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Observation of phase shifts in a vertical cavity quantum dot switch

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We have studied the possibility to utilize semiconductor quantum dots (QDs) as an optical phase shifter within a vertical geometry for ultrafast information processing. From theoretical analyses, an optical phase nonlinearity in QD structures has been predicted which can be enhanced through the use of an vertical optical cavity. Asymmetric cavity structures with 16/30 periods of GaAs/AlGaAs layers for the front/back mirrors have been fabricated to demonstrate a practical device with significant nonlinear characteristics for optical switching. A phase shift of 18° has been initially observed with a tilted pump scheme. This observation paves the way toward a Mach–Zehnder optical switch using QDs inside a vertical cavity. © 2011 American Institute of Physics. [doi:10.1063/1.3596704]

Semiconductor quantum dots (QDs) have been anticipated to be an ideal nonlinear material for the applications of ultrafast optical communications and quantum information processing.^{1–3} One of the most important benefits of QDs as a nonlinear medium is that the state filling effect only requires one electron–hole pair for each individual dot. This phenomenon results in the delta-function-like QD states exhibiting a high optical nonlinearity which can be induced using a very low operating power. However, due to the dispersive distribution of self-assembled QDs in both real and frequency space, the effective cross section of the light–QD interaction is extremely small. An enhancement of the interaction is therefore required for practical devices based on QD ensembles. Indeed, combined with either a two-dimensional photonic crystal waveguide or a vertical cavity, all-optical QD switches have been demonstrated recently.^{4,5} So far, the optical phase nonlinearity of QDs has been only observed in two-dimensional photonic waveguides for the development of an all-optical Mach–Zehnder (MZ) switch.⁴ Although QD switches with a vertical geometry have unique advantages, such as a small size, low power consumption, and ease of fabrication and packaging,⁶ the use of the phase nonlinearity of QDs in a vertical direction is, as yet, undeveloped.

In this work, the optical phase nonlinearity in a vertical cavity QD structure has been investigated. Theoretical results indicate that the phase shift in QDs can be greatly enhanced by simply increasing the number of periods of the distributed Bragg reflector (DBR) mirrors which form the cavity. Based on the theoretical prediction, phase shifts in a highly nonlinear QD-cavity have been tested experimentally.

Figure 1 presents a schematic diagram of a vertical-cavity QD switch. The cavity includes two DBR mirrors, which consist of alternative GaAs and AlGaAs layers each of which has a film thickness of $\lambda/4$. QD layers are inserted into the cavity at antinode positions of the electromagnetic field to achieve the nonlinear enhancement of the QD-light

interaction. Pump light injected into the cavity saturates the QD absorption and hence results in a differential reflectivity of the probe light. This is the normal working principle of a vertical cavity QD switch as reported in more detail elsewhere.^{5,6} However, to employ this vertical structure as a practical optical nonlinear phase shifter, some further optimization is required. In the QD-cavity structure, the center wavelength of the absorption saturation is defined by the wavelength of cavity mode. The QD absorption saturates with a spectral linewidth of δ , which is limited by the homogenous broadening of the absorption spectra of the QD ensemble. The change in the refractive index in the dot layer follows the Kramers–Kronig relation, as shown on the right hand side of Fig. 1. Assuming no carrier heating effects occur in the passive QD structure, the refractive index change is close to zero at the center wavelength. Away from the center wavelength, if the probe light is tuned to a different value within the spectral linewidth of the ensemble, the probe light will now experience a small refractive index

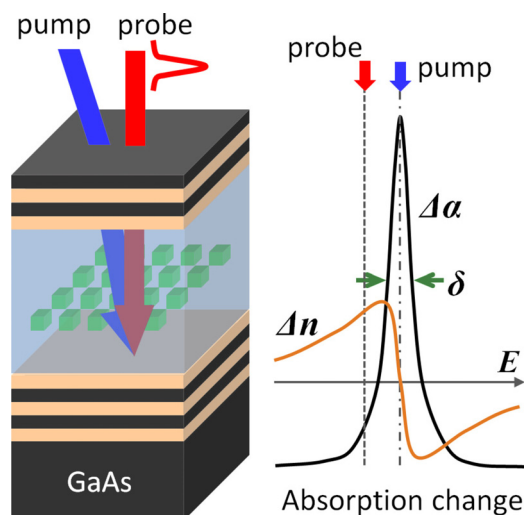


FIG. 1. (Color online) A schematic diagram of working principles for a vertical cavity QD switch. The right hand side diagram shows both the differential absorption and refractive index change in the dot layer.

