Criterion for Removing a Delayed Peak from the Ultrafast Nonlinear Response of Photonic Crystal / Quantum Dot Waveguides

Ferran Salleras, Masanori Honma, Jun Sakaguchi, Yoshiyasu Ueno
Dept. of Electronic Engineering, University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, 182-8585, Japan, Tel:+81-424-43-5207, Fax: +81-424-43-5207
salleras@ultrafast.ee.uec.ac.jp
Nobuhiko Ozaki, Yoshinori Kitagawa, Kiyoshi Asakawa
Center for Tsukuba Advanced Research Alliance (TARA), University of Tsukuba, 1-1-1, Tennoudai, Tsukuba, 305-8577, Japan
Naoki Ikeda, Yoshimasa Sugimoto
National Institute for Materials Science (NIMS), 1-2-1, Sengen, Tsukuba 305-0047, Japan

Abstract: Two photon absorption accompanied by a 25-ps-delayed nonlinear response was observed in nonlinear photonic crystal/quantum dot waveguides. Criterion for preventing such a delay time is studied for applications in ultrafast all-optical gates.

OCIS codes: (230.1150) All-optical devices, (320.7080) Ultrafast devices, (320.7110) Ultrafast nonlinear optics, (190.4720) Optical nonlinearity of condensed matter, (320.7130) Ultrafast processes in condensed matter, including semiconductors.

1. Introduction

One of the key elements in future photonic networks will be all-optical switches forming the basis for more advanced optical components such as add/drop multiplexers, demultiplexers, logic gates and optical memories.

In this direction and benefiting from the progress in nano-technology growth and fabrication, two-dimensional photonic crystal (2D-PC) straight waveguides and symmetric Mach-Zehnder (SMZ) structures with embedded quantum dots (QDs) as passive optical nonlinear media have been recently demonstrated by Nakamura et al. [1]. The SMZ all-optical switch operating in a push-pull configuration [2] is capable of ultrafast switching speed (25ps) with low pump energy (100fJ/pulse) due to the joint effect of PC (high confinement factor and slow light) and QDs (low saturation energy due to the high density of states). The pump pulse leads to the absorption saturation of the QD by resonantly filling the ground state of the QDs, which in turn produces a change in refractive index (i.e. a phase shift).

The study of the QD carrier dynamics in these PC/QD structures through time-resolved pump and probe transmission experiments provides useful information on their operating conditions.

2. PC/QD waveguide description

The PC/QD straight waveguides under study [1] are composed of air-bridge 2DPC slabs with a single missing line in a triangular lattice (lattice constant, a=348nm) of air holes (radius, r=110nm). A 250nm thick GaAs core layer with four stacked layers of InAs QDs is grown on top of a 2μm-thick $Al_{0.6}Ga_{0.4}As$ sacrificial clad layer on a GaAs substrate by molecular beam epitaxy. Input and output ports consist of solid-immersion-lens structures plus tapers, with about 10dB coupling loss per facet. The QDs are formed in Stranski-Krastanov mode growth by a two step growth technique. The QD sheet density of each layer is 4×10^{10} cm^{-2}. The peak wavelength and the full width at half maximum (FWHM) of the QDs in the measured photoluminescence spectrum is 1290nm and 30meV, respectively. Air-bridge structures are fabricated using high resolution electron-beam lithography, dry etching and selective wet-etching techniques. They are cleaved to lengths of 500μm. Using this technique, the propagation loss is reduced to 0.76dB/mm (for a waveguide without QDs)[3]

3. Experimental results

In order to study the ultrafast absorption QDs dynamics, we put in place a two-color subpicosecond pump and probe set up. A Ti: sapphire laser at 80MHz repetition rate and 300fs pulses is pumping an optical parametric oscillator (OPO). The OPO signal is then split in a polarizing beam splitter. The first beam is input into a 20cm-long single mode fiber (SMF) by means of a microscope objective lens and undergoes strong self phase modulation causing a broadened super-continuum (SC) spectrum at the output of the SMF. The probe beam is then selected by slicing the SC with band pass filters centered at the desired wavelength (from 1300nm to 1340nm, FWHM=10nm) with a temporal pulsewidth of about 400fs. The second beam after the polarizing beam splitter, i.e. the pump beam, is directed to a retroreflector mounted on a delay stage, enabling us to change the temporal delay between pump and probe and therefore to study the absorption dynamics as a function of pump power and spectral detuning between pump and probe beams. Both beams are then made collinear in a beam splitter and injected into and collected from the PC/QD waveguide by means of polarization maintaining lensed fibers (pump and probe are TE-polarized) and high precision translation stages. Detection is carried out with a lock-in amplifier plus chopper scheme.

Figure 1 shows the spectral transmission of the PC/QD waveguide with a transmission window of around 60nm and the maximum QD ground state absorption at 1290nm. The first excited state (not shown) is found at 1190nm (80meV above the ground state), suggesting a large energy confinement in the QDs.

