Metamaterial Antenna Integrated to $LiNbO_3$ Optical Modulator for Millimeter-Wave-Photonic Links

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***Abstract*—We report current research progress on a metamaterial antenna integrated to an optical modulator for millimeter-wave-photonic links. The metamaterial antenna is composed by an array of electric-LC resonators on a $LiNbO_3$ optical crystal. Large millimeter-wave electric field is induced across the capacitive gaps of the resonators due to free-space millimeter-wave irradiation. Optical modulation through Pockels effects can be obtained when light propagates along the capacitive gaps. The integrated device is operated effectively by considering interaction between millimeter-wave and lightwave electric fields along the capacitive gaps. Basic operations of the integrated device for 90GHz millimeter-wave bands are reported and discussed. Optical sidebands with carrier-to-sideband ratio of about -60dB by millimeter-wave irradiation power of ~20mW can be experimentally measured using optical spectrum analyzer.**

***Keywords*—Metamaterial antenna; $LiNbO_3$ optical modulator; Pockels effect, millimeter-wave-photonic link.**

I. INTRODUCTION

Recently, mobile communication is commonly used for transferring data to smart electronic devices in microwave bands [1]. Demands to high quality data and high-speed data transfer are always required. Additionally, the smart electronic devices in large numbers are developed and produced with several interesting features to user satisfaction. In order to overcome the requirement, the mobile communication networks should be improved with large bandwidth allocation. Since microwave bands have limited spectrum resources and used for several applications, sharing microwave spectrum with cognitive radio techniques or open new spectrum in millimeter-wave bands are promising for increasing operational bandwidth [2][3].

In the millimeter-wave bands, large operational bandwidth and high-speed operation can be obtained. However, they have large propagation loss in the free space and metal cables [4]. By considering characteristics of the millimeter-wave bands, short coverage (free-space) links can be coupled to photonic links using optical fiber links with lightwave carrier. The optical fibers have extremely low propagation loss, huge operation bandwidth, and immune to environmental noises [5]. Therefore, the demands for mobile communication can be met using millimeter-wave-photonic links.

In the millimeter-wave-photonic links, millimeter-wave antennas and high-speed optical modulators are required for free space millimeter-wave downlink and modulating it to lightwave carrier. Combinations of wireless antennas and optical modulators were studied with discrete, integrated, and fusion structures [6]–[8]. Their basic operations for optical modulation by free-space microwave/ millimeter-wave irradiation were investigated experimentally. These research activities are still interesting for further investigation to achieve high efficiency and simple configuration.

In this paper, we introduce a metamaterial antenna integrated to an optical modulator for operation to 90GHz millimeter-wave bands. The metamaterial antenna consists an array of electric-LC planar resonators on a $LiNbO_3$ optical crystal as the substrate. Large millimeter-wave electric field can be generated by free-space millimeter-wave irradiation. The millimeter-wave electric field can be used for optical modulation through Pockels effects can be obtained when light propagates along an optical waveguide located close to capacitive gaps. This integrated device has very simple and compact structures and operated with passively no additional electrical supply.

The detail structure and analysis of the metamaterial antenna and $LiNbO_3$ optical modulator are described and discussed. Current research progress in the device experiment for 90GHz millimeter-wave bands is also reported.

II. METAMATERIAL ANTENNAS

Figure 1 shows a proposal structure of the metamaterial antenna. It is fabricated on a $LiNbO_3$ optical crystal as the substrate. The $LiNbO_3$ optical crystal has relatively large dielectric constant. The metamaterial antenna using an array of electric-LC planar resonators is fabricated on the substrate using a metal gold material. A thin SiO_2 film is inserted between the metal and substrate as a buffer layer. There is no ground metal electrode on the reverse side of the substrate.

The proposed metamaterial resonators are composed mainly with inductive-capacitive (LC) circuits in planar structures. By considering values of inductance and capacitance in the circuits, resonant operational frequency can be designed [9]. When free-space millimeter-wave is irradiated

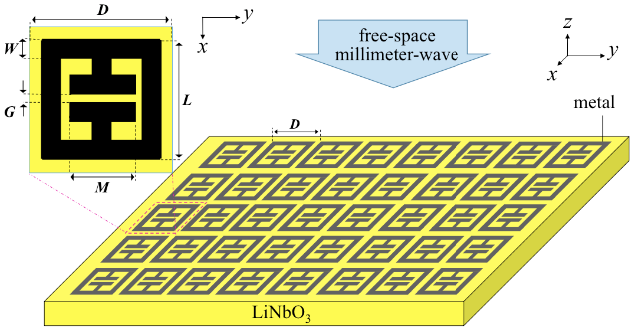
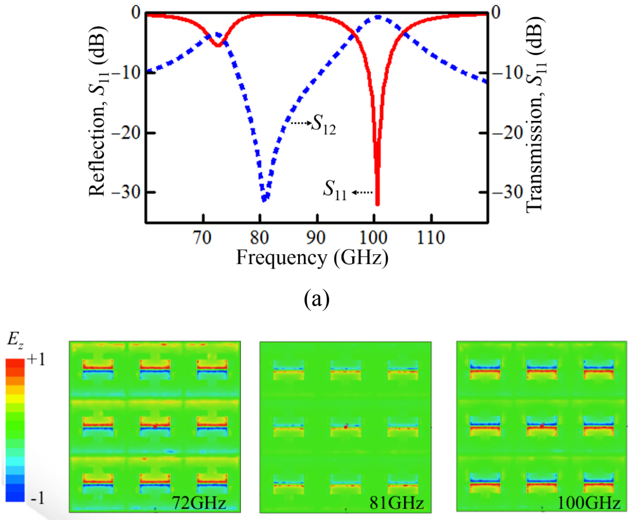


Fig. 1 Metamaterial antennas on $LiNbO_3$ optical crystal.



