Demonstration of all-optical modulation in a vertical guided-wave nonlinear coupler

Paul R. Berger, Yi Chen, Pallab Bhattacharya, and Jagadeesh Pamulapati
Solid State Electronics Laboratory, Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor, Michigan 48109-2122

G. C. Vezzoli
U.S. Army Materials Technology Laboratory, Watertown, Massachusetts 02172-0001

(Received 11 November 1987; accepted for publication 3 February 1988)

The performance characteristics of an AlGaAs dual waveguide vertical coupler with a nonlinear GaAs/AlGaAs multiquantum well coupling medium are demonstrated. The structure was grown by molecular beam epitaxy and fabricated by optical lithography and ion milling. The nonlinear coupling and modulation behavior is identical to that predicted theoretically. The nonlinear index of refraction and critical input power are estimated to be $n_2 = 1.67 \times 10^{-5}$ cm^2/W and $P_c = 170$ W/cm^2, respectively. This device also allows reliable measurement of the nonlinear refractive index for varying quantum well and optical excitation parameters.

All-optical coupling and switching of light in dual-channel coplanar waveguides based on intensity-dependent change of the refractive index due to nonlinear effects have been demonstrated with GaAs/AlGaAs[1] and strained InGaAs/GaAs[2] multiquantum wells (MQW's). The inherent problem in these coplanar guides is that the light energy has to be close to the excitonic resonance of the coupling region, thereby making the guides, also of the same material, very lossy. A vertical waveguide coupler with single layer waveguides and a MQW coupling region would solve this problem. In such a coupler, the waveguides can be low loss, while the MQW can be tailored so that the heavy hole excitonic resonance is close to the optical excitation energy. Such a vertical coupler, recently analyzed by Cada *et al.*,[3] has not been previously realized experimentally. In this letter, we report the performance characteristics of a nonlinear vertical coupler, which can also be used as a fast all-optical switch.

The dual channel waveguiding structure, the schematic of which is shown in Fig. 1(a), was grown by molecular beam epitaxy in a Varian Gen II system. The entire structure is undoped and growth was done under conditions which produced undoped GaAs with $p = 1 \times 10^{14}$ cm^{-3} at 300 K. The substrate temperature during growth was 630 °C, as read by an infrared pyrometer. Absorption measurements were made at room temperature to characterize the crucial MQW region. The experiments were done with a tungsten halogen light source and a 1-m Jarell–Ash scanning spectrometer. The data, shown in Fig. 1(b), exhibit $n = 1$ heavy and light hole excitonic resonances at 1.5312 and 1.5566 eV, respectively. The linewidth, half-width at half-maximum (HWHM) of the heavy hole peak is 5.7 meV, which is comparable to the best obtained. In contrast, the band gap of the $Al_{0.15}Ga_{0.85}As$ guiding layers is 1.6 eV.

The coupler was defined by lift-off and ion-milling techniques, using a 4-μm Ti/TiO$_x$ mask. The ion milling was done to a depth of 1 μm into the lower $Al_{0.17}Ga_{0.83}As$ cladding layer. An additional feature of the test structures is the extension of the lower guide by 900 μm beyond that of the upper guide, as seen in Fig. 2(a). This is done to ensure that light is only coupled to the upper guide using the lower guide as the input channel. From the cross section of the guides, seen in Fig. 2(b), it is apparent that straight walls were not obtained, and can even result in the lower guide being multimode.

