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Improvement of Modulation Efficiency of Electro-Optic Modulators with Gap-Embedded Patch Antenna Utilizing Stacked Structure

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Abstract In this report, we propose new electro-optic modulators using gap-embedded patch antennas with Yagi-antenna-like stacked structure. By utilizing the stacked structure, antenna gain and electric field E_z for optical modulation at the gap are increased with a shift of its resonance frequency toward the higher region. By tuning parameters of the patch antennas, the conversion efficiency from wireless millimeter-wave to lightwave signal is increased about 2 times compared with the modulator of non-stacked structure. The analysis and design of the device are reported.

Keywords Planar Patch Antenna, EO Modulation, Radio-Over-Fiber, $LiNbO_3$

1. Introduction

Recently, traffic volume of wireless communication systems increases drastically owing to widespread smart phones and tablet terminals with newly-coming wireless services. Therefore, millimeter-wave has been attracting a lot of attention because of its potential wide bandwidth of over several GHz. However, millimeter-wave is not suitable for long distance (>10 km) transmission since millimeter wave has a large transmission loss in air. Therefore, radio-over-fiber (ROF) technology is a good solution to connect many cells of a small coverage area in wireless millimeter-wave communication systems.

In millimeter-wave ROF systems, a converter from millimeter to light wave is important. We have proposed several antenna-based optical modulation devices using planner antennas and electro-optic (EO) crystals. In this report, we discuss improvement of modulation efficiency of the device by utilizing a stacked structure.

2. Structure of stacked device

The structure of the proposed device and its cross sectional view are shown in Fig.1. This device has stacked patch antennas using multiple substrates combined with a thin EO crystal ($LiNbO_3$) and a low-dielectric constant material (SiO_2). In the lower level patch, a narrow (~5μm) gap is introduced for optical modulation. When a wireless millimeter-wave signal with *x*-polarization is irradiated to the device from above, a strong millimeter-wave electric field (displacement current) is induced across the gap because of the continuity of the current. Therefore, by settling an optical waveguide close to the gap, the lightwave propagating in the optical waveguide is modulated by the millimeter-wave signal, and the signal conversion from the millimeter-wave to lightwave is obtained.

Utilizing the stacked structure as shown in Fig.1, the antenna gain and electric field across the gap are enhanced, since this structure can be regarded as a Yagi-Uda like antennas; the ground can be considered as a reflector and the patch antenna at the upper layer as a director.

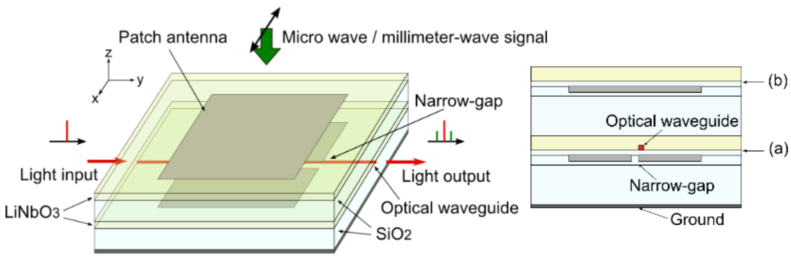

Fig.1. Stacked device structure and its cross section view.

3. Analysis

3.1 Non stacked structure

At first, the non-stacked structure device was designed using 3-D electromagnetic analysis software, HFSS. The designed parameters of the device with a 60 GHz operational frequency were set as follow: low-*k* substrate (SiO_2, ε_{rL} = 4, h_L = 250 μm), EO crystal ($LiNbO_3$, ε_{rx} = ε_{ry} =43, ε_{rz} = 28), gap-embedded patch-antenna (LxW=630x630 μm , gap=5 μm, h_A = 1 μm). The frequency response of the gap field in the single layer device was calculated, which is shown in Fig.2.

