Optical Modulator Using Channel Optical Waveguides and Planar Patch-Antennas with Gaps

Modulator Optik Menggunakan Pemandu Gelombang Optik Kanal dan Antena *Patch* Planar Bercelah

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Abstract

Optical modulator using channel optical waveguides and planar patch-antennas with gaps on ferroelectric optical crystals were proposed. Basic operations for receiving a wireless microwave signal and directly converting it to a lightwave signal were demonstrated successfully using a prototype device with simple and compact structure. These devices operate with no external power supply and no additional modulation electrode. Therefore the microwave-lightwave conversion with low microwave distortion can be obtained. The advanced microwave-lightwave converters using patch-antennas with a pair of narrow gaps and their applications are also discussed.

Keywords*: optical modulator, patch-antenna, electro-optic effect, radio-over-fiber.*

Abstrak

Modulator optik menggunakan pemandu gelombang optik dan antena *patc*h berstruktur planar dengan celah pada kristal optik *ferroeletric* telah diajukan. Dasar operasi untuk menerima sebuah sinyal gelombang mikro nirkabel dan merubah langsung ke sinyal cahaya telah berhasil didemonstrasikan menggunakan prototipe divais dengan struktur sederhana dan kompak. Divais ini beroperasi tanpa menggunakan tambahan *power supply* dan tanpa tambahan elektroda untuk modulasi. Sehingga, konversi dari gelombang mikro ke cahaya dengan distorsi gelombang mikro yang rendah dapat diperoleh. Konverter dari gelombang mikro ke cahaya yang lebih maju menggunakan sepasang celah sempit dan aplikasinya juga didiskuskian.

Kata kunci: modulator optik, *patch-antena*, efek elektro-optik, *radio-over-fiber*.

I. INTRODUCTION

Radio-Over-Fiber (ROF) is a system where a radio signal is converted to a lightwave signal, and the converted signal is transmitted over an optical fiber link. The ROF systems to facilitate wireless access are attracted much attention with their low loss transmission, no inductance, and low cost [1], [2]. The ROF systems are also attractive for electromagnetic-wave sensing. The conversion of a wireless signal to a lightwave signal is important to support the ROF systems.

Electro-optic (EO) microwave-lightwave converters using antennas and EO modulators are promising devices. Several EO microwave-lightwave converters for wireless applications were reported using integrated structures [3] - [5]. These integrated EO converters are composed of planar antennas, planar modulation electrodes, and their connection lines. Simple compact structures and no external power supply are their advantages. Low microwave distortion can be obtained using these EO converters, if they have a good matching condition between the patch-antennas, the modulation electrodes, and the connection lines. However, precise tunings of them are rather difficult. Therefore, EO microwave-lightwave converters using a planar antenna only with no additional modulation electrode is preferable to eliminating microwave distortion from the other planar structures.

In this paper, we propose optical modulator using channel optical waveguides and planar patch-antennas embedded with narrow gaps. The proposed devices can receive a wireless microwave signal and convert it into an optical signal directly with a simple and compact structure. It is operated with no external power supply, no additional modulation electrode, very-low microwave distortion, and no precise tuning. The device structure, analysis, design, fabrication, experiment and advanced designs are presented and discussed.

II. OPERATIONAL PRINCIPLE

Figure 1 shows the basic structure of the EO microwave-lightwave converter using a patch-antenna embedded with a narrow gap. It consists of an optical waveguide and a square patch-antenna embedded with a narrow gap fabricated on a ferroelectric optical crystal, such as $LiTaO_3$ or $LiNbO_3$. A wireless signal can be received by the patch-antenna and converted to an

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optical signal owing to the narrow gap embedded at the center of the patch-antenna. The channel optical waveguide is located under and along the edge of the narrow gap for effective EO conversion. A buffer layer is inserted between the substrate and the antenna. The reverse side of the substrate is covered with a ground electrode. The length of the patch-antenna is set at half a wavelength for the designed microwave wireless signal.

