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Basic Study of Both-Sides Retrodirective System for Minimizing the Leak Energy in Microwave Power Transmission

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SUMMARY In the beam-type microwave power transmission system, it is required to minimize the interference with communication and the influence on the human body. Retrodirective system that re-radiates a beam in the direction of arrival of a signal is well known as a beam control technique for accurate microwave power transmission. In this paper, we newly propose to apply the retrodirective system to both transmitting and receiving antennas. The leakage to the outside of the system is expected to minimize self-convergently while following the atmospheric fluctuation and the antenna movement by repeating the retrodirective between the transmitting and receiving antenna in this system. We considered this phenomenon theoretically using an infinite array antenna model. Finally, it has been shown by the equivalent circuit simulation that stable transmission can be realized by oscillating the system.

key words: *microwave power transmission, retrodirective system, beam propagation method, phase conjugator, feedback oscillation*

1. Introduction

Microwave power transmission is the most effective method for transmitting energy over a long distance without wires [1]. One application example of this technology is a power supply system for mobile devices and sensor terminals [2]–[4]. Such a system for distributing energy is called ubiquitous power supply [5]. Another application of microwave power transmission is to send energy at point-to-point like a wire using a large antenna with high directivity. The space-based solar power that connects a geostationary satellite and the ground is a well-known system [6]–[9]. In recent years, attention has been also focused on ground application steps such as power feeding to flying object [10], [11] and transmission of offshore natural energy [12].

In such a beam-type microwave power transmission dealing with high power, it is important to suppress the leak energy to the outside of the system for keeping human safety and avoiding the interference with other wireless devices. Several studies have been conducted on a design method of a low side lobe beam suppressed unnecessary energy radiation to the outside of the system [13]–[15]. In the practical system, however, it is necessary to control the beam direction against the antenna movement and atmospheric fluctuation. It is widely known that a retrodirective system is an effective technology of phased array antenna to transmit microwaves back in the arriving direction of the pilot signal from the power receiving antenna [16]–[18]. Particularly in the hardware retrodirective system, a phase conjugate circuit is usually used for re-radiating in the arrival direction of the pilot signal [19].

In a general retro directive system, the pilot signal spreads widely to notify the position of the receiving antenna. However, in the horizontal direction system on the ground, there is a problem that the pilot signal is disturbed by multipath interference. In order to solve this problem, a beam-type pilot signal with high directivity radiated from the whole of the power receiving antenna has been proposed [20]. In the above paper, the beam collection efficiency of the power signal always improved with respect to that of the pilot signal. This suggested the possibility of optimal beam formation by repeating the retrodirective operation.

Then, we propose in this paper a new microwave power transmission system adopting the retrodirective system, which was conventionally used only on the power transmitting antenna side, to the receiving antenna side. In addition to the proceedings of APMC 2018 [21], a beam tracking ability to the antenna shift of the proposed system was simulated. Furthermore, a theoretical consideration by the infinite array model and an analysis of the system operation by the equivalent circuit were described.

2. Concept of Both-Sides Retrodirective System

In the conventional hardware retro directive system, the phase conjugate circuits were adapted only to the power transmitting antenna [20]. On the other hand, the phase conjugate circuits are attached to both of the power transmitting and receiving antennas in the both-sides retrodirective system we proposed. As shown in Fig. 1, a part of the power signal arriving at the power receiving antenna is taken out by the directional coupler and re-radiated as a pilot signal through the phase conjugate circuit. In this system, the retrodirective operations are repeated between the transmitting and receiving antennas. The power ratio of the pilot signal and the power signal is determined by the coupling of the directional coupler and the gain of the amplifier. The power signal of 1 MW and the system gain of 20 dB are supposed in this figure.

Since the pilot signal is radiated from the entire surface

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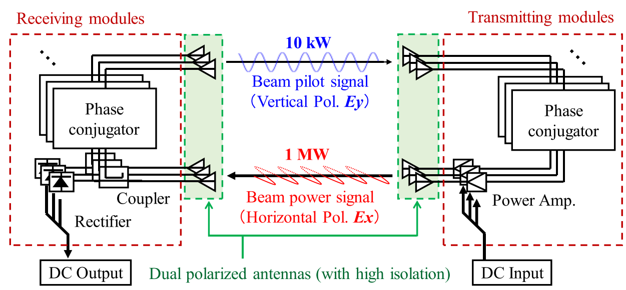

Fig. 1 Block diagram of a both-side retrodirective system.

