Multiple-Quantum-Well Asymmetric Fabry–Perot Modulators for Microwave Photonic Applications

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***Abstract*—We describe the development of InGaAsP multi-quantum-well asymmetric Fabry–Perot modulators (AFPM) for RF-over-fiber applications. Advantages of the AFPM include low drive voltage and loss, high linearity and simple fiber alignment. Experimental results of initial devices, exhibiting 5.5-dB modulation depth and >3-GHz operation, are described. The effect of the optical power on the device performance was assessed, and the modulation bandwidth was found to be unaffected by incident optical powers up to 0 dBm. The linearity of the modulation characteristic was measured by carrying out two-tone intermodulation distortion tests, and a third-order intercept point of 30 dBm was observed.**

***Index Terms*—Electroabsorption, microwave communication, optical fiber communication, optical modulation, optoelectronic devices.**

I. INTRODUCTION

FUTURE broad-band wireless networks will use optical fiber-based signal distribution within buildings and the urban environment. Optical modulators with high efficiency, linearity and long term stability will be required for electrical-to-optical signal conversion in such systems, and multiquantum-well (MQW) electroabsorption modulators (EAMs) [1], which employ the quantum-confined Stark effect to give a very efficient electro-optic response, exhibit all of these characteristics. While fiber-radio systems have been successfully demonstrated using waveguide EAMs, reduced cost and improved performance will be achievable with the use of asymmetric Fabry–Perot modulators (AFPMs) [2], in which the light propagates vertically through the wafer layers. The thickness of the MQW active region in an electroabsorption modulator is typically less than 1 μm, to allow the bias voltage to achieve a high electric field across the active region. If the light makes a single pass vertically through this layer, the interaction length is too short to obtain a modulation depth >1 dB. Hence, to increase the effective interaction length, the MQW layers are placed within a Fabry–Perot resonator, formed by InGaAsP/InP distributed Bragg reflectors (DBRs) or metal reflectors, significantly increasing the modulation depth [3]. In the AFPM, the back mirror reflectivity is designed to be close to 100% at the operating wavelength, while a lower front mirror reflectivity is used. The output light is reflected from the device and can be separated from the input path using an optical circulator. The modulation response of the AFPM is maximized by setting the spacing between the mirrors to obtain destructive interference between the light reflected from the front mirror and back mirror. A modulation depth of 20 dB for 5-V drive voltage was achieved with GaAs/AlGaAs AFPMs [4], while InGaAsP/InP AFPMs operating at 1.55 μm with a modulation depth of 21 dB and modulation bandwidth of 20 GHz have been demonstrated [5].

The AFPM offers a number of advantages for microwave photonic applications. Low insertion loss is possible, as no waveguiding occurs within the device. The large area of the device allows simple fiber alignment, reducing the packaging cost. An additional advantage is that, as the electric-field oscillations of the light are always in the plane of the quantum wells, the device characteristics are independent of the input polarization.

In the configuration most commonly considered, the top-addressed AFPM, both mirrors are formed from semiconductor DBRs. However, this requires a large number of layers to achieve a high back mirror reflectivity [5], and to avoid this, an alternative substrate-addressed design can be used, in which the p-contact metal doubles as the back mirror (Fig. 1). InGaAs/InP substrate-addressed AFPMs have been demonstrated with 3-dB modulation depth and 1.8-dB insertion loss [6]. In this paper, the design and fabrication of substrate-addressed AFPMs for microwave photonic applications is described. Results of high frequency measurements with a range of incident optical intensities are presented and the linearity of the modulation characteristic of the devices, important in multifrequency radio systems, is assessed.