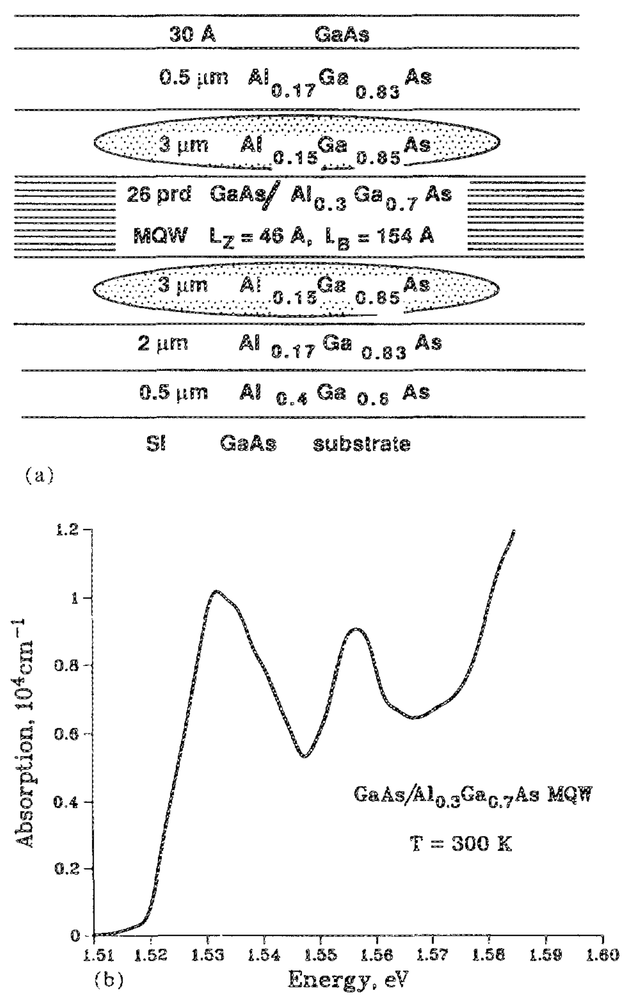

FIG. 1. (a) Schematics of the MBE grown vertical waveguide coupler and (b) absorption spectrum of the nonlinear MQW coupling region at room temperature.

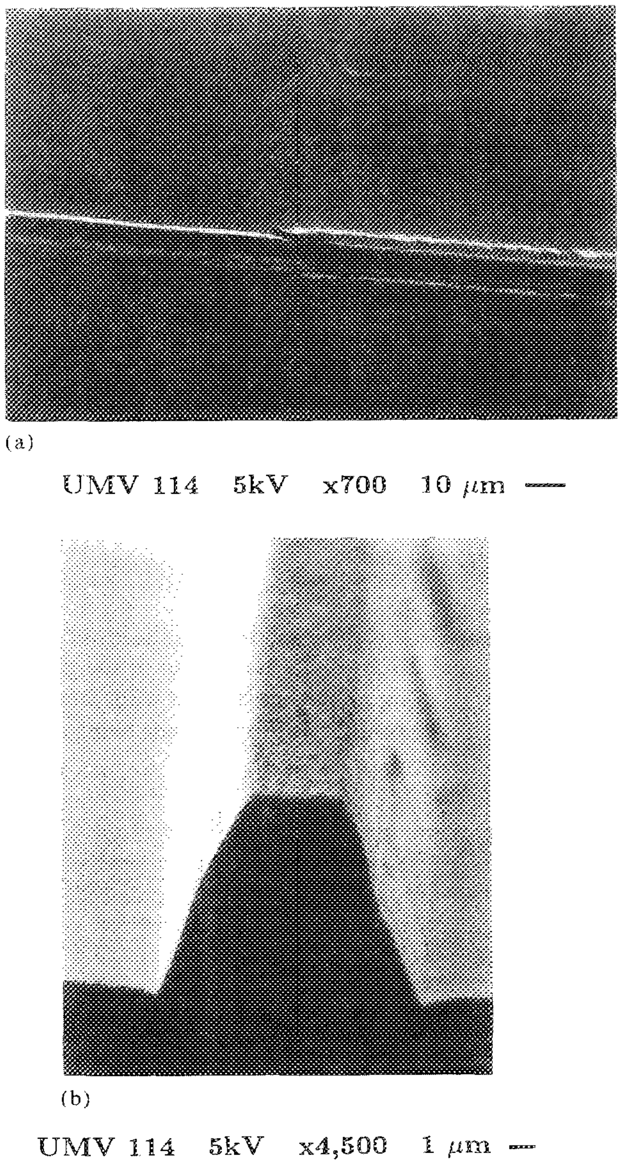

FIG. 2. SEM micrographs of (a) vertical coupler with input extension and (b) cleaved cross section of the vertical waveguide coupler.

Light coupling measurements were made by providing input excitation at the lower or upper guide from a temperature tunable AlGaAs laser. The energy of the output could be varied in the range 1.5175–1.5285 eV, and the laser output power could be varied by changing the drive current. The light incident on the input guide was focused to a 2–3 μm spot. The guided light in the two guides at the output end was collected and detected by an IR camera and viewed on a TV monitor. Detailed quantitative measurements of the output intensities were obtained by digitizing the displayed images and computer analysis of their intensity distributions. The input power was accurately measured with a calibrated Si photodiode.

