All optical, high contrast absorptive modulation in an asymmetric Fabry–Perot étalon

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We report a 27:1 switching contrast ratio with 2.5 mW of power in an asymmetric Fabry–Perot étalon. The modulation is achieved by optical saturation of the excitonic absorption profile of a 95 Å GaAs/AlGaAs multiple quantum well structure grown on a high-reflectivity dielectric stack mirror.

In recent years there has been a lot of interest in the development of optical processing elements for optical computing and neural networks. These devices are expected to exploit the high parallelism possible with optical systems. Several candidates have been proposed and demonstrated but it is still not clear which, if any, will be the clear leader in providing a cheap, reliable optical switching/modulation array capable of implementation in a working optical system. The field may be divided into all-optical and electro-optic devices. Both these types have several problems associated with them. The electro-optic devices such as the symmetric self electro-optic effect device[1] (S-SEED) have shown fast switching capabilities with extremely low light intensities. Contacting these types of devices in large scale arrays however, is a drawback that limits the inherent parallelism of optics to the restrictions of large scale electrical integration. Arrays of all-optical devices may be easier to realize, either by defining "mesa" arrays by etching techniques or simply using the light beams themselves to define active elements. However these all-optical devices also have some drawbacks. They tend to require high optical intensities for switching and the high finesse Fabry–Perot structures already demonstrated require strict tolerances on growth conditions and thermal stability while operating at high intensities to produce identical arrays of switches.[2]

It has been shown that the contrast of electro-optic modulators can be improved considerably by incorporating a Fabry–Perot structure into the device. Particularly successful is the asymmetric Fabry–Perot structure[3–6] which has achieved 100:1 contrast in reflection electro-optic absorption modulation. The asymmetric structure is achieved by reducing the reflectivity of the front mirror thereby reducing the finesse. In this letter we report all-optical modulation in a nonlinear asymmetric structure in the reflection mode. We achieve a 27:1 contrast ratio at low operating powers based on optical saturation of the excitonic absorption profile of a GaAs/AlGaAs multiple quantum well. The high all-optical contrast achieved means that low finesse structures can be useful. The reduced mirror reflectivity results in simpler structures which can be more reproducibly grown and which have a wide operating bandwidth although at the expense of higher insertion loss.

An asymmetric Fabry–Perot étalon has mirrors of unequal reflectivities. The reflectivity R of the étalon at a resonance mode is given by

$$R=\frac{R_f(1-R_\alpha/R_f)^2}{(1-R_\alpha)^2}, \qquad (1)$$

where R_f is the front mirror reflectivity, R_b is the back mirror reflectivity, and R_α is given by

$$R^2\alpha=(R_fR_b)\exp(-2\alpha d), \qquad (2)$$

for absorption coefficient α and cavity thickness d.

With R_f substantially less than R_b and no absorption in the cavity, the étalon reflectivity at resonance is high. With an absorbing cavity, the effective reflectivity of the back mirror is lowered and the étalon reflectivity at resonance is correspondingly smaller. From (1) above it can be seen that with the following condition:

$$R_f=R_b\exp(-2\alpha d), \qquad (3)$$

the étalon reflectivity is zero on resonance and the cavity is said to be impedance matched. Hence intensity modulation of the absorption in the cavity modulates the étalon reflectivity providing the basis of an optically addressed modulator with a theoretically infinite contrast ratio and potentially low insertion loss.

To achieve this modulation in an actual device we use the strong nonlinear absorption changes at the band edge of a GaAs/AlGaAs multiple quantum well (MQW) structure when excited optically. Optical generation of high densities of free carriers leads to absorptive and dispersive changes arising from many-body effects such as screening of Coulomb interactions, phase space filling, and band-gap renormalization.[7–9]

The asymmetric Fabry–Perot device, grown by atmospheric pressure metal-organic vapour phase epitaxy (MOVPE) on a semi-insulating GaAs substrate, has a *pin* structure. A high-reflectivity quarter-wavelength dielectric

