Amplifying Active Reflect-Antenna Using a Microstrip-T Coupled Patch—Design and Measurement

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***Abstract*—A compact design of an amplifying active reflect-antenna using a novel microstrip-T coupled-patch antenna is proposed. The dual-polarized ports of the microstrip-T coupled-patch antenna provide excellent RF isolation as well as dc isolation. The dc isolation helps in avoiding additional coupling capacitors in the RF path, thereby achieving reduced layout size and cross-polarization levels for the active reflect-antenna. The gain and monostatic radar cross section (RCS) measurement of the active reflect-antenna has been carried out using a time-domain technique based on a single dual-polarized antenna and vector network analyzer. The measured monostatic RCS and gains are then compared with the calculated ones using two different modeling approaches.**

***Index Terms*—Active reflect-antenna.**

I. Introduction

WITH THE advancement in the design of microwave integrated circuits and monolithic microwave integrated circuits, active integrated antennas and their applications has been a growing area of research over the last decade [1]. The application of active antennas ranges from its function as a simple space–circuit interface such as an on-chip active antenna element to large spatial power-combining arrays [2]. While most of the papers concerning spatial power combining use the incident and reflected beam of the array on the opposite sides of the array, some of the active array architectures recently proposed require the incident and transmitted beams of the array on the same side of the array, e.g., retrodirective arrays [3] and amplifying reflect-arrays [4]. Since the receiving and transmitting beams are located on the same side of the array, these arrays, in general, can be classified as active reflect-arrays. One of the principal requirements of the active reflect-arrays is to differentiate between the interrogating signal or incident beam from the answering signal or reflected beam. A common way to achieve this task is to use polarization diversity between the interrogating and answering signal, as in the retrodirective array reported in [5], and the power-combining reflect-array reported in [6]. Therefore, the design of active antennas for these arrays becomes more challenging for achieving a monolithic design, as most of the usual dual-polarized antennas (DPAs) are of multilayered type or complex [7]–[10]. For achieving polarization diversity, the reported retrodirective array in [5] uses a two-layer aperture-coupled antenna with a cross-shaped patch, whereas the amplifying reflect-array reported in [6] uses a conventional slot coupled patch with displaced slots. In this paper, we propose the design of an amplifying active reflect-antenna by using a novel dual-polarized patch antenna with electromagnetically coupled microstrip-T junction feeds. The DPA, called a microstrip-T coupled-patch antenna [11], has the principal advantage that it is compact and, therefore, suitable for active antenna integration. The proposed antenna also has the advantages of excellent RF isolation and inherent dc isolation between the ports. The inherent dc isolation helps us in eliminating dc blocking capacitors in the RF path of signal-processing circuits, e.g., an amplifier in the case of the amplifying type reflect-array. It has also been observed that the bandwidth of the microstrip-T coupled-patch antenna is comparatively larger than other single-layer feeding methods such as the probe and edge coupled feeding methods [7].

Accurate characterization of the single active reflect-antenna element is a crucial factor for the overall design success of the active reflect-arrays. The monostatic radar cross section (RCS) of the active reflect-antenna element is one such factor required for the design of the complete array. Due to the small aperture size and the usual low antenna gain of the reflect-antenna element, the monostatic RCS measurement can be challenging due to the weak reflected signal. Classical methods for the measurement of the monostatic RCS involves two orthogonally polarized probe antennas where one functions as the interrogating antenna and the other functions as the listening antenna. This method is prone to errors due to the mutual coupling between the probe antennas and their large sizes compared to the low-profile active antenna element at close distances [12]. In this paper, we follow a measurement technique for the gain and monostatic RCS of the amplifying reflect-antenna element based on a single dual-polarized probe antenna and a network analyzer operating in the time domain. Further, for studying the interaction of the active components on the transmit–receive performance of the amplifying reflect-antenna (ARA), we designed a passive reflect-antenna by bridging the dual-polarized ports of the microstrip-T coupled-patch antenna with a transmission line. The gain measurements of the active reflect-antenna are then compared with the prediction based on a single antenna and on the measurement based on the passive reflect-antenna.

