Carrier-Depletion-Type Multiple Quantum Well Optical Phase Modulators Operating at the 1.55 μm Wavelength Range

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Abstract: *We fabricated a carrier-depletion-type optical phase modulator with an InGaAlAs MQW and observed a large modulation efficiency of 87 degree/mm/V without any intensity modulation at the wavelength of 1.58 μm. The modulator has a smaller wavelength dependence than that of the QCSE based devices, and has an almost linear bias dependence. Carrier-depletion-type optical phase modulators are attractive for WDM optical transmission systems and optical signal processing.*

Introduction

Optical cross connects in the future optical networks require optical space switches driven by electronic signals [1]. For long-haul optical transmission systems with bit rates above 10 Gbit/s, Mach-Zehnder modulators are advantageous from their low-chirp characteristics [2]. Most of these optical switching devices utilize phase modulation effect based on the quantum-confined Stark effect (QCSE) under a reverse biased condition, or the carrier injection (plasma effect, band-filling effect) under a forward biased condition. For carrier-injection-type devices, switching time is limited to several nano-seconds by the carrier lifetime, while QCSE based devices have a large wavelength dependence. On the other hand, phase modulators based on a carrier depletion effect [3] are also known. In carrier-depletion-type modulators, depletion of carriers in a reverse-biased pn junction causes a large index change in conjunction with a linear and a quadratic electrooptic effect, and a large modulation efficiency of 96 degree/mm/V at the wavelength of 1.06 μm has been reported [4]. Although much smaller wavelength dependence than QCSE based devices is expected in the carrier-depletion-type modulators, their wavelength dependence hasn't been investigated in detail and there is only a limited number of reports on the 1.55 μm operations [5].

We fabricated carrier-depletion-type InGaAlAs multiple-quantum well (MQW) phase modulators by metal-organic vapour-phase epitaxy (MOVPE) and investigated their modulation characteristics at the 1.55 μm wavelength range under a reverse-biased condition. Efficient phase modulation of 87 degree/mm/V was observed at 1.58 μm and smaller wavelength dependence than QCSE based phase modulators was observed.

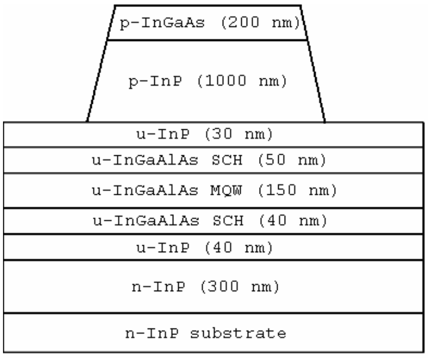


Fig. 1: Schematic illustration of the fabricated InGaAlAs MQW phase modulator with a shallow ridge waveguide structure.

Device Fabrications

Fig. 1 shows the schematic structure of the fabricated modulator. It consists of 10 sets of lattice-matched InGaAlAs MQW (9 nm InGaAlAs wells and 5 nm InAlAs barriers) and has 40 and 50 nm-thick InGaAlAs SCH layers. The overall structure was grown by MOVPE on an n$^+$InP(100) substrate. The MQW and SCH layers were not intentionally doped, but are of n-type due to residual impurities (mostly oxygen). The impurity density was measured to be $N_D \sim 4\times10^{16}$ cm^{-3} by a C-V method. As a result, the total structure constitutes a P-n-N structure in which the pn junction is formed between the p-clad and the upper-SCH layers. Absorption edge of the MQW was measured to be at 1430 nm by the photocurrent spectroscopy. 2 μm wide shallow-ridge waveguide phase modulators were fabricated by wet etching along the [0-11] crystal orientation.

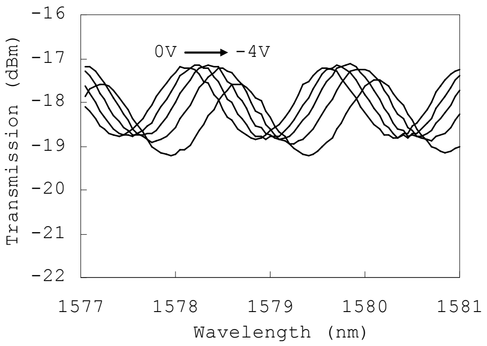


Fig. 2: Measured Fabry-Perot resonance spectra of the 230 μm-long phase modulator at 1580 nm under reverse bias voltages from 0 to -4V for TE mode.

