Discrimination of wireless electromagnetic signals by electro-optic modulators using an array of patch antennas embedded with orthogonal gaps

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Abstract. We proposed a new wireless electromagnetic signal discrimination device using electro-optic modulators and an array of planar patch antennas embedded with orthogonal gaps. Wireless electromagnetic signals can be detected and converted directly to lightwave signals through optical modulation. The magnitude, phase, and polarization of the wireless signal can be measured precisely and identified. By using meandering gap structures, the directivity of the wireless signal conversion can be tuned more precisely. Furthermore, the directivity of the wireless signal conversion in two-dimensional space can also be obtained by comparing two orthogonal modulated lightwave signals from two orthogonal optical waveguides. The design and analysis of the device and experiments at an operational frequency of 26 GHz are presented.

1. Introduction
Wireless-fibre technologies with low power consumption have been developed to establish a sustainable society. Wireless technologies provide convenience, mobility, and flexibility for users [1]. However, the wireless microwave signals are easily affected by environmental noise and high transmission loss. Their allocated bandwidth is relatively narrow. On the other hand, optical fibre technologies provide large bandwidth, low transmission loss, no inductance, and no interference [2]. The combination of wireless microwave and optical fibre technologies has been developed in order to exploit their advantages. The combined technologies can be used for communication, remote sensing, electromagnetic compatibility testing, identification, and so on.
Conversion between wireless microwave and lightwave signals is important in wireless-fiber systems, which can be obtained using optical modulators and optical detectors with microwave antennas. Several converters composed of discrete optical modulators and discrete antennas have been reported [3-4]. The attenuation of the received signal through the cable becomes a problem in high-frequency operation. Electro-optic (EO) converters using antenna-coupled optical modulation electrodes were also proposed for high-frequency operation with low distortion [5-8]. They are composed of antennas, resonant electrodes, and connection lines. Good impedance matching conditions and precise frequency tuning between the planar structures are required in order to obtain effective optical modulation. However, complete matching and precise tuning are rather difficult.
We have proposed EO wireless-optical converters using patch antennas embedded with a narrow gap [9,10]. The devices are composed of only patch antennas and there are no other planar elements on the
substrate. The proposed devices have simple compact structures and are operated with no precise tuning and no external power supply. Optical modulation with extremely low distortion was demonstrated. We have also proposed EO wireless-optical converters using patch antennas embedded with orthogonal gaps for dual-polarized wireless signal detection [11]. However, the modulation index was low owing to the limitation by the lightwave transit-time effect [12, 13].

In the present paper, a new EO modulator using planar patch antennas embedded with orthogonal gaps is proposed for wireless signal discrimination. The modulation index of the proposed devices can be enhanced by approximately three times by adding a number of the patch antennas in array form using a new design for the compensation of the transit-time effects. The magnitude and phase of the wireless signal is obtainable at the same time. The wireless directivity in the one-dimensional (1-D) plane and two-dimensional (2-D) space can also be tuned by meandering gap structures for phase-reversal. Therefore, the wireless electromagnetic signals can be identified and discriminated using the proposed device.

In the following sections, we will discuss the proposed device structure and analyze its characteristics in detail. The preliminary experimental results and advanced measurement setup for identifying wireless signals are also presented.

2. Device structures

![Figure 1](image)

**Figure 1.** (a) Basic structure of the wireless signal discrimination device using a combination of patch antennas with gaps: the entire device structure, (b) the patch antenna with a gap, and (c) the patch antenna with orthogonal gaps.

