Room temperature slow light in a quantum-well waveguide via coherent population oscillation

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Abstract: We report room temperature demonstration of slow light propagation via coherent population oscillation (CPO) in a GaAs quantum well waveguide. Measurements of the group delay of an amplitude modulated signal resonant with the heavy-hole exciton transition reveal delays as long as 830 ps. The measured bandwidth, which approaches 100 MHz, is related to the lifetime of the photoexcited electron-hole (e-h) plasma as expected for a CPO process.

OCIS codes: (190.4380) Nonlinear optics, four-wave-mixing; (190.5970) Semiconductor nonlinear optics including MQW; (999.9999) Optical buffering

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1. Introduction

Slow light propagation has recently been proposed as the key resource for realizations of compact, even chip-scale variable all-optical buffers for use in optical communications, phased-array antennas and optical signal processing [1]. The underlying premise is that a reduction of the group velocity by the slow-down factor $S = c/v_g$ allows for an S-fold

#8724 - $15.00 USD Received 7 September 2005; revised 15 November 2005; accepted 18 November 2005

reduction of the physical length scale necessary to achieve a desired group delay. Delay is relative to the fastest signal in the system which could, in principle, travel in air. This provides vast potential for miniaturization and favors slow light based optical buffers over bulky delay lines. In addition, physical mechanisms underlying slow light propagation typically feature a control parameter, which allows for continuous and variable tuning of the group delay. This clearly presents a highly desirable characteristic for practical applications.

Modifications of the material dispersion using nonlinear optical processes such as coherent population oscillation (CPO) and other wave mixing effects or electromagnetically induced transparency (EIT) have recently been explored in a variety of material systems and have lead to impressive demonstrations of slow light [2,3,13]. In these schemes, tunability of the slow-down factor is provided by the optical intensity of the control beam involved in the nonlinear optical process. The use of CPO or EIT for slow light propagation in semiconductors, however, has not been addressed until recently [1,4-7]. As far as material systems are concerned, semiconductors are the platform of choice for optical buffer devices. Besides the obvious practical reasons, relevant relaxation/decoherence rates in semiconductors far exceed those in atomic or solid-state systems [2,3] enabling significantly increased bandwidth in semiconductor-based devices.

Recently, we reported the first time-domain measurements of ultraslow light via CPO on the heavy-hole (HH) exciton transition in a GaAs multiple quantum well (MQW) structure at T = 10 K [7]. Slow-down factors as large as $S = 10^6$ were observed in a surface-normal geometry, for which the signal propagates along the growth direction. Similar demonstration of CPO-induced slow light propagation at room temperature (RT) is expected to be complicated by the presence of LO-phonons and thermally excited e-h pairs (plasma). Scattering with LO-phonons leads to rapid ionization of excitons, while screening of the Coulomb interaction by the e-h plasma (either thermally- or photo-excited) reduces the excitonic oscillator strength. In comparison with low temperature conditions, the QW optical depth is thus reduced while the saturation intensity of the excitonic optical nonlinearity is increased at RT [8].

In this paper we present RT time-domain measurements of slow-light propagation via CPO on the HH-exciton transition in a (110)-oriented GaAs single quantum well (SQW) waveguide (WG). To address the characteristics of excitonic optical nonlinearities at RT as described in the previous paragraph, we used a WG-geometry, which provides several advantages over the surface normal geometry. First, a large and variable optical depth can be easily achieved simply by controlling the length of the WG sample. Second, due to the strong optical confinement in the WG, high optical intensities required to achieve CPO at RT are more readily attained. Third, diffraction effects are suppressed as the optical field, while interacting with the QW region, is propagating as a confined WG-mode. Finally, the use of a WG facilitates future device integration.

