A Novel Bi-Directional Amplifier With Applications in Active Van Atta Retrodirective Arrays

Shyh-Jong Chung, *Member, IEEE*, Shing-Ming Chen, and Yang-Chang Lee

***Abstract*—A novel two-port bi-directional amplifier, which may simultaneously amplify the waves coming from both ports, is proposed and demonstrated in this paper. Using this amplifier, a two-element active Van Atta retrodirective array is implemented and compared to a four-element passive array. The bi-directional amplifier is constructed by two identical one-port reflection-type amplifiers and a 3-dB 90° hybrid. The reflection-type amplifier is designed using an FET with a single-power-supply configuration. A quarter-wavelength microstrip radial stub is connected to the device's source terminal to narrow down the negative-resistance frequency range so as to avoid oscillation at undesired frequencies. The fabricated bi-directional amplifier provides the transmission gain over the frequency band from 5.76 to 6.88 GHz, with a peak value of 9.1 dB at 6.04 GHz. Printed Yagi antennas with four directors are adopted to build both the active and passive Van Atta arrays. The 3-dB back-scattering beamwidth of the active array is measured as wide as 74°. Finally, it is observed from the measurements that, although only half of the antenna elements are used, the active Van Atta array produces a back-scattering field level 4.5 dB, on average, higher than the passive one does. This verifies the performance of the bi-directional amplifier.**

***Index Terms*—Bi-directional amplifier, printed Yagi antenna, reflection-type amplifier, retrodirective array.**

I. Introduction

RETRODIRECTIVE antenna arrays have found many applications in wireless communications, RF identification (RFID), and intelligent transportation systems (ITSs) [1]–[6]. They can reflect an incident wave toward the source direction without any prior information on its location. Two types of retrodirective arrays are usually used. One contains the phase-conjugated-array elements [7]–[9] and the other uses the Van Atta arrangement [10]–[12]. In a phase-conjugated retrodirective array, each antenna is connected to a mixer, which in turn is pumped by a local oscillator (LO) with double the frequency of the incident wave. When an incident wave (RF signal) is caught by the antenna, it is mixed with the LO signal, leading to an IF signal reradiated out from the antenna. This IF signal has the same frequency as the incident wave, but with a conjugated phase (opposite in sign). Due to the phase conjugation, all the IF signals from the antennas would thus coherently reach a remote receiver in the wave-incidence direction, resulting in an array reradiation beam in that direction. This type of retrodirective arrays has the advantage that the array elements can be arbitrarily located, not necessary with equal inter-element spacing, nor in the same plane, thus very conformable to objects. (Nevertheless, a large inter-element spacing may cause grating reradiation beams in other directions.) Another advantage is that, by changing the LO frequency, the reradiation wave can be easily frequency modulated. On the contrary, the phase-conjugated array suffers from the disadvantage that it needs a mixer circuit with a large-frequency difference between RF and LO signals for each array element. Also, an LO with double the system frequency and a corresponding distribution network from the LO to the entire array elements are required. These make the array complicated, bulky, and high cost.

The Van Atta retrodirective array has a much simpler configuration than the phase-conjugated array does. The antennas of the Van Atta array are paired and connected by transmission lines with length differences equal to multiples of a guided wavelength [11]. The two antennas of each pair should be located symmetrically with respect to the array center. The field received by each antenna is, through the connecting transmission line, reradiated from the corresponding paired antenna. Therefore, the phase distribution for the reradiation fields at the antennas becomes reversal to that for the receiving fields at antennas, thus producing a reradiation beam in the wave-incidence direction. Unlike the phase-conjugated array where active devices are always needed, the Van Atta array can be designed with a passive or active type. As shown in Fig. 1(a), the passive Van Atta array contains only antennas and connecting transmission lines. Each antenna serves both as a receiving and transmitting antenna. The total responding field $E_{\mathrm{Passive}}(\theta)$ at an incidence angle of θ can be expressed as [11]

$$E_{\mathrm{Passive}}(\theta) = C \cdot N \cdot F^2(\theta) \tag{1}$$

where N is the number of antennas in the array, C is a factor depending on the incidence field strength and the distance between the source and the array, and $F(\theta)$ is the radiation field pattern of a single antenna. Note that the responding field level is proportional to the number of the antennas. To obtain a higher level of responding wave, more antenna elements are needed, which would complicate the layout of the transmission lines. Another way to increase the responding field level is to use the active Van Atta array, which may be implemented by inserting an ordinary unilateral amplifier [12] [see Fig. 1(b)] or a bi-directional amplifier [see Fig. 1(c)] on the midway of each transmission line [13].

