100 ps WAVEGUIDE MULTIPLE QUANTUM WELL (MQW) OPTICAL MODULATOR WITH 10:1 ON/OFF RATIO

Indexing terms: Optics, Optical modulation, Optical waveguides

By incorporating two quantum wells into a capillary waveguide, we have made the first MQW optical modulator with an on/off ratio of at least 10:1. Furthermore, this device was used to generate an optical pulse less than 100 ps long, the fastest to date with an MQW device.

Semiconductor multiple quantum wells (MQWs) have recently been shown to have very interesting optoelectronic properties. Room-temperature exciton resonances were first seen near 0·8 μm in GaAs/AlGaAs MQWs;[1] recently these excitons in GaInAs/AlInAs MQWs were observed[2] near 1·55 μm and later confirmed.[3] Quantum wells at this longer wavelength are of interest because it matches the region of highest transparency of present optical fibres. Devices using the low-power optical nonlinearity of MQWs have been made,[4,5] and because they show an enhanced electroabsorption effect,[6] MQWs have been used as the active element in high-speed modulators[7] and optically bistable devices,[8] among other devices. Previous MQW modulators have generated optical pulses as short as 131 ps, with an on/off ratio of 1·7:1.[7]

In previous work on high-speed modulators, the light propagated perpendicular to the epitaxial layers. This resulted in an interaction length between the light and the MQWs that was limited to the epitaxial thickness, which was less than 1 μm.[7] Although simple to fabricate and optically excite, this geometry limited the device's on/off ratio. To improve this parameter, and to provide a device that could eventually be fabricated and coupled monolithically with laser sources, we have investigated the configuration shown in Fig. 1. In this device, the light propagates parallel to the grown layers and is guided parallel to the wafer by a leaky capillary waveguide of a short-period, low-refractive-index superlattice of GaAs/AlGaAs cladded by pure GaAs layers. As opposed to previous devices, this structure permits propagation of light polarised parallel and perpendicular to the layers.[9] For TE polarisation, the characteristic 2-peaked heavy- and light-hole exciton absorption spectrum is seen, but in the TM polarisation, only the light-hole exciton peak is observed. In both polarisations, the absorption features shift to longer wavelength with the application of an electric field perpendicular to the layers, which enables the device to be used as a modulator in either polarisation.[10]

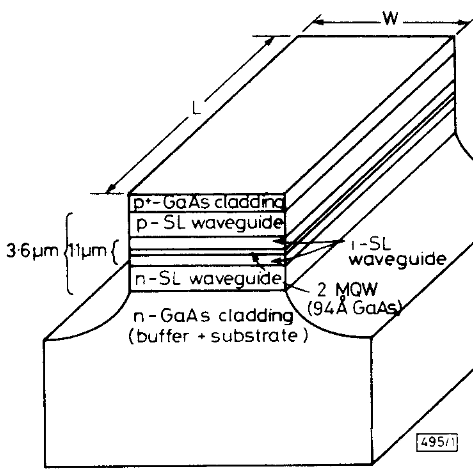

Fig. 1 *Schematic view of waveguide modulator*

SL represents a GaAs/AlGaAs superlattice. The two optically active MQWs are located in centre of guiding layers and electrical diode. Device was 150 μm long and 40 μm wide

To evaluate the performance of the device in Fig. 1 as a high-speed optical modulator, it was fabricated with a width $W = 40$ μm and a length $L = 150$ μm. In this MBE-grown device, a pair of 94 Å-wide quantum wells were grown in the centre of the 1·1 μm-wide intrinsic region of a PIN electrical diode. The diode is, in turn, in the centre of a 3·6 μm-wide capillary waveguide. The lateral overlap between the approximately 3·6 μm-wide optical mode and the MQWs, which occupy only 0·06 μm, was deliberately made small. However, we can achieve a good on/off ratio because the interaction length is long and the electroabsorption effect in MQWs is large.[6] For a device of this length and width, the lateral spreading of the optical beam is sufficiently small that we expect little interaction between the light and the edges of the mesa. Thus, the waveguide can be approximated as a slab.