Figure 1 shows the basic structure of the proposed device, which is fabricated on an EO crystal substrate. The proposed device is composed of two orthogonal optical waveguides, one patch antenna with orthogonal gaps, and four patch antennas with a single gap. The length, $L$, of each patch antenna is set as a half wavelength for the designed wireless electromagnetic signal. The patch antenna with orthogonal gaps is set at the centre of the device, where the size is set to $L \times L$. The patch antennas with a single gap are set surrounding the patch antenna with orthogonal gaps, where the size is set to $L \times W$. The width, $W$, of the patch antennas with a single gap can be set to be longer than a half wavelength but slightly shorter than one wavelength of the microwave signal in order to avoid unwanted higher-order mode effects. The width of the gaps is of micrometer order. The orthogonal optical waveguides are located under the edge of the gaps. A buffer layer is inserted between the substrate and the antennas. The reverse side of the substrate is covered with a ground electrode.
When a wireless signal at the design frequency with an arbitrary polarization is irradiated to the proposed device, a resonant standing-wave microwave current is induced on the patch antenna surface. The induced current can be separated into two components along the $x$- and $y$-axes. In the proposed device, displacement currents are induced across the gap, $G_1$, normal to the $x$-axis and the gap, $G_2$, normal to the $y$-axis, due to the continuity of the current flow. As a result, strong electric fields are also induced across the gaps. The strong electric field across the gaps can be used for optical modulation. Therefore, the wireless signal can be converted to the lightwave signal through optical modulation by the induced electric field across the gaps. The polarization of the wireless signal can also be identified by comparing the two orthogonal modulated lightwaves. Furthermore, the directivity of the wireless signal conversion is precisely controllable using meandering gap structures to compensate for the degradation of the optical modulation owing to the transit-time effect. Therefore, the wireless signals with different irradiation angles can be discriminated through optical modulation using the proposed device.

3. Patch antennas

3.1. Patch antenna with a single gap

The patch antenna with a gap shown in Figure 1(b) is considered. This antenna has a gap, $G_1$, parallel to the $y$-axis. When a wireless electromagnetic signal with a polarization in the $x$-axis is irradiated to the patch antenna with a normal irradiation angle, a standing-wave electromagnetic surface current is induced on the patch antenna along the $x$-axis [14-17]. The induced surface current along the $x$-axis, $K_{xp}$, can be expressed

$$K_{xp}(x,t) = K_{xp} \cos(\omega_m t) \cos\left(\frac{2\pi x}{\Lambda_m}\right),$$

where $K_{xp}$ is the amplitude of the surface current along the $x$-axis, $\omega_m$ is the wireless microwave signal angular frequency, and $\Lambda_m$ is the microwave wavelength. The patch antenna length, $L$, is set to the half wavelength of the wireless electromagnetic signal, when the fundamental mode is induced at the resonant frequency, i.e., $p = 1$. In a standard patch antenna with no gap, the surface current for the fundamental mode becomes maximum at $x = 0$ along the $x$-axis.

In the patch antenna with a narrow gap, the displacement current must be induced across the gap for the current continuity requirement [18-20]. The induced electric field, $E_x$, across the gap is obtained by time integration of the displacement currents as

$$E_x(0,t) = \frac{1}{\varepsilon} D_x(0,t) \propto \int K_{xp}(0,t) dt = K_{x1} \sin(\omega_m t),$$

where $D$ is the electric flux density ($D = \varepsilon E$), and $\varepsilon$ is the permittivity. The strong electric field across the gap can be used for optical modulation. The analysis of the patch antenna with the gap, $G_2$, parallel to the $x$-axis can be obtained using a similar procedure. When a wireless electromagnetic signal with polarization along the $x$-axis is irradiated to the patch antenna, a standing-wave electromagnetic surface current is induced on the patch antenna along the $y$-axis. The standing-wave electromagnetic surface current, $K_y$, along $y$-axis and the induced electric field, $E_y$, across the gap for the half-wavelength patch antennas are expressed as

$$K_y(y,t) = K_{yp} \cos(\omega_m t + \varphi) \cos\left(\frac{2\pi y}{\Lambda_m}\right),$$

$$E_y(0,t) = \frac{1}{\varepsilon} D_y(0,t) \propto \int K_{yp}(0,t) dt = K_{y1} \sin(\omega_m t + \varphi),$$
where $K_y$ is the amplitude of the surface current along the $y$-axis, and $\phi$ is the mutual phase shift between the $x$- and $y$-current components.

