Nonlinear Analysis and Performance Improvement of Amplifying Aperture Coupled Reflectarray Antenna

I. Aryanian, A. Abdipour, and G. Moradi

Department of Electrical Engineering
Amirkabir University of Technology, Tehran, 15914, Iran
iman_aryanian@aut.ac.ir, abdipour@aut.ac.ir, ghmoradi@aut.ac.ir

Abstract **─** Amplifying reflectarray antenna can be used to increase the overall gain of the antenna in large distance communication systems. However, amplifying reflectarray antenna may become nonlinear in some incident powers which may lead to performance degradation. In this paper nonlinear behavior of an amplifying reflectarray antenna is studied and a new method is proposed to improve the performance of the antenna. Nonlinear analysis of the active unit cell is performed using harmonic balance method considering nonlinear model of the amplifier. Then, the effect of nonlinear element in radiation pattern of the antenna is studied. Aperture coupled patch structure is used to analyze amplifying unit cell. Finally, an amplifying reflectarray antenna considering nonlinear behavior of the active elements is designed and the proposed balanced amplifier structure is used to improve performance of the amplifying antenna.

Index Terms **─** Active antenna, antenna array, harmonic balance method, nonlinear analysis, reflectarray antenna.

I. INTRODUCTION

Printed reflectarray has some advantages compared to the usual reflectors, four of which - i.e., saving volume, simplifying the mechanical design, applying easily to deployable reflectors, and capability of integrating active elements by the antenna structure are of great importance. Different unit cell shapes are proposed to improve the reflectarray antenna performance which introduce the required phase-shift on the reflected field to produce a focused or shaped beam. Required phase shift can be obtained using resonating patches [1] or by a transmission line of proper length connected [2] or aperture-coupled to the patches [3, 4] with different size or using active elements like PIN diodes [5] or varactor diodes [6].

Using high gain antenna for large distance communication is necessary to improve performance of communication link. In these cases, usually reflector antenna or phased array antenna is used. However, manufacturing reflector antenna is difficult especially in high frequencies and phased array antenna may have some problems like unwanted radiation from the feed network. Amplifying reflectarray antenna is proposed in [3, 4, 7] which uses amplifier in each unit cell to increase gain of the antenna. Using an amplifier in the antenna structure results in difficulties in the antenna design and some issues should be determined like stability of the antenna. Moreover, the active element acts nonlinear and this necessitates the nonlinear analysis of the antenna structure. So, [8] studies nonlinear analysis of amplifying reflectarray antenna and [6] studies nonlinear analysis of reflectarray antenna containing varactor diodes.

This paper shows the importance of nonlinear analysis of active reflectarray antenna, and also the influence of nonlinear element in radiation pattern is clarified. The main output of this work is that by the explained method, the impact of nonlinearities on the performance of reflectarrays can be investigated. Furthermore, any active reflectarray cell having active device by any nonlinear model can be used in the analysis and the impact of the model parameters can be studied. Also, a new structure using balanced amplifier is used to improve antenna performance. This performance improvement will be cleared by designing a sample antenna with and without using the proposed cell.

To analyze the active reflectarray antenna, first the cell removing the amplifier is simulated using HFSS software considering infinite array approach to obtain the passive unit cell scattering parameters in which the amplifier is replaced by a two port network and two spatial ports modelled as Floqute port are assumed representing two orthogonal polarizations. So, a 4 port network is obtained which its scattering parameters are known. In the next step, an amplifier which has nonlinear model is connected to the 4 port network and the active cell performance is studied to obtain the cell amplitude response by varying the incident power to the cell. Finally, obtained nonlinear response of the cell is used to design the antenna. Verification of the nonlinear response of the unit cell is done by ADS simulation.

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This process is carried out for a sample active unit cell in the center frequency of 6.2 GHz and detailed steps are explained.

