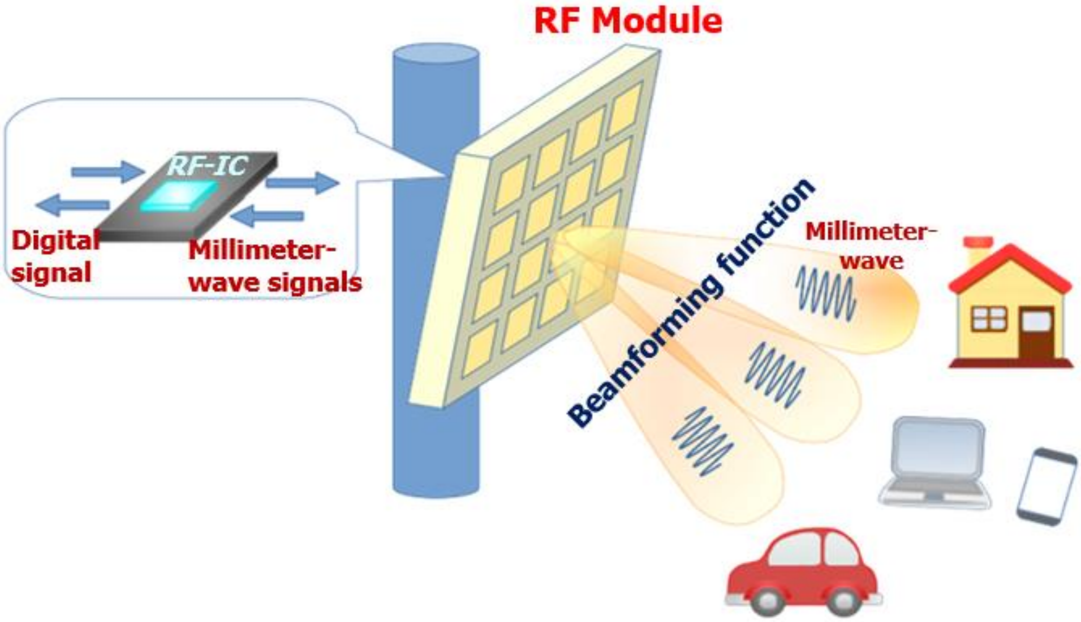
5G mmWave
Phased Array Antenna



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1. Introduction

The fifth-generation mobile communication system (5G) requires much more sophisticated wireless communications, and phased array antenna technology plays an important role in transmitting and receiving radio waves. This type of antenna has a high directivity and transmits radio waves over a long distance while electronically changing the direction toward moving devices.

Generally, 5G communication uses sub 6 GHz (lower than 6 GHz) and millimeter-wave (approx. 30 GHz and higher) frequency bands. Use of millimeter-wave frequencies is essential to realize high communication capacity between base stations and user terminals such as customer premises equipment (CPE) for fixed wireless access (FWA) and between the base stations and mobile devices.

This is because the higher the frequency, the more bandwidth available and the higher the communication data rate (communication capacity). (See Link Design for Millimeter-wave Communication [1])

On the other hand, since millimeter waves suffer high free-space losses, it is difficult to transmit radio waves over a long distance. To extend the transmission distance, a narrow-beamed high-gain antenna that equivalently increases the transmission power and reception sensitivity is indispensable. As a result, however, the communication angular range gets much narrower than that of the low-gain, omni-directional antennas. To expand the communication range by overcoming the disadvantages of millimeter waves while taking advantage of their features, the most important technology is the phased array antenna that creates highly directional beams and steers them to desired directions. This technology will also enable spatial multiplexing of radio waves and thus, is a key to 5G communication from the viewpoint of efficient use of frequencies in small cells. Many providers in the world have already started to install millimeter-wave base stations. They plan to operate a huge number of base stations within several years. As of March 2020, Japanese provider NTT DOCOMO has deployed 500 base stations and plans to have 20,000 in service by March 2022.

In most of these mmWave base stations, the providers will install phased array antennas due to the following advantages:

- Longer communication range with low power consumption.
- Quick beam steering to enable high-speed switching among users.
- Gb/s-order high-speed communication.

Figure 1 shows the block diagram of the RF module with a phased array antenna. It converts the IF signals to millimeter-wave signals then divides the signals among several phase shifters which are connected to antenna elements.

