Millimeter-Wave D-band Antenna-Coupled Electrode Electro-Optic Modulator

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Abstract

A new antenna-coupled electrode electro-optic (EO) modulator for direct conversion from D-band wireless signals to optical signals is analyzed and designed. In this EO modulator, the modulation efficiency in the D-band is increased by using the stacked structure of a thin $LiNbO_3$ film and fluorine-based resin substrate. In the simulation, modulation electric field of about 2500 times larger than received D-band wireless signal on the antenna surface was observed along the resonant standing-wave resonant electrode, which enables to have an effective signal conversion from D-band wireless to optical signals.

1. Introduction

In recent years, the fifth generation (5G) wireless mobile communication system using millimeter wave (MMW) has been launched in a lot of countries [1]. Since MMW is affected by a large propagation loss in both free space and metal cables, the radio-over-fiber (RoF) technology is useful for low-loss MMW signal transfer by converting MMW radio signals into optical signals and transmitting them over an extremely low-loss silica optical fiber (~0.2 dB/km at λ = 1.5 μm) [2-4]. In the future mobile systems for the beyond-5G communications, wireless carrier frequency will be shifted to the higher frequency band of the THz. Therefore, the importance of the RoF technology will be increased furthermore.

We have proposed and developed the passive antenna-coupled electrode electro-optic (EO) modulators which can convert wireless signals into optical signals directly without external power supply [5-7]. These devices are useful as signal converters in RoF systems for 5G mobile systems. In this paper, we report on the new design of an antenna-coupled electrode EO modulator operating in the D-band for the beyond 5G applications.

2. Antenna-Coupled Electrode EO Modulator

Figure 1 shows the structure of the D-band (~120 GHz) antenna-coupled electrode EO modulator. A pair of patch antennas and a standing-wave resonant modulation electrode are coupled by use of microstrip lines to form the antenna-coupled electrode. The antenna-coupled electrode is sandwiched between a $LiNbO_3$ crystal film (thickness t_{LN} = 10 μm) and a low dielectric constant fluorine-based resin (thickness t_F = 30 μm) substrate as shown in Fig. 2. A single-mode optical waveguide is fabricated along the resonant electrode on the reverse side of the $LiNbO_3$ crystal film. Therefore, this device is an optical phase modulator based on the Pockels effect in $LiNbO_3$ crystal as an optical device.

When an MMW (~120 GHz) wireless signal is irradiated to the antenna-coupled electrode EO modulator from above, a strong electric field is induced on the surface of a standing-wave resonant electrode owing to the mutual resonant effect of the antennas and electrode [5]. The amplitude of the induced electric field along the electrode is to be thousand times stronger than the MMW electric field received by the antenna adopting the matching conditions of the resonant frequency, input impedance and resonator Q-factor. By using this strong electric field for the modulation of optical waves propagating in the optical waveguide, MMW radio signals can be converted into optical signals without external power supply [6, 7].

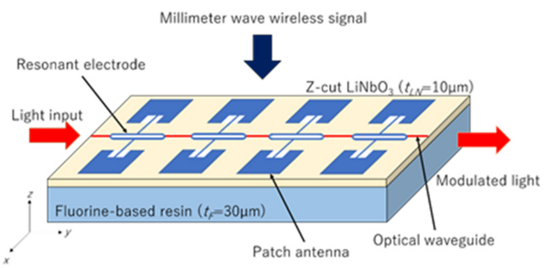

Figure 1. Structure of the proposed D-band antenna-coupled electrode EO modualator.

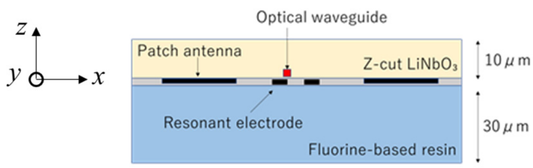

Figure 2. Cross sectional view of the D-band antenna-coupled electrode EO modulator.

