A Novel Phased Array Based on the Extended Resonance Power Dividing Technique

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Abstract **— A novel phased array based on the extended resonance power dividing technique has been presented. This phased array eliminates the need for a separate power splitter and phase shifters in a conventional phased array system. As a proof of principle, a 2 GHz extended resonance based phased array consisting of 4 microstrip patch antennas has been designed, fabricated and tested. The measured scan range was +/- 13.5 degrees with an average beamwidth of 26 degrees.**

I. INTRODUCTION

Phased arrays are extensively used in satellite communications, multipoint communications and radar systems. They are capable of steering the beam to the desired direction without mechanically rotating the antennas by electronically tuning their relative phases. In a conventional phased array system, the waveform to be sent is divided to the number of antennas in the system and each branch is then fed into a phase shifter and followed by an antenna. These systems are discussed in detail in [1]-[2]. The cost of a conventional phased array mainly depends on the cost of the phase shifters used. It has been estimated that almost half of the cost of a phased array is due to the cost of phase shifters used. Also, these systems turn out to be very complex and suffer from high loss and mass. Therefore, they are limited to a few sophisticated military applications and satellite communication systems. However, emerging commercial applications, such as automotive collision avoidance systems, blind spot indicators, compact scanning arrays etc., dictate that the cost of phased arrays to be reduced. Therefore, new techniques eliminating the need for phase shifters in phased arrays need to be developed. Recently, there were demonstrations of new beam steering techniques to address the above issues [3]-[4].

The extended resonance is a power dividing / combining technique, which results in a very compact circuit structure with high dividing / combining efficiency (> 90%) [5]. In this paper, a new application of this technique for the design of low-cost phased arrays is introduced. It eliminates the need for a separate power splitter and phase shifters in a conventional phased array system, hence results in a very compact and simple circuit structure.

II. THEORY

An N device extended resonance circuit is shown in Fig. 1 [5]. The admittance of the first and the last device is G+jB, whereas the admittance of the each interior device is G+2jB. The length of the transmission line, l_1, is designed such that the admittance of the first device is transformed to its conjugate, G-jB. The admittance at the plane of the second device will be 2G+jB. As can be seen, half of the susceptance of the second device is cancelled in this process. The length of the second transmission line, l_2, is designed to transform 2G+jB to its conjugate, 2G-jB. The admittance at the plane of the third device will be 3G+jB. This process is performed (N-1) times. At the last stage, the admittance at the plane of the (N-1)th transmission line will be (N-1)G-jB and the admittance at the plane of the Nth device will be NG, which is matched to the source impedance using a quarter-wave transformer. Resonating all the devices with one another essentially places them in shunt, and analysis of this structure shows that the voltage at each device node is equal in magnitude, but not in phase. This feature has been exploited for the design of power amplifiers at microwave and millimeter wave frequencies [5]-[10].

It can be shown that by correct selection of B and G, one can maintain equal power division, and vary the relative phase shift between device nodes by changing B. The device in Fig. 1 is modeled as a shunt combination of an antenna ($G=G_{ant}$) and a capacitor ($B=\omega C$). An inductor is used to transform the admittance to its conjugate instead of a transmission line. A schematic illustration of the proposed phased array is shown in Fig. 2. The antennas are assumed to be $\lambda/2$ apart, and the capacitors and inductors are assumed to be tunable. The analysis of this structure

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reveals that the required inductance to transform the admittance, $nG_{ant}+j\omega C$, to its conjugate, $nG_{ant}-j\omega C$, is:

$$L_n = \frac{2C}{(nG_{ant})^2 + (\omega C)^2} \tag{1}$$

Using the inductor value found in (1), the ratio of the voltages between successive antenna nodes is calculated to be:

$$\frac{V_n}{V_{n-1}} = \frac{((n-1)G_{ant} + j\omega C)^2}{((n-1)G_{ant})^2 + (\omega C)^2} \tag{2}$$

Therefore, the phase shift between successive antenna nodes will be:

$$\theta_{n,n-1} = \tan^{-1}\left\{\frac{2(n-1)G_{ant}\omega C}{((n-1)G_{ant})^2 - (\omega C)^2}\right\} \tag{3}$$