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change in the dot layer. This small change in the refractive index induces a phase shift when the light passes through the whole structure. Assuming a transfer matrix for an approximately quarter-wave layer with a small thickness deviation of $\varepsilon \cdot \lambda / 2\pi$ which has the form of

$$M_{\lambda/4} = \begin{bmatrix} -\varepsilon & i/n_H \\ in_H & -\varepsilon \end{bmatrix}, \quad (1)$$

where n_H is the refractive index of the GaAs. For the $m\lambda/2$ cavity, the transfer matrix of the active region becomes

$$M_{active} = \begin{bmatrix} -1 & -2mi\varepsilon/n_H \\ -2mi\varepsilon n_H & -1 \end{bmatrix}. \quad (2)$$

By writing down the transfer matrix for the whole structure including all DBR layers, the phase shift is derived as

$$\Delta\phi \cong \tan \Delta\phi = \frac{-2m\varepsilon n_H \left(\frac{n_H}{n_L}\right)^{2p}}{1 + n_H \left(-\frac{n_L}{n_H}\right)^{-2p+2q}}, \quad (3)$$

where n_L is the refractive index of AlGaAs, and p and q are the period number of the GaAs/AlGaAs layers in the front and back DBR mirrors. In the case of an asymmetric cavity with $q \gg p$, the phase shift can be simplified to be

$$\Delta\phi \cong -2m\varepsilon n_H \left(\frac{n_H}{n_L}\right)^{2p}. \quad (4)$$

The factor $(n_H/n_L)^{2p}$ represents the enhancement due to the vertical cavity. Hence, by increasing the number of periods of the front mirror, p , the optical phase shift for the whole structure can be amplified dramatically. It is therefore possible to achieve a large nonlinear phase shift in the vertical direction for QDs.

Following the above discussion and the more detailed theoretical description in Ref. 6, an asymmetric cavity with $p=16$ and $q=30$ periods of GaAs/AlGaAs DBR mirrors has been fabricated. The sample was grown epitaxially on GaAs (001) substrates using an Oxford V90 molecular beam epitaxy system. 2.6 ML InAs was deposited within an 8 nm $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ quantum well (QW) to give a dot-in-a-well (DWELL) structure which forms the active element. Three DWELLs closely placed in a stack were inserted at each antinode position of the electromagnetic field. A $3\lambda/2$ cavity is employed with three antinodes and therefore 3×3 dot layers inside the active region. The QD excited state emission peak is assigned to match the cavity resonant mode at $1.240 \mu\text{m}$.⁵ The switching dynamics of the vertical cavity QD switch were characterized by degenerated pump-probe measurements. 130 fs optical pulses with a repetition rate of 80 MHz were generated using an optical parametric oscillator. When the pump beam excited the front cavity mirror at the wavelength of the cavity mode, the differential reflectivity was then traced by the probe beam. A switching process with a time constant of 20 ps was demonstrated as shown in Fig. 2(a). The power-dependent differential reflectivity measurement indicates a saturation power density of $2.5 \text{ fJ}/\mu\text{m}^2$ and a maximum differential reflectivity close to 10% of the original intensity of the probe beam. The differential reflectivity is significantly enhanced from previous reported results,⁶ which indicates that the device is now working

