Metamaterial Antenna on Electro-Optic Modulator for Wireless Terra-Hertz Detection Through Radio-Over-Fibre Technology

Yusuf Nur Wijayanto¹, Ashif Aminuloh Fathnan¹², Atsushi Kanno³, Dadin Mahmudin¹, and Pamungkas Daud¹

¹ Research Centre for Electronics and Telecommunication, Indonesian Institute of Sciences, Bandung, Indonesia
² School of Engineering and Information Technology, University of New South Wales Canberra, Australia
³ National Institute of Information and Communication Technology (NICT), Tokyo, Japan

*Corresponding author: yusuf.nur.wijayanto@lipi.go.id

Abstract. We propose a new metamaterial antenna on electro-optic (EO) modulator for wireless terra-hertz detection through radio-over-fibre (ROF) technology. By wireless terra-hertz signal irradiation to the proposed device, strong terra-hertz electric field can be induced on the electric-LC metamaterial resonator. The induced terra-hertz electric field can be used for optical modulation through EO effects when a light-wave propagates into an optical waveguide located under the capacitive gap which the strongest induced terra-hertz electric field. Analysis of optical modulation is presented in details for operational frequency of 0.1 THz. The device fabrication process and the results of its measured characteristics are also reported.

Keywords: metamaterial antenna, electro-optic modulator, terra-hertz, radio-over-fibre

1. Introduction
Recently, wireless radio-wave are used widely with their advantages of easy in operation for many applications such us communication, sensing, imaging, and so on. In communication application based on Cisco’s report, global mobile data traffic will increase sevenfold between 2016 and 2021. Mobile data traffic will grow at a compound annual growth rate (CAGR) of 47 percent from 2016 to 2021, reaching 49.0 exabytes per month by 2021 [1]. Therefore, high-speed communication is required in the future to avoid traffic bottleneck. In sensing application, users always require precise and accurate measurement to make decision quickly [2]. In imaging application, high-resolution image are required and easy to analyse [3]. In order to meet the requirements, wireless radio-wave with high frequency operation is the candidate to anticipate the future problems.

Radio-wave has widely frequency operation bands include terra-hertz bands. The terra-hertz has a frequency ranges in the electromagnetic spectrum which in between microwave and infrared [4]. Terra-hertz wave has large propagation loss in air as shown in Fig. 1 due to environmental condition such as
humidity, rain, snow, smoke, fog, and soon [5]. The propagation loss characteristics of the terra-hertz is also depending on specific operational frequency, some specific frequency in terra-hertz bands has low propagation loss compare the others. Therefore, the specific low propagation loss terra-hertz wave can be considered for communication applications. Furthermore, it can be used for specific short area in applications by considering the drawbacks. The terra-hertz bands are promising for high-speed communication since large bandwidth characteristics and high-resolution imaging with small wavelength operation. In wireless terra-hertz, an important device is a detector of the terra-hertz wave. It can be realized by using an antenna with small size since the terra-hertz wavelength is small.

Figure 1. Wireless terra-hertz propagation loss in the air.

The main drawback of the wireless terra-hertz is large propagation loss in air. In order to overcome the drawback, optical fibre networks can be used to connect between the wireless terra-hertz cells by adopting Radio-Over-Fibre (ROF) technology [6,7]. As we know, optical fibre has extremely low propagation loss for carrying light-wave in several kilometre length. As a result, coverage areas of wireless terra-hertz can be improved furthermore. In this configuration requires a device to convert between wireless terra-hertz and light-wave. Conversion devices using an optical modulator with an antenna for converting wireless radio-wave to light-wave were proposed and reported [8,9]. The conversion devices using discrete, integrated, and fusion configurations with patch antenna and planar Yagi antenna were realized [10-13]. The realized conversion devices were successfully characterized. Basic operations of the conversion devices for converting wireless radio-wave to light-wave were performed. The reported conversion devices are operated in microwave bands by using an antenna with quite large size. In terra-hertz bands, a small antenna is required to detect the wireless terra-hertz wave.

In this paper, we propose and discuss a conversion device from wireless terra-hertz wave to light-wave using metamaterial antennas on an electro-optic (EO) modulator for wireless terra-hertz detection through ROF technology. The proposed conversion device is composed of a straight optical waveguide and metamaterial structure with electric-field-coupled resonators on an EO crystal. Basically, the resonators consist of planar inductance and capacitance for generating strong terra-hertz electric field. EO modulation using the induced electric field can be obtained. Meandering-gaps are also adopted to compensate for optical modulation degradation due to transit time effects. Based on that, the conversion device from wireless terra-hertz wave to light-wave can be obtained effectively.

