Phase evolution of the reemitted field in the semiconductor quantum wells under the femtosecond pulse train intersubband excitation

Jian Luo (罗 建), Shangqing Gong (龚尚庆), Yueping Niu (钮月萍),
Xiaohong Song (宋晓虹), Jun Qian (钱 军), and Ruxin Li (李儒新)

State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics,
Chinese Academy of Sciences, Shanghai 201800

Received December 13, 2006

Property of the phase of the reemitted field in the semiconductor quantum wells (QWs) excited by femtosecond pulse train is investigated. It is shown that the phase evolution of the reemitted field is controlled by the relative phase between the successive pulses of the incident train. For all the odd pulses excitation, the reemitted field is from out-of-phase to in-phase, then again to out-of-phase with the incident pulses, whereas for all the even pulses excitation, the situation is the opposite, i.e., it is from in-phase to out-of-phase, then again to in-phase with the incident pulses.

OCIS codes: 040.6070, 140.0140, 190.0190, 320.0320.

The research for the ultrashort pulse coherent control in the semiconductor, particularly in the low dimensional system, reveals some interesting properties, such as phase evolution of solitonlike optical pulses[1], hole burning within a homogeneous line[2], self-induced transmission[3], Rabi splitting with a single quantum dot[4], electromagnetically induced transparency[5], photon echoes[6], etc.. In the electronic band structure for the semiconductor, there are regions with continuous distributions (or bands) of energies and regions where electronic states are forbidden (bandgaps). The bands include two types: conduction bands, which consist of unoccupied states; and valence bands, which consist of occupied states. The carriers including electron and hole can transit between the bands. In the semiconductor quantum wells (QWs) coherent control, it was shown that the subpicosecond period and the phase of the Rabi oscillations are controlled by the properties of the mid-infrared driving pulse and the excited state population evolution is controlled by the amplitude of the incident pulse[7]. Since the phase of the material polarization and the connected electromagnetic field carry information[8], it could be applied in quantum information processing.

Meanwhile, some novel properties were discovered under the pulse train coherent control due to the pulses interference effect. Fortier *et al.*[9] reported carrier-envelope phase shifts for carrier-envelope phase-controlled quantum interference in the semiconductor using phase stabilized pulse train. In atom or molecular system, phase control of dispersion effects for an ultrashort pulse train propagating in a resonant medium was predicted theoretically by Mohamed *et al.*[10] and reported experimentally by Jacquey *et al.*[11]. Heberle *et al.*[12] found that the optical response is faster than the inverse of exciton linewidth superseding Fourier limits for a single pulse excitation due to ultrafast coherent control and destruction of exciton in QWs. Felinto *et al.*[13] discovered that the stimulated emission gives an important contribution to the coherently controlled process for accumulative effects in temporal coherent control. Weiner *et al.*[14] reported that molecular motion manipulated by optical field enhances with timed sequences of femtosecond pulses.

Intrigued by these studies, we here investigate the phase properties of the reemitted field in the semiconductor QWs under the femtosecond pulse train excitation. The semiconductor QWs are typical two-dimensional (2D) systems for studying quantum coherences in electron plasmas. III-V semiconductor heterostructures with GaAa/AlGaAs QWs to be a representative one[15] have benefited particularly. Our result shows that the phase evolution of the reemitted field is controlled by the relative phase between the successive pulses of the incident train; for all the odd pulses excitation, the reemitted field changes from out-of-phase to in-phase then again to out-of-phase with the incident pulses, whereas for all the even pulses excitation, the reemitted field changes from in-phase to out-of-phase then again to in-phase with the pulses of the incident train.

Figure 1(a) shows the scheme of the GaAs/AlGaAs QWs[7,15,16]. The sample consists of 51 GaAs QWs of 10-nm width, separated by 20-nm-thick $Al_{0.35}Ga_{0.65}As$ barriers, the centers of which are doped with Si, resulting in an electron concentration of $n_s = 5 \times 10^{10}$ cm^{-2} per QW[7]. Figure 1(b) shows the related energy level[7,15−18]. For the free motion of carriers parallels to the layer within the effective mass approximation (EMA) in the semiconductor QWs, a reasonable approximation for the low-lying 2D conduction subbands is parabola[19,20].