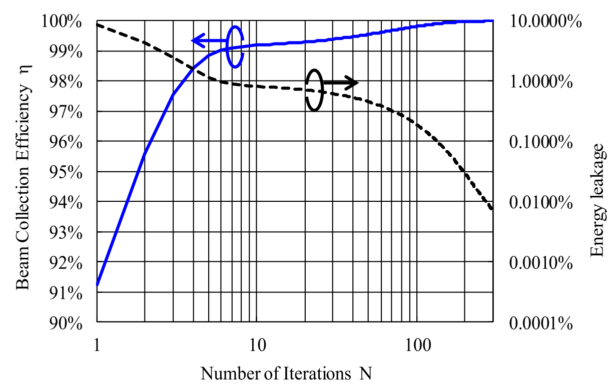

Fig. 2 Improvement of beam collection efficiency and energy leakage by the retrodirective iterations.

of the power receiving antenna, it becomes a "beam pilot signal" with high directivity [20]. Though the beam pilot signal cannot spread in a wide range, the system becomes strong against the multipath interference because the signal does not reach the ground or the sea surface. Moreover, the pilot signal and the power signal have the same frequency and are distinguished by the polarization. Dual polarized antennas with high orthogonality such as dual-mode dielectric resonator antennas [20] are used for array antenna elements.

The beam correction speed of the system can be estimated from the round-trip propagation time of the signal and the delay time of the circuit. If the propagation distance is 10 km and the delay time of the circuit is 1 μs, the correction time becomes about 68 μs. It can follow the antenna movement and the atmospheric fluctuation at high speed.

3. Simulation of Self-Convergent Beam Forming

3.1 Suppression of Leak Energy by Iterations

We evaluated the effect of the both-sides retrodirective system on the energy leakage using the simulation software Opti-BPM with beam propagation method [23].

The antenna size was set to 50 m in diameter, the size of the analysis space was 100 m square, the grid size in the cross section was 50 cm square in this simulation. Assuming that the propagation distance of the beam was 10 km, the calculation step length was set to 200 cm. The frequencies of the pilot signal and the power signal were 5.8 GHz (with orthogonal polarization). With the propagation direction of the pilot signal as the z-axis, the Rx and Tx antennas are arranged at $z = 0$ km and $z = 10$ km, respectively. The x-axis and y-axis represent horizontal and vertical directions, and the centers of the Rx and Tx were $(x, y) = (0, 0)$.

To clarify the effect of the retrodirective operation, the multipath problem of the ground assumed to be negligible in this simulation. The results of the beam pilot signal on the multipath effect were shown in [20]. It has been shown that accurate retrodirective operation is possible even when the lower part of the antenna is 5 m high from the ground by using the beam pilot signal. The other effect of the ground is that the reflection angle is slightly different depending on the polarization. In the practical system, it is necessary to determine the polarization of the pilot signal and the power signal including these influences, but the detailed study will be a future subject.

The distribution of the initial pilot signal was assumed to be uniform amplitude. The phase distribution focused 10 km ahead. The maximum number of iterations was set to 300 times. The odd number means the propagation of the pilot signal. The input field of the next propagation was determined by cutting the output electric field of the former propagation to the size of the antenna and inverting the sign of the imaginary component in each grid.

Figure 2 shows the change in the beam collection efficiency and the energy leakage due to repeated propagation. Beam collection efficiency is the ratio of the power passed into the receiving antenna plane to the total radiation power. On the other hand, the energy leakage means the ratio of the power radiated to other than the receiving antenna surface. As the number of iterations increases, the beam collection efficiency improves and the energy leakage decreases. The beam collection efficiency after repeating 300 times reached 99.99%, whereas it was 91.25% due to the energy leakage by the side lobe at the initial power signal. It almost became the limit value obtained from the size of the apertures.

Next, the beam profile at each number of repetitions was investigated. Figure 3 (a) shows the beam profile of the pilot signal at N = 1. It can be seen that a relatively large amount of energy leaked to the outside of the system by the side lobe. The beam profile of the pilot signal at N = 29 is shown in Fig. 3 (b). Although the beam shape was close to the distribution of the initial signal (N = 1), the leak energy by the side lobes was suppressed. The beam collection efficiency reached 99.38%. Figure 3 (c) shows the beam profile at N = 299. It turns out that the ideal beam shape with beam waist was obtained. From these results, it is considered that the side lobes were rapidly suppressed by reciprocating up to about N = 10, and then the beam profile gradually changed to the optimum shape. The time t in Fig. 3 represents the total propagation time assuming that it takes 34 μs for one propagation.

