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HIGH-SPEED NONLINEAR SWITCHING MECHANISMS AND DEVICES FOR MULTI-GIGABIT DATA PROCESSING

University of Arizona

N. Peyghambarian (University of Arizona)
S. Johns, M. Krol, R. Boncek, J. Stacy (Rome Laboratory)

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APPROVED:

STEVEN T. JOHNS
Project Engineer

FOR THE COMMANDER

JAMES W. YOUNGBERG, Lt Col, USAF
Deputy Director
Surveillance and Photonics Directorate

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N. Peyghambarian (University of Arizona)
S. Johns, M. Krol, R. Boncek, J. Stacy (Rome Laboratory)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Arizona
Optical Sciences Center
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13. ABSTRACT (Maximum 200 words)

A high contract, low intensity GaAlInAs/AlInAs multiple quantum well asymmetric Fabry-Perot reflection modulator for operation at 1.3 μm has been demonstrated. The reflection modulator takes advantage of the large absorptive and refractive nonlinearities associated with saturating the heavy-hole exciton resonance. We achieve an on/off contrast ratio in excess of 1000:1 (30 dB) and an insertion loss of 2.2 dB at a pump intensity of 30 kW/cm^2, corresponding to a carrier density of 4.5×10^{17} cm^{-3}. The modulator was demonstrated to have a large operating bandwidth, achieving an on/off contrast ratio of greater than 100:1 over a 5 nm optical band. The operating speed of the modulator was measured and found to approach 1 GHz.

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The project was conceived and initiated by Rome Laboratory personnel. Steven T. Johns, Mark F. Krol, Raymond K. Boncek, and John L. Stacy were the Rome Laboratory personnel involved in the effort. Dr. Nasser Peyghambarian from the University of Arizona was also involved in this effort.

Dr. Peyghambarian worked with Rome Laboratory Engineers in designing, fabricating, and testing a multiple quantum well reflection modulator for use in ultra-fast optical interconnects. The experimental work was performed at both the University of Arizona and Rome Laboratory Photonics Center with researchers at both institutions contributing equal effort. Analysis of the experimental data and the writing of several papers and conference presentations as a result of this work was a combined effort.

We wish to thank Hyatt Gibbs and Galina Khitrova at the University of Arizona for fabricating the MBE grown reflection modulators.

Table of Contents

A. Statement of the Problem Studied

The goals of this project were to investigate all-optical devices as high-speed optical switching elements for the development of a multi-gigabit optical time division multiplexing interconnect system. For this purpose, we designed and demonstrated an asymmetric Fabry-Perot all-optical reflection modulator that had a high on/off contrast ratio, and characterized its response time.

B. Summary of Results

An all-optical modulator that offers an on/off contrast ratio of greater than 1000:1 at wavelength of 1.3 μm was demonstrated. The modulator consisted of an asymmetric Fabry-Perot etalon with GaAlInAs/AlInAs multi-quantum wells (MQWs) for its spacer layer. The recovery time of the modulator, which determines its operating speed, was measured and found to be 730 ps. Design concepts of the modulator are described in section 1, experimental results both for its contrast ratio and response time are shown in sections 2 and 3, and its operating conditions are discussed in terms of the switching pump beam intensity and response time in section 4.

1. Operating Principles of ASFP Modulators

The resonance reflectance R_{FP} of an ASFP modulator with a spacer absorption coefficient α and thickness l is given by

$$R_{FP} = \left[\frac{\sqrt{R_F} - \sqrt{R_B} \exp(-\alpha l)}{1 - \sqrt{R_F R_B} \exp(-\alpha l)} \right]^2 ,$$

where R_F and R_B are the reflectance of the front and back mirrors, respectively. R_{FP} becomes zero when the cavity is matched, i.e., the condition $R_F = R_B\exp(-2\alpha l)$ is satisfied. Absorptive nonlinearities associated with photo-induced carrier populations unbalance the matching condition, which causes the modulator to switch to a high reflectance state. Refractive nonlinearities also contribute to increasing R_{FP} by shifting the Fabry-Perot resonance. As we shall see, the Fabry-Perot resonance must be placed on the long wavelength side of the exciton resonance to fully utilize the large absorptive and refractive nonlinearities.

