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Slow Light Using Semiconductor Quantum Wells and Quantum Dots for Future Optical Networks

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1. Introduction

Slowdown of optical pulses is important in advanced optical communication systems for which controllable optical buffers will be required in optical packet switching. The general idea is to create a steep variation in the refractive index spectrum with a positive slope within a frequency range or bandwidth. The group velocity v_g in a material is

$$v_g = c/n_g, \quad n_g = n + \omega \frac{\partial n}{\partial \omega} \tag{1}$$

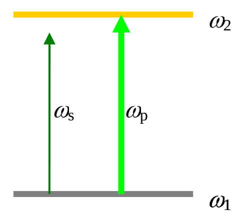
where n_g is the group index of the optical frequency. A large and positive slope increases the group index and reduces the group velocity of the optical signal. Previous experiments of slow light were performed using the electromagnetically induced transparency (EIT) effects in systems with a long decoherence time, e.g., atomic gas [1] at very low temperatures. Although a slowdown factor up to 10^7 could be achieved, the experimental conditions and setups are not practical for system applications. Slow-light devices based on semiconductors are preferred because of the easy integration with other optoelectronic components.

The radiative lifetime in semiconductors is a proper time scale for slow light. The nanosecond radiative lifetime corresponds to a gigahertz bandwidth and is suitable for practical applications. To utilize the radiative lifetime, a pump-probe setup sensing the population oscillation (PO) of the energy levels in the material system has been demonstrated [2][3].

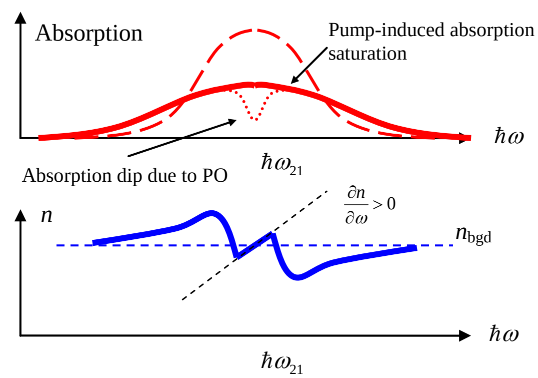
We will describe slow light using the PO effects from heavy-hole (HH) excitons in quantum wells (QWs). This corresponds to the PO in an absorption medium. Extensions of PO to quantum dot (QD) gain media bring about interesting applications for active devices at room temperature and will also be addressed.

2. Population Oscillation in Quantum Wells Due to Excitonic Transitions

In a two-level system, the optical absorption peak corresponds to a negative slope of the refractive index and leads to fast light, which is the so-called anomalous absorption dispersion. In the presence of an intense optical pump beam with the photon energy near the transition energy, absorption saturation occurs because of the depletion of the population of the lower energy state. If a weak signal beam with a frequency slightly detuned from that of the pump beam is present, as shown in Fig. 1(a), the population of the excited state will beat with a frequency determined by the pump-signal detuning. Significant population beating occurs when the population can follow closely the intensity profile due to the time-dependent interference between the optical fields of the pump and signal beams. Thus, a reduction of the absorption showing a coherent spectral hole characterized by the inverse radiative lifetime will be present, as shown in Fig. 1(b), top. From Kramers-Kronig relation, an absorption dip leads to a variation of the refractive index spectrum with a positive slope in the same frequency range, yielding a slow light effect.



(a)



(b)

Fig. 1 (a) A two level system in the presence of a resonant pump and a probe. (b) Top- absorption spectrum of the probe in the absence (long dashed curve) and the presence (solid) of a strong pump. The spectral hole (dotted curve) is caused by the population oscillation produced by the pump and probe beams. Bottom- the corresponding refractive index spectrum in the presence of population oscillation.

