

Wireless Millimeter-wave to Lightwave Signal Converters Using Simple Planar Antennas on LiNbO₃ Optical Crystal

Y. N. Wijayanto¹, A. Kanno¹, T. Kawanishi¹, H. Murata², and Y. Okamura²

¹National Institute of Information and Communication Technology, Japan

²Graduate School of Engineering Science, Osaka University, Japan

(Invited Paper)

Abstract— We propose wireless millimeter-wave (MMW) to lightwave (LW) signal converters using a simple planar antenna on LiNbO₃ optical crystal. The LiNbO₃ crystal is bonded with low- k dielectric material as the substrate. The simple planar antenna is formed with a rectangular patch antenna with a gap and inserted between the bonded structure. An optical waveguide are fabricated on the LiNbO₃ crystal and located between the gap. The LiNbO₃ crystal has relatively lower dielectric constant compared with a LiTaO₃ crystal. Larger antenna size can be obtained using the LiNbO₃ crystal. Additionally, an electro-optic coefficient of the LiNbO₃ crystal is larger than the LiTaO₃ crystal. Therefore, conversion efficiency enhancement can be achieved using the propose device.

1. INTRODUCTION

The wireless communication has attracted much interest in past decade, owing to its high mobility [1]. Since mobile devices are developed rapidly and high quality data are required, the wireless communication with high capacity should be developed furthermore. In order to enhance the capacity, the operational frequency of the microwave (MW) bands can be increased to millimeter-wave (MMW) bands. By increasing the operational frequency, the bandwidth becomes large. Now, 60 GHz MMW bands are one candidate for future wireless communication. However, the MMW bands have large transmission loss in the air and metal cables [2].

The large transmission loss in metal cable can be solved using optical fibers, where lightwave (LW) is used for carrying MMW signals. Several short coverage wireless links with pico/femto cells are required for solving large propagation loss of the MMW signal in the air. Therefore, optical fiber links are promising to contribute in the high capacity wireless communication. The important device is a converter from wireless MMW to LW signals [3].

We have studied and developed wireless MW/MMW to LW signal converters using patch antennas embedded with narrow gaps [4, 5]. The antennas were fabricated on an electro-optic (EO) crystal such as LiTaO₃ or LiNbO₃. The prototype devices were successfully fabricated on a LiTaO₃ crystal for MW and MMW bands. The LiTaO₃ crystal has relatively high dielectric constant of about 42. Since the dielectric constant of the LiTaO₃ crystal is high, antenna size and interaction length for MW/MMW-LW signal conversion is relatively small and short, respectively [6]. As a result the conversion efficiency is still low. In order to enhance it, a converter with large antenna size and long interaction length can be obtained using an optical crystal with lower dielectric constant. A LiNbO₃ crystal is promising, which has relative dielectric constant of about 28.

In this paper, we propose a wireless MMW to LW signal converters using a simple planar antenna fabricated on a LiNbO₃ crystal. The LiNbO₃ crystal with a thin thickness is bonded with a low- k dielectric material. The proposed device is composed of a straight optical waveguide and patch antenna with a gap. Large antenna size and long interaction length can be obtained. As a result, the conversion efficiency from wireless MMW to LW signals becomes larger. The proposed device has a simple and compact structure. It can be also operated with no external power supply.

2. DEVICE STRUCTURE

Figure 1 shows the proposed wireless MMW to LW signal converter. It is composed of simple planar antennas inserted between a thin LiNbO₃ crystal and low- k dielectric material. The planar antenna is formed using rectangular patch type. The antenna length, L , is set to a half wavelength of the designed MMW signal. The antenna width, W , is set to below one wavelength of the designed MMW signal to avoid unwanted higher order mode effects. A gap in μm -order, G , is introduced at the center of the patch, along y -axis. A straight optical waveguide is fabricated on the reversed side of the thin LiNbO₃ crystal and precisely aligned at the center of the gap. A ground electrode

