Electro-optic Modulation of InAs Quantum Dot Waveguides

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Abstract. *The linear electro-optic properties in waveguides containing self-organized InAs quantum dots were studied experimentally. Fabry-Perot measurements at 1515 nm on InAs/GaAs quantum dot structures yield a significantly enhanced linear electro-optic efficiency compared to bulk GaAs.*

Introduction

Semiconductor-based nonlinear optical and electro-optic materials would be useful for switching and modulation devices in photonic integrated circuits. Electro-optic (EO) modulators are candidates for use in external modulation links in telecommunications. These modulators can be realized using either bulk semiconductor materials [1] or materials with multiple quantum dots or wells [2]. Due to the modification in the density of states, quantum dots and quantum wells are expected to exhibit enhanced optical nonlinearities and enhanced electro-optic effects [3]. Since EO modulators require small size and low modulation voltages, possibility of obtaining quantum dots with enhanced electro-optic and/or electro-absorption coefficients makes them attractive for such applications.

In the literature there is limited data on EO effects in quantum dots. Furthermore, little has been reported on the voltage dependent modulation of quantum dot embedded waveguides [4-5-6-7]. In this article, we report on the measurements of EO properties of multilayer InAs/GaAs self-organized quantum dots. We use the transmission through Fabry-Perot resonators formed by two cleaved facets in waveguides at 1500 nm to determine the electro-optical properties of quantum dots.

Samples

The waveguide structures containing three layers of quantum dots (3QDs) were measured. Their lengths are in the range of 1-1.6 mm. These structures were grown by molecular beam epitaxy to be used as quantum dot lasers. The active region is formed by three layers of self-assembled InAs QDs, which are covered by a 5-nm $In_{0.15}Ga_{0.85}As$ QW and separated from each other by a 40-nm GaAs spacer layer. The areal dot density of the lens-shaped QDs is 3x10^{10} cm^{-2}. The devices are single mode ridge waveguide structures with varying widths between 2-5 μm. Both facets are as cleaved. For each sample lasing is peaked at nearly 1285 nm [8]. Detailed structure is given in **Figure 1**.

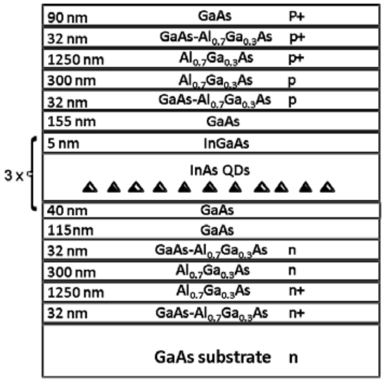

FIG. 1. Detailed structure of the samples used in the measurements**.** $Al_{0.7}Ga_{0.3}As$ layers at the GaAs interfaces are graded.

Measurements and results

The electro-optic coefficients were measured at 1515 nm by coupling a TE polarized light from a tunable laser (Santec Tunable LD Light Source TSL-520) onto one end of the waveguide with a lens shaped fiber. A DC voltage source was used to apply 0 to 20 Volt reverse bias to the samples. The detailed measurement set-up is shown in **Figure 2**. At each voltage level, the transmission through the device was recorded as a function of wavelength and voltage. Experimental results are given in **Figure 3**. Fabry-Perot resonances with large contrast were obtained and experimental data fitted well with the theoretical formula. The well known Fabry-Perot transmission equation is used in fitting to the measured data and the fitting parameters were mode effective index, loss coefficients and a voltage independent phase factor. The effective mode index was then calculated based on this curve fitting.

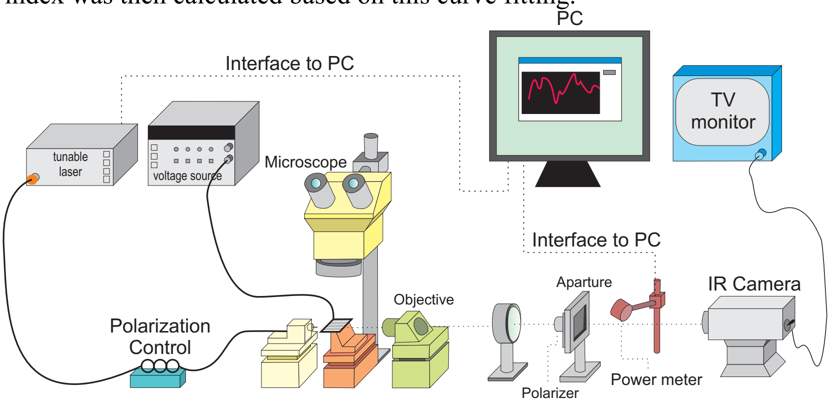

FIG. 2. The experimental set-up for measuring the Fabry-Perot resonances of quantum dot waveguides.