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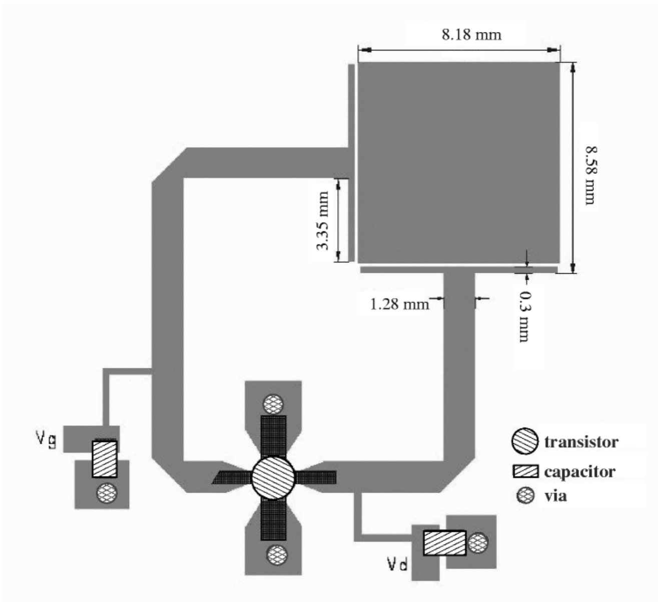

Fig. 1. Layout configuration of the amplifying active reflect-antenna.

II. Configuration of the Amplifying Active Reflect-Antenna

The layout configuration of the amplifying active reflect-antenna designed is shown in Fig. 1. As can be seen from Fig. 1, the passive antenna part of the active reflect-antenna designed at a frequency of 10.034 GHz consists of two similar electromagnetically coupled microstrip-T junctions on the adjacent sides of a square microstrip patch. The small width of the microstrip-T causes the direction of the currents in the two arms of the microstrip-T close to the patch to be in opposite directions and opposite to the exited TM-mode currents in the patch. Therefore, the normal patch radiation pattern is affected very little by the microstrip-T. For a given patch dimension, the parameters in attaining matching at the ports are the dimensions of the microstrip-T and its spacing from the patch. Therefore, the microstrip-T junction acts as an impedance transformer, transforming the high radiation resistance of the patch to the desired low impedance, which, in our case, is 50 Ω. As can be seen from Fig. 1, apart from the microstrip-T coupled passive antenna part, the other constituent building blocks of the ARA are the sandwiched amplifier between the dual-polarized ports and the dc-bias circuitry for the amplifier. Since the microstrip-T coupled patch is used as the radiating element, the dual-polarized ports of the antenna are dc isolated. Thus, additional coupling capacitors, which may increase the cross-polarization and design complexity, can be avoided in the RF path of the amplifier. The substrate used for the design has a thickness of 0.5 mm, $\varepsilon_r = 3.0$, and $\tan\delta = 0.003$. The microstrip-T coupled-patch antenna was designed using a method-of-moments-based computer-aided design (CAD) tool.[1] The dimensions of the microstrip-T coupled-patch antenna with identical port configurations, fabricated on a substrate of size approximately 6 × 6 cm is shown in Fig. 1. The total length of the antenna in Fig. 1, which is approximately 1.7 cm, may be further reduced for array applications by bringing the bends closer and with accurate characterization of the element. For the amplifier part of the active reflect-antenna, we used a packaged pseudomorphic high electron-mobility transistor (pHEMT) transistor (Agilent ATF-36077) having a manufacturer specified gain ($|S_{21}|$ referenced to 50 Ω) of about 11 dB at the design frequency. It is to be noted that in the configuration of Fig. 1, the transistor is not matched to optimum gain because of the 50-Ω input impedance offered by the microstrip-T coupled patch to the transistor ports. However, it may be possible to attain a match for the transistor by adjusting the dimensions of microstrip-T and its spacing with the patch. This method is useful for designing active antennas with optimum noise figure and gain, as in [13], or active antennas with high efficiency, as in [14]. One of the crucial parameter of the active reflect-antenna element is its stability over the frequency band of interest. Although stability of the active reflect-antenna element over the tuning range of the antenna has been verified experimentally, it is desirable to predict the stability before implementation. For a single active reflect-antenna element with active components isolated from radiating part, it may be possible to theoretically examine the stability by mapping the antenna impedances to the input and output of the active circuit through the transmission lines. A two-port stability analysis technique for active circuits, such as the method described in [15], may be useful in this context. Factors such as the proximity of the active components with the antenna and the strong electromagnetic fields due to finite ground plane along the surface where active devices are located has to be taken into account for accurate stability analysis. The methods described in [16] and [17] to study the interaction between the active component and antenna is promising in this context. For large arrays involving the active antenna, the modeling of overall stability may be even more challenging due to the mutual coupling between the elements and computational complexity in the analysis. The measurement of the dual-polarized passive antenna part of the amplifying active reflect-antenna was separately carried out for its return loss and isolation between the ports in [11]. The measured return loss and isolation between the ports at the tuning frequency of 10.034 GHz are approximately 27 and 32 dB, respectively. The 10-dB return-loss bandwidth of 2.1% for the microstrip-T coupled-patch antenna is higher than the bandwidth attainable using usual matching techniques such as a quarter-wave transformer for an edge coupled-patch antenna or for a coax fed patch antenna on a similar substrate [7]. The isolation between the ports, which is better than 27 dB for the entire ≤10-dB *return loss* range is also a desirable characteristic for active antenna applications [11]. Therefore, the proposed method of using a microstrip-T coupled patch for the active reflect-antenna not only makes the design low profile, but also helps us in achieving excellent electrical performance in terms of isolation and bandwidth. The measured radiation patterns of the microstrip-T coupled-patch antenna [11] was also found to be similar to the characteristics to a square patch antenna.

