

Ultrafast all-optical switching of 3D photonic band gap crystals.

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ABSTRACT

We present ultrafast optical switching experiments on 3D photonic band gap crystals. Switching the Si inverse opal is achieved by optically exciting free carriers by a two-photon process. We probe reflectivity in the frequency range of second order Bragg diffraction where the photonic band gap is predicted. We observe a large frequency shift of up to 1.5% of all spectral features including the peak that corresponds to the photonic band gap. We also demonstrate large, ultrafast shifts of stop bands of planar GaAs/AlAs photonic structures. We briefly discuss how our results can be used in future switching and modulation applications.

Keywords: photonic crystals, all-optical, switching, ultrafast, band gap, silicon, GaAs.

1. ULTRAFAST SWITCHING EXPERIMENTS

Currently, many efforts are devoted to a novel class of three-dimensional meta-materials known as photonic crystals [1]. Spatially periodic variations of the refractive index commensurate with optical wavelengths cause the photon dispersion relations to organize in bands, analogous to electron bands in solids. Generally, frequency windows known as stop gaps appear in which modes are forbidden for specific wave vectors. Experimentally, stop gaps appear as peaks in reflectivity spectra. The strong dispersion in photonic crystals can be used to control the propagation direction of light. Fundamental interest in 3D photonic crystals is spurred by the possibility of a photonic band gap, a frequency range for which no modes exist at all [2].

Exciting prospects arise when photonic band gap crystals are switched on ultrafast timescales. In particular, switching photonic band gap crystals provides dynamic control over the density of states that would allow the switching-on or -off of light sources in the band gap [3]. Furthermore, switching would allow the capture or release of photons from photonic band gap cavities [3]. Switching the directional properties of photonic crystals also leads to fast changes in the reflectivity, where interesting changes have been reported for Bragg stacks [4, 5], 2D photonic crystals [6, 7], and first-order stop bands of 3D opaline crystals [8, 9]. Ultrafast control of the propagation of light is essential to applications in active photonic integrated circuits [10].

In this article we study ultrafast switching of inverse opal photonic band gap crystals. The crystals have a sufficiently large refractive index contrast for a band gap to open up in the range of second order Bragg diffraction, while in the range of first order Bragg diffraction a pseudo gap occurs. In the region of the band gap, switching is expected to lead to ultrafast changes in the density of states.

2. ULTRAFAST SWITCHING OF SI INVERSE OPALS

Fig. 1 shows an SEM image of a 3D photonic crystal: a Si inverse opal with lattice parameter $a = 1427 \pm 20$ nm, fabricated by chemical vapor deposition of crystalline Si in an on-chip thin film opal [11,12].

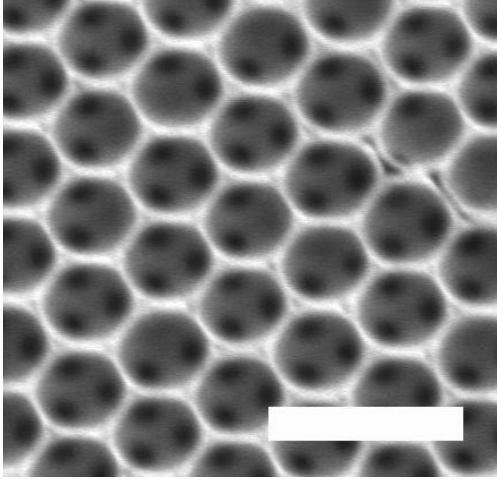


Fig. 1. High resolution SEM image of the Si inverse opal. [111] plane of a silicon inverse opal with lattice parameter $a = 1427 \pm 20$ nm. The scale bar is 2 μm [12].

