Coupled tandem cavities based electro-absorption modulator with asymmetric tandem quantum well for high modulation performance at low driving voltage

Byung Hoon Na,1 Gun Wu Ju,1 Hee Ju Choi,2 Soo Kyung Lee,3 Sooraj Ravindran,1 Yong Chul Cho,4 Yong Hwa Park,4 Chang Young Park,4 and Yong Tak Lee1,2,*

1School of Information and Mechatronics, Gwangju Institute of Science and Technology (GIST), 1 Oryong-dong, Buk-gu, Gwangju 500-712, South Korea
2Department of Physics and Photon Science, GIST, South Korea
3Department of Nanobio Materials and Electronics, GIST, South Korea
4Advanced Device Lab, Samsung Advanced Institute of Technology, Giheung, Yongin, 446-712, South Korea
*ytlee@gist.ac.kr

Abstract: We propose and demonstrate a new electro-absorption modulator (EAM) based on coupled tandem cavities (CTC) having asymmetric tandem quantum well (ATQW) structure with separated electrode configuration to achieve large transmittance change over a broad spectral range at low driving voltage for high definition (HD) 3D imaging applications. Our theoretical calculations show that CTC with ATQW structure can provide large transmittance change over a wide spectral range at low driving voltage. By introducing separated electrode configuration, the fabricated EAM having CTC with ATQW structure shows a large transmittance change over 50%, almost three times larger spectral bandwidth compared to that of EAM having single cavity with a single thickness quantum well without significantly increasing the applied voltage. In addition, the CTC with ATQW structure also shows high speed modulation up to 28 MHz for the device having a large area of 2 mm \( \times \) 0.5 mm. This high transmittance change, large spectral bandwidth and low voltage operation over a large device area for the EAM having CTC with ATQW demonstrates their huge potential as an optical image modulator for HD 3D imaging applications.

©2013 Optical Society of America

OCIS codes: (230.4110) Modulators; (230.2090) Electro-optical devices; (230.4205) Multiple quantum well (MQW) modulators; (100.6890) Three-dimensional image processing.

References and links
Quantum-confined Stark effect (QCSE) [1] based large area surface normal electro-absorption modulators (EAM) using GaAs/Al_{x}Ga_{1-x}As material operating at 850nm are attractive for high definition (HD) three dimensional (3D) imaging applications [2–5]. Low voltage operation, high transmittance change and high speed operation over a large area are the key requirements that are to be met by EAM in order to be used for imaging applications [2]. In addition, it is also desirable for EAMs to have a wide spectral bandwidth and tolerance to ambient temperature fluctuations and inaccuracies caused by imperfections during manufacturing. Recently, significant progress has been made in the performance of surface normal EAM such as enhanced amplitude modulation over wide spectral range, which makes EAM suitable as optical image modulator for HD 3D imaging applications [4, 5]. In spite of advances in modulation performance, however, the demonstrated EAMs require large operating voltage which leads to increased power consumption and larger heat generation during high speed operation, making them unsuitable for practical 3D imaging applications. Therefore, achieving low voltage operation is the key in order for EAMs to be used as optical image modulator for HD 3D imaging applications.

Several coupled quantum well (CQW) structures based on GaAs/Al_{x}Ga_{1-x}As material system have been proposed to achieve low voltage operation with enhanced exciton absorption change [6–9]. However, the CQW proposed in Ref [6–9] has higher absorption coefficient and has a larger residual absorption at the operating wavelength of 850 nm under zero bias compared to that of conventional rectangular quantum well, while providing a larger...
absorption change per unit bias. This high residual absorption of CQW significantly decreases the transmittance of Fabry-Perot cavity based EAM under zero bias at 850nm leading to high insertion loss. As a result, CQW structure is not suitable since it limits high transmittance change despite providing low voltage operation. Apart from CQW, broken-symmetry double [10] and stepped [11] quantum well (QW) structures having low insertion loss was introduced to reduce operating voltage in QW. Unfortunately, modulation performance of broken-symmetry double QW was not experimentally demonstrated and stepped QW showed negligible improvement in modulation performance due to broadened band-edge absorption [10, 11].

