Electrical-optical Converter Using Electric-field-coupled Metamaterial Antennas on Electro-optic Modulator

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Abstract— We propose an electrical-optical converter using electric-field-coupled metamaterial antennas on an electro-optic (EO) modulator for wireless millimeter-wave/terra-hertz applications. By wireless signal irradiation to the proposed device, strong millimeter-wave/terra-hertz electric field can be induced on the electric-field-coupled metamaterial antennas. The induced electric field can be used for optical modulation through EO effects when a lightwave propagates into an optical waveguide located under regions of the induced millimeter-wave/terra-hertz electric field. Analysis in millimeter-wave and optical modulation of the proposed device are discussed in detail for operational frequency of 100 GHz. Device experiment in fabrication and preliminary measurement are also reported.

1. INTRODUCTION

Radio-over-fiber (ROF) technology is promising for applications to broadband mobile communication, high-resolution imaging, low-induction electromagnetic compatibility measurement, and so on [1, 2]. By using the technology, microwave with high operational frequency for carrying large data size can be transferred through optical fibers with lightwave as a carrier. The required device in the ROF technology is a converter between electrical and optical signal signals. Electrical to optical converters for wireless radio-wave applications using microstrip antennas were proposed [3–6]. The microstrip antennas were fabricated on an electro-optic (EO) crystal such as $LiTaO_3$ or $LiNbO_3$. However, the antenna size has limitation due to very small size in operation to high frequency.

In order to improve the performance for high operational frequency in millimeter-wave or terra-hertz bands, an electrical-optical converters using metamaterial structure can be adopted. The device has small electrical size with compact structure. Interaction between capacitance and inductance of the metamaterial structure is considered to generate strong millimeter-wave/terra-hertz electric fields on the optical crystal for EO modulation. An EO modulator using metamaterial split ring resonator (SRR) for electrical-optical conversion was realized [7].

In this paper, we propose an electrical-optical converter using electric-field-coupled metamaterial antennas on an EO modulator for millimeter-wave/terra-hertz bands. The proposed device is composed of a straight optical waveguide and electric-field-coupled resonators on an EO crystal. Basically, the resonators consist of planar inductance and capacitance for generating strong millimeter-wave/terra-hertz electric field. EO modulation using the induced electric field can be obtained. Meandering-gaps are also adopted to compensate for EO modulation degradation due to transit time effects. Based on that, electrical-optical converter from wireless millimeter-wave/terra-hertz can be obtained. Additionally, the proposed device is easy in design and fabrication with planar structure. The device structure, analysis, and preliminary experiment results for 100 GHz operation frequency are discussed and reported.

2. DEVICE STRUCTURE

Figure 1 shows the basic structure of the proposed electrical-optical converter. Electric-field-coupled metamaterial antennas are fabricated on an EO crystal. A straight optical waveguide is fabricated on the EO crystal and located under the center gap of the electric-field-coupled metamaterial antennas as shown in Figure 1(b) for effective operation to electrical-optical conversion. The proposed device is composed in an array with large number single unit cell of the metamaterial antennas. It has small size as shown in Figure 1(a) with parts of capacitors and inductors. Polarization-reversed structures are required periodically to compensate for degradation of optical modulation due to transit-time effects. They can be realized by adopting meandering gap of the metamaterial antennas as shown typically in Figures 1(b) and (c). Additionally, a buffer layer is inserted between

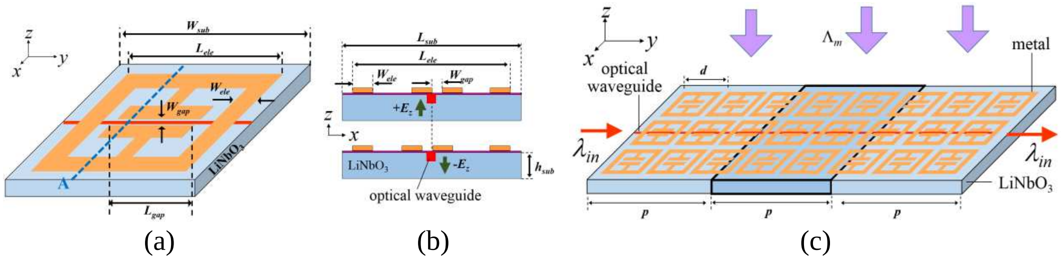

Figure 1: Structure of the proposed device: (a) a unit cell, (b) cross-sectional, and (c) whole views.

the EO crystal surface and the metal layer of the metamaterial antenna to minimize lightwave propagation loss.