In the following sections, we will discuss the proposed conversion device structure and analyse its characteristics in detail for 0.1THz operational frequency. The experiments and measurements of the fabricated prototype conversion device are also presented.

2. Device Structure

Figure 2 shows the proposed conversion device from wireless terra-hertz wave to light-wave using metamaterial antennas on an electro-optic modulator. The proposed conversion device is fabricated on
a substrate with an EO crystal such as LiNbO3, LiTaO3, EO polymer, and so on. The proposed conversion device is composed of a straight optical waveguide and planar antennas with metamaterial structures. The optical waveguide is fabricated using titanium diffusion method on the EO substrate. The metamaterial antennas 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 [14]. The metamaterial antennas using an array of electric-LC planar resonators is fabricated on the EO substrate using a metal material. A buffer layer with thin silicon dioxide (SiO2) film is inserted between the metal antennas and EO substrate for avoiding large optical propagation loss and protection. There is no ground metal electrode on the reverse side of the EO substrate. Additionally, polarization reversal with meandering gaps is also considered in this proposed conversion device for effective operation.

![Figure 2](image)

**Figure 2.** Basic structure of the metamaterial antenna on optical modulator: (a) whole structure and (b) a unit cell of the metamaterial structure.

The principle operation of the proposed conversion device for detecting and converting wireless terahertz wave to light-wave is discussed. When wireless terahertz wave is irradiated to the proposed conversion device. The LC circuits of the metamaterial antennas will be interacted. Effective performance can be achieved at the resonant operational frequency by considering parameters of inductance (L) and capacitance (C). As a result, effective reflection and transmission characteristics of the resonator can be obtained. Therefore, large terahertz electric field is induced along the capacitive gaps. This terahertz electric field can be used for EO modulation. When light-wave propagates to the optical waveguide located along to the capacitive gaps, the interaction between light-wave and terahertz electric fields can be occurred. During the light-wave propagation, the light-wave and terahertz electric field interaction should be controlled due to transit-time effect [15]. Effective EO modulation can be obtained by considering the light and terahertz electric field interaction. Therefore, the proposed conversion device can be used for detecting wireless terahertz wave and converting it to light-wave. The detail analysis of those phenomena will be discussed in next section.

### 3. Design and Analysis

#### 3.1. Microwave Analysis

The characteristics of the proposed conversion device in the terahertz frequency operation were analysed in detail by use of electromagnetic field analysis software. To understand the work of metamaterial electric-LC resonator as an antenna receiver for EO modulators, we show the simulated scattering parameters result of the structure in Fig. 3, with the corresponding design parameters are shown in Table 1. It is clearly seen that when a transverse electric (TE) plane wave is irradiated to the structure, a high transmission at specific frequency is detected, in which the EO modulation is expected to work. This transmission is a result of pure electric resonance due to the fact that the capacitive element
of the structure corresponds with parameter of the capacitor gap width couples strongly to the incident electric field.

![Graph showing S-parameters result of simulated Electric-LC Resonators of the metamaterial antenna.](image)

**Figure 3.** S-parameters result of simulated Electric-LC Resonators of the metamaterial antenna.

Furthermore, the symmetry configuration of the resonators revokes the collective magnetic flux, making the structure theoretically having neither magnetic nor magneto-electric responses [16,17]. For the purpose of modulation using Pockels effects, this strong electric resonance without magnetic involvement is most enticing to realize, due to the fact that only local electric fields are needed in changing refractive index of the optical crystal.

**Table 1.** Design Parameters of the proposed conversion device

| Parameters          | Value (μm) |
|---------------------|------------|
| Substrate Width (W_{sub}) | 210        |
| Electrode Length (L_{ele})   | 190        |
| Electrode Width (W_{ele})    | 30         |
| Capacitor Gap (g)          | 10         |
| Capacitor Length (L_{gap})  | 110        |
| Substrate Depth (h)        | 200        |

We further analyzed the proposed structure using 3D electromagnetic simulation and observe that the electric field at the capacitor gap is the higher field across the entire structure. As shown in Fig. 4, the electric field is captured in 2D (x-y and x-z plane). The strong electric field confinements between the capacitor gaps, resulted at the resonance frequency, are the main mechanism to gain modulation effect onto LiNbO3 crystal through the Pockels effects. In Fig. 5, 1D cut of x-y plane at z = 100 μm just below the capacitor gap (y = 0) is also captured, showing the electric field profile across the x-axis.
Figure 4. Electric field distributions (V/m) on the simulated electric-LC resonator at (a) x-y plane (z = 100 μm or just below the buffer layer), (b) x-z plane (y = 0 μm or at the centre of the structure).

