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Low Voltage InGaAs/InAlAs Quantum Well Mach-Zehnder Modulator with Single Microring Resonator

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1. Introduction

Semiconductor Mach-Zehnder (MZ) modulator is one of the key devices for the next generation ultra-high-capacity optical communications [1] owing to not only low chirp modulation characteristics but also their adaptability to spectrally efficient multilevel modulation formats such as quadrature phase-shift keying (QPSK). On the other hand, a non-linear phase shift effect in microring resonators [2,3] has attracted much attention recently and its application to photonic devices has been reported. If we utilize the microring-enhanced phase shift for MZ modulators and switches, very low voltage modulators and switches are expected to be realized [2-5].

In this paper, we propose and demonstrate a novel low-voltage InGaAs/InAlAs multiple quantum well (MQW) MZ modulator with a single microring resonator. The modulation response of the proposed device is theoretically and experimentally discussed.

2. General Instructions Enhanced Phase Shift Effect in Microring Resonator

Figure 1 shows the schematic view of a microring resonator with a busline waveguide. The effective phase ϕ_{eff}, that is, the phase of the electric field transmitted from Port 1 to 3, is given by[2,3]

$$\phi_{\mathrm{eff}} = \arg\left(\frac{E_3}{E_1}\right)$$

$$= \pi + \phi + \tan^{-1}\left(\frac{r\sin\phi}{a - r\cos\phi}\right) + \tan^{-1}\left(\frac{ar\sin\phi}{1 - ar\cos\phi}\right) \quad (1)$$

where E_1 and E_3 are the optical electric fields at ports 1 to 3, r and t are the transmission and coupling coefficients, ϕ is the single-pass phase shift in the microring, respectively.

Figure 2 shows the effective phase shift ϕ_{eff} as a function of the single-pass phase shift ϕ for the coupling efficiency K=0.25, the propagation loss α= 1.04 dB/round, and the round-trip length L_{ring}=480 μm, respectively. At around ϕ=0, that is, on resonance, the remarkable nonlinearity and the single-pass phase shift is strongly enhanced. Using this

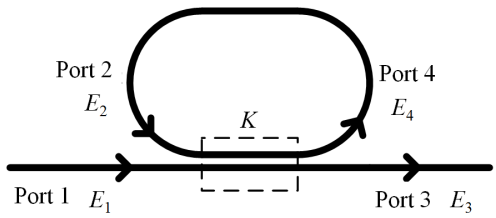

Fig. 1. Schematic of microring resonator.

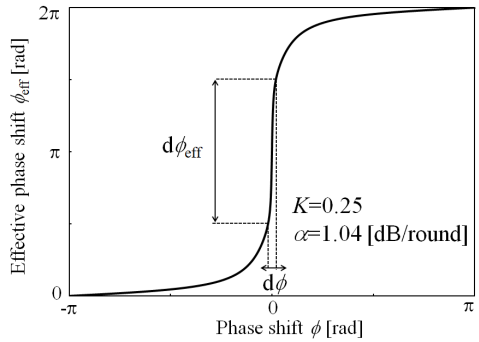

Fig. 2. Effective phase shift ϕ_{eff} as a function of the single-pass phase shift ϕ.

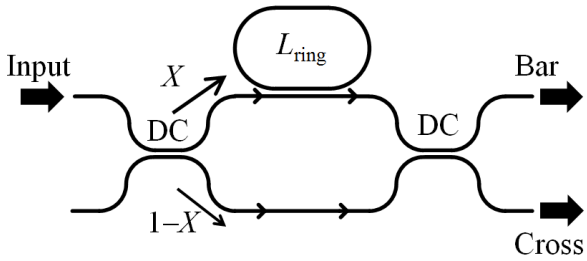

Fig. 3. Schematic view of microring MZmodulator.

phase shift enhancement effect in the one arm of the MZ interferometer, the driving voltage of the MZ modulator can be significantly reduced. That is, if a microring resonator is coupled with one arm of the MZ modulator and use the change of the effective phase shift $d\phi_{\mathrm{eff}}$ =π from ϕ_{eff} =π/2 to 3π/2, the output light can be modulated with the small change of the single-pass phase shift dϕ.

3. Fabrication of MZ modulator and Its Static Modulation Characteristics

We fabricated an InGaAs/InAlAs MQW MZ modulator with a single ring as shown in Fig. 3. It is composed of an MZ interferometer with a single ring resonator in the one arm, and two directional couplers. By applying a reverse bias voltage to the microring, the output light from the bar port is modulated. Considering the propagation loss in the microring resonator, the input light power asymmetrically splits with the ratio of X: 1–X (X=0.6) to suppress the reduction of extinction ratio. The round-trip length of the microring resonator L_{ring} was 480 μm.

