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Array Antenna Integrated Quantum Well Optical Modulator for 60 GHz Band Radio over Fiber System

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Abstract

We propose and demonstrate a planar array antenna-coupled InGaAs/InAlAs multiple quantum well (MQW) optical phase modulator for use in radio over fiber systems, targeting 60 GHz-band millimeter-wave wireless transmissions. This modulator includes an assembly of five types of five-layer asymmetric coupled quantum wells (FACQWs) and a two-element array antenna. The design of the FACQWs enables a considerable change in the refractive index in response to minimal electric fields generated by the antenna. The modulator achieved a carrier-to-sideband ratio (CSR) of up to 45.9 dB at a power density of 11 W/m^2, which corresponds to a phase shift of 10.1 mrad. The phase shift characteristics of a four-element array antenna modulator are also analyzed.

1. Introduction

Millimeter-wave signals are crucial for next-generation high-speed wireless communications but suffer from limited range and high attenuation. The millimeter-wave radio-over-fiber (MMW RoF) technology facilitates the efficient transmission of these signals over optical fibers. In RoF systems, an optical modulator is one of the key devices.

Antenna-coupled optical modulators utilizing electrooptic (EO) materials such as EO polymer waveguides, lithium niobate, and compound semiconductors have been proposed and developed [1,2]. We also previously reported on an InGaAs multi-quantum well (MQW) optical phase modulator integrated with a single antenna [3]. In this device, a carrier-sideband ratio (CSR) of 59.9 dB was observed at 60.0 GHz radio signal irradiation.

This paper discusses a planar array antenna-coupled MQW optical modulator for 60 GHz band millimeter-wave signals [4]. To enhance the modulation efficiency, a newly designed five-layer asymmetric coupled quantum well (FACQW) structure, along with an array antenna structure, is introduced.

2. Device Structure

Schematic overall and cross-sectional views of a two-element-array antenna-coupled FACQW modulator are shown in Figs. 1(a) and (b). The modulator has a single transverse electric (TE) mode high mesa with a height of 2.1 μm and a width of 1.45 μm. The waveguides are embedded with benzocyclobutene (BCB). The substrate of this modulator is 200 μm-thick semi-insulating Fe-doped InP (Fe-InP). The waveguide consists of a core layer of MQWs and cladding layers of p-InP and n-InP above and below the core layer. This PIN structure allows the applied electric field from the antenna to be concentrated in the core layer of the waveguide [5].

This device has a small gap of 3.0 μm in the center of the planar antenna and ground electrode because the electric field derived from the received radio signals can be concentrated in the gap [6]. The waveguides are placed just below the antenna gap [3].

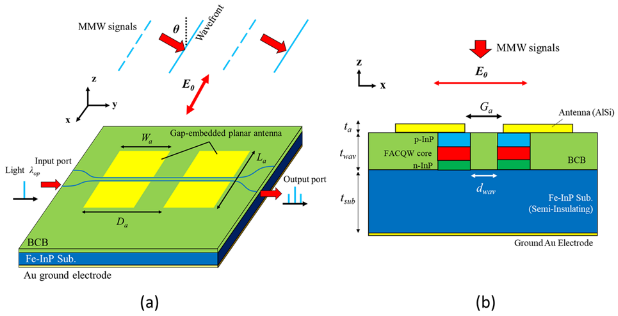

Figure 1. Schematic views of modulator. (a) Whole view. (b) Cross-sectional view.

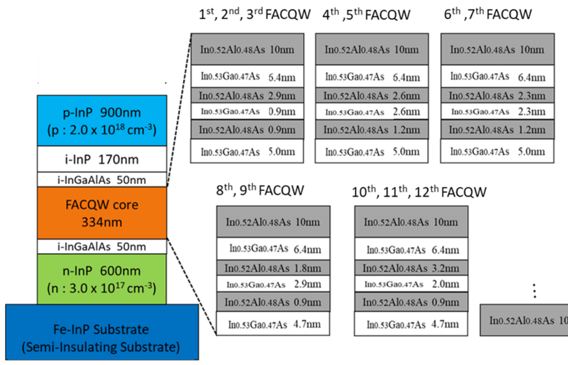

Figure 2. Schematic cross-sectional view of waveguide with FACQW core layer.

The waveguide core layer of the modulator comprises $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ FACQWs, which exhibit giant refractive index change characteristics due to the unique quantum-confined Stark effect (QCSE) [13, 17]. The characteristics of the electric-field refractive index change in the FACQW are highly sensitive to the electric field in the core layer. The electric field is non-uniform in the non-doped intrinsic layer owing to the space charge caused by residual impurities. We designed and optimized the FACQW core layer considering the non-uniformity of the electric field and its operation region, as shown in Fig. 2.

The geometry of the rectangular patch antenna in this device has already been discussed in [3]. The dependence of the accumulated phase shift on a distance D_a in Fig. 1(a) for the array device with two antenna elements is shown in Fig. 3. On the basis of this result, D_a is set to 1450 μm in order to maximize the accumulated phase shift.

Figure 4 shows the scanning electron microscopy (SEM) images of the fabricated modulator. The FACQW waveguide layer structure was grown on an Fe-InP wafer using molecular beam epitaxy and fashioned into a 1×1 cm^2 chip. Multiple devices were created on this chip involving sequential steps like deposition of SiO_2 and resist, pattern formation by electron beam lithography, pattern transfer via reactive ion etching, and embedding waveguides with BCB.