[1]*Momentum* EM Simulation Tool, Agilent Technol., Palo Alto, CA.

III. Modeling and Measurement of the Active Reflect-Antenna

The characteristics of the amplifying active reflect-antenna studied are its monostatic and bistatic-RCS patterns [18] and

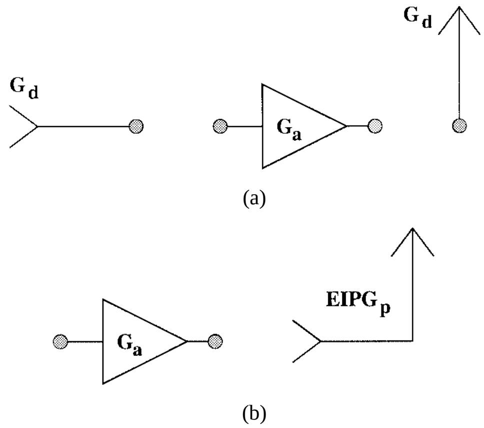

Fig. 2. Two methods followed for modeling the ARA. (a) Single-antenna method. (b) Passive reflect-antenna method.

the effective isotropic power gain (EIPG) [19], [20]. Two different approaches were followed to model the EIPG. In the first method, hereafter referred to as the single-antenna method [see Fig. 2(a)], the ARA is modeled as an interconnection of the horizontally polarized antenna (HPA), amplifier, and the vertically polarized antenna (VPA). Assuming that the horizontally and VPAs have the same gain G_d, the EIPG for the ARA EIPG_a using this model can be written as

$$\mathrm{EIPG}_a = G_d^2 G_a \tag{1}$$

where G_a is the amplifier gain. In the second modeling approach [see Fig. 2(b)], hereafter referred to as the passive reflect-antenna method, a passive reflect-antenna is fabricated similar to Fig. 1 and of the same size by bridging the ports of the microstrip-T coupled-patch antenna with a microstrip line and removing the amplifier and its associated bias circuitry. The EIPG of the ARA can be written as the product of the EIPG of the passive reflect-antenna EIPG_p and the amplifier gain G_a as

$$\mathrm{EIPG}_a = \mathrm{EIPG}_p G_a \tag{2}$$

The EIPG of the amplifying or passive reflect-antenna can be found out from a monostatic RCS measurement. The classical measurement setup [12] for the monostatic RCS needs two separate orthogonally polarized probe antennas similar to the bistatic RCS measurement method [see Fig. 3(a)]. However, due to the small aperture size and low antenna gain of the reflect-antenna element, the reflect-antenna element and the probe antennas are located in close proximity, yet at the far field of each antenna. If we use high-gain probe antennas such as horn antennas, their sizes becomes large. This results in geometrical errors in the monostatic RCS measurement setup when the vertically and horizontally polarized probe antennas and the active reflect-antenna element are close together. In the method followed for the monostatic RCS measurement, we used a single DPA, as shown in Fig. 3(b). A similar setup using a DPA with a high degree of isolation between the ports has also been used for the characterization of the ARA in [6]. The DPA used in our measurement is the microstrip-T coupled-patch part of the ARA shown in Fig. 1 [11]. The magnitude of the forward transmission between the orthogonally polarized ports of the DPA $|S_{21}|$ for this case can be written using the two-way Friis transmission formula as

