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Observation of electromagnetically induced transparency in a three-subband quantum well system

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Abstract. The phenomenon of Electromagnetically Induced Transparency is demonstrated for the first in a subband quantum well system. Applying strong coupling field which is two-photon-resonant with the 1–3 intersubband transition, produces dramatic change in the 1–2 intersubband absorption profile. This effect can be accounted for in terms of 1–2 and 2–3 dipoles being driven into coherence by a strong coupling field and is similar to Fano-type destructive interference of probability amplitudes.

Strong resonant optical field, applied to a 3-level atomic system, may create an ensemble of phase-coherent atoms, with interesting properties, caused primarily by the quantum interference between probability amplitudes of the atomic states. The study of such a system has led, in the last decade, to prediction and experimental demonstration of exciting (and sometimes counter-intuitive) effects, such as electromagnetically induced transparency (EIT) [1] and lasers without inversion (LWI) [2]. The most recent examples include observation of ultraslow ($\sim 10^{-7}$ s) propagation of light in a Bose-condensed atom system [3].

To our knowledge, observations of EIT have so far been restricted to comparatively sharp transitions in atomic vapours [1]. In these experiments, the condition that the Rabi frequency, $\Omega = \mu E / \hbar$, (where μ is a transition dipole matrix element and E is an amplitude of the coupling EM field) is greater than the linewidths is readily achieved. Although there is much theoretical interest in EIT and LWI in semiconductor quantum wells (QW's), the observation of coherent phenomena in these systems is complicated by their large (~ 100 fs^{-1}) dephasing rates.

Devices based on intersubband (ISB) transitions in QW's offer a great potential for applications in lasers and nonlinear optics (NLO) because of their inherent advantages, such as large electric dipole moment, high NLO coefficients, and the possibility to engineer key microscopic properties, such as energy levels and wavefunctions, matrix elements and even decay rates [4]. Gigantic NLO coefficients in asymmetric double QW's (ADQW's) can also be created, via bandgap engineering [5], and efficient optical frequency conversion can be achieved [6]. However, the full potential of this system could not be realized because of the in-built resonant ISB absorption. Coherent population control in ADQW will make it possible to engineer efficient NLO devices which, by analogy with atomic systems [7], utilize an absorption transparency while maintaining gigantic, resonantly enhanced NLO coefficients.

EIT typically involves a three-level system, having two dipole-allowed transitions ($|1\rangle \rightarrow |2\rangle$ and $|2\rangle \rightarrow |3\rangle$) and a third ($|1\rangle \rightarrow |3\rangle$) dipole forbidden transition (Fig. 1). Driving this with a 'coupling field', of angular frequency (ω_c, resonant with the ($|2\rangle \rightarrow |3\rangle$ dipole
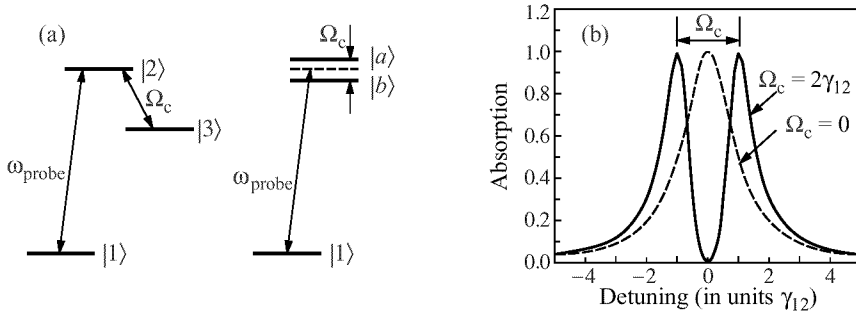
Fig. 1. Electromagnetically Induced Transparency in atoms. Driving a three-level system with a coupling field (Ω_c resonant with the $|2\rangle \rightarrow |3\rangle$ dipole transition (a) establishes a coherent super-position of the probability amplitudes and makes quantum interference possible, thus eliminating absorption in the $|1\rangle \rightarrow |2\rangle$ line center (b). Here (γ_{12} is $|1\rangle \rightarrow |2\rangle$ dephasing rate (inverse linewidth).
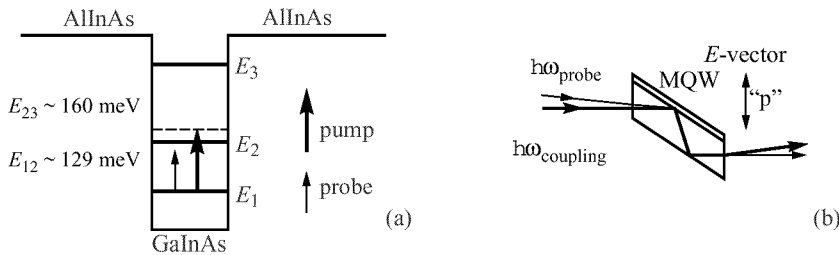

Fig. 2. (a) Transition energies in the 3-level QW structure ($T = 30$ K) and (b) schematic of the pump-probe mid-IR experiment.

transition establishes a coherent superposition of the probability amplitudes and makes quantum interference possible. In this case ($|1\rangle \rightarrow |2\rangle$ transitions occur through two coherent paths ($|1\rangle \rightarrow |a\rangle$ and ($|1\rangle \rightarrow |b\rangle$, where the 'dressed states' are given by $|a\rangle = (|3\rangle - |2\rangle)/\sqrt{2}$ and $|b\rangle = (|3\rangle + |2\rangle)/\sqrt{2}$, whose transition probability amplitudes interfere destructively and cancel the original absorption at energy difference E_{12}.

