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Ultrafast all-optical switch in Bragg-spaced quantum well contained uniform quantum dots

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All-optical switching in Bragg-spaced quantum well contained uniform quantum dots (QDs) is investigated in theory. With our design, it is nonresonant excitation for pumping a few meV below the photonic band-gap. The active photonic band-gap structure is shifted by the optical Stark effect, and the circular dichroism and birefringence are induced by the circular polarized pump light. Thus, the optical switching can be realized based on the ultrafast nonlinear effect. The switch, with great advantages of lower requirement of pump light intensity and high contrast ratio, is a promising candidate for the ultrafast all-optical switching devices in future.

Keywords: optical switching, circular dichroism, quantum dots.

1. Introduction

All-optical polarization switches based on Bragg-spaced quantum wells (BSQWs) have been reported [1–4], which take advantage of the properties of an optical Stark effect and have achieved control-pulse-width-limited switching time due to the ultrafast suppression and recovery of the active photonic band-gap structure in BSQWs. However, the thermalization of the excitons in quantum wells makes this switch work only at low temperature [3, 4], and cannot be applied in the practical optical communication system.

In the same time, QDs applied in the optical device have been researched widely. Many works have been carried out on how to grow the QDs uniformly and controllably [5–9]. Until now, the QDs' inhomogeneous broadening caused by the fluctuations of QD sizes can be reduced to about 10 meV [9]. QDs also are the perspective material to fabricate all-optical switching according to their large nonlinearity. The requirements of all-optical switches are an ultrafast response time, a high repetition rate, low switching energy, a high extinction ratio, and a low insertion loss. QDs have been utilized in all-optical switching in different ways. An early report on all-optical switching contained QDs was semiconductor-doped glasses [10, 11], but it required an impractically high excitation power due to the use of non-resonant nonlinearity, and its extinction ratio is not big enough. In Ref. [12], PRASANTH *et al*. reported all-optical switching due to state filling in quantum dots within a Mach–Zehnder interferometer switch. In Ref. [13], HITOSHI NAKAMURA *et al*. demonstrated a two-dimensional photonic crystal based symmetric Mach–Zehnder type all-optical switch with InAs QDs acting as a nonlinear phase-shift source. In Ref. [14], CHAO-YUAN JIN *et al*. developed a vertical-geometry all-optical switch device based on self-assembled InAs QDs within a GaAs/$Al_{0.8}Ga_{0.2}As$ vertical cavity structure. However, there are some limitations in the above all-optical QDs switching, and the requirements are not all satisfied.

In the present paper, we design an all-optical switching in Bragg-spaced quantum well contained uniform quantum dots. The QDs with homogeneous broadening are considered. We theoretically investigate the switching characteristics by a transfer matrix method. The switch shows great advantages of lower requirement of pump light intensity and high contrast ratio.

2. Model and theory

In Figure 1, a schematic of the studied switching structure is shown. It is a system consisting of the uniform QDs embedded in the Bragg-spaced InGaAs/GaAs layers which exhibit a one-dimensional photonic band-gap [15, 16]. The QD with the enhanced activation energy can prevent the thermal ionization of excitons, and improve the switch's temperature characteristic [17]. The exciton energy is 0.83 eV (1500 nm) by capping with InGaAs layer [18]. The parameters of the structure and some main parameters used in the calculations are listed in Table 1. In our optical switch,

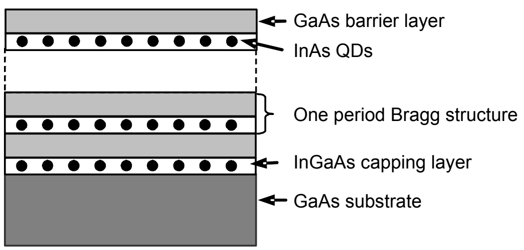

Fig. 1. The schematic of one Bragg period of the switching structure.

Table 1. The value of the parameters.

Symbol	Quantity	Value
d_w	Thickness of InGaAs	9 nm
d_b	Thickness of GaAs	199 nm
h	Diameter of QDs	7 nm [19]
γ	Nonradiative decay rate	5 ns^{-1} [24]
Γ	Radiative decay rate of QDs layer	7 ns^{-1} [25]

the sample is placed between crossed polarizer in reflection geometry [20]. The control light which is a Gaussian pulse is spectrally centered 3 meV below the exciton resonance (0.83 eV) to assure it is non-resonant, and has 1 ps duration with an intensity of 0.5 MW/cm^2. Similar to the control light, the detuning of the signal light is 3 meV below the exciton resonance, the duration is 160 fs and the intensity is 1% intensity of the control light.