Becasue of the periods of the intersubband (ISB) transition in the semiconductor GaAs are in between ∼ 300 and 100 fs[17,18,20,21], femtosecond pulse train creates a coherent ISB excitation which is resonant to the 1 ↔ 2 ISB transition. The model of the ISB direct transition in the GaAs/AlGaAs QWs has been adopted in this paper. Under these conditions, the noninteracting two-level

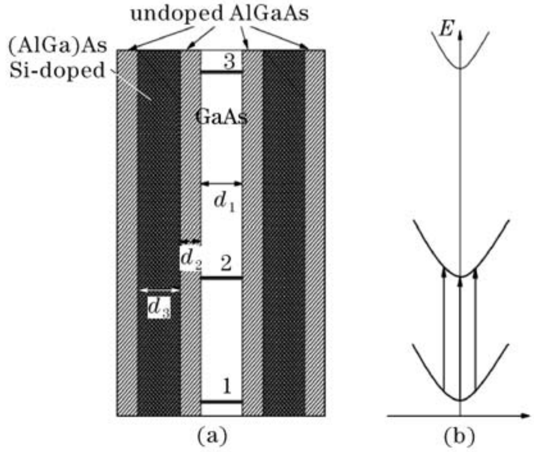

Fig. 1. (a) Sequence of layers and relative position of the conduction band edges in Si-doped GaAs/AlGaAs QW structures[7,10], (b) the corresponding dispersion of the subband in the QW.

model which describes the transition in the semiconductor QWs could be used. Luo *et al.*[7] has confirmed that this model is qualitatively valid for describing the coherent control in the semiconductor QWs. The Rabi oscillations of the polarization amplitude and of the population inversion can be forecasted by the Maxwell-Bloch equations for noninteracting two-level systems[22−24]

$$\frac{\partial f_{12}}{\partial t} = \left(i\omega - \frac{1}{T_2}\right) f_{12} + i\Omega(t)(1-2f_{22}), \tag{1}$$

$$\frac{\partial f_{22}}{\partial t} = -\frac{1}{T_1} f_{22} + 2\Omega(t)\mathrm{Im}(f_{12}), \tag{2}$$

$$P(t) = 2Nd\mathrm{Re}(f_{12}), \tag{3}$$

$$\left(\frac{\partial^2}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) E(z,t) = \mu_0 \frac{\partial^2}{\partial t^2} P(z,t), \tag{4}$$

where f_{ij} $(i=1,\ j=2)$ are the diagonal (populations) and off-diagonal elements (coherences) of the density matrix, ω is the transition angle frequency between the two levels, d is the electronic dipole moment, ε_0 is the vacuum permittivity, c is the speed of light in vacuum, n is the refraction index of the material surrounding the QWs[22], $\Omega(t) = E_{\mathrm{in}}(t)d/h$ is the instantaneous Rabi frequency of the incident field E_{in}, and T_1 and T_2 are the longitudinal relaxation time and the transverse relaxation time of the system, respectively. $E(z,t)$ is the classical radiation field after propagating through the interaction region.

Within the envelope function approximation, the z dependence of the macroscopic polarization is determined by the electron and hole confinement wave functions located at the positions z_n of the nth QW, $P(z,t) = \sum\limits_n P^n(t)\varphi_{\mathrm{e}}^n(z)\varphi_{\mathrm{h}}^n(z) \approx \sum\limits_n P^n(t)\delta(z-z_n)$, and considering the first set of boundary conditions, the Eq. (4) can be simplified as[23]

$$E_{\mathrm{em}} = -\frac{1}{2\varepsilon_0 cn}\frac{\partial P}{\partial t}. \tag{5}$$

The reemitted field $E_{\mathrm{em}}(t) = E_{\mathrm{tr}}(t) - E_{\mathrm{in}}(t)$ is proportional to the time derivative of the macroscopic polarization $P(t)$[22], which in turn is proportional to the electric dipole moment d and to the total sheet density N of coherently oscillating carriers. E_{tr} is the transmitted field from the sample GaAs/AlGaAs QWs. It could be attenuated for the destructive interference or amplified for the constructive interference between the reemitted field E_{em} and the driving field E_{in}.

