# PERFORMANCE EVALUATION OF A MWQ ALL OPTICAL MODULATOR

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## Abstract

Optically controlled Multiple Quantum Well (MWQ) modulators promise to be of great interest for all optical data processing.

In this paper we analyze a device, based on a GaAs/AlAs MQW structure, whose principle of operation depends on the controlled excitonic absorption by means of free carrier generation. Such a device, experimentally tested in [1,2,3], is able to give a modulation depth close to one; its operation frequency is limited by carrier lifetime up to about some ten megahertz and it can be promising for high speed parallel processing.

The numerical results show a good agreement with experimental data reported in [1].

## 1 Introduction

In recent years several devices, for optical signal processing, based on Multiple Quantum Well (MQW) structures have been proposed and some of them have also been experimentally demonstrated. In the present paper a GaAs/AlAs MQW intensity modulator, in which the signal reflection from a stratified structure is controlled by the power of a control pump, is numerically modelled. Such a device has been proposed and already realized; experimental data and measured results can be found in [1,2,3,4].

The device structure is schematically represented in Fig.1. The MQW section is sandwiched between an antireflection coating (AR) and a dielectric mirror (DM); in this way the MQW region is exploited both in the forward and in the backward direction.

The working principle of the device is briefly described in the following. The operating wavelength for the signal is chosen to be near resonance with the basic electron-heavy hole excitonic absorption line; hence, in absence of the control beam (Pump in Fig.1), the signal experiences a large absorption in the MQW section and so the reflection coefficient can be rather small. When a proper power level at the pump wavelength (which lies in the continous absorption spectrum above the two-dimensional bandgap $E_{g2D}$) is injected, the electron-hole plasma generated gives rise to a bleaching of the excitonic absorption through screening of the coulombic interaction and band-filling [5,6]; as a consequence an increase of reflected signal power is observed.

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A schematic representation of the operating conditions is shown in Fig.2, where the idealized connection between the temporal evolution of the pump power and of the signal power reflectivity ($R_s$) is reported.

A numerical analysis of the performances of this device is presented and discussed in the following sections.

# 2 Device modelling

For the numerical analysis of the previously discussed device, the modelling of both the pump and the signal wavelegth is required.

## 2.1 Signal behaviour

As regards the signal power reflectivity, it is determined by the losses in the MQW structure. Since we are mainly interested in the modulation parameter [2]:

$$m = \frac{R_{s(P)} - R_{s(P=0)}}{R_{s(P)}} \tag{1}$$

clearly the effects of background losses and of the DM cancel in the above ratio. The attenuation constant at the signal wavelenght is evaluated by the imaginary part of the excitonic contribution to the dielectric permittivity which, in a two dimensional model can be written as [6,7]:

$$\Delta\varepsilon(\omega, N_i) = \Delta\varepsilon_o(\omega, N_i)\, g(N_i) \tag{2}$$

where $N_i$ is the free carrier density per unit area in the i-th well and $\Delta\varepsilon_o$ can be represented by:

$$\Delta\varepsilon_o(\omega, N) \simeq \frac{\frac{2}{d\hbar}\, |\sum_k R(k)\, \Phi_k|^2}{\frac{E_{ex}(N)}{\hbar} - \omega - i\gamma} \tag{3}$$

In the previous expression $d$ is the well thickness, $\hbar$ is the Planck constant divided by $2\pi$, $R(k)$ is the dipole matrix element of the transition between valence and conduction bands at the same wavevector $k$, $\Phi_k$ is the normalized excitonic eigenfunction in $k$ space for $N = 0$, $\gamma$ represents the linewidth of the lorentzian absorption curve and finally $E_{ex}(N)$ is the excitonic transition energy. In our numerical simulation it was numerically fitted by:

$$E_{ex}(x) = E_{g2D} - E_{o2D}(1 + b\, x^c) \tag{4}$$

where $x = Na^2$ is the free carrier density normalized with respect to $a^2$, being $a$ one half the 3D Bohr radius, $E_{o2D}$ is the strictly two dimensional exciton binding energy for $N = 0$. Numerical values for $b$ and $c$ are: $b = 4.75$ (HH), 4.92 (LH), $c = 0.87$ (HH), 0.86 (LH).