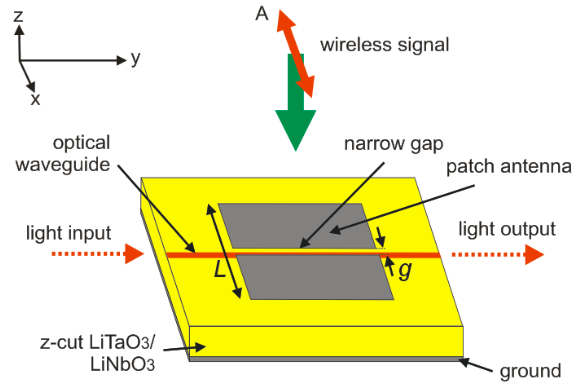

Figure 1. Basic Structure of Patch-Antenna with a Narrowgap.

As its operational principle, when the wireless signal at the designed frequency is irradiated to the antenna, the resonant standing-wave microwave current is induced on the surface of the patch-antenna. The current direction is parallel to the direction of the wireless signal polarization. The current magnitude becomes maximum at the center, while the electric field is strong at the edges of patch-antenna for a standard patch-antenna without a gap. Then, we introduce a narrow gap in a micrometer order at the center of the patch-antenna. The gap is set to be perpendicular to the current direction. In this patch-antenna with a gap, the displacement current is induced across the gap, and the very strong electric field is also induced there. When a lightwave propagates into the channel optical waveguide located under and along the narrow gap, the lightwave is modulated by the induced electric field across the narrow gap. Therefore, the microwave signal is converted to the lightwave signal.

III. ANALYSIS

In a standard microstrip patch-antenna with no gap, the standing-wave microwave surface current can be expressed as,

$$K_{pq}(x,y,t) = K_0 \cos(\omega_m t)\cos\left(p\frac{2\pi}{\lambda_m}x\right)\cos\left(q\frac{2\pi}{\lambda_m}y\right) \quad (1)$$

where p and q are integers indicating modes of the patch-antenna, ω_m is the wireless microwave angular frequency and λ_m is the microwave wavelength [6], [7]. The patch-antenna is usually operated in the fundamental mode (p = 1, q = 0). In this case, the resonant current varies with half a wavelength along the x-direction and there is no variation along the y-direction. Therefore, the standing wave surface current can be expressed as,

$$K_{10}(x,t) = K_0 \cos(\omega_m t)\cos\left(\frac{2\pi}{\lambda_m}x\right) \quad (2)$$

The current distribution and electric field profile of the standard patch-antenna with no gap are shown in Figure 2 (a).

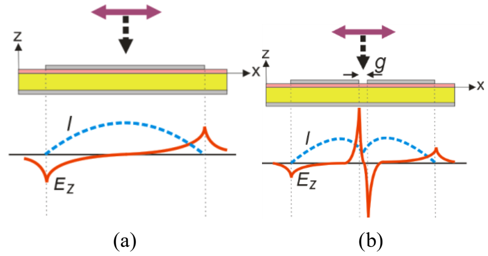

Figure 2. Current Distributions and Electric Field Profiles of, (a) The Standard Patch-Antenna with No Gap, and (b) The Proposed Device.

Next, a narrow gap is introduced at the center of the patch-antenna. Owing to the requirement of the current continuity on the patch-antenna, a displacement current K_d should be induced across the gap. It is expressed as

$$K_d = \frac{\partial D}{\partial t} \quad (3)$$

where D is the electric flux density, $D = \varepsilon E$ and ε is the permittivity. Therefore, the induced electric field across the gap is obtained by the time integration of the displacement current. It can be represented as

$$E_m(x,t) \propto \int K_{10}(x,t)\,dt \quad (4)$$

Therefore $x = 0$,

$$E_m(t) \propto K_0 \sin(\omega_m t) \quad (5)$$

The current distribution and electric field profile of the proposed device are shown in Figure 2 (b).