For the active Van Atta array, shown in Fig. 1(b), since only the fields received by half of the antennas are amplified by the

Manuscript received January 24, 2002; revised September 6, 2002. This work was supported by the Ministry of Education and by the National Science Council, R.O.C., under Contract 89-E-FAO6–2-4.

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Digital Object Identifier 10.1109/TMTT.2002.807814

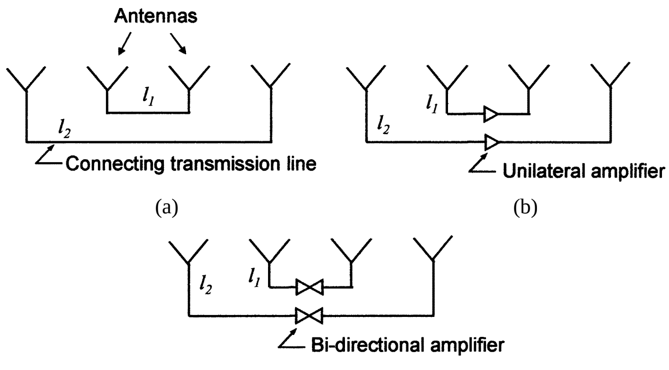


Fig. 1. (a) Passive Van Atta retrodirective array. (b) Active Van Atta retrodirective array with unilateral amplifiers. (c) Active Van Atta retrodirective array with bi-directional amplifiers.

unilateral amplifiers, the total responding field $E_{\rm Uniamp}(\theta)$ can be written as

$$E_{\rm Uniamp}(\theta) = C \cdot \frac{N}{2} \cdot G \cdot F^2(\theta) \tag{2}$$

with G being the field gain of the unilateral amplifier. For a given number of antennas, the responding field level of this active array is $G/2$ times higher than the passive one. On the other hand, the total responding field $E_{\rm Biamp}(\theta)$ of the active Van Atta array using bi-directional amplifiers [see Fig. 1(c)] is

$$E_{\rm Biamp}(\theta) = C \cdot N \cdot G \cdot F^2(\theta). \tag{3}$$

It is seen that, for a given number of antennas and a given amplifier gain, the active Van Atta array using bi-directional amplifiers possesses the responding field level 6 dB higher than that using unilateral amplifiers. In other words, to get the same responding field level, only half the number of antennas or amplifiers with 6-dB lower gain are needed in the array of bi-directional amplifiers.

Although several investigations have reported on designing bi-directional amplifiers [14], [15], they are not suitable for use in active retrodirective antenna arrays. This is because the amplification direction of these amplifiers was controlled by switches and, thus, the amplifiers could not simultaneously function in both directions. Karode and Fusco [13] developed an active Van Atta array by using a bi-directional amplifier. In their design, the bi-directional amplifier was constructed by using two Wilkinson power dividers and two unilateral amplifiers. The power dividers were connected back-to-back to form a two-port circuit, and the two unilateral amplifiers were embedded, with opposite directions, on the midways of the two microstrip lines connecting the dividers. When a wave enters either port of the bi-directional amplifier, it is amplified by one of the unilateral amplifiers and then leaves from the other port. Since the wave would pass through two power dividers for either direction, there will be 6-dB power loss in the path. Therefore, the responding power level of this design is the same as that of unilateral amplifiers [see Fig. 1(b)], although twice the number of amplifiers and extra power dividers were used. Popović and Mortazawi [16] implemented a bi-directional amplifier array using dual-polarized patch antennas. Two

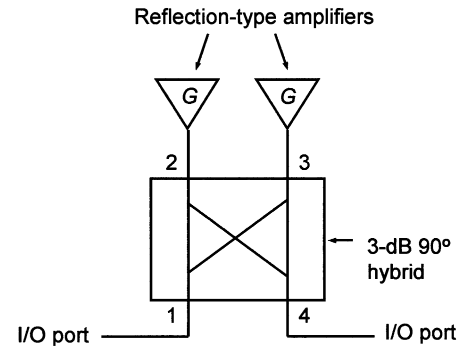


Fig. 2. Configuration of the proposed bi-directional amplifier.

unilateral amplifiers, one for each direction, were used for the bi-directional amplification. Both the vertical and horizontal field polarizations were needed in the operation of their system. In each propagation direction, the amplified retransmitting wave from the array was orthogonal in polarization to the wave incident on the array.