II. MODULATOR DESIGN

A. MQW Characterization

The first step in the design process was the measurement of the electroabsorptive effect in the InGaAsP MQW active region, to obtain accurate material parameters for the modulator optimization. A test structure was grown with 60 90 Å quantum

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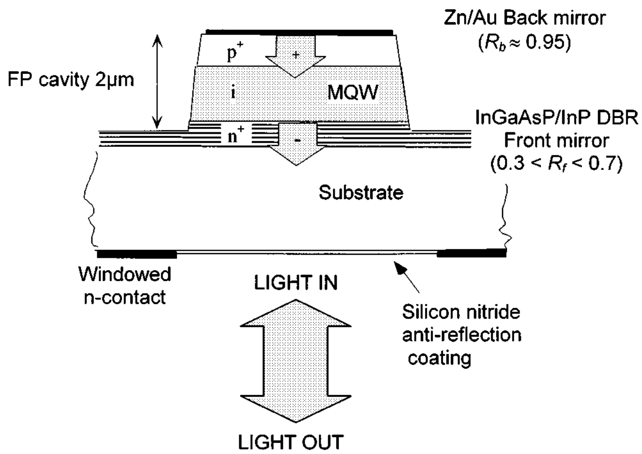

Fig. 1. Schematic of substrate-addressed AFPM structure.

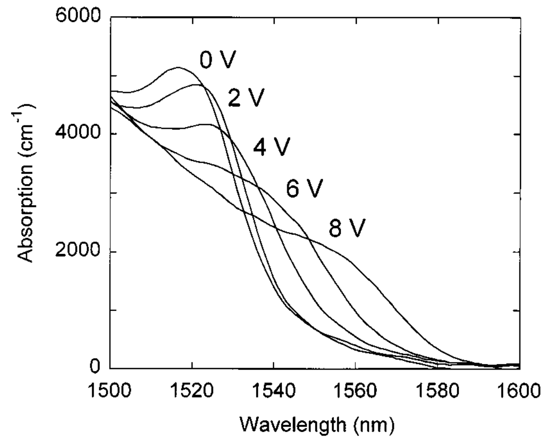

Fig. 2. Measured MQW absorption spectra.

wells of InGaAsP (bandgap wavelength $\lambda_{\rm bg} = 1.6$ μm), separated by 75 Å barriers ($\lambda_{\rm bg} = 1.1$ μm). Shallow quantum wells with quaternary well and barrier material were used to reduce the lifetimes of the photo-induced holes which saturate the absorption of deeper InGaAs/InP quantum wells at high optical intensity [6]. The 1-μm-thick MQW structure was grown by MOVPE in a p-i-n diode structure, and individual devices isolated by wet-etching mesas through the p- and i-layers. The electric field across the MQW was applied by reverse-biasing the diode. Tunable narrow linewidth light from a monochromator was transmitted through the biased MQW layers and detected, allowing measurements to be made of the wavelength and voltage dependent absorption coefficient of the layers. The measured values of absorption for the MQW test structure are shown in Fig. 2. A maximum electroabsorptive effect of $\Delta\alpha = 348\,{\rm cm}^{-1}{\rm V}^{-1}$ at $\lambda = 1.55$ μm was measured at the bias voltage of 4 V, corresponding to an electric-field strength $E = 4 \times 10^6$ V/m across the active region.

B. AFPM Design

A range of design parameters were considered, to obtain a structure giving the optimum performance for analog microwave link applications. The measured MQW absorption values plotted in Fig. 2 were used to calculate the reflectivity, R, of ideal AFPMs with back mirror reflectivities $R_b = 1.0$, at the resonant wavelength, given by [7]

$$R = \left(\frac{\sqrt{R_f} - \sqrt{R_b}e^{-\alpha d}}{1 - \sqrt{R_f R_b}e^{-\alpha d}}\right)^2 \tag{1}$$

where R_f is the front mirror reflectivity, α is the MQW absorption, and d is the thickness of the MQW active region. The modulation efficiency $\Delta R/R\,{\rm V}^{-1}$, insertion loss and absolute change in reflectivity with voltage, $\Delta R\,{\rm V}^{-1}$, are plotted in Fig. 3 at $\lambda = 1.55$ μm and electric-field dc-bias point of 4×10^6 V/m for structures with front mirror reflectivities $0 < R_f < 1$ and MQW active region widths $d = 0.5$, 1.0, and 1.5 μm. Although these calculated values are higher than those achievable in practice, due to the assumption of an ideal 100% reflective back mirror, they provide a reference against which the performance of practical devices can be compared.

