Response characterization of integrated nano-structured semiconductor waveguides aiming at 40-Gb/s optical memories

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ABSTRACT

Two-dimensional photonic crystal nano-structures with embedded quantum dots are candidates for all-optical switches due to their ultrafast switching times and low energy operation. Using a two-color sub-picosecond pump and probe set up, we measured the dynamic response of such structures as a function of pump pulse energy and wavelength. We observed the onset of two photon absorption for pump pulse energy above 200-300fJ, whose temporal signature is a delayed response. Such a delayed response is to be avoided in ultrafast telecommunication applications.

1. INTRODUCTION

The present optical telecommunication systems are limited to a bit rate at 40Gb/s by their electronic parts. To circumvent this limitation, all-optical devices are actively studied because they have better characteristics than their electronic counterparts in terms of energy consumption, size and operating speed. That is, all-optical switches will be one of the key elements in future photonic networks as building blocks for more advanced optical components such as add/drop multiplexers, demultiplexers, logic gates and optical memories.

Due to the recent progress in nano-technology growth and fabrication, GaAs-based two-dimensional photonic crystal (2D-PC) straight waveguides (ST-WGs) and Symmetric Mach-Zehnder (SMZ) structures with embedded InAs-based quantum dots (QDs) as passive optical nonlinear media are attracting attention as promising novel all-optical devices for ultrafast and ultralow-energy operation in photonic integrated circuits, e.g. PC flip-flop memory (PC-FF) [1]. Recently, it has been reported [2] that PC/QD-SMZ all-optical switch operating in a push-pull configuration [3] is capable of ultrafast switching speed (25ps) with low pump pulse energy (100fJ) due to the joint effect of PC (high confinement factor and slow light) and QD (low saturation energy due to the high density of states). The pump pulse produces the absorption saturation of the QDs by resonantly filling the ground state (GS). The study of QD dynamics in these PC/QD structures through time-resolved pump and probe transmission experiments provides useful information on their operating conditions that can aid at improving their designs.

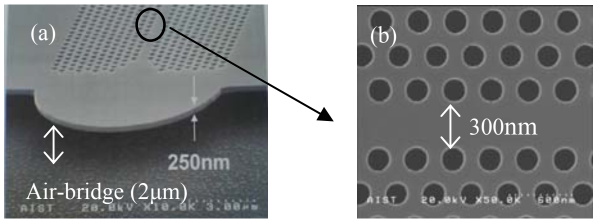

Fig. 1: Scanning electron microscope (SEM) images of PC/QD waveguide. (a) Input/output port area with solid-immersion-lens plus taper. (b) A single missing line of air hole. (from TARA)

We have measured QD dynamics in PC/QD ST-WGs as a function of pump pulse energy and wavelength, observing a delayed transmission peak related to the onset of TPA for pump pulse energy above 200-300fJ.

2. PC/QD WAVEGUIDE DESCRIPTION

PC/QD ST-WGs under study [2] were composed of air-bridge 2D-PC slabs with a single missing line in a triangular lattice (lattice constant, a=348nm) of air hole (radius, r=110nm). A 250nm thick GaAs core layer with 4 stacked layers of InAs QDs were 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 (MBE). Input and output ports consist of solid-immersion-lens structures plus tapers, with about 10dB coupling loss per facet (Fig. 1). The QDs were formed in Stranski-Krastanov mode growth technique. The QD sheet density of each layer was 4×10^{10} cm^{-2}. The peak wavelength and the full-width at half-maximum (FWHM) of the QDs in the measured photo-luminescence (PL) spectrum were 1290nm and 30meV, respectively. Air-bridge structures were fabricated using high resolution electron-beam (EB) lithography, dry etching and selective wet-etching techniques. They were cleaved to lengths of 500μm. Using this technique, the propagation loss was reduced to 0.76dB/mm (for a waveguide without QDs) [4].

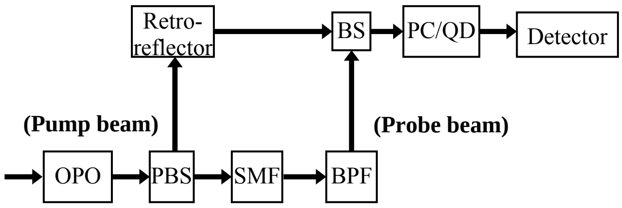

Fig. 2: Schematic of experimental setup

3. EXPERIMENTAL SETUP

We study the ultrafast absorption dynamics in QDs using a two-color sub-picosecond pump and probe set up (Fig. 2). 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 (PBS). The first beam after the PBS, i.e. the probe 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 the SMF. The probe beam is then selected by slicing the SC with band-pass filters (BPFs) centered at the desired wavelength (from 1300 to 1340nm, 3dB bandwidth=10nm) with a temporal pulsewidth of about 400fs. The second beam, i.e. the pump beam, is kept at the OPO signal wavelength, and directed to a retroreflector mounted on a delay stage, enabling us to change the temporal delay between pump and probe. Therefore, we can 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 (BS) and injected into and collected from the PC/QD ST-WG by means of polarization maintaining lensed fibers (pump and probe are TE-polarized) and high precision translation stages. Detection is using a lock-in amplifier plus chopper scheme.

4. RESULTS

Figure 3 shows the spectral transmission of the PC/QD waveguide with a transmission window of about 60nm and the maximum QD GS absorption at 1290nm. The first excited state (ES) is not shown in this figure but PL spectra show that it is found at 1190nm (80meV above the GS), suggesting a large energy confinement in the QDs.