3. HFSS Analysis and Design

The operational frequency was set at f = 120 GHz. The antenna-coupled electrode analysis model was formed by connecting the resonant electrode with a resonant frequency of 120 GHz and two patch antennas with a center frequency of 120 GHz through micro-strip lines. Then, 3-dimentional field analysis was conducted using HFSS. Figure 3 shows the designed antenna-coupled electrode model and the calculated electric field distribution when an MMW plane wave signal with x-polarization is irradiated to the antenna-coupled electrode normally. In the Righthand side figure of Fig.3, clear resonance of the received MMW signal is shown along the resonant electrode.

Figure 4 shows the field distribution on the surface of the resonant electrode in Fig. 3 along the y-direction when a 120 GHz plane wave signal with x-polarization is irradiated to the antenna-coupled electrode normally. We can see that the strong electric field of about 2500 times of the irradiated field is induced along the resonant electrode. By utilizing this strong electric field, a passive conversion from MMW wireless to optical signals is possible, we believe, comparing with the calculation and experimental results of our previous antenna-coupled electrode EO modulator operating in Ka- and W-bands [6, 7]. The parameters of the designed antenna-coupled electrode are summarized in Table 1.

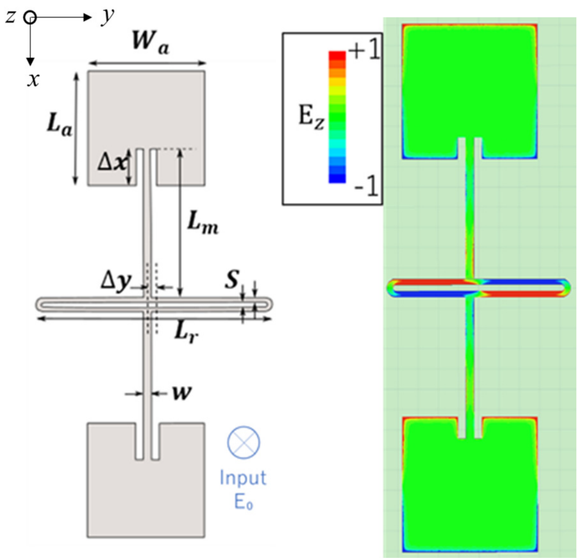

Figure 3. Designed model of the antenna-coupled electrode (Left) and calculated field distribution on the surface of the designed antenna-coupled electrode (Right). The designed MMW wireless frequency of MMW signal is f = 120 GHz.

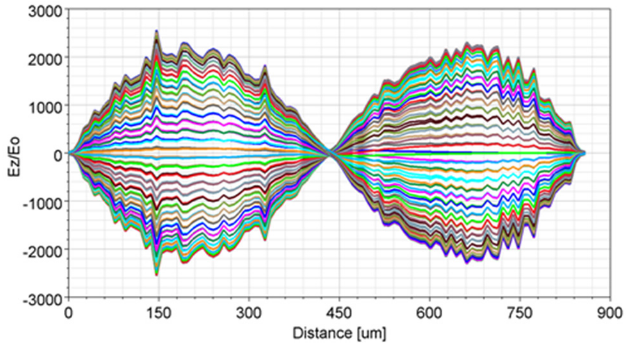

Figure 4. Calculated electric field distribution along the resonant electrode electric field in the designed antenna-coupled electrode when a f = 120 GHz MMW plane wave signal is irradiated to the antenna-coupled electrode.

Table 1. Designed parameters of antenna-coupled electrode for the D-band.

Patch antenna length, L_a	668 μm
Patch antenna width, W_a	668 μm
Microstrip line feeding position, Δx	107 μm
Resonant electrode length, L_r	819 μm
Resonant electrode width, W	30 μm
Resonant electrode gap, S	30 μm
Microstrip line feeding position, Δy	43 μm
Microstrip line width, w	40 μm
Microstrip line length, L_m	700 μm

4. Conclusions

In the designed modulator, a clear resonance effect around 120 GHz was obtained successfully. An MMW electric field of about 2500 times of the wireless signal received at the antenna part was induced at the metal surface of the resonant electrode. With this strong electric field, it is possible to modulate the input light around 120 GHz effectively by using the array structure of the antenna-coupled electrodes as shown in Fig. 1.

We are now trying to fabricate the designed EO modulator for wireless-optical signal conversion in beyond-5G mobile demonstration systems.

Acknowledgements

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