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Large optical Kerr signal of GaAs/AlAs multilayer cavity with InAs quantum dots embedded in strain-relaxed barriers

Ken Morita *, Tomoya Takahashi, Toshiyuki Kanbara, Shinsuke Yano, Takuya Mukai, Takahiro Kitada, Toshiro Isu

Center for Frontier Research of Engineering, Institute of Technology and Science, The University of Tokushima, Tokushima 770-8506, Japan

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ABSTRACT

A strong and ultrafast optical Kerr signal at $\sim 1.5\,\mu m$ has been demonstrated in a GaAs/AlAs multilayer cavity containing self-assembled InAs quantum dots (QDs) embedded in strain-relaxed $In_{0.35}Ga_{0.65}As$ barriers. Time-resolved optical measurements using 100 fs pulses with 100 kHz repetition rate were carried out in the various excitation powers at room temperature. Although only 2 layers of the InAs QDs were inserted in the half-wavelength ($\lambda/2$) cavity layer, the strongly enhanced optical Kerr signal was observed compared to that of a GaAs $\lambda/2$ cavity which had no QDs, in the whole range of excitation power (1–10 mW). The signal enhancement becomes more significant with decreasing excitation power because two-photon absorption is suppressed in the $\lambda/2$ cavity consisting of the 2 QD layers and strain-relaxed $In_{0.35}Ga_{0.65}As$ barrier. In the low-excitation power regime of 1–2 mW, the optical Kerr signal was about 2 orders of magnitude larger than that of the GaAs $\lambda/2$ cavity due to the large nonlinearity of the resonant InAs QDs.

1. Introduction

Ultrafast all-optical switch operating in the $1.55\,\mu m$ waveband are among the most important devices in the high-bit-rate optical fiber communication system. Many kinds of switches using ultrafast nonlinear responses of semiconductor materials have been reported [1–5]. The optical Kerr gate switches using the planar typed semiconductor multilayer cavity structures are especially attractive for dense parallel processing and simultaneous multichannel demultiplexing in the optical communication system. In the multilayer cavity structure, an internal optical filed of the cavity mode is strongly enhanced in the cavity layer [6], which results in the large optical Kerr signal intensity [7]. In addition, we can also expect a fast response time of <1 ps by tuning the quality factor (Q-value) of the cavity which depends on the number of distributed Bragg reflector (DBR) layers. We have already observed clear ultrafast optical Kerr signals with a high contrast ratio of $>100:1$ (20 dB) and a fast response time of <1 ps using a cavity mode with a $\lambda/2$ GaAs layer inserted in a GaAs/AlAs multilayer cavity at the two-photon resonant region in the $1.55\,\mu m$ waveband [8,9]. However, the switching energy needs to be further reduced for the practical use.

The effective method to reduce the switching energy of an optical Kerr gate switch with a GaAs/AlAs multilayer cavity is to use a strongly nonlinear material as the $\lambda/2$ cavity layer. We have previously shown that the optical Kerr signals are strongly enhanced in this arrangement using the self-consistent transfer matrix method, and proposed the use of InAs quantum dots (QDs) embedded in strain-relaxed barriers [10,11]. The InAs QDs embedded in the $In_{0.35}Ga_{0.65}As$ strain-relaxed barriers are expected to be a good choice of material for the cavity layer. The resonance of QDs shifts to the longer wavelength (1.35 to $1.65\,\mu m$), which results in the high degree of nonlinearity at the range of $1.55\,\mu m$ waveband [12]. In addition, a fast carrier relaxation (~ 18 ps) attribute to the carrier relaxation into the nonradiative centers can reduce the pattern effects during high-bit-rate operation [10,12]. Recently, we successfully fabricated a GaAs/AlAs multilayer cavity which contains 2 layers of self-assembled InAs QDs embedded in strain-relaxed barriers (QD cavity), and a large optical Kerr signal with an ultrafast response was demonstrated using a time-resolved pump and probe method [13]. We have shown that a strong optical Kerr signal of QD cavity results from the strong cavity effect and the large optical nonlinearity of the resonant InAs QDs in the $\lambda/2$ cavity layer.

In this work, excitation power dependence of the optical Kerr signal was clarified for the QD cavity. Strongly enhanced Kerr signal was demonstrated in the low-excitation power regime compared with the GaAs $\lambda/2$ cavity having no QDs inserted in the same GaAs/AlAs DBR multilayer (GaAs cavity).

* Corresponding author. Tel.: +81 88 656 7671; fax: +81 88 656 7674.
E-mail address: morita@frc.tokushima-u.ac.jp (K. Morita).

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2. Experimental details

The samples were grown by molecular beam epitaxy on GaAs (0 0 1) substrates. In the QD cavity sample, $\lambda/2$ layer which consists of 2 layers of self-assemble InAs QDs and $In_{0.35}Ga_{0.65}As$ strain-relaxed barriers were inserted in the 26 pairs of GaAs(111 nm)/AlAs(130 nm) DBR multilayer [13]. The GaAs cavity sample consists of a $\lambda/2$ GaAs layer (222 nm) in the same GaAs/AlAs DBR multilayer. The reflectance spectra of the QD cavity and GaAs cavity were measured under a white light lamp as shown in Figs. 1(a) and (b), respectively. A clear cavity modes with narrow peaks were observed at 1459 nm and 1540 nm, respectively, which indicates good crystal quality within the fabricated cavities.