The ASFP modulator was designed for the operating wavelength of 1.3 μm using GaAlInAs/AlInAs MQWs as the nonlinear spacer, and satisfies the matching conditions in the absence of a photogenerated carrier population. The schematic structure of the 1.3 μm ASFP modulator is shown in Fig. 1. The nonlinear spacer consisted of 65 periods of 69 Å $Ga_{0.376}Al_{0.094}In_{0.53}As$ well/89 Å $Al_{0.48}In_{0.52}As$ barrier MQWs with a total thickness of 1.03 μm. The rear mirror was formed by 24 periods of 936 Å $Ga_{0.3}Al_{0.18}In_{0.52}As$/1003 Å $Al_{0.48}In_{0.52}As$ quarter-wave stack. The interface between the spacer and air was used as the front mirror. The reflectances of the back and front mirrors were $R_B \cong 0.92$ and $R_F \cong 0.3$, respectively.

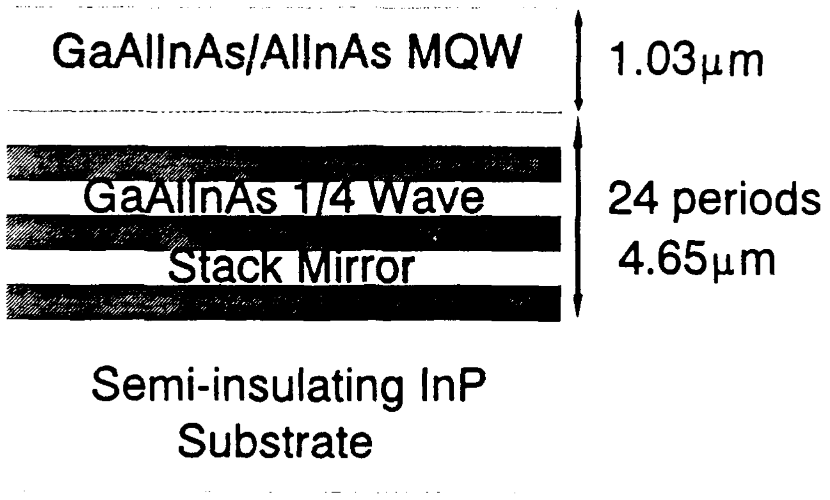

Fig. 1. Schematic structure of the GaAlInAs/AlInAs modulator.

2. Switching Characteristics

The nonlinear behavior of the modulator was investigated in a pump/probe geometry. Both pump (control) and probe beams were normally incident on the modulator from the MQW spacer side, and the reflectance of the probe beam was modulated by switching the pump (control) beam.

The 1.064-μm line from a Q-switched Nd:YAG laser was used as the pump source, and the probe beam was generated by difference frequency mixing between the 1.064-μm line and the output of a tunable dye laser. The pulse durations of the pump and probe beams were 10 ns and 4 ns, respectively. Figure 2 shows the reflectance spectra of the modulator with pump intensities of 0, 6.6, and 41 kW/cm^2. The corresponding carrier densities calculated from the rate equation for these pump intensities were 0, 1.0×10^{17} cm^{-3}, and 5.7×10^{17} cm^{-3}, respectively, assuming a carrier lifetime of 0.73 ns and an MQW layer absorption coefficient of 5.7×10^3 cm^{-1} at 1.06 μm. As shown in the linear spectrum (no pump), a minimum reflectance of $(5.5 \pm 0.8) \times 10^{-4}$ was achieved at a wavelength of 1.314 μm. As the pump intensity increases, the reflectance increases due to bleaching of the heavy-hole exciton absorption. In

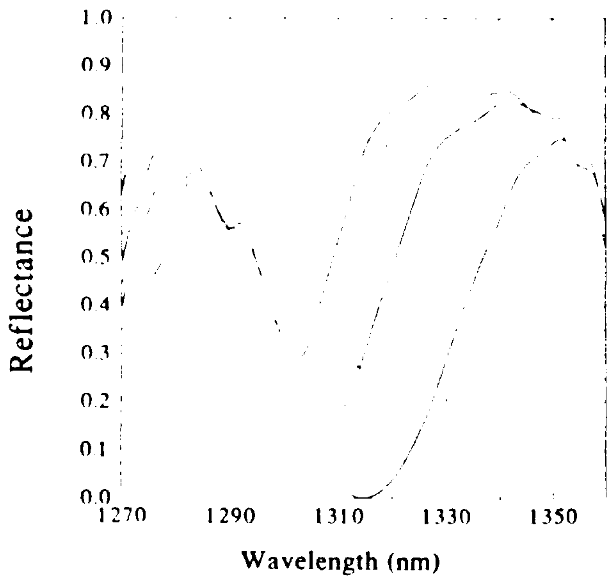

Fig. 2. Measured reflectance spectra of the GaAlInAs/AlInAs asymmetric reflection modulator for pump intensities of (1) 0.0 (linear), (2) 6.6, ad (3) 41 kW/cm^2.

addition, the Fabry-Perot resonance shifts toward shorter wavelengths due to the refractive index change associated with the absorption change. The combination of absorptive and refractive nonlinearities results in a maximum reflectance of larger than 0.7 at the resonance wavelength of 1.314 μm. This yields a contrast ratio in excess of 1000:1. The operating bandwidth over which the contrast ratio is greater than 100:1 is approximately 5 nm. The relatively wide bandwidth results from the low finesse of the asymmetric Fabry-Perot resonance.