An arbitrary polarization of the wireless signal can be also analyzed. The standing-wave current surface can be separated into two components along the $x$- and $y$-axes. Therefore, strong electric fields are induced across the two orthogonal gaps in both patch antennas.

### 3.2. Patch antenna with orthogonal gaps

A patch antenna with two orthogonal gaps is shown in Figure 1(c), the size of which was set to be $L \times L$ for receiving dual polarization wireless signals. When a wireless electromagnetic signal with an arbitrary polarization is irradiated to the patch antenna with a normal irradiation angle, a standing-wave electromagnetic surface current is induced on the patch antenna along the $x$- and $y$-axes. The standing-wave electromagnetic surface currents, $K_x$ and $K_y$, along the $x$- and $y$-axes can be expressed by Equations (1) and (3), respectively. Then, displacement currents must be induced across both gaps in order to satisfy the current continuity requirement. Therefore, the induced electric fields across the gap, $E_x$ and $E_y$, are obtained. These electric fields can be also expressed by Equations (2) and (4), respectively. The strong electric field across the two gaps can be also used for optical modulation.

By measuring the modulation indices and phases, the polarization of the wireless signal can be identified completely.

### 3.3. Numerical analysis

The field distributions on the surfaces of the patch antennas were analyzed using HFSS 3-D electromagnetic field analysis software. Figure 2 shows the calculated electric field distributions on the substrate surface when microwave signals with different polarization conditions are irradiated to the device.

![Figure 2](image)

**Figure 2.** (a) Top view of the patch antenna array. Field distributions in the $z$-component on the substrate surface with the polarization at (b) 0 degrees, (c) 30 degrees, (d) 45 degrees, (e) 60 degrees, and (f) 90 degrees.

First, when the wireless signal with a linear polarization along the $x$-axis (0 degrees) is irradiated to the patch antenna array, as shown in Figure 1(a), a strong electric field is induced across the gap, $G_1$,.
normal to the x-axis and a negligible electric field is induced across the other gap, $G_2$, parallel to the x-axis, as shown in Figure 2(b). When a linear polarized wireless signal with an angle of 30 degrees to the x-axis is irradiated to the device, strong electric fields are induced across both orthogonal gaps, as shown in Figure 2(c). However, the magnitudes of the electric fields across the gaps are different. Then, when a linear polarized wireless signal with an angle of 45 degrees to the x-axis is irradiated to the device, strong electric fields are induced across both orthogonal gaps with almost the same magnitude, as shown in Figure 2(d). Figure 2(e) shows the electric field distribution when the wireless signal with the 60-degree polarization condition is irradiated to the device. The electric field magnitudes along the gaps are the inverse of those for the 30-degree polarization condition. Finally, when the polarization condition of the radiated wireless signal is rotated 90 degrees (along the y-axis), a strong electric field is induced across the gap, $G_2$, normal to the y-axis and a negligible electric field is induced across the gap, $G_1$, parallel to the y-axis, as shown in Figure 2(f). Using these characteristics, the linear polarization condition of the wireless signals can be identified.

Furthermore, when a microwave signal with circular polarization states is irradiated to the device, the induced electric fields across all gaps have the same magnitude but their phases differ by 90 degrees between the x- and y-axes. Therefore, the circular polarization of the wireless signals can be measured using the proposed device.

4. Optical modulation

4.1. Transit-time effect

In order to calculate modulation indices through the EO effect, the microwave electric field that would be observed by the lightwave propagating in the optical waveguides should be considered while taking the transit-time effect into account.