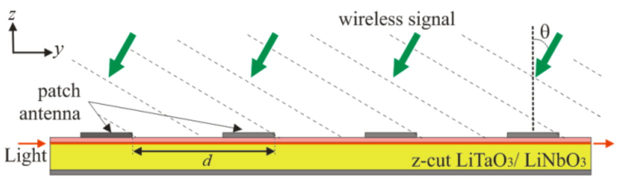

Figure 3. Cross-Section View of an Array of The Patch-Antennas.

A patch-antenna array structure is illustrated in Figure 3, where each patch-antenna has a narrow gap as shown in Figure 1. The induced electric field across the gap E_m^h at h-th patch-antenna can be expressed by,

$$E_m^h(t) = E_0 \sin\left[\omega_m t + d(h-1)k_m n_0 \sin\theta\right] \quad (6)$$

where k_m is the wave number of the microwave in vacuum, n_0 is the refractive index of the microwave along the modulation electrode, d is a distance between patch-antennas, and θ is the wireless signal irradiation angle.

In order to calculate the EO modulation characteristic correctly, the modulation electric field, which is observed by the lightwave propagating in the optical waveguide, should be considered. The induced electric field across the gap observed by the lightwave is obtained by using the transformation of $y' = y - v_g t$, where y' denotes the point of the lightwave in the coordinate system moving with the lightwave andv_g is the group velocity. Therefore, it become as,

$$E_m^h(y) = E_0 \sin[k_m n_g y + d(h-1)k_m n_0 \sin\theta + \phi] \quad (7)$$

where n_g is the group index of the lightwave in the waveguide and ϕ is an initial phase.

The conversion efficiency or modulation index, $\Delta\phi$ can be determined by taking account of the overlapping between of the induced electric field and the lightwave in the cross section. It is expressed as,

$$\Delta\phi(\theta) = \frac{\pi r_{33} n_e^3}{\lambda} \Gamma \sum_{h=1}^{N} \int_{(h-1)d}^{(h-1)d+L} E_m^h(y)\,dy \qquad (8)$$

where λ is the lightwave wavelength, r_{33} is the EO coefficient, n_e is the extraordinary refractive index of the optical waveguide, and Γ is a factor expressing the overlapping between the induced microwave electric field and the lightwave.

IV. DESIGN

The proposed EO microwave-lightwave converter was designed at an 18 GHz microwave frequency using a 0.4 mm-thick *z*-cut $LiTaO_3$ crystal, which has a large dielectric constant, ~42. The length of a square patch-antenna can be estimated using the transmission-line method [6]. The estimated length of patch-antenna was approximated 1.3 mm. Then, the detail characteristics of the patch-antenna embedded with a narrow gap at the center were analyzed using electromagnetic software, HFSS ver. 9. We found that the resonance frequency of the patch-antenna embedded with a gap changes over 10% by the gap-width. The frequency dependences of a 1.4 mm-long square patch-antenna embedded with a narrow gap is displayed in Figure 4, for several gap-width values with the same patch-antenna length. We can see that the effective resonance frequency becomes lower and the peak electric field becomes stronger as decreasing the gap width, clearly.

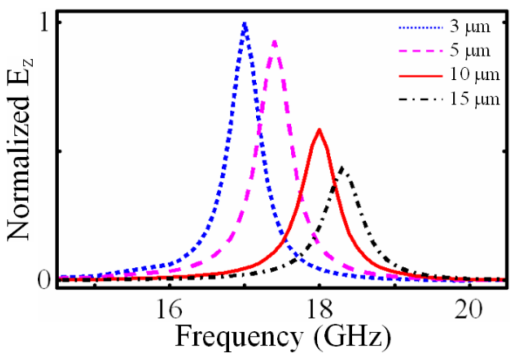

Figure 4. Calculated Frequency Dependences of The Induced Electric Field Across The Gap for Several Gap-Width Values in The Same Patch-Antenna Length.

The optical waveguide was designed for a single-mode operation at a 1.55 μm optical wavelength. A proton exchange method is applied for the optical waveguide design. The channel optical waveguide size was calculated as 2 μm-thick and 4 μm-wide using the Marcatili's method.

