# Wireless Millimeter-wave to Lightwave Signal Converters Using Simple Planar Antennas on $LiNbO_3$ Optical Crystal

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(*Invited Paper*)

**Abstract**— We propose wireless millimeter-wave (MMW) to lightwave (LW) signal converters using a simple planar antenna on $LiNbO_3$ optical crystal. The $LiNbO_3$ 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 $LiNbO_3$ crystal and located between the gap. The $LiNbO_3$ crystal has relatively lower dielectric constant compared with a $LiTaO_3$ crystal. Larger antenna size can be obtained using the $LiNbO_3$ crystal. Additionally, an electro-optic coefficient of the $LiNbO_3$ crystal is larger than the $LiTaO_3$ 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 $LiTaO_3$ or $LiNbO_3$. The prototype devices were successfully fabricated on a $LiTaO_3$ crystal for MW and MMW bands. The $LiTaO_3$ crystal has relatively high dielectric constant of about 42. Since the dielectric constant of the $LiTaO_3$ 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 $LiNbO_3$ 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 $LiNbO_3$ crystal. The $LiNbO_3$ 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 $LiNbO_3$ 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 $LiNbO_3$ crystal and precisely aligned at the center of the gap. A ground electrode

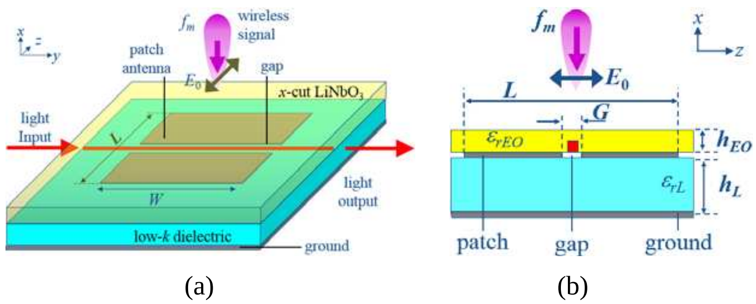


Figure 1: Proposed device structure: (a) whole-structure and (b) cross-section view in the $xz$-plane.

is covered on the reversed side of the low-$k$ dielectric material. The thin $LiNbO_3$ 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 $LiNbO_3$ 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 $LiNbO_3$ crystal, lower effective dielectric constant can be obtained since the $LiNbO_3$ crystal has relatively low dielectric constant value compared to the $LiTaO_3$ 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 $\varepsilon_{eff}$,

$$L = \frac{c}{2f_m\sqrt{\varepsilon_{eff}}} \tag{1}$$

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 conveter, a new device structure using a thin $LiNbO_3$ 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 $LiNbO_3$ bonded with low-$k$ dielectric material is expressed as

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

where $\varepsilon_{rL}$ and $h_L$ are the dielectric constant and thickness of the low-$k$ dielectric material, respectively, and $\varepsilon_{rEO}$ 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,

$$E(t) = E_0 \cos\left[2\pi f_m t\right] \tag{3}$$

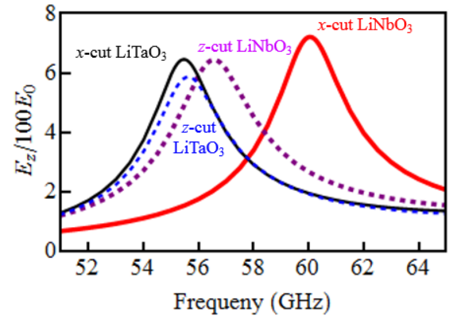


Figure 2: The calculated MMW electric field across the gap for several crystal types.

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 µm and low-$k$ dielectric material thickness was set 130 µm 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 µm-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 $LiNbO_3/LiTaO_3$ 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,

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

where $v_g$ is the group velocity of the LW and $\varphi$ is the initial phase of the LW, $\lambda$ 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 $\Gamma$ 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 µm-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 µm-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

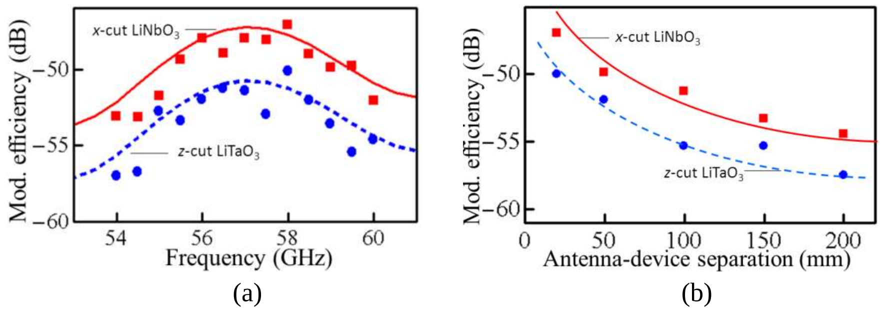


Figure 3: Measured modulation efficiency as functions of (a) MMW operational frequency and (b) separation of the fabricated device and antenna.

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 $LiNbO_3$ crystal has larger conversion efficiency about 3 dB compared with such device using a $z$-cut $LiTaO_3$ crystal. The device using the $z$-cut $LiTaO_3$ crystal was reported in detail [5]. Several factors might contribute for the enhancement of the conversion efficiency. First, the $LiNbO_3$ crystal has relatively larger EO coefficient than the $LiTaO_3$ crystal. Second, the $LiNbO_3$ crystal has relatively lower dielectric constant than the $LiTaO_3$ 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 $LiNbO_3$ 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 $LiNbO_3$ crystal has 3 dB larger conversion efficiency compared with the $z$-cut $LiTaO_3$ device. Lower dielectric constant and large EO coefficient of the $LiNbO_3$ 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".

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