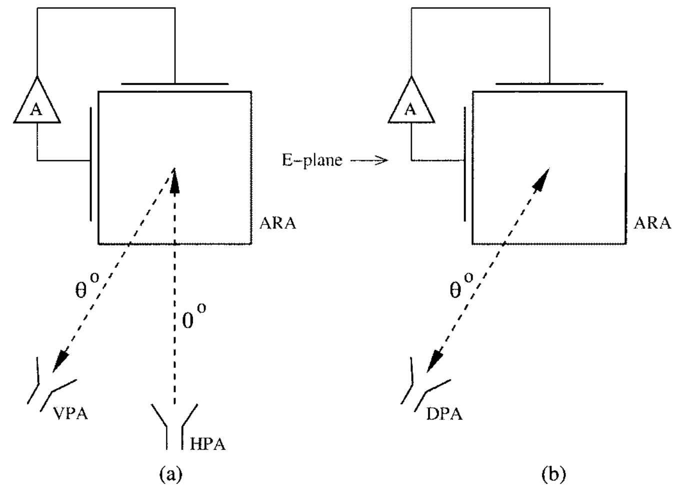

Fig. 3. (a) Setup for the measurement of the bistatic RCS of the ARA using a VPA and HPA. (b) Setup for the measurement of the monostatic RCS using a single DPA.

$$|S_{21}|^2 = G_r G_a G_t G_d^2 \left(\frac{\lambda}{4\pi R}\right)^4 \tag{3}$$

where G_r and G_t are the receiving and transmitting antenna gains of the active reflect-antenna, respectively, and G_a is the amplifier gain. The broad side gain of the transmitting and receiving parts of the DPA are equal and are represented as G_d in (3), λ is the measurement wavelength, and R is the distance between the reflect-antenna and DPA [see Fig. 3(b)]. Using the definition of monostatic RCS σ_m [18], we can write

$$\sigma_m = G_r G_a G_t \frac{\lambda^2}{4\pi}. \tag{4}$$

Therefore, from (3) and (4), we can write

$$\sigma_m = |S_{21}|^2 \frac{(4\pi)^3 R_4}{G_d^2 \lambda^2}. \tag{5}$$

The product $G_r G_a G_t$, which is the EIPG, can be written in terms of σ_m as

$$\mathrm{EIPG}_a = \frac{4\pi\sigma_m}{\lambda^2}. \tag{6}$$

It is to be noted that the same analysis, i.e., (3)–(6), holds for the passive reflect-antenna, as well as with $G_a = 1$ and EIPG_a replaced with EIPG_p in (6). From (5) and (6), we can see that, by measuring the forward transmission between the DPA ports, $|S_{21}|$ using a vector network analyzer, we can find the monostatic RCS and EIPG of the active or passive reflect-antenna element.

One of the principal concerns in the single DPA measurement method is the coupling from the transmitting port to the receiving port of the DPA. This can result in the phase cancellation of the reflected signal with the coupled signal between the vertically and horizontally polarized ports of the DPA. In the method, we followed the mutual coupling between the vertically and horizontally polarized ports of the DPA when it radiates into

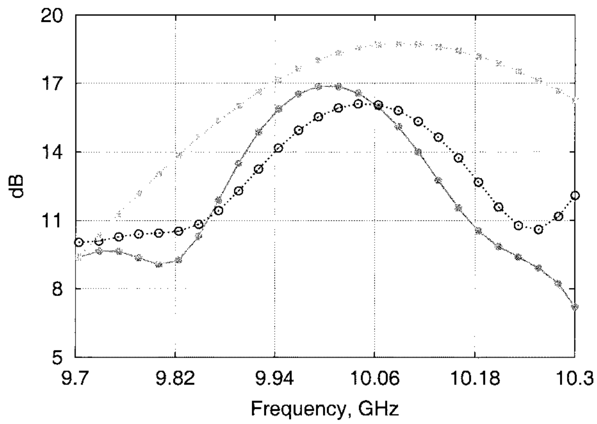

Fig. 4. EIPG of the amplifying reflect-antenna. ■: calculated using the measured gain of the single antenna. ○: calculated using the measured EIPG of the passive reflect-antenna. ●: measured.