The transformation for considering the transit-time effect for a lightwave propagating in the optical waveguide, $WG_1$, along the y-axis can be expressed by $y' = y - v_y t$, where $y'$ denotes the point of the lightwave in the coordinate system moving with the lightwave, and $v_y$ is the group velocity of the lightwave. Therefore, the microwave electric fields would be observed by the lightwave propagating along the waveguide $WG_1$ at the $h$-th patch antenna in the array structure become

$$E_{\text{opt}}^y(y) = E_x \left( t = \frac{y - y'}{v_{y1}} \right)$$

$$= K_{x0} \sin \left( \omega_n \frac{y - y'}{v_{y1}} + d(h - 1)n_x k_{my} y \sin \theta_1 \right)$$

$$= K_{x0} \sin(k_{m1} n_{x1} y + d(h - 1)n_x k_{my} y \sin \theta_1 + \zeta_1), \quad (5)$$

where $n_{y1}$ is the group index of the lightwave propagating in the waveguide $WG_1$ ($n_{y1} = c/v_{y1}$), $\zeta_1$ is the initial phase of the lightwave in waveguide $WG_1$ ($\zeta_1 = k_{m1} n_{y1} y'$), and $d$ is the distance of each unit cell. Using a similar method, the microwave electric fields that would be observed by the lightwave propagating, $E_{\text{opt}}^y$, along waveguide $WG_2$ in the unit cell device is expressed as

$$E_{\text{opt}}^y(x) = K_{y0} \sin(k_{m2} n_{y2} x + d(h - 1)n_y k_{mx} x \sin \theta_2 + \zeta_2 + \phi), \quad (6)$$

where $n_{y2}$ is the group index of the lightwave propagating in $WG_2$ ($n_{y2} = c/v_{y2}$), and $\zeta_2$ is the initial phase of the lightwave in $WG_2$ ($\zeta_2 = k_{m2} n_{y2} x'$).

4.2. Modulation index

The lightwaves propagating in the orthogonal optical waveguides, $WG_1$ and $WG_2$, are modulated by the induced electric field across gaps $G_1$ and $G_2$ through optical modulation. The phase-modulated lightwaves by the wireless signal are obtained. The modulation indices, $\Delta \phi_1$ and $\Delta \phi_2$, of the phase-
modulated lightwaves can be determined taking into account the overlapping between of the induced electric fields across the gaps and the lightwave in the cross section, which are expressed as:

\[
WG_i : \Delta \phi_i(\theta) = \frac{\pi r_{33} n_e^3}{\lambda} \left[ \int_{-\frac{W}{2}}^{\frac{W}{2}} E_{y_i}^{\text{opt}}(y) dy + \int_{-\frac{L}{2}}^{\frac{L}{2}} E_{x_i}^{\text{opt}}(y) dy + \int_{-\frac{W}{2}}^{\frac{W}{2}} E_{y_i}^{\text{opt}}(y) dy \right],
\]

(7)

\[
WG_2 : \Delta \phi_2(\theta) = \frac{\pi r_{33} n_e^3}{\lambda} \left[ \int_{-\frac{W}{2}}^{\frac{W}{2}} E_{x_i}^{\text{opt}}(x) dx + \int_{-\frac{L}{2}}^{\frac{L}{2}} E_{y_i}^{\text{opt}}(x) dx + \int_{-\frac{W}{2}}^{\frac{W}{2}} E_{x_i}^{\text{opt}}(x) dx \right],
\]

(8)

where \( \lambda \) is the wavelength of lightwave propagating in the optical waveguides, \( r_{33} \) is the EO coefficient, \( n_e \) is the extraordinary refractive index of the substrate, \( \Gamma \) is a factor expressing the overlapping between the induced microwave electric field and the lightwave, and \( L \) and \( W \) are the lengths of the patch antenna.

The modulation indices, \( \Delta \phi_i \) and \( \Delta \phi_2 \), are function of the irradiation angle of the wireless signal, as shown in Equations (7) and (8), respectively. These indices contain information of the irradiation angle of the wireless signal along the \( yz \)- and \( xz \)-planes independently. The 1-D directivities of the wireless electromagnetic signal using the proposed device can be obtained. The directivity can be tuned using meandering gap structures for phase-reversal.

