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Proposal of Quantum Well Microring Resonator-Loaded Mach–Zehnder Optical Modulator Integrated with Antenna-Coupled Electrodes for Radio over Fiber

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Abstract

A quantum well microring resonator (MRR)-loaded Mach–Zehnder optical modulator integrated with an antenna-coupled electrode is proposed for radio-over-fiber systems, and its modulation characteristics are theoretically analyzed. The proposed modulator is expected to be driven by a received electric power of as low as 3.6 W/m² with the combination of the resonant effects in the resonant electrode and the MRR.

1. Introduction

Wireless millimeter-wave (MMW) technology is a communication method with excellent capacity and high speed owing to its abundant frequency resources. It has been demonstrated for use in sensors and radars. However, the number of antenna units to construct such wireless MMW systems is enormous, and the signals have relatively high propagation losses, A radio-over-fiber (RoF) technology that offers seamless connections between wireless and optical networks has been investigated[1] With the RoF technology, MMW signals received by an external antenna are sent through a coaxial cable. However, it has been pointed out that distortions and delays in MMW signals occur in coaxial cables, and the MMW speed may be impaired. Therefore, an antenna-integrated optical modulator is attracting attention as a new modulation device.

This modulator is driven directly by received signals without external power supply. Therefore, it has a high affinity that enables low latency communication. There have been reports on antenna-integrated optical modulators based on the Pockels effect of electro-optical (EO) materials such as lithium niobate (LN) [2] and nonlinear optical polymers (EOP) [3]. However, there are some issues such as a relatively small change in refractive index induced by an electric field, high power consumption, poor integration with semiconductor light-emitting devices such as laser diodes (LDs), and enlargement and high losses of the entire system.

In this study, we propose a quantum well (MQW) microring resonator (MRR)-loaded Mach–Zehnder optical modulator integrated with antenna-coupled electrodes. Although we have proposed and developed patch-antenna-integrated MQW modulators [5,6], the proposed modulator is expected to be driven with much lower electric power with the combination of the resonant effects in a resonant electrode and MRR.

2. Proposed Modulator Structure and Design Method

The structure of the proposed modulator is shown in Fig. 1. The MMW radio signal received by the patch antenna is sent to the standing-wave resonant electrodes, and the wireless 60 GHz-band standing-wave electric field is generated along the resonant electrode. A Mach–Zehnder interferometer with 2 MRRs on both arms, a total of 4 MRRs were loaded, below the resonant electrode. The electric field is applied to the core layer of the MRR waveguide and the change in refractive index is induced. As the core layer, a multiple InGaAs five-layer asymmetric coupled quantum well (FACQW) [4] is assumed. In the FACQW core layer, a large refractive index change and low absorption loss are expected owing to its unique quantum confinement Stark effect. The core layer as a PIN structure for the enhancement of a received electric field, as discussed later.

In order to prevent end-face reflections at the joints of each section, each parameter was designed considering impedance matching by the finite element method. In addition, to improve the performance of the antenna, a semi-insulating Fe-doped InP substrate was adopted.

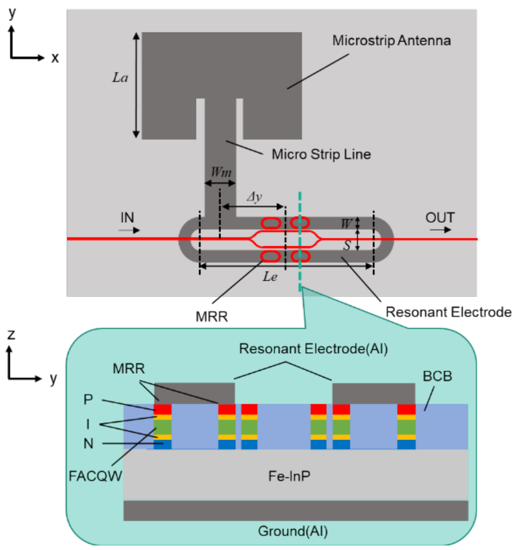

Fig. 1 Schematic view of proposed phase modulator.

The InGaAs FACQW is designed for the proposed modulator [5]. It has an electric field of 8 to 16 kV/cm as its operating region, and it operates push-pull depending on the applied electric field.

In addition, a large phase shift enhancement is expected in an MRR at the vicinity of its resonant wavelength [7], and the modulator can be driven with a low electric field. The Mach–Zehnder interferometer is operated with a push-pull drive for intensity modulation. There is a trade-off between the modulation speed and the phase enhancement effect in an MRR [7]. Therefore, the device parameters of MRR were determined to satisfy the minimum modulation speed of 30 GHz, which is the minimum required for the 60 GHz band signal for the carrier wave.