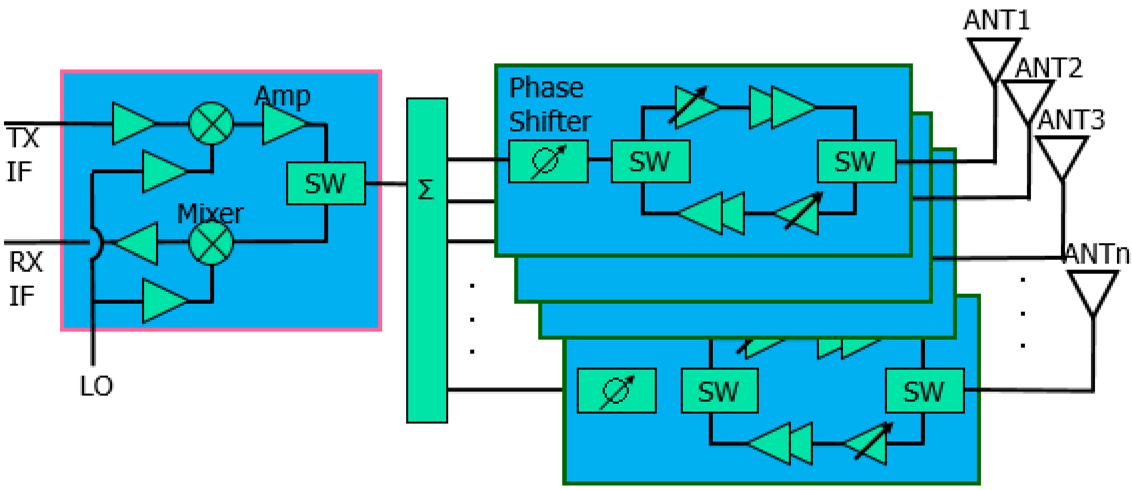


Fig. 1 Block diagram of RF module with phased array antenna

2. Phased Array Antenna Principles

Figure 2 shows a configuration of a phased array antenna. Although there are many types of phased array antennas for different purposes and frequencies, this paper discusses one used mainly for millimeter-wave communication. As shown in Fig. 2, there are several square patterns (16 pieces for this example) in an orderly manner on the substrate. Each of the square patterns represents an antenna element. They collectively form a phased array antenna, which radiates phase-controlled signals simultaneously from each antenna element and operates as a larger antenna that has higher gain and directivity. For example, when all the elements are excited by in-phase signals, the phased antenna operates as an antenna with strong directivity toward the front. Three-dimensional structure of each patch element and their alignment generally define the total phased array antenna performance and thus the actual antenna has a far more complicated structure.

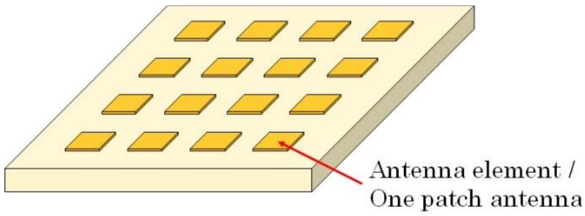


Fig. 2 Configuration of phased array antenna

Figure 3 shows a schematic diagram of the drive circuit configured inside or on the opposite side of the phased array antenna substrate. There is a transmitter near the center, from which signals branch into 16 antenna elements. The devices placed between the last branches and antenna elements are phase shifters. These phase shifters have important functions for the operation of the phased array antenna, namely, to control the direction of a beam freely.

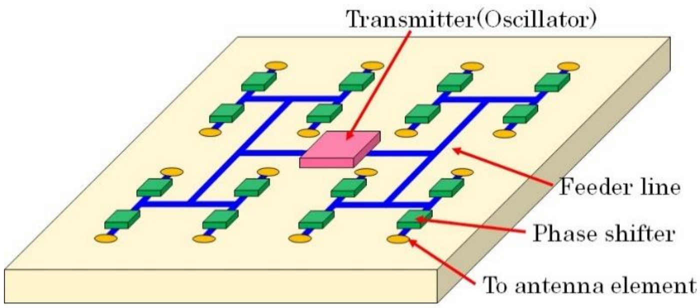


Fig. 3 Schematic diagram of driving circuit of phased array antenna

This section presents the transmitter as an example, but the receiver has almost the same structure. In addition, sometimes, both transmitting and receiving are carried out using the similar structure.