Each value of active region thickness d has a corresponding optimum value of the front mirror reflectivity R_f to achieve the maximum modulation response. For example, with $d = 1.0$ μm, the optimum value is $R_f = 0.40$, giving a modulation response $\Delta R = 0.11\,{\rm V}^{-1}$. The increasing ΔR with reducing d is due to the larger change of the applied electric field in the MQW region, which is related to the applied voltage by $E = V/d$. In analog microwave links, the performance is measured by the link gain, or ratio of the RF power received to that applied to the modulator. The link gain increases with the square of the incident optical power P_I and the modulation response ΔR [8]. Although devices with low values of d exhibit higher modulation response, they also require a smaller area A to achieve a low capacitance $C = \varepsilon A/d$ and hence high modulation bandwidth, $f_{3\,{\rm dB}} = 1/2\pi RC$. The low device area increases the difficulty of fabricating and aligning the AFPM and limits the optical spot size on the modulator, reducing the optical power P_I it can handle and hence offsetting the improvement to the link gain due to the larger modulation response. Experimental measurements of the reduction in AFPM modulation response by high optical power are described in Section III-B.

An MQW active region thickness of 1.0 μm was therefore used. A substrate-addressed configuration was chosen, allowing the modulator to be designed using a relatively low number of DBR layers, and the structure consisted of a 60 period MQW active region and a near optimum front mirror reflectivity, $R_f = 0.38$, achieved by a 7.5-period front DBR with $\lambda/4$ layers of InP and InGaAsP of bandgap $\lambda_{\rm bg} = 1.4$ μm (Fig. 4). The Au/Zn p-contact was not annealed, to maintain the high reflectivity at the metal–semiconductor interface. The measured MQW absorption values and calculated corresponding refractive index changes were used to model the modulation characteristics of the AFPM. Reflection spectra were calculated using the transfer matrix method and a 3-dB modulation depth with 0–5 V applied voltage and an intrinsic loss in the on state of 3 dB were predicted. The intensity modulation characteristics are shown in Fig. 5. A modulation efficiency $\Delta R/R = 14\%\ {\rm V}^{-1}$ and an absolute reflectivity modulation $\Delta R = 0.076\,{\rm V}^{-1}$ at a 4.0-V dc operating point were calculated at $\lambda = 1550$ nm, 69% of the theoretical maximum value of ΔR given by (1) due to absorption in the DBR layers and substrate and the $<$100% back mirror