II. UNIT CELL MODELING

In aperture coupled microstrip antenna structure, each cell consists of a microstrip line coupled to the radiating patch on the opposite side of the substrate via an aperture in the ground plane as shown in Fig. 1. In this paper cross-polarized element configuration is used like [3, 4] to prevent instability, where the incident and scattered fields are orthogonally-polarized. Unit cell consists of a dual-polarized aperture coupled microstrip patch and an amplifier connected between the two ports in the microstrip line path. Also, as in this paper our goal is to evaluate the performance of the active element, an ideal phase shifter is used to control the phase of the reflected signal. Parameters of the unit cell are given in Table 1. Dielectric constant of top substrate is 3.02 with a height of 1.524 mm, and dielectric constant of bottom substrate is 6.15 with a height of 1.28 mm.

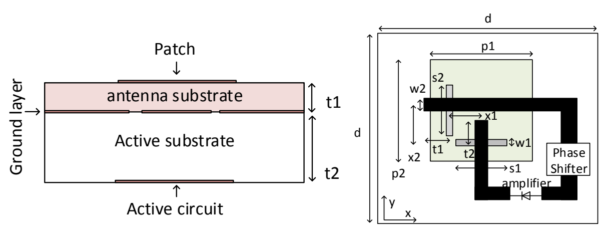

Fig. 1. Antenna unit cell schematic.

Table 1: Unit cell parameters

Parameter	Value	Parameter	Value
d	33.56 mm	t1	6 mm
p1	14.3 mm	t2	2.5 mm
P2	13.9 mm	W2	1.87 mm
S1	6.3 mm	X1	1.5 mm
S2	8.8 mm	X2	5.7 mm
W1	0.75 mm		

The passive part of the cell is modelled as a 4 port network in which ports 3 and 4 are spatial ports modelled as Floqute port [9], and the amplifier is connected between ports 1 and 2. So, the passive part of the unit cell removing the amplifier is simulated using HFSS software supposing infinite array to obtain 4 port scattering parameters as shown in Fig. 2.

Next, active element is connected between ports 1 and 2 of the obtained 4 port network as shown in Fig. 2 to obtain the active cell response in linear or nonlinear states. Active element used in this work is NE4210 which has nonlinear TOM model [10] and can be simulated in ADS software. Nonlinear TOM model is shown in Fig. 3 which has two nonlinear capacitances of C_{gs} and C_{gd}, and one nonlinear current source of I_{ds}. Relations for current source of I_{ds}, and capacitances of C_{gs} and C_{gs} of TOM model are given in (1) to (5) and parameters of the nonlinear model of NE4210 are given in Table 2.

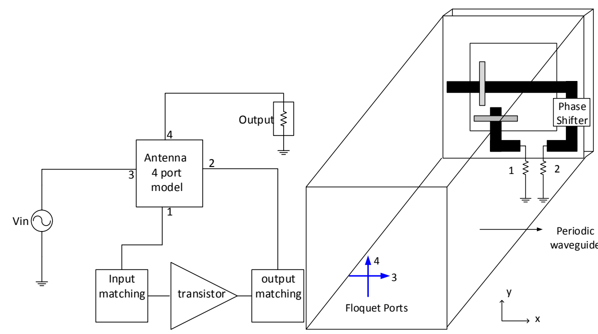

Fig. 2. Four port modelling of the unit cell.

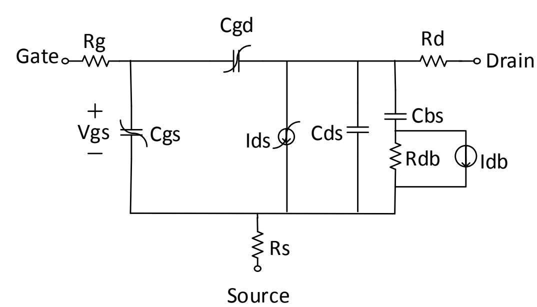

Fig. 3. Nonlinear TOM model.