As shown in Fig. 3, two-dimensional array of antenna elements allows a phased array antenna to steer beams both vertically and horizontally. To make the explanation more easily understandable, only one row of the elements serves as a one-dimensional array antenna here and describes details of operation.

Figure 4 shows a schematic diagram of the one-dimensional phased array antenna with four elements. The feeder branches off from the oscillator into four, each of which is connected to the antenna element through the phase shifter. If all the feeders are of the same length, that is, the lengths from the oscillator to each antenna element are the same, the radio waves radiated from each element are in phase.

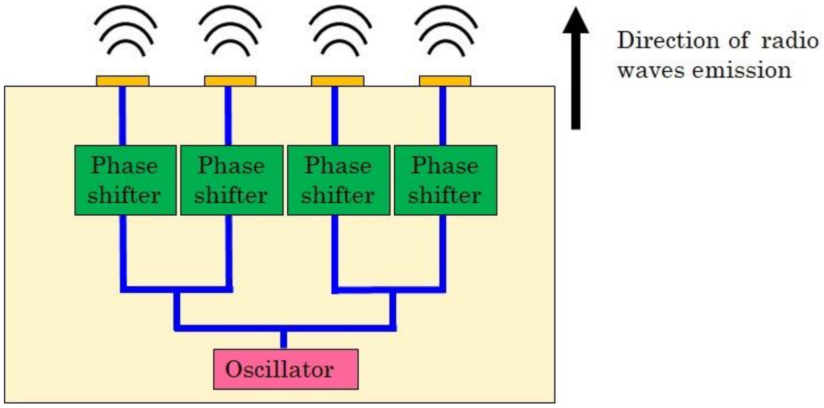
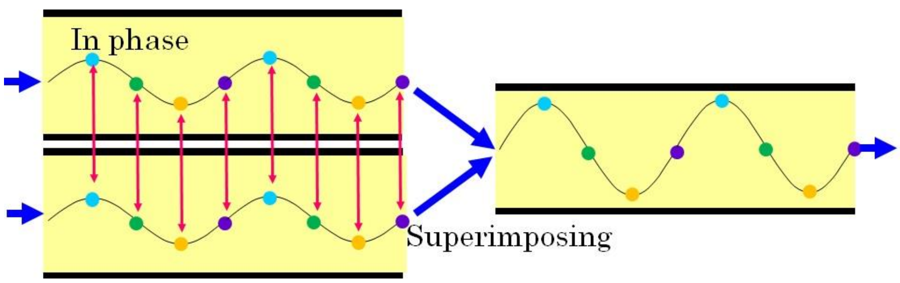
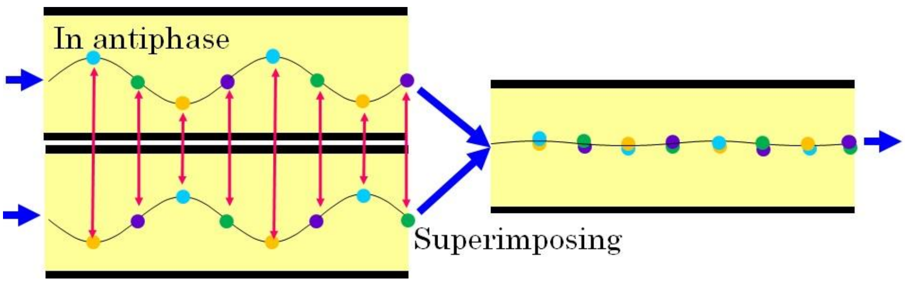


Fig. 4 Schematic diagram of phased array antenna consisting of four elements

A phased array antenna is an antenna that controls the direction of emission of radio waves by superimposing the signals of different phases. The characteristic of radio waves as a single wave helps better understanding of operation of phased array antennas. Figure 5 shows the image of waves. When two waves of the same amplitude or in phase in the left diagram of Figure 5a travel in the same direction, they are superimposed. As shown on the right, the resulting waveform consists of larger amplitudes. In contrast, if two waves in antiphase are superimposed, they cancel each other out to leave little or no energy as shown in Fig. 5b.