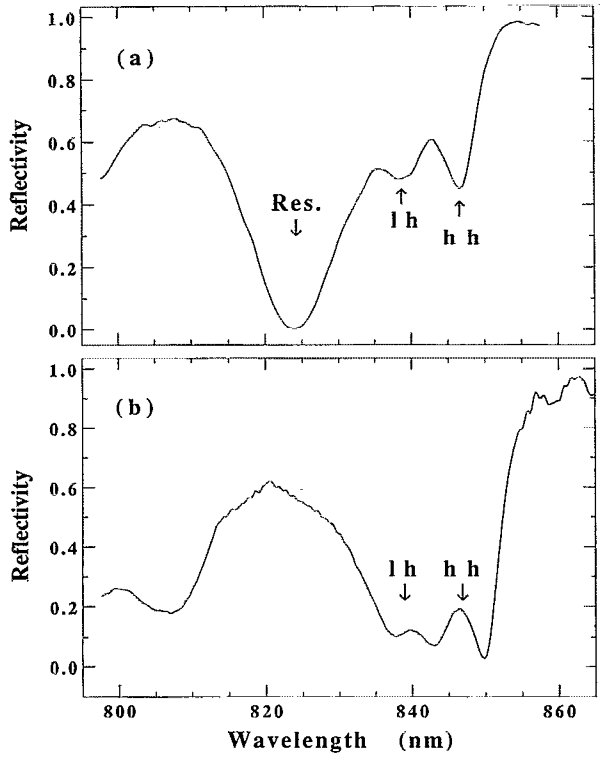

FIG. 1. Reflectivity of asymmetric Fabry–Perot étalon as a function of wavelength at two different sample positions (a) and (b). The light hole (lh) and heavy hole (hh) excitons are clearly resolved in (a) and the Fabry–Perot resonance (Res.) can be seen to shift spectrally due to small changes in cavity dimensions from (a) to (b).

stack mirror consisting of 15 periods of alternating layers of Zn-doped AlAs (low index) and $Al_{0.1}Ga_{0.9}As$ (high index) was grown on a 2-μm-thick p^+ GaAs buffer layer. This structure has a reflectivity greater than 95% at the operating wavelength of 850 nm. On top of this was grown a nominally intrinsic MQW structure consisting of 75 periods of 95 Å GaAs well + 60 Å $Al_{0.3}Ga_{0.7}As$ barrier, which from previous work is expected to have a residual doping of $1–2\times10^{15}$ cm^{-3}. The cavity is completed by an n^+ $Al_{0.3}Ga_{0.7}As$ layer and a thin 50 Å n^+-GaAs capping layer for contacting purposes. This capping layer was made thin enough to have a negligible absorptive effect in the device. The front reflectivity is simply the air/semiconductor interface reflectivity of approximately 30%. We do not expect the doping in the device to have a significant effect when it is operated as an all-optical modulator.

In order to obtain a high contrast ratio by meeting the required cavity conditions, i.e., to match the high absorption around the heavy hole exciton wavelength to a resonance mode, we relied on small changes in thickness uniformity of the cavity dimensions across a sample wafer. Figure 1 shows reflectivity spectra at two different positions on the sample. Figure 1(a) shows a Fabry–Perot resonance mode at 824 nm and clearly resolved light hole and heavy hole excitons at 840 and 847 nm, respectively. The reflectivities at the exciton wavelengths are high because they are not at a Fabry–Perot resonance. The Fabry–

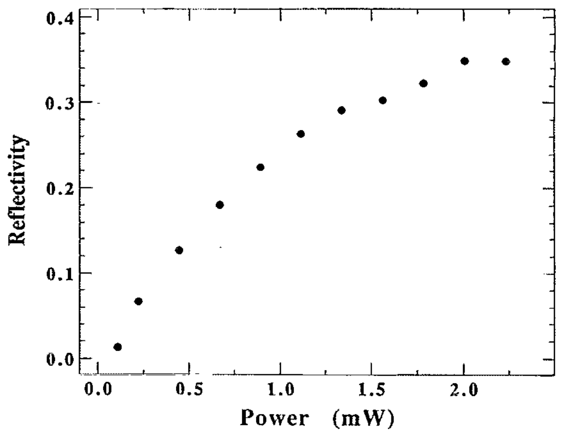

FIG. 2. Reflectivity of asymmetric Fabry–Perot étalon, at the resonance wavelength of 850 nm, as a function of incident power.

Perot resonance at 824nm has a very low reflectivity. This is due to the high non-saturable absorption above the bandgap balancing the mirror reflectivities. As the cavity width increases across the sample, the Fabry–Perot resonance moves spectrally to longer wavelengths while the exciton positions remain fixed. This change in cavity width is due to small changes in the dimensions of the multiple quantum well and the doped $Al_{0.3}Ga_{0.7}As$ layer. The change in an individual well width is not large enough to affect the exciton wavelengths significantly. Figure 1(b) shows a very low reflectivity dip at $\approx$850 nm. This wavelength is $\approx$ 3 nm longer than the heavy hole exciton wavelength and hence the absorption is such that, combined with the Fabry–Perot resonance, impedance matching conditions are almost achieved. The complicated spectrum between 835 and 850 nm will be discussed further in a future paper. At wavelengths greater than 850 nm the reflectivity rises rapidly to the maximum of 1 due to the strong absorption and dispersive changes. The resonance is much narrower than that in Fig. 1(a).