Based on the Eqs. (1)—(3) and (5), we study the properties of the coherent control in the semiconductor QWs accounting for the incident pulse train excitation,

$$E_{\mathrm{in}} = \sum_{k=0}^{M-1} E_k^0 \mathrm{sech}[1.76\pi(t-kT)/\tau_{\mathrm{p}}] \times \cos[\omega_{\mathrm{L}}(t-kT)+\phi_k], \tag{6}$$

which is hyperbolic-secant carrier-envelope form. Here E_k^0 is the kth pulse amplitude of the train, τ_{p} is the kth pulse epochal duration, ω_{L} is the carrier frequency, T is the delay time between the successive pulses of the incident train, ϕ_k is the relative phase between the successive pulses of the incident train, and $k = 0, 1, 2, \cdots, M-1$. Such pulse train has been obtained in the experiment[25−30]. In the following numerical analysis, we consider the resonance situation between the ISB transitions, and all the material parameters are based on Ref. [7], $\tau_{\mathrm{p}} = 200$ fs, $\omega_{\mathrm{L}} = \omega = 2\pi/100\ \mathrm{fs}^{-1}$. When we take into account the phonon induce relaxation, the damping T_1 and T_2 are longer compared with the femtosecond pulse train scales. For simplicity we neglect any damping: $T_1 = T_2 = \infty$, which means that we only consider coherent part in the QWs. The reemitted field variation with the amplitude of the incident pulse has been investigated in Ref. [7]. Herein the reemitted field variation under the incident pulse train excitation is researched, which we use the ansatz $E_k^0 = 50$ kV/cm in this paper.

Figure 2(a) shows the reemitted field as a function of the time in the case of the delay time $T = 2$ ps and the relative phase $\phi_k = \pi$. It is found that during the first pulse excitation, the reemitted field $E_{\mathrm{em}}(t)$ is the first $(t < 0.9$ ps) out-of-phase with $E_{\mathrm{in}}(t)$, for intermediate

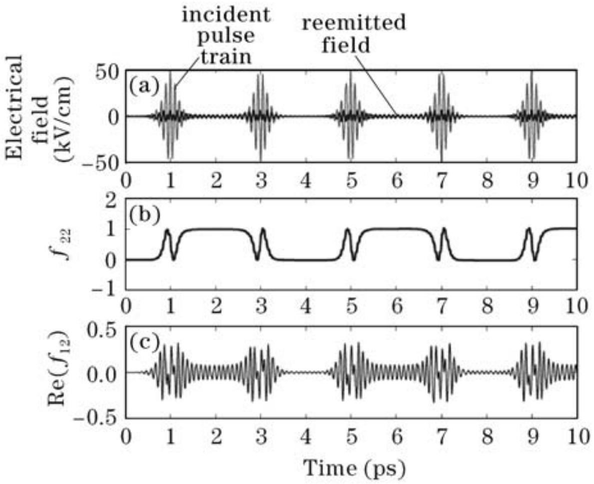

Fig. 2. (a) Reemitted field and the incident pulse train, (b) excited state population, and (c) coherent of the density matrix versus time in the case of the incident train amplitude of 50 kV/cm, delay time $T = 2$ ps, and relative phase $\phi_k = \pi$.

time (0.9 ps$< t <$ 1.1 ps) in-phase with $E_{\text{in}}(t)$, and last ($t >$ 1.1 ps) again out-of-phase with $E_{\text{in}}(t)$. This is consistent with Fig. 2(c) in Ref. [7]. Compared with the situation during the first pulse excitation, the phase evolution of the reemitted field during the second pulse excitation is intrinsically different. The reemitted field is from in-phase to out-of-phase, then again to in-phase with the second pulse of the incident train. During the third pulse excitation, the phase relationship between the reemitted field and the third incident pulse comes back to the situation of the first pulse excitation, and during the fourth pulse excitation, it reproduces the situation of the second pulse excitation, etc., i.e., for all the odd pulses excitation the phase evolution of the reemitted field is a regularity, whereas for all the even pulses excitation the phase evolution of the reemitted field is another regularity. This phenomenon can be explained as follows. In Eq. (5), it predicts that the reemitted field is proportional to the time derivative of $P(t)$, i.e., $\pi/2$ out-of-phase with the polarization $P(t)$. In the semiconductor QWs system, the polarization $P(t)$ induced by the driving field is $\pi/2$ phase difference with the driving field under the absolutely resonant condition[31]. The polarization $P(t)$ being $\pi/2$ out-of-phase or in-phase with the driving field depends on whether the time derivative of the excited population f_{22} is negative or not[7]. The result of the excited state population f_{22} versus time is shown in Fig. 2(b). During the first pulse excitation in Fig. 2(b), the excited state population increases from 0 to 0.9 ps, then decreases from 0.9 to 1.1 ps, and lastly again increases after 1.1 ps. However, during the second pulse excitation, the excited state population decreases until 2.9 ps, then increases from 2.9 to 3.1 ps, and lastly again decreases after 3.1 ps. The regularity of the excited state population evolution during the first pulse excitation is the same as the situation during the third pulse excitation, etc. This is consistent with the phase relationship between the reemitted field and the pulses of the incident train.