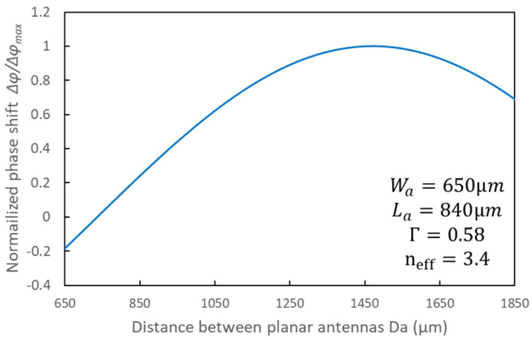

Figure 3. Dependence of normalized phase shift on distance in two antenna elements D_a.

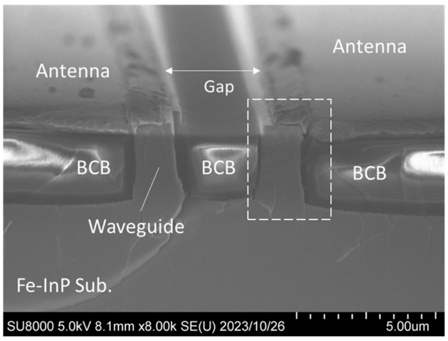

Figure 4. SEM images of cross-sectional view of fabricated device.

3. Modulation characteristics of modulator with two-element array antenna

Figure 5 shows one of the optical spectra of the output from the antenna-coupled optical modulator under the irradiation of 60 GHz band radio signals emitted from a horn antenna. A sideband signal with a CSR of 45.9 dB (λ=1540 nm) at minimum is observed. The RF power density input to the device of $P \sim 11$ W/m^2. The CSR corresponds to a phase shift of 10.1 mrad. The EO coefficient was estimated to be 36×10^{-11} m/V from the estimated wireless signal irradiation power and electric field enhancement factor. This EO coefficient is approximately 2.5 times higher than that obtained in our previous report [3].

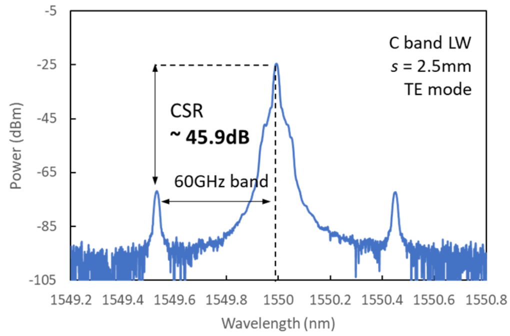

Figure 5. Measured optical spectra of the output from the antenna-coupled optical modulator under the irradiation of 60 GHz band radio signals.

4. Analysis of phase modulation characteristics of four-element array antenna

An array antenna with multiple antenna elements has higher directivity in reception, and at the same time, the amount of phase shift increases as the number of elements increases. In this section, we performed theoretical calculations of the amount of phase shift as a function of the number of elements.

Figure 6 shows the calculated dependence of the phase shift on the number of arrays. The simulation assumes an irradiation power density of 10 W/m^2 and an electric field enhancement factor of 669. For the electrooptic coefficient and carrier density, we used the values for which the best characteristics were obtained in Ref. [4]. A phase shift of approximately 0.67 rad is obtained for the 4-array antenna, which is approximately 4 times larger than that of a single-element antenna. The phase shift corresponds to the CSR of 9.5 dB, which is sufficient for practical use in digital communication systems. As the number of arrays is increased, the phase shift increases linearly.

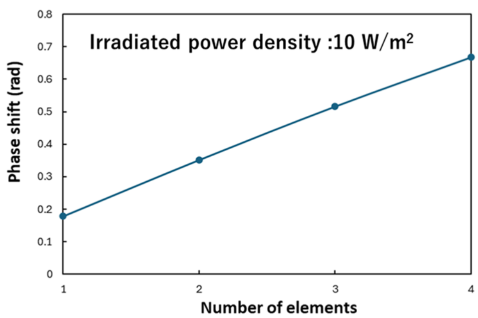

Figure 6. Calculated phase shift as function of number of antenna elements.

However, since the four-array antenna is highly directional, it is still under investigation whether the same magnitude of the electric field is applied to each antenna element. The electric field enhancement factor can also vary with the thickness and size of the substrate.

5. Conclusion

A novel two-element planar array antenna-coupled InGaAs/InAlAs FACQW optical phase modulator, designed for the 60 GHz-band millimeter-wave wireless signals, was demonstrated. These FACQWs are engineered to achieve a substantial change in refractive index when exposed to minimal electric fields generated by the antenna. In the fabricated modulator, a carrier suppression ratio (CSR) as low as 45.9 dB was achieved at a power density of 11 W/m^2, correlating to a phase shift of 10.1 mrad. The electrooptic coefficient for the FACQW is calculated at 36×10^{-11} m/V, which is ten times greater than that of $LiNbO_3$. Additionally, the phase shift characteristics of a four-element array antenna modulator were analyzed, showing an expected phase shift of 0.67 rad under an irradiation of 10 W/m^2.

Acknowledgements

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