The reflectivity measurements were done using an argon ion pumped titanium-sapphire laser. To reduce any thermal effects in the sample the exciting beam was pulsed using an acousto-optic modulator giving 1 μs pulses at a repetition rate of 1 kHz. The beam was focused on the sample to a spot size of 7 μm using a X30 microscope objective and the measurements were made using both an oscilloscope and lock-in amplification. All measurements were normalized against a highly reflecting infrared mirror with a reflectivity $>99.9\%$ at 850 nm.

The characteristic change in reflectivity and the high contrast ratio is illustrated in Fig. 2 which shows the reflectivity of the étalon as a function of the incident pump power. The operating wavelength is 850 nm, the lowest reflectivity point in Fig. 1(b). The low-power residual reflectivity is 1.3%. As the incident power increases the absorption in the cavity reduces while the reflectivity increases. With only 2.5 mW of power, the absorption begins to saturate and the reflectivity levels off at 35%. Hence we have achieved a contrast ratio of 27:1 with only 2.5 mW of power and an insertion loss of 4.5 dB. As expected, even

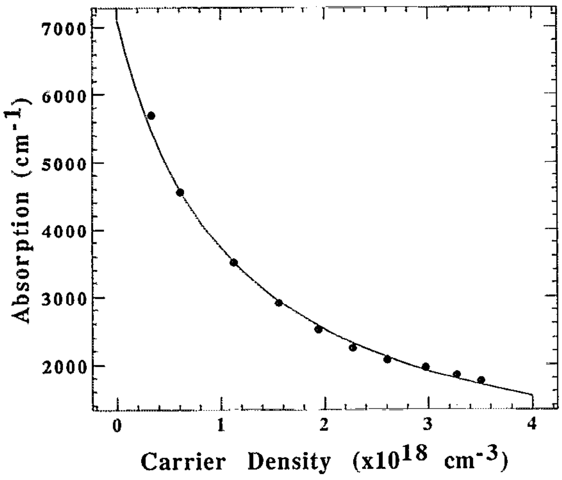

FIG. 3. Saturation of heavy hole exciton absorption line in GaAs/$Al_{0.3}Ga_{0.7}As$ multiple quantum well. The dots are experimentally obtained from reflectivities of the asymmetric Fabry–Perot resonance; the solid line is a theoretical fit using a simple absorption saturation model.

for a low finesse device the contrast ratio varies rapidly around the resonance peak, mainly due to the narrow line width of the excitonic resonance. We were able to obtain half the maximum contrast ratio over a wavelength range of approximately 2 nm. The contrast ratio is limited only by the low-power reflectivity, which can be reduced by adjusting the cavity absorption.

Since the absorption saturation is determined by many-body effects and hence by the free carrier density (N), we estimated the saturation in the cavity using a simple model for the absorption coefficient α,

$$\alpha=\alpha_0\frac{1}{1+N/N_s}, \tag{4}$$

where α_0 is the linear absorption coefficient and N_s is the saturation carrier density.

Figure 3 shows the actual absorption values in the cavity together with the theoretical fit using Eq. (4). The experimental values were obtained from the reflectivities in Fig. 2 using Eq. (1). We calculated the carrier density N from the cavity intensity I using the steady-state equation

$$N=\alpha(N)I\tau/\hbar\omega, \tag{5}$$

with a carrier lifetime τ of 20 ns and $\hbar\omega$ the exciting photon energy at the operating wavelength, 850 nm. The intensity was calculated from the intracavity power and our measured spot size of 7 μm. We obtained the best fit with $\alpha_0 = 7100$ cm^{-1} and saturation carrier density $N_s = 1.1\times 10^{18}$ cm^{-3}. The value for N_s is in good agreement with other work.[10]

In conclusion, we have investigated the intensity-dependent modulation of an asymmetric Fabry–Perot étalon. We have obtained a high contrast ratio by impedance matching the device using the heavy hole absorption profile of a GaAs/AlGaAs MQW cavity. With 2.5 mW of power we obtained a contrast ratio of 27:1 and half this value over an operating wavelength range of approximately 2 nm. This contrast can be improved by optimizing the structure. By employing only one integrated mirror the device can be more reproducibly grown than its high finesse counterparts, an essential requirement for fabricating large scale arrays of such devices. The device shows promise as an optically addressed modulator for applications in optical computing and telecommunications.

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