Firstly, because the quantum dots' dimension is very small compared to the signal wavelength, the QDs can be treated as electrically small objects. The effective medium theory [21] can be used to calculate the electromagnetic response. Here we will use the Maxwell–Garnett approach [22] to describe the dielectric properties of the nano-composite. The effective permittivity

$$\frac{\varepsilon_{\rm eff} - \varepsilon_{\rm h}}{\varepsilon_{\rm eff} + 2\varepsilon_{\rm h}} = \frac{\varepsilon_{\rm QD} - \varepsilon_{\rm h}}{\varepsilon_{\rm QD} + 2\varepsilon_{\rm h}} f \tag{1}$$

with $\varepsilon_{\rm QD}$ ($\varepsilon_{\rm h}$) – the permittivity of the QDs (GaAs host medium) and $\varepsilon_{\rm h} = 3.5$; f is the QD volume fraction which is much smaller than the volume fraction of the host medium $f = 0.05$. And now, the QD layer will be approximated by a thin layer with an average refractive index, $n = \sqrt{\varepsilon_{\rm eff}}$.

After that, we will use the transfer matrix method [20, 23] to calculate the reflectivity of the Bragg quantum well contained uniform QDs. The exciton susceptibility is

$$S = \frac{\Gamma}{\omega - \omega_0 - \Delta\omega + i\gamma} \tag{2}$$

where Γ is the QDs radiative decay rate [24], γ is the QDs nonradiative decay rate [25], ω_0 is the exciton resonance frequency, $\Delta\omega_0$ is the variable quantity of the exciton resonance frequency caused by the Stark effect [26]

$$\hbar\Delta\omega_0 \approx \frac{D^2 I_p}{\varDelta\sqrt{\varepsilon/\mu}}$$

while D is the dipole moment of the transition, and ε and μ are the permittivity and permeability of the material, I_p is the pump laser intensity, $\varDelta$ is the pump laser energy detuned from the QD transition.

The N blocks transfer matrix can be written as

$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = T_b^{1/2} \left[T_w(S)\right]^N T_b^{1/2} \tag{3}$$

where $T_b^{1/2}$ is the transfer matrix through the halves of the barriers surrounding the quantum well, $T_w(S)$ is the transfer matrix of a block and is the function of S. Then, the reflectivity can be calculated by $R = |T_{21}/T_{22}|^2$.

In Figure 2, the reflectivity spectrum of Bragg well contained QDs is shown. Here, we only consider the normal incidence. With the pump laser, there is a blue shift in the Bragg well reflectivity because of the Stark shift. Especially, at the phone energy 0.827 meV, the reflectivity declines from 0.9 without the pump laser to 0.05 with the pump laser. When we set the signal pulse at 0.827 eV (1503 nm), it applies to all-optical switch according to the great change of the reflectivity. In addition, the collapse in the reflectivity is due to the nonlinearity in the QDs.

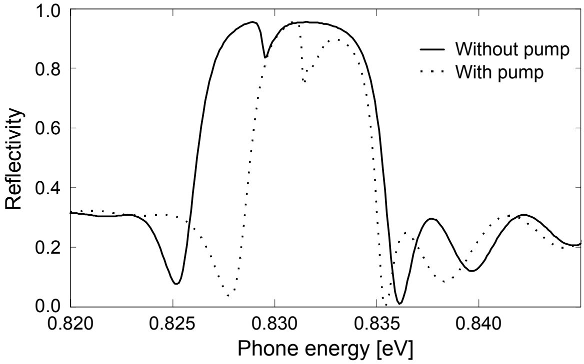

Fig. 2. The reflectivity spectrum of Bragg quantum well contained QDs with the pump pulse 0.827 meV, intensity $I_p = 0.5\times10^{10}$ W/m^2, $N = 100$.

What is more, the circular pump laser also can bring about circular dichroism and birefringence in the quantum dot layers due to the spin-dependence selection rules [1]. The linearly polarized signal light contains equal amounts of right (σ^+) and left (σ^-) circularly polarized light. The right circularly polarized control light are both almost normally incident to the quantum well plane. Without the control light, the signal light is perpendicular to the linear analyzer and cannot pass through the analyzer (which is perpendicular to the signal light) due to the unchanged polarization state of the signal light (*i.e.*, the switch is tuned off). With the control light, the reflectivity stopband of σ^+ polarization component is partially suppressed, but that of σ^- polarization is almost unchanged. Consequently, σ^+ and σ^- components of the signal light have a different amplitude and phase. The signal polarization is thus rotated and becomes elliptically polarized, which means that a portion of the signal light is allowed to pass the analyzer (*i.e.*, the switch is tuned on). So, the polarization state of a linearly polarized light is changed in the control pulse time scale, and it also is another principle for the optical switching.

In QDs, the refractive index change is given by $\Delta n = \mathrm{Re}(\chi/2n)$; χ is the optical susceptibility, n is the refractive index, Δn is influenced by the control light amplitude [27]. Under the operation with the external light field, the third-order nonlinear refractive index is changed. This property is the cause of the light-induced circular dichroism. The polarization ellipse defining the orientation angle θ can be written by the following expression:

$$\theta(\omega, t) = -\frac{\omega L}{2c}\Delta n(\omega, t) \tag{4}$$

where L is the sum of QDs layers thickness $L = Nd_w$, $d_w = 9$ nm is QDs layers thickness, c is the speed of light. There is an ellipticity, but it is very small, we assume it is approximately equal to zero. Taking the extremely small extinction ratio of the polarizer $\eta \approx 10^{-5}$ into count, the reflected intensity has a form:

$$I_{\text{out}}^{\text{on}}(t) = \int \mathrm{d}\omega I_{\text{in}}(\omega, t) R^{\text{on}}(\omega) \sin^2\left[\theta(\omega, t)\right] \tag{5}$$

$$I_{\text{out}}^{\text{off}} = \eta \int \mathrm{d}\omega I_{\text{in}}(\omega, t) R^{\text{off}}(\omega) \tag{6}$$

where the on/off superscripts denote the on/off state of the switch, and in/out subscripts denote the in/out signal pulse. $R(\omega)$ represents the reflective spectrum of the structure. The contrast ratio (CR) can be written:

$$\text{CR}(t) = \frac{I_{\text{out}}^{\text{on}}(t)}{I_{\text{out}}^{\text{off}}} = \frac{\int \mathrm{d}\omega I_{\text{in}}(\omega, t) R^{\text{on}}(\omega) \sin^2\left[\theta(\omega, t)\right]}{\eta \int \mathrm{d}\omega I_{\text{in}}(\omega, t) R^{\text{off}}(\omega)} \tag{7}$$

Figure 3 depicts the time response of the contrast ratio which we calculated by (7). When the control and signal light arrive in the sample simultaneously, the strongest control light intensity induces maximal changes of susceptibility and reflectivity index. The signal becomes elliptically polarized and a large portion of the signal light can

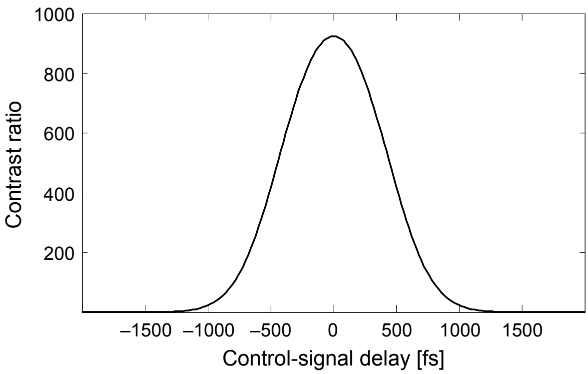

Fig. 3. Calculated contrast ratio as a function of control-signal delay at room temperature, 100 periods, $I = 0.5$ MW/cm^2.

transmit this polarizer. At the end of control light, the signal light passes the quantum--dot layers without any polarization state change due to the vanishing of the circular dichroism, and it cannot pass through the polarizer. The switching time is pulse-width limited. Because it is nonresonant excited, there is not any free carrier generated. The switching can recover quickly after the pump pulse and the repetition rate is not restrained [1].

Figure 4 shows the dependence of the contrast ratio on the increase of the control light intensity. The contrast ratio is up to the maximum value 1600 at the control light intensity of 2 MW/cm^2 which is smaller than that of the structure made of BSQWs [1]. After that, the contrast ratio does not change greatly with the increase of the control light intensity, because the absorption coefficient is saturated due to the dramatically enhanced third order susceptibility.

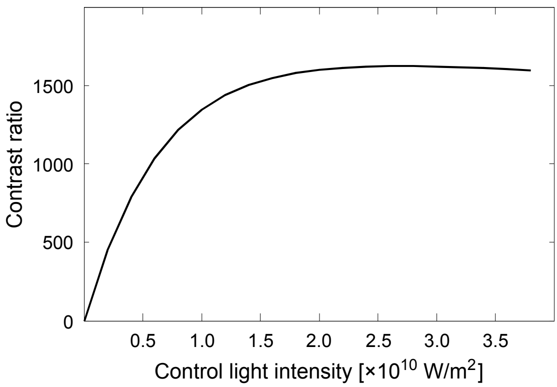

Fig. 4. Dependence of the contrast ratio on the increase of the control light (0.827 eV) intensity.

Finally, we should discuss the influence of the inhomogeneous broadening on our all-optical polarization switch. Our switch is sensitive to the inhomogeneous broadening. The inhomogeneous broadening of the QDs fabricated by the Stranski–Krastanow growth mode usually is more than 10 meV. On the one hand, if we set the pump pulse too close to exciton resonance energy, the non-resonant condition may not be met according to the large inhomogeneous broadening. Some of the QDs are excited resonantly and cannot recover instantaneously because of the long life time of the carrier. Or we can set the pump pulse farther below the exciton resonance energy, but the nonlinearity will be very small and we have to aggrandize the power of the pump pulse. On the other hand, the reflectivity spectra also are related to the inhomogeneous broadening. If the inhomogeneous broadening is very big, there is not high reflectivity in the sample according to our calculation. And the refractive index change also is averaged by the inhomogeneous broadening of the QDs. As to the above-mentioned, our switch can be put into effect under small inhomogeneous broadening condition.

3. Conclusions

In conclusion, we have established an all-optical polarization switch based on Bragg well contained uniform QDs for optical communication. The switch shows a high contrast ratio 930 (~30 dB) and lower requirement of pump light intensity (0.5 MW/cm^2). It is a promising candidate for the all-optical switching devices in ultrafast optical communication in future. To realize the performance of this switch, more work should be done to reduce the inhomogeneous broadening of QDs.

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