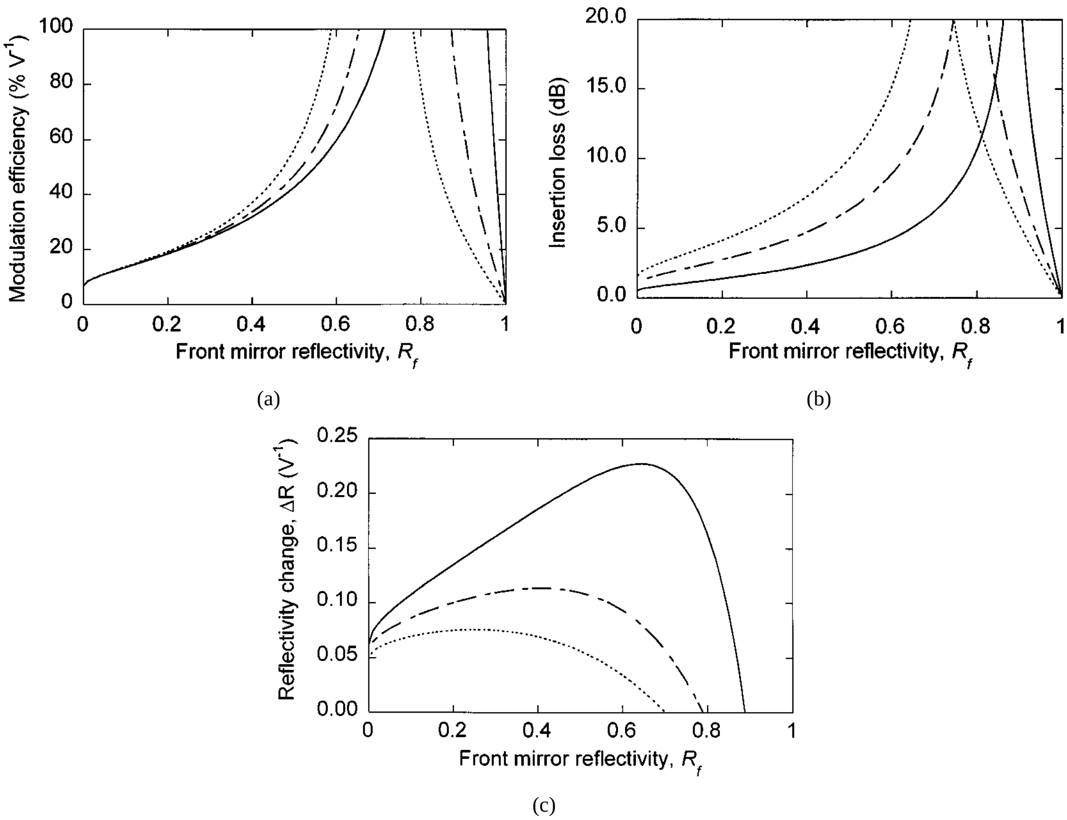

Fig. 3. Calculated values of: (a) modulation efficiency $\Delta R/R$. (b) Insertion loss. (c) Modulation response (absolute reflectivity change per volt) for ideal AFPM structures with front mirror reflectivities $0 < R_f < 1$, back mirror reflectivity $R_b = 1$ and MQW active region widths 0.5 μm (solid lines), 1.0 μm (dashed lines) and 1.5 μm (dotted lines), from (1).

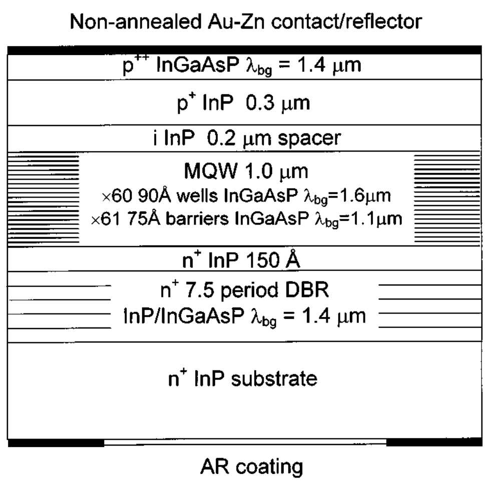

Fig. 4. Substrate-addressed AFPM structure, with 1.0-μm-thick MQW active region and 7.5 period front distributed Bragg reflector.

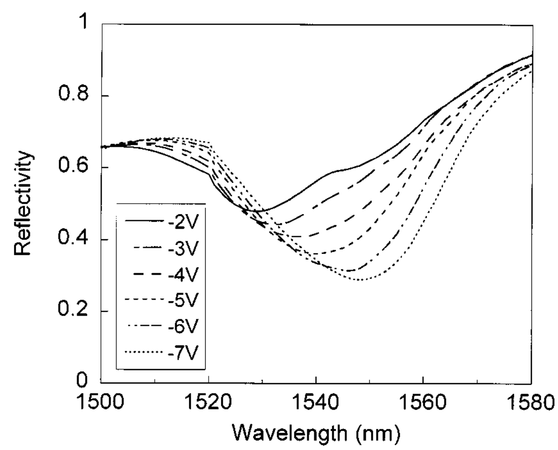

Fig. 5. AFPM reflectivity spectra calculated by transfer matrix method.

reflectivity. The expected variation in the modulation depth was less than 10% over the 1548–1552-nm wavelength range with the operating point maintained at 4.0 V.

III. Experiments

A. Low Frequency Measurements

Modulators with the design shown in Fig. 4 were fabricated, with the same growth and processing techniques as used for the MQW test devices. Measurements of the voltage dependent reflectivity spectra with 100-μW input power are plotted in Fig. 6. The modulation efficiency was lower than predicted, with a peak value of 6% V^{-1} at a 6.0-V operating point and wavelength of 1547 nm. The low reflected power in this measurement was due in part to the losses in the free-space measurement system, and a measurement of the device reflectivity, normalized to the reflectivity of an air-gold interface, showed an intrinsic loss of 7 dB with 0-V bias at 1547 nm. Secondary ion mass spectroscopy measurements of the wafer showed diffusion of the Zn dopant from the p^+ layer into the MQW layers, the diffused dopant resulting in a nonuniform electric field across the active region, and explaining the higher than predicted loss and drive voltage. Reduction of this diffusion during the growth would lower the