The conversion efficiency from millimeter-wave to light wave of the device is proportional to the optical phase modulation depth, $\Delta\varphi$. It can be expressed as

$$\Delta\varphi = \frac{\pi r_{33} n_e^3}{\lambda} \Gamma \int_0^W E_0 \sin\left(n_g\, k_m\, y\right) dy, \qquad (1)$$

where λ and n_g are the wavelength and the group index of lightwave propagation in the waveguide, respectively, r_{33} is the EO coefficient, n_e is the extraordinary refractive index of substrate, Γ is the overlapping factor between the induced microwave electric field and lightwave, and k_m is the wave number of the millimeter-wave in vacuum.

3.2 Stacked structure

The 2 layer stacked device was designed using the same method for the single layer device. The size of the patch metal is set as the same with that of the single layer device. We selected the two case for the upper patch antenna: with a 5 μm gap at the center and without a gap as shown in Fig.1. Fig.3 shows the surface distribution of E_z/E_0 at 67.4 GHz for the structure of Fig.1. The field distributions of E_z/E_0 are mutually in opposite phase between the upper layer and the lower layer. This is the same with the Yagi-Uda antennas. Fig.4 shows the E_z/E_0 at *ll'* in Fig.3 (a). Fig.5 shows the calculated frequency dependences of the magnitude of E_z/E_0 at the gap for the 2 case of the upper patch metal (with / without gap). Utilizing the stacked structure, the resonance frequency became higher and the magnitude of E_z/E_0 increased. It should be noted that we found an interesting characteristic in the design of the stacked structure; both the $LiNbO_3$ layer and the SiO_2 layer are to be stacked for having the stronger electric field. If there is no $LiNbO_3$ layer on the top of the upper layer, the electric field at the waveguide is not so enhanced.

By tuning the resonant frequency to the 60 GHz, the patch length L becomes longer, from 0.63 mm to 0.81 mm at the device whose patch of upper layer has a gap, and the patch length L becomes longer, from 0.63 mm to 0.77 mm at the device whose patch of upper layer has no gap. Fig.6 shows the calculated frequency dependence of the magnitude of E_z/E_0 at the gap at the 60 GHz-tuned 2 layer stacked structures and the single stacked structures. Utilizing the stacked structure, the length of the patch becomes 1.28 times, and E_z/E_0 become 2.0 times at the same resonant frequency. Using the equation (1), we can get the 2.56 times modulation depth of the single stacked one.

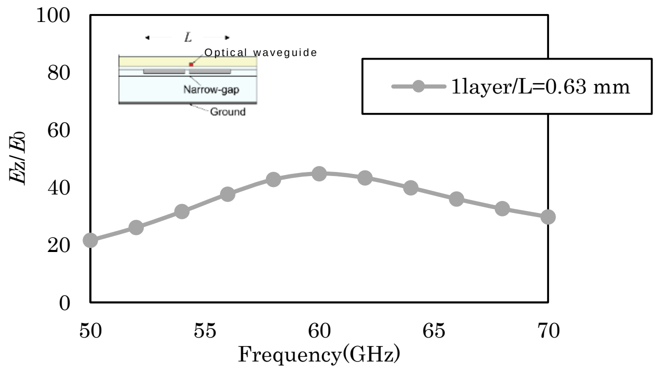

Fig2. Frequency responses of normalized electric field for optical modulation E_z / E_0 in non-stacked devices

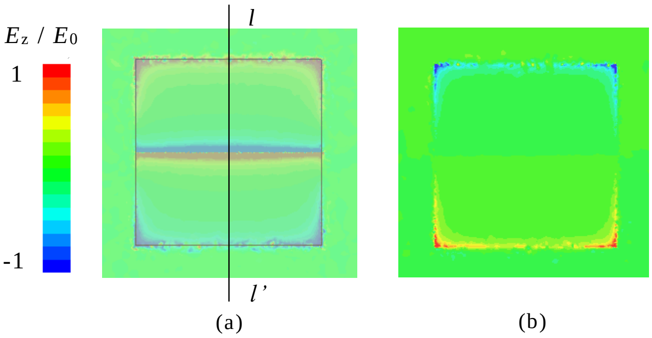

Fig.3 Surface distribution of E_z / E_0 at 67.4 GHz (a) at lower layer and (b) at upper layer.