(a)

(b)

Fig. 2 (a) The calculated reflection and transmission characteristics of the designed metamaterial antennas and (b) the calculated millimeter-wave electric field distribution on the substrate surface for several operation frequencies.

to the proposed metamaterial antenna, the LC circuits interact. Effective performance can be achieved at the resonant operational frequency. As a result, effective reflection and transmission characteristics of the resonator can be obtained. Therefore, large millimeter-wave electric field is induced along the capacitive gaps. This electric field can be used for electro-optic modulation, it will be discussed in next section.

We have analyzed the proposed metamaterial antenna using 3-D electromagnetic analysis software with following parameters: 300µm-thick $LiNbO_3$ optical crystal as the substrate, 0.2µm-thick SiO_2 film as the buffer layer, and 1.5µm-thick gold material as the metal electrode. The unit cell of the electric-LC resonators as shown in Fig. 1 were set to following parameters: the unit cell size (*D*) of ~210mm^2, the outer metal electrode length (*L*) of ~190µm with a square form, the metal electrode width (*W*) of ~30µm, the capacitive gap length (*M*) of ~110µm and the capacitive gap width (*G*) of ~10µm. In simulation, the unit cell of electric-LC resonators with master and slave boundary and floquet excitation port was assigned for infinite resonator number in an array.

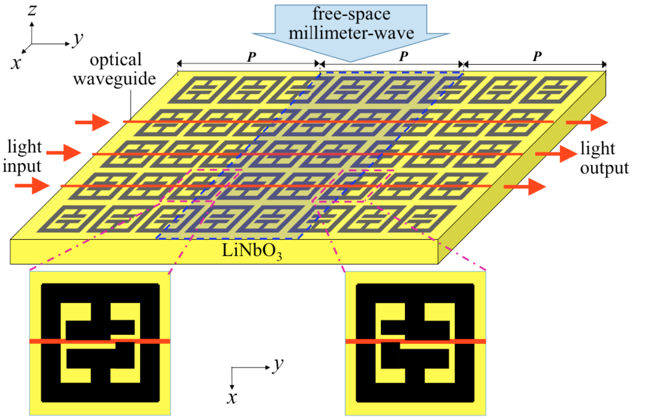


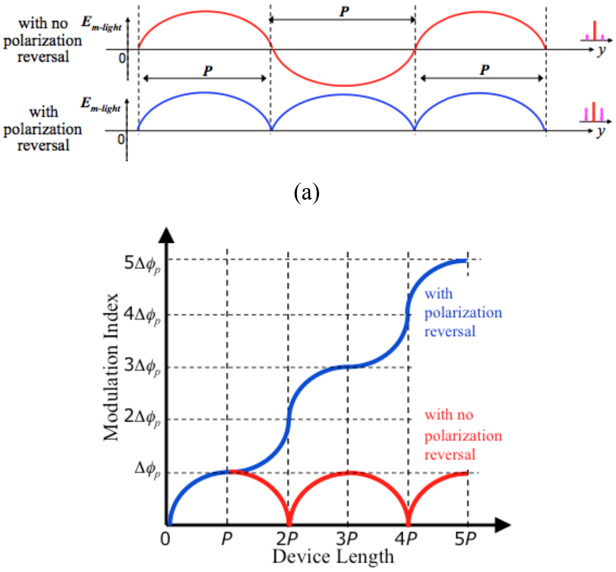
Fig. 3 $LiNbO_3$ optical modulator using metamaterial antennas with meandering capacitive gaps.

Characteristics of the designed metamaterial antennas are shown in Fig. 2 for reflection (S_{11}) and transmission (S_{12}) parameters. We can see that the designed metamaterial antennas are operated for ~90GHz millimeter-wave bands. The calculated millimeter-wave electric field distributions are shown in Fig. 2(b) for several operational frequencies. We can see that there are interactions between the LC circuits. Among the calculation results, the strongest millimeter-wave electric field is induced along the capacitive gaps for 100GHz operation frequency with extremely weak electric field coupled to neighbor unit cells. Based on that, it can be used effectively for electro-optic modulation.

III. $LiNbO_3$ OPTICAL MODULATOR

Based on characteristics of the metamaterial antennas on a $LiNbO_3$ optical crystal in previous section, this structure can be adopted for electro-optic modulation. In order to realize it, the device structure is slightly modified as shown in Fig. 3. We introduce a straight optical waveguide located close to the strongest induced millimeter-wave electric field regions as shown in Fig. 3. We also introduce periodic polarization reversal on the electro-optical modulator for optical modulation compensation due to transit time of lightwave. The polarization reversal using simple meandering capacitive gaps are used as shown in Fig. 3 with a distance of *P*.