Data obtained from experiments done with the input light 13 meV lower in energy than the peak energy of the heavy hole resonance of the MQW are shown in Figs. 3(a)–3(c) for different coupling lengths. In these experiments, both guides are of the same length, and the input light, 3 μm diameter, is coupled to the upper waveguide. The data shown in Fig. 3, where the power remaining in the input guide is plotted as a function of the incident excitation, indicate that for small lengths, 0.9 mm, full transfer of power does not occur. On the other hand, with a 2.0-mm guide length, Fig. 3(b), all the power is transferred to guide 2 for $P_{inc} \leqslant 11.5\ \mu$W, which is perhaps close to the critical power P_c for this geometry. This is the linear coupling region. As the incident power is increased, the local refractive index in the MQW decreases, thereby reducing the coupling between the guides. This has been referred to as the nonlinear back-coupling effect by Li Kam Wa *et al.*[1] However, as the power in the input guide increases due to increased confinement, the local refractive index in the MQW increases again, returning L_c, the coupling length for maximum power transfer, to a finite value. Therefore, beyond the critical input power, coupling between the two guides is restored, though at a reduced level due to a lower refractive index in the MQW. This is the cause for the oscillations of the input guide power at higher input intensities in Fig. 3(b). The data of Fig. 3(c) for a longer guide length and at higher input levels are similar. It should be noted that in Fig. 3(b) the power in the input guide should reach $\sim 100\%$ at 25 μW of incident power, but does not do so probably because of the unequal propagation constants in the two guides due to the trapezoidal etching profile. The coupling experiments were repeated with a 3.5-meV energy separation between the laser output and the exciton resonance of the MQW. The coupling behavior for a 2.0-mm guide is shown in Fig. 3(d), which is essentially identical to the previously discussed results. In general, lower powers are measured in the output guide due to the stronger absorption in the MQW region. We expect a small birefringence in the MQW, but can make no measurement due to the output fiber from the AlGaAs laser which carries hybrid modes.

We have analyzed the data by considering the theory of the nonlinear coherent coupler developed by Jensen.[4] The power flow in the two coupled guides can be expressed as

$$-i\frac{da_1}{dz} = Q_a a_1 + Q_b a_2 + (Q_c|a_1|^2 + 2Q_d|a_2|^2)a_1, \quad (1)$$

$$-i\frac{da_2}{dz} = Q_a a_2 + Q_b a_1 + (Q_c|a_2|^2 + 2Q_d|a_1|^2)a_2, \quad (2)$$

where a_1, a_2 are the field amplitiudes in each guide and Q_a, Q_b are related to different types of field overlapping integrals of guided modes in both waveguides. Q_a is the perturbed susceptibility induced by changes in β, which is negligible in our case. Q_b is the linear coupling coefficient. Q_c and Q_d are nonlinear coupling coefficients which are proportional to the nonlinear refractive index. Because of the slight asymmetry in the guide shapes and because of multiple modes forming in the lower guide, it is difficult to get an accurate estimate of the overlapping field integrals. We have therefore simply used the coupling coefficients as fitting parameters in order to estimate the behavior of light transmission in the nonlinear coupler.

The above set of equations was solved numerically with appropriate experimental parameters used in our study. The