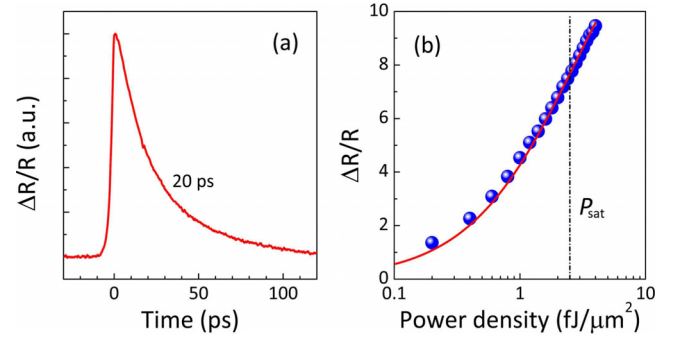


FIG. 2. (Color online) (a) Switching dynamics from all-optical QD switches with 16/30 periods GaAs/AlGaAs for the front/back DBR mirror. (b) Differential reflectivity as a function of pumping power density. The solid curve is simulation results considering a saturable absorption behavior in the dot layers, using a theoretical model described in Ref. 6.

within a highly nonlinear region. It is therefore possible to achieve practically significant values of nonlinear phase shift.

Figure 3 describes a MZ interferometer setup for the evaluation of phase shifts in vertical cavity QD switches. To achieve the small wavelength shift between the pump and probe beams, as suggested in Fig. 1, the pump beam was slightly tilted with an angle $\theta=20^\circ$. Because the femtosecond pulse in the system has a spectral broadening of around 20 nm, the use of tilted injection automatically selects a pump wavelength 5 nm shorter than the probe. Thus, 5 nm detuning is achieved with the degenerated pump-probe setup. The spectral linewidth of the absorption saturation in the dot ensemble is limited by the homogeneous broadening linewidth at room temperature, which has a typical value around 6 meV.⁷ Therefore, the 5 nm detuning is approaching the maximum refractivity change defined by the Kramers–Kronig relation. In the MZ scheme, the probe beam is divided into two beams with an optical beam splitter. One of the beams passes through the optically pumped QD switching sample and the other beam is modified by an optical phase compensator. Those two beams join together after a beam splitter and give the output signal. All the optical components in this setup are integrated into a compact box with fiber based input and output connections to achieve high signal to noise ratio. Very small optical phase shifts with a resolution of ~ 0.5 degree can be evaluated by this arrangement by comparing the interference patterns with and without the pump beam.

Figure 4(a) shows the results of the phase shift measurement. By adjusting the phase compensator, the output intensity follows a sinusoid function with observable bright and

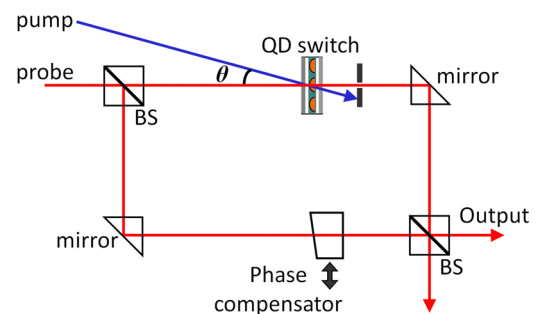


FIG. 3. (Color online) A schematic diagram of a MZ interferometer setup for the evaluation of optical phase shifts inside QDs. BS: beam splitter.

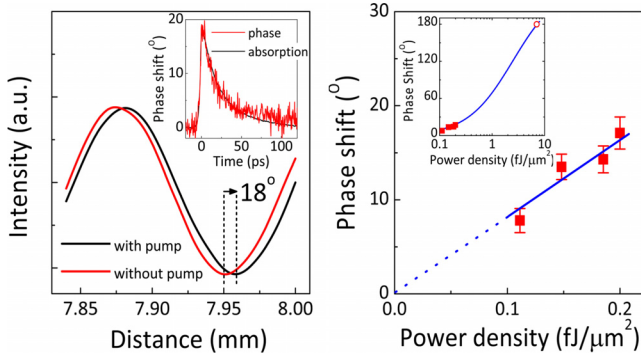


FIG. 4. (Color online) (a) Interference patterns from the MZ interferometer with and without optical pumping of the QD switch sample. The inset shows the phase dynamics (solid curve) compared to the absorption dynamics (dashed curve). (b) Phase shifts as a function of pumping power density. The inset shows simulation results assuming that the refractive index change inside QDs follows a saturation function. The solid squares are from the experimental data shown in the main figure. The open circle indicates a π phase shift could be achieved with a pump power intensity of $7 \text{ fJ}/\mu\text{m}^2$ with the present device.

