Large aperture asymmetric Fabry Perot modulator based on asymmetric tandem quantum well for low voltage operation

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Abstract: Large aperture image modulators used as demodulator in receiver path are an important component for the use in three dimensional (3D) image sensing. For practical applications, low voltage operation and high modulation performance are the key requirements for modulators. Here, we propose an asymmetric Fabry-Perot modulator (AFPM) with asymmetric tandem quantum wells (ATQWs) for 3D image sensing. By using ATQWs for the AFPM design, the device operated at ~4.25V, and the operating voltage was significantly lower by about 23% compared to ~5.5V of a conventional AFPM with 8nm thick multiple QW with a single QW thickness (SQWs), while achieving high reflectivity modulation in excess of 50%. The performance of the fabricated devices is in good agreement with theoretical calculations. The pixelated device shows a high modulation speed of 21.8 MHz over a large aperture and good uniformity. These results show that AFPM with ATQWs is a good candidate as an optical image modulator for 3D image sensing applications.

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1. Introduction

Asymmetric Fabry-Perot modulators (AFPM) have been widely explored for the many applications such as optical interconnects [1], free space optical communication [2, 3], radio over fiber system [4], optical correlator [5, 6], signal processing and optical beam steering [7] and optical vector-matrix multiplicator [8] due to their characteristic features such as extremely high contrast ratio [9, 10], ease of forming two dimensional array over large area [11] and high modulation speed. AFPM consists of an absorptive Fabry-Perot (FP) multi-quantum well (MQW) cavity sandwiched between two mirrors with different reflectivity. The field induced absorption change of the MQW region, known as the quantum-confined Stark effect (QCSE) [12], modulate the reflectivity of the device, thereby modulating the light intensity.

An interesting application for AFPM which has not been investigated before is their use for three dimensional (3D) image sensing applications. 3D image of an object can be realized by extracting distance information from traveling time of light, also known as time of flight method (TOF) [13, 14]. A key component used in TOF method is a large aperture optical image modulator, so called optical shutter which demodulates the light reflected from the object in the optical domain before it is detected electrically. Various types of large aperture optical image modulators, such as Kerr cell, Pockels cell and micro-channel plate (MCP) have been suggested for 3D image sensing [15]. Unfortunately, these modulators suffer from extremely high operating voltage of the order of few kilovolts and occupy large volume.

Another potential candidate which can replace the existing image modulator for 3D image sensing is an AFPM. AFPMs are small in size, easy to fabricate, and operates at low voltage,
and hence have huge potential to be used for 3D image sensing. For AFPMs to be used for 3D image sensing, they should meet large reflectivity modulation from >50% to 0%, high modulation speed (>20MHz) over a large aperture area range of few cm², and should operate at low voltages. To achieve low voltage operation and high modulation performance simultaneously, several quantum wells (QWs) designs such as stepped QWs [16], symmetric [17] and asymmetric [18] coupled QWs have been proposed. However, in the commonly used GaAs/AlGaAs system, there was no improvement of modulation performance even through stepped QWs [19] showed an enhanced QCSE. Coupled QWs are inappropriate for 3D image sensing application since it has a large residual absorption which leads to a low reflectivity modulation at the target wavelength despite having a high absorption change per applied electric field. Moreover, coupled QWs are difficult to grow due to requirement of extremely thin barrier between adjacent QWs.

In this paper, we propose and experimentally demonstrate AFPM structure with asymmetric tandem quantum wells (ATQWs) so as to reduce the operating voltage while simultaneously achieving enhanced modulation performance for 3D image sensing. Theoretical calculation of ATQWs geometry shows higher reflectivity modulation and a 23% reduction in the operating voltage compared to ~5.5V of multiple QWs with an 8nm thick single QW thickness (SQWs). Experimental results show that AFPM with ATQWs operates at lower voltage, exhibits high reflectivity modulation and sufficient modulation speed.

![AFPM with ATQWs structure](image)

Fig. 1. (a) The schematic of AFPM with ATQWs structure as depicted (not to scale). (b) The calculated zero-field reflectivity for SQWs with different well thickness and ATQWs. The inset shows maximum reflectivity change of AFPM with ATQWs and various SQWs widths at 850nm.

2. Design, growth and fabrication

Figure 1 shows the schematic of AFPM with ATQWs structure. The intrinsic ATQWs are composed of two sets of 20 pairs of QWs; the first set consists of 7nm thick GaAs QWs while the second set consists of 8.5nm thick GaAs QWs. The barrier for both the QWs sets is 4nm thick Al0.31Ga0.69As. Top distributed Bragg reflector (DBR) consists of 3 pairs of p-doped Al0.31Ga0.69As/Al0.87Ga0.13As followed by 10nm heavily p-doped GaAs contact layer. The
bottom DBR consists of heavily n-doped 500nm thick GaAs contact layer and 25.5 pairs of n-doped Al_{0.31}Ga_{0.69}As/Al_{0.87}Ga_{0.13}As. The reflectivity spectra of the structures are obtained using a Transfer matrix method (TMM) where the reflectivity of multilayer are modeled as a transfer matrix [20]. Behavior of QCSE is obtained after calculating the eigen energy states by solving the Schrodinger equation with appropriate boundary conditions. These eigen values and states are used to evaluate the excitonic absorption spectra for each electric field. Also, it can be numerically calculated by a commercial the self-consistent modeling APSYS software [21]. Line shape used in the field-dependent absorption calculation was a Lorentzian function with a line width whose HWHM (half width at the half maximum) broadens when electric field is applied to QWs [22]. The HWHM for the electron-heavy hole exciton under zero electric field was 4.166 meV and 4.576 meV, for 8.5nm QW and 7nm QW respectively. When we calculate the reflectivity of the modulator under electric field, absorption spectra of the QWs under applied field can be included to transfer matrix so as that it successfully show the reflectivity change due to QCSE.

