131 ps Optical Modulation in Semiconductor Multiple Quantum Wells (MQW's)

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Abstract–**A new optical modulator has been fabricated which uses the recently discovered electroabsorption effect in MQW's. Optical pulses 131 ps long were generated when the device was driven with 122 ps electrical pulses. The input–output characteristics of the device show that it has low insertion loss with reasonable modulation depth and drive voltage.**

INTEREST in external modulators for injection lasers in optical communication systems in increasing because of awareness of problems with direct modulation of such lasers. These include chirp at modulation rates exceeding 1 Gb/s [1] and the difficulty of maintaining stable frequency and phase in directly modulated coherent systems [2]. Several materials for external modulators exist, notably electrooptic lithium niobate [3] and electroabsorptive III-V semiconductors [4], but higher performance devices are needed. Recently, we reported a new effect, electroabsorption in multiple quantum wells (MQW's) of GaAs/GaAlAs with electric fields applied perpendicular to the well layers [5]. Use of this effect for modulation has the advantage of compatibility with technology already used for sources and detectors; it does not display the polarization sensitivity of the electrooptic materials [3]; it should be equally adapted to multimode and single-mode systems; and the strong electroabsorptive effect seen in these MWQ's should allow smaller, and thus faster, devices than possible with bulk electroabsorptive materials [4]. In this letter, we report a new modulator made with this technology and show for the first time that it can achieve modulation speeds approaching 100 ps. We also describe the input–output characteristics of the device.

The device is shown schematically in Fig. 1. A set of 50 GaAs quantum wells, each 95 Å wide, is fabricated by molecular beam epitaxy in the intrinsic region of a p-i-n diode, which is operated back-biased [5]. This allows us to vary the electric field applied to the MQW's quickly and conveniently. As the applied voltage is increased, the absorption edge in the MQW's shifts towards longer wavelength, and the consequent change in optical transmission produces intensity modulation. The thickness of the active MQW layer is 0.965 μm. The device is defined by a mesa 95 μm in diameter, with a 25 μm diameter optical window. This mesa is etched only about 2.5 μm high, so the device can be supported on the n^+ semiconductor contact. A layer of silicon nitride approximately 1500 Å thick was put down as a field insulator, but it also served as a partial antireflection coating on one surface.

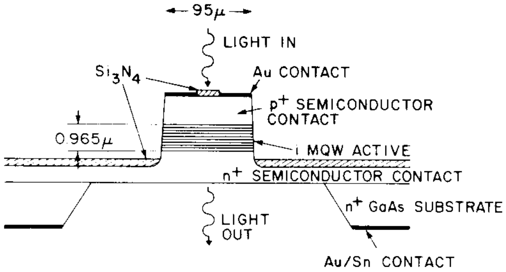

Fig. 1. Schematic view of modulator. For details of layer thicknesses and compositions, see [5].

At the operating bias, the capacitance of the device alone was only 0.54 pF. Our contacting scheme produced a contacted device with 1.3 pF capacitance, which implies an RC time constant of only 65 ps when driven with a 50 Ω source.

To measure the modulator impulse response, the device was connected to a microstrip line and bridged with a 50 Ω resistor. It was driven with the output of a commerical step recovery diode (HP 33002A). This electrical drive is shown as the upper trace in Fig. 2; it has a deconvoluted FWHM of 122 ps and varies between −0.5 and −8.5 V. The modulator was illuminated with 180 μW of focused light from a commerical single frequency laser operating CW at a wavelength of 8580 Å. The output light was directed to a Spectra-Physics 403B fast Si p-i-n photodiode, whose output was preamplified with a B&H DC7000HL preamp to drive a digital sampling oscilloscope.