In Eq.(2) $g(N)$ describes the bleaching of the excitonic contribution to the dielectric permittivity and its numerically computed behaviour is shown in Fig.3. The following approximate analytical expression was used to represent $g(N)$:

$$\begin{aligned} g(x) &\simeq 1 + c_1 x + c_2 x^2 + c_3 x^3 + c_4 x^4 + c_5 x^5 \quad && x < x_s \\ g(x) &= 0 && x > x_s \end{aligned} \tag{5}$$

A fitting with numerically calculated values of $g(x)$ gives: $c_5 = -2972$,-7801; $c_4 = 1953$, 4452; $c_3 = -414$, $-808$, $c_2 = 42.7$, 62.1, $c_1 = -6.79$, $-8.19$; $x_s = 0.25$, 0.215 for HH and LH respectively.

In the evaluation of the quantity $m$ defined in Eq.1, one must obviously take into account that N, determined by the pump power, changes from one well to another, as explained in the following subsection.

## 2.2 Pump behaviour

The rate equation for the free carrier concentration $N_i$ per unit area in the i-th well ($N$ represents both electrons and holes since an intrinsic material is assumed) reads:

$$\frac{dN}{dt} = -AN - BN^2 + \frac{P_a}{\hbar\omega_p} \tag{6}$$

where the coefficients $A$ and $B$ account for the effect of recombinations and the last term corresponds to the carrier generation due to the pump photon absorption; in effect $P_a$ is the absorbed power in a given well per unit area and $\omega_p$ is the pump angular frequency. The evaluation of $P_a$ is obtained approximately through:

$$P_a \simeq \omega_p |E_p|^2 |\Phi(0)|^2 \frac{\mu\gamma}{d\pi\hbar} \int_{E_{g2D}}^{\infty} \frac{|R(E)|^2 \, dE}{(\hbar\omega_p - E)^2 + \hbar^2\gamma^2} \tag{7}$$

where $|E_p|$ gives the local electric field intensity corresponding to the stationary wave due to the mirror, $\mu$ is the reduced electron-hole mass, $R(E)$ is the dipole matrix element of the transition between valence and conduction bands at the energy $E$, $|\Phi(0)|^2$ accounts for excitonic enhancement in the continous spectrum [5] and finally $E_{g2D}$ is the two dimensional bandgap.

# 3 Numerical results

The numerical modelling, described in section 2, has been applied to the device structure presented in [1,2,3], which refers to a AlAs/GaAs MQW. The MQW section contains 20 wells with $d = 200$Å and barrier thickness of 800Å; the dielectric reflectivity was taken from the experimental results given in [1] and a perfect input matching due to the AR has been assumed.

To calculate energy subbands in conduction and in valence band, a band offset parameter (defined as $\Delta E_c/\Delta E_g$) of 0.6 was used; the wavelength of the pump was assumed to be $\lambda_p = 790nm$. All the other material data used in the computation are reported in Table I.

| Material | $\gamma_1$ | $\gamma_2$ | $m_e/m_o$ | $E_g(eV)$ | $\varepsilon_r$ | $\gamma\ (s^{-1})$ | $A\ (s^{-1})$ | $B\ (cm^{-2}s^{-1})$ |
|---|---|---|---|---|---|---|---|---|
| GaAs | 6.85 | 2.1 | 0.067 | 1.424 | 13.18 | $10^{13}$ | $0.2\ 10^9$ | $2.5\ 10^{-4}$ |
| AlAs | 3.45 | 0.68 | 0.124 | 3.018 | 10.08 | - | - | - |

Table I: material parameters.

The quantity $m$ in stationary conditions is shown in Fig.4 as a function of the signal wavelength; the heavy-hole (a) and light-hole (b) effects are separately reported, together with the global result (c). The pump power density for this computation was $0.2\,mW/\mu m^2$, while the DM power reflectivity was assumed to be 0.4. It appears that, owing to the relatively large value of $d$, both heavy and light hole excitons play an important role in determining the total system response. For this reason in all the simulations both excitons have been taken into account.

In Fig.5 the quantity $m$, in the same conditions of Fig.4, is shown as a function of the incident pump intensity (per unit area) for three values of $\lambda_s$: 870 (a), 865 (b) 860 nm (c). A saturation behaviour can be clearly seen (connected to $g(N)$ of Fig.3), in rather good agreement with the experimental results of [1].