We calculated the reflection spectra of the modulator using a multilayer model of the structure that includes the quarter-wave stack back mirror. The parameters of the layer structure were taken from the values of the samples used for the experiment. The back mirror was treated as a stack of nonabsorbing layers. The nonlinear exciton absorption and the refractive index change of the MQW space layer were calculated as a function of wavelength and pump intensity using the plasma theory.

The exciton absorption spectra were calculated as shown in Fig. 3(a) for carrier densities of (1) 0 and (2) 2.8×10^{17} cm^{-1}. The corresponding refractive index change was obtained from a Kramers-Kronig transformation of the difference of these absorption spectra, as shown in Fig. 3(b). Figure 4 shows the calculated reflectance spectra using the nonlinear absorption and refractive indices of Fig. 3. The reflectance at the resonance wavelength increases from 2×10^{-4} to 0.29 as a result of the injected carrier density. Since the Fabry Perot resonance coincides with the wavelength at which the nonlinear

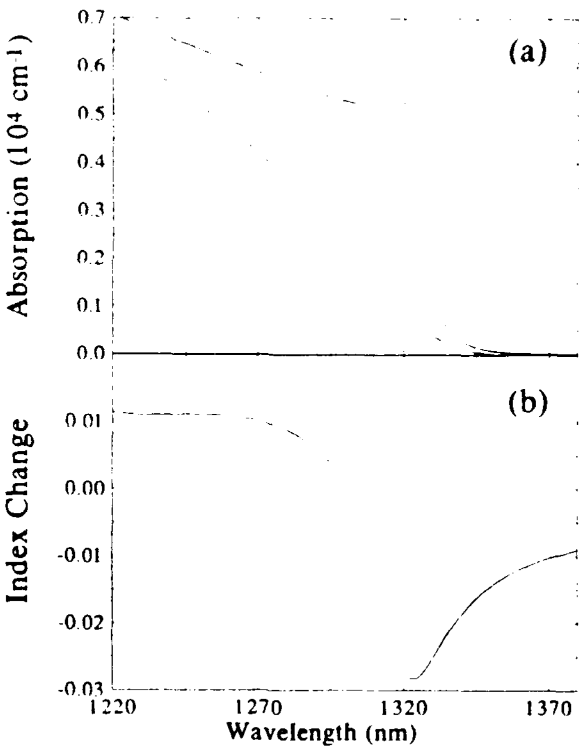

Fig. 3. (a) Calculated nonlinear absorption spectra of GaAlInAs/AlInAs MQW for carrier densities of (1) 0.0 (linear) and (2) $2.8 \times 10^7 cm^{-3}$. (b) Calculated refractive index change using the Kramers-Kronig transformation of the spectra in Fig. 3(a).

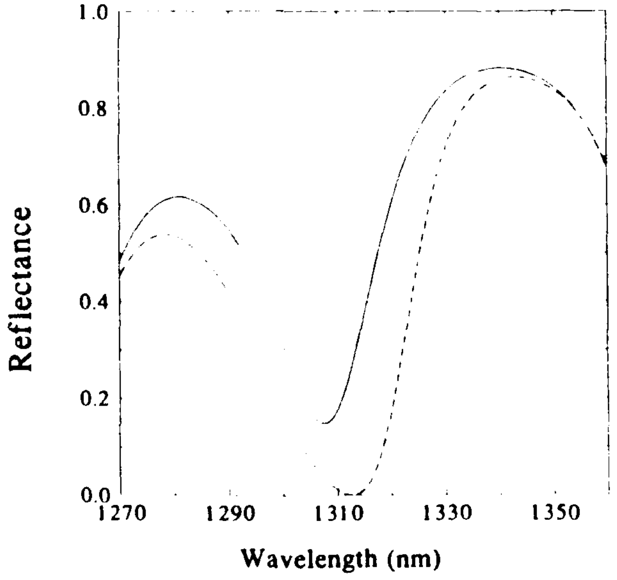

Fig. 4. Calculated reflectance spectra of the GaAlInAs/AlInAs asymmetric reflection modulator for carrier densities of 0.0 (dashed line) and 2.8×10^7 cm^{-3} (solid line). The absorption coefficients and refractive index changes were taken from the calculated values shown in Fig. 4.

refractive index change becomes maximum, a significant shift of the resonance wavelength was obtained. When the refractive nonlinearity was ignored, i.e., only the absorption saturation was taken into account, the reflectance at the Fabry-Perot resonance reaches only a value of 0.2. Thus, the combined effect of absorptive and refractive nonlinearities increased the modulation by a factor of 1.4. In order to fully use the refractive nonlinearities, the Fabry-Perot resonance must be placed on the low-energy side of the heavy-exciton resonance.