Characterizations

Modulation characteristics of the fabricated devices were measured by the Fabry-Perot method. In this method, cleaved facets of the waveguide form a Fabry-Perot resonator, and the transmission of the resonator was measured as a function of the wavelength. Absorption coefficient was determined from the peak to valley ratio of the transmission spectra, and phase shift was determined from the peak shift $\Delta\lambda$. Fig. 2 shows the measured Fabry-Perot resonance spectra around 1580 nm for TE mode under reverse bias voltages from 0V to -4V. A positive refractive index change was observed without any intensity modulation up to -3V. Fig. 3 shows the phase shift of the modulator determined from the Fabry-Perot spectra. Large phase modulation was observed from +0.5V to -1V, which shows an almost linear bias dependence.

For a comparison, an undoped InGaAsP MQW phase modulator was also measured. It consists of 10 sets of InGaAsP MQW (7 nm InGaAsP wells and 10 nm InGaAsP barriers) with the absorption edge of 1490 nm, and has almost the same structure as Fig. 1. The residual impurity density in the MQW was measured to be $N_A \sim 1 \times 10^{16}\mathrm{cm}^{-3}$. The results are plotted in Fig. 4. On the contrary to the InGaAlAs MQW with a higher impurity density, an almost quadratic phase shift due to the QCSE is observed throughout the measured bias range.

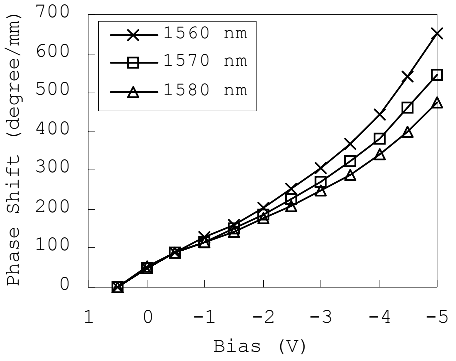


Fig. 3: Measured phase modulation characteristics of the InGaAlAs MQW modulator for TE-mode.

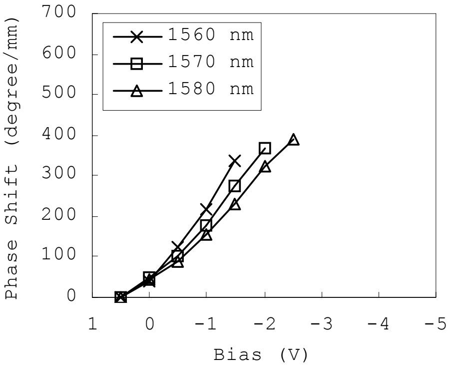


Fig. 4: Measured phase modulation characteristics of the InGaAsP MQW modulator for TE-mode.

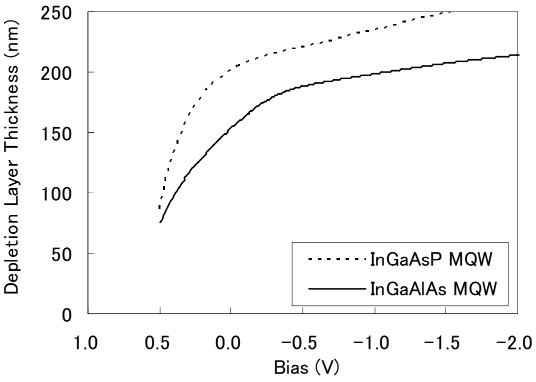


Fig. 5: Measured depletion layer thicknesses of the InGaAsP and InGaAlAs MQWs as a function of the bias voltage.

The reverse bias dependence of the depletion layer thicknesses was determined by measuring the junction capacitances. The results are plotted in Fig. 5 both for the InGaAsP and InGaAlAs MQWs. It shows that for the InGaAlAs MQW with a high impurity density, most of the MQW layer is out of the depletion layer at a bias voltage of +0.5V and the MQW layer is gradually depleted by applying a reverse bias from +0.5V to -0.5V. On the other hand, for the InGaAsP MQW, the MQW is rapidly depleted by applying a reverse bias.