The conversion efficiency of the proposed device is a function of the wireless signal irradiation angle, θ. It can be calculated using Equation 8. The calculated directivity of the conversion efficiencies with several antenna distance values are shown Figure 5, where the wireless signal frequency was set at 18 GHz and the gap-width was set at 10 μm. We can see that the directivity can be tuned by the antenna distance like a standard array antenna.

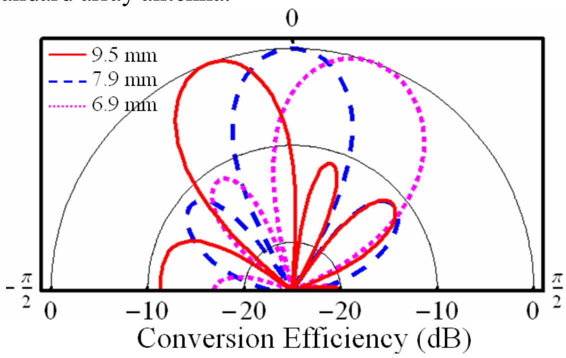

Figure 5. Calculated Directivity for Several Antenna Distance Values.

The parameters of the designed device are summarized in the Table 1, which are used for the fabrication of the prototype device.

TABLE 1
DESIGN PARAMETER FOR THE PROTOTYPE DEVICE.

Parameter	Value
Substrate	
- z-cut $LiTaO_3$, ε_r	42
- Thickness, *h*	0.4 mm
Patch-antennas with a gap	
- Square type	
- Operation frequency, f_m	18 GHz
- Length, *L*	1.4 mm
- Gap-width, *g*	10 μm
- Peak conversion angle, θ	-20 degree
- Element distance, *d*	9.5 mm
- Number of antenna	4
Channel optical waveguide	
- Single mode operation	
- Operation wavelength, λ	1.55 μm
- Core size	2 × 4 μm

V. EXPERIMENT

Based on the design, the proposed device was fabricated using *z*-cut $LiTaO_3$ as a substrate material. First, a straight single-mode channel optical waveguide was fabricated by using the proton-exchange method with benzoic acid. A thin SiO_2 buffer layer was deposited on the surface of the substrate after the proton-exchange process.

Next, square patch-antennas embedded with a gap at the center were fabricated using 1 μm-thick aluminum film on the buffer layer by use of thermal vapor deposition and a standard photolithography technique. The edge of the gap was set onto the optical waveguide for efficient conversion. Thermal annealing process was also done to increase the performance of the optical waveguide. Finally, a 1 μm-thick aluminum film was deposited on the reverse side of the substrate as a ground electrode. The photograph of the fabricated prototype device is shown in Figure 6.

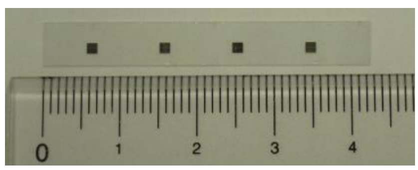

Figure 6. Fabricated Prototype Device.

The measurement configuration is illustrated in Figure 7. The lightwave source was used a Distributed-Feed-Back laser of 1.55 μm wavelength. A wireless microwave signal of +30 dBm from a microwave signal generator was irradiated to the fabricated device using a horn antenna. The light output spectrum was observed and monitored by use of an optical spectrum analyzer.

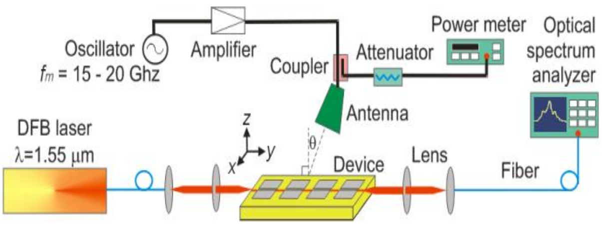

Figure 7. Measurement Setup.