Table 2: Parameters of the nonlinear model

Parameter	Value	Parameter	Value
V_{t_0}	-0.798 (V)	C_{gs0}	0.36 pF
α	8 (1/V)	C_{gd0}	0.014 pF
β	0.0952 (A/V^Q)	Δ_1	0.3 (V)
$T_{q\Delta}$	0.5 (1/W)	Δ_2	0.6 (V)
$T_{q\gamma}$	0.065	Rg	8 Ohm
Q	2.5	Rd	0.5 Ohm
Cds	0.12 pF	Rs	3 Ohm
Rdb	5 KOhm	Cbs	1 nF
F_c	0.5	V_{bi}	0.6 (V)

Current source of I_{ds} in TOM model is given as:

$$I_{ds} = \frac{I_{ds_0}}{1+T_{q\Delta} \times V_{ds} \times I_{ds_0}}, \quad (1)$$

where

$$I_{ds_0} = \begin{cases} \beta\left(V_{gs} - V_t\right)^Q \times \left[1 - \left[1 - \dfrac{\alpha V_{ds}}{3}\right]^3\right] & 0 < V_{ds} < 3/\alpha, \\ \beta\left(V_{gs} - V_t\right)^Q & V_{ds} \geq 3/\alpha, \end{cases} \quad (2)$$

$$V_t = \left(V_{t0} + V_{t0sc}\right) - T_{q\gamma} \times V_{ds}, \quad (3)$$

and Q, $T_{q\gamma}$, $T_{q\Delta}$, α, V_{t_0}, β are parameters of the model. Also, capacitances of C_{gs} and C_{gs} in TOM model are obtained as:

$$C_{gs} = \frac{\partial Q_{gs}}{\partial V_{gs}} + \frac{\partial Q_{gd}}{\partial V_{gs}} = \frac{C_{gs0}}{2\sqrt{1 - \frac{V_n}{V_{bi}}}} \left[1 + \frac{V_{eff} - V_{t_0}}{\sqrt{\left(V_{eff} - V_{t_0}\right)^2 + \Delta^2}}\right] \times \frac{1}{2} \times \left(1 + \frac{V_{gs} - V_{gd}}{\sqrt{\left(V_{gs} - V_{gd}\right)^2 + \Delta^2}}\right) + \frac{C_{gd0}}{2}\left(1 - \frac{V_{gs} - V_{gd}}{\sqrt{\left(V_{gs} - V_{gd}\right)^2 + \Delta^2}}\right), \quad (4)$$

$$C_{gd} = \frac{\partial Q_{gd}}{\partial V_{gd}} + \frac{\partial Q_{gs}}{\partial V_{gd}} = \frac{C_{gs0}}{2\sqrt{1 - \frac{V_n}{V_{bi}}}} \left[1 + \frac{V_{eff} - V_{t_0}}{\sqrt{\left(V_{eff} - V_{t_0}\right)^2 + \Delta^2}}\right] \times \frac{1}{2} \times \left(1 + \frac{V_{gs} - V_{gd}}{\sqrt{\left(V_{gs} - V_{gd}\right)^2 + \Delta^2}}\right) + \frac{C_{gd0}}{2}\left(1 + \frac{V_{gs} - V_{gd}}{\sqrt{\left(V_{gs} - V_{gd}\right)^2 + \Delta^2}}\right), \quad (5)$$

where

$$V_{new} = \frac{1}{2}\left(V_{eff} + V_{t_0}\right) + \sqrt{\left(V_{eff} - V_{t_0}\right)^2 + {\Delta_2}^2}, \quad (6)$$

$$V_{eff} = \frac{1}{2}\left[\left(V_{gs} + V_{gd}\right) + \sqrt{\left(V_{gs} - V_{gd}\right)^2 + \Delta^2}\right], \quad (7)$$

$$\Delta = \begin{cases} \Delta_1 & if \quad \Delta_1\, is \quad specified \\ 1/\alpha & else \end{cases}, \quad (8)$$

$$V_n = \begin{cases} V_{new} & if \quad V_{new} < \min(\mathrm{F}_c \times \mathrm{V}_{bi}, \mathrm{V}_{\max}) \\ \min(\mathrm{F}_c \times \mathrm{V}_{bi}, \mathrm{V}_{\max}) & else \end{cases}. \quad (9)$$

III. HARMONIC BALANCE ANALYSIS

Using harmonic balance method [11], the nonlinear analysis of the unit cell is performed by dividing the unit cell into two nonlinear and linear networks as shown in Fig. 4. Nonlinear part consists of nonlinear capacitances and nonlinear current source. Also, linear part consists of 4-port network of the unit cell and passive elements. Voltages of V_1, V_2 and V_3 of Fig. 4 should be evaluated so that $I_i + \tilde{I}_i = 0$. Harmonic balance equation can be solved with different methods, among which the Newton-Raphson [11] technique is the most common technique and is used in this paper. Assuming nonlinear TOM model for the transistor, total directivity of the unit cell will be obtained in Section V for different incident power which will show the nonlinear behavior of the cell.