Fig. 6 shows the wavelength dependence of the phase modulation efficiency of the InGaAlAs MQW modulator at 0V for both TE and TM modes. Wavelength dependence is small especially at the longer detuning wavelengths and a large phase modulation efficiency of 87 degree/mm/V was observed at 1580 nm for TE mode.

Fig. 7 shows the wavelength dependence of the modulation efficiencies under reverse bias voltages of 0V and -2V for TE mode. At -2V where the MQW is completely depleted and the QCSE is dominant, wavelength dependence is fairly large and the modulation efficiency quickly drops as the operating wavelength detunes from the absorption edge.

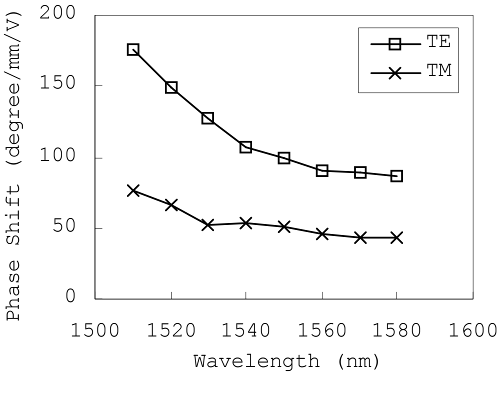


Fig. 6: Wavelength dependence of the phase modulation efficiency of the InGaAlAs MQW modulator at 0V for TE- and TM-mode.

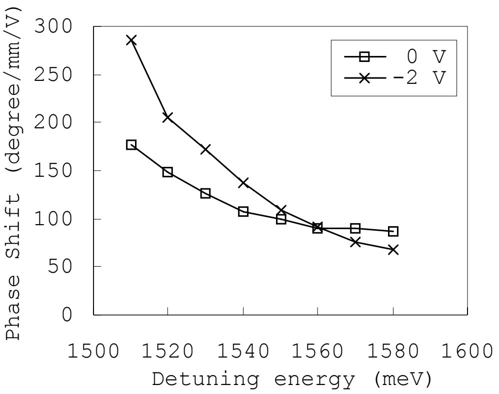


Fig. 7: Wavelength dependence of the modulation efficiency of the InGaAlAs MQW modulator at different bias voltages (0 and -2V) for TE-mode.

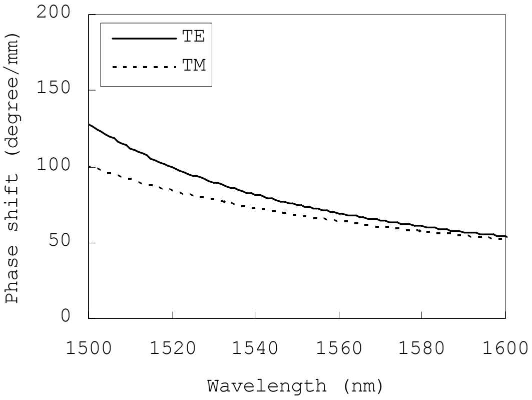
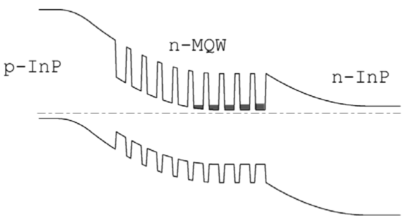


Fig. 9: Calculated phase shift due to the carrier depletion effect in the InGaAlAs MQW for TE and TM mode.

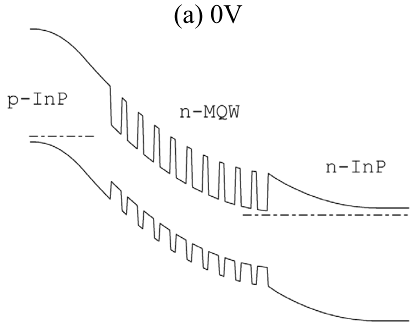
Discussion

The large phase shift observed in the InGaAlAs MQW around 0V is mainly attributed to the carrier depletion effect. For a pn junction with an n-type MQW, part of the MQW is out of the depletion layer at 0V and electrons are accumulated in the conduction subbands of the MQW as shown in Fig. 8 (a). When a reverse bias is applied, the depletion layer thickness increases and the carriers are swept out as shown in Fig. 8 (b). This causes a large positive index change of the MQW by the band-filling effect.