It can be concluded from (3) that changing the capacitance will result in a change in the phase shift between the successive antenna nodes. In a phased array, the phase shifts between successive antenna nodes must be equal to each other ($\theta_{21}= \theta_{32}= \theta_{43}\ldots$). Depending on the number of antennas, N, and the tunability of the capacitor, there exists an optimum capacitive susceptance, which results in the same phase shift between the successive antenna nodes while dividing the power equally. Therefore, a phased array system with one dimensional scanning capability can be built. Since realizing tunable inductors is not very easy and the antennas have to be spaced approximately $\lambda/2$ apart depending on the design, the circuit of Fig. 2 may not be practical. Instead, artificial tunable inductors can be realized using an impedance inverter consisting of two quarter-wave transformers with a shunt tunable capacitor in between. Phase offsets must be introduced prior to the antennas since the absolute phases of the voltages at the antenna nodes are not equal to each other. The proposed extended resonance based phased array system is shown in Fig. 3. Based on the theory outlined, simulated scanning for a five antenna extended resonance phased array at 2 GHz for various capacitor values, C, is shown in Fig. 4. In this simulation, no loss from the tunable capacitors or transmission lines is included.

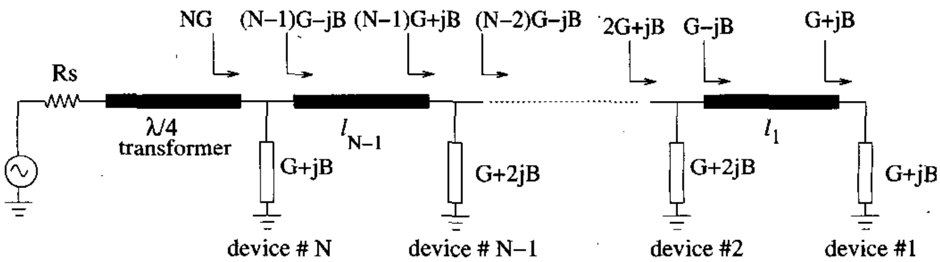

Fig. 1. Extended resonance concept incorporating N devices.

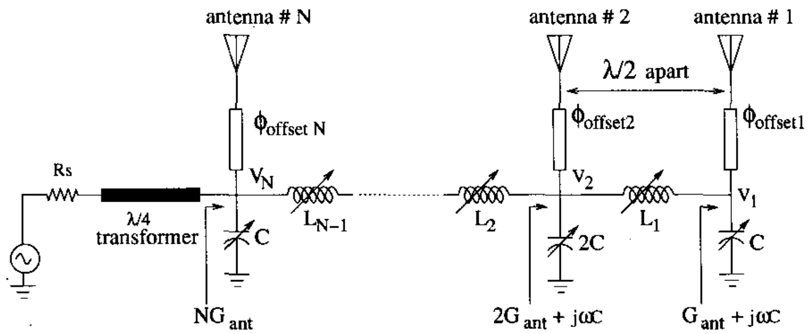

Fig. 2. The extended resonance based phased array concept.

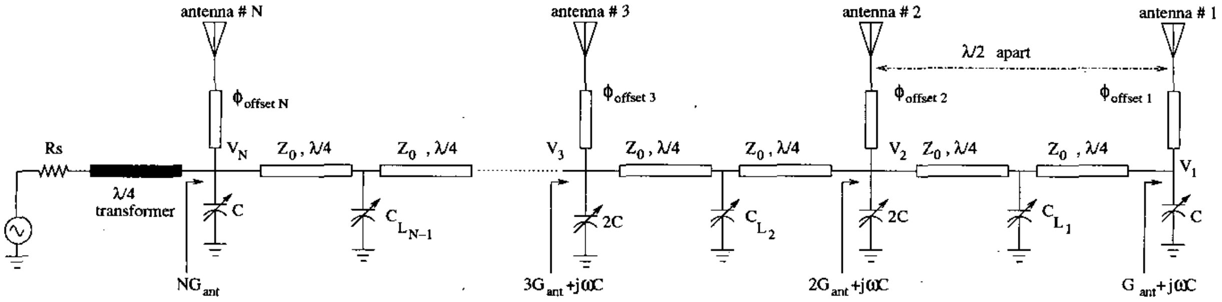

Fig. 3. The practically realizable extended resonance based phased array.

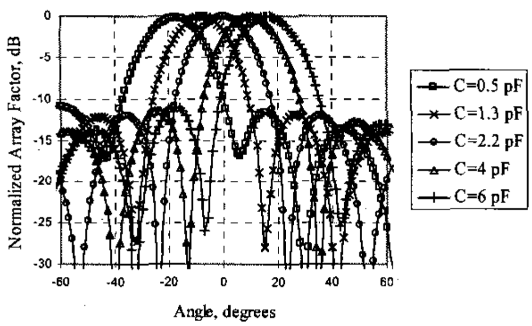

Fig. 4. Simulated scanning for a five antenna extended resonance phased array (no loss is included).