The results presented in this paper elucidate the effect of rapid exciton ionization on CPO induced group delay in QWs at RT. Despite exciton ionization, results are similar to those obtained at low temperature and reflect the general properties associated with a CPO process. More specifically, the measured operating bandwidth is related to the recombination rate of e-h pairs. The induced transparency, and hence the maximum achievable fractional delay, scale with the optical depth of the linear response. We demonstrate maximum fractional delays of 3.2% for an initial optical depth of $\Gamma\alpha L \approx 4$ (Γ: confinement factor, α: absorption coefficient, L = sample length).

2. Experiment

The QW WG sample used in this study was grown on a 2-inch (110)-oriented n-type GaAs wafer using a Varian Modular Gen-II molecular beam epitaxy (MBE) system. The growth (starting from the substrate) includes 1.19 μm of $Al_{0.26}Ga_{0.74}As$, 0.17 μm of $Al_{0.15}Ga_{0.85}As$, 60 nm $Al_{0.3}Ga_{0.7}As$, 5.4 nm GaAs QW, 0.345 μm of $Al_{0.3}Ga_{0.7}As$, and 20 nm GaAs cap layer. The structure was grown at 485˚C, with a relatively higher As_2 flux and reduced growth rate typical for (110) GaAs substrates. The overall structure provides a single mode planar WG.

#8724 - $15.00 USD Received 7 September 2005; revised 15 November 2005; accepted 18 November 2005

The QW is located slightly off center from the fundamental mode. Numerical simulation using this structure shows that only the fundamental mode propagates. The confinement factor is $\Gamma \approx 1\%$. The sample was mechanically polished, and a L = 440 μm long WG strip was cleaved. The strip was mounted on a thin copper bridge using silver paste to provide good thermal contact.

In order to demonstrate slow light propagation via CPO in a SQW WG at room temperature, we measure the group delay of a sinusoidal RF amplitude modulation (AM) imposed onto the output of a continuous-wave (cw) single-mode Ti:Sapphire laser. AM is achieved by means of an electro-optic modulator (EOM), which is continuously tunable up to 500 MHz. TE-polarized light is coupled in and out of the WG using a 20X (N.A. = 0.42) and 50X (N.A. = 0.55) microscope objective respectively. For convenience we have used a single beam for both control and signal. The sidebands and a small fraction of the carrier represent a weak, deeply modulated signal while the remainder of the carrier acts as the high intensity control. In a real device these would be independent beams. The coupling efficiency, measured with the laser input tuned below the absorption edge, varies depending on facet quality, but is typically on the order of 5%. Spatial filtering applied at the output is crucial to separate scattered light from the transmitted WG mode (see inset in Fig. 1). The transmission, detected by a photoreceiver, is displayed and stored using a fast digital scope [7]. To provide a stable time base, we split the output of the RF-synthesizer driving the EOM. The respective other branch of the output is used as external trigger for the scope. Two measurements are carried out to measure the group delay resulting from CPO at the HH-exciton transition. First, we tune the wavelength of the Ti:Sapphire laser below the absorption edge of the QW and record the respective modulation trace. The wavelength is then tuned on resonance with the HH-exciton transition, and a second trace is recorded. Note that CPO is not generated in the first case for which the QW is transparent. By measuring the time offset between the modulation traces for the on- and off-resonant case, we therefore record the delay resulting from CPO and eliminate contributions from non-resonant effects, e.g. the background refractive index in the experiment.

3. Results

The top graph in Fig. 1 shows the transmission T through the QW WG, revealing the QW absorption and a band edge around $\lambda \sim 828$ nm. The transmission is normalized with respect to that below the absorption edge. Careful spatial filtering suppressed the contribution from scattered light into the detection path, as can be seen by the absence of a constant background in the spectrum. Note that the spatial filtering is crucial for the time-domain measurements. Collection of scattered light, which is not interacting with the QW, could mask or even prohibit measurements of the delay, since only the WG-mode is subject to group delay via CPO in the QW active region.