We measured pump and probe transmission experiments for two different pump wavelengths at 1290nm and 1340nm. One is to allow us the observation of saturation effects from resonant photon absorption, the other is to investigate the effects of two photon absorption (TPA).

Figure 4 (a) shows pump transmittance as a function of input pump pulse energy for 1290nm (resonant to QD absorption peak). We observed that pump transmittance is increasing below ~200fJ/pulse due to QD absorption saturation and decreasing above ~200fJ/pulse due to the onset of TPA. Fig. 4 (b) shows QD absorption dynamics as a function of delay time between pump (1290nm) and probe (1310nm) for different pump pulse energies. We can see an instantaneous rising in probe transmission immediately after zero delay position (pump resonantly filling the QD

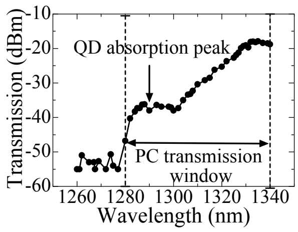

Fig. 3: Spectral transmission of PC/QD waveguide

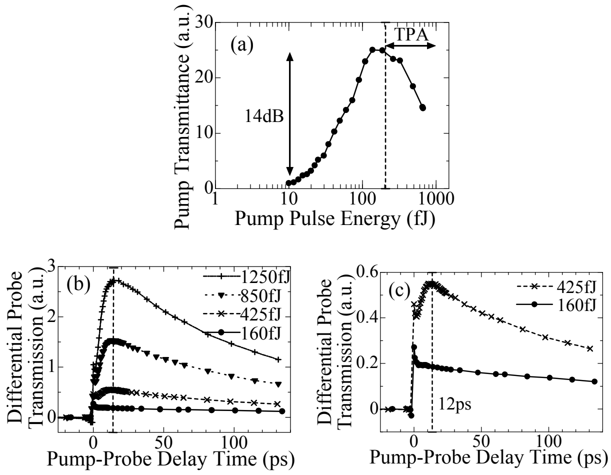

Fig. 4: (a) Pump (1290nm) transmittance as a function of pump pulse energy and the onset of TPA at ~200fJ. (b) Probe (1310nm, 1.25fJ) transmission as a function of delay time between pump and probe for different pump (1290nm) pulse energies. (c) Magnification of two pump pulse energies (160fJ and 425fJ). The 12ps-delayed peak is attributed to TPA.

GS). For the lowest pump energy (Fig. 4 (c), 160fJ/pulse curve), absorption recovery has two different time scales of ~3ps and ~200ps, attributed to carrier escape from the GS to the ES by nonradiative recombinations (thermal radiation and Auger effect) and spontaneous emission, respectively [5]-[7]. As for pump energies above 425fJ/pulse, probe transmission shows the same instantaneous rising and after that a second transmission peak appears at ~12ps after pump arrival [8].

TPA generates electron-hole pairs in high energy levels which are captured into the QDs with an intrinsic time (appearing as a rise time in the probe transmission), corresponding to the filling up of the GS and the probe delayed transmission peak (Fig. 4 (b)). The carrier capture mechanism from high energy levels to the GS has not yet been fully established in the literature and at least two hypotheses exist: the first is using the ES as an intermediate state and the second is directly through the continuum background [9].

From the pump transmittance decrease in Fig. 4 (a) and the simultaneous appearance of the delayed transmission peak in Figs. 4 (b) and (c), we can then estimate a threshold energy of 200-300fJ/pulse as the onset of TPA. The delayed transmission peak related to TPA is an unwanted feature when aiming at ultrafast applications and therefore must be

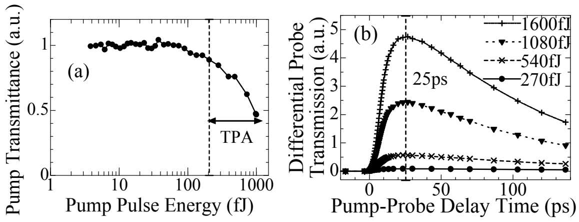

Fig. 5: (a) Pump (1340nm) transmittance as a function of pump pulse energy and the onset of TPA at ~200fJ. (b) Probe (1300nm, 1.25fJ) transmission as a function of delay time between pump and probe for different pump (1340nm) pulse energies. The 25ps-delayed peak is attributed to TPA.

avoided.

In order to investigate the effects of a pure TPA, we changed pump wavelength to 1340nm which is non-resonant to QD absorption but within the PC transmission window (Fig. 3). Fig. 5 (a) shows pump transmittance as a function of input pump pulse energy for 1340nm. The flat behavior in low pump pulse energies indicates that there is no effect of absorption saturation. Thus, the transmission decay for higher energies is attributed to only TPA. Fig. 5 (b) shows the probe (1300nm) transmission as a function of pump (1340nm) and probe delay. In this case, there is no instantaneous rising in probe transmission at zero delay position but there is a smooth rising and a peak appears at ~25ps after pump arrival. The different rise time for the two different pump wavelengths (1290nm and 1340nm) indicates that the latter case is affected by slow-light (Fig. 3, the edge of PC transmission window for longer wavelengths).

5. CONCLUSION

We observed TPA for pump pulse energy above 200-300fJ, accompanied by 25ps-delayed response when pump wavelength is near the PC band edge, i.e. affected by the slow-light regime. On the other hand, for pump wavelengths far from the PC band edge, the delayed transmission peak is reduced to 12ps. We speculate that the TPA and the delayed peak are caused by a combination of (1) strong optical confinement in the PC structures, (2) recovery time of TPA-induced electrons and holes, and (3) the slow-light effect near the PC band edge. For the ultrafast applications, these results indicate that we must avoid TPA which induces deleterious delayed responses.

6. REFERENCES

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