When a wireless millimeter-wave signal is irradiated to the proposed device, millimeter-wave currents are induced on the electric-field-coupled metamaterial resonator. Millimeter-wave interaction of inductive and capacitive occurs on the proposed device. As a result, strong electric fields of the millimeter-wave are induced between them. The strong millimeter-wave electric field can be used for changing refractive index of an EO crystal due to the Pockel effects. Therefore, when lightwave propagates to an optical waveguide located close to region of the strong millimeter-wave electric field, optical phase modulation can be obtained. Based on the phenomena, the proposed device can be used for electrical to optical conversion by wireless millimeter-wave irradiation.

3. DEVICE ANALYSIS

The millimeter-wave resonator can be described qualitatively in terms of its equivalent circuit with a capacitor and two inductors [8]. The capacitor is connected in parallel to two loops, which provide inductance to the circuit and couples to the electric field. The electric-field-coupled circuit resonances due to electric field between capacitor and inductors.

The proposed device was analyzed in detail using electromagnetic analysis software. Table 1 shows the device parameters for millimeter-wave analysis. A single unit cell of the metamterial resonator was calculated using periodic boundary condition.

The calculated millimeter-wave characteristics of the reflection (S_{11}) and transmission (S_{12}) for several variations of the parameters are shown in Figure 2. We can see that, operational frequency of the proposed device can be tuned by changing several variations of the designed parameters such as its substrate length in a unit cell, electrode length, and electrode width. The parameter changes contribute for values of capacitances and inductance in the metamaterial structure. The capacitance and inductance values are the main parameter for tuning the resonant frequency operation of the proposed device. Strong millimeter-wave electric field is induced across the gap as the capacitive circuit, it can be used for EO modulation. The designed metamaterial antennas were optimized for 100 GHz frequency operation.

Since the proposed device is an optical phase modulator, modulation efficiency can be used as a measure of the conversion efficiency of electrical-optical signals. The transit-time effect during

Table 1: Design parameters of the proposed device.

Parameter	**Value**
Operational frequency	~100 GHz
Substrate with z-cut $LiNbO_3$ crystal	
• Thickness (h_{sub})	250 μm
Metal with gold material	
• Thickness	1.5 μm
Unit cell	
• Total size (L_{sub})	~250 μm
• Length of the metal (L_{ele})	~190 μm
• Width of the metal (W_{ele})	~30 μm
• Width of the center gap (W_{gap})	10 μm

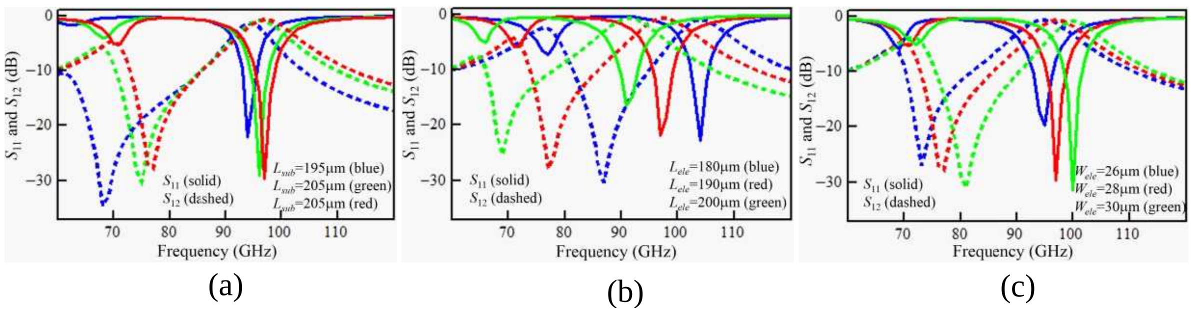

Figure 2: Calculated S11 and S12 characteristics of the proposed devices for variations of: (a) unit cell size (L_{sub}), (b) metal length (L_{ele}), and (c) metal width (W_{ele}).