Figure 5. Electric profile along x position where y = 0 μm, z = 100 μm.

In order to properly design the frequency operation of the EO modulator, we use a qualitative approach to model the electric-LC resonator by its equivalent circuit. As shown in Fig. 6(a), the electric-LC resonator is described as capacitive element of plate with gap equivalent to a capacitor, connected in parallel to two loops inductive element, equivalent to inductors. This configuration leads to an electric field driven LC-resonance, it can be expressed as following equation.

\[ f_0 = \frac{1}{2\pi\sqrt{LC}} \]  

(3.1)

Accordingly, the resonance frequency or working range of optical modulation can be tuned by ariation to the design parameters. Particularly, by only investigating the role of capacitive element, an effective adaptation to the working frequency can be done by altering the value of \( L_{gap} \) and \( W_{gap} \). Adding the value of the width of capacitor gap (\( W_{gap} \)) can lower its capacitance, thus making the resonance frequency higher. Contrarily, adding the value of its length (\( L_{gap} \)) can increase its capacitance thus decreases resonance frequency. The corresponding graph can be seen from Fig. 6(b).

In the proposed electric-LC resonator, the terra-hertz electric field across the capacitive gap can be expressed as

\[ E_{THz} = E_0 \sin(\omega_{THz}t) \]  

(3.2)

Where, \( \omega_{THz} \) is the wireless terra-hertz signal angular frequency.

3.2. Microwave Analysis

The EO modulation characteristics driven by the terra-hertz electric fields across the capacitive gaps on the metamaterial antennas are discussed also. In order to calculate conversion efficiency (sensitivity) of the proposed conversion device, the terra-hertz electric fields observed by the light-wave propagating in the optical waveguides should be considered by EO effects and by taking into account of the transit-time effect [15].
Figure 6. Equivalent circuit of ELC resonator (a) and S11 of the simulated structure (b) where the value of Lgap and Wgap are varied.

The transformation due the transit-time effect during the light-wave propagation in the optical waveguide can be expressed by \( y^\prime = y - v_g t \), where \( y^\prime \) denotes the point of the light-wave in the coordinate system moving with the light-wave, and \( v_g \) is the group velocity of the light-wave. Therefore, the terahertz electric field observed by the light-wave along the optical waveguide become as

\[
E_{THz-Light} = E_{THz} \left( t = \frac{y - y^\prime}{v_g} \right) = E_0 \sin \left( \frac{\omega_{THz} \left( y - y^\prime \right)}{v_g} \right) = E_0 \sin \left( k_{THz} n_g y + \varphi \right)
\]

where \( k_{THz} \) is the wave number of the terahertz in vacuum (\( k_{THz} = \frac{\omega_{THz}}{c} \)), \( n_g \) is the group index of the light-wave propagating in the optical waveguide (\( n_g = \frac{c}{v_g} \)), \( \varphi \) is an initial phase of the light-wave in the optical waveguide (\( \varphi = k_{THz} n_g y^\prime \)), and \( c \) is the light velocity in vacuum.

The light-wave propagating in the optical waveguide is modulated by the induced terahertz electric field across the capacitive gap through the EO effect. The obtained light-wave from the optical waveguide is optical phase modulation by the wireless terahertz wave. The modulation index, \( \Delta \phi \), can be calculated by taking into account of the overlapping between of the induced terahertz and light-wave electric fields. It is expressed as follows,

\[
\Delta \phi = \frac{\pi r_{33} n_e^2}{\lambda} \Gamma \int_{0}^{P} E_{THz-Light}(y) \, dy
\]

where \( \lambda \) is the light-wave wavelength propagating in the optical waveguide, \( r_{33} \) is the EO coefficient, \( n_e \) is the extraordinary refractive index of the substrate, \( \Gamma \) is a factor expressing the overlapping between the induced terahertz and the light-wave electric field, and \( P \) is the length of the electric field interaction in a one period for effective optical modulation. When the modulation index is smaller than unity, the
conversion efficiency (sensitivity) from the wireless terahertz wave to the light-wave corresponds to the square of the calculated modulation index of the optical phase modulation [18].

\[
\Delta \phi_n = \frac{\pi \varepsilon_{33} n^3}{\lambda} \left( \sum_{n=0}^{\text{even}} \int_0^P E_{THz-Light}^n(y) dy - \sum_{n=1}^{\text{odd}} \int_0^P E_{THz-Light}^n(y) dy \right)
\]

where \( n \) denotes \( n \)-period electric field interaction, \( P \) is the length of the electric field interaction in a one period effective optical modulation.