Several asymmetric Fabry-Perot modulators showing high amplitude modulation at low driving voltage have been reported [12–14]. In addition, extremely low voltage operation with high modulation performance over wide spectral range was achieved by using quasi-waveguide angled facet architecture [15]. However, these reflection-type structures are not suitable for HD 3D imaging system since they significantly reduce the field of view and require complex optics system. Another simple approach to reduce operating voltage is to use thin absorptive region, however, a thin region results in a degraded modulation performance. Consequently, it is highly essential to develop a transmission-type EAM achieving high amplitude modulation (large transmittance change) over wide spectral range operating at low driving voltage for HD 3D imaging system. Unfortunately, there have been few reports on 850 nm Al$_x$Ga$_{1-x}$As/GaAs based surface normal transmission-type EAM [16–20]. The amplitude modulation of devices in literature has a low transmittance change below 30% and a very narrow spectral bandwidth. In our previous work, we had successfully demonstrated surface normal transmission EAM achieving high amplitude modulation over wide spectral range, however, our previously reported device required high driving voltage [4].

In this study, we develop and demonstrate a large area transmission modulator that can be used for HD 3D imaging system having large transmittance change over wide spectral range and high modulation speed with low driving voltage at 850nm by introducing coupled tandem cavities (CTC) with asymmetric tandem quantum well (ATQW). A theoretical study of EAM using CTC with ATQW shows a large transmittance change over 50% and a wide spectral bandwidth over 10nm with no increase in the driving voltage compared to that of single cavity based EAM. The operating characteristics of device grown by molecular beam epitaxy (MBE) are in good agreement with calculated results.

2. Design, growth and fabrication

The modulator structure comprises of two absorptive resonance cavities and three distributed Bragg reflector (DBR) mirrors as shown in Fig. 1(b). The epitaxial structure was grown on a semi-insulating GaAs substrate using P600 DCA MBE system. First, 500nm AlAs etch-stop layer was grown, followed by a 50nm thick n-doped GaAs contact layer. After forming GaAs contact layer, 2 pairs of n-doped λ/4 thick DBR layers consisting of Al$_{0.31}$Ga$_{0.69}$As and Al$_{0.88}$Ga$_{0.12}$As was grown, followed by two intrinsic absorptive cavities which are separated by 11.5 pairs of p-doped middle DBR mirror, called coupled tandem cavities (CTC), followed by 50nm thick p-doped GaAs contact layer. Each absorptive cavity contains asymmetric tandem quantum well (ATQW) structure. The first stack of ATQW consists of 31 pairs of 7.5 nm thick GaAs wells with 4 nm barriers followed by second stack consisting of 28 pairs of 8 nm thick GaAs wells with 4 nm barriers, providing a total thickness of 3-λ (0.7146µm). The modulator structure was completed by 2 pairs of p-doped λ/4 thick DBR layer and 10nm thick n-doped GaAs contact. Figure 1(d) shows the scanning electron microscope (SEM) cross-sectional image of grown modulator structure before GaAs substrate removal process.