![Calculated reflectivity modulation performance of AFPM with ATQWs and an 8nm SQWs design.](image)

For comparison, AFPMs with SQWs structure are also studied. The QWs thickness of SQWs is varied as 7nm, 7.5nm, 8nm and 8.5nm while the number of QW pairs is 43, 41, 39 and 38 respectively. The top DBR consists of 4 pairs of p-doped Al_{0.31}Ga_{0.69}As/Al_{0.87}Ga_{0.13}As so as to match the effective bottom DBR reflectivity with cavity loss. Figure 1(b) shows the calculated zero-field reflectivity for SQWs with different well thickness and ATQWs. In the case of ATQWs, zero reflectivity can be obtained using Eq. (1).

\[ R_T = R_B e^{-2\alpha L} \]  

where \( R_T \) is the top DBR reflectivity, \( R_B \) is the bottom DBR reflectivity, \( \alpha \) and \( L \) are the absorption coefficient and thickness of QWs in ATQWs, respectively. From Fig. 1(b), it is noted that the reflectivity for all three SQWs samples have two dips. The dip at shorter wavelength (\( \lambda_{ex} \)) is due to the zero-field absorption of heavy-hole exciton while the dip at longer wavelength (\( \lambda_{FP} \)) is due to Fabry Perot resonance. On the other hand, ATQWs shows three dips on the reflectivity spectrum. The first and second dip (at shorter wavelengths) is due to the zero-field absorption of heavy-hole exciton of QWs having different well thickness, and the third dip is due to Fabry Perot resonance. It is well known that the operating voltage of SQWs decrease as the spacing between \( \lambda_{FP} \) dip and \( \lambda_{ex} \) dip (\( \lambda_{FP} - \lambda_{ex} \)) decreases. However, a smaller spacing results in a high insertion loss at \( \lambda_{FP} \) thereby limiting high reflectivity modulation at low operating voltages as shown in inset of Fig. 1(b). On the other hand, ATQWs achieves high reflectivity modulation at a lower operating voltage since it has almost same absorptive region thickness (4.764\( \mu \)m) as 4.755\( \mu \)m of 8.5nm-thick SQWs. The ATQWs has two \( \lambda_{ex} \) dips: the first \( \lambda_{ex} \) dip has large spacing (\( \lambda_{FP} - \lambda_{ex} \)), which helps in reducing the
insertion loss and the second $\lambda_{ex}$ dip being close to the $\lambda_{FP}$ results in a reduced operating voltage.

Figure 2 shows calculated reflectivity modulation performance of AFPM with ATQWs and an 8nm SQWs design. At a $\lambda_{FP}$ of 850nm, both the structures can attain high reflectivity modulation of more than 50%. The operating voltage of 8nm-thick SQWs and ATQWs are 8.1V/µm and 5.6V/µm respectively to satisfy ‘matching’ condition. It is seen that to obtain high reflectivity modulation, ATQWs require a lower applied electric field in comparison to that of SQWs. It is thus evident that by using an ATQWs structure for AFPM, a reduction in the operating voltage is obtained, while maintaining high reflectivity modulation. In addition, our calculation reveals that the stack order of the first and the second QWs of ATQWs does not affect the modulation performance of ATQWs modulator.

To confirm the feasibility of AFPM with ATQWs for low voltage operation, ATQWs structure having two sets of QWs that are stacked (7nm and 8.5nm thick) was grown by solid state molecular beam epitaxy (MBE) on a semi-insulating GaAs substrate. For comparison, four AFPMs having four different SQWs structure (7nm, 7.5nm, 8nm and 8.5nm thick) were also grown. During the growth, reflectivity of modulators was monitored in situ to ensure 850nm operation [23]. After growth, p- and n-GaAs contact layer of devices were etched using inductively coupled plasma reactive ion etching (ICP-RIE) to define ohmic contact area. Then, Benzocyclobutene (BCB) was spin-coated on the devices and cured at 210°C in a convention oven so as to form a passivation layer. Finally, p-contact and n-contact metallization and rapid thermal annealing process were carried out for forming ohmic contacts. Pixellization was carried out to achieve high speed, thereby overcoming the speed restrictions induced by the thin active region and large aperture area of the modulator [24]. Thus, the dimension of fabricated device was 5mm x 4mm containing 2mm x 1mm pixels in a 2 x 3 array, so as to improve the modulation speed. In addition, fish-bone grid metal contact which provides uniform frequency response over a large aperture was used [25].