Transit time of lightwave propagating to the optical waveguide should be considered to compensate for optical modulation degradation as shown in Fig. 4. Fig. 4(a) shows the interaction between millimeter-wave and lightwave electric field along the optical waveguide with and with no polarization reversal. In order to compensate for optical modulation degradation periodic polarization reversal is necessary to adopt. The distance of the periodic polarization reversal (*P*) can be expressed as,



(a)

(b)

Fig. 4 Millimeter-wave electric field observed by lightwave (a) and its modulation index (b).

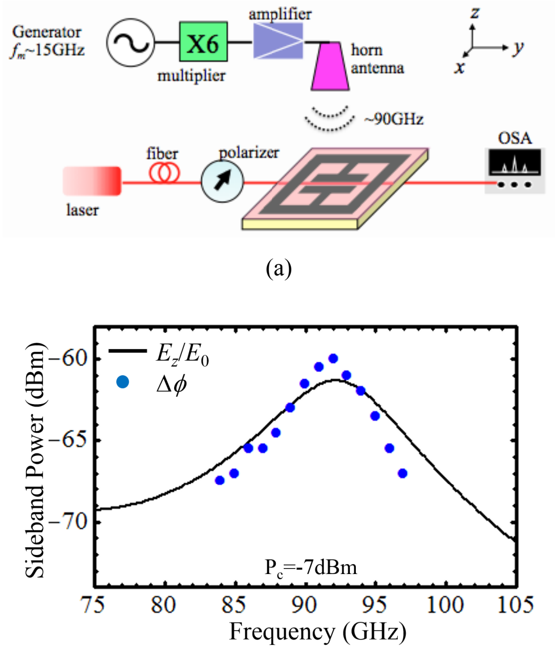
$$2\pi = Pk_m n_g \tag{1}$$

where k_m is the wave number of the millimeter-wave in vacuum, and n_g is the group index of the lightwave propagating in the waveguide. The polarization reversal with meandering capacitive gaps is easy to realize. Therefore, effective optical modulation can be obtained using the simple methods to compensate for the degradation due to transit time effects. In total, the modulation efficiency can be illustrated in Fig. 4(a) where the polarization reversal using meandering capacitive gaps are effectively to use.

By considering the deveice analysis of the millimeter-wave electric field strength induced across the capacitive gaps, modulation efficiency of the designed device with periodic polarization reversal (P) of ~0.7mm and total device length of ~20mm can be calculated. The calculated result is shown by solid line in Fig. 5(b).

IV. EXPERIMENT

We have successfully fabricated the designed device using standard fabrication process such as metal deposition, UV lithography, and lift-off etching. Then, measurement for performance of the fabricated device was also done. The measurement setup is shown in the Fig. 5. A 1.55μm-wavelength light from laser was propagated to the fabricated device through a light polarization controller. 90GHz-band millimeter-wave from generator was amplified and irradiated to the fabricated device. The output lightwave was measured using an optical spectrum analyzer.



(a)

Fig. 5 (a) Measurement setup to investigate device performance for receiving free space millimeter-wave and modulate it to lighwave. (b) The measured optical sideband power with optical carrier power of -7dBm under free space millimeter-wave irradiation of ~10dBm.

Optical sidebands were clearly obtained using the optical spectrum analyzer by irradiation of 90GHz millimeter-wave. The ratio of optical carrier and sidebands of ~60dB was measured. Furthermore, the measured optical sideband power as a function of millimeter-wave operational frequency is also reported by dotted curve in Fig. 5(b) when free space millimeter-wave irradiation power of ~10dBm and optical carrier power of ~7dBm. The measurement results have a good agreement to the calculated optical modulation efficiency and the calculation of millimeter-wave electric field strength across the capacitive gaps.

Based on that, the proposed device composed by the metamateral antennas and LiNbO$_3$ optical modulator can be received millimeter-wave and modulated the millimeter-wave to lightwave. The, it can be easy to distribute through optical fibers. Therefore, it can be used for free-space millimeter-wave to lightwave conversion in millimeter-wave-photonic links.

V. CONCLUSION

The metamaterial antenna integrated to an optical modulator was proposed for operation to 90GHz millimeter-wave bands. The current research progress on the device development was reported. Analysis and design of the metamaterial antennas on LiNbO$_3$ optical crystal and optical modulator using the metamaterial resonator were discussed for 90GHz millimeter-wave operation. Simple structures for polarization reversal using meandering capacitive gaps were used to compensate for optical modulation degradation due to transit time of lightwave along the optical waveguide. Optical sideband power of ~60dB was obtained with optical carrier power of ~7dBm. Therefore, optical modulation by free space millimeter-wave using the proposed device can be achieved successfully. The proposed device is important for future microwave-photonic links with high-frequency operation in millimeter-wave or terra-hertz bands. For improvement, high electro-optic coefficient and high antenna gain can be adopted [10] – [12].

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