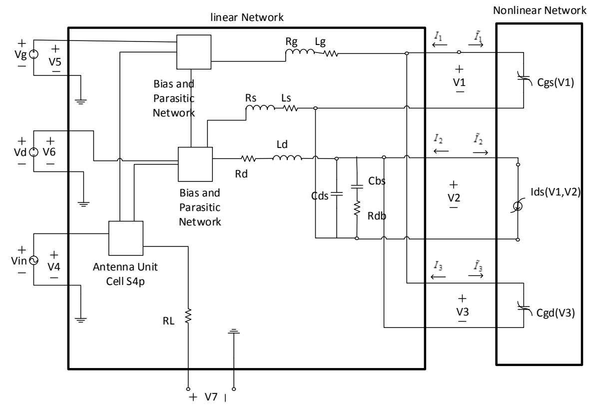

Fig. 4. Dividing the unit cell to nonlinear and linear networks.

IV. PERFORMANCE IMPROVRMENT OF THE CELL

In this part a new configuration using balanced amplifier is introduced to improve stability of the designed amplifying reflectarray antenna as shown in Fig. 5. Also, this configuration increases the power compression point of the cell which improves the antenna gain in nonlinear states. Using balanced amplifier in amplifying reflectarray antenna has some advantages. First, if the amplifiers are identical, the VSWR from the balanced structure is near 1 and it improves stability of the structure which is a problem in active reflectarray antenna. Moreover, output power is twice that achieved from the single amplifier, and if one of the amplifiers fails, the balanced amplifier unit will still work with reduced gain. Another important advantage of using balanced amplifier in amplifying reflectarray antenna is the ability of easily cascading active unit with other units, like phase shifter, since each unit is isolated by the coupler.

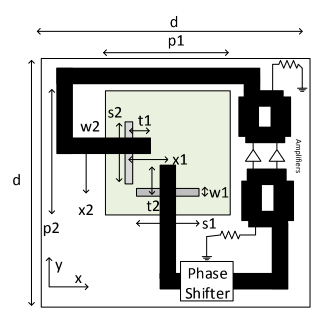

Fig. 5. Proposed unit cell for performance improvement.

V. RESULTS

Stability of the active part is identified by geometrically derived stability factor M [12]. This measurement gives the distance from the center of the Smith chart to the nearest output (load) stability circle. This stability factor is given by:

$$M = \left(\frac{1-|S_{11}|^2}{|S_{22} - conj\,(S_{11}) * \Delta| + |S_{12} * S_{21}|} \right), \qquad (10)$$

where Δ is determinant of the S-parameter matrix. Having $M > 1$ is the single necessary and sufficient condition for unconditional stability of a 2-port network. M factor for one stage amplifier is given in Fig. 6, which shows that the active part may become unstable in the frequency of operation.

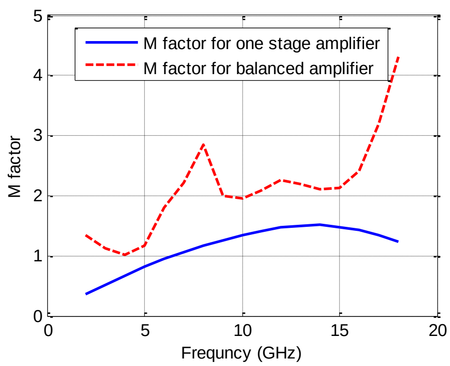

Fig. 6. M factor for one stage amplifier and balanced amplifier.

M factor for balanced amplifier is shown in Fig. 6 which has minimum of 1.01 and shows improvement in stability of the active part. Also, output power of the cell versus incident power for first design and improved cell is shown in Fig. 7 and gain of the cell versus incident power for first design and improved cell is shown in Fig. 8.