Figure 4 shows a schematic cross-sectional view of the waveguide. The waveguide consists of a core layer with 12-set $In_{0.53}Ga_{0.47}As$ /$In_{0.52}Al_{0.48}As$ MQW, 50 nm $In_{0.52}Al_{0.24}Ga_{0.24}As$ separated confinement heterostructure

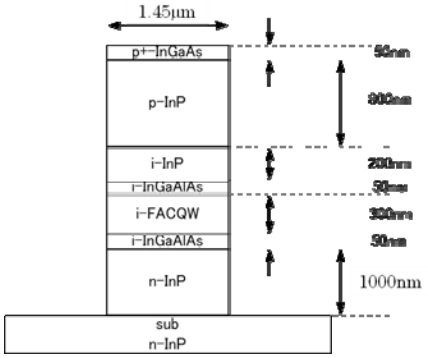

Fig. 4. Waveguide structure of proposed device.

(SCH) layers, and p/n-doped InP cladding layers. In the device, InGaAs/InAlAs five-layer asymmetric coupled quantum well (FACQW) structures [6] were used as the MQW. The large field-induced phase shift in the microring is obtained by the quantum confined Stark effect (QCSE) in the multiple FACQW. The total thickness of the core layer is approximately 300 nm. All layers are lattice-matched to the InP substrate. To reduce the absorption loss caused by the p-doped upper cladding layer, a 200 nm undoped InP layer was inserted close to the core layer. The waveguide is buried by benzo-cyclo-butene (BCB). For the coupling region between the microring waveguide and one arm of the MZ modulator, a directional coupler with a shallow groove [7]. The device parameters are summarized in Table I.

Table I Device Parameters

Parameter	Designed value
Round-trip length of microring resonator L_{ring}	480 μm
Length of coupling region between ring resonator and busline l	64 μm
Coupling efficiency K	0.25
Propagation loss in microring resonator α	1.04 dB/round
Free spectral range (FSR)	1.30 nm

An epitaxial wafer was grown by solid-source molecular beam epitaxy (MBE). To fabricate a directional coupler with a shallow gap, we adopted a two-step etching technique. First, using an electron beam lithography technique, the gap was formed by inductively coupled plasma reactive ion etching (ICP-RIE) with a Br-based gas. Next, using a photolithography technique, the high-mesa waveguides were formed by ICP-RIE.

The measured bar-port spectrum responses at various reverse biases are shown in Fig. 5. The free spectral range (FSR) and the full-width at half-maximum (FWHM) of the spectrum dip were 1.33 nm and 0.16 nm, respectively. These values are comparable to the designed ones.

Figure 6 shows the static modulation characteristics of the microring MZ modulator at the wavelength of 1550.0 nm. For comparison, the modulation characteristics of a conventional MZ modulator with the same waveguide structure are also plotted. The half-wave voltage of the microring MZ , V_π, was approximately 4.2 V for L_{ring} = 480 μm ($V_\pi L_{ring}$ =2.0 Vmm). The extinction ratio was 17.5 dB.

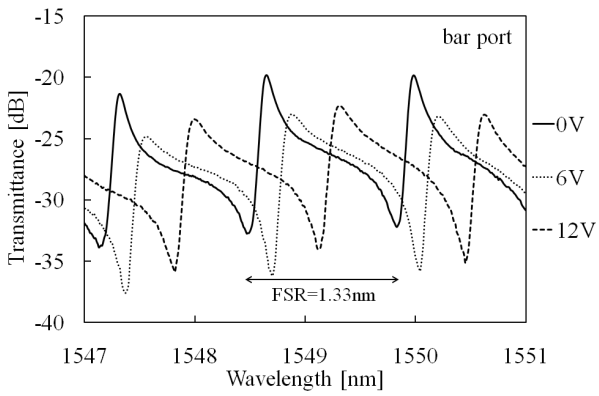

Fig.5. Measured bar-port spectrum responses at various reverse biases.

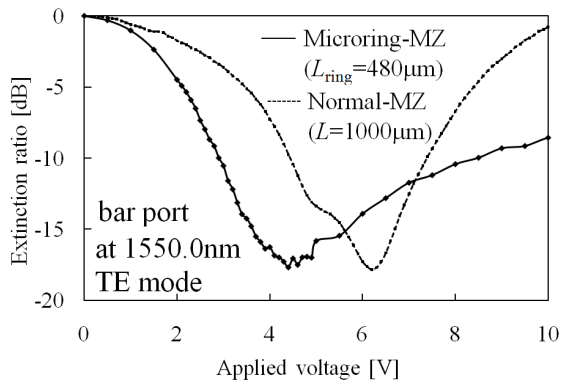

Fig. 6. Modulation characteristics of the microring MZ modulator at the bar port.

The V_π of the conventional MZ with the phase shifter length L of 1000 μm was approximately 6.2 V ($V_\pi L$ =6.2 Vmm). This result indicates that V_π of the microring MZ was successfully reduced to one-third compared to the normal MZ modulator.

4. Conclusion

A novel low-voltage InGaAs/InAlAs MQW MZ modulator with a single microring resonator was proposed and demonstrated. The half-wave voltage of the proposed modulator was successfully reduced to one-third compared to a conventional MZ modulator due to the phase shift enhancement effect in the microring resonator.

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