In this paper, we propose a novel bi-directional amplifier and apply it in designing an active Van Atta array. The bi-directional amplifier is constructed by two identical reflection-type amplifiers [17]–[19] and a 3-dB 90° hybrid. Without introducing extra path loss or using different wave polarizations, this amplifier provides the same gain as the reflection-type amplifiers in both directions. Besides applied in building active retrodirective arrays, the present bi-directional amplifier design can also be used in a compact communication system [15]. Section II presents the configuration of the proposed bi-directional amplifier. The operation principle of the amplifier is shown. Section III describes the amplifier's design and implementation. Transistors are used to accomplish the reflection-type amplifiers and a branch-line coupler provides the function of the 3-dB 90° hybrid. The fabricated bi-directional amplifier is then used to construct a two-element active Van Atta array, as shown in Section IV. Printed Yagi antennas [20], which possess wide bandwidths and endfire patterns, are used in the array. A four-element passive Van Atta array using the same antennas is also built for comparison. Section V presents the conclusions.

II. Principle of the Bi-Directional Amplifier

Fig. 2 shows the proposed configuration of the bi-directional amplifier, which contains two reflection-type amplifiers with a gain of G and a 3-dB 90° hybrid. The amplifiers are separately connected to ports 2 and 3 of the hybrid. The other two ports (ports 1 and 4) of the hybrid serve as the input/output (I/O) ports of the bi-directional amplifier.

The scattered wave $\overline{V}^-$ $(= [V_1^-, V_2^-, V_3^-, V_4^-]^t)$ of the quadrature hybrid is related to the incident wave $\overline{V}^+$ $(= [V_1^+, V_2^+, V_3^+, V_4^+]^t)$ through the scattering matrix [21]. Let a wave be incident on the bi-directional amplifier from port 1 of the hybrid with port 4 terminated (i.e., $V_4^+ = 0$). By using the scattering matrix of the quadrature hybrid, and noticing that $V_2^+ = GV_2^-$ and $V_3^+ = GV_3^-$, one obtains

$$V_1^- = 0,\ V_4^- = jGV_1^+. \tag{4}$$

It is seen that no power is reflected back to the input port and that the transmission gain $|V_4^-/V_1^+|$ is exactly the same as the gain G of the reflection-type amplifier. The same results can also be derived when the wave is incident on the bi-directional amplifier from the other I/O port (namely, port 4 of the hybrid).

In a hybrid circuit design, the two reflection-type amplifiers are usually built by separate active devices. This would cause a small deviation ΔG between the gains of the reflection-type amplifiers. Under this condition, the reflection coefficient $|V_1^-/V_1^+|$ and transmission gain $|V_4^-/V_1^+|$, for an incident wave from port 1 can be derived as

$$\left|\frac{V_1^-}{V_1^+}\right| = \frac{\Delta G}{2} \tag{5}$$

and

$$\left|\frac{V_4^-}{V_1^+}\right| = G\left(1 + \frac{\Delta G}{2G}\right). \tag{6}$$

The same results can be obtained when the wave is incident from port 4. It is seen that the transmission gain has little change and the input matching is somewhat deteriorated when the two reflection-type amplifiers are not entirely symmetrical.

III. Design and Implementation of the Bi-Directional Amplifier

The design of the proposed bi-directional amplifier includes designing a 3-dB 90° hybrid and a reflection-type (one-port) amplifier. In this study, a branch-line coupler is used to provide the function of the quadrature hybrid. At the design frequency of 6 GHz, the measured return loss and the isolation of the coupler are both better than 25 dB. The insertion loss from ports 1 to 2 and that from ports 1 to 3 are −3.2 dB, which are very close to the design value (−3 dB). Within the frequency band from 5.42 to 6.67 GHz, the measured power split ratio between ports 2 and 3 is smaller than 1.26 and the return loss and isolation are better than 15 dB.

