Operating Point Optimization of Self-linearized Differential Quantum Well Electroabsorptive Modulator

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Abstract — **Eletroabsorbtive modulators (EAM) require large depth of modulation and maximum length of in-out linearity. A systematic approach to optimize the operation of these modulators based on quantum confined Stark effect is presented here. The conventional operation of differential modulator is presented following with linearity span maximization by adjusting the incident power of laser beams and modulation depth enhancement by reverse bias voltage adjustment. The results show the optimum bias voltage as 8 V and read out beam power as 175 nW.**

Keywords — **Quantum confined Stark effect, Self-Electrooptic efect device; SEED, Self-linearized mode, Eletroabsorptive modulator.**

I. INTRODUCTION

Electroabsorptive (EA) multi-quantum well modulators (MQWM) are important in optical signal processing such as real space image filtering [1-3]. The amazing potential of AlGaAs/GaAs MQW pin diode technology and the impressive speed of MQW modulators make them suitable for many electroptical applications. Large array of MQWM are used vastly in optical information processing such as optical correlators, optical image filters, laser beam control, and high frequency analog modulation [4-7].

Surface reflection modulators have a particular interest, provding a double length of interaction between the light and the material, improving the modulation contrast [8-10]. The modulating signal is the current supplying to the reverse bias modulator diode and the carrier is the illuminating beam of diode. A feedback is made by the current, absorbed power and the voltage across the diode. Linear analog modulation is performed at band edge wavelength of absorption, where the absorption enhances through higher voltage, giving rise to a negative feedback, known as self-linearized mode of operation [9-10].

Span of linearity is enhanced using differential quantum well modulators (DQWM; see Fig.1), making easy to work with bipolar modulating signal [9-13]. In addition, eliminates the effect of carrier beams fluctuation, using a single carrier source.

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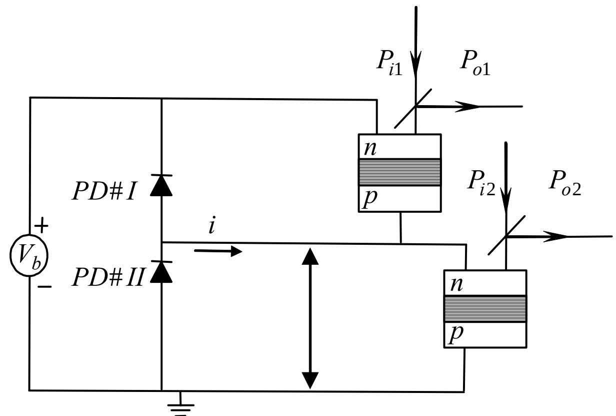

Fig. 1. Self-linearized differential modulator circuits with two conventional photodiodes providing a current proportional to the input beams at 780 nm.

The differential output power (P_{o1}-P_{o2}) is a linear function of modulating current i as:

$$P_{o2} - P_{o1} = P_{i2} - P_{i1} + \frac{\hbar\omega_i}{e} i \,, \tag{1}$$

where P_{i1}-P_{i2}, is the differential power of the carrier and $\hbar\omega_i$ is the energy of the incident photons. Using a single source of carrier:

$$P_{o2} - P_{o1} = \frac{\hbar\omega_i}{e} i \,. \tag{2}$$

Although, this equation shows the linear mode of carrier modulation, the effect of operating point is not so clear. In the literature, the applied voltage is adjusted at about 7 V without any notes about the power of carrier beams [12-13].

In this paper, we verified the effect of reverse bias voltage and input power on span of linearity and modulation depth. We showed the bias voltage of about 8 V and carrier power of about 175 nW can optimize the operation. Also, we encountered a trade-off between the bias voltage and carrier power to operate in self-linearized mode. These arguments are explained in the following Section, finalized by conclusion, in section III.

II. EXPERIMENTAL DETAIL

MQW p-i-n diode has been grown by molecular beam epitaxy over an undoped dielectric mirror. The multiple quantum well region is ~1.2 μm thick consisting of 95 alternate thin layers of GaAs wells of 90 Å width, and 35 Å thickness barriers of $Al_{0.3}Ga_{0.7}As$ in intrinsic region. The fabrication process is discussed in Ref. 14. The 95 periods of quantum wells in intrinsic region realizes to have the exciton peak at zero bias shorter than 850 nm wavelength. The current control element is a differential photodiode (PD). Area of MQW modulators are 7×7 μm^2 and the area of the photodiodes are 10×10 μm^2. An antireflection coating has been used to avoid the resonator effects. The integrated configuration of diodes is reverse biased with 8 V in default. All experiments were taken at room temperature.