The measured reflectance at the Fabry-Perot resonance wavelength of 1.314 μm is shown in Fig. 5 as a function of carrier density. As the pump intensity increases, the reflectance rapidly increases initially, and saturates to a value of 0.72 as a result of absorption saturation of the spacer layer. The absorption saturation of the MQW spacer layer is characterized by its saturation carrier density N_S, which is defined by $\alpha(N) = \alpha_0/(1 + N/N_S)$. The saturation carrier density for the GaAlInAs/AlInAs MQWs is approximately 1.0×10^{18} cm^{-3}. The reflectance saturates when the carrier density approaches N_S, as shown in Fig. 5. Therefore, the laser power required for the maximum possible modulation depth can be estimated from the intensity value corresponding to the saturation carrier density. Thus, materials which have low saturation carrier densities would make modulators that operate at low carrier densities.

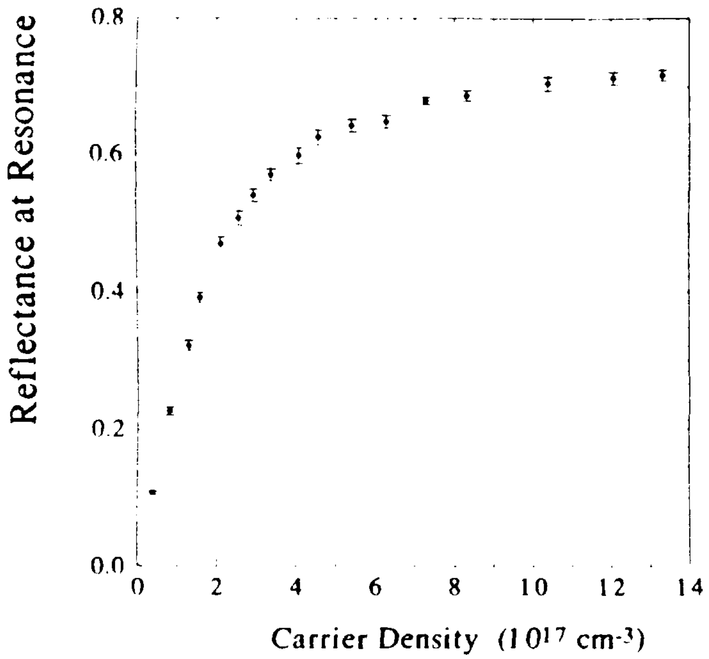

Fig. 5. Reflectance of the GaAlInAs/AlInAs asymmetric reflection modulator at the resonance wavelength of 1,314.3 nm, as a function of carrier density generated by the pump beam. The error bars were determined from the standard deviations of measured data.

The carrier density in the quasi-steady state is given by $N = \alpha I \tau / \hbar\omega$, where α is the absorption coefficient at the pump wavelength, I is the pump intensity, τ is the carrier lifetime, and $\hbar\omega$ is the pump-photon energy. For a fixed carrier density N, larger absorption coefficients α would reduce the required pump intensity I.

3. Response Time of the ASFP Modulator

The response time of the modulator was measured at the Photonics Laboratory in Rome, which determines its maximum operating speed. Optical pulses of 1.5-ps duration from a 1.313-μm, 100 MHz Nd:YLF laser and fiber-grating pulse compressor were used as both the pump and probe pulses.

Figure 6 shows the measured temporal change of the reflectance for an excited carrier density of 1.4×10^{16} cm^{-3} in the GaAlInAs/AlInAs modulator. The measured time constant was 730 ps, which is in good agreement with the carrier lifetime of GaAlInAs/AlInAs MQW material. In order to achieve faster modulation speeds, reduction of the carrier lifetime is required. Shorter carrier lifetimes, however, result in a higher pump intensity requirement for the same carrier density if the durations of pump pulses are longer than the carrier lifetime. To take advantage of shorter carrier lifetime, pump and probe pulses shorter than the carrier lifetime are required.

