Chapter

Polarization Modulation

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Abstract

Conventional wireless communication systems use amplitude, frequency, and phase of the carrier wave to carry information. However, actual radio waves also have vector parameters, such as polarization and propagation direction. In this chapter, a modulation scheme using polarizations is explained. The polarization modulation provides an additional degree of freedom for the modulation of the carrier waves. Furthermore, the polarization modulation is suitable to realize simple transceivers using RF signal processing. Antennas are the most important key parts of the polarization modulation systems. Polarization agile antennas, active integrated array antenna which integrates an oscillator and modulators, and polarization discrimination antenna are also introduced.

Keywords: polarization, antenna, polarization modulation communication, polarization discrimination, active integrated array antenna, RF signal processing

1. Introduction

Nowadays, consumer wireless communication systems like a cell phone and wireless local area network (WLAN) are widely used in the world, and they have become an indispensable part of our daily lives. Much higher data rate and higher capacity are strongly required as well as high-frequency utilization efficiency. To meet the requirements, many advanced technologies such as multiple-input, multiple-output (MIMO) and orthogonal frequency-division multiple access (OFDMA) have been developed.

In the classical wireless communication systems, only the time domain parameters such as amplitude, frequency, and phase are used to modulate the carrier wave. However, actual radio waves are vector quantity, and they have spatial parameters like a polarization and direction of propagation. In the next-generation wireless communication systems, utilization of the spatial parameters is essential to achieve higher data rates, larger capacity, and higher-frequency utilization efficiency since the spatial parameters have not been effectively used in traditional wireless communication systems. Recent advanced wireless communication systems utilize a part of these spatial parameters. MIMO and polarimetric radar as well as the traditional polarization diversity are the examples. The massive MIMO technology, which is expected to be employed in the fifth-generation (5G) mobile communication system, is another example. However, these systems require power-consuming digital signal processing. Therefore, RF signal processing technology utilizing the characteristics of the radio wave is expected to realize advanced transceiver module for many wireless applications. To achieve wireless communication systems which effectively utilize the spatial parameters, antenna technology based on the RF signal processing is one of the most important technologies.

In this chapter, the basic concept of the wireless communication system employing a polarization modulation scheme and antenna technology based on the RF signal processing is introduced.

2. Polarization modulation communication

As classic wireless communication systems use the amplitude, frequency, and phase of the carrier wave to carry information, the radio wave is treated as a scalar signal as follows:

$$s(t) = A \sin(2\pi f t + \varphi) \tag{1}$$

where A, f, and φ are the amplitude, frequency, and phase of the carrier wave, respectively. However, the actual radio wave is a vector signal. For example, the electric field of the radio wave is given by

$$\boldsymbol{E}(r, t) = \boldsymbol{E}_0 \sin(2\pi f t - \boldsymbol{k} \cdot \boldsymbol{r} + \varphi) \tag{2}$$

where $\boldsymbol{E}_0$ is the vector amplitude that shows the direction of the electric field, i.e., the polarization, and $\boldsymbol{k}$ is the wave number vector specifying the direction of propagation. Even though the spatial parameters have not been effectively used in classic wireless communication systems, these spatial vector parameters have the potential to realize new wireless systems.

Figure 1 shows the basic concept of the wireless communications using the polarization modulation. The transmitter (TX) antenna radiates radio wave while changing its polarizations between $+45^\circ$ and -45° according to the input binary data. At the receiver (RX), the polarization of the radio wave is detected, and the binary data are recovered. As the binary data can be transferred using the orthogonal polarizations as shown in this figure, the polarization can be used as an additional modulation parameter.