Time-resolved Kerr signals were measured by a cross-Nicol configuration using 100 fs pulses with 100 kHz repetition rate [8,9,13]. The spectral width of pulse was $\sim$35 nm and the wavelength was tuned at the center of each cavity mode. The GaAs substrates were removed by mechanical polishing and selective wet etching in order to eliminate nonlinear signals originating in the thick substrate [6]. The pump and probe (0.1 mW) beams were polarized along the [1 1 0] and [0 1 0] directions of the sample, respectively. The probe beam intensity of the x ([1 0 0]) polarization (I_x) passing through an analyzing polarizer was detected as the optical Kerr signal. We also measured the probe beam intensity of the y ([0 1 0]) polarization (I_y) in order to investigate the differential transmission due to the optical nonlinearity effect.

3. Transmittance properties

We first measured the excitation power dependence of the y polarized one-beam transmittance. Fig. 2 shows the excitation power dependence of the transmittance for both cavities. In the case of QD cavity, a linear one-photon absorption process with a nearly constant transmittance was observed in the lower-power regime (<0.2 mW). Above 0.2 mW, the transmittance increases owing to a saturable absorption effect and saturates at 2 mW. When the excitation power is higher than 3 mW the two-photon absorption effect becomes responsible and the transmittance starts to decrease. On the other hand, in the GaAs cavity, transmittance gradually decreases owing to the two-photon absorption process in the whole measured range.

Figs. 3(a) and (b) show delay time (Δt) dependencies of the y polarized transmitted signals (I_y) for the both cavities at 2 and 6 mW, respectively. The probe beam intensity was set at 0.1 mW, at which the nonlinear effect is negligible. In the case of the QD cavity, a large increase of transmittance (ΔT) caused by a saturable absorption effect of the QDs layers is observed for $\Delta t > 0$ at 2 mW. When the excitation power is at 6 mW, the strong two-photon absorption from the QDs and/or InGaAs strained-relaxed barriers become responsible which results in the decrease of ΔT compared to that at 2 mW. On the other hand, for the GaAs cavity, a slight decrease in transmittance, with a quick recovery, due to the two-photon absorption process is observed for $\Delta t = 0$ at 2 mW. At 6 mW, in addition to the increase of two-photon absorption signal the free carrier absorption is observed after 1 ps. The power dependencies for the both cavities observed in Fig. 3 are qualitatively consistent to the result of one-beam power dependencies observed in the Fig. 2. Noticed that when the results were compared between the two cavities, the transmittance intensities for the $\Delta t = 0$ in Fig. 3 quantitatively disagrees with that in Fig. 2, since the transmittance of the QD cavity in the Fig. 2 is quite larger than the GaAs cavity especially in the power range of 1–7 mW. In our two-beam measurements, the polarization direction of the pump beam is different to that of the probe beam. Therefore, the quantitative disagreement between the result of Figs. 2 and 3 might attribute to the polarization dependence of the pump beam with respect to the probe beam [14].

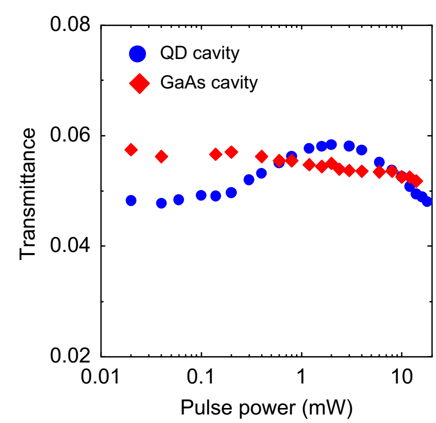

Fig. 2. Excitation power dependence of the y polarized one-beam transmittance.

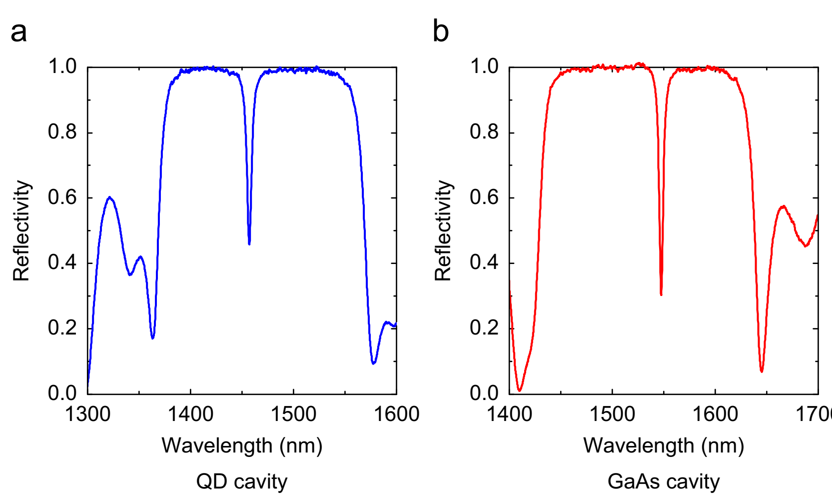

Fig. 1. Reflectance spectrum from the (a) QD cavity and (b) GaAs cavity.