Optical precursors with tunneling-induced transparency in asymmetric quantum wells

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A scheme for separating optical precursors from a square-modulated laser pulse through an asymmetric double $Al_xGa_{1-x}As$/GaAs quantum-well structure via resonant tunneling is proposed. Destructive interference inhibits linear absorption, and a tunneling-induced transparency (TIT) window appears with normal dispersion, which delays the main pulse; then optical precursors are obtained. Due to resonant tunneling, constructive interference for nonlinear susceptibility is created. The enhanced dispersion in a narrow TIT window is about one order of magnitude larger than that of the linear case. In this case, the main pulse is much delayed and the precursor signals are easier to obtain. Moreover, the main pulse builds up due to the gain introduced by the enhanced cross-nonlinearity.

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I. INTRODUCTION

Precursors are characteristic wave patterns caused by dispersion of an impulse's frequency components as it propagates through a medium. Optical precursors were first theoretically studied by Sommerfeld and Brillouin about 100 years ago [1]. When a step-modulated optical pulse enters a dispersive medium with a complex refractive index, the front of the pulse always propagates at the light velocity in vacuum, c. This forerunner pulse is now known as the Sommerfeld-Brillouin precursor. The phenomena of precursors have been observed in γ rays [2], microwaves [3], and sound waves [4]. In 1991, Aaviksoo *et al.* reported the observation of optical precursors when a single-end exponential pulse propagated through a GaAs crystal [5]. Recently, the observation of an optical precursor in water [6] and an abnormal dispersion medium [7] revived the old topic. Due to the potential application of precursors in detection, medical images, and underwater communication [6,8], many theoretical [9–13] and experimental [14–16] works have been carried out.

In general, precursor signals are always mixed with main pulses. It is difficult to extract the optical precursors while the main pulse remains. With the aid of electromagnetically induced transparency (EIT) [17], optical precursors can be separated from a main pulse through an opaque medium in time [18–20]. In this case the precursor signals are significantly ahead of the delayed main pulse due to the slow-light effect. Similar results are also obtained via self-induced transparency induced by the propagating field itself [21]. Very recently, stacked optical precursors were generated from a series of square pulses passing through a cold atomic ensemble [22,23]. Although many works have investigated the characteristics of optical precursors, most of them are based on EIT in atomic systems and consider a linear situation.

Recently, more attention has been paid to semiconductor nanostructure for its important application in optoelectronics and solid-state quantum information science. A quantum well (QW) is a one-dimensional confined semiconductor nanostructure in which electrons and holes exhibit discrete energy levels. This atomiclike property allows the investigation of many quantum coherence and interference phenomena, which were first studied in atomic media, such as Fano interference [24,25], EIT [26], Rabi oscillations [27], coherent population trapping [28], gain without inversion [29], and self-induced transmission [30]. Apart from some advantages than an atomic system involving high nonlinear optical coefficients and flexibility in device design offers, a QW system has its own characteristics, for example, tunneling-induced coherence [24,31]. Based on these properties, applied research is increasingly being performed in QW systems, including ultrafast all-optical switching [32], pulse control [33], enhanced nonlinearity [34,35], slow light [36], optical solitons [37,38], bistability [39], and so on.

Motivated by these works, we propose a scheme for separating optical precursors from a long square-modulated laser pulse through an asymmetric GaAs QW system via resonant tunneling-induced quantum interference and further explore the phenomenon of optical precursors in a case of enhanced nonlinearity. Two resonant subband levels in adjacent QWs are mixed by tunneling and split into a doublet. A probe field couples the transitions between the doublet and another state; then destructive interference between the two transitions leads to a tunneling-induced transparency (TIT) window [31]. When a long square-modulated pulse propagates through this EIT-like window, optical precursor signals are separated from the delayed main pulse at the step-on rising edge. It is more interesting that, since tunneling induces a constructive interference in nonlinear susceptibility in the presence of a control field, enhanced nonlinear dispersion plus linear dispersion substantially delays the main pulse. Thus, it is easier to separate the optical precursors. In addition, the main pulse builds up because of the gain introduced by enhancement of the cross-nonlinearity.