interaction of the millimeter-wave and lightwave electric fields ($v_g t = y - y'$) is considered for the optical modulation [9]. The modulation efficiency of the proposed device corresponds to the sum of the integration of the millimeter-wave electric field observed by the lightwave. Optical modulation degradation due to the transit-time can be compensated for by polarization-inversed structure. The millimeter-wave and lightwave electric field interaction is periodically changed along the optical waveguide where the distance of the polarization-inversed structure as shown in Figure 1(c) can be expressed as,

$$p = \frac{2\pi}{k_m n_g} \tag{1}$$

where k_m is the wave number of the millimeter-wave in vacuum and n_g is the group index of the lightwave. In this propose device, polarization-inversed structure using simple meandering gap by controlling the position between the optical waveguide and gap edge as shown in Figure 1(b) is used to compensate for the optical modulation degradation.

4. DEVICE EXPERIMENT

The designed device was fabricated experimentally on a z-cut $LiNbO_3$ crystal a thickness of 250 μm. An optical waveguide for single mode operation in 1550 nm was fabricated on the crystal using titanium diffusion method. The titanium film was diffused with 11000°C for 10 hours. After that, silicon dioxide film layer with thickness of about 0.2 μm was deposited on the crystal. Planar metal electric-field-coupled metamaterial resonators were also fabricated on the crystal. The metal with a 1.5 μm-thick gold film were fabricated on the crystal using a thermal vapor deposition, standard photo-lithography, and lift-off technique. The optical waveguide was aligned precisely under one side of the gap edge for effective modulation since the z-cut $LiNbO_3$ crystal is used. A photograph of the fabricated device is shown in Figure 3. Additionally, the fabricated device was polished and cut using dicing machine at the end of the optical waveguide for lightwave coupling. Then, the fabricated device was coupled with optical fibers at the both sides of the optical waveguide ends as shown in Figure 3(c).

The optical waveguides in the fabricated device were coupled with optical fibers with measured insertion loss of about −8 dB. Basic operations of the fabricated device were also experimentally

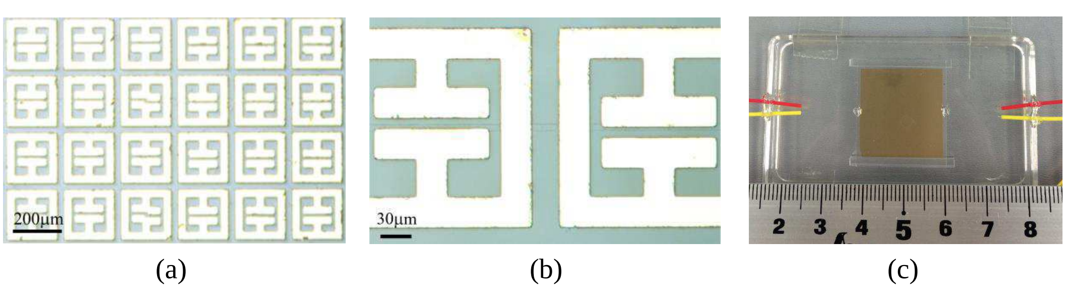

Figure 3: Photograph of the fabricated device, (a) metal resonator by microscope, (b) zoom-view for polarization-inversed structure, and (c) whole device view coupled with optical fibers ready for measurement.

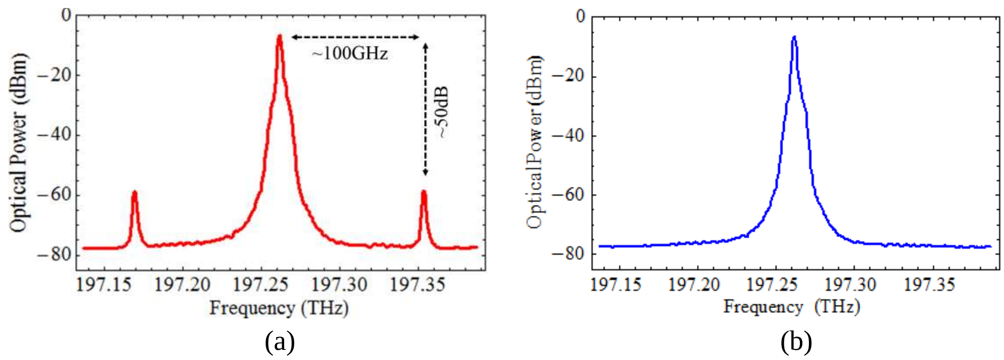

Figure 4: The measured optical spectra of the fabricate device by (a) irradiation and (b) no irradiation of millimeter-wave signals.