4.3. Phase-reversal

The degradation of the optical modulation can be compensated by phase-reversal by considering the transit-time effect. As a result of the electric field distribution, the direction of the \( z \)-component of the electric field under the gap edge is reversed between the edges. The characteristics of the \( z \)-component can be used for phase-reversed structures. We have proposed an EO wireless-optical converter using quasi-phase-matching array of patch antennas with a gap [13]. The degradation of the optical modulation can be compensated for by shifting the position of the patch antennas with a gap along the optical waveguide. The device has been worked properly to increase the modulation index.

![Figure 3.](image)

**Figure 3.** (a) Patch antenna with a meandering gap, (b) cross-sectional view along line-A, and (c) cross-sectional view along line-B.

Here, phase reversal by meandering gap structures is proposed. The degradation of the optical modulation with tuning for several wireless irradiation angles can be obtained using meandering gap structures. The typical structure of patch antennas with a meandering gap is shown in Figure 3. The cross-sectional views for the structures A and B are also shown in Figures 3(b) and 3(c), respectively. The directions of the electric fields across the optical waveguide are reversed along the \( z \)-component. Therefore, control of the modulation polarity along the optical waveguide is obtainable. These characteristics are very useful for the design of the directivity in the array structures.

5. Experiments

As a preliminary experiment, a prototype device composed of only patch antennas embedded with orthogonal gaps was designed and fabricated. The prototype device was designed at a 26-GHz microwave operational frequency using a 0.4-mm-thick \( z \)-cut LiTaO\(_3\) crystal. The patch antennas were 0.8-mm squares having 5-\( \mu \)m-wide gaps at the centre. In the device, 4x4 patch antennas were aligned with a separation of 5.5 mm.
In the device fabrication, 4x4 channel optical waveguides for single-mode operation at a wavelength of 1.55 µm was fabricated in 12 hours using the annealed proton-exchange method with benzoic acid at 513 K [21,22]. A thin SiO2 buffer layer was deposited on the surface of the substrate after optical waveguide fabrication. Then, patch antennas with gaps were fabricated using a 1-µm-thick aluminium film on the buffer layer by thermal vapour deposition, a standard photolithography technique, and a lift-off process. The edges of the gaps were placed on the optical waveguides for efficient conversion. Thermal annealing at 623 K was also performed for 1 hour in order to increase the optical waveguide performance. Finally, a 1-µm-thick aluminium film was deposited on the reverse side of the substrate as a ground electrode.

In the device measurement, two lightwaves of 1.55 µm in wavelength from a distributed-feedback laser were coupled to the fabricated device. A wireless microwave signal of 200 mW from a microwave signal generator was irradiated to the fabricated device using a horn antenna. The light output spectra were observed and monitored using an optical spectrum analyzer. The measured lightwave spectra are shown in Figures 4(a) and 4(b), when the polarization of the microwave signal was set to 0 degrees (x-polarization). In this case, optical sidebands were clearly observed in the output lightwave from the optical waveguide \( WG_1 \), and no optical sideband was observed from the waveguide \( WG_2 \), as shown in Figures 4(a) and 4(b). Furthermore, Figure 5 shows the measured optical modulation for the wireless irradiation angle dependence. The experimental results approximately coincided with the calculation results.

\[\text{Figure 4. Measured lightwave output spectra from optical waveguides (a) } WG_1 \text{ and (b) } WG_2 \text{ when the wireless electromagnetic signal polarization was set to be 0 degrees.}\]

\[\text{Figure 5. Measured optical modulation for the wireless irradiation angle dependence.}\]

Based on the measurement results, the basic operations of the device were successfully confirmed. The polarization of the wireless electromagnetic signal can be identified. The magnitude of the wireless electromagnetic signal can be also measured. The 1-D directivity of the wireless signal conversion was also measured and confirmed.
6. Advanced device for 2-D directivity

6.1. Design

In order to realize more advanced functionality with 2-D directivity for discriminating space-division-multiplexed (SDM) or multiple-input-multiple-output (MIMO) wireless signals, a new device using an \(M \times N\) array of the proposed device is also proposed, as shown in Figure 6. The device is composed of \(M \times N\) orthogonal optical waveguides and an \(M \times N\) array of patch antennas embedded with gaps, as shown in Figure 1(a) (dashed-line area in Figure 6). The optical waveguide is placed under the edge of the gaps for effective modulation.