Figure 2 shows a vector diagram of the polarization modulated signal. The $\pm 45^\circ$ polarizations can be decomposed into the x and y components as shown by the red and blue arrows, respectively. As only the y component is changed according to the data, the $\pm 45^\circ$ polarization modulated signal is equivalent to the composition of a binary phase shift keying (BPSK) signal and carrier wave. Therefore, the polarization modulated signals can be generated by simply inverting one of the orthogonal polarizations. As the phase inversion of the signal is easily achieved in RF, the polarization modulation scheme is suitable for RF signal processing and realizing a simple transmitter. The polarization modulation also provides great benefits to receivers. As the carrier wave component is included in the polarization modulated signal and it is transmitted to the receiver, the receiver does not require

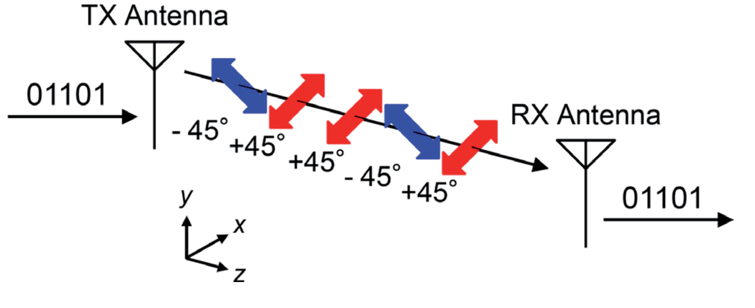

Figure 1.
Basic concept of the polarization modulation communications.

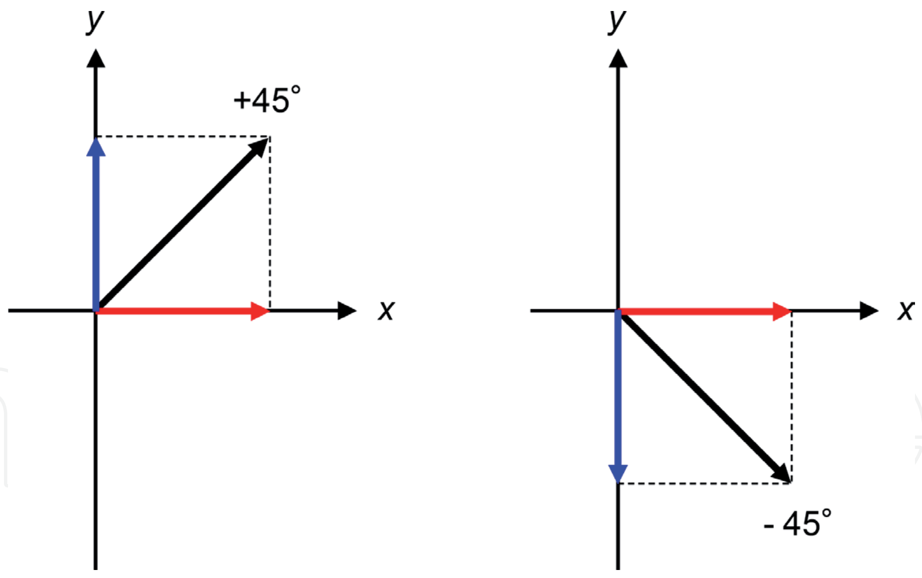

Figure 2.
Vector diagram of the polarization modulation.

carrier recovery circuits, and the phase noise of the local oscillator does not affect the performance of the communication system. The detection in RF with simple receiver configuration is also applicable.

Antennas are one of the key elements to achieve polarization modulation systems because polarizations are generated in antennas. The antennas used in the polarization modulation systems have to switch their polarizations according to the input data. Therefore, polarization agile antennas are required [1, 2].

3. Basics of polarization agile antennas

Basically, any polarizations can be expressed in the sum of two orthogonal polarizations. For example, the electric field propagating along the z-axis can be expressed as follows:

$$\boldsymbol{E}(z,t) = \boldsymbol{i}_x E_x \sin(2\pi f t - kz) + \boldsymbol{i}_y E_y \sin(2\pi f t - kz + \varphi) \tag{3}$$

where $\boldsymbol{i}_x$, $\boldsymbol{i}_y$, E_x, E_y, and φ are the unit vectors of the x and y direction, the amplitude of x and y component of the electric field, and the phase difference between the components, respectively. Eq. (3) expresses elliptical circularly polarized waves in general. When the electric field has only the x or y component, the radio wave becomes a linearly polarized wave. When $\varphi = 0$ or π, the radio wave also becomes a linearly polarized wave. On the other hand, the radio wave becomes a circularly polarized wave when $\varphi = \pm\pi/2$ and $E_x = E_y$.