HH- and LH-exciton resonances are clearly observed if we plot -ln(T) as shown in the bottom graph of Fig. 1. Assuming that the absorption below the band edge as well as the wavelength dependence of the reflection are negligible, the optical depth can be approximated by $\Gamma\alpha L \approx -\ln(T)$. The arrows indicate the spectral position for on- and off-resonant measurements as explained above. For the on-resonant case, the optical depth from the HH-absorption is on the order of $\Gamma\alpha L \approx 4$. With L = 440 mm and $\Gamma = 1$ %, we obtain $\alpha = 9\mathrm{x}10^3/\mathrm{cm}^2$, consistent with typical values of RT GaAs QW absorption coefficients [8].

#8724 - $15.00 USD Received 7 September 2005; revised 15 November 2005; accepted 18 November 2005

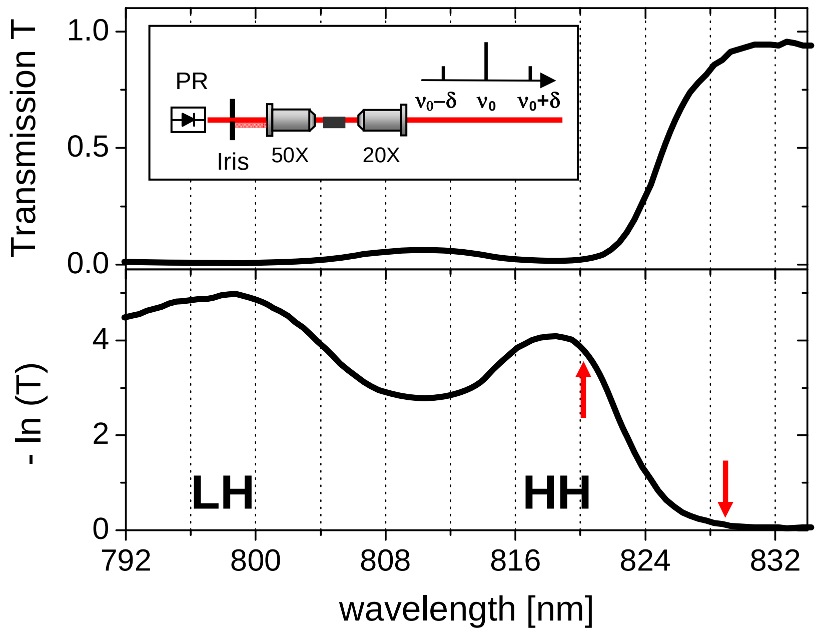

Fig. 1. Top. transmission spectrum from the L = 440 µm long QW WG sample. The spectrum was recorded with the AM switched off. The inset shows a schematic of the setup. HH and LH exciton absorption resonances are clearly resolved in the absorption spectrum shown in the bottom graph. Arrows indicate the spectral position for the on- and off-resonant conditions used in the measurements of group delay induced via CPO at the HH-exciton transition.

Figure 2(a) shows a generic example of two modulation traces recorded for on- and off-resonant conditions, with modulation frequency f = 100 MHz and input power P = 75 mW. The resonant trace exhibits a delay τ with respect to the off-resonant trace. To demonstrate that the observed slow down does indeed result from CPO, we record a series of modulation traces for different modulation frequencies and input power levels. The results are summarized in Fig. 2(b), in which delay is plotted as a function of modulation frequency at three different power levels. The solid lines are Lorentzian fits centered at f = 0 MHz. Delays up to 830 ps are measured for the highest available input power P = 75 mW and f = 25 MHz. The inset shows the power dependence of the linewidth (FWHM) $\Delta\nu$, which is obtained from the Lorentzian fits.

Figure 3(a) presents the power dependence of the fractional delay $\xi = \tau f$ for different modulation frequencies. The power dependence demonstrates the ability to optically control the group delay using the CPO nonlinear optical process. For increasing input power, the delay saturates. Maximum fractional delay of 3.2 %, corresponding to an RF-phase shift of ϕ = 11.5˚, is measured for highest pump powers and f = 100 MHz.