The detected response of the modulator is shown as the lower trace in Fig. 2. The FWHM of this response is 174 ps. We would like to deconvolve the response of the driving pulse and the measuring system from the observed response to obtain the response time of the modulator itself. However, the nonlinear transmission versus voltage (T-V) response of the modulator, described below, makes usual deconvolution methods invalid. To determine the actual speed of response of the modulator, we have numerically convolved the Gaussian electrical drive pulse with an adjustable modulator impulse response, processed this through the observed modulator nonlinear T-V function, and then convolved the result with the specified impulse response functions of the detector, preamp, and oscilloscope. An assumed modulator time constant of 117 ps reproduced the 174 ps width observed on the sampling oscilloscope. This time constant is somewhat longer than that calculated for the contacted device; we ascribe this discrepancy to mounting parasitics, difficulties aligning the photodiode for fastest re-

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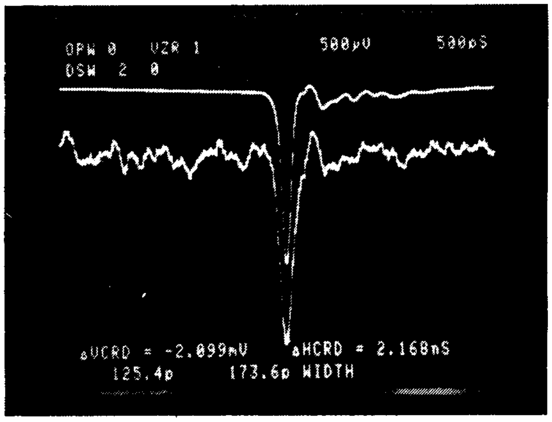

Fig. 2. Upper trace is electrical drive pulse, with a measured FWHM of 125 ps. Lower trace is the optical response, with a measured FWHM of 174 ps.

sponse, and uncertainties associated with the deconvolution. From the deconvolution of the detection system response we deduce that the optical pulse width is 131 ps. The nonlinear modulator *T-V* provides for considerable pulse compression: an equivalent linear modulator would have to exhibit a time constant of 42 ps to generate this optical pulse.

Fig. 3 shows the *T-V* characteristics of the device at four different laser wavelengths. These were measured by applying a 10 μs, 11 V triangular pulse to the device and observing the optical response. The incident optical power was 260 μW. The plotted transmission is that of the device itself and does not include any loss due to the focusing or collimating lenses. These curves can be understood qualitatively by comparison to the MQW's spectra [5], although a quantitative comparison is impossible because the modulator in this work has an antireflection coating on one surface. This increases the overall transmission and reduces Fabry-Perot effects, which complicate the spectra of [5].

The insertion loss and modulation depth can be determined from these data. At 8580 Å, for example, the maximum and minimum transmissions observed are 76 and 45 percent, respectively, which corresponds to an insertion loss of 1.2 dB and a modulation depth of 2.3 dB. This insertion loss (which does not include loss associated with coupling to fibers) is quite low compared to other devices [3], [4] and could be improved by providing proper antireflection coatings on both surfaces. The modulation depth is still far below that of comparable devices [3], [4], and improving this figure will be the subject of future work.

Fig. 3 also shows that the response of the device can be adjusted by choosing the operating wavelength and the dc bias. Linear, nonlinear, and quadratic response regimes can be obtained easily. At 8580 Å the nonlinear response of the device means that, in the presence of a dc bias of 4 V, the signal drive voltage for maximum extinction can be reduced from 8.5 to 4.5 V with only a 0.3 dB insertion loss penalty. We also see that, although the device response depends on wavelength, it is not so highly dependent that source drifts of a few angstroms will be troublesome.

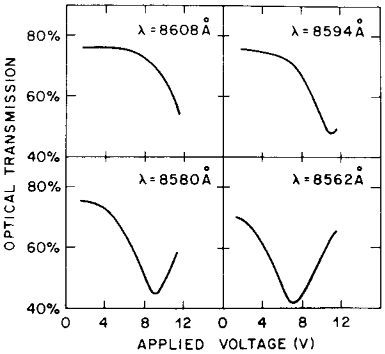

Fig. 3. Transmission versus voltage (*T-V*) plots for the modulator at four optical wavelengths.

Fig. 3 also shows the enhanced magnitude of the electroabsorption effect in these MQW's. To achieve this modulation depth in an active layer 0.965 μm long, we must achieve a change in absorption coefficient of 5400 cm^{-1} with electric field application. For comparison, in bulk GaAs, Stillman *et al.* observed changes in absorption coefficient 40 times smaller for electric field changes about half as large [4].

In conclusion, we have demonstrated a new, very high speed optical modulator which makes use of the electroabsorption effect in MQW's. We have demonstrated a response speed that is close to the best observed in any modulator technology [3], and we believe that this speed can be improved still further by such straightforward steps as further decreasing device size and stray capacitances.

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