Figure 3 shows basic configurations of several types of polarization agile antennas. The antenna shown in **Figure 3a** is a linear polarization switchable antenna, and it consists of a switch and dual-polarized antenna which radiates horizontal and vertical polarizations. The polarization modulated signals can be excited by simply switching the horizontal and vertical polarizations.

The antenna shown in **Figure 3b** is a circular polarization switchable antenna. A 90-degree hybrid is placed between a switch and dual-polarized antenna. As the input signal fed to one of the input ports of the hybrid is divided into two signals with the phase difference of $\pi/2$, a circularly polarized wave is excited. By switching the input ports of the hybrid, the antenna switches right-handed and left-handed circular polarizations (RHCP and LHCP).

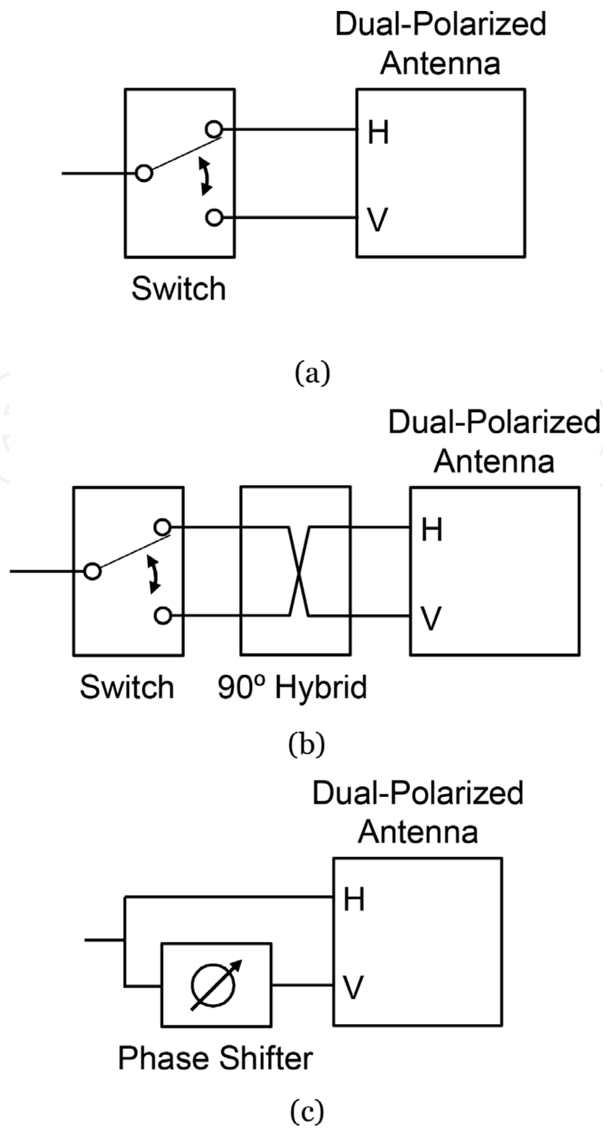

Figure 3.
Basic configurations of polarization agile antenna. (a) Linear polarization switchable antenna; (b) circular polarization switchable antenna and (c) linear/circular polarization switchable antenna.

Figure 3c shows a basic configuration of a polarization agile antenna which switches four polarizations of $\pm 45^{\circ}$ linear polarizations, RHCP and LHCP. The antenna consists of a phase shifter and dual-polarized antenna. When the phase shift value $\varphi = 0$ or π, the antenna excites $\pm 45^{\circ}$ linear polarizations. Furthermore, when $\varphi = \pm\pi/2$, the antenna excites circular polarizations.