A. Operation at conventional operating point

Linear operation of modulator can be verified through the differential output power measurement as a function of input control current. Since the input current is supplied by the differential photodiodes the linearity is verified through optical in-out considering the linear operation of PDs. The linearity of photodiodes is promised by double size of photodiodes and the sufficient reverse bias. Positive polarity of current is supplied by illumination of PD #1 and negative one by illumination of PD #2. The result of measurements is shown in Fig. 2.

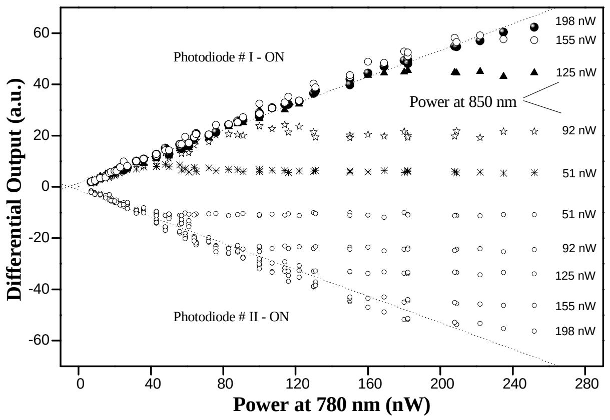

Fig. 2. Differential output of modulator as a function of current (incident beam on PD#I or II considering the power of carrier beams as a parameter. Bias field of 6.7×104 Vcm^{-1}.

As illustrated, the modulation is partially linear. The linearity span is in order of the carrier input power due to equal quantum conversion efficiency in modulators and detectors. Beyond this value, the differential output was maintained approximately constant, called as the saturation. It is due to the insufficient exciton generation by the incident carrier beams in comparison to net photocurrent generation of PDs. The linearity span can be extended applying more power of readout beams P_{850}, in which generates more excitons, supporting larger net photocurrent. Although the linear dynamic range varies as function of readout beams, the modulation-depth is constant, indicated by invariable gradient of the in-out curve, as predicted by Equation 2. The improvement of linearity span is slowed-down at P_{850} >155 nW due to sublinear increase of heavy hole (hh) photocurrent as function of readout beam power and is terminated at P_{850}=198 nW with maximum extension of linearity of 235 nW (solid spheres). It can be explained by the exciton saturation, such that the high intensity of ionized excitons changes the dielectric constant, increasing the size of remaining excitons. Therefore, the optical absorption strength decreases [17-18].

B. Effect of reverse bias voltage

The optimized bias voltage was encountered, fixing the readout beams (175 nW). For a given bias voltage, the differential output power is verified as a function of modulating current (PD "I" on) as illustrated in Fig. 3. Low bias voltage such as 1 V is not sufficient to extend the depletion layer to the intrinsic region of MQW photodiodes such that the probability of recombination of photocarriers is high. The reduced recombination time or (carrier life time) gives rises to small quantum efficiency. Hence, the linear dynamic range of PDs is small, influencing the measurement of in-out characteristic of the modulator. On the other hand, insufficient bias voltage increases insignificantly the exciton area. This gives origin to small reduction of exciton energy or insignificant shift of exciton resonance to a longer wavelength, although the density of exciton is high (generated by 175nW incident beam). Hence, the quantum confined stark effect (QCSE) is not considerable, corresponding to insignificant modulation depth. Also, the small quantum efficiency of quantum well modulators produces insignificant photocurrent, reduces the saturation level and linearity range of EAMs.

