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Y. H. Lee, J. L. Jewell, S. J. Walker, C. W. Tu, J. P. Harbison, and L. T. Florez

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# Electrodispersive multiple quantum well modulator

Y. H. Lee, J. L. Jewell, S. J. Walker, and C. W. Tu<sup>a)</sup>  
AT&T Bell Laboratories, Holmdel, New Jersey 07733

J. P. Harbison and L. T. Florez  
Bellcore, Red Bank, New Jersey 07701-7020

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Quantum-confined Stark effect is combined with a Fabry-Perot resonance to build a multiple quantum well electro-optic modulator. The structure consists of GaAs/AlGaAs quantum wells between two epitaxial AlAs/AlGaAs dielectric multilayer mirrors, all grown by molecular beam epitaxy. The modulator uses refractive index changes induced by applied electric fields. In reflection mode of operation, the modulator demonstrates  $> 5:1$  contrast ratio and  $> 50\%$  absolute maximum reflectivity with 17 V applied.

Recently, the electric field dependence of optical absorption near the band gap of multiple quantum well (MQW) semiconductors has been studied extensively. For the field perpendicular to the quantum wells, it is called the quantum-confined Stark effect (QCSE).<sup>1</sup> The main consequences of the QCSE are broadening and large red shifts of the exciton absorption peaks. Direct modulation of optical absorption of the exciton by the QCSE leads to a MQW electro-optic modulator.<sup>2,3</sup> Major drawbacks of this absorption modulator are poor contrast and/or low absolute transmission and a large voltage requirement. Moreover, since the operating wavelength of the light is usually close to an exciton peak, there is always strong absorption inside the modulator which turns into heat. Refractive index changes due to electric fields (electrodispersive effects) were also measured by interferometric measurements<sup>4,5</sup> and by electroreflectance measurements.<sup>6</sup> Applications of the electrodispersive effects to waveguide devices have been reported for longer wavelengths.<sup>7</sup>

We have demonstrated an electro-optic modulator based on the refractive index modulation by the QCSE in a Fabry-Perot resonator. The basic structure of this modulator is a MQW Fabry-Perot étalon with an applied electric field perpendicular to the MQW layers.<sup>8,9</sup> By the Kramers-Kronig relation, an absorption change is related to a corresponding index change. Using a previously constructed self-electro-optic effect device,<sup>10</sup> we measured absorption changes due to the QCSE and calculated the electrodispersive changes by Kramers-Kronig transformations (Fig. 1). The validity and accuracy of the transformation have been shown experimentally.<sup>11</sup> This sample has the heavy-hole exciton peak at 8521 Å. If one forms a Fabry-Perot étalon at the transparent spectral region where the electrodispersive effect by the QCSE is large, an electro-optic modulator can be realized.

There are two possible operating regions for this modulator. One is the narrow spectral region just below the exciton peak where refractive index change and absorption changes are large (region I in Fig. 1). The electric field induced index change is negative for this spectral region and the Fabry-Perot transmission peak will be blue shifted. The

optical modulation will be combined absorptive and dispersive effects and possibly with lower voltages. The other spectral region (region II in Fig. 1) is broader and located 100–250 Å below the exciton wavelength where it is transparent and the dispersive effect becomes dominant. Here, the changes in refractive index are positive with an applied electric field.

The sample for electrodispersive MQW modulator was grown by molecular beam epitaxy (MBE) and has three substructures, a bottom mirror on a GaAs substrate, a GaAs/Al<sub>0.35</sub>Ga<sub>0.65</sub>As MQW region, and a top mirror. The bottom mirror region consists of 12.5 pairs of 726 Å AlAs and 625 Å Al<sub>0.2</sub>Ga<sub>0.8</sub>As, starting and ending with AlAs layers. The active MQW region is 82.5 pairs of alternating GaAs/Al<sub>0.35</sub>Ga<sub>0.65</sub>As (90 Å/70 Å) MQW and shows a