4. Practical implementation of polarization agile antenna

In this section, practical implementations of polarization agile antennas employing microstrip antenna elements and planar microwave circuits are introduced.

4.1 Linear polarization switchable antenna

Figure 4 shows a practical implementation of a polarization agile antenna which switches two orthogonal linear polarizations. The configuration is similar to the antenna shown in **Figure 3a**, and it consists of a dual-polarized microstrip array antenna and single-pole double-throw (SPDT) switch [3, 4].

The dual-polarized array antenna has four microstrip antenna elements and employs a feed network using a combination of microstrip lines and slot lines.

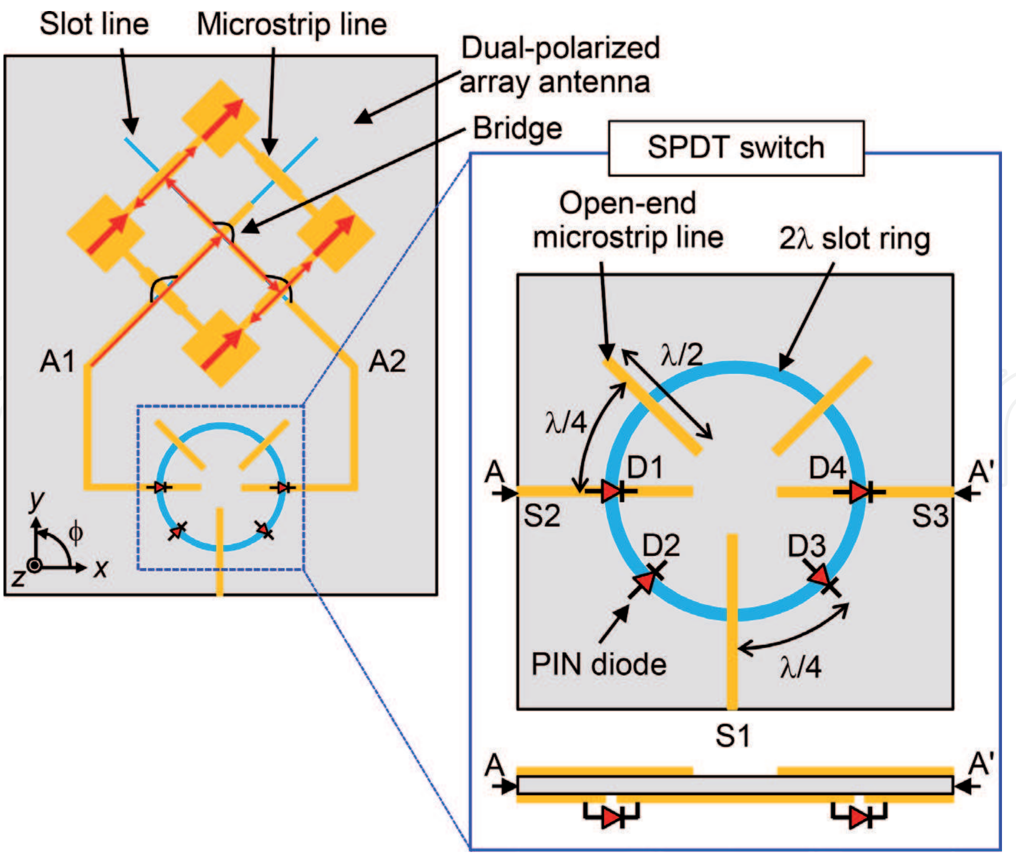

Figure 4.
Structure of a linear polarization switchable antenna [3].