When the microwave irradiation with the linear polarization perpendicular to the narrow gap (*x*-polarization) was irradiated to the device, optical sidebands were observed clearly. It is shown in Figure 8 (a). Figure 8 (b) shows the measured optical spectrum under the irradiation of the microwave with the linear polarization parallel to the narrow gap (*y*-polarization). We can see that no optical sideband was observed for the *y*-polarization microwave irradiation. In this case, weak optical modulations by the electric fields at the two ends of the patch-antenna might be occurred, however they might be cancel-out, since the two electric fields are mutually in opposite polarity.

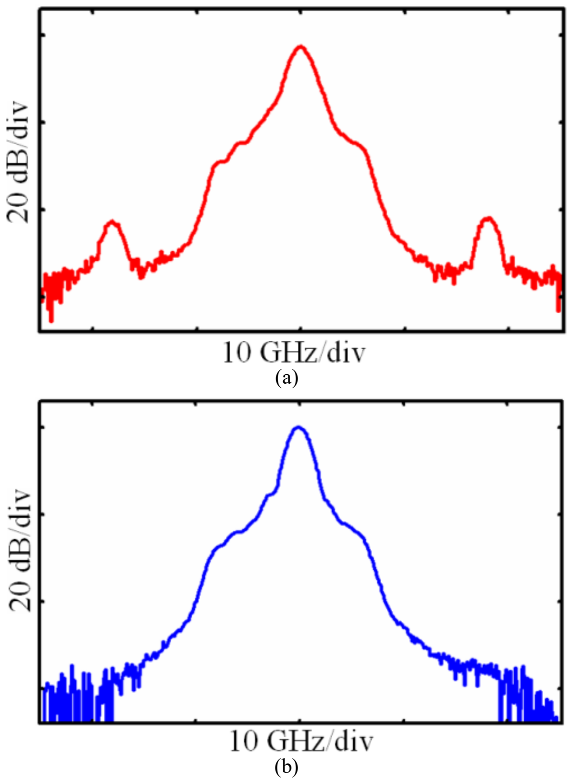

Figure 8. Measured optical spectra under wireless signal irradiation, (a) with *x*-polarization, and (b) with *y*-polarization.

The measured frequency dependence of the conversion efficiency is shown in Figure 9. The measured frequency dependence coincides well with the calculated characteristic using electromagnetic analysis software.

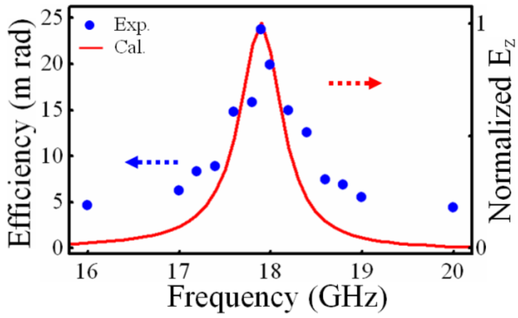

Figure 9. Measured Frequency Dependence of The Conversion Efficiency.

The measured directivity of the conversion efficiency is shown in Figure 10. It is matched to the calculated directivity dependence of the fabricated device.

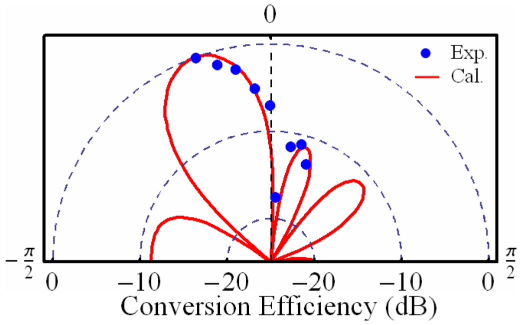

Figure 10. Measured Directivity of The Conversion Efficiency.

The basic operations of the proposed device were successfully verified at the design frequency. Based on the measurement results, the proposed EO microwave-lightwave converter using patch-antennas embedded with a 10 μm-wide gap has been proven to work and operate for optical modulation. The conversion efficiency can be increased further using a many elements (more than 10 elements) in an array antenna structure with a narrower gap (~5 μm). Phase-reversed structures of the patch-antenna or polarization-reversed structures of the ferroelectric optical crystal can be applied for increasing conversion efficiency with short antenna distance along the optical waveguide.

