There is generally a great interest to store photons in a small volume. This feat can be achieved in solid state structures with tiny cavities, with dimensions of the order of the wavelength of light. Light is so strongly confined in such cavities that large electric field enhancements occur. This field enhancement notably leads to large modifications of the emission rate of an elementary light source embedded inside a cavity.\cite{1, 2} It is highly desirable, both from fundamental and applied viewpoints, to switch the optical properties of cavities on ultrafast time scales. This ultrafast switching of cavities will allow the catching or releasing of photons, changing the energy and bandwidth of confined photons, and even the switching-on or -off of light sources, see Refs.\ 3–7. It is therefore important to systematically study the dynamic behavior of switched cavities. Surprisingly, such studies are scarce. Recently, Almeida et al. studied relaxation at two frequencies for a large 10 μm diameter Si ring resonator, revealing decay times of 0.45 ns.\cite{8} Here, we use broadband tunable femtosecond pump-probe reflectivity to study the dynamics of planar thin λ-microcavities made from III-V semiconductors, an important class of solid-state cavities that are notably used in vertical-cavity surface-emitting lasers.\cite{9}

Our sample consists of a GaAs λ-cavity with a thickness of 277 nm. The layer is sandwiched between two Bragg stacks consisting of 12 and 16 pairs of λ/4 thick layers of nominally pure GaAs or AlAs. The sample is grown with molecular beam epitaxy at 550 °C to optimize the optical quality. A slight variation of a few percent in stopgap and linewidths within a few picoseconds. The switching-off occurs with a decay time of ~50 ps. They derive the dynamic behavior of the carrier density and of the complex refractive index. They propose that the inferred 10 GHz switching rate may be tenfold improved by optimized sample growth. © 2007 American Institute of Physics. [DOI: 10.1063/1.2779106]

Our setup consists of two independently tunable optical parametric amplifiers (OPAs) (Topas), that are the sources of the pump and probe beams. The OPAs have pulse durations of τp=140±10 fs corresponding to a spectral width of 1.4%. The pump beam has a much larger Gaussian focus of 113 μm full width at half maximum (FWHM) than the probe beam (28 μm), ensuring that only the central flat part of the pump focus is probed. Free carriers are excited in the GaAs by two-photon absorption at λ=1720 nm, to obtain a spatially homogeneous distribution of carriers.\cite{10} A versatile measurement scheme was developed to subtract the pump background from the probe signal, and to compensate for possible pulse-to-pulse variations in the output of our laser.\cite{12, 13} Continuous-wave (cw) reflectivity was measured with a broadband white light setup with a resolution of ~0.2 nm.

Figure 1 shows a cw reflectivity spectrum of the planar...
width
inance returns to the unswitched case with a time constant
finite switching-on time is due to carrier thermalization, and
resonance quickly shifts to shorter wavelengths. The
due to the recombination of the free carriers.
changes in differential reflectivity have nearly vanished
and thereby blueshift the cavity resonance. After about 50 ps,
thicknesses of the GaAs
Pérot fringes. The only free parameters in the model were the
reproduces the experimental resonance, stopband, and Fabry-
persion and absorption of GaAs
=605. A transfer matrix
color online
blue
of instantaneous probe absorption.
an instantaneous nonlinear process. Figure 2
2
briefly decreases during
the dynamic behavior of the carrier density
with a TM calculation that includes a Drude model to ac-
Drude damping time accounting for
some of probe pulse, which meets the pump on its way back
where it gets absorbed. At pump and probe coincidence,
the differential reflectivity has decreased and reveals a broad
minimum. The decreased reflectivity is attributed to nonde-
generate two-photon absorption, since the sum of the pump and
probe frequency \( E_{\text{tot}} = 1.99 \text{ eV} \) is much above the optical
band gap of GaAs (1.44 eV). At \( \Delta t > 0 \) ps, the differential
reflectivity acquires a dispersive shape, typical for the shift
of a resonance. Until \( \Delta t = 6 \) ps, the amplitude of the disper-
sive differential reflectivity increases in magnitude, due to
the cavity’s resonance shift, indicated by the bars in Fig. 3.
By interpreting the measured differential reflectivity at 6 ps
with a TM calculation that includes a Drude model to ac-
count for the excited carriers, we obtain a carrier density of
\( N = 1.27 \pm 0.2 \times 10^{19} \text{ cm}^{-3} \).20
From the time- and wavelength-resolved data, we obtain
the dynamic behavior of the carrier density \( N \) shown in Fig.
4(a). The Drude model was extended to include electron-
electron (\( e-e \)), electron-hole (\( e-h \)), and electron-phonon
scattering.21 The only free parameter is a correction to the
Drude damping time accounting for \( e-e \) and \( e-h \) scattering,
and was found to be $10^5$ m/s. Absorption due to interband effects appears to be only 1% of the free carrier absorption for our experimental conditions. Using the Drude model before 6 ps is unphysical as the electrons have not yet thermalized. After the maximum density of $N=1.27 \times 10^{19}$ cm$^{-3}$ at $\Delta t=6$ ps, the carrier density decreases with an exponential time constant of 55 ps due to recombination. Thus, the total on-off cycle can be accomplished in about 100 ps, one order of magnitude faster than previously reported.\textsuperscript{8} The maximum switching rates of microcavities may further be tenfold increased\textsuperscript{22} by growing samples with a larger number of recombination centers at the GaAs/AlAs interfaces.

