MCQW INTENSITY OPTICAL MODULATOR FOR InP BASED MMIC/PHOTONICS INTEGRATED CIRCUITS

M.T. Camargo Silva*, M.A.G. Martinez, and P.R. Herczfeld

Center for Microwave/Lightwave Engineering
Drexel University - Philadelphia, PA 19104

ABSTRACT

This paper is concerned with chip level integration of photonic devices and MMICs. The focus is on a InP-based multicoupled quantum well intensity optical modulator. In the proposed configuration, the microwave field induces a periodic structure via the electrorefractive effect. The interaction of light with the induced grating yields a modulated optical signal. The paper discusses the structure and the expected performance of the device.

INTRODUCTION

The merging of photonic and microwave devices on a MMIC chip will enhance many applications: phase-array radar, antenna remoting, optical processing of microwave signal, and CATV signal distribution, Herczfeld [1].

The presence of applied electric fields in quantum well (QW) structures significantly alters the optical absorption and the index of refraction. The source of this phenomenon is the quantum-confined Stark effect (QCSE), which red shifts the absorption spectrum in the vicinity of the band edge, and at same time alters the refractive index for photon energies below the band edge. The change in the absorption and index are interrelated; however, they can be optimized relative to each other at a particular wavelength by suitable tailoring of the QW. This approach may be exploited in the fabrication of electroabsorption and electrorefraction type modulators.

Zucker [2] and Bigan [3] have shown that electrorefraction and electroabsorption modulators fabricated with uncoupled quantum wells will provide small size and potentially large bandwidth, but will suffer from high drive voltage and insertion loss.

Coupled quantum wells have attracted attention during the last few years for use in optical devices. Debbar [4] showed that symmetric coupled quantum wells are more attractive than uncoupled wells for modulator applications. A model for the optical properties of arbitrary semiconductor quantum well structures, including asymmetric coupled quantum wells, has been reported by Nakamura [5].

An intensity electrorefraction modulator operating at 1.3 μm, based on multicoupled quantum well (MCQW) structure, is proposed here. The modulator uses an electrically induced periodic structure, a grating, in place of an interferometric device. It is expected to reduce both the operating voltage and insertion loss.

MODULATOR STRUCTURE AND OPERATION

The basic device configuration under consideration, shown in Fig. 1, resembles the one reported by Camargo Silva and Herczfeld earlier [6]; however, this device uses coupled quantum wells. The structure consists of an integrated optical waveguide fabricated on a semi-insulating substrate (SI -InP). The waveguide consists of a 5×10^{17} (cm^{-3}) n-doped 0.34 μm thick core layer of $In_{0.87}Ga_{0.13}As_{0.28}P_{0.72}$ ($n_1 = 3.3226$). The "active cladding" consists of five layers (periods) of undoped coupled wells, giving a total thickness of 0.1 μm. The coupled well comprises of two 35 Å $In_{0.70}Ga_{0.30}As_{0.65}P_{0.35}$ ($n_w = 3.52$) layers separated by a 30 Å InP barrier ($n_b = 3.2091$). In the MCQW, the wells are decoupled from each other by 100 Å InP barriers. The two layers, the core and the active cladding, are enclosed in a 1.0 μm thick 5×10^{17}(cm^{-3}) n and p-doped InP ($n_3 = 3.2091$) layers, which serve as passive claddings. The refractive index data for InP and InGaAsP were taken from Broberg [7]. A periodic electrode is patterned on top of the device and the ground electrode at the bottom of

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buffer layer is deposited through a via hole, which provide ohmic contacts.

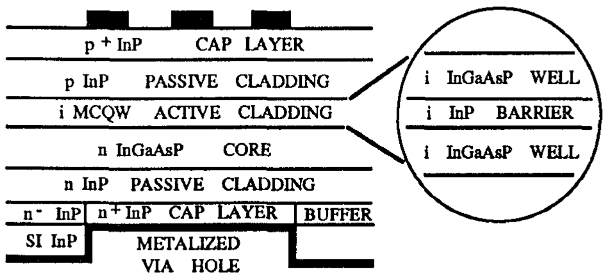

Fig. 1. MCQW optical intensity modulator structure.

The device operates as follows. With no applied voltage, the light coupled to the waveguide core is guided through the device, as in a conventional waveguide. When a reverse voltage is applied between the electrodes, the electric field changes the refractive index of the "active cladding," forming a periodic alteration of the refractive index. The interaction of light with the electrically generated grating scatters light out the device, instituting a modulated optical output.

RELEVANT OPTICAL PROPERTIES OF QUANTUM WELLS

When an electric field is applied perpendicular to a quantum well structure, the ground-state exciton peak is red shifted, resulting in an increased absorption and refractive index below band-edge. To fabricate an electrorefractive intensity modulator with low insertion loss and drive voltage, it is imperative to maximize the refractive index change while minimizing the absorption.