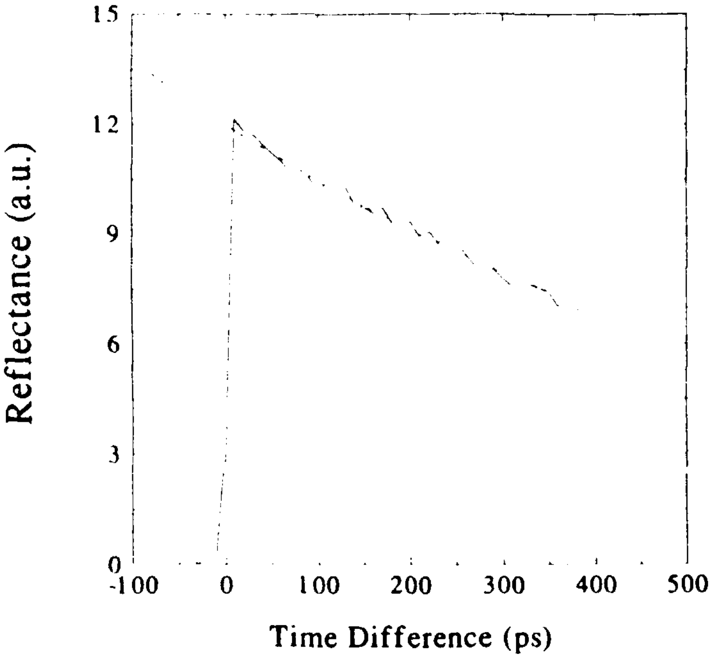

Fig. 6. Reflectance recovery time of the GaAlInAs/AlInAs asymmetric reflection modulator. The dashed curve is an exponential fit to the measured data, indicating a recovery time constant of 730 ps.

4. Conclusion

We have demonstrated the all-optical GaAlAs/AlInAs MQW asymmetric reflection modulator for operation at 1.3 μm. By using the combined absorptive and refractive nonlinearities associated with saturating the heavy-hole exciton resonance, an on/off contrast ratio exceeding 1:1000 and an insertion loss of 2.2 dB has been achieved at a pump intensity of 30 kW/cm^2, corresponding to a carrier density of 4×10^{17} cm^{-2}. This value is consistent with the saturation carrier densities of the MQW materials used for the nonlinear spacer. The pump beam intensities required for maximum possible modulation were related to the saturation carrier densities of the nonlinear spacer materials using the carrier lifetimes and absorption coefficients at the pump wavelengths. The modulator had an operating bandwidth of 5 nm over which the contrast ratio is greater than 100:1. The response time of the modulator was 730 ps. The modulator with the high contrast, low-insertion loss, and reasonably high speed has potential for use in optical interconnect and signal processing applications, where spatial light modulators and optical gates are needed.

C. Publications and Presentations

1. Journals

1. M. F. Krol, T. Ohtsuki, G. Khitrova, R. K. Boncek, B. P. McGinnis, H. M. Gibbs, and N. Peyghambarian, "All-Optical, High Contrast GaAlInAs Multiple Quantum Well Asymmetric Reflection Modulator at 1.3 μm," Appl. Phys. Lett., to be published.

2. T. Ohtsuki, M. F. Krol, G. Khitrova, R. Jin, R. K. Boncek, B. P. McGinnis, G. M. Gibbs, and N. Peyghambarian, "All-Optical Asymmetric Fabry-Perot Reflection Modulators," invited paper for *Optical Switches, Limiters, and Discriminators, International Journal of Nonlinear Optical Physics.*

2. Conferences

1. M. F. Krol, S. T. Johns, R. Boncek, T. Ohtsuki, B. P. McGinnis, C. C. Hsu, G. Khitrova, H. M. Gibbs, and N. Peyghambarian, "Nonlinear GaAlInAs/AlInAs Multiple Quantum Well Materials and Devices at 1.3 μm for Ultrafast TDMA Interconnects," invited talk at the Electrochemical Society 182nd Meeting, October 1992.

2. T. Ohtsuki, M. F. Krol, R. Jin, S. T. Johns, R. K. Boncek, B. P. McGinnis, G. Khitrova, H. M. Gibbs, and N. Peyghambarian, "High Contrast All-Optical Asymmetric Fabry-Perot Reflection Modulator at 0.92 μm and 1.3 μm," Eighth Interdisciplinary Laser Science Conference (ILS-VIII), September 1992.

3. M. F. Krol, R. K. Boncek, T. Ohtsuki, G. Khitrova, B. P. McGinnis, H. M. Gibbs, and N. Peyghambarian, "High-Contrast, All-Optical GaAlInAs/AlInAs MQW Reflection Modulator at 1.3 μm," Quantum Optoelectronics Topical Meeting, March 1993.

D. Degrees Earned

Mark Krol, MS, 1992

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