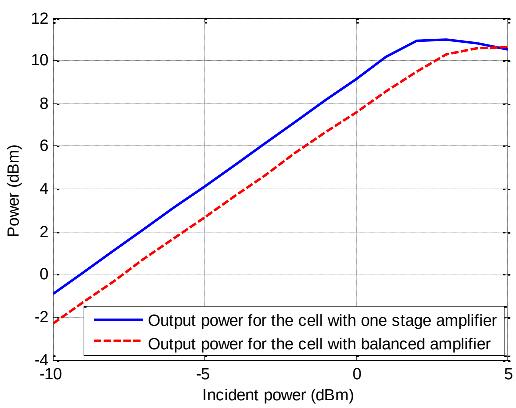

Fig. 7. Output power of the cell versus incident power for the first design and improved cell.

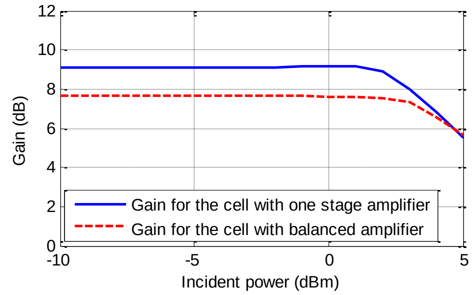

Fig. 8. Gain of the cell versus incident power for the first design and improved cell.

VI. SAMPLE ANTENNA DESIGN

In this section it is shown that the power received in each cell is different and as a result each cell may have different gain and phase. Phase of the received field from the feed antenna at each cell is shown in Fig. 9.

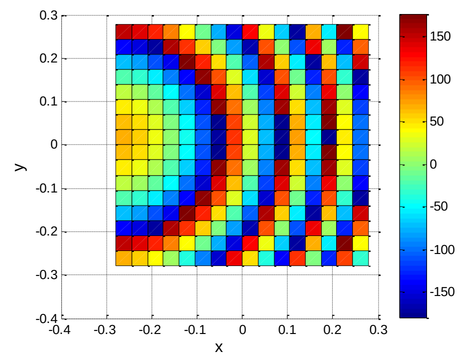

Fig. 9. Phase of the received field from the feed antenna at each cell.

Knowing the magnitude of y polarization electric field in each cell $\tilde{E}_y^R(u,v)$, power delivered to each cell is obtained as:

$$P(x,y) = \frac{\left(\tilde{E}_y^R(u,v)\right)^2}{2 * \eta_0}. \qquad (11)$$

To simulate the active antenna, a 59.2 cm * 59.2 cm antenna is designed in the center frequency of 6.2 GHz by focal length of 74 cm. If we assume center of the antenna as center of Cartesian coordinates, feed antenna is placed in (-29.6 cm, 0, 74 cm). Assuming transmitted feed antenna power in a way that the power distribution on the antenna surface is like Fig. 10, most active elements become nonlinear, and the impact of nonlinearity of each cell should be considered. For this reason amplitude and phase differences caused by the nonlinear amplifier in each cell should be considered.

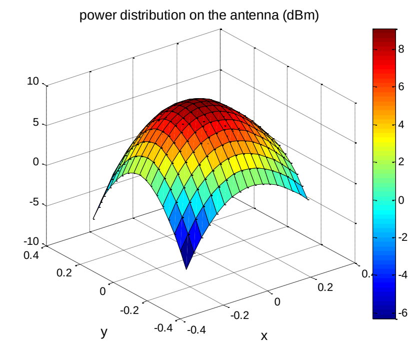

Fig. 10. Supposed power on the antenna surface.

Considering amplitude behavior of the unit cell shown in Fig. 8, and the power distribution on antenna surface shown in Fig. 10, amplitude error of each unit cell is calculated as shown in Fig. 11.

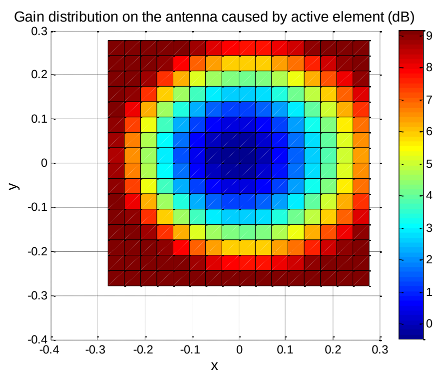

Fig. 11. Amplitude error of each unit cell.