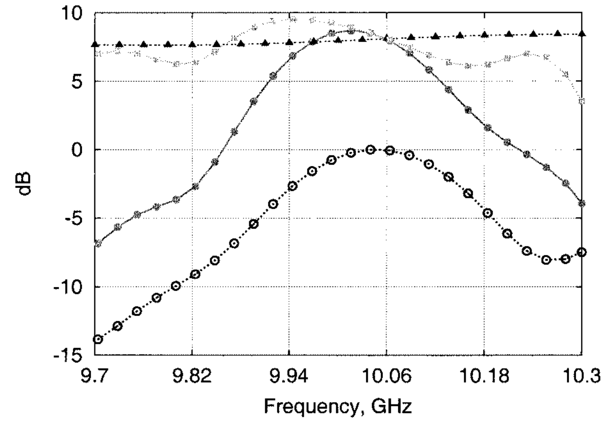

Fig. 5. ●: measured monostatic RCS of the amplifying reflect-antenna normalized to the maximum measured monostatic RCS of the passive reflect-antenna. ○: measured normalized monostatic RCS of the passive reflect-antenna. ■: calculated amplifier gain using the measured monostatic RCS of the amplifying reflect-antenna and the passive reflect-antenna. ▲: measured gain of the isolated amplifier.

free space and is removed prior to the measurement using the time-domain gating facility of the vector network analyzer. For the measurements of the active and passive reflect-antennas, the time gated signal between the ports of the DPA is converted back into frequency domain using the fast Fourier transform (FFT) facility of the network analyzer. The gating technique used for the vector network analyzer (Anritsu-360B) is the time bandpass mode with a sweep bandwidth of 4 GHz. The gating interval is approximately 11 ns and the range R is 5.4 cm.

IV. Comparison of Modeling Approaches With the Measured Results

The calculated EIPG of the amplifying reflect-antenna using the modeling approaches discussed in Section III is compared with the measured results in Fig. 4. It can be seen from Fig. 4 that the EIPG calculated using the single-antenna method [see Fig. 2(a)] is less erroneous compared to the measured results at frequencies below the tuning frequency of the antenna. In general, the single-antenna approach yielded more optimistic gain results than the actual measured EIPG. As can also be seen from Fig. 4, the EIPG calculated using the passive reflect-antenna method [see Fig. 2(b)] follows the measured EIPG with approximately 1–2-dB accuracy for most of the frequencies. From the comparative study, it can be concluded that it is very important to preferably characterize the full active reflect-antenna or at least the equivalent passive reflect-antenna for accurate modeling of the array in which the active reflect-antenna element is involved. The large error in the single-antenna method is due to the drop in antenna gain because of the influence of feed-line radiation and the bends that are close to the antenna. On the other hand, measurement of the passive reflect-antenna eliminates these source of errors in the modeling, as its monostatic RCS is used first to find the EIPG EIPG_p. Therefore, the EIPG_p, which is used in (2) to determine the EIPG of the active reflect-antenna, involves the influence of the stray radiations such as from the feed and bends. The S-parameter-based model used in [6] for the active reflect-antenna based on an aperture coupled patch may also be extended to the development for the single-layer active reflect-antenna when the feed line bends are far away from the radiating edge of the patch.

Fig. 5 shows a comparison of the monostatic RCS of the amplifying reflect-antenna and the passive reflect-antenna normalized to the maximum gain of the passive reflect-antenna. The normalized monostatic RCS of the amplifying reflect-antenna should be equal to the amplifier gain, but only at the frequency where the normalized passive reflect-antenna RCS is equal to zero. The calculated amplifier gain using the measured monostatic RCS of the amplifying reflect-antenna and the passive reflect-antenna is also compared with the measured gain of the isolated amplifier with a 50-Ω source and load impedance. The measured gain ($|S_{21}|$) of the amplifier is shown in Fig. 5, whereas $|S_{11}|$ and $|S_{22}|$ of the amplifier are approximately constant at -3 and -8 dB, respectively, all over the band. The corresponding measured S-parameters for the antenna can be found in [11]. As can be seen from Fig. 5, at the tuning frequency of the microstrip-T coupled patch, the measured isolated amplifier gain is almost equal to the normalized gain of the amplifying reflect-antenna. On either side of the maximum active reflect-antenna gain, the amplifier gain calculated from the measurement of the passive and active reflect-antenna showed a ripple with respect to the isolated amplifier gain. This is due to the dependence of the amplifier gain on its source and load impedances. The 50-Ω source and load impedances used in the amplifier measurement is attained only at the resonant frequency of the antenna. At frequencies other than the resonant frequency of the antenna, the source and load impedances of the amplifier is equal to the complex impedances of the antenna presented through the sections of transmission lines.