II. THE MODEL AND BASIC EQUATIONS

We consider an asymmetric QW system with the same band structure as in Ref. [35]. As shown in Fig. 1, one would

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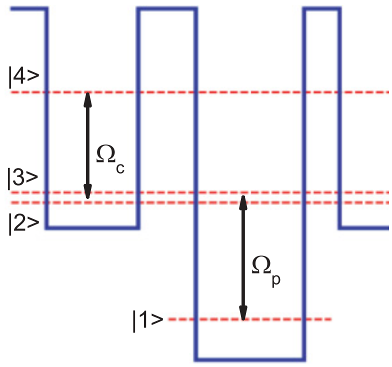

FIG. 1. (Color online) Conduction subband of asymmetric double QWs. An $Al_{0.16}Ga_{0.84}As$ layer with a thickness of 6.7 nm is separated from a GaAs layer with a thickness of 7.9 nm by a 4.2 nm $Al_{0.44}Ga_{0.56}As$ potential barrier. On the right side of the right well is a thin 2.6 nm $Al_{0.44}Ga_{0.56}As$ barrier, which is followed by a thick $Al_{0.17}Ga_{0.83}As$ layer. In the deep well, the energies of states $|1\rangle$ and $|2\rangle$ are 46.0 and 179.2 meV. In the shallow well, states $|3\rangle$ and $|4\rangle$ have the energies 183.1 and 304.8 meV.

observe two states, the ground and first excited states, in the shallow and deep wells, respectively. Resonant subbands $|sg\rangle$ (the ground subband of the shallow well) and $|de\rangle$ (the first excited subband of the deep well) are coupled by tunneling and split into a $|2\rangle$-$|3\rangle$ doublet. Because both $|2\rangle$ and $|3\rangle$ tunnel to the same continuum, the doublets are coupled together. Although our QW system has a similar configuration to an atomic system with characteristic doublets such as alkali-metal vapor, there exists coherence between $|2\rangle$ and $|3\rangle$ states induced by resonant tunneling, which is the inherent property of our QW system. A probe field couples subband $|1\rangle$ to subbands $|2\rangle$ and $|3\rangle$, and a control field couples $|4\rangle$ to $|2\rangle$ and $|3\rangle$. The wave function of the subband $|4\rangle$ in the right continuum can be neglected and the direct optical resonance $|1\rangle$ to the continuum is much weaker than those two mediated resonance paths. So we can ignore the interaction between subband $|4\rangle$ and the continuum and the influence of the direct transition $|1\rangle$ to the continuum. According to the standard process [40], the dynamical equations of the system can be described by equations of motion for the probability amplitudes of the states in a rotating frame as follows:

$$\begin{aligned} \dot{a}_1 &= i\Omega_p(a_2 + qa_3), \\ \dot{a}_2 &= i\Omega_p^* a_1 + i\Omega_c a_4 + i(\Delta_p + \delta + i\gamma_2)a_2 + \kappa a_3, \\ \dot{a}_3 &= iq\Omega_p^* a_1 + i\xi\Omega_c a_4 + i(\Delta_p - \delta + i\gamma_3)a_3 + \kappa a_2, \\ \dot{a}_4 &= i\Omega_c^*(a_2 + \xi a_3) + i(\Delta_p + \Delta_c + i\gamma_4)a_4, \end{aligned} \tag{1}$$