The design of the reflection-type amplifier is quite similar to that of an oscillator. The reflection coefficient Γ at the input port of the circuit is expressed as

$$\Gamma = \frac{Z_{\text{in}} - Z_S}{Z_{\text{in}} + Z_S} \tag{7}$$

where Z_{in} $(= R_{\text{in}} + X_{\text{in}})$ is the input impedance of the one-port circuit to be designed and Z_S is the output impedance of the previous circuit, which is usually 50 Ω at the design frequency, but would vary at other frequencies. For an oscillator, the real part $\text{Re}\{Z_{\text{in}} + Z_S\}$ of the denominator in (7) is designed negative and the imaginary part $\text{Im}\{Z_{\text{in}} + Z_S\}$ is set to be zero at the desired frequency. For a reflection-type amplifier, the real part can be designed to have a small absolute value to obtain a high reflection gain and the imaginary part is designed nonzero to avoid oscillation. Both circuits need a negative input resistance.

The reflection-type amplifier in this investigation is designed using the device NE32584c (a pseudomorphic heterojunction FET), whose nonlinear equivalent-circuit model can be obtained from the NEC web site. The commercial software HP Series IV (Hewlett-Packard Company, Santa Rosa, CA) is used for the simulation. Fig. 3 shows the circuit diagram of the reflection-type amplifier. To simplify the biasing of the circuit, we adopt the single-power-supply configuration. A dc voltage V_{DD} is applied to the drain of the device through a high-impedance choke. The gate is dc short circuited via another choke and the source is connected to ground through a resistor in parallel with an ac bypass capacitor. This source resistor would result in a negative-bias voltage between the gate and source terminals, and also introduce a negative feedback path to stabilize the biasing current (I_D). To produce a negative input resistance, the device should operate in the unstable region. To this end, a short section of microstrip line, which is equivalent to a series inductor, is inserted between the device's source terminal and source resistor. Also, an open-ended microstrip line is connected to the drain terminal. By suitably controlling the lengths of these microstrip lines, the input resistance at the gate could exhibit negative values.

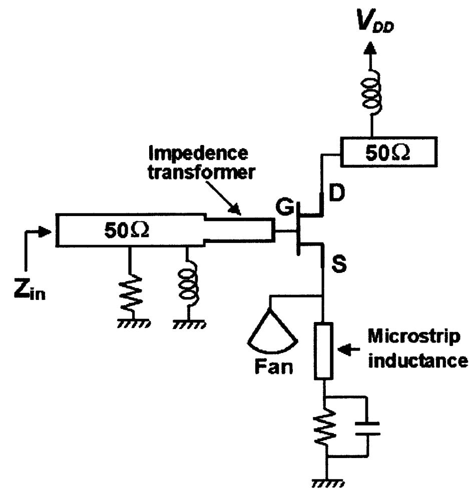


Fig. 3. Circuit diagram of a reflection-type amplifier.

After simulation, it was found that two wide negative-resistance frequency bands, including that (namely, the lower band) containing the design frequency, appear in the range from dc to 20 GHz. This phenomenon is not desired since the circuit may oscillate at frequencies in these negative-resistance bands. To reduce the frequency range with negative resistance, a quarter-wavelength microstrip radial stub for the higher negative-resistance band is connected to the source terminal of the device. This radial stub produces an ac short at the source terminal, thus preventing the device from operating in the unstable region at the higher frequency band. Note that, in Fig. 3, an impedance transformer is used to transform the negative input resistance at the gate to a value near −50 Ω. Also, a shunt resistance is added at the input 50-Ω line. Simulation shows that the negative-resistance frequency range can be further reduced by adding this shunt resistance.