In order to estimate the magnitude of the phase modulation due to the carrier depletion effect, numerical calculations were performed. Here, only the band-filling effect of the MQW was considered. The calculated results are shown in Fig. 9. We assumed that 5 sets of the InGaAlAs MQW (10 sets) are depleted by applying a reverse bias, as schematically shown in Fig. 8. Compared with the measured phase shift shown in Fig. 6, the calculation results are almost consistent with the measurement results for TM mode, whereas for TE mode, measured magnitude of the phase shift and wavelength dependence is larger than those of the calculation. These disagreements are mainly due to the addition of the polarization dependent Pockels effect and some contributions from the QCSE to the actual device. Although carrier effect itself is an almost polarization independent effect, these additional effects render the phase modulator to be polarization dependent. For a polarization independent operation, adoption of a tensile strained MQW is necessary.



(a) 0V



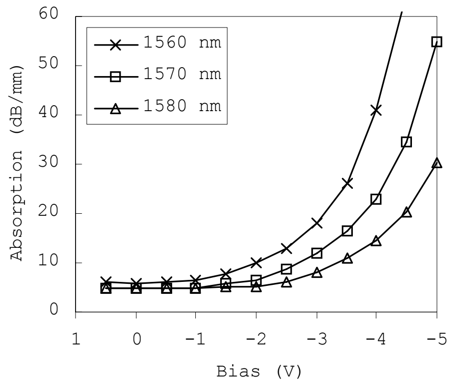
(b) -1V

Fig. 8: Schematic illustration of a carrier depletion effect in a pn junction with a shallowly n-doped MQW. Quasi-Fermi levels are depicted by dashed lines.

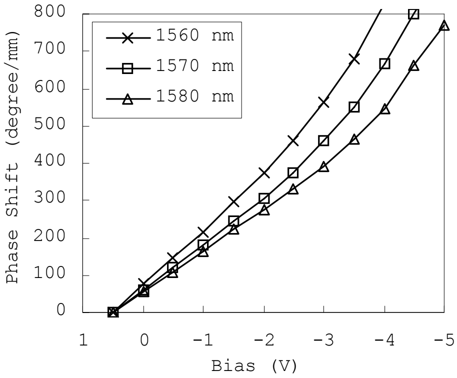
Such polarization insensitive and small wavelength dependent phase modulators are attractive for integrated optical switches with nano-second switching times, which are suitable for optical cross connects and other optical devices for future photonic networks. Carrier-depletion-type optical switches require no current injection, hence no static power consumption is needed.

In the device fabricated, however, carrier depletion effect is observed only in a limited bias range (+0.5V to -1V) because of the relatively low impurity density. Maximum refractive index change will be enhanced to $\Delta n \sim 0.001$ by increasing the impurity density in the MQW. Fig. 10 shows the modulation characteristics of another InGaAlAs MQW modulator (9 nm InGaAlAs well, 5 nm InAlAs barrier, $\lambda_{PL} = 1465$ nm) with a higher donor density of $N_D \sim 9 \times 10^{16}\text{cm}^{-3}$. As the impurity density is increased, the reverse bias voltage at which the MQW is completely depleted is higher and is about -2V. Consequently, an almost linear phase shift of 109 degree/mm/V without any intensity modulation was observed up to -2V at the wavelength of 1580 nm.

Such linear phase modulation characteristics are advantageous for low-chirp push-pull driven Mach-Zehnder modulators, because nonlinear phase shift results in positive chirpings and bias voltage dependent modulations.



(a) Absorption coefficient



(b) Phase shift

Fig. 10: Modulation characteristics of a highly doped InGaAlAs MQW phase modulator for TE mode.

Conclusion

Carrier-depletion-type MQW optical phase modulators which operate in the 1.55 μm wavelength range were fabricated and a highly efficient phase modulation of 87 degree/mm/V without any intensity modulation was observed at the wavelength 150 nm detuned from the absorption edge. It was shown that these modulators have a small wavelength dependence and a linear bias dependence, which is difficult to be realized in the QCSE based phase modulators. Although there is a trade-off between the modulation efficiency and the frequency bandwidth, carrier-depletion-type phase modulators are useful for optical integrated circuits for future optical networks.

References

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