where $\Omega_p = E_p\mu_{12}/2\hbar$ and $\Omega_c = E_c\mu_{34}/2\hbar$ are the Rabi frequencies of the probe and control fields, respectively. The electric dipole matrix elements are denoted by μ_{12} and μ_{34}, $q = \mu_{13}/\mu_{12}$, and $\xi = \mu_{34}/\mu_{24}$ is the ratio between the relevant subband transition dipole moments. $\Delta_p = \omega_p - (\omega_{21} + \omega_{31})/2$ and $\Delta_c = \omega_c - (\omega_{42} + \omega_{32})/2$ are the detunings of the corresponding fields. $\delta = (\omega_3 - \omega_2)/2$. In semiconductor QWs, the total electron decay rate γ_i $(i = 2,3,4)$ consists of the population decay γ_i^{pd} and the dephasing rate γ_i^{deph}. Many factors contribute to the dephasing effect, such as electron-electron scattering, electron-phonon scattering, and inhomogeneous broadening due to scattering on interface roughness. For temperatures up to 10 K and electron density smaller than 10^{12} cm^{-2}, the dephasing rates can be estimated according to [32]. In our QW system, $\gamma_2^{\text{pd}} = 0.58$ meV, $\gamma_3^{\text{pd}} = 0.66$ meV, and $\gamma_4^{\text{pd}} = 0.09$ meV [35]. $\kappa = (\gamma_2^{\text{pd}}\gamma_3^{\text{pd}})^{1/2}$ represents the cross-coupling term that gives rise to Fano interference. Its strength is assessed by $\eta = \kappa/\sqrt{\gamma_2\gamma_3}$; this can be increased by decreasing the temperature, which generally leads to a smaller dephasing rate. Its limit values $\eta = 0$ and $\eta = 1$ correspond to no interference and perfect interference.

It is well known that the response of the QW system to the probe field is governed by its total polarization,

$$P = \varepsilon_0\chi_{\text{eff}}E_p, \tag{2}$$

where the effective susceptibility $\chi_{\text{eff}} = \chi^{(1)} + 3\chi^{(3)}|E_c|^2$ (here the control field is weak, so we consider linearity and third-order nonlinearity) and E_p is the amplitude of the probe field. $\chi^{(1)}$ and $\chi^{(3)}$ are the linear and third-order nonlinear susceptibility, respectively. In the limit of the weak probe field, almost all electrons would remain in state $|1\rangle$, $|a|^2 \approx 1$. Applying the perturbative iterative method, we solve the amplitude equations (1) in steady state and ultimately get the analytical expression of $\chi^{(1)}$ and $\chi^{(3)}$ as follows:

$$\chi^{(1)} = \beta\frac{B + Aq^2 + 2iq\kappa}{AB + \kappa^2}, \tag{3}$$

$$\chi^{(3)} = -\beta\frac{|\mu_{34}|^2}{\hbar^2}\frac{[B + A\xi q + i(\xi + q)\kappa]^2}{C(AB + \kappa^2)^2}, \tag{4}$$

where $\beta = c\alpha_0\gamma_2/(2\omega_p)$, N is the electron volume density, and $\alpha_0 = N|\mu_{12}|^2\omega_p/(c\varepsilon_0\hbar\gamma_2)$ is the absorption cross section. $A = (\Delta_p + \Delta) + i\gamma_2$, $B = (\Delta_p - \Delta) + i\gamma_3$, and $C = (\Delta_p + \Delta_c) + i\gamma_4$.

A step-modulated pulse serves as the probe field,

$$E(0,t) = E_0\Theta(t)e^{-i\omega_p t}, \tag{5}$$

where $\Theta(t)$ is the Heaviside function. Formally, the propagation of the input pulse through a dispersive medium is given by the integral

$$E(z,t) = \frac{1}{2\pi}\int E_0(\omega)e^{i[k(\omega)z - \omega t]}d\omega, \tag{6}$$

where $E_0(\omega)$ is the spectrum of the input pulse, and $k(\omega) = k_0\sqrt{1 + \chi_{\text{eff}}}$ with $k_0 = \omega_{21}/c$. The exponent part of Eq. (6) is the complex phase originating from propagating through the QW system. Tunneling-induced quantum interference results in a transparency window to the probe pulse where the slow-light effect separates the precursor signals from the delayed main pulse. According to theoretical analysis in Refs. [19,21], the output pulse is given by

$$E(z,t) = E_{\text{SB}}(z,t) + E_M(z,t). \tag{7}$$

The first part is the Sommerfeld-Brillouin precursor

$$E_{\text{SB}}(z,t) = E_0 J_0(\sqrt{2\alpha_0 z\gamma_2\tau})\Theta(\tau)e^{-\gamma_2\tau}e^{i(k_p z - \omega_p\tau)}, \tag{8}$$