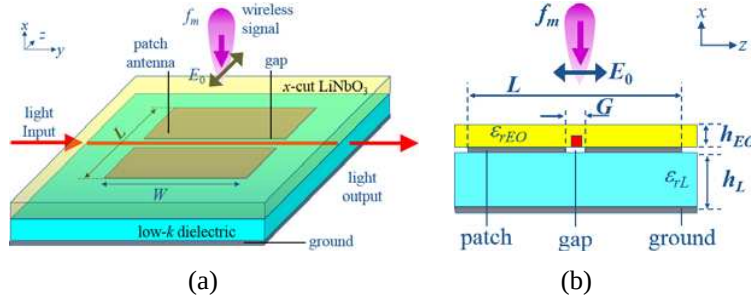


Figure 1: Proposed device structure: (a) whole-structure and (b) cross-section view in the xz -plane.

is covered on the reversed side of the low- k dielectric material. The thin LiNbO₃ crystal, h_{EO} , is required to eliminate the unwanted substrate mode effect in the MMW bands.

When a wireless MMW signal is irradiated to a standard patch antenna with no-gap, a standing-wave current is induced on the patch surface and becomes maximum at the center [7]. Then, a narrow gap is located at the center of the patch perpendicular to the surface current. Since the narrow gap width is used, the antenna characteristic in the proposed device are almost the same with standard patch antenna with no gap. By introducing the gap, a displacement current and strong electric field is induced across the gap for current flow continuity [8]. The strong electric field can be used for optical modulation through the Pockels effect of the LiNbO₃ crystal. A LW propagates into an optical waveguide located at the center of the gap is modulated by the wireless MMW signal. Therefore, wireless MMW signal can be received and converted directly to the LW signal using the proposed device.

Low effective dielectric constant can be achieved using the low- k dielectric substrate bonded with EO crystal. By using a LiNbO₃ crystal, lower effective dielectric constant can be obtained since the LiNbO₃ crystal has relatively low dielectric constant value compared to the LiTaO₃ crystal. Larger antenna size, longer interaction length, larger EO coefficient, and minimize substrate mode can be realized using the proposed device.

3. DEVICE ANALYSIS

An antenna size for receiving a wireless MMW signal can be calculated using the following equation by considering effective dielectric constant of the substrate of ϵ_{eff} ,

$$L = \frac{c}{2f_m \sqrt{\epsilon_{eff}}} \quad (1)$$

where c is the speed of light in vacuum and f_m is an operational frequency of MMW signal. The size of the antenna is inversely proportional to the square-root of the effective dielectric constant. By reducing the effective dielectric constant, the size of the antenna is enlarged. In order to reduce the effective dielectric constant of the substrate for the MMW-LW signal converter, a new device structure using a thin LiNbO₃ crystal bonded with a low- k dielectric material is adopted as shown in Figure 1.

The effective dielectric constant of the proposed device using a LiNbO₃ bonded with low- k dielectric material is expressed as

$$\epsilon_{eff} = \frac{h_L + h_{EO}}{\left(\frac{h_L}{\epsilon_{rL}} + \frac{h_{EO}}{\epsilon_{rEO}} \right)} \quad (2)$$

where ϵ_{rL} and h_L are the dielectric constant and thickness of the low- k dielectric material, respectively, and ϵ_{rEO} and h_{EO} are the dielectric constant and thickness of the EO crystal, respectively. By using a bonded material structure with a thin EO crystal, the effective dielectric constant becomes low.

Analysis of the proposed device are discussed as follow. When a wireless MMW signal at an operational frequency of f_m is irradiated to the proposed device, the standing-wave MMW current is induced along the patch surface. Displacement current and strong electric field are induced across the gap. The induced electric field across the gap can be expressed as,

$$E(t) = E_0 \cos[2\pi f_m t] \quad (3)$$

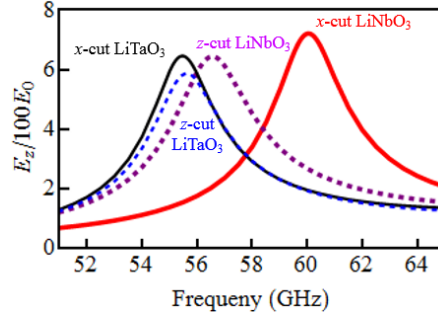


Figure 2: The calculated MMW electric field across the gap for several crystal types.