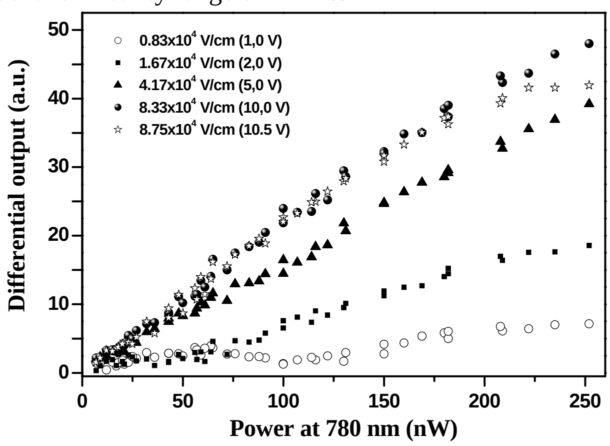

Fig. 3. Differential output of modulators for PD#I ON, considering the bias fields as a parameter (P_{850}=175 nW).

As can be seen in Fig. 3, applying a bias voltage lager than 2 V enhance the linear dynamic range to maximum and increase the depth of modulation due to quantum efficiency elevation. This improvement of quantum efficiency of PDs is because of the extension of the depletion layer through the entire intrinsic region, such that almost all photocarriers are collected in the external contacts by the applied field. The sufficient applied field reduces well the probability of photocarrier capture in the wells, enhancing the carrier life time and linear dynamic range of PDs. The same phenomenon is occurred in MQW modulators, giving rise to quantum efficiency enhancement. Also the high electric field increases the 2D-radius of the exciton corresponding to exciton energy reduction; hence the frequency resonance of exciton is reduced, giving rise to a considerable QCSE. The large red-shift of the absorption spectra enhances the contrast of the electro-absorptive modulation.

The maximum depth of modulation and span of linearity is acquired at 10 V. More bias voltage such as 10.5 V enhances the area of the exciton, reduces the resonance frequency of the exciton, and reduces the strength of the exciton absorption. The large 2D-radius of exciton enhances the probability of exciton ionization [15-16]. This phenomenon reduces the exciton life time, therefore deteriorates the electro-absorption effect. This case corresponds to the large stark shift, such that the exciton resonance moves to longer wavelength than 850 nm. In this case, the differential MQW modulator does not operate more in self-linearized mode. The feedback is changed to positive, such that the optical absorption of MQW modulator is reduced by higher electric field [9-11]. This subject is explained more in the following section.

C. Effect of reverse bias voltage at low intensity of carrier

Previous experiment was repeated at low intensity of readout beams (P_{850}= 51 nW) to show the effect of the power of readout beams on the optimized bias voltage (see Fig. 4). The comparison of Fig. 3 with Fig. 4 shows that at insufficient bias voltage such as 1 V the linearity span and the modulation contrast are reduced considerably. The reduced span of linearity and modulation depth is due to reduced density of exciton produced by incident readout beams.

As explained before, the modulation depth and linearity range are improved at higher bias voltage such as 2 V. This bias voltage is sufficient to extend the depletion layer to entire intrinsic region of PDs, maximizing the quantum efficiency. Therefore, the PDs work linearly. However, the insufficient density of excitons reduces the linearity range of modulator to 32 nW. Also, bias voltage of 2 is sufficient to obtain the maximum modulation depth that is nearly one order of magnitude less than the previous result. The linear dynamic range was improved to 65 nW at 3 V that is nearly the same as the incident power.

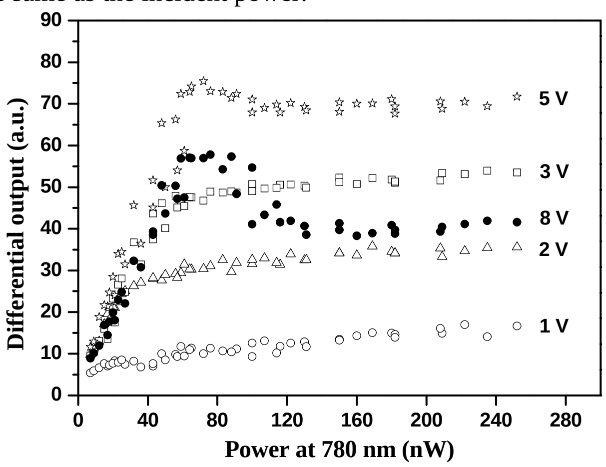

Fig. 4. Differential output of modulators for PD#I ON, considering the bias fields as a parameter (P_{850}=51 nW)..

