proposed by Isaac Newton, although 200 years passed before Albert Einstein correctly calculated the deflection using his theory of general relativity. The foreground 'lens' effectively magnifies the light coming from a background source, and the displaced light can be measured directly by a powerful telescope: it's an effective means of searching for planets. In the case of a Jupiter-sized foreground object, the transient lensing effect lasts a couple of days, and is detectable by the surveys Microlensing Observations in Astrophysics (MOA) and Optical Gravitational Lensing Experiment (OGLE).

Takahiro Sumi and collaborators report the results of both groups in their surveys of the Galactic Bulge within the Milky Way. They found a population of exoplanets that do not seem to be bound to any detectable host stars. MOA detected ten Jupiter-sized exoplanets, of which seven were also observed by OGLE. Their origin is a mystery, although the authors speculate that they may have formed in protoplanetary disks and were subsequently scattered into unbound, or possibly very large, orbits.

From the top

Phys. Rev. D **83,** 091501 (2011)

As Fermilab's Tevatron enters its last months of running and CERN's Large Hadron Collider fires up fully, the baton passes, along with various 'wrinkles' in the experimental data — measurements that don't quite tally with the standard-model predictions but whose statistical significance is not (yet) convincing enough.

Among them is the so-called forward–backward (FB) asymmetry in the production of pairs of top and anti-top quarks: the details of quantum chromodynamics indicate that the spatial distribution of the pairs is not isotropic but subtly distorted. The FB asymmetry measured is larger than expected, and at odds with the standard model by as much as three standard deviations.

Biplob Bhattacherjee and colleagues have investigated what more can be done with Tevatron data to understand this effect, and what the LHC can offer — working instead with a 'one-sided' FB asymmetry, because the LHC has two colliding proton beams, not the proton–antiproton collisions of the Tevatron. It could be possible soon, they say, to decide whether these data indicate the existence of either a Z' or a W' particle, which are possible additions to the standard model.