EAM based on CTC with ATQW allows low voltage operation while maintaining large transmittance change over a wide spectral range. The CTC based on coupled Fabry-Perot (CPF) cavity effectively widens the transmittance spectrum under zero field [21–23] and ATQW provides a transmittance change over wide spectral range [4]. In addition, by employing a n-i-p-i-n structure with separated electrode configuration, the two stacked diode with absorptive cavities of the modulator can operate simultaneously. This is the reason why
CTC with ATQW based EAM can reduce voltage requirements without degrading modulation performance. Figure 1(a) and 1(c) shows the top view schematic of electrode and SEM surface image of fabricated modulator, respectively. To form the p-electrode, the inner mesa was etched up to the top surface of p-doped GaAs contact layer to form a trench of width 50µm, while to form the n-electrode, the outer mesa was etched up to the top surface of n-doped GaAs contact layer so that the device consists of two pixels having an area 2mm × 0.5mm. Fish-bone grid n-electrode was formed on top of n-GaAs contact layer to achieve uniform frequency response over a large area [2, 24]. To operate both the absorptive cavities simultaneously, the edges of the finger lines at the outer periphery is connected to the bottom n-electrode by using SiNx as the isolating layer, as shown in Fig. 1(c). Then, p- and n-metallization and rapid thermal annealing process was carried out to define ohmic contacts. To measure the transmittance of the fabricated device, GaAs substrate was partially removed by selective wet etching with the pH-adjusted NH₄OH/H₂O₂ solution after passivating the top area with SiNx. Finally, the SiNx passivation and AlAs etch stop layers were removed by buffered oxide etchant.

To investigate the low voltage operation capability of CTC with ATQW based EAM while maintaining large transmittance change over a wide spectral range, an EAM having a 3-λ thick single cavity (SC) consisting of QWs in which all the QWs have a single thickness of 8 nm (SQW) and another EAM having a CTC with ATQW structure were numerically studied. The SC with SQW based EAM has six pairs of top and bottom DBR. Calculations show that this structure exhibits a large transmittance change of more than 50%. Here, the transmittance change (ΔT) is defined as the difference between transmittance under zero bias (T₀) and transmittance under bias (Tᵥ). Figure 2(a) and 2(c) shows the contour plots of the calculated transmittance change as a function of applied voltage for SC with SQW and CTC with ATQW based EAM, respectively. The transmittance spectra for these structures were calculated by using transfer matrix method [25] with complex refractive index for the

Fig. 1. (a) Top-view and (b) design schematic of coupled tandem cavity based electro absorption modulator with asymmetric tandem quantum wells (not to scale). SEM image of (c) top surface and (d) cross-sectional image, of the fabricated modulator.

To investigate the low voltage operation capability of CTC with ATQW based EAM while maintaining large transmittance change over a wide spectral range, an EAM having a 3-λ thick single cavity (SC) consisting of QWs in which all the QWs have a single thickness of 8 nm (SQW) and another EAM having a CTC with ATQW structure were numerically studied. The SC with SQW based EAM has six pairs of top and bottom DBR. Calculations show that this structure exhibits a large transmittance change of more than 50%. Here, the transmittance change (ΔT) is defined as the difference between transmittance under zero bias (T₀) and transmittance under bias (Tᵥ). Figure 2(a) and 2(c) shows the contour plots of the calculated transmittance change as a function of applied voltage for SC with SQW and CTC with ATQW based EAM, respectively. The transmittance spectra for these structures were calculated by using transfer matrix method [25] with complex refractive index for the
absorptive material. The excitonic absorption coefficient of the QW was obtained by solving the Schrödinger equation with appropriate boundary conditions. The detail calculation procedure has been described elsewhere [4]. Figures 2(a) and 2(c) show the contour plots of transmittance change for various applied bias and wavelength for SC with SQW and CTC with ATQW structures, respectively. As seen from Fig. 2(a) and 2(c), CTC with ATQW and SC with SQW structures can achieve large transmittance change over 50% at the operating wavelength of 850 nm with a bias of −5.8V. The spectral bandwidth and transmittance change for various applied bias is also plotted in Fig. 2(b) and 2(d) for SC with SQW and CTC with ATQW structures, respectively. It is noteworthy that, the spectral bandwidth of CTC with ATQW structure is much larger than that of SC with SQW structure at a bias of −5.8V.