The induced MMW electric field across the gap can be utilized for optical modulation through the Pockels effect. Therefore, wireless MMW signals can be received and converted directly to LW signals.

The induced electric field across the gap was calculated using electromagnetic software analysis. The optical crystal thickness was set $80\text{ }\mu\text{m}$ and low- k dielectric material thickness was set $130\text{ }\mu\text{m}$ with dielectric constant of 4. The length and width of the patch antenna with aluminum metal were set 0.8 mm . A gap with $5\text{ }\mu\text{m}$ -wide was located at the center of the patch antenna. Ultraviolet adhesive glue as a buffer layer was also inserted between the bonded structures. The calculated electric field across the gap as a function of MMW frequency are shown in Figure 2.

The MMW operational frequency is shifted depends on optical crystal types as shown in Figure 2. The shifted frequency is induced due to change the effective dielectric constant of the proposed device with bonded structure. As we know that the $\text{LiNbO}_3/\text{LiTaO}_3$ crystal are anisotropic crystal with different dielectric constant depends on crystal orientation. The proposed device using x -cut LiNbO_3 crystal has larger induced MMW electric field. Therefore, we expected that the proposed device using x -cut LiNbO_3 crystal has large conversion efficiency.

Since the proposed device is an optical phase modulator, we can take modulation efficiency for optical phase modulation as a measure of the efficiency of MMW-LW signal conversion. It can be calculated by considering the interaction of the MMW and LW electric fields. In order to calculate the modulation index, the transit time effect must be considered since the MMW electric field across the gap changes its phase during the time for the LW propagation. Therefore, the MMW electric field as would be observed by the LW propagating in the optical waveguide can be calculated. The modulation index can be calculated by the integration of the MMW electric field as would be observed by the LW along the gap, which is expressed as,

$$\Delta\phi = \frac{\pi r_{33} n_e^3}{\lambda} \Gamma \int_{\frac{W}{2}}^{\frac{W}{2}} E_0 \cos \left[2\pi f_m \frac{y}{v_g} + \varphi \right] dy \quad (4)$$

where v_g is the group velocity of the LW and φ is the initial phase of the LW, λ is the wavelength of the LW propagating in the optical waveguides, r_{33} is the EO coefficient, n_e is the extraordinary refractive index of the LiNbO_3 crystal, W is the width of the antenna as the interaction length between the MMW and LW signal and Γ is a factor expressing the overlap of the MMW and LW signals.

4. EXPERIMENT

In device fabrication, an optical waveguide was fabricated using the titanium diffusion method on a $500\text{ }\mu\text{m}$ -thick x -cut LiNbO_3 crystal. The antenna with a gap was fabricated using aluminum metal on the LiNbO_3 crystal, where the optical waveguide was set between the gap. On the bottom surface of a low- k dielectric material was covered a ground electrode. For bonding process, an optical adhesive was layered on the top surface of the low- k dielectric material. Then, the LiNbO_3 crystal was flipped over and attached on the low- k dielectric material. Finally, the x -cut LiNbO_3 crystal was polished using diamond slurry to the designed thickness of $80\text{ }\mu\text{m}$ -thick.

The fabricated device was measured experimentally. A MMW was irradiating to the fabricated device and a LW was coupled to the optical waveguide. The LW output was measured by an optical spectrum analyzer. An optical sidebands was obtained clearly as the converted LW signal. The conversion efficiency or modulation efficiency can be obtained by comparing optical powers

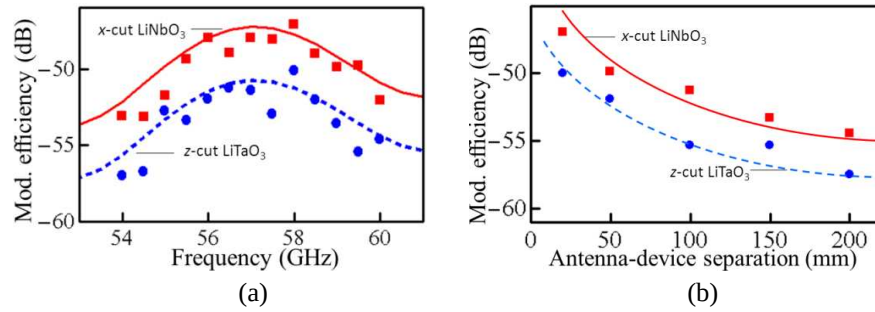


Figure 3: Measured modulation efficiency as functions of (a) MMW operational frequency and (b) separation of the fabricated device and antenna.