The coupled quantum well structure is composed of two narrow wells separated by a thin barrier, as discussed above. The wave functions are shared between the adjacent wells since the electrons and holes can tunnel through the thin barrier. Wells made with identical material and thickness lead to symmetric CQW, otherwise to asymmetric CQW. It has been shown, [4], that the electron and hole wave functions in uncoupled quantum wells are only slightly altered by the electric field, but in coupled quantum wells with tailored dimensions, the wave functions are significantly distorted by the electric field. The coupled quantum well exciton peak shifts linearly with the electric field while the uncoupled quantum wells exciton peak shifts quadratically. Thus, to shift the exciton peak to a given energy, coupled wells will require less voltage than uncoupled wells. Moreover, this feature allows one to set the operating wavelength close to the exciton peak, where the refractive index change is large, without incuring a high optical insertion loss.

The quantum well refractive index change is related to the biaxial birefringence induced by an electric field, the linear electro-optic effect, and the quantum-confined Stark effect (which is a quadratic electro-optic effect). The well and barrier refractive index changes are written as:

$$\Delta n_w = \frac{n_w^3}{2}\left[R_w\left(\frac{V}{d}\right) + S_w\left(\frac{V}{d}\right)^2\right] \qquad (1)$$

$$\Delta n_b = \frac{n_b^3}{2}\left[R_b\left(\frac{V}{d}\right) + S_b\left(\frac{V}{d}\right)^2\right] \qquad (2)$$

where Δn_w and Δn_b are the well and barrier refractive index change. The well and barrier linear electro-optic coefficients are denoted by R_w and R_b, while S_w and S_b represent the well and barrier quadratic electro-optic coefficients. The applied voltage and the depletion region thickness are denoted by V and d, respectively.

Experimental linear and quadratic electro-optic coefficients, 43 meV below the exciton ground-state transition for InGaAsP uncoupled quantum well, have been reported by Zucker, who has estimated the linear and quadratic electro-optic coefficients at 1.3 μm wavelength to be $R_w = 2.11 \times 10^{-12}$ m/V and $S_w = 3.36 \times 10^{-18}$ m^2/V^2 [8]. The same coefficients for InP at 1.3 μm are $R_b = 1.59 \times 10^{-12}$ m/V and $S_b = 5.26 \times 10^{-21}$ m^2/V^2. Equations (1) and (2), together with this data, are used in the design of the modulator.

DESIGN OF THE OPTICAL WAVEGUIDE

To estimate the MCQW refractive index ($n_2 = 3.3212$) needed to calculate the propagation conditions for the planar waveguide depicted in Fig. 1, the thin-film approximation of Alman [9] for a layered dielectric was employed. The InP layers were assumed to be semi-infinite in extent. For guided modes in this structure, two cases must be considered: (1)

$n_1 > n_2 \geq N_{eff} \geq n_3$ and (2) $n_1 \geq N_{eff} \geq n_2 > n_3$, where n_1, n_2, and n_3 denote the core, MCQW, and cladding refractive indecies, respectively. The effective refractive index is defined as $N_{eff} = \beta/k_0$, where $k_0 = 2\pi/\lambda_0$, β is the longitudinal propagation constant, and λ_0 is the free-space wavelength. The suitable solution for the optical waveguide is given by the first case [6].

The dispersion diagram for the first two guided modes of the waveguide, calculated using the data provided above, is shown in Fig. 2. For core thickness, T, less than 0.65 μm the waveguide is single-mode.

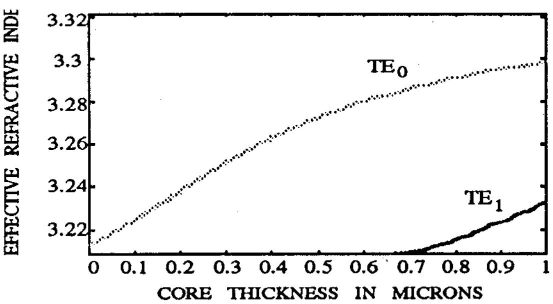

Fig. 2. Optical waveguide dispersion diagram.

The structure confinement factor (Γ) was also simulated and the result is shown in Fig.3. At a core thickness of T = 0.2 μm the well and barrier confinement factors are optimal; however, for this thickness the core confinement factor is only 0.3. For core thickness of T = 0.34 μm, however, the well and barrier confinement factor is 0.045 and 0.08 respectively and the core confinement factor is 0.5. Therefore, a core thickness is of 0.34 μm appears most desirable.

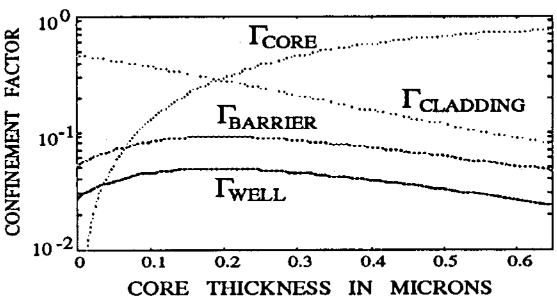

Fig. 3. Structure confinement factor.

DEVICE PERFORMANCE

To study device performance, simulations of the coupling coefficient, device geometry, bandwidth, and insertion loss were carried out.