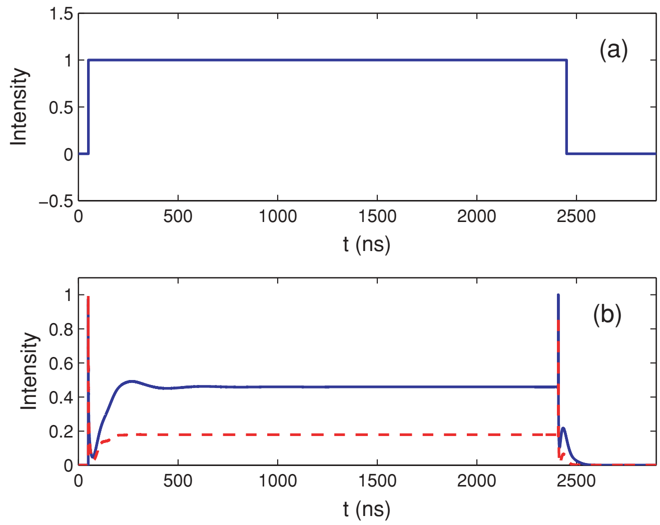

FIG. 2. (Color online) Observation of optical precursors from a square-modulated pulse through a QW system. (a) The input square pulse with no QWs present. (b) The optical precursor signal and delayed main pulse with TIT (blue solid line) and without TIT ($\kappa = 0$, red dashed line). Optical depth $\alpha_0 z \approx 43$ and $\Omega_c = 0$.

where $\tau = t - z/c$ and J_0 is the zero-order Bessel function of the first kind. The second part is the delayed main pulse

$$E_M(z,t) = \int_{-\infty}^{\infty} G_{\mathrm{TIT}}(z,t-\tau)E(0,-\tau)\,d\tau. \qquad (9)$$

Here, the main pulse is expressed as the convolution of the input pulse and the Green function $G_{\mathrm{TIT}}(z,t)$ to avoid the singularity of the rising and falling edge of the input pulse at $\Delta_p = 0$.

III. RESULTS AND DISCUSSIONS

At first, the control field is absent, and we consider the steady-state transmission of a long square-modulated pulse through the TIT window. Figure 2(a) shows the 2.4 μs input pulse. The output pulse is determined by the linear susceptibility $\chi^{(1)}$ [solid blue line in Fig. 2(b)], and we can see the optical precursor signals ahead of the main pulse. In this case, the probe field couples the ground subband $|1\rangle$ and the new subbands $|2\rangle,|3\rangle$ that tunnel to the continuum; then a Fano-type interference arises between the two transition pathways. In our QW configuration, the tunneling-induced destructive interference reduces the linear absorption effectively and a TIT window appears with large normal dispersion. Then, the slow-light effect delays the main signal and allows us to obtain the precursor signals. This result is somewhat similar to the recent experimental report [19], although we separate the optical precursors from the main pulse by a different mechanism, tunneling-induced Fano interference. If there is no interference effect ($\kappa = 0$), our QW system becomes a general three-level system. The precursor signals tend to mix with the main pulse because of a bad slow-light effect [dashed red line in Fig. 2(b)].

Next, we turn to the case with a continuous control field, when tunneling-induced large cross-nonlinearity becomes pronounced. Then the former TIT window splits into two