Figure 4 shows a comparison of the beam patterns at z = 10km. In the case of N = 1 propagation, the side-lobe level of about −24 dB was observed outside the antenna area. On the other hand, it can be seen that the side-lobe

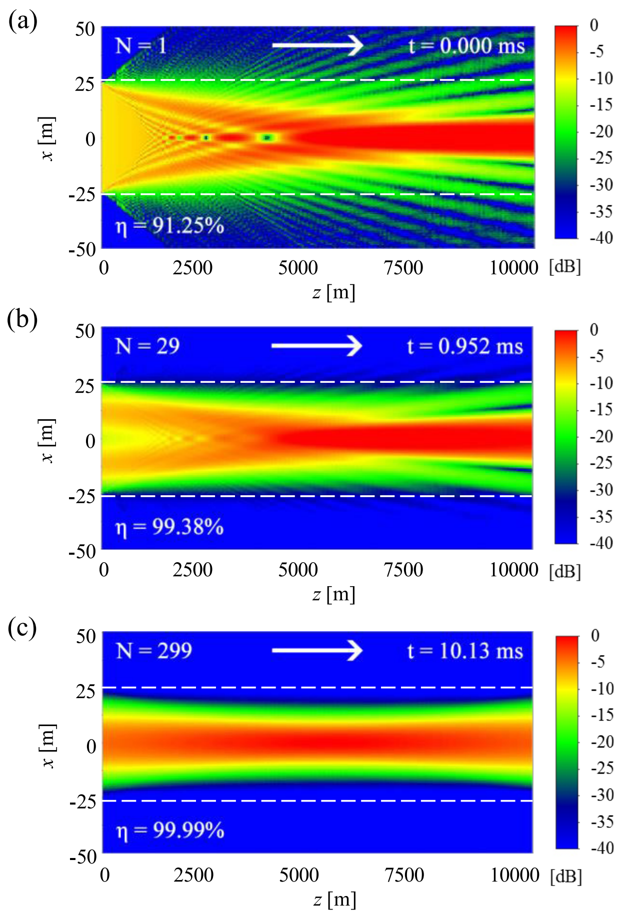

Fig. 3 Beam profile of the pilot signal at each number of propagation (a) N = 1, (b) N = 29, (c) N = 299.

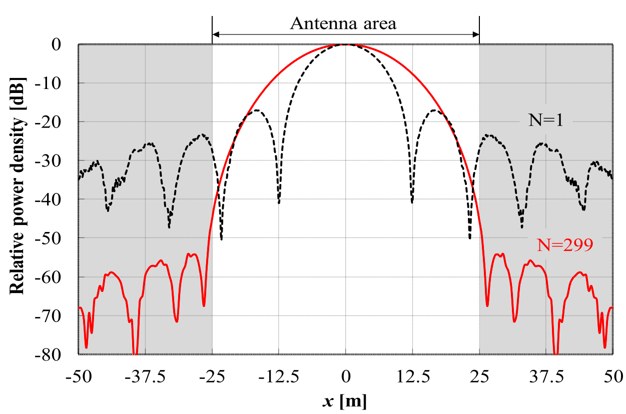

Fig. 4 Comparison of the beam patterns at z = 10km.

level was extremely suppressed in the propagation of N = 299.

The simulation shows that the propagation of the pilot signal and the power signal is repeated and the energy leakage to the outside is minimized. We named such an effect "self-convergent beam". This effect could not be obtained with the conventional retrodirective systems. Typical retrodirective systems have a uniform intensity distribution. Only phase distribution changes to move the beam direction. Therefore, its beam collection efficiency is the same as the value of N = 1 propagation. On the other hand, in the proposed system the intensity distribution is updated as well as the phase distribution. As a result, the energy leakage to the outside becomes minimized. It is expected that an optimum self-convergent beam is formed in various transmission paths by using the both-sides retrodirective system.