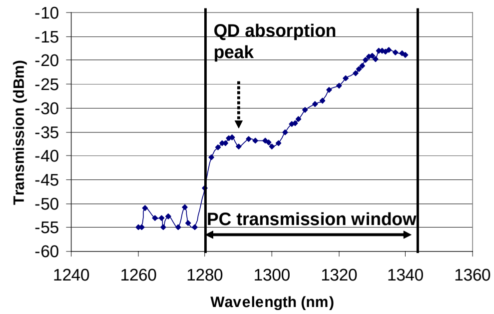
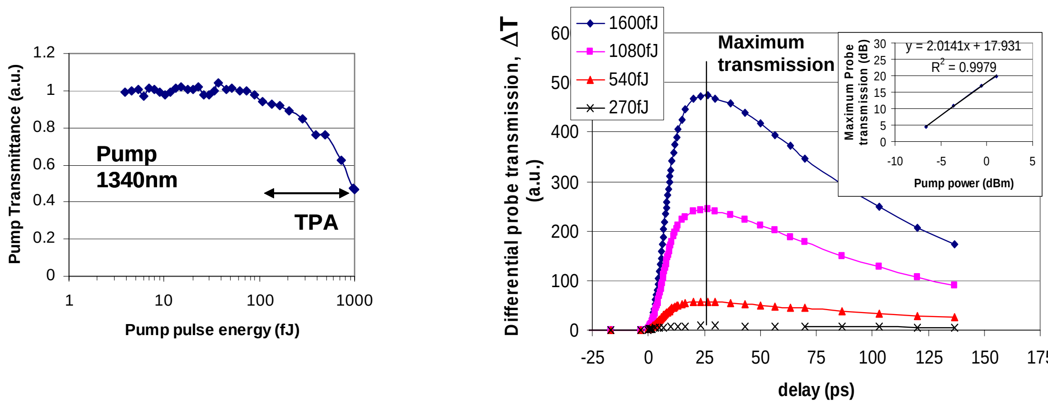


Fig. 1. Spectral transmission of the Photonic Crystal/Quantum dot waveguide

We performed pump and probe (P&P) transmission experiments for two different pump wavelengths. First, to investigate the effects of a pure two photon absorption (TPA) saturation [4], we set the pump wavelength to 1340nm, non-resonant to QD absorption but within the PC transmission bandwidth (Fig. 1). The second set of measurements had a pump wavelength of 1290nm (resonant to QD absorption peak) to allow us the observation of saturation effects from one (resonant) photon absorption.

Figure 2 (a) shows the normalized pump transmittance as a function of input pulse energy for a pump wavelength of 1340nm. The flat transmittance at low pulse energies confirms that there is no effect of absorption saturation since the pump is redshifted (non-resonant) with respect to QD absorption. The transmittance decrease for higher pulse energies is attributed to TPA. Keeping that in mind, we can analyze Fig. 2 (b), displaying probe transmission (probe at 1300nm, 1.25fJ) as a function of the delay between pump and probe pulses for different pump pulse energies. TPA generates high-energy photocarriers which are captured into the QDs with a characteristic time (appearing as a rise time in the probe transmission of 25ps), filling up the ground state and leading to the probe transmission increase depicted in Fig. 2 (b). The inset of Fig. 2 (b) displays the maximum probe transmission (in dB) as a function of the input power (in dBm) together with a linear fit showing a slope of 2, confirming the quadratic dependence of probe transmission on pump power due to its TPA origin. The carrier capture mechanism from higher energy levels (GaAs barriers, wetting layer) to the ground state, either using the excited state as an intermediate state or directly through the continuum background [5], will be investigated shortly by resonantly probing the excited state while pumping the ground state.

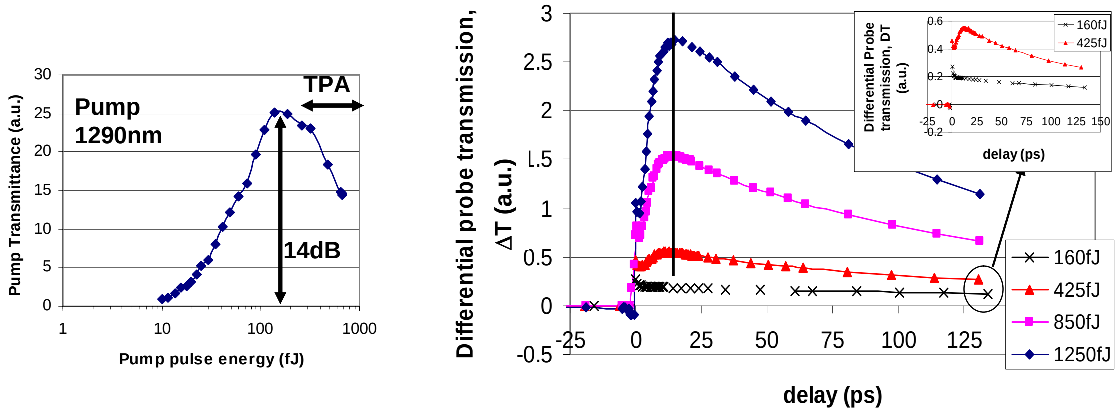


(a) (b)