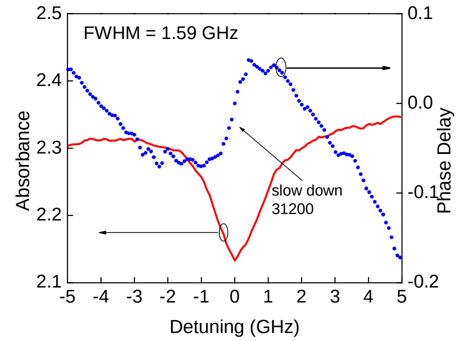
In semiconductors, examples of such quasi two-level systems are excitons in quantum wells or self-assembled quantum dots. In the experiment of slow light using population oscillation [4], an intense beam with a narrow linewidth from a Ti-sapphire laser acted as the pump beam. The photon energy of the pump beam was tuned in resonance with the HH exciton transition in a sample with 15 GaAs/AlGaAs QWs. A tunable diode laser with a variable detuning from the pump frequency served as the probe beam. The optical fields of the pump and probe are incident with the same polarization from the top of the QW structure. The experiment was carried out at a temperature of 10K. The absorption was obtained from the transmission spectrum of the signal beam. In addition, a Mach-Zehnder interferometer setup is used to measure the phase delay of the signal. The measured absorbance and phase delays are shown in Fig. 2(a). An absorption dip with a full width at half maximum (FWHM) of 1.59 GHz has been obtained. This linewidth corresponds to a radiative lifetime of 200 ps, which is typical of QW HH excitons at low temperature. Corresponding to this absorption dip, the phase delay exhibits a steep positive slope and yields a slowdown factor of 3.12×10^4. We have developed a theoretical model based on the density-matrix formalism taking into account the spin-up and spin-down HH excitons, the dipole selection rule, and other nonlinear effects coupling the two spin subsystems [5]. Our theoretical results, shown in Fig. 2(b), agree well with the experimental results. The slowdown factor can be further increased if the pump power is increased to deepen the absorption dip.

3. Population Oscillation in Semiconductor Quantum-Dot Amplifiers

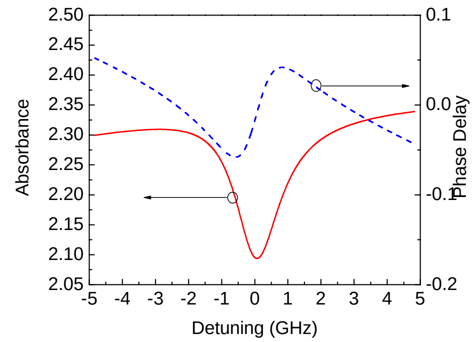
Population oscillation (or carrier beating) also occurs in semiconductor optical amplifiers, for which cross-gain modulation and four-wave mixing have been intensively studied [6]. We have recently investigated this process in a QD SOA for new applications such as fast light and slow light with a configuration in which the pump and probe beams propagate in opposite directions. The configuration helps isolate the pump from the probe when measuring the effects of population oscillation. We have measured the spectra of the optical gain and group index change at various pump powers at a fixed bias current of the QD SOA. Both fast light and slow light with a bandwidth of 13 GHz at room temperature are demonstrated. By using PO, the group index is found to be changed by 1.0 (about 30%) over a current increment of 200 mA (slow light), -0.4 by gain depletion, and -0.2 at an optical power of 0.3 mW (fast light). We will show that our theoretical model with PO and dynamic grating in SOAs explains the experimental results very well.

4. Conclusions

We have investigated population oscillation for slow light and fast light applications in semiconductor QW and QD devices. In a QW structure, when the pump and probe beams are close to the exciton transition energy, coherent excitonic PO leads to a significant slow down factor of 31,200 at 10K. On the other hand, in a semiconductor QD optical amplifier with current injection, carrier population oscillation leads to both slow light and fast light effects at room temperature. Although the slow down factor is small, the bandwidth can reach many GHz. Further improvement is in progress.



(a)



(b)

Fig. 2 (a) Experiment and (b) Theory for the absorbance and the refractive index change (phase delay) in the presence of coherent population oscillation (After [5]).

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