![Fig. 2. Contour plots of the calculated transmittance change as a function of applied reverse voltage for EAM having (a) SC with SQW structure, (c) CTC with ATQW structure. Calculated transmittance and transmittance change for (b) SC with SQW structure, and (d) CTC with ATQW structure at a bias of −5.8V. The insets of Fig. 1(b) and 1(d) show the maximum transmittance change at 850nm and the corresponding spectral bandwidth for transmittance change = 25% as a function of applied voltage.](image)

Each of the absorptive cavities of CTC that are stacked has a structure similar to that of SC, except that it uses the ATQW structure instead of the SQW. SC based EAM can provide only a narrow spectral bandwidth as shown in Fig. 2(b). Moreover, our previous results show that though ATQW provides a broader spectral bandwidth, it cannot achieve large transmittance change due to a weaker exciton [4]. A possible remedy is to use a thicker absorptive cavity so as to achieve large transmittance change, however, this results in increased driving voltage. Rather than using a thicker absorption cavity, in our design, we use two separate absorptive cavities that contain ATQW that are stacked which operate simultaneously. In addition, these two cavities are placed between three DBR mirrors and are weakly coupled, which broadens the transmittance spectrum as shown in the inset of Fig. 2(d). Since each absorptive cavity has the same thickness of 3-λ with that of SC structure, CTC with ATQW structure can achieve high transmittance change at the same operating voltage similar to that of SC structure, in addition to much wider spectral bandwidth.
Therefore by combining CTC with ATQW structure, large transmittance change over a wide spectral range can be obtained without significantly increasing the driving voltage compared to SC with SQW structure, and hence we have compared the performance between SC with SQW structure and CTC with ATQW structure.

Furthermore, as shown in Fig. 2(d), transmittance change and spectral bandwidth slightly increases for ATQW structure until the operating voltage reaches −7.5V since the excitonic peak of 7.5 nm thick QW of ATQW structure move towards 850 nm, whereas for SC structure, transmittance change and spectral bandwidth rapidly decrease as the operating voltage exceeds −5.8V as seen in Fig. 2(b). With a bias voltage larger than −7.5V, transmittance change of CTC with ATQW structure decreases since the excitonic peak of the constituent 7.5 nm thick QW red shifts from 850 nm.

3. Device characterization

Figures 3(a) and 3(b) show, respectively, the calculated and measured transmittance of EAM having CTC with ATQW structure as a function of applied voltage. The measurement of transmittance in our experiments was carried out as follows. We used a white light source (halogen lamp) and the light was delivered to the device through a fiber optic cable bundle and a collimating lens. The illuminated light passes through the device and the light transmitted from the device is coupled to the optical fiber. The transmittance is measured by using a commercial spectrometer (Filmetric F-30). The spectral transmittance of the device is generally measured by the ratio of the transmitted light intensity to the incident light intensity. The measurements are done in a dark room, and in spite of darkness, a spectrum is generated due to the photo-detector dark current. After final measurements, this spectrum is subtracted from the measured spectrum to eliminate the error due to dark current.

![Fig. 3. (a) Calculated and (b) measured transmittance of EAM having CTC with ATQWs for various applied voltages.](image)

As shown in Figs. 3(a) and 3(b), the calculated transmittance is in good agreement with the experimentally measured values. However, there is a discrepancy in the applied voltage between calculated and measured values and the measured values show a higher operating voltage. This is because in calculations, the resistance of only the intrinsic region was taken into account, and the resistance of p and n doped regions were neglected. From the measured values of transmittance shown in Fig. 3(b), it can be seen that a large transmittance occurs over a broad spectral range at zero bias owing to the CTC structure, as predicted by our calculations. Moreover, with increasing reverse bias, the transmittance decreased over a wide spectral range, which is attributed to redshift of the two absorption peaks corresponding to constituent 7.5 nm and 8 nm thick QW of ATQW structure.
Fig. 4. (a) Measured transmittance at 852nm and (b) spectral bandwidth at ΔT = 25% as a function of applied voltage for EAM having CTC with ATQW and SC with SQW structures. The insets of Fig. 4(a) and 4(b) show contrast ratio (CR) at 852nm and spectral bandwidth at CR = 2 as a function of applied voltage for EAM having CTC with ATQW and SC with SQW structures.