The transient behaviour of $m$, during one square wave pump pulse of time length $t = 4\,ns$, is reported in Fig.6 for $\lambda_s = 870\,nm$ at different pump power intensities: 5 (a), 0.5 (b), 0.1 (c), 0.05 (d) $mW/\mu m^2$.

It can be of some interest to analyze the effect of the number $n$ of wells, to know the maximum achievable value of $m$, changing the value of $n$ in a reasonable range. Typical results are shown in Fig.7 at pump levels of 0.01 (a), 0.05 (b), 0.5 $mW/\mu m^2$ (c) and for $\lambda_s = 870\,nm$.

# References


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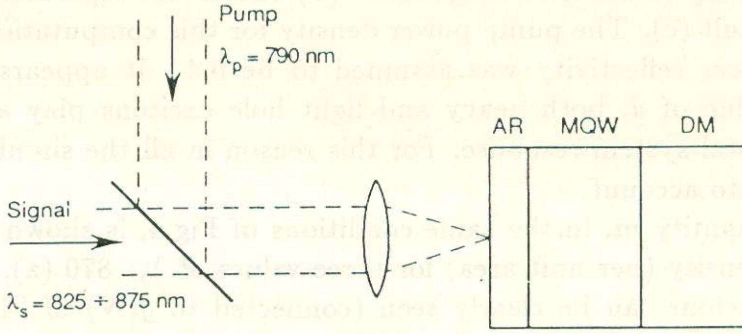


Fig.1: Schematic device representation

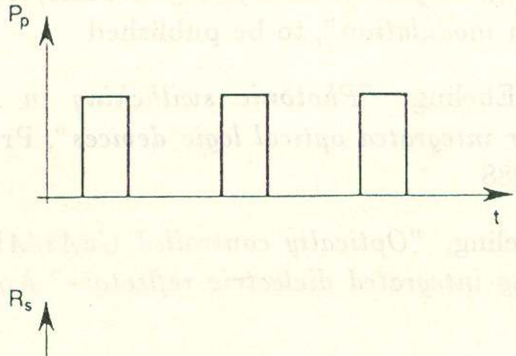


Fig.2: Idealized operating principle

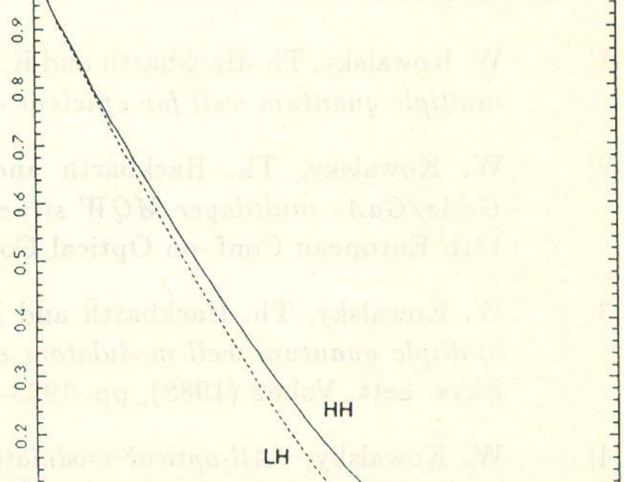


Fig.3: Saturation of the excitonic line as a function of carrier density (a = 0.5 times the 3D Bohr radius); HH (LH) for heavy (light) hole exciton.