III. Fabrication and Measurement Results

To demonstrate the operation of this technique, a 2 GHz extended resonance based phased array consisting of 4 edge coupled microstrip patch antennas placed half wavelength apart was designed, fabricated and tested. A 31 mil thick RT/duroid 5880 substrate from Rogers Corporation was used to build the phased array. MSV34 series chip varactor diodes from Metelics Inc. were utilized as tunable capacitors. A photo of the phased array can be seen in Fig. 5. The overall size of the phased array was 39x25 cm^2. The measured H-plane pattern of the phased array for various diode voltages is shown in Fig. 6 and the measured performance is summarized in Table 1. The results show that the phased array can scan the beam +/- 13.5 degrees with the application of 2 V to 30 V reverse bias to the varactor diodes. The side lobe level was better than 7 dB. The gain of the phased array was measured to be 8.3 dB at 30 V reverse bias applied to the varactors. It can be seen from Fig. 6 that the gain at 2 V is 6.9 dB lower than the gain at 30 V. This is due to the low quality factor of the varactor diodes at this voltage (Q_{2V} = 22, Q_{30V} = 121 at 2 GHz), resulting in significant amount of RF power disssipation within the diode and change in the input impedance, which degrades the return loss. It should be noted that any type of tunable capacitors, such as ferroelectric [11] or MEMS based tunable capacitors, switched capacitors using PIN diodes or MEMS switches, which have been known to have lower loss, can be utilized to fabricate the phased array. In extended resonance based phased arrays, fewer number of devices are employed compared to a conventional phased array system, thereby reducing the cost.

Diode Voltage (V)	Scan Angle (degrees)	Beamwidth (3 dB), deg.	Side Lobe Level (dB)
2	18	26	-7
4	5	28	-13
8	0	26	-14
12	-2	25	-13
18	-5	26	-10
24	-8	27	-9
30	-9	29	-7.5

Table 1. The measured performance of the phased array.

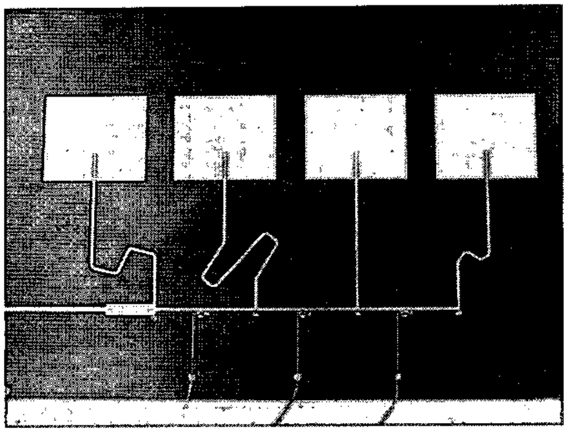

Fig. 5. A photo of the phased array.

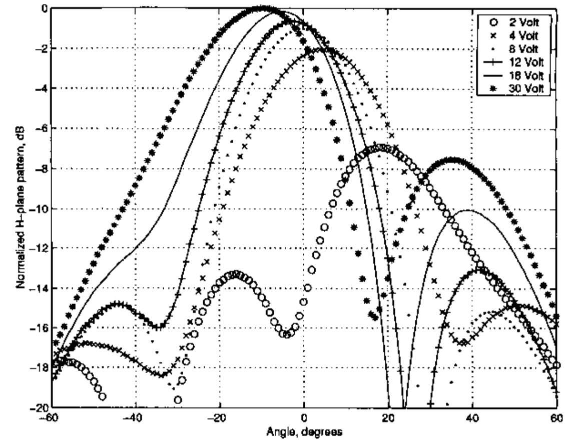

Fig. 6. Measured H-plane pattern for various diode voltages.

IV. Conclusion

An extended resonance based phased array has been presented, which eliminates the need for a separate power splitter and phase shifters in a conventional phased array system. Since the phasing and power division is performed simultaneously at the same stage, this phased array needs fewer number of devices compared to a conventional phased array system, thereby reducing the cost substantially. As a proof of principle, a 2 GHz extended resonance based phased array consisting of 4 microstrip patch antennas was demonstrated. The measured scan range was +/- 13.5 degrees with an average beamwidth of 26 degrees.

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