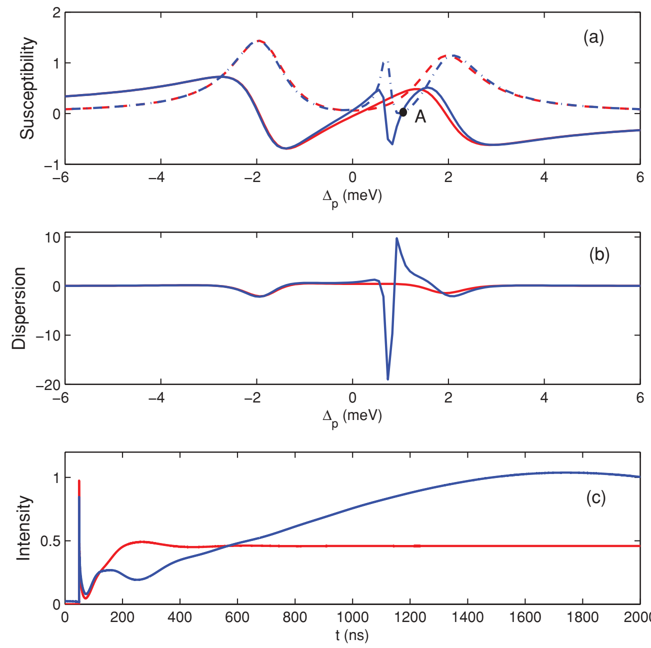

FIG. 3. (Color online) (a) Re[$\chi^{(1)}/\beta$] (red solid line), Im[$\chi^{(1)}/\beta$] (red dashed line), Re[$\chi_{\mathrm{eff}}/\beta$] (blue solid line), and Im[$\chi_{\mathrm{eff}}/\beta$] (blue dash-dotted line); (b) dispersion of QWs and (c) intensity of optical precursors at the rising edge of input pulse, red line for $\Omega_c = 0$, blue line for $\Omega_c = 0.2$ meV and $\Delta_c = 0.73$ meV. Optical depth $\alpha_0 z \approx 43$.

[see blue dash-dotted line in Fig. 3(a)]. It is interesting to find that, at a certain detuning, there is a narrow transparency window with steep normal dispersion, for example, at point A ($\Delta_p = 1$ meV) in Fig. 3(a). We notice that, in the presence of the control field, the real part of the effective susceptibility χ_{eff} in the narrow TIT window becomes steeper than that of the linear case. The corresponding dispersions of the QWs in the two cases are plotted in Fig. 3(b). We can see that the enhanced dispersion of the QW system at point A is about one order of magnitude larger than the linear dispersion at the resonant frequency. When an input pulse propagates through this narrow TIT window, the precursors are significantly ahead of the main field. For comparison, the transmissions of two step-modulated incident pulses in the linear and nonlinear cases are plotted in Fig. 3(c). It is easy to see that optical precursors appear at the rising edge of the input pulse. More important, for the nonlinear case, the main pulse is much delayed and its strength is enhanced. According to the description in Refs. [5,19], the separation of precursor and main pulses requires that the duration of the precursors is less than the delay time of the main pulse; thus we need to calculate the group delay time to qualitatively scale their separation. The time delay of the main pulse can be calculated according to $\tau = l(1/v_g - 1/c)$, where the group velocity $v_g \approx c/[1 + 2\pi\omega d\,\mathrm{Re}(\chi_{\mathrm{eff}})/d\omega]|_{\omega=\omega_0}$ and ω_0 denotes the resonant frequency in the TIT window. In the linear case, the main pulse is delayed 139 ns [red solid line in Fig. 3(c)], while, in the nonlinear enhanced case, the time delay is 1.46 μs for $\Omega_c = 0.2$ meV, $\Delta_c = 0.73$ meV, and the other parameters the same as in the linear case [see blue solid line in Fig. 3(c)]. This time delay is about tenfold longer than that of the linear case. So optical precursors are much better separated

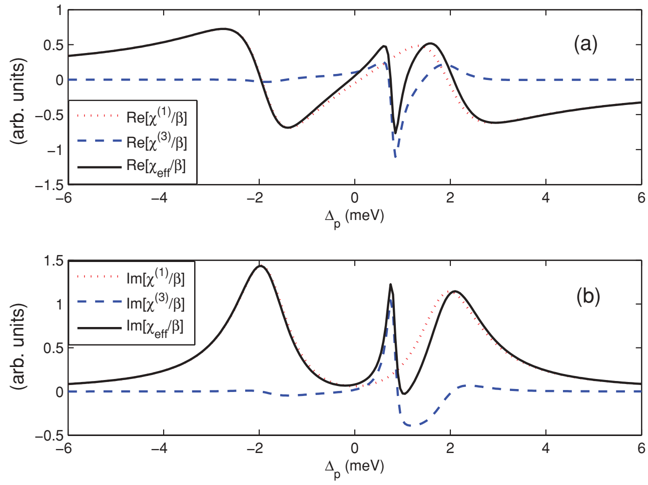

FIG. 4. (Color online) (a) Real and (b) imaginary parts of $\chi^{(1)}/\beta$, $\chi^{(3)}/\beta$, and $\chi_{\rm eff}/\beta$ vs the probe detuning Δ_p. $\Omega_c = 0.2$ meV, $\Delta_c = -0.73$ meV.

in the proposed scheme. Physically, resonant tunneling induces constructive interference for the nonlinear susceptibility; then steep normal dispersion appears, which substantially delays the main pulse and allows us to obtain optical precursors more easily.