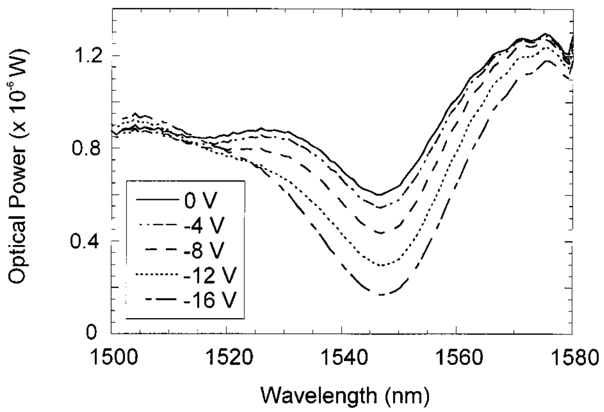

Fig. 6. Measured optical power reflected from AFPM with 100-μW input from tunable laser.

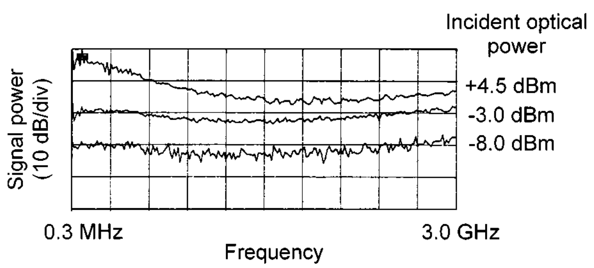

Fig. 7. Detected RF signal power with a range of optical powers, -8.0- to $+4.5$-dBm, input to the AFPM.

loss of the modulator and improve its modulation response. The experimental results confirmed that $>$3-dB modulation depth is possible with this design, with a modulation depth of 3 dB requiring 0–11-V applied voltage.

In all the experiments described in the following sections, substrate addressed devices from the same wafer were used, and the measurements were carried out at a dc-bias point of 6 V to obtain the maximum modulation response with the MQW layers in this wafer.

B. Measurements at High Frequencies and High Optical Powers

The performance of the AFPM at microwave frequencies and with high incident optical intensities was assessed. Modulators formed from 100-μm-diameter circular mesas were used, with a capacitance of 0.85 pF, resulting in an expected 3.7-GHz 3-dB bandwidth. The output of a tunable laser was reflected from the modulator via a 3-dB fiber coupler, and the modulated light was detected using a high bandwidth photodetector. A network analyzer was used to drive the AFPM and measure the output signal, and a variable attenuator at the output of the laser enabled the optical power to be adjusted. An incident spot size on the modulator with a 3-dB width of approximately 20 μm was used. Fig. 7 shows the detected RF signal power for a range of optical powers, -8- to $+4.5$-dBm incident on the AFPM operated at a dc-bias point of 6 V. The modulator operated to frequencies above 3 GHz, and increasing modulation efficiency above 1.5 GHz resulted from electrical resonance between the modulator and the package connector.

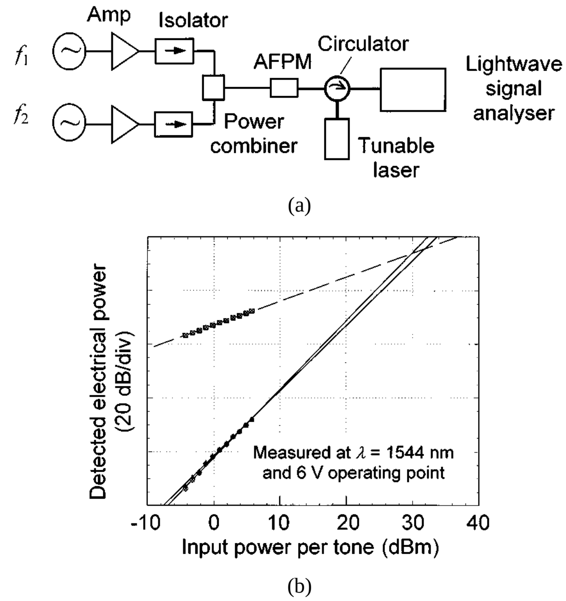

Fig. 8. (a) Experimental setup for two-tone intermodulation distortion measurements. (b) Measured RF powers of fundamental and third-order intermodulation products.