Fig. 4 shows general agreement in the shape of the response between the simulated and measured gains (i.e., the reflection coefficients Γ) of the reflection-type amplifier. The measurement (by using an HP 8510 network analyzer) shows that a peak reflection gain of 8.1 dB occurs at the frequency of 6.26 GHz. In the frequency range from 5.6 to 7 GHz, the fabricated amplifier provides a reflection gain larger than 0 dB. It has also been

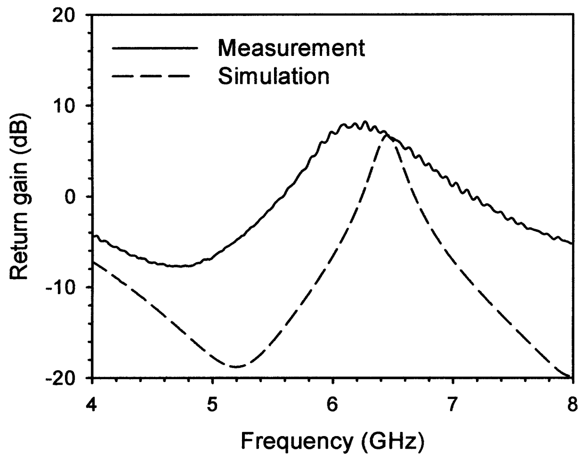


Fig. 4. Measured and simulated gains of the reflection-type amplifier.

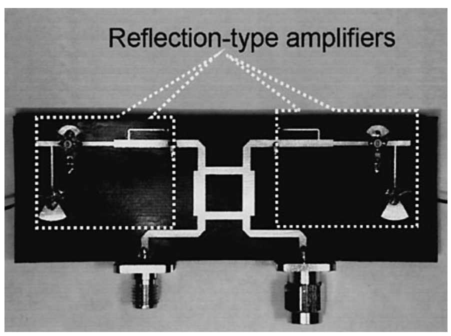


Fig. 5. Photograph of the finished bi-directional amplifier.

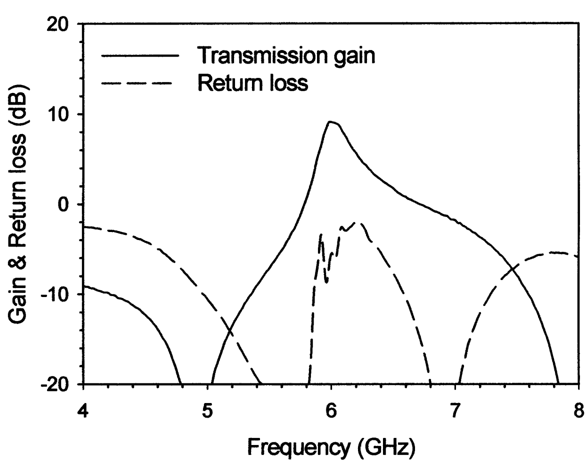


Fig. 6. Measured transmission gain and return loss of the bi-directional amplifier.

checked by using a spectrum analyzer that, from dc to 20 GHz, no self-oscillating signals were produced from the amplifier.

The reflection-type amplifier is integrated with the branch-line coupler to form a bi-directional amplifier, as shown in Fig. 5. The measured frequency responses of the return loss and transmission gain of this amplifier are illustrated in Fig. 6. It is observed that the amplifier provides the transmission gain over the frequency band from 5.76 to 6.88 GHz. At 6.04 GHz, the transmission gain has a maximum value of 9.1 dB, which is 1 dB higher than that of the reflection-type amplifier. The reason for this gain deviation is due to the performance fluctuation between separate devices (NE32584c). As stated earlier, in the design of the reflection-type amplifier, the real part $\mathrm{Re}\{Z_{\mathrm{in}} + Z_S\}$ of the denominator in (7) is designed near zero in order to get a higher gain. The fluctuation of the device performance would cause a small variation in Z_{in}, thus resulting in a change of the reflection gain. Also noticed from Fig. 6 is that, although the measured return loss of the bi-directional amplifier is lower than 0 dB over the whole interested frequency band, the result is not good enough. At the maximum-gain frequency (6.04 GHz), the return loss is only -6 dB, which is higher than that (-16 dB) of the simulation one. (Here, the measured scattering parameters of a reflection-type amplifier were used to simulate the behaviors of the bi-directional amplifier.) As shown in (5), the return loss of the bi-directional amplifier may be raised due to the asymmetry of the circuit, namely, the performance deviation of the two active devices. For further verification, instead of using identical scattering parameters for the two reflection-type amplifiers, separate sets of the scattering parameters measured from two individual reflection-type amplifiers were adopted in the simulation of the bi-directional amplifier. The new simulation shows that, the return loss enhances to −8 dB at the frequency of 6.04 GHz, which is very close to the measured one. Nevertheless, the poor match of the bi-directional amplifier would cause direct radiation from each antenna element in an active Van Atta array, thus interfering the back-scattering field pattern of the array. To reduce the return loss of the bi-directional amplifier, a monolithic microwave integrated circuit (MMIC) process may be used to increase the similarity of the two devices.