In the following we will investigate the reemitted field affected by the relative phase ϕ_k. The result for the relative phase $\phi_k = 0$ is shown in Fig. 3. During the first pulse of the incident train, the phase evolution of the reemitted field is the same as the case of the Fig. 2(a).

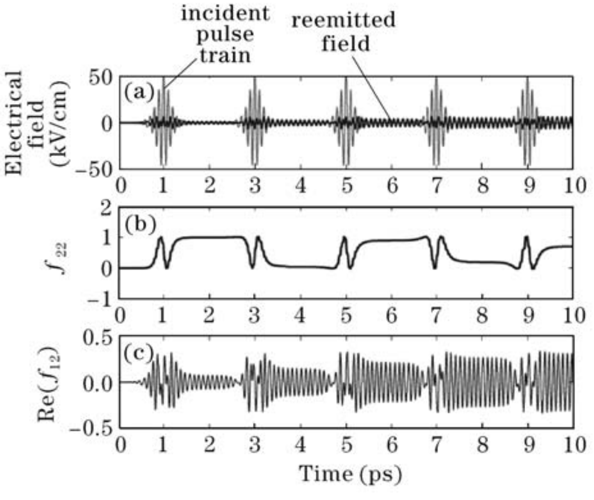

Fig. 3. The same as Fig. 2, but for the relative phase $\phi_k = 0$.

For the second pulse excitation, although the phase relationship between the reemitted field and the pulse of the incident train does not change, the reemitted field shape is inverted compared with Fig. 2(a), i.e., the phase of the reemitted field changes π with the relative phase of the pulses of the incident train.

In Figs. 2 and 3, it is shown that the amplitude of the reemitted field between the successive pulses of the incident train for different relative phases is obviously different. For the relative phase $\phi_k = \pi$ in Fig. 2(a), the amplitude of the reemitted field between the successive pulses almost becomes to zero, whereas it increases with the serial number of the pulses for the relative phase $\phi_k = 0$ in Fig. 3(a). These can be explained by the Maxwell-Bloch Eqs. (1)—(5). From the Eq. (3) and (5), it is shown that the amplitude of the reemitted field is proportional to the time derivative of the real part of the off-diagonal element f_{12}. The relative phase between the successive pulses of the incident train can induce f_{12} change. The real part of the element f_{12} versus time is plotted in Fig. 2(c) for the relative phase $\phi_k = \pi$ and in Fig. 3(c) for the relative phase $\phi_k = 0$. Obviously, the destructive interference leads the real part amplitude of the f_{12} to decrease between the successive pulses in Fig. 2(c), however, the constructive interference leads real part amplitude of the f_{12} to increase between the successive pulses in the Fig. 3(c). So, it could be concluded that the amplitude of the reemitted field between the successive pulses is controlled by the relative phase between the successive pulses of the incident train.

In addition, the reemitted field affected by the different delay time between the successive pulses of the incident train was also investigated. However, we find that the phase of the reemitted field is little influenced by the delay time.

In conclusion, we have investigated the coherent control of the phase of reemitted field in the GaAs/AlGaAs QWs under the femtosecond pulse train excitation. The result shows that the phase evolution of the reemitted field is determined by the relative phase between the successive pulses of the incident train. During interaction between all the odd pulses of the incident train and the semiconductor QWs, the reemitted field is from out-of-phase to in-phase, then again to out-of-phase with the incident pulses. However, during interaction between all even pulses of the incident train and the semiconductor QWs, the reemitted field is from in-phase to out-of-phase, then again to in-phase with the incident pulses. The amplitude of the reemitted field between the successive pulses is controlled by the relative phase of the pulses of the incident train.

This work is supported by the National Natural Sciences Foundation of China (No. 60478002) and the Key Basic Research Foundation of Shanghai (No. 04JC14036 and 05DJ14003). J. Luo's e-mail address is jlsiom@siom.ac.cn.