Up to 0-dBm optical power, the detected RF power increased uniformly with the power over the 0–3-GHz range. At higher optical powers, the build-up of photogenerated carriers in the MQW resulted in a reduction of the modulation sensitivity at high frequencies. With an input power of $+4.5$ dBm, the received signal was reduced by 10 dB at 3 GHz, due to the reduced modulation depth resulting from the screening of the applied field by the carriers.

The maximum incident optical power and modulation response can be used to estimate the performance of the AFPM in a microwave link. The voltage gain of the link is given by

$$\frac{V_{\text{out}}}{V_{\text{in}}} = \Delta R \cdot P_I(1-L)S_D \tag{2}$$

where ΔR is the reflectivity change per volt, P_I is the incident optical power on the modulator, L is the combined circulator and coupling loss, and S_D is the receiver sensitivity with dimensions volts per watts. From the measurement of the modulator saturation with input power, the maximum optical power is $P_I = 0.0025\, w^2$ mW, where w is the optical spot 3-dB width expressed in μm. Assuming the combined coupling and circulator loss is 2 dB, and using the value of $\Delta R = 0.076\ \text{V}^{-1}$, calculated in Section II-B, the expected voltage gain of the link is $V_{\text{out}}/V_{\text{in}} = 1.2 \times 10^{-7}\, w^2 S_D$, for modulators with a 1-μm-thick active region comprising the InGaAsP MQW structure used in the test device. Improved MQW design, for example the use of strained quantum wells, would increase the optical power that could be used, and hence improve the link gain.

C. Linearity Measurements

A linear modulation characteristic is desirable for applications in multifrequency RF systems, to avoid interference from intermodulation products. To assess the linearity of the AFPM, the third-order distortion products generated by the modulator were measured [see Fig. 8(a)]. The AFPM was driven simultaneously with two signals centered around 4.87 GHz and separated by 1 MHz. The output of a tunable laser was reflected from the AFPM via an optical circulator, and the modulated output was detected and the detected signal spectrum displayed using a lightwave signal analyzer (LSA). With an incident optical power of 0.83 μW and LSA resolution bandwidth of 10 Hz, the equipment noise floor was 6 dB below the lowest measured intermodulation product power. The powers of the fundamental component and third-order intermodulation products are plotted in Fig. 8(b) at a wavelength of 1544 nm and at a 6-V dc operating point. Good modulation linearity was observed, with a measured third order intercept point of 30 dBm. The power of the intermodulation products was measured at 48 dB below the fundamental when an input RF power of 0 dBm per tone was used.

IV. Conclusions

The high efficiency, low loss, and low cost of MQW asymmetric Fabry–Perot modulators make them attractive for radio-over-fiber applications. In this work, we considered AFPMs comprising 60 InGaAsP quantum wells and a 7.5-period distributed Bragg reflector front mirror. A substrate-addressed configuration was used, with the p-contact also acting as the back mirror, allowing a relatively low number of semiconductor layers to be used in the design. We have shown by numerical modeling that it is possible to achieve a modulation response of 14% V^{-1} with approximately 3-dB intrinsic loss. Initial experimental devices exhibited a modulation depth of 3 dB with 0–11-V bias, and a maximum modulation response of 6% V^{-1}, with performance improvements of future devices expected through the reduction of the Zn dopant diffusion into the MQW. Measurements of the high frequency operation of the modulators showed $>$3-GHz bandwidth, limited by the device capacitance, and the modulation response at microwave frequencies was unaffected by varying the incident optical power up to 0 dBm.

The linearity of the AFPM modulation characteristic was assessed by carrying out two tone tests and measuring the power of the resulting third-order intermodulation distortion products. Good linearity was demonstrated, with the experimental AFPM's displaying a third-order intercept point at 30 dBm per tone input RF power.

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