When the signal is fed to the antenna from A1, the signal propagates along the microstrip line as shown by the red line. Here, the signal from A1 is divided into two inphase signals on the slot line. Each signal on the slot line is divided again into two antiphase signals on the microstrip line. Therefore, the signal fed from A1 excites the $+45^{\circ}$-polarized wave as shown by the arrows on the microstrip antenna elements. Similarly, the signal fed from A2 excites the -45°-polarized wave. The input impedance of the array is the same as the input impedance of each microstrip antenna element as the feed network is constructed with a parallel branch and series branch. Therefore, larger array antennas can be easily achieved by simply repeating the same feed structure.

The SPDT switch is constructed with a two-wavelength slot ring, four switching diodes D1–D4, and two half-wavelength open-end microstrip lines. Three microstrip lines are coupled for input and output. The switching diodes are placed over the slot ring with a quarter-wavelength interval. When a positive voltage is applied to the inner conductor of the slot ring, the diodes D1 and D2 become *off*, and D3 and D4 become *on*. Then the signal fed from Port S1 propagates to Port S2 because the *on*-state diodes make short circuits on the slot ring. The half-wavelength open-end microstrip lines also make short circuits on the slot ring. The slot lines from output ports to the open-end microstrip lines act as open circuits because the distance from the diode D1 or D2 to the open-end microstrip line is a quarter wavelength. Similarly, when a negative voltage is applied to the inner conductor of the slot ring, the signal fed from Port S1 emerges at Port S3. Hence, the polarization can be switched by changing the polarity of the voltage applied to the inner conductor of the slot ring.

A circular polarization switchable antenna shown in **Figure 3b** can be realized by placing a 90-degree hybrid between the antenna and switch [5]. A polarization agile antenna which switches four polarizations using phase shifters and magic-T is also demonstrated in [6].

4.2 Active integrated array antenna for polarization modulation

Active integrated antennas integrate active devices such as transistors or Gunn diodes to build in RF signal processing capabilities in an antenna [7, 8]. There are several types of the active integrated antennas. For example, antennas integrating a power amplifier, oscillator, voltage-controlled oscillator (VCO), or injection-locked oscillator have been successfully demonstrated. Furthermore, a frequency-switchable antenna and radiation pattern-switchable antenna have been also proposed.

In this section, an active integrated array antenna which has oscillation and polarization modulation functionalities is introduced. The active integrated array antennas are suitable for the polarization modulation because polarization switching can be realized by simply inverting the phase of one of the two orthogonal polarizations. The active integrated array antenna using an RF signal processing technique achieves a simple transmitter module.

Figure 5 shows a basic block diagram of the active integrated array antenna [9]. In this configuration, an oscillator and two PSK modulators are integrated with two pairs of antenna elements for horizontal and vertical polarization. The oscillator has four output ports and feeds RF signals to the antenna elements. The PSK modulators invert the phase of the RF signals for the vertical polarization. Hence, $\pm 45^{\circ}$ linear polarization switching can be realized.

Figure 6 shows a practical implementation of the active integrated array antenna [10]. A four-port Gunn oscillator with slog-ring resonator is located at the center of the array antenna. Two PSK modulators using a slot ring and PIN diodes are inserted in the feed line for the vertical polarization. The array antenna consists of 12 antenna elements and feed network using microstrip lines and slot lines.

The Gunn oscillator consists of two Gunn diodes mounted on a two-wavelength slot ring. Four microstrip lines are coupled to the resonator with a half-wavelength interval. Therefore, the output ports O1 and O2 (O3 and O4) generate inphase signals, and the phases of O1 and O3 (O2 and O4) become antiphase with each other.