Figure 4(a) shows the transmittance of the EAM having CTC with ATQW and SC with SQW structures at 852nm as a function of applied bias. The inset of Fig. 4(a) shows the contrast ratio (CR) at 852nm for CTC with ATQW (red circles) and SC with SQW (black squares) structures. As shown in Fig. 4(a), the minimum transmittance for CTC with ATQW structure occurs at −11V, which is comparable to −10V in the case of SC with SQW structure. With further increase in applied bias, the transmittance of CTC with ATQW structure remains low, while that of SC with SQW structure increases. This is because, with increased applied bias, while the absorption peak of 8 nm thick QW of ATQW structure red shifts from the operating wavelength, the absorption peak of 7.5nm thick QW of ATQW structure simultaneously approaches the operating wavelength. Therefore, it is advantageous to simultaneously operate the two absorptive cavities of the CTC structure that are stacked in order to compensate for the degradation of transmittance modulation caused by ATQW. In addition, both the structures showed a contrast ratio above 3 as shown in the inset of Fig. 4(a).

Figure 4(b) shows the spectral bandwidth of the EAM having CTC with ATQW and SC with SQW structures. It is noteworthy that the spectral bandwidth of CTC with ATQW
structure at −11V is almost three times larger than that of SC with SQW structure at −10V as seen in Fig. 4(b). The wide spectral bandwidth of CTC with ATQW structure is attributed to two effects; one is due to the CTC structure based on CFP cavities which broadens the transmittance spectrum under zero bias, and the other is due to the ATQW which provides absorption over a wide spectral range. The inset of Fig. 4(b) shows the spectral bandwidth of CTC with ATQW and SC with SQW at CR = 2 as a function of applied bias. It can be seen that the spectral bandwidth at CR = 2 for the CTC with ATQW structure is much larger than that of the SC with SQW structure. Thus by combining CTC and ATQW structure along with the usage of separated electrode configuration which can drive the individual cavities simultaneously, high transmittance change over a wide spectral range was successfully achieved without significant increase in the operating voltage.

Figure 5 shows the normalized electro-optic (EO) response for the EAM having CTC with ATQW structure for each device (see inset of Fig. 5). The area of each device is 2 mm x 0.5 mm. A sinusoidal signal having a voltage swing of ± 3V with a DC bias of −7.5V was used to drive the individual devices (device 1 and 2). The EO response was measured by simultaneously operating the two devices at the operating wavelength of 852nm. As seen from Fig. 5, the 3dB bandwidth of both the devices was about 28MHz, which is sufficient for HD 3D imaging applications. It is also noted that both the devices show an identical EO response, indicating excellent uniformity of the fabricated devices.

4. Conclusion

We have proposed and demonstrated a new EAM based on CTC having ATQW with separated electrode configuration to achieve large transmittance change over a broad spectral range at low driving voltage for HD 3D imaging applications. Our theoretical calculations showed that, CTC with ATQW structure can provide large transmittance change over a wide spectral range at low driving voltage. To verify the feasibility of the proposed structure, CTC with ATQW and SC with SQW were grown using MBE and were fabricated. EAM having CTC with ATQW structure showed almost three times larger spectral bandwidth compared to that of EAM having SC with SQW, beyond the operating voltage of −10V. Experimental results also demonstrated that CTC with ATQW structure could achieve a large transmittance change of more than 50% which is comparable to that observed in SC with SQW structure, without any increase in the operating voltage. The EAM device based on CTC with ATQW structure also demonstrated high speed modulation up to 28 MHz for the device having an area of 2 mm x 0.5 mm. The individual devices of the modulator also showed identical EO response, indicating excellent uniformity between them. Our results therefore suggest that
EAM having CTC with ATQW structure is highly promising as an optical image modulator for HD 3D imaging applications.

Acknowledgment
This research was partially supported by Samsung Advanced Institute of Technology (SAIT) and the World Class University Program (Grant No. R31-10026) funded by the Korean Ministry of Education (MOE).