between the carrier and sidebands. The modulation efficiency as function of MMW operational frequency and separation between the fabricated device and antenna are shown in Figure 3. The measurement results of the proposed device have good agreements with the calculation results.

Based on the measurement results, the proposed device using the *x*-cut LiNbO₃ crystal has larger conversion efficiency about 3 dB compared with such device using a *z*-cut LiTaO₃ crystal. The device using the *z*-cut LiTaO₃ crystal was reported in detail [5]. Several factors might contribute for the enhancement of the conversion efficiency. First, the LiNbO₃ crystal has relatively larger EO coefficient than the LiTaO₃ crystal. Second, the LiNbO₃ crystal has relatively lower dielectric constant than the LiTaO₃ crystal. Larger antenna size are obtained for improving antenna gain and interaction length. Third, overlapping factor between MMW and LW electric fields might also contribute for conversion efficiency improvement.

5. CONCLUSION

The wireless MMW to LW signal converters using simple planar antennas was proposed. The proposed device was fabricated on a LiNbO₃ crystal bonded with a low-*k* dielectric material. Large antenna size and long interaction length can be obtained. The proposed device in 60 GHz-bands operational frequency was successfully fabricated and measured experimentally. The fabricated device with an *x*-cut LiNbO₃ crystal has 3 dB larger conversion efficiency compared with the *z*-cut LiTaO₃ device. Lower dielectric constant and large EO coefficient of the LiNbO₃ crystal might be contributed to the conversion efficiency enhancement. The conversion efficiency can be enhanced furthermore using low dielectric constant EO polymer with large EO coefficient [9].

ACKNOWLEDGMENT

Authors would like thanks to Dr. H. Shiomi and Dr. K. Kitatani from Osaka University Japan for their constructive comments in discussion and kind supports in experiment.

Y. N. Wijayanto, A. Kanno, and T. Kawanishi would like thank to the Ministry of Internal Affairs and Communications, Japan, for the financial support partly thru the project entitled “Research and Development of high-precision imaging technology using 90 GHz band linear cells” funded by the “Research and Development to Expand Radio Frequency Resources”.

REFERENCES

1. Pi, Z. and F. Khan, “An introduction to millimeter-wave mobile broadband systems,” *IEEE Communications Magazine*, Vol. 49, No. 6, 101–107, Jun. 2011.
2. Shi, J.-W., C.-B. Huang, and C.-L. Pan, “Millimeter-wave photonic wireless links for very high data rate communication,” *NPG Asia Materials*, Vol. 3, 41–48, 2011.
3. Chen, A. and E. Murphy, *Broadband Optical Modulators: Science, Technology, and Applications*, CRC Press, Taylor and Francis Group, North West, 2012.
4. 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 Transaction on Electronics*, Vol. E96-C, No. 2, 212–219, 2013.
5. 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.

6. Gupta, V. R. and N. Gupta, “Characteristics of a compact microstrip antenna,” *Microwave and Optical Technology Letters*, Vol. 40, No. 2, 158–160, 2004.
7. Lee, K. F. and K. M. Luk, *Microstrip Patch Antennas*, Imperial College Press, London, 2011.
8. Gupta, K. C., R. Garg, and I. Bahl, *Microstrip Lines and Slotlines*, Artech House, Inc., Norwood, 2001.
9. Zhang, X., B. Lee, C. Lin, A. X. Wang, A. Hosseini, and R. T. Chen, “Highly linear, broadband optical modulator based on electro-optic polymer,” *IEEE Photonics Journal*, Vol. 4, No. 6, 2214–2228, 2012.