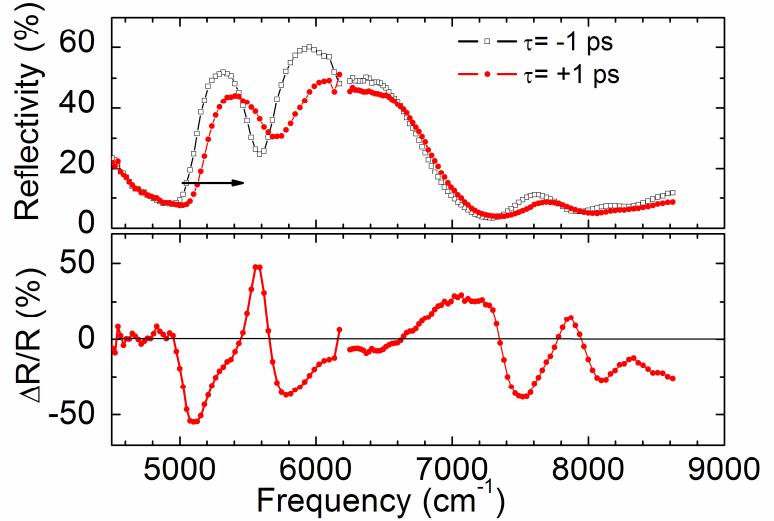


Fig. 2. (upper panel) Unswitched (open squares) and switched (closed circles) reflectivity spectra of the sample at normal incidence measured with our broadband tunable laser. In experiments on the red part of the spectrum ($\omega_{\text{probe}} < 6250$ cm^{-1}), the pump frequency was chosen to be ($\omega_{\text{pump}} = 6450$ cm^{-1}). In experiments on the blue edge ($\omega_{\text{probe}} > 6250$ cm^{-1}), the pump frequency was reduced to $\omega_{\text{pump}} = 5000$ cm^{-1} . The pump irradiance for the switched spectrum was $I_0 = 11 \pm 2$ GWcm^{-2} on the red part and $I_0 = 24 \pm 2$ GWcm^{-2} on the blue part of the stop band. The switched spectra were measured at a pump-probe time delay of ≈ 1 ps. We observe a large blue shift of up to 1.5% of the complete stop band in the range of second order Bragg diffraction as well as of features outside the stop band. (lower panel) Differential reflectivity spectrum. A blue shift of the peak at $\omega = 5320$ cm^{-1} is illustrated by strong decreases and increases of the reflectivity below and above this frequency respectively. Similar dispersive curves are centered at frequencies of 5960, 6450, and 7600 cm^{-1} .

The crystal was pumped by two-photon absorption to maximize the spatial homogeneity of the excited carriers [13]. The probe frequency was scanned over a broad frequency range. Fig. 2 (top panel) shows the observed large blue shift of the second order stop band around $\omega = 6000$ cm^{-1} , at various pump irradiances. The reflectivity peak centered around $\omega = 5800$ cm^{-1} corresponds to the predicted band gap position.

Large dispersive variations in reflectivity are observed in the range of second order Bragg diffraction (Fig. 2, lower panel). During the switching process, all spectral features in the observed stop bands, shift towards higher frequencies by as much as $\Delta\omega/\omega > 1.5\%$ within a few hundred fs, indicating the absence of separate dielectric and air bands in our crystal. We have thus demonstrated the first switching of a 3D photonic band gap crystal [14]. From a comparison to quasi-static band structure calculations of Ref. [3] we infer a large refractive index change of about $\Delta n/n = 2\%$. The deduced refractive index change is predicted to strongly modify the density of states inside the crystal [15].

3. SWITCHING OF PLANAR GaAs/AlAs PHOTONIC STRUCTURES

In Fig. 3, we present time resolved reflectivity measurements that demonstrate a large and ultrafast change in the stop gap reflectivity of a GaAs/AlAs photonic structure, induced by selectively pumping the GaAs layers by two-photon absorption. We observe both large decreases up to $\Delta R > 40\%$ as well as large increases up to $\Delta R > 8\%$ in the reflectivity.