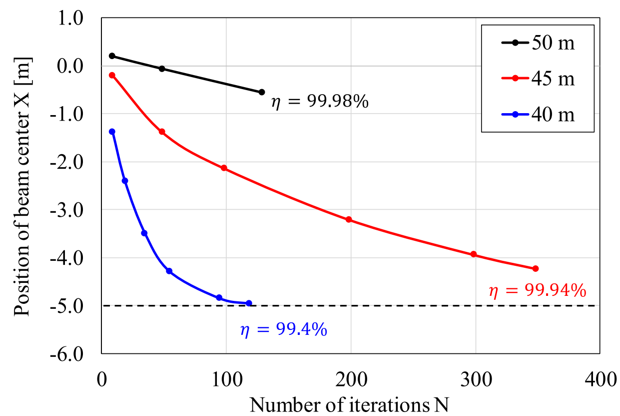

Fig. 5 Change of the beam center of the pilot signal at Z = 10 km by the retrodirective iterations with different diameters of the antennas.

3.2 Beam Tracking to Antenna Shift

It has been shown in the previous sub-section that the beam converges to the optimum state by repeating the retrodirective when the antennas are confronting each other. Next, we investigated beam tracking ability to the antenna shift. The retrodirective area on the power transmission antenna side at Z = 10 km was moved downward −5 m along the x axis. For the initial distribution (N = 1) of the pilot signal, a sufficiently convergent distribution in the confronting state was used. In order to observe the tracking speed due to the difference in the leakage amount, we compare the pair of transmitting and receiving antennas with three diameters. The retrodirective operation was repeated using the same conditions as in the previous section for other parameters.

Figure 5 shows the change in the beam center of the pilot signal at Z = 10 km due to the repetition of the retrodirective operation. In the case of the antenna diameter of 40 m, the beam center almost matched the antenna center at approximately N = 100 (t = 3.4 ms). The beam collection efficiency was 99.4% in this iteration. In the case of the antenna diameter of 45 m, the center of the beam almost coincided with the antenna center at N = 350 (t = 11.9 ms). Then, the beam collection efficiency became 99.94%. The beam profile of the power signal at N = 350 is shown in Fig. 6. In the case of the antenna diameter of 50 m, the beam center hardly moved even at N = 130 (t = 4.4 ms). However, the beam collection efficiency already reached 99.98%.

From this result, it can be seen the tracking speed of the beam center become fast when the diameter of the an-

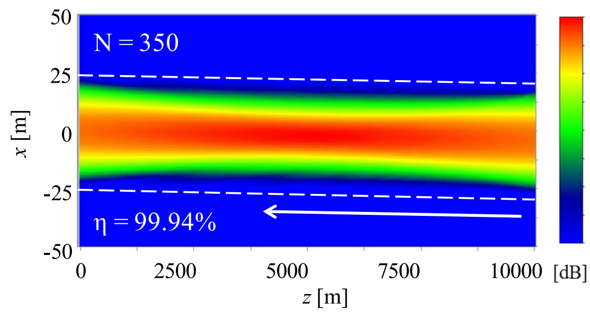

Fig. 6 Beam profile of the tilted power signal (ϕ = 45 m).

tenna is small. The amount of movement of the antenna was equal to −5 m for all antenna diameters. When the antenna diameter is small, the energy leakage amount with respect to the antenna deviation increases. Therefore, it can be said that the amount of energy leakage to the outside of the system determines the tracking speed of the beam. The beam converged at about t = 10 ms for 5 m antenna movement in this simulation. This indicates that the system can follow the object with a velocity of at least 500 m/s.

4. Theoretical Considerations by Infinite Array Model

It showed that the beam converges to the optimum state by repeating the retrodirective operation in the previous section. We considered this phenomenon theoretically using an infinite array antenna model.

4.1 Mathematical Expression of Retrodirective Operation

We considered the retrodirective operation by the infinite array antenna model as shown in Fig. 7. In this model, the receiving and transmitting array antenna with infinite size are opposed to each other by a certain distance. The antenna elements are numbered axially symmetrically from the center towards the ends. The numbers of the power receiving antenna and the power transmitting antenna are i and j, respectively. It is assumed that each antenna element can independently radiate a pilot signal and a power signal of the same frequency and orthogonal polarization. Also, we assume a two-dimensional beam by a one-dimensional array antenna for simplicity.