References

1. N. C. Nielsen, T. H. Siederdissen, J. Kuhl, M. Schaarschmidt, J. Förstner, A. Knorr, and H. Giessen, Phys. Rev. Lett. **94,** 057406 (2005).
2. J. Förstner, A. Knorr, and S. W. Koch, Phys. Rev. Lett.

86, 476 (2001).
3. H. Giessen, A. Knorr, S. Haas, S. W. Koch, S. Linden, J. Kuhl, M. Hetterich, M. Grün, and C. Klingshirn, Phys. Rev. Lett. **81,** 4260 (1998).
4. T. Yoshie, A. Scherer, J. Hendrickson, G. Khitrova, H. M. Gibbs, G. Rupper, C. Ell, O. B. Shchekin, and D. G. Deppe, Nature **432,** 200 (2004).
5. M. C. Phillips, H. Wang, I. Rumyantsev, N. H. Kwong, R. Takayama, and R. Binder, Phys. Rev. Lett. **91,** 183602 (2003).
6. W. A. Hügel, M. F. Heinrich, M. Wegener, Q. T. Vu, L. Bányai, and H. Haug, Phys. Rev. Lett. **83,** 3313 (1999).
7. C. W. Luo, K. Reimann, M. Woerner, T. Elsaesser, R. Hey, and K. H. Ploog, Phys. Rev. Lett. **92,** 047402 (2004).
8. C. Monroe, Nature **416,** 238 (2002).
9. T. M. Fortier, P. A. Roos, D. J. Jones, S. T. Cundiff, R. D. R. Bhat, and J. E. Sipe, Phys. Rev. Lett. **92,** 147403 (2004).
10. M. A. Bouchene, Phys. Rev. A **66,** 065801 (2002).
11. M. Jacquey, S. Bonhommeau, and M. A. Bouchene, Opt. Lett. **28,** 1272 (2003).
12. A. P. Heberle, J. J. Baumberg, and K. Köhler, Phys. Rev. Lett. **75,** 2598 (1995).
13. D. Felinto, C. A. C. Bosco, L. H. Acioli, and S. S. Vianna, Phys. Rev. A **64,** 063413 (2001).
14. A. M. Weiner, D. E. Leaird, G. P. Wiederrecht, and K. A. Nelson, Science **247,** 1317 (1990).
15. S. Schmitt-Rink, D. S. Chemla, and D. A. B. Miller, Adv. Phys. **38,** 89 (1989).
16. J. Faist, F. Capasso, D. L. Sivco, C. Sirtori, A. L. Hutchinson, and A. Y. Cho, Science **264,** 553 (1994).
17. J. Faist, C. Sirtori, F. Capasso, L. Pfeiffer, and K. W. West, Appl. Phys. Lett. **64,** 872 (1994).
18. D. F. Nelson, R. C. Miller, and D. A. Kleinman, Phys. Rev. B **35,** 7770 (1987).
19. W. Kohn and L. J. Sham, Phys. Rev. A **140,** 1133 (1965).
20. K. Ploog and G. H. Döhler, Adv. Phys. **32,** 285 (1983).
21. V. M. Axt and T. Kuhn, Rep. Prog. Phys. **67,** 433 (2004).
22. T. Stroucken, A. Knorr, P. Thomas, and S. W. Koch, Phys. Rev. B **53,** 2026 (1996).
23. J. E. Sipe, J. Opt. Soc. Am. B **4,** 481 (1987).
24. F. Bloch, Phys. Rev. **70,** 460 (1946).
25. A. M. Weiner and D. E. Leaird, Opt. Lett. **15,** 51 (1990).
26. V. Blanchet, M. A. Bouchene, O. Cabrol, and B. Girard, Chem. Phys. Lett. **233,** 491 (1995).
27. E. Yoshida and M. Nakazawa, Opt. Lett. **22,** 1409 (1997).
28. J. Azaña and M. A. Muriel, Opt. Lett. **24,** 1672 (1999).
29. R. Jason Jones and J.-C. Diels, Phys. Rev. Lett. **86,** 3288 (2001).
30. S. Pitois, J. Fatome, and G. Millot, Opt. Lett. **27,** 1729 (2002).
31. H. Haug and S. W. Koch, *Quantum Theory of the Optical and Electronic Properties of Semiconductors* (World Scientific Publishing Co. Pte. Ltd., Singapore, 2004) p.3.