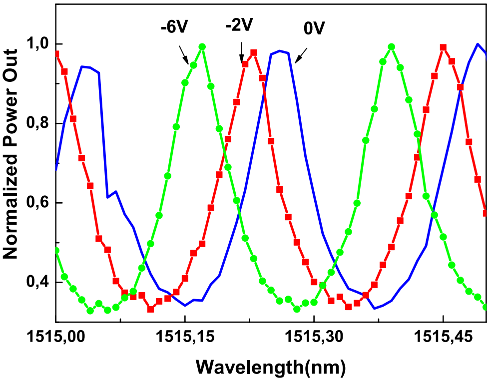

FIG.3. Voltage dependent shift of Fabry-Perot resonances. Significant tuning is observed with relatively low voltages.

The linear electro-optic coefficients are obtained by fitting the measured data to the equation of transmission through a Fabry Perot modulator [3] and calculating the refractive index difference between two specific voltages. The change in refractive index due to applied voltage is $\Delta n(V)$ is given as [3]:

$$\Delta n(V) = \frac{1}{2} n_e^3 r_{41} \frac{V}{t} \Gamma \tag{1}$$

where r_{41} is the electro-optic coefficient, t is the thickness of the epilayer, n_e is the effective index, V is the voltage difference between two curves and confinement factor Γ is the overlap of the vertical electric field component with the optical mode. To obtain r_{41}, Γ needs to be known precisely. The overlap factor of InAs quantum dot layers is calculated using finite difference beam propagation method simulations and is approximately 0.015 for all samples. Using this confinement factor the electro-optic coefficient of the InAs quantum dot structures are obtained as 9x10^{-11} which is significantly enhanced linear electro-optic efficiency compared to bulk GaAs. Figure 4 shows the Beamprop simulation results.

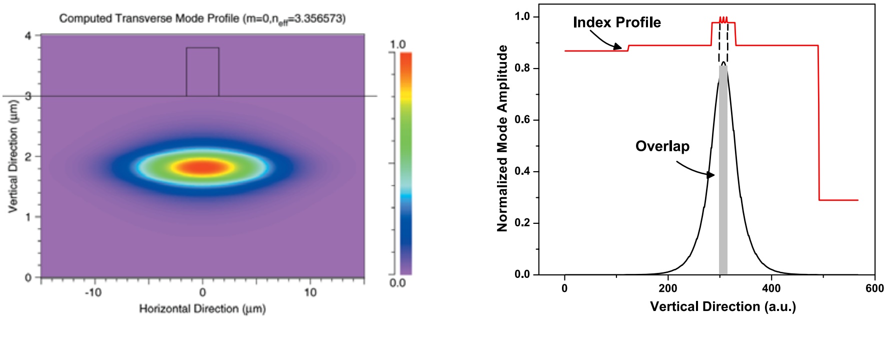

FIG.4. (a) Fundamental mode profile of the quantum dot waveguide structure. The effective index of the structure is obtained as 3.356. Note that the field is confined to the core region

where the quantum dots are placed. **(b)** The graphical representation of the calculation of overlap factor. The locations of the InAs layers are determined using the index profile, and these points are mapped onto the vertical mode profile. The confinement factor is calculated from this overlap region by simply integrating the shaded area.

As a matter of fact examination of **Fig. 1a** reveals that full on/off modulation is possible for 1.6 mm long 3 QD sample using 6 V. This corresponds to less than 1 V-cm modulation efficiency. In other words using this modulator as the arms of a push pull driven Mach-Zehnder modulator, less than 1 V drive voltage would result for 1 cm long arms

Conclusions

In conclusion, the low voltage modulation in InAs quantum dot waveguides was observed. The linear electro-optic coefficients of multilayer InAs quantum dot structures far away from the lasing wavelength were measured and is found to be significantly larger than that of GaAs bulk material. This result is promising for QD-based electro-optic modulators.

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