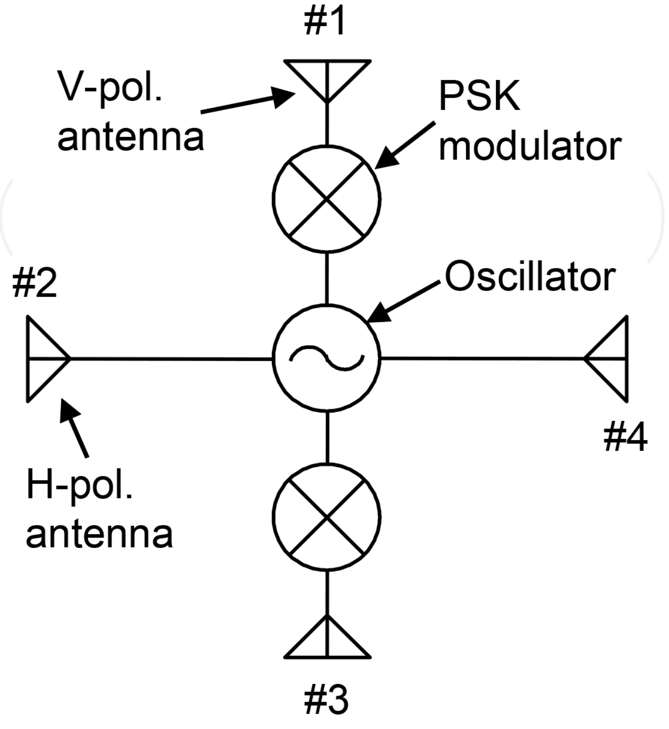

Figure 5.
Basic block diagram of the active integrated array antenna [9].