The complex amplitude of the n-th round-trip pilot signal radiated from the i-th receiving antenna element is represented as $A_{i,n}^{\mathrm{pilot}}$. Also, the complex amplitude of the n-th round-trip power signal radiated from the j-th transmitting antenna element is represented as $A_{j,n}^{\mathrm{power}}$. In the hardware retrodirective system, the transmitting antenna radiates the phase conjugate signal of the pilot signal as the power signal as follows:

$$A_{j,n}^{\mathrm{power}} = G_j^{\mathrm{T_x}} \left[\sum_i^{\infty} S_{j,i} A_{i,n}^{\mathrm{pilot}} \right]^* . \tag{1}$$

Where, $S_{j,i}$ means the scattering matrix from the receiving antenna to the transmitting antenna, and $G_j^{\mathrm{T_x}}$ means the transfer function of the transmitting antenna circuit.

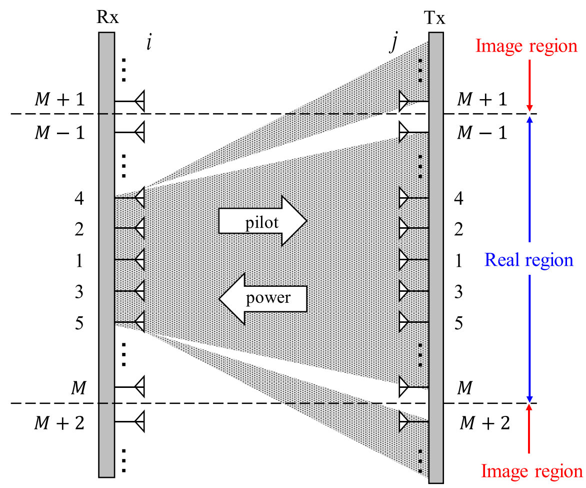

Fig. 7 Infinite array antenna model in one dimension.

In the both-sides retrodirective system, the same relation is also satisfied on the receiving antenna side:

$$A_{i,n+1}^{\mathrm{pilot}} = G_i^{\mathrm{R_x}} \left[\sum_i^{\infty} S_{i,j} A_{j,n}^{\mathrm{power}} \right]^* . \tag{2}$$

Where, $S_{i,j}$ means the scattering matrix from the receiving antenna to the transmitting antenna, and $G_i^{\mathrm{R_x}}$ means the transfer function of the receiving antenna circuit.

In this model, there is no energy leakage to the outside because the infinite array antennas are assumed. However, by using an integer M and assuming the M-th or more terminated antenna elements as an “image antenna region,” it is possible to consider a system with the finite-size antennas. In this case, the amplitude of the signals in the image antenna region is expressed as follows:

$$A_{i,n}^{\mathrm{pilot}} = A_{j,n}^{\mathrm{power}} = 0 \ \ (\text{if } i > M,\ j > M). \tag{3}$$

It is assumed that there is no reflection of the pilot signal and the power signal.

4.2 Case of Infinite Array Antenna

First, the case of the infinite array antennas ($M = \infty$) is considered. In this case, From the Eqs. (1) and (2), the amplitude of the pilot signal is expressed by the following recurrence formula:

$$A_{i,n+1}^{\mathrm{pilot}} = G_i^{\mathrm{R_x}} \left[\sum_j^{\infty} S_{i,j} G_j^{\mathrm{T_x}} \left[\sum_i^{\infty} S_{j,i} A_{i,n}^{\mathrm{pilot}} \right]^* \right]^* . \tag{4}$$

When the transfer function is a constant value for each antenna element ($G_i^{\mathrm{R_x}} = G_R$, $G_j^{\mathrm{T_x}} = G_T$), Eq. (4) can be rewritten as follows:

$$A_{i,n+1}^{\mathrm{pilot}} = G_R G_T \sum_j^{\infty} S_{i,j}^* \sum_i^{\infty} S_{j,i} A_{i,n}^{\mathrm{pilot}} . \tag{5}$$

Furthermore, when the propagation space is lossless, the following equation is obtained since the S matrix is a unitary matrix [23]:

$$A_{i,n+1}^{\text{pilot}} = G_R\, G_T\, A_{i,n}^{\text{pilot}}. \tag{6}$$

From this equation, it can be seen that the field distribution of the pilot signal does not change by repeating the retrodirective when a sufficiently large antenna is used.

In this case, the whole system can be represented by an equivalent circuit having one loop transmission path. This loop transmission path is discussed in detail in Sect. 5.