IV. Active Van Atta Retrodirective Array

A two-element active Van Atta array was built using the fabricated bi-directional amplifier. The printed Yagi antenna [20], which has a wide bandwidth and an endfire radiation pattern, was adopted as the array element. The antenna was designed on the substrate of Duroid 5880 with $\varepsilon_r = 2.2$ and $h(\text{thickness}) = 0.508$ mm. The signal is fed from the input 50-Ω microstrip line, through a quarter-wave transformer, to the printed driven dipole (see the inset of Fig. 7). The driven dipole has one arm printed on the top side of the substrate and the other arm on the bottom side. The truncated ground plane of the microstrip line on the bottom side serves as the reflector of the Yagi antenna. Four printed metal strips are used as the directors. The measured results show that the antenna has a minimum return loss of −16 dB, with a 10-dB return-loss bandwidth of 500 MHz (from 5.88 to 6.38 GHz). Fig. 7 presents the measured E-plane radiation pattern of the antenna at 6.04 GHz. It is seen that the antenna gain is 7.4 dBi, with a half-power-beamwidth of 55°.

The fabricated two-element active Van Atta array is shown in Fig. 8(a). For comparison, a four-element passive Van Atta array, as illustrated in Fig. 8(b), was also constructed. Consider that a plane wave with parallel polarization is incident toward the active Van Atta array at an angle θ, as illustrated in Fig. 8(a). The field received by one of the Yagi antennas is amplified by the bi-directional amplifier, and then reradiated from the other antenna. Similarly, the field received by the other antenna will

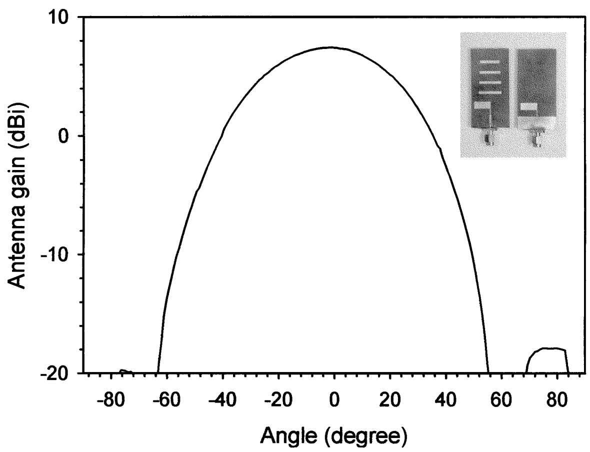
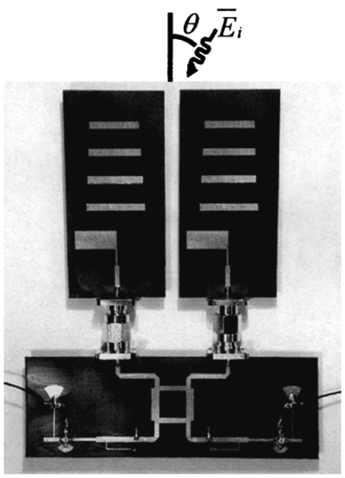
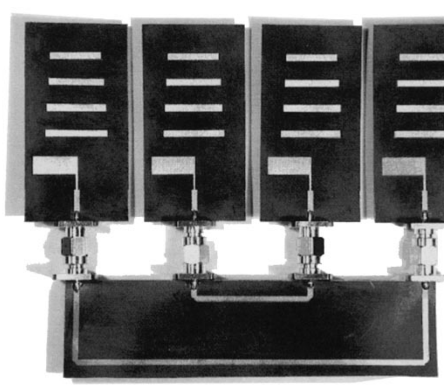


Fig. 7. Measured E-plane radiation pattern of the printed Yagi antenna, as shown in the inset ($f = 6.04$ GHz).