In the present work we study a three-level QW system where, according to selection rules, ISB transitions 1–2 and 2–3 are allowed and 1–3 is dipole-forbidden. The QW sample consists of forty symmetric 10 nm n-doped ($n_s = 6 \times 10^{11}$ cm^{-2}) In$_{0.47}$Ga$_{0.53}$As wells with 10 nm Al$_{0.48}$In$_{0.52}$As barriers, lattice matched to an undoped InP substrate [8]. Transition energies (Fig. 2(a)) were $E_{12} \sim 129$ meV and $E_{23} \sim 160$ meV (at $T = 30$ K) and matrix elements ($\mu_{12} = 2.34$ nm and ($\mu_{23} = 2.64$ nm.

A double pass 45° waveguide geometry was used to couple p-polarized light to ISB transitions (Fig. 2(b)). Independently tunable ($\lambda \sim 6-12$ μm) synchronised coupling (ω_c) and probe (ω_p) laser pulses, with similar temporal profiles (FWHM $\sim 70-80$ ps), were generated in separate erbium-laser-pumped Optical Parametric Generators [9] based on ZnGeP$_2$ and CdSe nonlinear crystals.

Peak intensity of the incoming mid-IR coupling field reached 20 MW/cm^2. Taking into account that only E_z — the component of the optical field (i.e. normal to the QW layers) couples the ISB transitions, this corresponds to the Rabi frequency $\Omega_c = \mu_{12} E_z/\hbar \sim$ 5 meV. The coupling and the probe beams were separated by 10°; the probe beam intensity
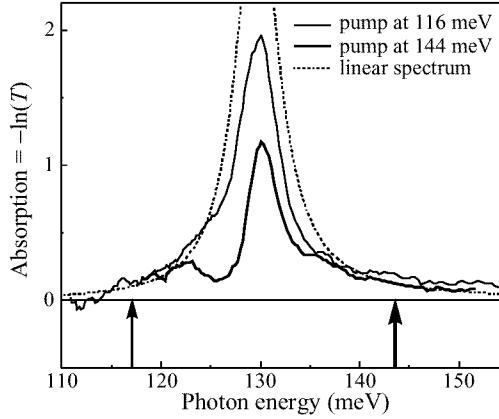
Fig. 3. Comparison between measured absorption spectra with $\hbar\omega_c \sim E_{13}/2$ (thick line) and with, $\hbar\omega_c = 116$ meV (light line) i.e. at an equal but opposite detuning from the E_{12} resonance. Quantum interference feature near 126 meV can be seen in the former case. Dotted line — linear spectrum.

was 10^3 times weaker than the coupling intensity, and a 300 μm pinhole was attached to the sample facet — to assure the beam overlap. Linear 1-2 absorption spectrum at $T = 30$ K (partly shown in Fig. 3, dotted line) was best fitted with the Lorentzian shape with FWHM $\sim$5 meV. Thus the coupling Rabi frequency was of the same order as the ISB linewidth. At $T = 30$ K, only the lowest state was populated so that the E_{23} transition was not seen and E_{23} energy were measured using the induced absorption method [8].

While tuning the coupling energy to $\hbar\omega_c = E_{12}$ produced almost complete saturation of the E_{12} absorption line, the most interesting effect was observed when the coupling beam frequency was tuned half-way between E_{12} and E_{23} ('two-photon' 1–3 resonance, $\hbar\omega_c \sim E_{13}/2$). A pronounced (67% reduction in absorption) narrow (FWHM $\sim$3.6 meV) dip appears in the absorption spectrum (thick line in Fig. 3). Its spectral narrowness, the non-obvious relationship between its position (126 meV) and the coupling photon energy (144 meV), both suggest an origin in quantum interference. Moreover the transparency feature disappeared when the coupling laser was tuned to its 'mirror image' with respect to E_{12} position ($\hbar\omega_c = 116$ meV, thin line in Fig. 3).

We theoretically treat the three-level system within a density-matrix formalism where we assumed an intersubband relaxation time $\tau = 1$ ps [10] and non-diagonal relaxation rates $\gamma_{12} = \gamma_{23} = \gamma_{13} = 5$ meV. In agreement with experiment, the strongest quantum interference effect is predicted when the coupling frequency is tuned to $\omega_c = E_{13}/2$ (Fig. 2). When this occurs, the model finds 'dressed state' energies of 132 and 116 meV for the superposition states $|a\rangle$ and $|b\rangle$. These two states are coherently coupled by the two-photon coupling field [11]. Absorption at $\sim$125 meV, half way between these two 'dressed states', is the result of two interfering pathways which contribute to the absorption dipole moment with opposite sign, giving strong absorption cancellation.

Acknowledgements

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