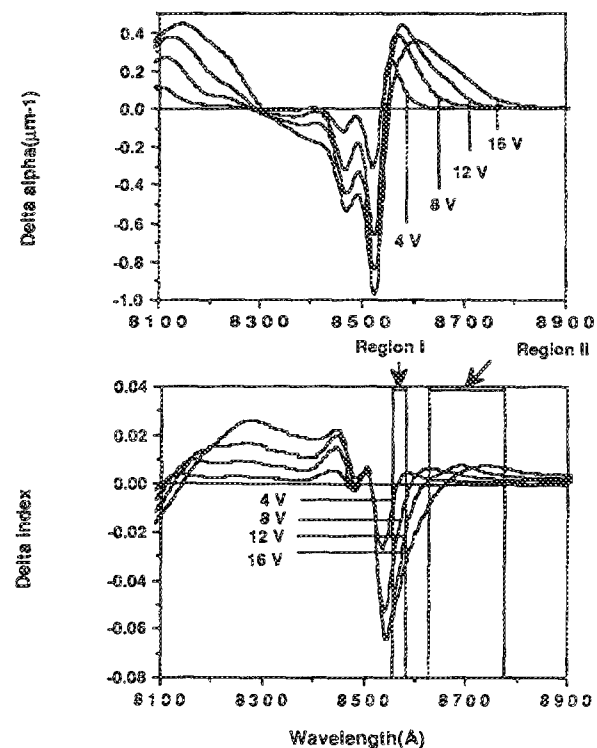


FIG. 1. Changes in absorption (measured) and refractive index (Kramers-Kronig transformed) with reverse bias voltages of 4, 8, 12, 16 V. This sample has an exciton peak at 8521 Å.

<sup>a)</sup> AT&T Bell Laboratories, Murray Hill, NJ 07974.

heavy-hole exciton at 8369 Å. The top mirror region consists of eight pairs of 726 Å AlAs and 625 Å Al<sub>0.2</sub>Ga<sub>0.8</sub>As, with the topmost being an Al<sub>0.2</sub>Ga<sub>0.8</sub>As layer. These mirrors<sup>12,13</sup> are quarter-wave dielectric thin-film stacks spectrally centered at 8650 Å. The reflectivities of the mirrors (peak reflectivity, ~90%) are optimized for the operation in region II, which is between 8450 and 8600 Å for this structure. The absolute average optical thickness of quarter-wave AlAs/Al<sub>0.2</sub>Ga<sub>0.8</sub>As layers determines the center wavelength of the mirror and needs to be controlled within 3% of the design value during MBE growth. The concentration of aluminum in AlGaAs layer was not as critical. Because reliable refractive index data for GaAs/AlGaAs MQW structures were not available, the wafer was not rotated during the growth of MQW layers to introduce an intentional thickness variation. The resultant thickness variation is about 10% over a 2-in. wafer. On the other hand, the mirrors were made as uniform as possible by rotating the wafer during their MBE growth and the resultant thickness uniformity over the wafer is less than 2%. The bottom and top mirrors were *n*-doped and *p*-doped, respectively.

Reflection modulators are easier to fabricate than transmission devices with GaAs substrates because substrate removal is not necessary. Initially, the bottom of the GaAs substrate was ground to 300 μm thickness. The ground side was then electroplated with gold/tin for an *n*-type ohmic contact. The modulator was defined on the epitaxial layer side of the sample by chemical etching as an array of 400 × 400 μm<sup>2</sup> mesas with 200 μm spacing. Gold electrodes (2000 Å thick) were deposited on the top for *p*-type ohmic contacts. Finally, the device was silver epoxied on a chip mount and gold wires were bonded to the mesas.

For reflection mode operation, an asymmetric étalon design was adapted to minimize the reflection at an étalon resonance. Theoretically, one can achieve an infinite contrast ratio for a reasonable background absorption. Calculated and measured spectral reflectivities are shown in Fig. 2. Refractive indices and absorption of AlAs, Al<sub>0.2</sub>Ga<sub>0.8</sub>As, and Al<sub>0.05</sub>Ga<sub>0.95</sub>As were obtained as functions of wavelength from the Afromowitz modified single-oscillator mode.<sup>14</sup> To simulate the MQW layer, a 12750-Å-thick

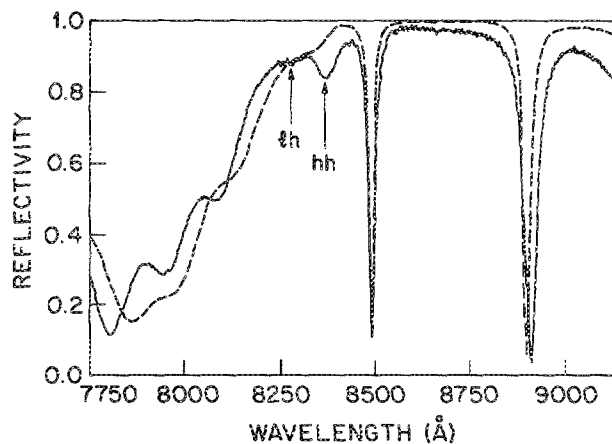


FIG. 2. Measured (solid line) and calculated (dotted line) reflection spectra for the electrodispersive MQW modulator without bias voltage.

Al<sub>0.05</sub>Ga<sub>0.95</sub>As (band gap at 8367 Å) layer was used. The measured finesse of the Fabry-Perot étalon is 22, while theoretically it is 29. The full width at half-maximum of the transmission peak is 20 Å. The measured reflection minimum shifts to a longer wavelength with an applied dc bias, indicating an increase of the refractive index as shown in Fig. 3. The peak shift with 15 V dc bias is 15 Å. At 8488 Å, one can expect > 5:1 contrast ratio with better than 50% maximum reflectivity from these dc measurement spectra. Actual optical modulation of a dye laser beam tuned to 8488 Å, shown in Fig. 4, operates just as predicted from dc measurements. Reflectivity was calibrated with respect to the gold contact ( $R = 98\%$ ).