VI. ADVANCED EO CONVERTERS AND APPLICATIONS

A. Patch-Antenna with Orthogonal Gaps

We have been verified that the fabricated EO microwave-lightwave converter using a patch-antenna with a narrow gap can be operated only for the microwave with the polarization perpendicular to the gap. For advanced operations, the new EO microwave-lightwave converter using patch-antennas embedded with orthogonal gaps is proposed. The device structure is shown in Figure 11. It consists of two orthogonal channel optical waveguides and a square patch-antenna embedded with two orthogonal narrow gaps, which should be fabricated on a *z*-cut ferroelectric optical crystal.

Using the new proposed device, two orthogonal polarization components of the wireless signals can be received, separated, and converted to the two lightwave signals independently and simultaneously. The magnitude and phase of the wireless signals can be also observed at the same time. Therefore, this device can be applied for electromagnetic-wave precise measurement.

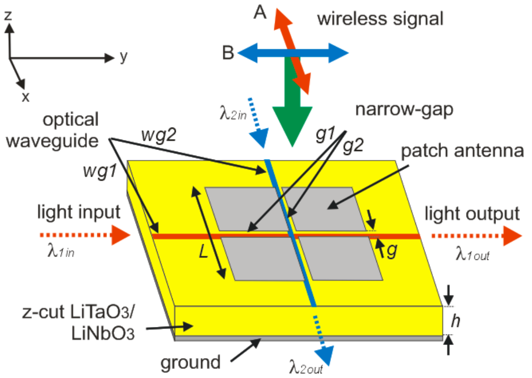

Figure 11. Device Structure of a Patch-Antenna with Orthogonal Gaps.

B. Patch-Antenna with Parallel Gaps

For another advanced operation, an EO microwave-lightwave converter using two parallel optical waveguides and a patch-antenna embedded with two parallel gaps is proposed. The proposed device structure is shown in Figure 12. The induced electric field strength across each the gap of the proposed device is almost the same with the field strength across the single gap at the center of the patch-antenna, if the separation of two gaps is still in order micrometer.

Based on the device configuration, it can be applied for intensity modulator using a Mach-Zehnder structure. The proposed device in an array structure can be used for the wireless Space-Division-Multiplexed (SDM) signal receiver by utilizing polarization-reversed structures [4], [5].

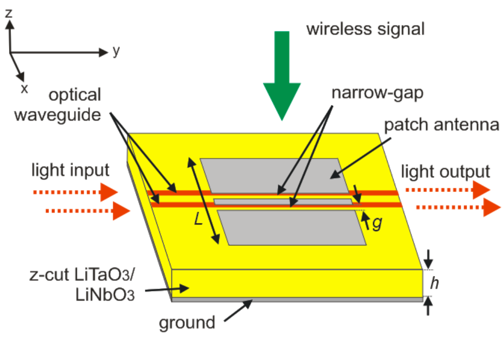

Figure 12. Device Structure of a Patch-Antenna with Parallel Gaps.

Conclusion

The optical modulator using cxhannel optical waveguides and planar patch-antennas embedded with gaps were proposed. The basic operation of the fabricated prototype device was demonstrated and verified successfully. The experimental results are almost matched to the calculation results. The fabricated device consists of only an optical waveguide and patch-antennas embedded with a gap on a ferroelectric optical crystal substrate. Therefore, EO microwave-lightwave conversion with low microwave distortion can be obtained.

The advanced device design was also discussed based on the basic structure of the fabricated device. Dual-polarized EO microwave-lightwave converter using patch-antennas embedded with orthogonal gaps is proposed for electromagnetic-wave measurement. The other advanced design, EO microwave-lightwave converters using patch-antennas embedded with parallel gaps can be applied for wireless-optic communication, such as wireless SDM signals devices with polarization-reversed structures and intensity optical modulators using Mach-Zehnder structures.

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