The errors in the amplitude and phase of the reflected signal from each cell can cause gain reduction. However, phase error is low in comparison to amplitude error and can be neglected in this scenario. Antenna directivity with and without considering the nonlinear effect of active elements is shown in Fig. 12, when feed power is so that some cells are in nonlinear region and maximum difference between linear and nonlinear analysis can be obtained. In this case, nonlinear analysis shows degradation in gain which cannot be assessed by linear analysis. So, because of the nonlinear behavior of the active elements, maximum gain of the designed antenna decreases from 41 dBi to 37.5 dBi as shown in Fig. 12. Therefore, to assess the pattern of the active reflectarray antenna correctly, for all feed power, the nonlinear impact of amplifier should be considered. It is worth mentioning when feed power is so that all cells are in linear region, linear and nonlinear simulations have the same results.

Using the balanced amplifier by nonlinear response shown in Fig. 8 and considering the power distribution like Fig. 10, the antenna is analyzed again which shows that the antenna gain is increased to 40.2 dBi where gain reduction is decreased to about 0.8 dB and 2.7 dB improvement is reached.

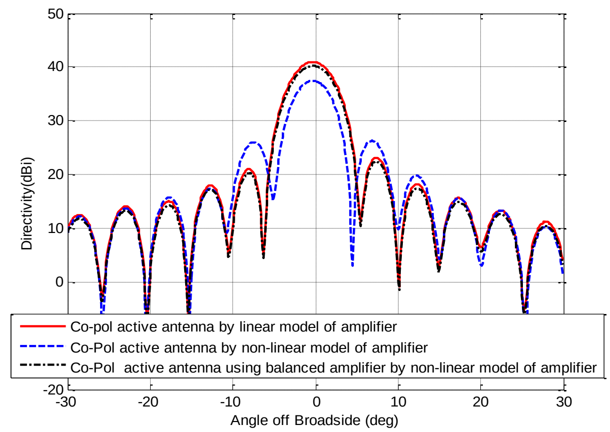

Fig. 12. Performance improvement of the antenna using balanced amplifier when feed power is so that some cells are in nonlinear region.

VII. CONCLUSION

It is shown that in some cases, nonlinear analysis of amplifying reflectarray antenna is needed. This paper uses a method combining linear full-wave simulations with the harmonic balance method to predict impact of nonlinearities on the unit cell characteristics of active reflectarrays, as well as on the pattern produced by the reflectarrays. Next, result of nonlinear analysis has been used to design a sample antenna which shows that predicting pattern of the antenna with linear modelling of the active element has error. Finally, a new structure is proposed to improve performance of amplifying reflectarray antenna which improves stability of the antenna and increases total gain of the antenna when incident power is such that the active elements are in nonlinear state. Using the proposed cell, antenna gain reduction in nonlinear state is decreased.

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Iman Aryanian was born in Iran in 1986. He obtained his B.Sc. in Electrical Engineering from Amirkabir University of Technology, Tehran, Iran in 2008. Then he received his M.Sc. in Electrical Communication Engineering from Amirkabir University of Technology, Tehran, Iran in 2010, and his Ph.D. degree in the same field from Amirkabir University of Technology, Tehran, Iran in 2016. His research interests are in the areas of reflectarray antenna, computational electromagnetic, semiconductor RF modeling, electromagnetic theory, and computational electromagnetics.

Abdolali Abdipour was born in Alashtar, Iran, in 1966. He received his B.Sc. degree in Electrical Engineering from Tehran University, Tehran, Iran, in 1989, his M.Sc. degree in Electronics from Limoges University, Limoges, France, in 1992, and his Ph.D. degree in Electronic Engineering from Paris XI University, Paris, France, in 1996. He is currently a Professor with the Electrical Engineering Department, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran.

Gholamreza Moradi was born in Shahriar, Iran in 1966. He received his B.Sc. in Electrical Communication Engineering from Tehran University, Tehran, Iran in 1989, and the M.Sc. in the same field from Iran University of Science and Technology in 1993. Then he received his Ph.D. degree in Electrical Engineering from Tehran Polytechnic University, Tehran, Iran in 2002. His research areas include applied and numerical Electromagnetics, Microwave measurement and antenna.