3.3. Experiment

The proposed conversion device was designed at about 0.1THz operational frequency using a 0.25 mm-thick z-cut LiNbO3 crystal. The size of the electric-LC resonators was calculated using electromagnetic analysis software as shown in the previous section.

In the fabrication process as shown in Fig. 8(a), an EO crystal of z-cut LiNbO3 was prepared as the substrate of the proposed conversion device. A straight optical waveguide was fabricated on the substrate by using titanium diffusion method and effective for operation in 1.55 μm wavelength [19]. A thin SiO2 buffer layer was deposited on the surface of the substrate after the optical waveguide fabrication. Next, electric–LC resonators with a polarization reversal pattern were fabricated using a 1 μm-thick gold metal film on the buffer layer by use of thermal vapor deposition, a standard photolithography technique, and a lift-off process. The edges of the gaps were aligned onto the optical waveguides for effective conversion. The typical pictures of the fabricated conversion device are shown in Fig. 8(a) using microscope. After device fabrication process, the fabricated conversion device was coupled with optical fibres for easy in measurement. The photograph of the fabricated conversion device is shown in Fig. 8(b).
4. Result and Discussion

The characteristics of the fabricated conversion device were measured experimentally with a measurement setup as shown in Fig. 9. A 0.1 THz wireless signal was generated by use of multiplying several time of the microwave signal. The terra-hertz power was improved using an amplifier. Finally, the terra-hertz signal was irradiated to the air using a horn antenna. As a result, the terra-hertz wireless signal can be radiated to the air. Then, light-wave with operational wavelength of 1.55μm from laser were propagated to optical fibres and coupled to the fabricated device. Optical polarizer was inserted between the lasers and fabricated device and set to the z-axis by considering EO crystal orientation. In order to measure the light-wave output, an optical spectrum analyser (OSA) was used to identify the optical carrier and sidebands due to terra-hertz radiation.

The optical waveguides in the fabricated conversion device were coupled with optical fibres with measured insertion loss of about -8dB. The basic operation of the proposed conversion device was measured. Typical of the measured light-wave spectra are shown in Fig. 10 without and with wireless terra-hertz irradiation. We can see that clear optical sidebands can be obtained using the fabricated conversion device by 0.1 THz wireless irradiation. The power ratio between optical carrier and sidebands of about 60 dB were obtained using the fabricated conversion device.

Fig. 11 shows the measured frequency dependence of the terra-hertz wireless irradiation for characteristics of the fabricated conversion device. The experiment result almost coincided with the calculation result. The operational frequency can be tuned furthermore by adjusting the electric-LC resonator of the metamaterial antenna. Based on the experiment results, basic operations of the proposed conversion device were successfully demonstrated. The wireless terra-hertz signal can be received and converted to the light-wave signal directly using the proposed conversion device.

The conversion efficiency or sensitivity can be improved furthermore by considering longer interaction length of terra-hertz wave and light-wave electric fields. In this proposed device, an optical phase modulation was obtained. Therefore, single-sideband modulated light-wave with high power is required for detecting to a photo-detector. It can be realized using a a sharp-cut optical filter and an optical amplifier [20, 21]. The power levels of the optical sideband and the carrier can be set almost the same by tuning the filter characteristics to improve conversion efficiency or sensitivity.

5. Result and Discussion

The conversion device from wireless terra-hertz to light-wave using metamaterial antenna on EO modulator was proposed for terra-hertz wireless detection through ROF technology. The proposed conversion device was analysed, designed, and optimized for 0.1 THz operational frequency. The
designed device was fabricated successfully. The fabricated device was measured also for its basic operation of detection and conversion of wireless terra-hertz to light-wave. Clear optical sidebands were obtained by irradiating 0.1 THz operational frequency. Therefore, the basic operations of the proposed device for the detection and conversion were demonstrated successfully. The proposed device has a compact and simple structure, passive operation, and low terra-hertz loss. The results show that this device is promising for future high-speed wireless communication and extremely low loss electromagnetic compatibility measurement using ROF technology.

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