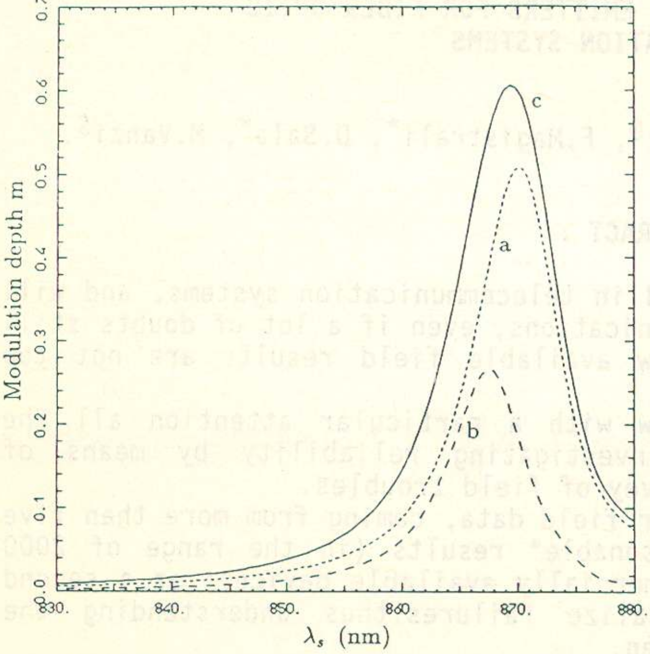


Fig.4: Wavelength response of the considered device, for a given pump power density (see text).

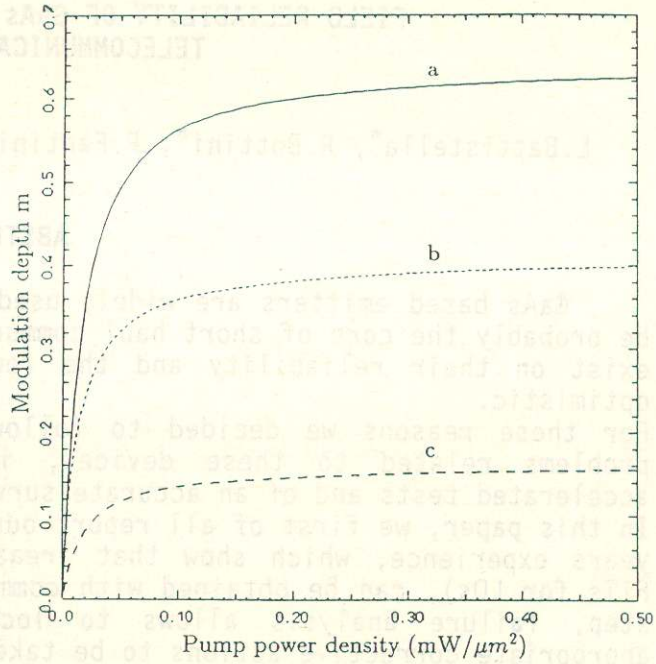


Fig.5: Device response as a function of pump intensity with $\lambda_s$ as a parameter (see text).

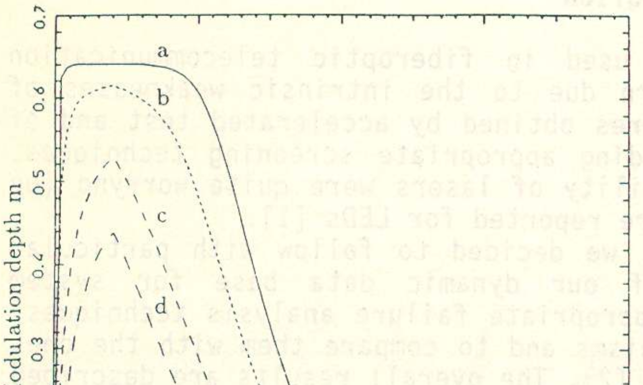


Fig.6: Transient device response for some values of pump power density at $\lambda_s = 870nm$.

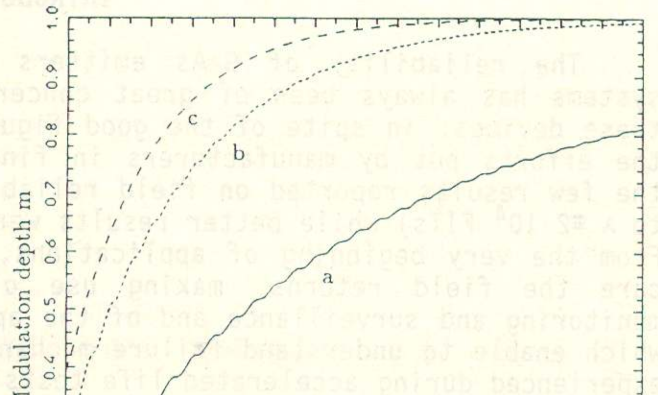


Fig.7: Response for devices with different well numbers; pump intensity is taken as a parameter.