Fig. 2. (a) 1340nm pump transmittance as a function of pump pulse energy. (b) Probe (1300nm, 1.25 fJ) differential transmission as a function of delay time for pump at 1340nm and various pump energies (1600fJ, 1080fJ, 540fJ, 270fJ). Inset: maximum probe transmission as a function of pump power

Next we shall discuss the effect of setting the pump at 1290nm, resonant to QDs ground state. Figure 3 (a) shows pump transmittance as a function of the input pump pulse energy. We observe a large saturation of the QDs leading to a large increase in pump transmittance (up to 14dB) followed by a decrease attributed to TPA. The effects of pump pulses on probe transmission (1310nm, 1.25fJ) can be observed in Fig. 3 (b). For the lowest pump pulse energy (160fJ, see figure inset for details), we see an instantaneous increase in probe transmission (P&P spectral overlapping and homogeneous broadening), followed by an absorption recovery with two different times scales of about 1ps and 200ps, attributed to hole and electron escape from the ground state, respectively [6,7]. As we increase pulse energy to 425fJ, TPA effects become significant (Fig. 3 (a)). Probe transmission shows the same instantaneous increase followed by a second transmission peak at about 12ps after pump arrival (Fig. 3 (b)), which we ascribe to TPA. We can then extrapolate a threshold value of about 200-300fJ of pump pulse energy (i.e. pump peak power about 0.7-1W) for the onset of TPA. We also observe a difference in the rise time for pump at 1290nm (12ps) and pump at 1340nm (25ps) which may be due to the slow light effect when light approaches the edge of PC transmission window for longer wavelengths.

For larger pump pulse energies, the TPA contribution becomes dominant, accounting for more than half of the total absorption bleaching for pump pulse energies of 850fJ (12.5dB) and 1.25pJ (15.2dB), with absorption recovery times of 135 and 130ps respectively. The relatively long absorption recovery may be explained by the large energy separation between ground state and excited state (high dot confinement), preventing efficient electron thermal activation to excited state.



(a) (b)

Fig. 3. (a) 1290nm pump transmittance as a function of pump power. (b) Probe (1310nm, 1.25 fJ) transmission as a function of delay time for pump at 1290nm and various pump pulse energies. Inset: detailed transmission for 160 fJ and 425 fJ pump pulse energies

4. Conclusion

In our nonlinear PC/QD waveguides, we observe TPA for pump pulse energy above 200-300fJ (i.e. peak power above 0.7-1W). In addition to TPA, a 25-ps-delayed nonlinear response peak is observed when the pump pulse wavelength is set near the PC band edge.

We speculate that the TPA and the 25-ps-delayed peak are caused by a combination of (1) strong optical confinement in the PC structure, (2) relaxation time of the TPA-induced electrons and holes, and (3) the slow-light effect near the PC band edge.

These results indicate that the pump power should be kept below the TPA threshold to prevent such a delayed nonlinear response in the PC/QD waveguides.

5. References

[1] H. Nakamura et al., “Ultra-fast photonic crystal/quantum dot all-optical switch for future photonic networks,” Optics Express **12** (76), pp. 6606-6614 (2004)

[2] K. Tajima, “All-optical switch with switch-off time unrestricted by carrier lifetime,” Jpn. J. Appl. Phys. **32**, pp. L1746-L1749 (1993)

[3] Y. Sugimoto et al., “Low propagation loss of 0.76dB/mm in GaAs-based single-line-defect two-dimensional photonic crystal slab waveguides up to 1cm in length,” Opt. Express **12**, pp. 1090 (2004)

[4] H. Nakamura et al., “Nonlinear optical phase shift in InAs quantum dots measured by a unique two-color pump/probe ellipsometric polarization analysis,” J. Appl. Phys. **96** (3), pp. 1425-1434 (2004)

[5] E.W. Bogaart et al., “Carrier capture and relaxation through continuum background in InAs quantum dots,” Physica E 32, pp. 163-167 (2006)

[6] J. Inoue et al., “Characterization of highly stacked InAs quantum dot layers on InP substrate for a planar saturable absorber at 1.5um band,” Phys. Stat. Sol. (c) **3** (3), pp. 520-523 (2006)

[7] P. Borri et al., “Ultrafast carrier dynamics and dephasing in InAs quantum-dot amplifiers emitting near 1.3-µm-wavelength at room temperature,” Appl. Phys. Lett. **79** (16), pp 2633-2635 (2001)