To obtain high-speed performance, care was taken to reduce stray capacitance and parasitic resistance. Measurements on a microwave network analyser up to 4 GHz indicate the mounted device has a capacitance of 0·93 pF with a series resistance of 7·5 Ω. This implies an *RC* time constant of 54 ps when the device is driven from a 50 Ω source.

The transfer function of the modulator was first measured at low speed using TM-polarised CW light from a single-mode injection laser operating at $\lambda = 851$ nm. Fig. 2 shows the transmitted light as a function of applied voltage for this device. The ratio of maximum to minimum transmitted power is 10:1, which is almost six times greater than that achieved in the device where light propagated perpendicular to the grown layers.[7] The insertion loss was 7 dB. About 3 dB of this is due to reflection from the two uncoated facets of the device, and a further ~3 dB is due to built-in radiation loss from the capillary waveguide.[9] Thus, these two effects, which can both be reduced by appropriate design changes, account for almost all the insertion loss.

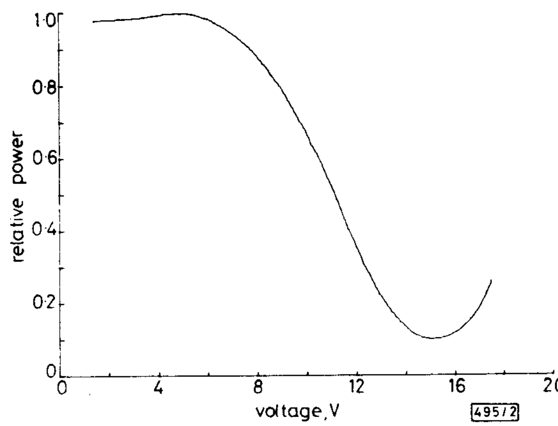

Fig. 2 *Relative transmission of modulator as a function of voltage, when illuminated by 851 nm light*

To measure the device at high speeds, the modulator was driven by 60 ps FWHM pulses from a 1 GHz comb generator. This electrical drive is shown as the lower trace in Fig. 3. The optical output from the modulator was detected with a high-speed GaAs Schottky photodiode,[11] preamplified, and measured on a sampling oscilloscope. The resulting optical pulse is shown as the upper trace in Fig. 3. The pulse has a FWHM of 128 ps on the oscilloscope; when the detection system bandwidth was deconvolved from this[7] we concluded that the generated optical pulse had a FWHM of 97 ps.

The speed of the device is ultimately limited by its *RC* charging time constant. Using the 54 ps *RC* time constant measured by the microwave network analyser, we would predict that a 93 ps optical pulse would be generated, assuming a linear transfer function for the modulator.[7] The agreement between the predicted and observed optical pulse-widths is good, indicating that the *RC* charging time is the dominant speed limit in this device.

In conclusion, we have generated the shortest optical pulses reported to date with a MQW modulator, and have done so with the highest on/off ratio so far achieved, 10:1. Further work will go towards making even faster devices, by lowering capacitances still further.

We wish to thank S. Y. Wang of Hewlett-Packard for providing the high-speed detector used in this work.

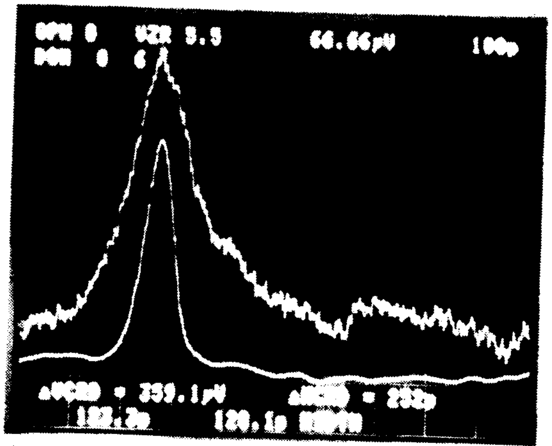

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Fig. 3 *Sampling oscilloscope traces*

Lower curve is electrical signal applied to modulator; upper trace is detected optical signal. Horizontal scale is 100 ps/div; optical pulse has a deconvolved FWHM of 97 ps

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