4.3 Case of Finite Array Antenna

Next, the case of the transmitting antenna with finite size is considered. In this case, the pilot signal is absorbed according to Eq. (3) in the image antenna region of $j = M + 1$ or more. The amplitude of the pilot signal is represented by the following recurrence formula:

$$A_{i,n+1}^{\text{pilot}} = G_i^{\text{R}_\text{x}} \left[\sum_j^M S_{i,j}\, G_j^{\text{T}_\text{x}} \left[\sum_i^M S_{j,i}\, A_{i,n}^{\text{pilot}} \right]^* \right]^*. \tag{7}$$

The amplitude distribution of the power signal is truncated at $j = M$ in the transmitting antenna. However, this truncated field is represented by the sum of the amplitude distribution from the infinite array antenna and the inverted phase radiation field from the image antenna [20]. The former becomes the equivalent distribution to the n-th pilot signal in the same way as the transformation from Eq. (4) to Eq. (6). Therefore, Eq. (7) can be rewritten as follows:

$$A_{i,n+1}^{\text{pilot}} = G_R\, G_T \left(A_{i,n}^{pilot} - \sum_{j=M+1}^{\infty} S_{i,j}^* \sum_i^M S_{j,i}\, A_{i,n}^{\text{pilot}} \right). \tag{8}$$

From Eq. (8), it can be seen that the $(n + 1)$-th pilot signal changes so as to cancel the energy arriving at the image antenna with the n-th pilot signal. This means that the amplitude distribution changes for minimizing the leakage power to the outside.

5. System Operation with Feedback Oscillation

In the both-sides retrodirective system, the beam converges to the optimum state. However, since one loop transmission path is created by the pilot signal and the power signal, it is necessary to maintain the signals. We propose to oscillate the entire system with the pilot signal as the feedback transmission line.

When the antenna is sufficiently large, the amplitude distribution of the pilot signal does not change by the phase conjugate circuit on both sides regardless of the initial distribution as shown in Eq. (6). In this case, the system is represented by an equivalent circuit having one loop transmission path. The oscillation condition of this loop transmission path is expressed by the following equation:

$$G_R\, G_T = 1. \tag{9}$$

Unlike general feedback oscillation, the oscillation condition does not depend on the length of the loop transmission path because of the phase conjugate circuit.

We simulated the oscillation operation using the equivalent circuit of the system. Figure 8 shows the circuit simulation model of the system. This model consists mainly of three parts: the transmitter part, the receiver part, and the trigger part. In this study, the retrodirective system with a transmission distance of 400 m by the antennas with a diameter of 10 m was assumed, taking simulation time into account.

The transmitter part includes a mixer, a filter and an amplifier for generating a power signal from a pilot signal.