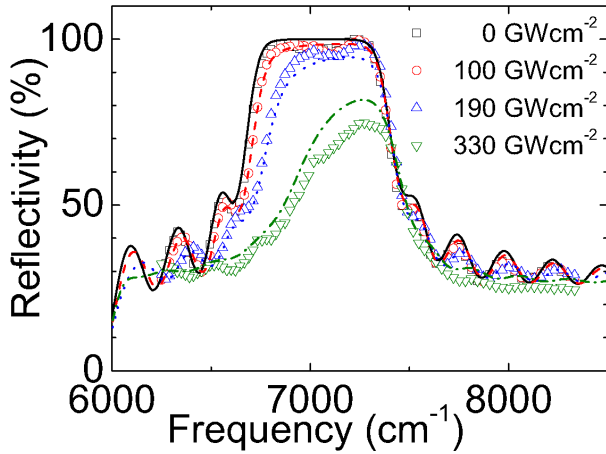


Fig. 3. Ultrafast switching of the first order stop band reflectivity of large GaAs-AlAs multilayer structures (25 pairs). We use spatially homogeneous two-photon absorption at $\lambda_{\text{pump}} = 1720$ nm, and vary the pump irradiance is varied from 0 to 330 ± 30 GWcm^{-2} . The absolute reflectivity measurements (symbols) show both large absolute reflectivity decreases up to $\Delta R > 40\%$ on the red edge of the stop band as well as large increases of up to $\Delta R > 8\%$ on the blue edge of the stop band. Switched spectra were measured at a fixed probe delay $\tau = 4$ ps. The curves are transfer matrix calculations that take into account both the nonlinear absorption of pump light, as well as the Drude model for the GaAs layers.

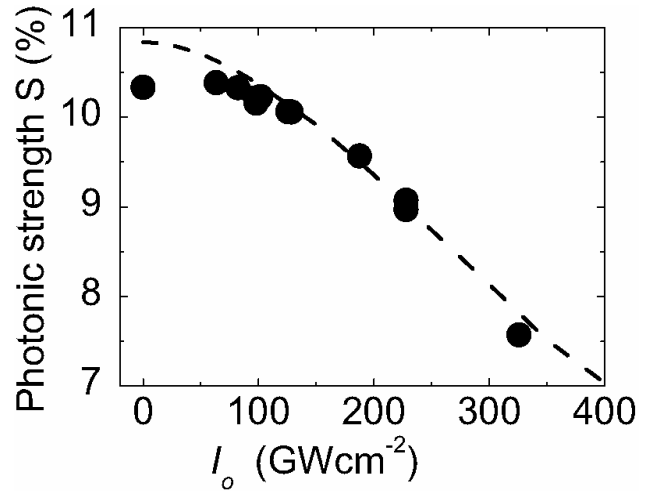


Fig. 4. The photonic interaction strength S , which is proportional to the relative stop band width, as a function of pump irradiance. The data were obtained from both the measured spectra (symbols) and modeled spectra (curves) and are plotted versus pump irradiance. The observed large decrease of the stop band width with increasing pump irradiance, indicates a strongly reduced photonic strength S of the structure, caused by the reduced refractive index contrast. We find good agreement for pump irradiance up to 300 ± 30 GWcm^{-2} .

The curves in Fig. 3 represent transfer matrix calculations that take into account both the nonlinear absorption of pump light, as well as the Drude model for free carriers. We find good agreement for a two-photon absorption coefficient $\beta = 0.89$ cmGW^{-1} , which is slightly smaller than the value for bulk GaAs $\beta = 1.5 \pm 0.5$ cmGW^{-1} that we obtained by a z-scan measurement. From our model, we obtain a large maximum refractive index change of $\Delta n'/n' = 2.9\%$ in the first GaAs layer for a pump irradiance of 330 GWcm^{-2} and a probe frequency $\omega = 7000$ cm^{-1} . The corresponding change in the 25th GaAs layer of the switched structure is still $\Delta n'/n' = 2.6\%$, indicating excellent spatial homogeneity of the excited free carriers.

In Fig. 4, the photonic strength S , which is proportional to the stop band width, was obtained from both the measured spectra (symbols) as well as from the modeled spectra (curves) and is plotted versus pump irradiance. The photonic strength decreases with increasing pump irradiance, consistent with the lowered refractive index contrast in the structure. We find good agreement for pump irradiances up to 300 GWcm^{-2} . For even higher pump irradiances additional nonlinear effects in the AlAs layers must also be taken into account.