The coupling coefficient, which gives the strength of the interaction between the light and the electrically generated periodic structure, was calculated using coupled mode theory. The coupling coefficient for a first order grating, having a period of 0.2 μm, is shown in Fig. 4. For the deisred core thickness (T = 0.34 μm), the coupling coefficient increases from 15 cm^{-1} at -2.0 V to 33 cm^{-1} at -4.0 V. These voltage requirements appear acceptable for most applications.

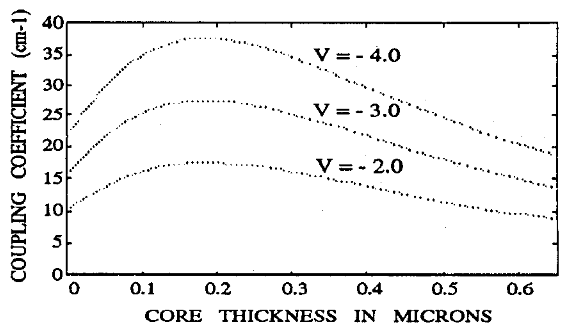

Fig. 4. Coupling coefficient vs.core thickness for different voltages.

The device length as a function of the modulation depth is shown in Fig. 5. For example, a device with a modulation depth of 0.5 and an applied voltage of -4.0 V requires a length of 270 μm. Increasing the modulation depth and decreasing the applied voltage results, as expected, in a longer device.

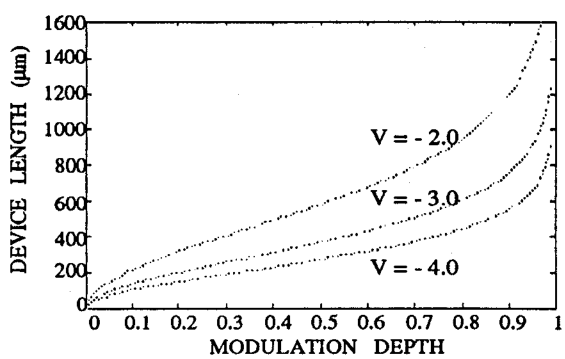

Fig. 5. Device length as a function of the modulation depth for different applied voltages.

The device bandwidth as a function of the modulation depth is shown in Fig. 6. An electrode length of 3μm is assumed. For this device, a bandwidth of 14 GHz is predicted at a modulation depth of 0.5 and applied voltage of -4.0 V. Increasing the modulation depth and decreasing the applied voltage results in narrow bandwidth devices.

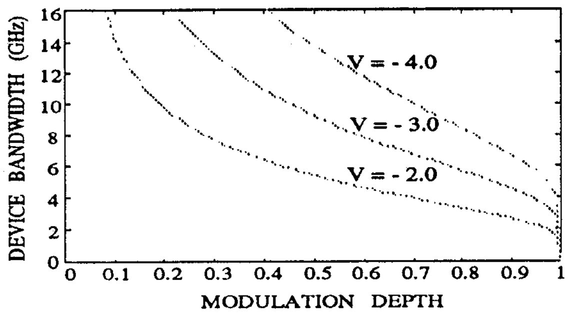

Fig. 6. Device bandwidth as a function of the modulation depth for different applied voltages.

Fiedler [10] calculated the optical attenuation of InP and InGaAsP, and his results were utilized in this simulation. The optical attenuation of the InGaAsP quantum well, 120 dB/cm, was estimated from experimental data [2].The optical insertion loss, which depends on the core thickness, is caused primarily by the quantum well, as shown in Fig. 7. At a core thickness of 0.34 μm, the device loss is 9.0 dB/cm. Thus, for a 270 μm long device, the theoretical optical loss is only 0.24 dB.

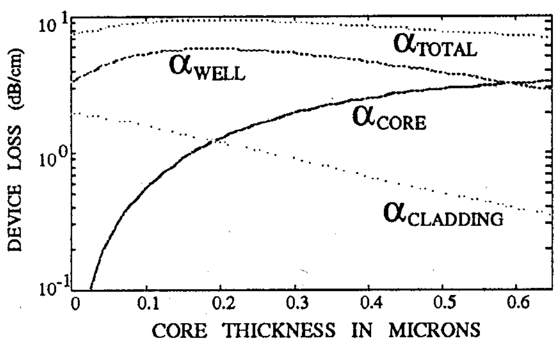

Fig. 7. Device loss as a function of core thickness.

CONCLUSIONS

The objective of this research, the merging of photonics and MMICs on a single chip, was achieved through the design of a MCQW optical intensity modulator compatible with InP/MMIC fabrication processes. The interaction of the microwaves and the MCQW results in a periodic structure, which modulates the light intensity. Simulations revealed that a 270 μm long device, operating at - 4.0 V, has a projected bandwidth of 14 GHz at a modulation depth of 0.5. The optical loss for this device length is only 0.24 dB.

ACKNOWLEDGMENTS

The authors wish to thank the Brazilian Secretary of Science and Technology, RHAE Program Grant #111/90, CNPq (Brazilian Research Council), US Army ETDL Grant # DAAL01-89-C-0937, and NSF INT 900-2289 for financial support.

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* Permanent Address: Department of Electrical Engineering, Engineering School of Sao Carlos, University of Sao Paulo, 13560 Sao Carlos, SP - Brazil.