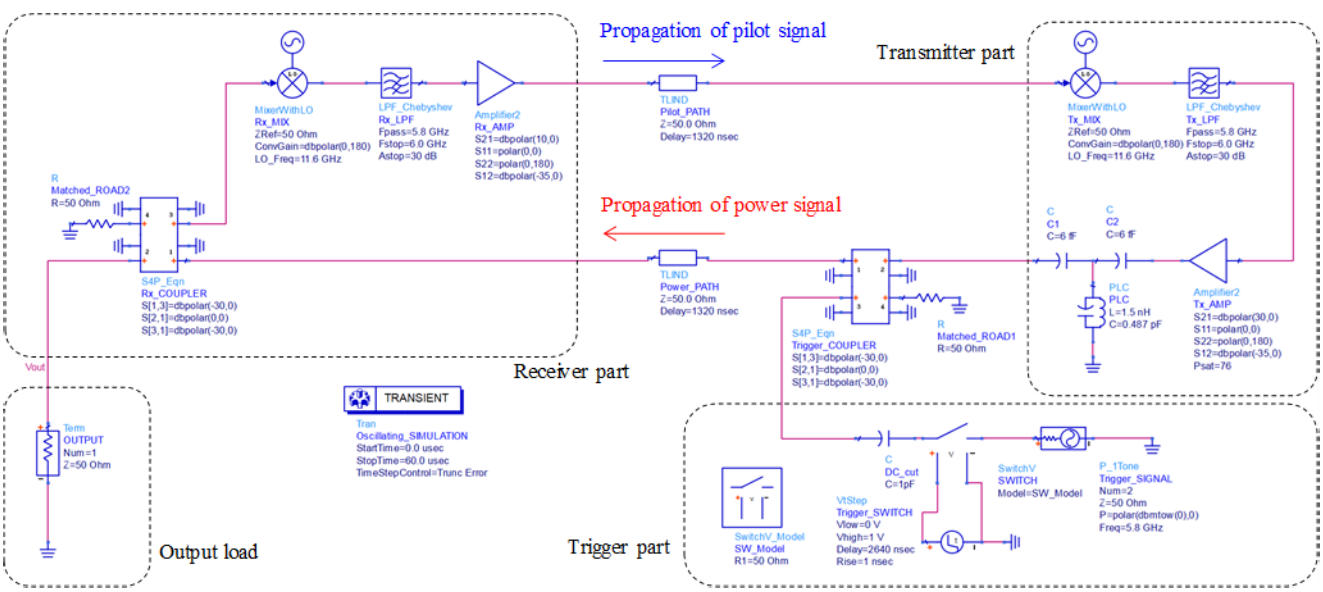

Fig. 8 Simulation model of the both-side retrodirective system in Advanced Design System (ADS).

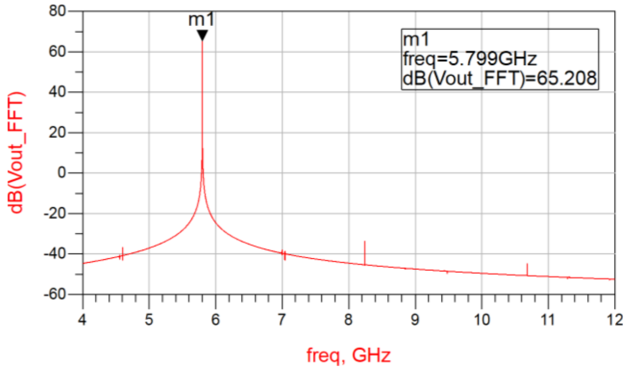

Fig. 9 Simulation result of the oscillation spectrum.

An ideal LC filter for removing harmonics was connected to the output part of the amplifier. The gain of the amplifier was set to 30 dB and the saturation output was set to 76 dBm. In the receiver part, a part of the power signal is extracted by the 30dB directional coupler. Also, a 10dB amplifier was installed to control the output of the pilot signal. Since there is no loss in each element in this simulation, the gain of this amplifier matches the loop gain of the system.

The trigger part is constituted by an oscillator and a switch for inputting an initial trigger signal to the loop line satisfying the oscillation condition. The transmission paths of the pilot signal and the power signal were put between the transmitter unit and the receiver unit. A loop is formed by these two transmission paths. When the transmission distance is 400 m, one propagation time is 1.32 μs. The trigger section was connected to this loop via a 30dB directional coupler. In an actual retrodirective system, it is now assumed that a part of the power transmitting antenna is used as the antennas for the trigger signal. The trigger signal turned off the switch after 2.64 μs corresponding to the propagation time of one loop. The level of the trigger signal was set to 0 dBm.

The transient analysis was performed under the above conditions, and the spectrum of the voltage applied to the output load was as shown in Fig. 9. It can be confirmed that oscillation occurred at 5.8 GHz. The error of the oscillation frequency is due to the accuracy of the LC filter. It was found that the output power was 75.2 dBm (65.2 dBV) and reached the saturation output of the amplifier of the power transmission section.

The input trigger signal obtains loop gain every time it circulates around the loop transmission path and finally reaches saturation output. The theoretical system activation time τ is expressed by the following equation:

$$\tau = 2T \frac{P_{\text{sat}} - P_{\text{init}}}{G_{\text{loop}}}. \tag{10}$$

Where T is the propagation time of the loop transmission path, P_{sat} is the saturation output of the amplifier, P_{init} is the input trigger signal level, and G_{loop} is the loop gain. The theoretical starting time in this simulation condition became 28 μs according to Eq. (10), and we confirmed that it almost agrees with the calculated value.

6. Conclusion

A both-sides retrodirective system is proposed and its basic operation is studied. In this system, the beam converges to the optimum state by repeating the retrodirective operation. It is also possible to follow the movement of the antenna and atmospheric fluctuations at high speed. Assuming an infinite antenna, the shape of the beam is invariant. The amplitude distribution changes for canceling energy leakage to the outside of the system in the finite antenna case. Stable power transmission becomes possible by oscillating the system.

The post-stage circuits with the ideal dynamic range are assumed in this simulation. In the future, we will clarify the specifications of the circuit necessary to satisfy the desired characteristics for the realization of the system.

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