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Proposal and simulated characteristics of high-extinction-ratio electroabsorption modulator based on multimode interference waveguide

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We proposed an electroabsorption modulator (EAM) based on a 1×1 multimode interference waveguide (MMI-EAM). A partial electroabsorption (EA) region is asymmetrically placed in a MMI. In a multiple quantum well core layer of the region, the electrorefractive index change is also exhibited in addition to the EA effect, which leads to change in the position of a self-image at the output port of the MMI waveguide. Owing to the combination of the EA effect and change in electrorefractive index, the extinction ratio is significantly improved compared with a conventional EAM with almost the same area of the EA region. We discuss the optimization of the MMI-EAM structure and investigate its modulation characteristics theoretically using the beam propagation method. The results show that the extinction ratio can be increased by 25 dB in the MMI-EAM with the length of $152 \mu\text{m}$ and the width of $6 \mu\text{m}$. © 2019 The Japan Society of Applied Physics

1. Introduction

An electroabsorption modulator (EAM)^{1,2)} is one of the key optical devices for high-capacity optical communication because of its high-speed modulation, simple structure, and the feasibility of integration with compound semiconductor photonic devices such as laser diodes (LDs). To date, there have been developed many types of high-speed EAMs and modules based on InGaAsP^{3,4)} and InGaAlAs with a larger conduction band offset.^{5–11)} Lately EAMs for pulse amplitude modulation have also been demonstrated.^{12,13)} Most of the EAMs are integrated with distributed feedback lasers which are also known as electroabsorption (EA) modulator-lasers. In addition, several sophisticated and unique structures have also been proposed, such as an EAM with a strained asymmetric quantum well absorption layer for small-chirp operation,¹⁴⁾ a Mach–Zehnder interferometer-type EAM for very-low-voltage operation,¹⁵⁾ and a lateral p-i-n structure EAM for high-speed modulation.¹⁶⁾

On the other hand, multimode interference (MMI) devices^{17,18)} are widely applied to photonic integrated circuits as passive couplers,^{19–27)} LDs,²⁸⁾ photonic switches,^{29–34)} tunable couplers,^{35,36)} signal processing,^{37,38)} and polarization beam splitters.^{39,40)} Novel optical modulators based on MMIs have also been proposed.^{41,42)} However, this previous studies^{41,42)} only proposed a preliminary concept and have not investigated a specific structure for high extinction ratio based on precise electric field induced changes in refractive index and absorption coefficient in the quantum confined Stark effect (QCSE)⁴³⁾ in a multiple quantum well (MQW).

In this paper, we propose a compact EAM based on a 1×1 MMI waveguide (MMI-EAM) and investigate its structure design and modulation characteristics. A partial electrode region is asymmetrically positioned in an MMI waveguide. Using both EA effect and electrorefractive index change in a MQW core layer, the extinction ratio of the modulator is significantly improved compared with a conventional EAM. We discuss the optimization of the MMI-EAM structure and investigate its static modulation characteristics theoretically using the finite-difference beam propagation method (FD-BPM). The results show that the extinction ratio can be increased by more than 25 dB in the MMI-EAM with the length of $152 \mu\text{m}$ and the width of $6 \mu\text{m}$. Even though the basic

Fig. 1. (Color online) Schematic view the proposed MMI-EAM. (a) Top view. (b) Cross section with a trench for electric isolation.

concept of the proposed modulator is slightly similar to that of Refs. 41 and 42, utilization of both effects in a small region of an MMI waveguide and its precise and practical design for high extinction ratio have never been discussed so far.

2. Structure and operation principle of MMI-EAM

2.1. Structure of MMI-EAM

Figure 1 shows a schematic top view and cross section of the proposed MMI-EAM. It has a 1×1 MMI waveguide with a

Fig. 2. (Color online) (a) Calculated absorption spectra of the InGaAs (7.0 nm)/InAsAs (8.8 nm) QW and (b) calculated change in the refractive index under various electric fields.

p-i-n junction. The length and width of the MMI waveguide are 152 μm and 6 μm , respectively. The core layer is a 169 nm thick MQW sandwiched with 50 nm undoped InGaAlAs layers. The upper and lower cladding layers are p- and n-doped InP layers. The thickness of the upper cladding layer is 1 μm . There is a partial electrode region where the refractive index and absorption of the core layer

are changed by applying a reverse voltage. The region is surrounded by a trench for electric isolation. The length and width of the MMI and the size of the electrode region are optimized, as discussed in Sect. 3.