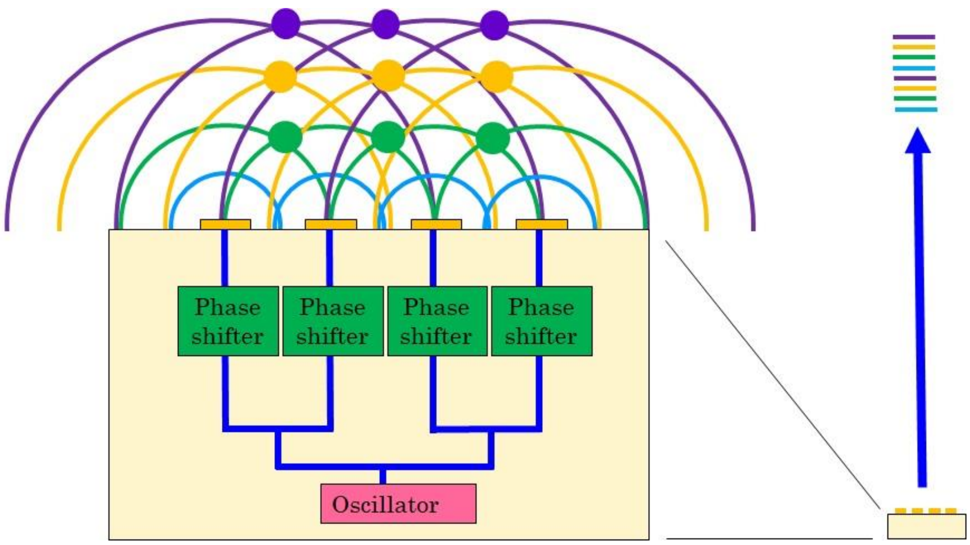
a. In phase



b. In antiphase

Fig. 5 Image of superimposing waves

The radio waves radiated from each antenna element spread in a concentric configuration, as illustrated in Fig. 6a. Figure 6 describes how the peaks of waves in phase emitted from each antenna element move in order of time using concentric circles of purple, orange, green and blue. Under the conditions, at the points where the circles of the same color (peaks of the waves) are superimposed, or where the waves are in phase, the waves add together to increase radiation. (See circles in Fig. 6a). Since the superimposed points start from purple and shift to orange, green and blue, as shown in Fig. 6, the waves heading forward interfere constructively and thus have stronger directivity.



a: Superimposing of waves near antenna b: Superimposing of waves far from antenna

Fig. 6 Spread of waves from antenna element and their superimposing

Figure 6a shows that the waves coming from the four elements do not sufficiently overlap since the travel distances (radius of concentric circle) of waves are short. However, when these waves travel a certain distance from the antenna, each radius of the circles increases, and overlaps as one wave, as illustrated in Fig. 6b.

As mentioned above, a larger number of antenna elements produces higher antenna gain on the front side, which allows for high gain antenna directivity. Arranging the elements in two dimensions allows the antenna to become highly directional both vertically and horizontally.

3. Beamforming

The preceding sections have discussed the case where multiple antenna elements radiate electromagnetic waves in phase. Shifting the phase of radio waves appropriately enables the antenna to direct a narrowly focused beam in directions other than front-facing. This technology is called beamforming or beam steering.

Figure 7 illustrates the radio waves output from the transmitter as parallel waves. In Fig. 6 in the previous section, the radio waves from each antenna element are expressed with concentric circles. In contrast, Fig. 7 explains how the signals, which are sent out from the transmitter and divided into four, reach the antenna elements through the phase shifter and are radiated. The length from the purple circle to the next purple circle is one wavelength with a phase shift of 360˚. This means that each successive change of the circle color represents a phase shift of a quarter wavelength, or 90˚. The line connected between the same color circles is the wave front moving forward.