3. Electro-optic characterization

![Fig. 3. The measured reflectivity spectrum of fabricated AFPM with ATQWs for bias voltage ranging from 0 to 7.5V. The inset shows calculated and measured reflectivity spectra of ATQW AFPM at zero bias.](image)

To verify the feasibility of our design, the reflectivity of the fabricated modulators with ATQWs was measured at different bias voltages. The white light source from fiber is illuminated perpendicularly on the device through the collimating lens. The illuminated beam spot diameter is much smaller (below 0.5mm) than the device area. The reflected light from modulator is coupled back to the fiber through the collimating lens and is analyzed using an optical spectrum analyzer.

Figure 3 shows the measured reflectivity spectrum of fabricated AFPM with ATQWs for bias voltage ranging from 0 to −7.5V. Reflectivity spectrum of AFPM with ATQWs agrees well with the calculated results as shown in the inset of Fig. 3. $\lambda_{FP}$ of the device is 850.4nm.
and the first and second $\lambda_{ex}$'s corresponding to the first and second sets of QWs of ATQWs are 833nm and 842nm at 0V bias, respectively. As the bias voltage is increased, the first $\lambda_{ex}$ dip is red shifted from 842nm to 850nm. Minimum reflectivity (2.64%) is achieved, when exciton peak of 8.5nm QWs red shifts and overlap with Fabry-Perot dip at $-4.25V$.

Figure 4(a) shows the insertion loss variation with applied bias voltage at an operating wavelength of 850nm for all five AFPM designs mentioned above. When the $\lambda_{ex}$ dip is shifted near to $\lambda_{FP}$, insertion loss of all AFPM increases. For AFPM with SQWs, the maximum insertion loss occurs at voltage of $-8V$, $-7V$, $-5.5V$ and $-4.5V$ with thickness of 7nm, 7.5nm, 8nm and 8.5nm, respectively. It can be seen that in the case of AFPM having SQWs, as the well width increases from 7nm to 8.5nm, the operating voltage at which maximum reflectivity modulation occurs decreases. Also, the insertion loss at 0V increases from 2dB to 4.11dB as the well width is increased. Figure 4(b) shows that all modulators except the one with 8.5nm SQWs can achieve a reflectivity change of more than 50% at an operating wavelength of 850nm. However, it is noteworthy that AFPM with ATQWs provides a reflectivity change of 54.33% for the lowest applied voltage of $-4.25V$. Moreover, the insertion loss of AFPM with ATQWs is low (2.36 dB) at 0V. The two stacks of 20 pairs of 7nm and 8.5nm thick SQWs provide two main effects. First, as seen from Fig. 4(a), the reduced number of 8.5nm thick SQWs (20 pairs) of ATQWs increases the measured reflectivity to 57.93% in comparison to 38.89% for 8.5nm thick SQWs having 39 pairs at 850nm under zero electric field. This means that ATQWs give higher reflectivity change (>50%) than 8.5nm thick SQWs. Second, zero reflectivity for ATQWs structure can be obtained by modified reflectivity matching condition as given by Eq. (1). Under matching condition, reflectivity drops to around zero. This makes the modulation characteristics of ATQWs different from that of the 8.5nm-thick QW modulator having 39 sets. In all the cases, the active layer thickness remained the same (~4.76 $\mu$m), hence the operating voltage of modulator with ATQW was $-4.25V$ similar to $-4.5V$ of
8.5nm thick SQW while maintaining high reflectivity modulation as shown in Fig. 4(b). We believe that the overlap between the absorption of 7nm QW and 8.5nm QW leading to a broader absorption spectrum for ATQWs is the reason to obtain low voltage operation and high reflectivity modulation.

Figure 5 shows the electro-optic (EO) response of AFPM with ATQWs for frequencies from 0.2 MHz to 50 MHz for a 2mm x 1mm pixel. The modulation response of AFPM with ATQWs at 10 MHz is also shown in the inset of Fig. 5, and the response is found to be linear. The EO response is measured at 850nm, with a DC bias of −2.5V superimposed with an AC sinusoidal signal having a voltage swing of ± 1.5V. The EO response of all the pixels of the modulator shows a similar 3dB cut-off frequency of 21.8 MHz, which indicates that the device shows a good uniformity, which is crucial for 3D image sensing applications.

4. Conclusion

We have proposed and experimentally demonstrated an AFPM structure with ATQWs to achieve reduced operating voltage as well as to enhance the modulation performance of AFPMs for 3D image sensing. It can be seen that AFPM with ATQWs significantly reduced the operating voltage (by about 23%) to −4.25V in comparison with −5.5V of the conventional AFPM with 8nm thick SQWs, while achieving a reflectivity modulation of above 50%. Experimental results are in excellent agreement with numerical calculations and the fabricated AFPM with ATQWs showed over 50% reflectivity modulation for an operating voltage as low as −4.25V. The 3dB cut-off frequency was approximately 21.8 MHz for all the pixels indicating a good uniformity for the fabricated device. These results show that AFPM with ATQWs is a good candidate as an optical image modulator for 3D image sensing applications.

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