(a)



(b)

Fig. 8. (a) Two-element active Van Atta array. (b) Four-element passive Van Atta array.

pass the amplifier in the reverse direction and be reradiated by the first antenna. It is noticed that the two reradiated fields from the antennas have levels G times those of the received fields. Also, they have the same phase delay in the wave-coming direction and, thus, would be constructively added in that direction.

The back-scattering patterns of the active and passive retrodirective arrays were measured and compared, as shown in Fig. 9. It is seen that both the back-scattering patterns are wide. The

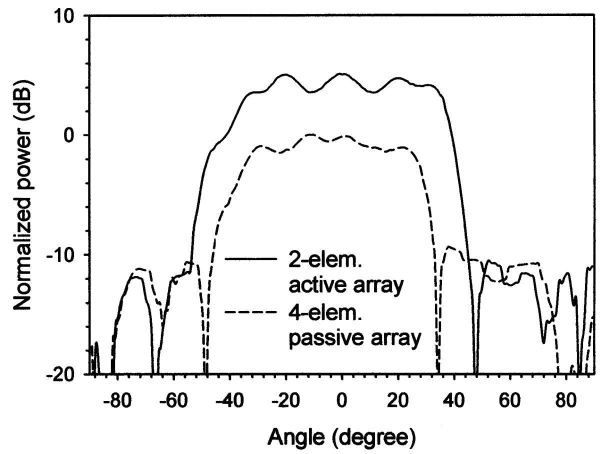


Fig. 9. Measured back-scattering field patterns of the active and passive retrodirective arrays ($f = 6.04$ GHz).

3-dB beamwidth of the active array is 74° and that of the passive array is 65°. Theoretically, from (1) and (3), these patterns should have the same beamwidths as that of the square pattern of the Yagi antenna. The increase of the back-scattering beamwidths in these arrays may be due to the interaction between the antennas and circuits. The mutual coupling between the antennas may also affect the patterns. It is observed from this figure that the back-scattering field level of the active array is, on average, 4.5 dB higher than that of the passive one, although the antenna number of the former array is only half that of the latter one. Comparing (3) and (1), the ratio ξ of the back-scattering field levels of the two arrays is expressed as

$$\xi \equiv \frac{E_{\text{active}}(\theta)}{E_{\text{passive}}(\theta)} = \frac{N_{\text{active}}}{N_{\text{passive}}} G = \frac{G}{2} \tag{8}$$

where N_{active} $(= 2)$ and N_{passive} $(= 4)$ are the number of antennas in the array. Thus, the field gain of the bi-directional amplifier in the active array can be estimated as $G = 2\xi = \xi_{dB}{+}6$ dB $= 4.5$ dB$+6$ dB $= 10.5$ dB. This estimation is based on the theoretical formula in (3) and (1), and is higher than that of the bi-directional amplifier measured without antennas. Note that, when measuring the gain of the bi-directional amplifier using a network analyzer, the two ports of the amplifier are both connected to two perfect 50-Ω loads. However, in the active Van Atta array, two Yagi antennas are mounted to the amplifier's ports. This would slightly influence the impedances (Z_S) seen by the reflection-type amplifiers, thus changing the amplifier's gain.

V. Conclusions

A bi-directional amplifier composed of two reflection-type amplifiers and a 3-dB 90° hybrid has been proposed and demonstrated. The operation principle and design procedure of the amplifier have been thoroughly described. A two-element active Van Atta retrodirective array using the bi-directional amplifier was built and compared to a four-element passive array. The measurement results showed that the bi-directional amplifier provided a peak transmission gain of 9.1 dB at 6.04 GHz, which was a little higher than that of a reflection-type amplifier. The active Van Atta array possessed a 3-dB back-scattering beamwidth as wide as 74°. Finally, it was measured that, due to the amplification of the bi-directional amplifier, the back-scattering field level of the two-element active array was 4.5 dB higher than that of the four-element passive one.

In the design of the bi-directional amplifier, it was found that the circuits to be connected to the amplifier should have higher return-loss bandwidth than the negative-resistance bandwidth of the reflection-type amplifiers. This can avoid the signal oscillation in the reflection-type amplifiers. It was also observed that the similarity of the devices' characteristics has an influence on the performance of the bi-directional amplifier, especially on the amplifier's return loss.