We have recently also studied the ultrafast switching-on and -off of planar GaAs/AlAs microcavities [16], in which switching is achieved by optically exciting free carriers resulting in 0.8% refractive index changes. The cavity resonance is dynamically tracked by measuring reflectivity versus time delay with tunable laser pulses. The cavity resonance shifts by as much as 3.3 linewidths within a few ps.

4. CONCLUSION

Since we have studied semiconductor photonic crystals that operate near the telecom frequency range, it is interesting to consider the applicability of ultrafast all-optical switching. Importantly, the pulse energy should be considerably reduced. This is feasible for devices such as modulators wherein a cavity resonance with quality factor Q is switched by one linewidth. Then, a small refractive index change $\Delta n'/n' = 1/Q$ suffices. Furthermore, for cavities, switching homogeneity is not important, which considerably relaxes our requirements. Therefore, we conclude that ultrafast photonic crystal switching also opens exciting opportunities in device applications.

REFERENCES

1. 'Photonic Crystals and Light Localization in the 21 Century', Ed. C.M. Soukoulis (Kluwer, Dordrecht, 2001).
2. E. Yablonovitch, *Phys. Rev. Lett.* **58**, 2059 (1987).
3. P. M. Johnson, A. F. Koenderink, and W. L. Vos, *Phys. Rev. B.* **66**, 081102(R) (2002).
4. A. Haché and M. Bourgeois, *Appl. Phys. Lett.* **77**, 4089 (2000).
5. S. R. Hastings, M. J. A. de Dood, H. Kim, W. Marshall, H. S. Eisenberg, and D. Bouwmeester, *Appl. Phys. Lett.* **86**, 031109 (2005).
6. S.W. Leonard, H.M. van Driel, J. Schilling, and R.B. Wehrspohn, *Phys. Rev. B* **66**, 161102(R) (2002).
7. A. D. Bristow, J. P. R. Wells, W. H. Fan, A. M. Fox, M. S. Skolnick, D. M. Whittaker, A. Tahraoui, T. F. Krauss, and J. S. Roberts, *Appl. Phys. Lett.* **83**, 851 (2003).
8. D. A. Mazurenko, R. Kerst, J. I. Dijkhuis, A. V. Akimov, V. G. Golubev, D. A. Kurdyukov, A. B. Pevtsov, and A. V. Sel'Kin, *Phys. Rev. Lett.* **91**, 213903 (2003).
9. C. Becker, S. Linden, G. von Freymann, M. Wegener, N. Tétreault, E. Vekris, V. Kitaev, and G. A. Ozin, *Appl. Phys. Lett.* **87**, 091111 (2005).
10. H. Nakamura, Y. Sugimoto, K. Kanamoto, N. Ikeda, Y. Tanaka, Y. Nakamura, S. Ohkouchi, Y. Watanabe, K. Inoue, H. Ishikawa and K. Asakawa, *Opt. Express* **12**, 6606 (2004).
11. Y. A. Vlasov, X.-Z. Bo, J.C. Sturm, and D. J. Norris, *Nature* **414**, 289-293 (2001).
12. J. Kalkman, E. de Bres, A. Polman, Y. Jun, D. J. Norris, D. C. 't Hart, J. P. Hoogenboom, and A. van Blaaderen, *J. Appl. Phys.* **95**, 2297 (2004).
13. T. G. Euser and W. L. Vos, *J. Appl. Phys.* **97**, 043102 (2005).
14. T. G. Euser, H. Wei, J. Kalkman, Y. Jun, A. Polman, D. J. Norris, and W. L. Vos, <http://arxiv.org/abs/0705.4250>; *J. Appl. Phys.* (accepted, 2007).
15. T. G. Euser, 'Ultrafast optical switching of photonic crystals', ISBN 90-978-90-365-2470-1, University of Twente (2007).
16. P. J. Harding, T. G. Euser, Y. Nowicki-Bringuier, J. M. Gérard, W. L. Vos, <http://arxiv.org/abs/0706.2385>.