3. Derivation of Modulation Characteristics

Figure 2 shows the z-direction electric field E_z intensity distribution on the antenna surface and a cross section of the modulator. The analysis was performed using the finite element method with 60 GHz plane waves incident from above the modulator. The positive and negative electric fields E_z are induced on the surface of the resonant electrode by MMW incidence. In addition, the induced electric field is concentrated and applied efficiently to the waveguide core layer owing to the PIN structure. Furthermore, it was found that the electric field applied to an MRR is enhanced more than 1900 times larger than the input electric field E_0.

Figure 3 shows the E_z characteristics of the core layer for the frequency of the input electric field. The results of the analysis show that the field strength at 60.2 GHz is the maximum. Table I summarizes the design device parameters.

Figure 4 shows the modulation characteristics of the proposed modulator with a total of four rings were loaded and the previous study device [5]. For comparison, the extinction ratio per the input power density for the previous study device is also shown. In the previous device, the calculated extinction ratio of 20 dB was obtained when the electric field with a power density of 244 W/m^2 was incident on the modulator. On the other hand, in the proposed device, the calculated extinction ratio of 20 dB is obtained when the electric power of 3.6 W/m^2 is incident on the modulator, which is approximately 1/63 of the power density required to drive the previous study device.

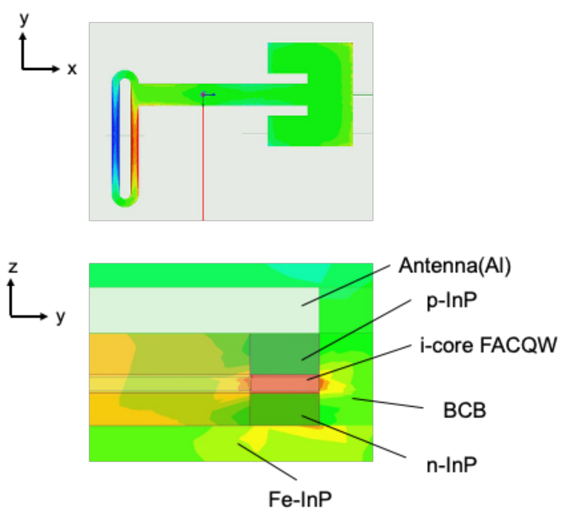

Fig. 2 Calculated distribution of z-component of electric fields E_z/E_0. (a) Top view. (b) Cross sectional view.

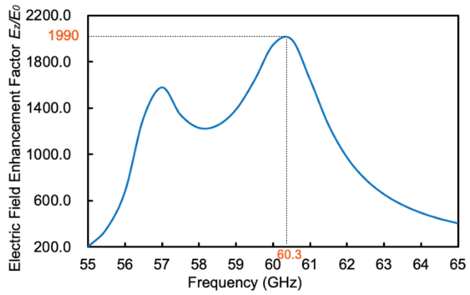

Fig. 3 Calculated electric field enhancement factor E_z/E_0 as function of frequency of MMW plane waves.

Table I. Designed parameters

Parameters	Value
Patch Antenna Length L_a	653 μm
Electrode length, L_e	776 μm
Electrode separation, S	91 μm
Electrode width, W	60 μm
Feeding position to modulation electrode, Δy	297 μm
Micro-strip line width, W_m	166 μm
Patch Antenna width, W_a	979 μm
Patch Antenna slot, y_0	265 μm

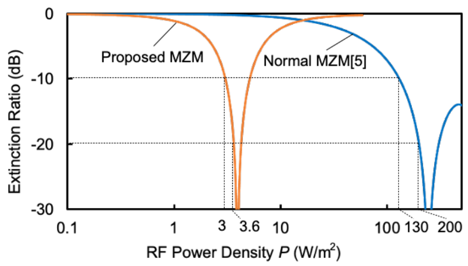

Fig. 4 Modulation characteristics of proposed modulator.

3. Conclusions

An MQW MRR-loaded Mach–Zehnder optical modulator integrated with an antenna-coupled electrode is proposed for radio-over-fiber systems, and its modulation characteristics are theoretically discussed. The proposed modulator is expected to be driven by a received electric power of as low as 3.6 W/m^2 with the combination of the resonant effects in the resonant electrode and the MRR.

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