The core layer is composed of nine pairs of lattice-matched $\text{In}_{0.53}\text{Ga}_{0.436}\text{Al}_{0.034}\text{As}$ (10.0 nm)/ $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ (8.8 nm) QWs for the operation at a 1550 nm wavelength region. The InGaAlAs/InAlAs QW has a higher band offset for the conduction band than InGaAsP QWs and it is advantageous to the confinement of electrons into the QW when a large electric field is applied. The optical confinement factor is calculated to be 32.9%. The refractive index is changed by the QCSE in the MQW. Figures 2(a) and 2(b) show the calculated absorption spectra of the QW and the change in the refractive index under various electric fields. In the calculation, we considered the effect of valence band mixing using the $\mathbf{k}\cdot\mathbf{p}$ perturbation theory with a 4×4 Luttinger–Kohn Hamiltonian and the effect of excitons using a nonvariational approach. The change in the refractive index was calculated using the above absorption coefficient by the Kramers–Kronig relation. The details of the calculation procedure are described in Ref. 44.

As shown in Fig. 2(a), the absorption peak at the band-edge is shifted to a longer wavelength with the increase in the electric fields, showing a typical QCSE behavior. When the electric field is 110 kV cm^{-1} which corresponds to an applied voltage of 3.0 V, the change in the absorption coefficient is calculated to be approximately 690 cm^{-1} . At this electric field, the change in refractive index is evaluated to be -0.051 . In the following discussion, the above values are used.

In the proposed EAM, the isolation trench is required to apply an electric field only to the electrode region. The width of the trench is designed to be 0.1 μm , considering practical fabrication process using electron beam lithography. The length and width of the electrode region are optimized, as described in Sect. 3.1.

In order to obtain a larger extinction ratio, it is preferred that a uniform electric field is only applied to the core of the QW just under the electrode. Then we investigated electric field distributions in the core layer using the finite element method (FEM). Figure 3 shows the electric field distribution in the undoped layers including the MQW core layer when the voltage of 3.0 V is applied to the p-i-n junction. In the calculation, the undoped and doped layers are respectively assumed to be perfect insulators and conductors for simplicity of calculation.

Fig. 3. (Color online) Calculated electric field distribution in the undoped MQW layers when the voltage of 3.0 V is applied to the pin junction. In the calculation, the undoped and doped layers are respectively assumed to be perfect insulators and conductors for simplicity of calculation.

Fig. 4. (Color online) Light propagation in the MMI-EAM calculated with the FD-BPM when (a) no reverse voltage is applied to the electrode region, and (b) the reverse voltage of 3.0 V is applied to the electrode region.

Fig. 5. (Color online) Calculation model for the design of the MMI-EAM. The parameters for optimization, x_1 , x_2 , and y , are denoted.

simplicity of calculation. Although the electric field in the region of the core layer was approximately 110 kV cm^{-1} , the other region in this device was approximately 10 kV cm^{-1} . In the investigation of the device design and modulation characteristics, the electric field distribution just under the electrode region were considered. Since the electric field in the other areas is as low as 10 kV cm^{-1} and its influence on the modulation characteristics is negligible, it was not considered in the calculation.

2.2. Operation principle of MMI-EAM

In a conventional EAM, only the EA effect is used for modulation. In the proposed MMI-EAM, the electrorefractive index change is used in addition to the EA effect for higher extinction ratio. Figure 4 shows the light propagation in the MMI-EAM calculated with the FD-BPM (OptiBPM, Optiwave Corp.). The dimensions of the MMI and its electrode region are optimized, as discussed in Sect. 3. The width and depth of the trench is 0.1 and 1.1 μm , respectively, as described in Sect. 2.1. When no reverse voltage is applied to the electrode region, the single self-images in the MMIs are on the center line of the MMI even though the self-images are asymmetrical due to the isolation trench, as shown in Fig. 4(a). When the reverse voltage of 3.0 V is applied to the region, the absorption in the MQW core layer in the region is increased and refractive index is also changed simultaneously. As a result, the position of the single self-image at the output port shifts in addition to the light extinction owing to the EA effect. The synergy of both effects significantly enhances the extinction of the light output compared with a conventional EAM with the same area for absorption as the MMI-EAM. The detail of the reason for the large extinction ratio is discussed in Sect. 3.2.

Fig. 6. (Color online) Dependences of the extinction ratio on length x_2 for various y when x_1 is 25 μm and the reverse voltage of 3.0 V is applied to the electrode region.

3. Design and modulation characteristics of MMI-EAM

3.1. Design of MMI structure and electrode region

As a reference structure for the design of the MMI-EAM, we calculated the modulation characteristics of a straight-waveguide EAM with the same layered structure as that in Fig. 2. The width and the length of the EAM are 1.8 and 150 μm , respectively. The extinction ratio was calculated to be 12.0 dB for the applied voltage of 3.0 V.