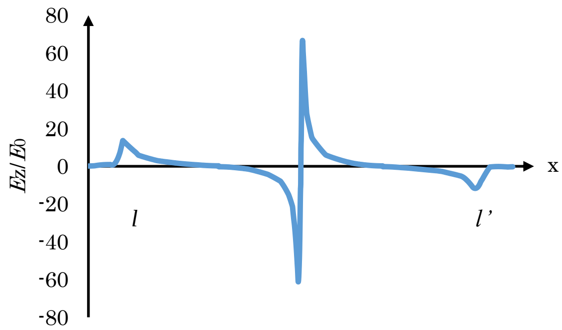

Fig.4 Normalized electric field of E_z / E_0 along *ll'* in Fig.2 (a)

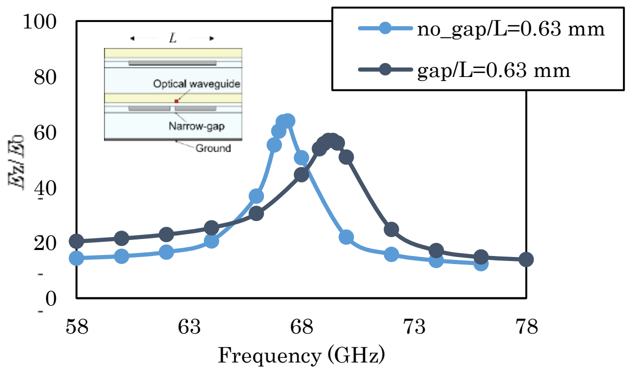

Fig.5 Frequency responses of normalized electric field for optical modulation E_z / E_0 in stacked device with/without a gap at the top patch metal

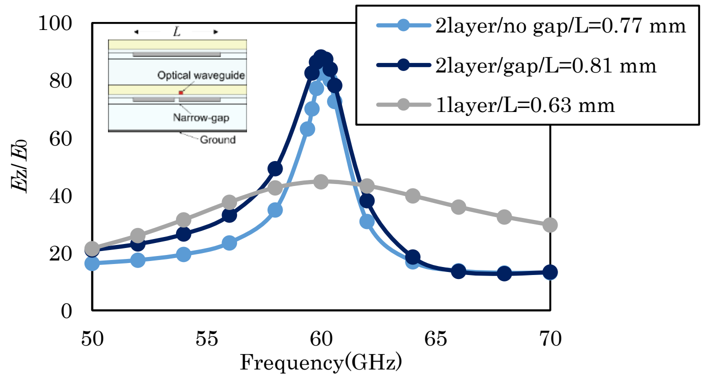

Fig6. Frequency responses of normalized electric field for optical modulation E_z / E_0 in stacked/non-stacked devices

4. Conclusion

In this report, we proposed the electro-optic modulators using the stacked structure of the gap-embedded patch antennas. By stacking the patch antennas with the same size and the same layers vertically, the resonant frequency shifts higher and the magnitude of E_z/E_0 across the gap for optical modulation increases. By tuning the resonant frequency, the patch length becomes longer, and the magnitude of E_z/E_0 becomes larger. These effects are contributed to the improvement of modulation efficiency, and 2.56 times larger efficiency can be obtained.

Now, we are going to fabricate the proposed device. We are also trying to analyze more stacked structure devices.

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References

[1] Y. N. Wijayanto, H. Murata, Y. Okamura ’’High-Speed Guided-Wave Electro-Optic Modulators Using an Array of Gap-Embedded Patch Antennas with Phase Reversal’’ , IEICE Technical Report MWP2011-72, 2012.

[2] O. Kramer, T. Djerafi, K. Wu” Very Small Footprint 60 GHz Stacked Yagi Antenna Array, ”*IEEE Trans. Antennas Propag.* vol. 59, no.9, pp.3204-3210, 2011.

[3] O. Kramer, T. Djerafi, K. Wu “Vertically Multilayer-Stacked Yagi Antenna With Single and Dual Polarizations” *IEEE Trans. Antennas Propag.* vol.58, no.4, pp.1022-1030, 2010.