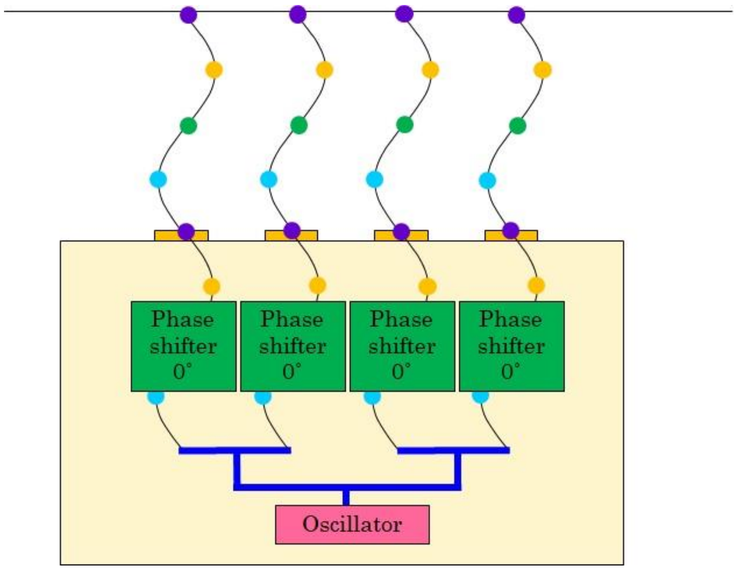
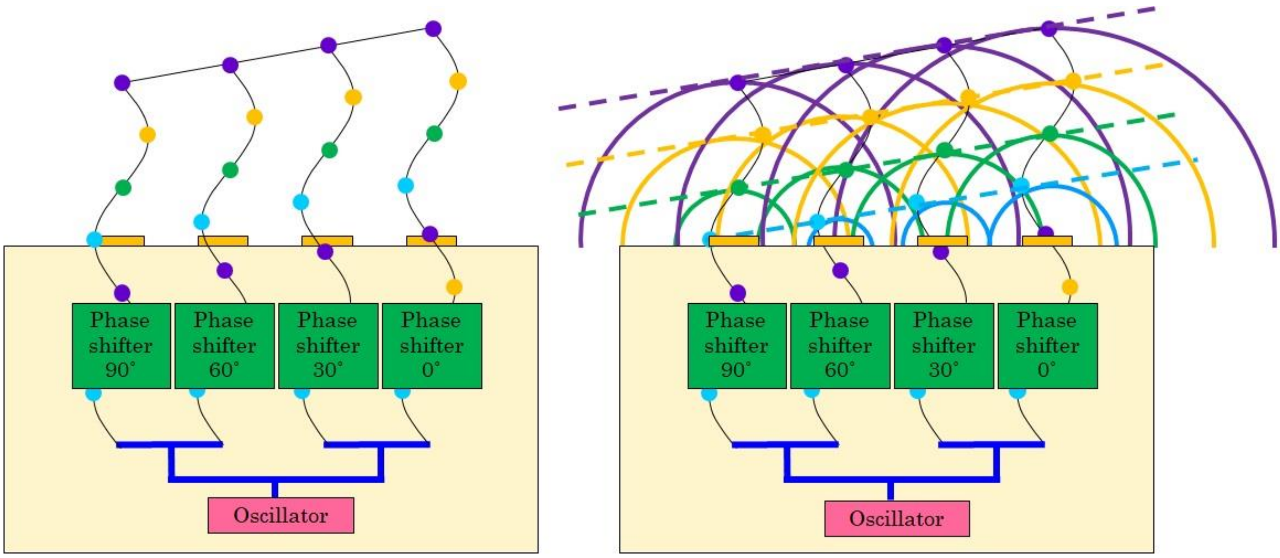


Fig. 7 Propagation of radiated radio waves in phase

In Fig. 8, each phase shifter changes the phase by 0˚ (as is), 30 ˚, 60 ˚, and 90 ˚ from the right to the left, respectively, where the phase is maximized on the left side. By delaying waves that were in phase when entering the phase shifter, the peaks of the waves output from the antenna element are also delayed. The wave front peaks, where multiple waves come together to be intensified, are represented as a tilted wavefront when the four elements output radio waves at short regular intervals. This indicates that the angle of the beam can vary. Figure 8a illustrates sinusoidal waves. In addition, Fig. 8b describes the superimposing of radio waves radiated from the antenna elements and spread in a concentric manner.



a: Radio waves with controlled phase shift b: Spread of radio waves

Fig. 8 Propagation of radiated radio waves with controlled phase shift

In Fig. 8, the antenna elements are spaced one-half wavelength apart. In this case, as the diagram shows, when the phase between each antenna element is set to 30˚, the beam tilts about 9˚.