![Figure 6](image)

**Figure 6.** Wireless signal discrimination device using \(M \times N\) orthogonal optical waveguides and patch antennas with gaps, where the dashed-line area is as shown in Figure 1(a).

![Figure 7](image)

**Figure 7.** (a) Several patterns of patch antenna arrays with meandering gap structures, where the thick line is \(E^{opt}\) with phase-reversed structures and (b) the calculation results for the proposed device according to the directivity in 1-D using the meandering gap patterns.

When the polarization of the wireless signal at 45 degrees is irradiated to the device with an arbitrary wireless irradiation angle, strong electric fields are induced across all gaps with same magnitude...
strength. The induced electric fields can be converted to lightwaves through optical modulation. Using meandering structures, the degradation of the optical modulation can be compensated for by tuning the directivity. The effective optical modulation function of the irradiation angle of the wireless signal can be obtained by modifying Equations (7) and (8) for several array structures. The electric field that would be observed by the lightwave should be considered.

In the device design, the parameters were set as follows: \( f_m = 26 \) GHz, \( n_o = 1 \), \( n_g = 2.1 \), \( d = 5.5 \) mm, \( L = 0.8 \) mm, and \( M = N = 5 \). First, considering the 1-D directivity of the wireless signal conversion, the patch antennas with meandering gap structures for several wireless signal angles are shown in Figure 7(a). The calculation results with the meandering gap structures are shown in Figure 7(b) for 1-D directivity analysis. The 1-D directivity was analyzed independently along the \( yz \)-plane (\( \theta_2 \)) and the \( xy \)-plane (\( \theta_1 \)).

6.2. Analysis

Based on the designed 1-D directivity of the wireless signal conversion, the 2-D directivity can be obtained by considering the two orthogonal modulated lightwaves. The 2-D directivity can be measured by multiplying or comparing the modulated lightwaves.

Figure 8 shows the typical calculated 2-D directivity of the wireless signal conversion in the \( xy \)-plane for several wireless irradiation angles. The first combination of the two orthogonal modulated lights was set to be effective for the normal wireless irradiation angle, as shown in Figure 8(a). The other combinations of the orthogonal modulated lights for wireless irradiation angle in the \( xz \)-plane (\( \theta_1 \)) and the \( yz \)-plane (\( \theta_2 \)) are shown in Figure 8(b) for \( \theta_1 = \theta_2 = 30 \) degrees and Figure 8(c) for \( \theta_1 = \theta_2 = -15 \) degrees. The proposed device has \( M \times N \) 2-D directivity combinations of the wireless signal conversion, according to the number of orthogonal modulated lightwaves. Therefore, the proposed device can be used for discriminating the wireless electromagnetic signals.

7. Conclusion

The discrimination of the wireless electromagnetic signal by EO modulators using planar patch antennas embedded with orthogonal gaps was proposed. The wireless signal can be received, separated, and converted to a lightwave directly and simultaneously using the device. The directivity of the wireless signal conversion can be tuned by controlling the phase reversal with meandering gap structures. The typical basic operations of the device were demonstrated successfully. The magnitude, phase and polarization of the wireless signals can be measured and identified through optical modulation. The discrimination directivity of the wireless signal in two-dimensional space can be obtained by considering the two orthogonal modulated lightwaves. The proposed device can be applied to SDM/ MIMO wireless signals and electromagnetic compatibility test systems.
At present, we are attempting to demonstrate and measure the performance of the device in wireless-over-fibre links.

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