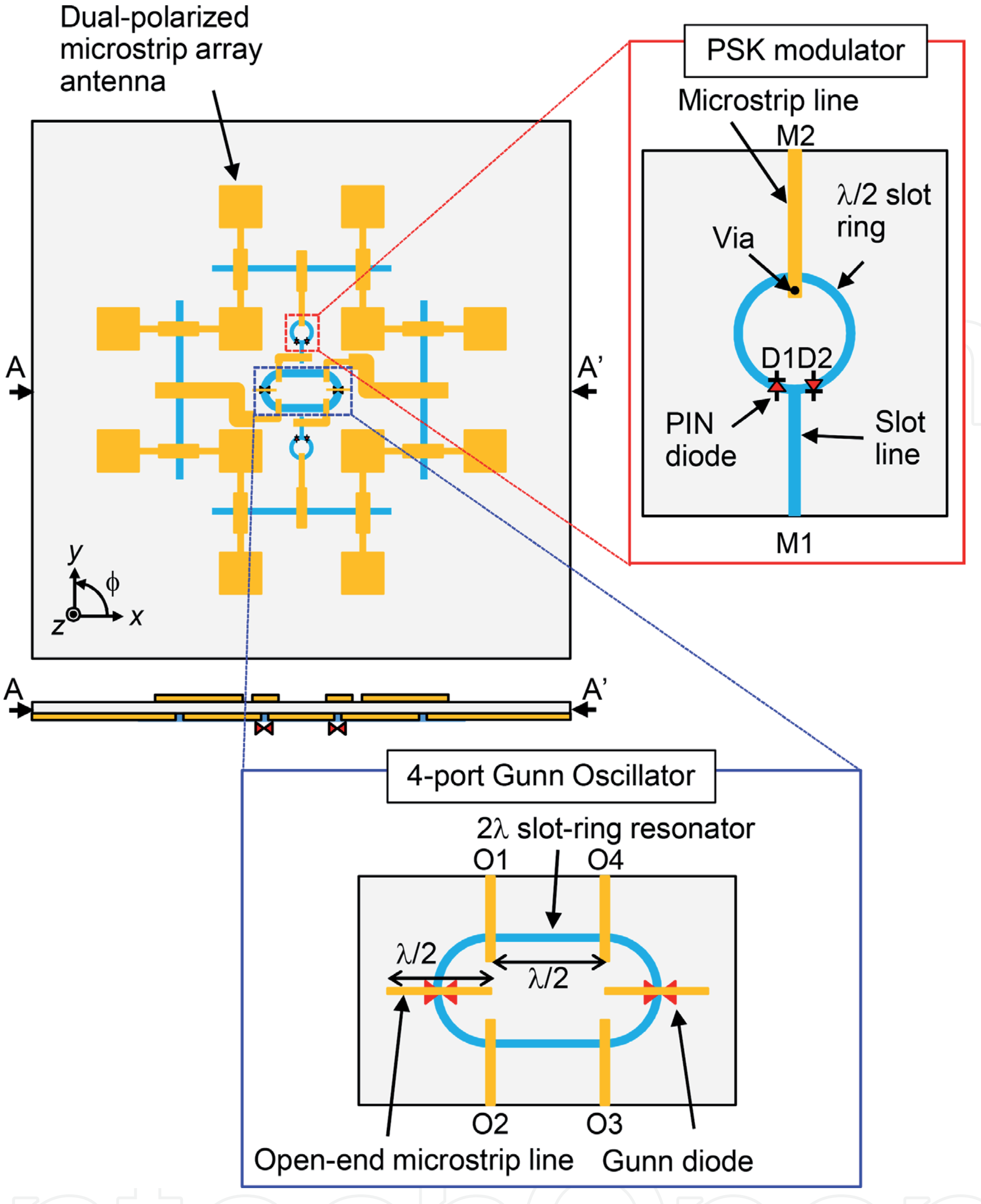

Figure 6.
Structure of the active integrated array antenna [10].

The half-wavelength open-end microstrip lines just above the Gunn diodes stabilize the resonant field in the slot-ring resonator. The bias voltage of the Gunn diodes is applied between the inner and outer conductors of the slot-ring resonator.

The PSK modulator consists of a half-wavelength slot ring and two PIN diodes. A microstrip line and slot line are connected to the slot ring for input and output. The two PIN diodes are mounted at the junction of the slot ring and slot line, and the directions of the PIN diodes are opposite to each other. When positive voltage is applied to the inner conductor of the slot ring, diode D1 becomes *off* and D2 becomes *on*. Therefore, a signal fed to Port M1 propagates along the left half of the slot ring and goes to Port M2. Similarly, when negative voltage is applied, the signal fed to Port M1 propagates along the right half of the slot ring. With this operation, the phase of the signal appeared at Port M2 is inverted by the applied voltage. As a result, polarization switching is achieved.

5. Polarization detection

5.1 Detection of polarization modulated signal

The simplest way to detect the polarization at receivers is to use two orthogonally polarized antennas and compare the signals received by the two antennas.

Figure 7 shows a basic configuration to detect the polarization. Two antennas for horizontal and vertical polarization are connected to a comparator. Comparison of the signals received by the two antennas discriminates the polarizations.

The polarization discrimination can be easily achieved in RF by using an RF multiplier as a comparator. When a polarization modulated radio wave has polarizations of ±45°, the vertical and horizontal components of the radio wave are separately received by using the two orthogonally polarized antennas, and the voltage of each component is expressed as follows:

$$V_{\mathrm{H}} = V \sin(\omega t) \tag{4}$$

$$V_{\mathrm{V}} = V \sin(\omega t + \varphi) \tag{5}$$

where φ is the phase difference between the horizontal and vertical components and it is 0 or π in the case of ±45° polarization modulation.

The DC output voltage of the multiplier is

$$V_{\mathrm{out}} \propto V^2 \cos\varphi. \tag{6}$$

Therefore, when the phase difference φ = 0, the output voltage of the multiplier V_{out} becomes positive, and it becomes negative when φ = π. Therefore, the polarization modulated signal can be demodulated in RF.

5.2 Polarization discrimination antenna

Figure 8 shows a practical implementation of the polarization discrimination antenna. The antenna consists of 12 microstrip antenna elements, feed network and double-balanced multiplier [11]. The feed network employs microstrip lines and slot lines and achieved simple planar structure. The double-balanced multiplier is located at the center of the array antenna and composed of a slot ring and four detector diodes mounted on the slot ring.

The horizontal and vertical components of the radio wave are separately received by the antenna. The blue and red arrows show the signal of the horizontal and vertical polarizations, respectively. Each received signal is applied to the RF multiplier, and the detected voltage is obtained at the inner conductor of the slot ring.