The device characteristic at 5 V showed a little improvement of modulation depth, but the linearity range was remained at 65 nW**.** A dip after the knee was observed for powers larger than 65 nW. After the knee the differential output was reduced as a function of the incident power up to 107 nW. Then, it saturates such that the differential output remains fix as a function of input. At higher input current to the modulators the optical absorption is reduced indicating the exciton resonance shift to longer wavelengths than 850 nm. It stands for the change of operation mode of the modulators from self-linearized mode to bistable mode [10]. The same behavior is observed at 8 V with a slight reduction of modulation depth. This effect is explained through the large red-shift of hh-exciton peak, such that the peak is shifted to longer wavelength than 850 nm at 8 V and the absorption strength of the exciton peak is reduced. From the above observations, the optimum bias voltage must be less than 5 V, demonstrating the trade-off between optimum incident power and optimum reverse bias.

D. Critical voltage

The critical voltage is defined as a voltage that the self-linearized mode of operation (negative feedback) changes to bistable mode (positive feedback). At this voltage, the exciton peak is shifted to longer wavelength than 850 nm such that the exciton strength is reduced. This voltage depends on the intensity of the incident beams, shifting to lower voltages at lower intensity of control beams. Fig. 5 shows the differential output power as a function of the bias voltage where the power of readout beams is considered as a parameter and the PD #1 was illuminated by a 252 nW beam. This incident power can produce sufficient control current for differential modulators.

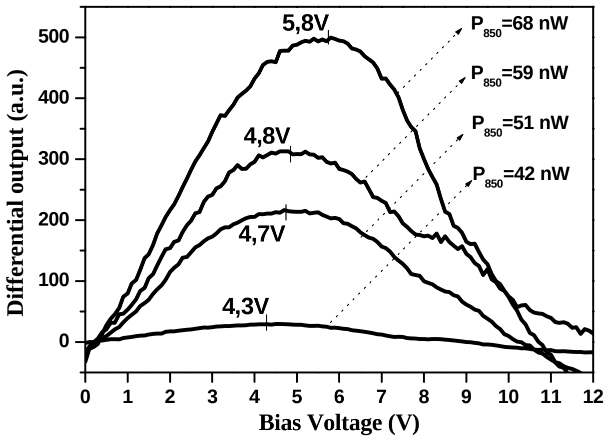

Fig. 5. Differential output of modulators for PD#I On as a function of bias voltage, considering the power of carrier beams as a parameter. Incident power on PD #I is 252 nW.

The modulation depth was insignificant at low voltages and P_{850}=42 nW and was improved a little at higher voltages. It is due to the insufficient exciton generation, giving rise to insignificant electro-absorptive modulation. Therefore, the extension of the depletion layer does not help to enhance the modulation contrast. However, at more incident power P_{850}, such as 51, 59, and 68 nW, the enhancement of the modulation depth was observed. Up to ~2 V, the elevation is due to quantum efficiency improvement of both the photodiode and the MQW modulators. The depletion region is extended entirely through the intrinsic region at ~2 V. Hence, the quantum efficiency of the photodiode is saturated while yet more Stark shift is possible through the QCSE for modulators.

The improvement was continued up to a critical voltage, such that more bias voltage gave rise to the reduction of differential output indicating the change of mode of operation to bistable or positive feedback [10]. Therefore, the hh-exciton resonance is red-shifted to the longer wavelength than 850 nm. In Fig. 5. the rising of the differential output as a function of incident light (P_{850}) indicates the modulation saturation corresponding to the modulation depth enhancement. The critical voltage rises as the function of incident light P_{850}. It was enhanced from 4.3 V at P_{850}=42 nW, to 5.8 V at 68 nW and to 10.5 V at 175 nW (using the results of section II-B). The increment of this voltage might be explained through nearly constant electric field strength per exciton density.

III. CONCLUSION

The monolithic electroabsorptive device is based on the AlGaAs/GaAs multiple quantum wells technology. The differential modulator was biased optically-electrically to operate in analog self-linearized mode. State of the diodes is read-out using a beam pair in bandtail wavelength. The linearity of operation was theoretically discussed and experimentally was verified followed by the operation optimization. We observed the optimum bias voltage as 8 V, readout beam power as 175 nW, and the trade off between optimum bias voltage and power of incident readout beams.

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