REFERENCES

[1] C. W. Pobanz and T. Itoh, "A conformal retrodirective array for radar applications using a heterodyne phased scattering element," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1995, pp. 905–908.

[2] E. L. Gruenberg and C. M. Johnson, "Satellite communications relay system using a retrodirective space antenna," *IEEE Trans. Antennas Propagat.*, vol. AP-12, pp. 215–223, Mar. 1964.

[3] S. L. Karode and V. F. Fusco, "Self-tracking duplex communication link using planar retrodirective antennas," *IEEE Trans. Antennas Propagat.*, vol. 47, pp. 993–1000, June 1999.

[4] C. Luxey and J.-M. Laheurte, "A retrodirective transponder with polarization duplexing for dedicated short-range communications," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 1910–1915, Sept. 1999.

[5] S.-J. Chung, T.-C. Chou, and Y.-N. Chiu, "A novel card-type transponder designed using retrodirective antenna array," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 2001, pp. 1123–1126.

[6] C. Cavello, B. Baertlein, and J. Young, "Radar retro-reflective patch for vehicle convoying applications," in *IEEE Intelligent Transportation System Conf. Dig.*, 1997, pp. 667–671.

[7] C. Y. Pon, "Retrodirective array using the heterodyne technique," *IEEE Trans. Antennas Propagat.*, vol. AP-12, pp. 176–180, Mar. 1964.

[8] R. Y. Miyamoto, Y. Qian, and T. Itoh, "A novel retrodirective array using balanced quasioptical balanced FET mixers with conversion gain," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1999, pp. 655–658.

[9] ——, "A reconfigurable active retrodirective/direct conversion receiver array for wireless sensor systems," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 2001, pp. 1119–1122.

[10] L. C. Van Atta, "Electromagnetic reflector," U. S. Patent 2 908 002, Oct. 1959.

[11] S.-J. Chung and K. Chang, "A retrodirective microstrip antenna array," *IEEE Trans. Antennas Propagat.*, vol. 46, pp. 1802–1809, Dec. 1998.

[12] H.-T. Chen and S.-J. Chung, "Design of a planar array transponder with broad responding beam," *IEEE Microwave Guided Wave Lett.*, vol. 7, pp. 297–299, Sept. 1997.

[13] S. L. Karode and V. F. Fusco, "Multiple target tracking using retrodirective antenna arrays," in *IEE Nat. Antennas and Propagation Conf.*, 1999, Conf. Pub. 461, pp. 178–181.

[14] T. Tsukii and S. G. Houng, "Wideband bi-directional MMIC amplifiers for new generation T/R module," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1990, pp. 907–910.

[15] J. W. Archer, O. Sevimli, and R. A. Batchelor, "Bi-directional amplifiers for half-duplex transceivers," in *21st Annu. GaAs Integrated Circuits Symp.*, 1999, pp. 251–254.

[16] Z. Popović and A. Mortazawi, "Quasi-optical transmit/receive front ends," *IEEE Trans. Microwave Theory Tech.*, vol. 46, pp. 1964–1975, Nov. 1998.

[17] H. Tohyama and H. Mizuno, "23-GHz band GaAs MESFET reflection-type amplifier," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 408–411, May 1979.

[18] P. Gardner and D. K. Paul, "Aspects of the design of low noise, negative resistance, reflection mode transistor amplifiers," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 1869–1875, Nov. 1991.

[19] H. Barth and M. Pirkl, "A 2 W solid state transmitter for short range data communication at 60 GHz," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1990, pp. 931–933.

[20] Y.-C. Lee and S.-J. Chung, "Design of a 38-GHz printed Yagi antenna with multiple directors," in *IEEE AP-S Int. Symp. Dig.*, 2001, pp. 606–609.

[21] D. M. Pozar, *Microwave Engineering*, 2nd ed. New York: Wiley, 1998, ch. 7.

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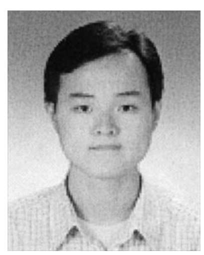

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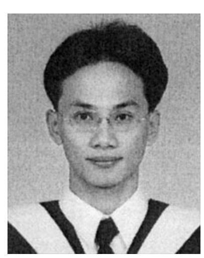

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