measured using simple measurement setup. 1.55 μm-wavelength light from laser was propagated and coupled to a light polarization controller, then connected to the fabricated device. 100 GHz-band millimeter-wave from generator was amplified and irradiated to the fabricated device. The output lightwave were measured using an optical spectrum analyzer. Typical of the measured output light spectra are shown in Figure 4 with and without millimeter-wave irradiation. We can see that clear optical sidebands can be obtained using the fabricated device by 100 GHz millimeter-wave irradiation. The power ratio between optical carrier and sidebands of about 50 dB were obtained using the fabricated device.

5. CONCLUSION

The electrical-optical converter using electric-field-coupled metamaterial antennas on an EO modulator was proposed for millimeter-wave/terra-hertz bands. The proposed device was analyzed and optimized for 100 GHz millimeter-wave bands. The optimized device was fabricated successfully. The fabricated device was measured also for its basic operation for electrical-optical conversion. Clear optical sidebands were obtained by irradiating 100 GHz millimeter-wave. Therefore, the basic operations of the proposed device for electrical-optical conversion were demonstrated successfully. The proposed device has a compact and simple structure, passive operation, and low millimeter-wave loss. Now, we are still attempting to measure the detail characteristics of the proposed device and investigate in further for promising applications.

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REFERENCES

1. Chen, A. and E. Murphy, *Broadband Optical Modulators: Science, Technology, and Applications*, Taylor and Francis Group, CRC Press, North West, 2012.
2. Kanno, A., P. T. Dat, I. Hosako, T. Kawanishi, and H. Ogawa, "Radio-on-terahertz over fiber system for future mobile fronthauling," *2014 IEEE Global Communications Conference (GLOBECOM)*, 2218–2222, 2014.
3. Murata, H., N. Kohmu, Y. N. Wijayanto, and Y. Okamura, "Integration of patch antenna on optical modulators," *IEEE Photonics Society News*, Vol. 28, No. 2, E/O, Apr. 2014.
4. Wijayanto, Y. N., H. Murata, and Y. Okamura, "Electro-optic wireless millimeter-wave-lightwave signal converters using planar Yagi-Uda array antennas coupled to resonant electrodes," *17-th Opto-Electronic Communications Conference*, 5E1-2, Busan, Korea, Jul. 2–6, 2012.
5. Wijayanto, Y. N., H. Murata, and Y. Okamura, "Wireless microwave-optical signal conversion in quasi-phase-matching electro-optic modulators using gap-embedded patch-antennas," *IEICE Transactions on Electronics*, Vol. E96-C, No. 2, 212–219, 2013.

6. Wijayanto, Y. N., H. Murata, and Y. Okamura, "Electro-optic millimeter-wave-lightwave signal converters suspended to gap-embedded patch antennas on low-k dielectric materials," *IEEE Journal of Selected Topics in Quantum Electronics*, Vol. 19, No. 6, Nov./Dec. 2013.
7. Murata, H., J. Nishioka, and Y. Okamura, "100 GHz-band electro-optic modulator using two-dimensional coupled-split-ring resonator array," *19th Optoelectronics and Communications Conference (OECC) and the 39th Australian Conference on Optical Fibre Technology (ACOFT)*, 167–169, Engineers Australia, Barton, ACT, 2014.
8. Schurig, D., J. J. Mock, and D. R. Smith, "Electric-field coupled resonators for negative permittivity metamaterials," *Appl. Phys. Lett.*, Vol. 88, Article No. 041109, 2006.
9. Yariv, A., *Quantum Electronics*, 3rd Edition, Wiley, New York, 1989.