Figure 5 shows the calculation model for the design of the MMI-EAM. The width of the input and output waveguides is fixed to 1.4 μm . The beat length of the first and second order modes is given by,⁴⁵⁾

$$L_\pi = \frac{4nW^2}{3\lambda_0} \quad (1)$$

where n is the equivalent refractive index of the MMI waveguide, W is the width of the MMI, and λ_0 is an operation wavelength. In the 1×1 MMI waveguide where only even modes are excited, single images of the input light are obtained at

$$L = m \left(\frac{3L_\pi}{4} \right) \text{ with } m = 0, 1, 2, \dots \quad (2)$$

To obtain an MMI with the length comparable to that of the straight-waveguide EAM as the reference for $\lambda_0 = 1.55 \mu\text{m}$, W is set at 6 μm . For the MMI with the above dimensions, the positions of the first to third single images from the input port are calculated to be 75, 152, and 226 μm for $m = 1-3$, respectively. In the design of the MMI-EAM, we selected the MMI length of 152 μm comparable to that of the reference EAM structure.

Next, optimization of the position and the size of the electrode region was investigated. The dimensions x_1 , x_2 , and y are used as optimization parameters. Figure 6 shows the dependences of the extinction ratio on x_2 for various y when x_1 is 20 μm and the reverse voltage of 3.0 V is applied to the electrode region. The highest extinction ratio of 38 dB is expected for $(x_1, x_2, y) = (20 \mu\text{m}, 106 \mu\text{m}, 2.4 \mu\text{m})$. We regard these dimensions as the optimized values. This extinction ratio is larger than that of the straight-waveguide EAM by 25 dB.

Figure 7 shows the calculated extinction ratios of the optimized MMI-EAM and the conventional EAM as

Fig. 7. (Color online) Calculated extinction ratios of the optimized MMI-EAM and the conventional EAM as functions of applied reverse voltage.

Fig. 8. (Color online) Calculated extinction ratios of the optimized MMI-EAM considering with only refractive index change, only absorption coefficient change in the MQW, and with both changes.

functions of applied reverse voltage. The extinction ratio of the MMI-EAM steeply increases at the voltages between 1.6 and 3.0 V. If a bias voltage is set at 1.6 V, the driving voltages for the extinction ratio of 20 and 38 dB are approximately 1.1 and 1.4 V, respectively, showing that the driving voltage can be markedly reduced compared with a conventional EAM. The area of the electrode is approximately $254 \mu\text{m}^2$, which is smaller than that of the conventional EAM ($270 \mu\text{m}^2$). This will contribute to a higher modulation speed for a lumped electrode because of a smaller CR time constant.

In order to investigate the contribution of the changes in refractive index and absorption coefficient to the high extinction ratio, we calculated static modulation characteristics when only one of them is changed. Figure 8 shows the calculation results. When only the refractive index and absorption coefficient are changed, the extinction ratios are 7 and 2 dB, respectively. Even though the contribution of the change in refractive index is greater than that in absorption coefficient, they are both small. This means that the synergistic effect of both changes in refractive index and absorption coefficient leads to the high extinction ratio. That is, as shown in Fig. 4(b), the position of the single self-image at the output port moves off from the port and the most part

Fig. 9. (Color online) Dependence of extinction ratio on wavelength for the proposed MMI-EAM and the conventional EAM.

Fig. 10. (Color online) Dependence of extinction ratios on the applied voltage for the MMI modulators with and without the isolation trench. For the extinction ratios of the MMI with the trench, the electric field distribution in the core layer is considered.

of the transmitted light is not output. In addition, the small part of the light transmitting on the side without the EA region to the output port interferes with that on the side with the EA region. When the difference in phase of both lights becomes π rad and their powers get well balanced, the high extinction ratio can be obtained, as will be discussed in Sect. 3.2.

Figure 9 shows the dependence of the extinction ratio on the wavelength for the optimized MMI-EAM and the conventional EAM. In the wavelengths longer than 1545 nm, the MMI-EAM is expected to have a larger extinction ratio than the conventional EAM, although it shows sharp dependence on the wavelength. This is because the interference effect in the MMI is also used in the proposed modulator in addition to the EA effect, the change in wavelength of the input light causes change in phase and power balance at the output port, leading to the change in extinction ratio. The insertion loss of both EAMs are comparable in the whole wavelength region.

3.2. Influence of isolation trench on modulation characteristics

We discuss the effect of the isolation trench on the modulation characteristics. Figure 10 shows the dependence of

Fig. 11. (Color online) Distribution of light power in the MMIs with and without the isolation trench. The lengths of the MMIs are extended to the light propagation direction to make it easier to find the self-images.

Fig. 12. (Color online) Distributions of the light power and phase of the propagated lights in the MMIs with the isolation trench. (a) Light power distribution, (b) normalized light power distribution in the y direction in the vicinity of the output port, (c) phase distribution, and (d) phase distribution in the y direction in the vicinity of the output port.