Monostatic RCS pattern of the active reflect-antenna element is a parameter of interest for designing retrodirective arrays [3] since the reflected beam from the array is usually steered to the same location as the source of the interrogating signal. On the other hand, the reported amplifying reflect-arrays such as in [4] and [6] uses the receiving and transmitting beam in different locations. For this case, a bistatic RCS pattern of the active reflect-antenna element is more interesting. We study both the monostatic and bistatic RCS pattern of the designed amplifying reflect-antenna. For the monostatic RCS pattern of the am-

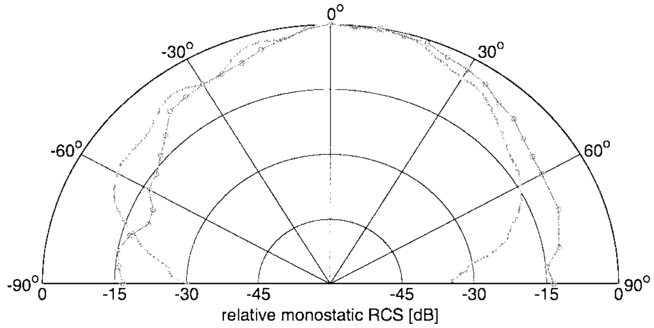

Fig. 6. Normalized monostatic RCS pattern: measured (circles) and calculated (solid line) using the measured patterns of a single antenna.

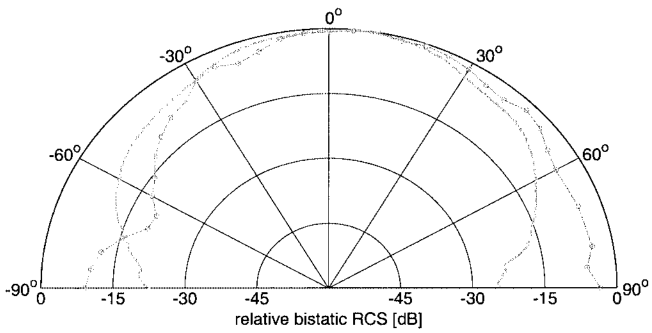

Fig. 7. Normalized bistatic RCS pattern: calculated using the measured monostatic RCS pattern and the measured E-plane pattern of the single antenna (circles) and the measured H-plane pattern of the single antenna (solid line).

plifying reflect-antenna, the scattering parameters between the vertical and horizontally polarized ports of the DPA $(|S_{21}|)$ [see Fig. 3(b)] is measured at a constant far-field distance for various angle θ. The measurement was carried out at 10.034 GHz, which is the resonant frequency of the isolated microstrip-T coupled-patch antenna. In the isolated amplifier–antenna approach, the normalized monostatic RCS pattern can be calculated as the normalized sum of the measured E- and H-plane pattern of the single antenna [11]. This is because the amplifying active reflect-antenna receive and transmit signal in the E- and H-plane of the microstrip-T coupled patch, respectively. The calculated and measured monostatic RCS patterns of the amplifying reflect-antenna are shown in Fig. 6. It can be seen from Fig. 6 that the calculated monostatic RCS pattern almost follows the measured monostatic RCS pattern in broadside. The difference between the measured and calculated monostatic RCS for large angles from the broadside may be attributed to the feed-line bends and the interference from the amplifier. Due to the small aperture size of the amplifying reflect-antenna and nonavailability of high gain probe antennas of small size, the bistatic RCS of the amplifying reflect-antenna was not separately measured. However, the bistatic RCS pattern can be calculated as the difference between the monostatic RCS and E-plane gain of the passive reflect-antenna. The bistatic RCS pattern using the single-antenna approach should be equal to its normalized H-plane pattern. The measured H-plane pattern of the single antenna [11] and the calculated bistatic RCS pattern are shown in Fig. 7.

V. Conclusions

A novel amplifying active reflect-antenna compatible with monolithic integration techniques has been designed using a microstrip-T coupled antenna. Two different modeling approaches have been pursued to study the amplifying reflect-antenna for its monostatic RCS and EIPG. From the comparison of the modeling approaches with the measured results, it is found that the passive reflect-antenna method yielded least deviation with the measured ones. On the other hand, the single-antenna approach yielded only approximate result. The DPA method using time-domain gating of the network analyzer has proven to be a flexible and accurate technique for monostatic RCS measurement of active reflect-antennas. The proposed amplifying reflect-antenna finds application as an array element in the design of amplifying reflect-arrays.

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