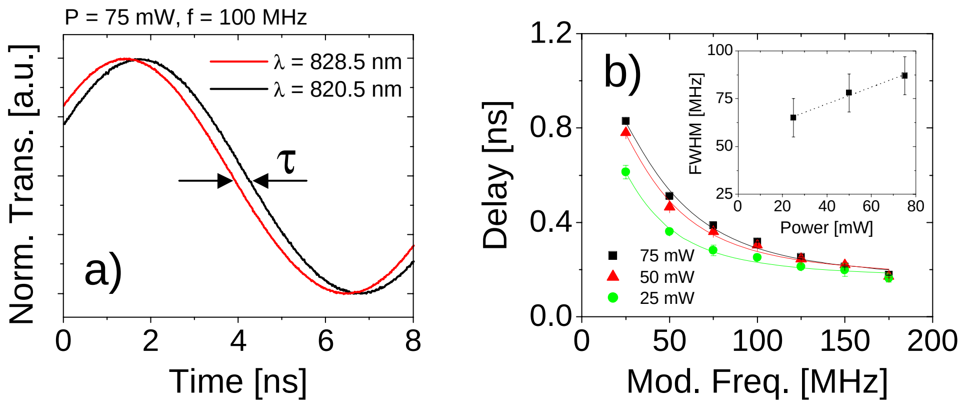

Fig. 2. (a) Generic example of two modulation traces recorded on- and off- resonance (f = 100 MHz and P = 75 mW). The trace obtained on-resonance with the HH-excition transition is delayed. (b) Delay as a function of modulation frequency for P = 25, 50, 75 mW input power. Solid lines are Lorentzian fits. The inset shows the power dependence of the FWHM as obtained from the numerical fits.

4. Discussion

The CPO nonlinear optical response results from wave-mixing between two optical fields via a resonant dipole optical transition [9]. In our experiment the sidebands generated by the amplitude modulation provide the signal fields, whereas the carrier provides the control field (inset in Fig. 1). Wave-mixing between the optical fields gives rise to a temporal modulation (grating) of the excited-state population associated with the resonant transition. The grating oscillates at the frequency f determined by the control-signal detuning and mediates a coherent energy transfer between control field and signal field. This results in a dip in the nonlinear signal absorption, which is centered about the energy of the control field. In a $\chi^{(3)}$-regime, the linewidth $\Delta\nu$ (FWHM) of the CPO resonance is determined by the upper state lifetime T_1 since the excited state population can no longer follow the beating induced by the external fields if $f > 1/2\pi T_1$ (see [4] for plots and further details of coherent dip). In a strongly nonlinear regime, it can be shown for the simple case of a two-level system that the CPO resonance exhibits a linear power broadening according to $\Delta\nu = (1+P/P_0)/(\pi T_1)$, where P_0 denotes the saturation power [10].

According to Kramers-Kronig relations, the CPO absorption dip is accompanied by a positive dispersion and hence slow light. For a Lorentzian line profile, the resulting group delay of a sinusoidally AM signal as a function of the modulation frequency is also Lorentzian with same linewidth [10]. Fig. 2(b) mirrors therefore the CPO resonance, from which the lifetime of the photoexcited e-h-plasma can be extracted. A linear fit to the power dependence according to $\Delta\nu = (1+P/P_0)/(\pi T_1)$, as shown in the inset of Fig. 2(b), reveals $T_1 = (5.9\pm0.3)$ ns and $P_0 = (123\pm13)$ mW. The measured e-h recombination time is in very good agreement with that previously measured in a (001) oriented GaAs QW [11], which demonstrates that the mechanism underlying the observed delay is indeed CPO. The good agreement shows furthermore that substrate orientation does not affect the CPO response as recombination time as well as oscillator strength are comparable in (001)- and (110)-oriented QWs. The use of (110) QWs, however, allows us to simultaneously explore the possibility of slow-light propagation via EIT based on the robust electron spin coherence, which in (110)-oriented QWs, as opposed to (001)-oriented QWs, persists up to RT [12].