We further examine the real and imaginary parts of $\chi^{(1)}/\beta, \chi^{(3)}/\beta, \chi_{\rm eff}/\beta$, as shown in Fig. 4. Obviously, one can see that $\chi^{(3)}$ is approximately coincident with $\chi_{\rm eff}$ in the narrow transparency window. We know that resonant tunneling induces an enhancement of cross-nonlinearity. Its real part mainly contributes to the steep dispersion of $\chi_{\rm eff}$ in the narrow transparency window [see Fig. 4(a)], and negative absorption in its imaginary part introduces the buildup of the main pulse [see Fig. 3(b)]. In other words, the constructive interference induced by resonant tunneling results in the narrow TIT window where the enhanced cross-nonlinearity causes the well-separated optical precursors and the gain of the main pulse.

Finally, we compare the optical precursors at different optical depths and probe detunings. As the optical depth increases, the arrival time of the main pulse becomes more delayed due to the slow-light effect [see Fig. 5(a)]. Figure 5(b) shows steady-state transmission at the narrow TIT window for different probe detunings, $\Delta_p = 0.72$ meV, $\Delta_p = 1$ meV, and $\Delta_p = 1.28$ meV. It is easy to see that only when the incident pulse propagates through the narrow TIT window at a certain detuning [$\Delta_p = 1$ meV, i.e., point A in Fig. 3(a)], can the precursor signals be well separated from the main pulse.

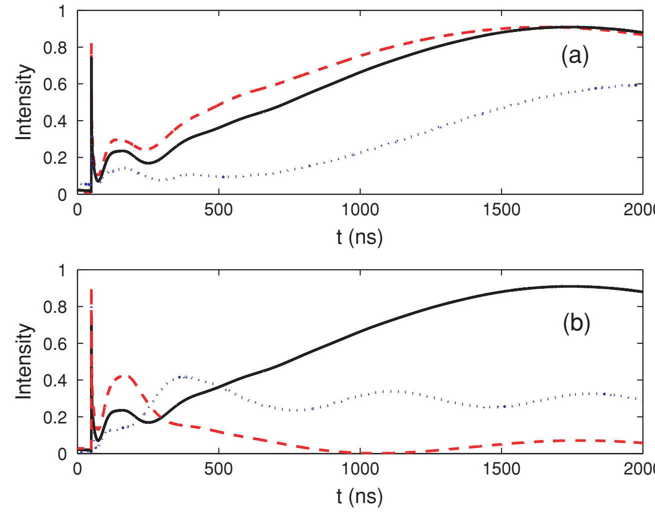

FIG. 5. (Color online) Optical precursor at the rising edge (a) for different optical depths $\alpha_0 z \approx 21$ (red dashed curve), 43 (black solid curve), 64 (blue dotted curve) and (b) for $\Delta_p = 0.72$ meV (red dashed curve), $\Delta_p = 1$ meV (black solid curve), $\Delta_p = 1.28$ meV (blue dotted curve), $\alpha_0 z \approx 43$. $\Omega_c = 0.2$ meV, $\Delta_c = -0.73$ meV.

IV. SUMMARY

In conclusion, we propose a scheme for obtaining the optical precursors in asymmetric semiconductor QWs via tunneling-induced quantum interference. The normal dispersion induced by resonant tunneling in the TIT window delays the main pulse of the input pulse, so that the precursor signals are separated from the input pulse. More interesting, when a control field is applied, resonant tunneling induces constructive interference for cross-Kerr-nonlinearity, and much larger normal dispersion appears in a narrow TIT window, which much delays the main pulse. Then it is easier to obtain the optical precursors from the incident pulse. Moreover, we notice that the main pulse builds up because of the gain introduced by the enhanced cross-nonlinearity.

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