Fig. 13. (Color online) Distributions of the light power and phase of the propagated lights in the MMIs without the isolation trench. (a) Light power distribution, (b) normalized light power distribution in the y direction in the vicinity of the output port, (c) phase distribution, and (d) phase distribution in the y direction in the vicinity of the output port.

Fig. 14. (Color online) Dependence of the calculated insertion loss on the depth of the isolation trench.

Fig. 15. (Color online) Dependence of the extinction ratio of the optimized MMI-EAM on (a) the length of the electrode region, x_2 , (b) the width of the electrode region y , and (c) the width of the MMI, W .

extinction ratios on the applied voltage for the MMI modulators with and without the trench. In the MMI without the trench, the position of the electrode is the same as that of the MMI with the trench. The maximum extinction ratio of the MMI with the trench is larger by approximately 20 dB than that without the trench.

To investigate the reason for the large extinction ratio in the MMI with the trench, we calculated the light power

distribution in the proposed MMIs with and without the isolation trench, as shown in Fig. 11. Their lengths are extended to the light propagation direction to make it easier to find the self-images. In the case of the electric field $E = 0 \text{ kV cm}^{-1}$, the single images in both MMIs are on the center line of the MMI even though the mode behavior in the MMI with the trench is asymmetric, as shown in Figs. 11(a) and 11(b). When the electric field

$E = 110 \text{ kV cm}^{-1}$ is applied to the MMIs, the distributions changes significantly. In the MMI without the trench, the single self-images are still on the center line even though their positions move to the direction parallel to the center line and their intensity is decreased, as shown in Fig. 11(d). On the other hand, in the MMI with the trench, the single images move off from the center line, as shown in Fig. 11(a), which leads to the significant decrease in the output light power from the output port and larger extinction ratio than that of the MMI without the trench.

Figures 12 and 13 show the distributions of the power and phase of the propagated lights in the MMIs with and without the trench. We compare the power and phase in the vicinity of the output port of both MMIs. In the case of the MMI with the trench, as shown in Fig. 12, the light powers at the two observation points is almost the same, as shown in Figs. 12(a) and 12(b), and they are out of phase by approximately π rad, as shown in Figs. 12(c) and 12(d). This leads to the large extinction ratio because both light electric fields at the observation points add up destructively and become a leaky mode, as occurs in an interferometer. On the other hand, in the case of the MMI without the trench, as shown in Fig. 13, the light intensity at the two observation points is slightly different and their phases are nearly equal.

As discussed above, the large extinction is obtained owing to both the considerable change in the position of the single self-image at the output port and the cancellation of the light electric fields with each other by the interference effect. Therefore, adopting of the asymmetry in the MMI structure with the trench is very important for the proposed modulator.

The dependence of the calculated insertion loss on the depth of the trench is shown in Fig. 14. The proposed structure is the one with the depth of 1000 nm. The excess insertion loss caused by the trench with the depth of 1100 nm is approximately 2.4 dB. Even though the insertion loss is increased using the trench, a significantly large extinction ratio can be obtained in the MMI modulator with the trench. This is the great advantage of the proposed modulator.

3.3. Tolerance to fabrication error

We discuss tolerance to the fabrication errors in the size of the MMI. Figures 15(a)–15(c) show the dependence of the extinction ratio of the optimized MMI-EAM on the length of the electrode region x_2 , the width of the electrode region y , and the width of the MMI W , respectively. As shown in Fig. 15(a), the MMI-EAM shows the smaller dependence and has great tolerance to the error in x_2 . Similar large tolerance of the length of the MMI was also obtained. On the other hand, the extinction ratio of the MMI-EAM is very sensitive to y and W , as shown in Figs. 15(b), 15(c) and high accuracy of dimension is required to exhibit large extinction ratio. To obtain the extinction ratio of larger than 20 dB which is comparable to that of the conventional EAM, the fabrication error needs to be within about $\pm 0.05 \text{ }\mu\text{m}$.

4. Conclusions

We proposed a high-extinction-ratio MMI-EAM. A partial electrode region is asymmetrically placed in an MMI waveguide. Using both EA effect and electrorefractive index change in an MQW core layer, the extinction ratio of the modulator is significantly improved compared with a conventional EAM with a similar device length and smaller electrode region. We

discussed the optimization of the MMI-EAM structure and investigate its modulation characteristics theoretically using the FD-BPM. The results show that the extinction ratio can be increased by more than 25 dB in the MMI-EAM with the length of $152 \text{ }\mu\text{m}$ and the width of $6 \text{ }\mu\text{m}$. The tolerance to the fabrication error was also discussed. The extinction ratio of the MMI-EAM is sensitive to the width of the MMI waveguide.

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