dark regions in the interference pattern. By pumping the QD switch with a 20 pJ optical pulse, the pattern is shifted by $9.0 \mu\text{m}$, which corresponds to an 18° phase shift inside the switching device. The phase dynamics has been measured by tracing the intensity change in the interference pattern in the time scale, which was further converted into the phase space as shown in the inset of Fig. 4(a). The switching curve in terms of the absorption dynamics (dashed curve) has been rescaled to compare with the phase dynamics (solid curve). The phase dynamics follows almost the same tendency as the absorption dynamics, although the last part of it is slightly slower, similar as the previous reports on the QD-photonic crystal switches⁸ and the passive region of QD semiconductor optical amplifiers.^{9,10} Using Eq. (4), the refractive index change in the dot layer can be calculated

$$\Delta n_{\text{QD}} = \frac{D_a}{d_{\text{QD}}} \times \frac{\varepsilon}{\pi/2} = -\frac{D_a}{d_{\text{QD}}} \frac{\Delta\phi}{\pi m n_H \left(\frac{n_H}{n_L}\right)^{2p}}, \quad (5)$$

where $D_a = 3\lambda/2$ is the thickness of the active region and $d_{\text{QD}} = 10 \text{ nm}$ is the thickness of each individual dot layer. With $n_H = 3.461$, $n_L = 3.045$, and $m = 3$, the refractive index change is evaluated to be $\sim 0.3\%$ of the original value of QDs. This value of refractivity nonlinearity is smaller than previous reported values in Ref. 1. The reason for this decrease is that the pump beam from the fiber has a spot size of $\sim 300 \mu\text{m}$, which provides a pump power density of $0.22 \text{ fJ}/\mu\text{m}^2$. This is at least a decade below the saturation influence, which will be around $2.5 \text{ fJ}/\mu\text{m}^2$. A linear dependence of the optical phase shift on the pump beam power is observed, as shown in Fig. 4(b). The inset in Fig. 4(b) presents the power-dependent phase shift in a large scale from the simulation result in which we assume the refractive index change follows a saturation function. Accordingly, up to a π phase shift from the device could be achieved if an additional focusing component were to be integrated into the compact system. Another possible approach to enhance the phase shift is to increase the number of periods of the DBR

mirror as indicated in Eq. (4), although this requires the growth of thicker vertical cavities.

Several approaches have been already proposed to accelerate the switching dynamics for vertical cavity QD switches down to the picosecond timescale using mechanisms such as the optical Kerr nonlinearity,^{11,12} carrier tunneling mechanisms from an additional QW,¹³ or impurity doping.¹⁴ Comparing these previous approaches to our new strategy of utilizing the optical phase nonlinearity in a MZ scheme, we believe our approach could achieve ultrafast switching with less limitations placed on it by the carrier dynamics inside the QDs while also retaining ultralow power operation.¹⁵ Moreover, the vertical insertion of such samples into a MZ scheme provides a geometry which has advantages for massive integration and lower packaging costs.

In summary, we have proposed and demonstrated an approach to vertically utilize all-optical QD switches as nonlinear optical phase shifters for use in a MZ interferometer configuration. The theoretical results predict a large enhancement of the phase nonlinearity using a vertical cavity. An 18° phase shift has been observed from a 0.3% change in the reflective index inside QDs at an excitation density of $0.22 \text{ fJ}/\mu\text{m}^2$. This observation provides a possibility of fabricating low-cost, low-power-consumption, all-optical MZ switches based on InAs/GaAs QDs.

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