In practice, as Fig. 2 shows, the phased array antenna with several tens of antenna elements arranged two-dimensionally on a plane will be put to use, which can freely direct a beam up, down, left and right. The antenna steers a high gain, directional beam toward the receiver within its coverage. This brings higher electric power to a receiver compared to a single antenna and thus, provides higher communication speed and spatially efficient communication.

Figure 9 shows an example of beam patterns of a phased array antenna designed and fabricated by Fujikura. Beamforming has been satisfactorily accomplished, which steers a highly directional beam to an angle within ±45˚ along the axis.

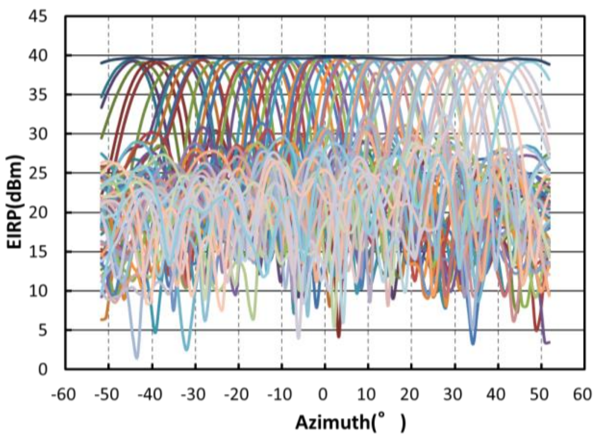


Fig. 9 Example of beamforming (graph of beam profile)

4. Beam Search

As mentioned in the previous section, the phased array antenna can steer the beam of radio waves in a certain direction for efficient communication. However, a communication device with this type of antenna cannot establish a connection with another communication device if their beams are not facing each other.

A communication system using a phased array antenna requires functions to find a right direction to steer a beam and automatically adjust it for stable communication, especially, when either of the communication devices is moving. Such a function has been already implemented into the existing systems.

When the communication device tries to establish a connection initially or loses a signal from a counterpart, it cannot detect the location of another communication device or even the existence of another device. In such a case, it is difficult to find a counterpart when each device is using a highly directional beam. If a communicable angle range of the beam is 5% of the total and the direction of each beam is random, the possibility where both of them can find their counterpart is 0.25%. The possibility to find the counterpart is further decreased when the beam is more narrowly focused. Consequently, the communication devices are required to steer the beam in so many different directions.

To deal with the issue, a typical solution is decreasing the directivity to capture the counterpart. This method generally uses only one or a few antenna elements in the entire phased array antenna to create a wide spreading beam pattern. This beam pattern is called quasi-omni. In this state, although the communication devices cannot perform high-speed communication particular to millimeter-waves, it is sufficiently possible to identify the directions of both devices by using an appropriate control procedure such as "Sector Level Search (SLS)." Since the phased array antenna is electrically controlled, it can readily establish a connection by decreasing its directivity while being highly directional. The detailed procedures are specified in common standards such as IEEE 802.11ad/WiGig and other standards.

5. Fujikura Technology for Phased Array Antenna

Fujikura has a long history of providing communication infrastructure. Our product line includes high-speed communication equipment as well as electrical and optical cables. Based on our electromagnetic field analysis technology and flexible printed circuit (FPC) production technology, we have developed our phased array antenna design technology. With our in-depth knowledge on materials, processes, measurement, simulation and RF-IC technology, we can develop leading-edge millimeter-wave phased array antennas and modules.

6. Conclusion

This paper has introduced the characteristics and principle of the phased array antenna design, which is an important technology to achieve high-speed communication using millimeter waves. The principle of a phased array antenna is quite simple. However, designing and manufacturing cutting-edge phased array antennas require unique skills that only Fujikura has, especially, in the millimeter-wave area. Careful attention must be applied to building the system architecture and implementation of the technology to reap the rewards from this design technology. Fujikura millimeter-wave products will include innovative phased array antenna design to provide significant performance advantages.

Please contact Fujikura ”mmwavetech@jp.fujikura.com” to discuss further.

Reference

[1] https://mmwavetech.fujikura.jp/

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