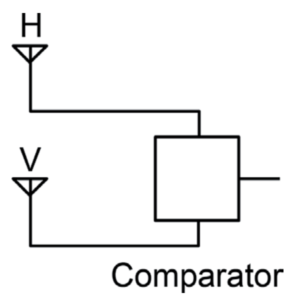

Figure 7.
Basic configuration to detect the polarization.

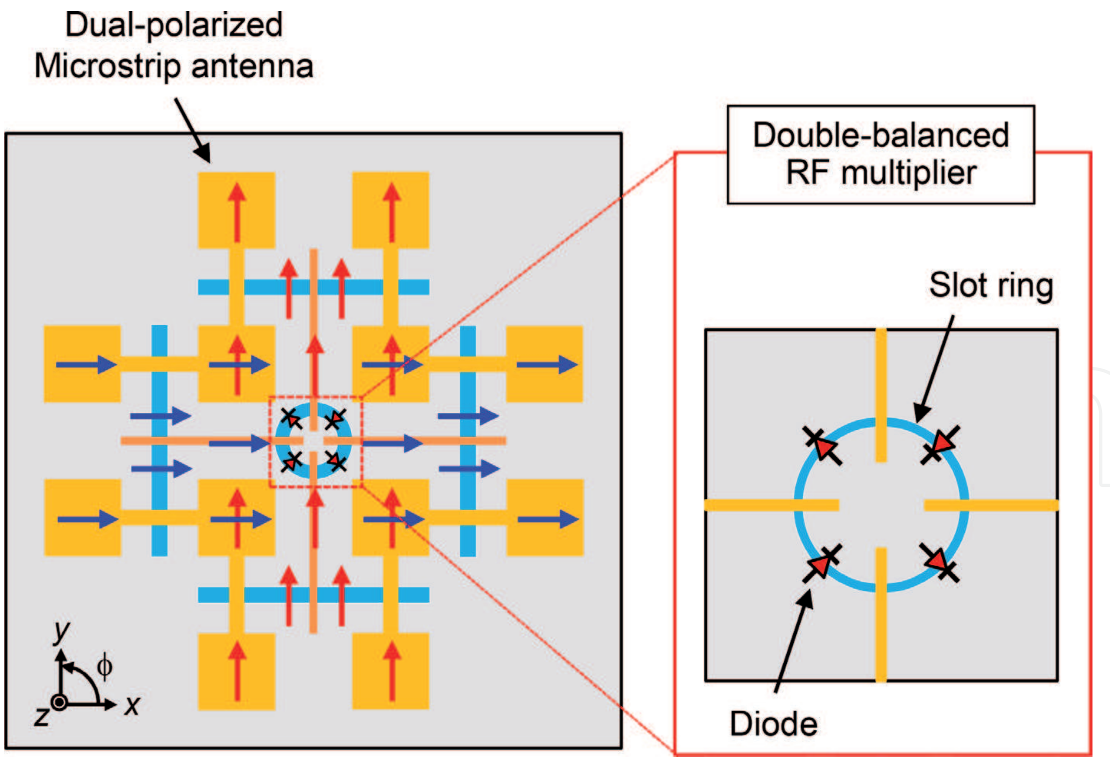

Figure 8.
Polarization discrimination antenna [11].

Polarization discrimination for circular polarizations is similarly achieved by adding 90° phase difference between the horizontal and vertical components [12].

6. Conclusions

In this chapter, a modulation scheme which effectively utilizes the polarization of the radio wave is introduced. The polarization modulation gives a new degree of freedom in the modulation adding to the phase, amplitude, and frequency. Antenna technology is a key to achieve the polarization modulation communication systems. Basics of the polarization modulation and several examples of the polarization agile antennas are introduced. Furthermore, the detection of polarizations and a polarization discrimination antenna are also explained. The concept utilizing polarizations gives new vistas to the next-generation advanced wireless communication systems.

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