From the free carrier density $N$ and the extended Drude model, we have also calculated the time-dependent real ($n'$) and imaginary ($n''$) parts of the refractive index of the GaAs layers [Figs. 4(b) and 4(c)]. The real part mostly determines the shift of the resonance wavelength, whereas the imaginary part allows one to assess possible changes of the quality factor $Q$ of the cavity. The real part decreases by $n'_{\text{GaAs}}=-0.027\pm0.004$, or 0.8$,\%$, corresponding to a 3.3 linewidth shift. The imaginary part increases to $n''_{\text{GaAs}}=0.8\times10^{-3}$ due to the free carriers, before returning to the unswitched value. From the maximum value of $n''$ at 6 ps, we estimate from a TM calculation that $Q$ has decreased to 220. Useful switching requires the Bragg length $L_B$ to be shorter than the absorption length of either the pump ($l_{\text{hom}}$) or probe ($l_{\text{abs}}$); a natural figure of merit (FOM) is then $(l_{\text{hom}}^{-1}+l_{\text{abs}}^{-1})^{-1}/L_B$. In our case, FOM=22, comparable to Ref. 8 but much larger than Ref. 6, mostly due to their use of linear absorption. Near $\Delta t=0$ fs, the imaginary index is briefly as large as $n''=(1.6\pm0.3)\times10^{-2}$, corresponding to a decrease of $Q$ to 20. Here, $n''$ was obtained by fitting a TM calculation with a complex $n$ to the measured differential reflectivity (Fig. 3), and corresponds to a nondegenerate two-photon absorption coefficient for GaAs of $\beta_{12}=17\pm3$ cm GW$^{-1}$, in agreement with $\beta_{12}=10$ cm GW$^{-1}$ derived from Ref. 23. While this period of relatively high absorption lasts rather briefly, it is recommended to keep the sum of the probe and pump frequencies below the optical band gap of the constituent materials or to reduce the probe and pump fluences (see below).

In summary, we present unprecedented wavelength-resolved dynamic behavior of a cavity resonance, with femtosecond resolution. Our experiments were optimized for spatially homogeneous switching by two-photon excitation to facilitate a physical interpretation of the free carrier effects with an extended Drude model. Considerably lower switching powers useful for future applications can be realized by improving four features. (1) Using a much smaller pump focus, a reduction in pump energy by a factor of $\sim 700$ can easily be achieved. (2) Using one-photon absorption near the band gap of GaAs leads to a 100-fold reduced pump energy. Besides, it has been predicted that a lower spatial homogeneity may be favorable.\textsuperscript{5} (3) Relaxing the shift of the cavity to only one linewidth reduces the pump power by another factor of 3. (4) Since the required pump energy scales inversely with $Q$, feasible cavities with $Q\sim50$ 000 (Ref. 24)

will reduce the pump power by two orders of magnitude at the expense of the same reduction in switching rate. Therefore, these simple considerations already amount to a reduction of the pulse energies by a factor of more than $2 \times 10^7$ to fJ, within reach of on-chip light sources such as diode lasers.

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\textsuperscript{10}The maximum unBroadened refractive index change of the dots amounts to only $10^{-4}$, while the absorption at resonance is less than 0.02 cm$^{-1}$.
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\textsuperscript{18}We have derived the wavelength of the cavity resonance by using the identity

$$\frac{d(\Delta R/R)}{dx} = \frac{1}{R_0(\lambda)} \left( R_0(\lambda) \frac{dR(\Delta\lambda)}{d\lambda} - R(\Delta\lambda) \frac{dR_0(\lambda)}{d\lambda} \right),$$

where $R_0(\lambda)$ is the unswitched reflectivity, and $R(\Delta\lambda)$ is the switched reflectivity at delay $\Delta t$. Setting $dR(\Delta\lambda)/d\lambda=0$, which is the necessary extremal condition for the cavity resonance, we obtain

$$0 = \frac{d(\Delta R(\Delta\lambda)/R_0(\lambda))}{d\lambda} + R(\Delta\lambda) \frac{dR_0(\lambda)}{d\lambda}. $$

Thus, the dynamic resonance wavelength is completely determined by the experimental data.

\textsuperscript{20}From this density we infer a degenerate absorption coefficient of $\beta=0.53\pm0.11$ cm GW$^{-1}$.