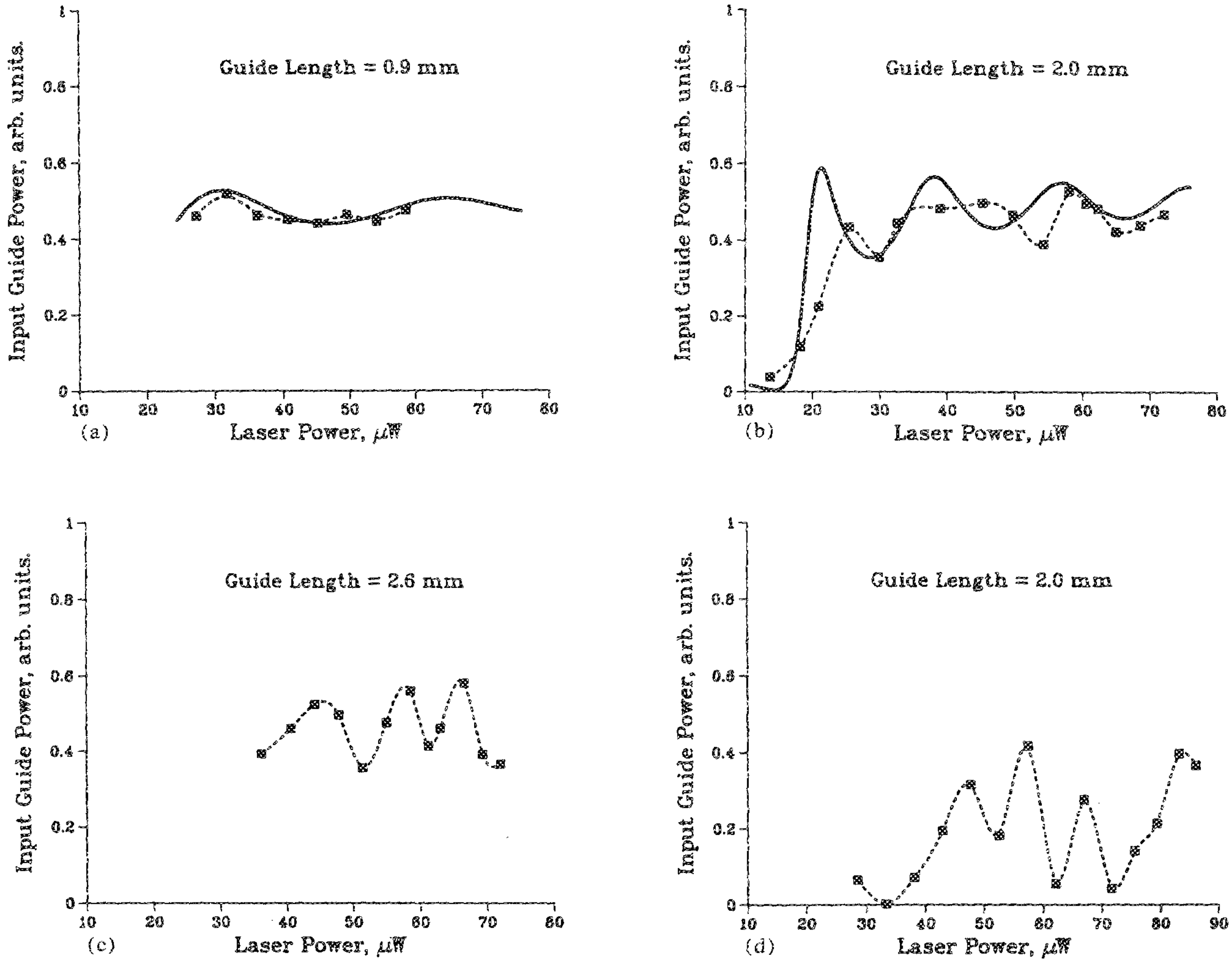

FIG. 3. Power remaining in input guide as a function of excitation power for different guide lengths. (a)–(c) are for the case when the laser energy is 13.0 meV below the heavy hole excitonic resonance of the MQW. (d) is for the case when the separation is 3.5 meV. The solid lines in (a) and (b) are calculated plots.

calculated values of the power remaining in the input guide are shown in Figs. 3(a) and 3(b) by the bold lines. It is clear that the experimental results mimic the calculated data. A value of $L_c = 2.3$ mm was measured by the cutback method using light energy far from the exciton resonance. Using this value of L_c in our fitting, we estimate $n_2 = 1.67\times10^{-5}$ cm^2/W. A higher value of n_2 is obtained from the data of Fig. 3(d), being closer to the excitonic resonance.

From the data of Fig. 3(b) it is obvious that large modulation of the input light can be obtained by changing the intensity of the excitation. This makes such devices very attractive for ultrafast modulation and switching applications. One potential application is the optical switching between field-effect transistors, where the guides (with a single quantum well channel) are formed underneath the gate contacts. We are in the process of investigating such a device. Another application is the photonic modulation of external cavity lasers. More importantly, if the two guides have identical propagation constants, then the nonlinear refractive index coefficient, n_2, and the nonlinear susceptibility, $\chi^{(3)}$, can be obtained from an accurate fitting of the coupling characteristics.

Several discussions on the basic ideas and principles one of us (P.K.B.) had with Dr. M. Cada are gratefully acknowledged. The work is being supported by the National Science Foundation Lightwave Technology Program under grant ECE-8610803 and the Army Research Office under contract DAAL03-86-K-0105.

[1]P. Li Kam Wa, J. E. Sitch, N. J. Mason, J. S. Roberts, and P. N. Robson, Electron. Lett. **21**, 26 (1985).
[2]U. Das, Y. Chen, and P. Bhattacharya, Appl. Phys. Lett. **51**, 1679 (1987).
[3]M. Cada, R. C. Gauthier, B. E. Paton, and J. Chrostowski, Appl. Phys. Lett. **49**, 755 (1986).
[4]S. M. Jensen, IEEE J. Quantum Electron. **QE-18**, 1580 (1982).