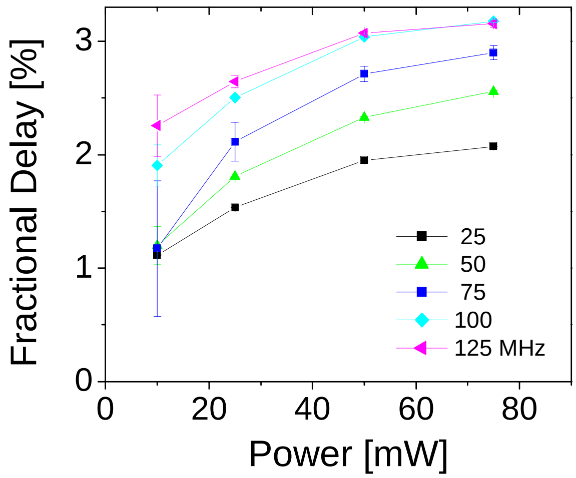

Fig. 3. Power dependence of the fractional delay for various modulation frequencies demonstrating optical control over the group delay.

Due to limitations in available optical power (P < 75 mW) we could not fully saturate the CPO response in this study. The power dependence in Fig. 3 shows consistency with the saturation power as obtained from the CPO linewidth power broadening. Note that in a CPO process, the maximum fractional delay is achieved for $P = P_0$. This is due the fact that the depth of the induced CPO transparency saturates, whereas the CPO linewidth keeps increasing linearly with increasing power [10]. Since we are still below saturation, we expect that the maximum achievable fractional delay can be slightly higher than the measured 3.2 %.

For the maximum delay of τ = 830 ps measured, we obtain a slow-down factor S = 565 ($S = c\tau/L$, L = 440 μm), which is three orders of magnitude smaller than that obtained in our low-temperature study [7]. The discrepancy is mainly due to the fact that we are using a WG rather than a surface normal geometry here. Whereas the entire optical mode interacts with the QW active region in surface normal geometry, it does so with a significantly reduced confinement factor Γ in the case of a WG. The discrepancy in slow-down factors thus mainly reflects the effect of reduced overlap of the optical mode with the active region. With an improved WG design, e.g. higher confinement factor, increased slow-down factors are expected. Furthermore, a ridge WG structure could provide lateral confinement for still increased intensities at a given power input.

5. Conclusion

We report the first RT experimental demonstration of slow-light propagation via CPO on the HH-exciton transition in a (110) GaAs SQW WG. A maximum delay of 830 ps and bandwidth approaching 100 MHz are obtained. The measured maximum fractional delay of ξ = 3.2% is comparable to that obtained at low temperature in the surface normal geometry. Since the fractional delay scales with the optical depth for a CPO process, this agreement is not surprising as the optical depth (~ 4) is comparable in the two measurements. The use of a WG structure provides the optical intensities necessary to saturate the QW excitonic nonlinear optical response, and hence, to ultimately observe CPO-induced group delay at RT. Despite rapid ionization of excitons at room temperature, CPO-based slow light is thus attained at RT. Note that the response to a sinusoidal modulation predicts the first-order delay a pulse would experience, and further experiments are required to quantify second-order effects such as broadening and distortion.

#8724 - $15.00 USD Received 7 September 2005; revised 15 November 2005; accepted 18 November 2005

Finally, note that our observation of the CPO response in a (110)-oriented QW demonstrates predominantly intrinsic carrier recombination. This is not trivial due to increased strain and hence possibly increased dislocation density in (110) QWs. The results presented lay the necessary grounds for investigating slow-light propagation at RT via electromagnetically induced transparency (EIT) using long-lived electron spin coherence in (110)-oriented QWs.

Acknowledgments

We acknowledge helpful discussions with Profs. Hailin Wang (University of Oregon) and S. L. Chuang (University of Illinois, Urbana-Champaign). We also thank the support of DARPA grants F30602-02-2-0096 and HR0011-04-1-0040 (CONSRT) Airforce contract FA 9550-04-1-0196.

#8724 - $15.00 USD Received 7 September 2005; revised 15 November 2005; accepted 18 November 2005