For bias voltages smaller than 5 V, the shifts of the transmission peaks were very small and nonlinear as expected. For bias voltages higher than 17 V, the maximum reflectivity does not increase; the modulation saturates. In this high-voltage regime, electric field induced absorption begins to dominate, resulting in a decrease of the cavity finesse. At the same time the refractive index slowly starts to decrease at higher voltages. Our simulation indicates that the operating voltage could be reduced to 5 V with a thinner MQW layer combined with a proportionally higher finesse cavity.

The average power of the incoming beam was 3–50 mW. Thermal effects were observed as a 10–20% degradation (relative value) in the maximum reflectivity for long pulses. The main reason for the thermal effect is the absorption of the incoming beam by the GaAs substrate which is opaque at the operating wavelength (8488 Å), not the absorption by the modulator itself. Temperature of the modulator is higher with no bias since incoming light is transmitted through the étalon and absorbed by the GaAs substrate than with bias, in which case about half of the light will be reflected. Therefore, with bias on, the modulator begins to cool off and degrades the maximum reflection for longer pulses. This thermal effect is not an intrinsic property of the modulator and can be reduced significantly by using a transparent substrate. Actually, thermal balancing can be achieved with a transparent substrate. If the electro-optic modulator is set to a high transmission state without an applied electric field and to a low transmission state with an applied electric field, absorption will be minimal at both levels. Namely, with no bias,

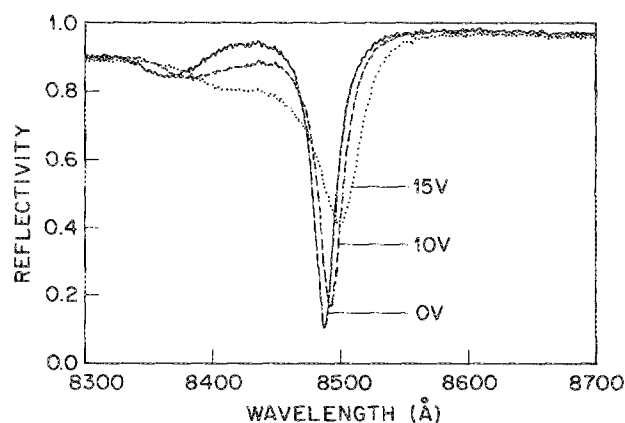


FIG. 3. Shifts of a measured reflection minimum with dc bias voltages of 0, 10, and 15 V.

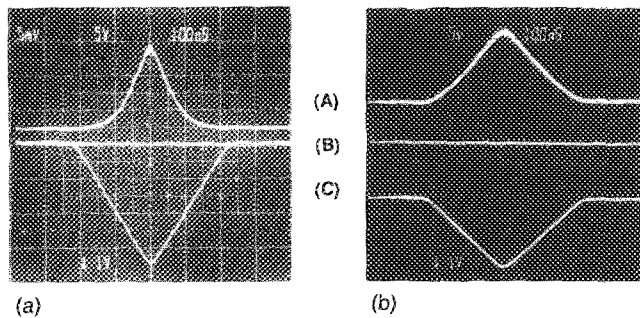


FIG. 4. Reflection modulation of a dye laser beam at 8488 Å. Traces (A), (B), and (C) are modulated optical signals, the ground line (both optical and electrical), and the applied triangular pulse shape, respectively. (a) and (b) are taken with 0–17 V and 7.5–17 V applied, respectively.

there is very small intrinsic background absorption for operation in Region II. With bias, the Fabry–Perot resonance peak will be shifted to a longer wavelength and the incoming beams will be largely reflected. Consequently, the device will absorb a small fraction of the incoming beams even though there is significant absorptivity induced by the QCSE. Thus absorption remains at a nearly constant low value regardless of input data as was previously achieved in an optically activated NOR gate.<sup>15</sup>

Although the device was not optimized for high-speed operation, we were able to modulate 15 ns pulses, which was limited by the pulse generator used. The speed of the modulator will be limited by the circuits and devices used to apply electric fields, because photogenerated carriers are swept out by the field in a fraction of a nanosecond. Smaller devices should be capable of many GHz operation.

In summary, we have proposed and demonstrated a MQW electrodispersive modulator based on the Fabry–Perot resonance and the quantum-confined Stark effect. This modulator shows > 5:1 contrast ratio and > 50% absolute reflectivity. Performance agrees well with simulation. Further simulation based on higher finesse and a thinner MQW layer points to lower operating voltage ( $\sim 5$  V) and

much higher contrast with similar insertion loss. Such high-speed, high-contrast low-voltage spatial light modulators will be a critical component for optical processing and optical computing applications.

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