A Low-Complexity Low-Cost Phased Array

M. Askari, H. Kaabi

Abstract— **A low-complexity low-cost structure is proposed for phased array systems. It is shown that the change in the phase reference of the antenna array leads to a less complexity system, which is very essential for RFIC processes. There is no need to use the bulky and lossy "gain control" circuits. Therefore, the complex "magnitude tapering" algorithms, which are used to reduce the sidelobes level of array patterns, are simply implemented in the proposed structure. The phase shifters of the proposed scheme are structurally simpler than those of the conventional phased arrays. The comparison between the proposed and the conventional phased array structures in such areas as array pattern, tapering, and directivity is studied using simulation.**

***Index Terms*— Directivity, Low-cost, Low-complexity, Phased array, Tapering algorithm**

I. Introduction

PHASED arrays as an important category of the modern communication systems have many attractive benefits such as high directivity, signal-to-noise ratio improvement in the receiver, large effective isotropic radiated power (EIRP) in the transmitter, high system capacity, and good interference suppression [1-3]. In addition to these benefits, other advantages such as fast beam scanning and multiple beamforming introduce the phased array systems as an appropriate candidate for emerging radar applications. For example, a significant number of valuable researches have been done on commercial phased array vehicular-radar in the last decade [4-9]. However, such systems have complex circuits, and hence are expensive in design and implementation. It should be noted that the cost and the complexity are very important issues in commercial applications.

The number and the cost of the phase shifters and the complexity of the control circuitry are major factors in determining the cost and the complexity of the phased arrays [10, 11]. In the conventional phased arrays, a 1-to-N way power divider splits the RF signal into N branches; each branch includes a phase shifter, a gain control circuit, one or more stages of power amplifiers, and an antenna element at the end. Since the phase shifters are generally bulky and lossy elements, applying them can increase the cost and the complexity of the system [12]. Phase shifters can be passive or active. Although the passive phase shifters can achieve good linearity without DC power consuming, they have large insertion loss [13].

Several stages of variable gain amplifiers (VGAs) are often used as gain control circuit to compensate the loss. As a result, the complexity of the system is obviously increased. On the other hand, the active phase shifters consume high DC power, and have complex digital control circuits [14]. By reducing the number of phase shifters, the system complexity and thus the cost of electronic products can be reduced. This is especially vital for emerging low-cost high-volume RFIC processes.

Some efforts have been done in the literature to reduce the complexity and the cost of the phased array systems. Reference [15] employs barium–strontium–titanate (BST) as a ferroelectric material to design and implementation of very compact size tunable phase shifters, and hence low-cost phased array structure. A novel method based on an extended resonance technique in order to combine phase shifter and power divider into a single circuit is proposed in [10]. However, due to use of several bulky transmission lines (TLs), it may be unsuitable for RFIC process. Also, the maximum scanning rang of 20° limits its applications. In reference [11], a beam steering system has been presented that uses only one phase shifter at 2 GHz. In this design, nonfeeding end of a serially feed array is connected to a grounded phase shifter. This phase shifter reflects signal back to array after phase shifting. However, due to the use of a coupler, an amplifier, a variable gain amplifier (VGA), a power combiner, and a complicate digital control circuit for each antenna, this is still a complex design. A millimeter-wave dual-fed phased array based on the superposition of two squinted antenna beam is proposed in [16]. In addition to the low scanning range of the scheme (Maximum continuous scan range for a 4-antennas scheme is 32°), another problem is that the scanning range is reduced more (Maximum continuous scan range for a 10-antennas scheme is 12°) by increasing the number of antennas. Finally, although the integration of system on a single chip in [17-19] reduces the cost, but the complexity and the difficulties of calibration are still remain as notable issues in such designs [16].

This paper presents a novel approach to design RFIC phased arrays. Unlike the conventional designs that require one phase shifter for each antenna element, the number of phase shifters are half (or even less) the number of antenna elements in the proposed structure. This purpose is achieved by change in the phase reference of antenna array. Meanwhile, the all phase shifters have identical structure. It is an important note in design of a low-cost phased array. In conventional

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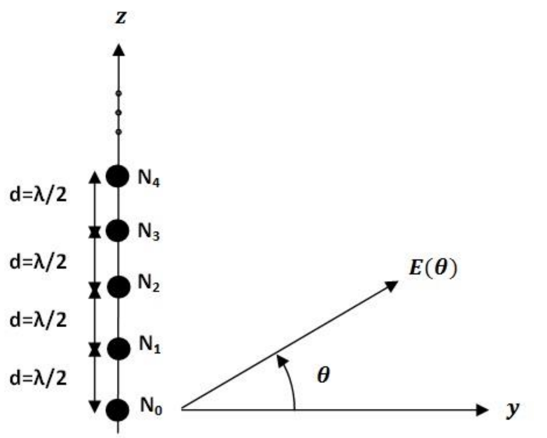

Fig. 1. An N-elements conventional phased array antenna

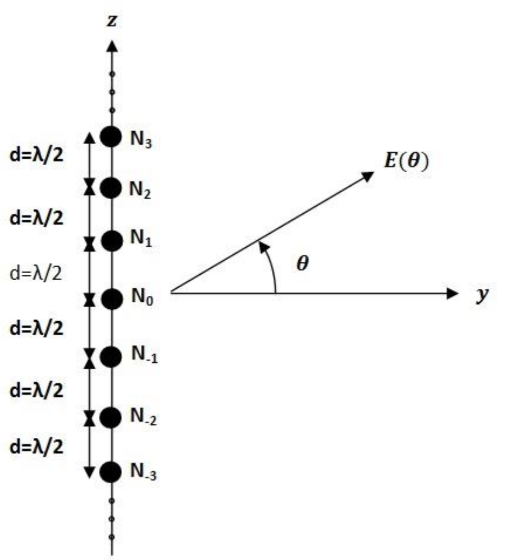

Fig. 2. Symmetric phased array antenna arrangement by moving phase reference to the centre element.

phased arrays, the required phase shift of each phase shifter is separately adjusted using digital control circuit. But in the proposed structure, since all of the phase shifters have equal phase shift at any given time, they are similarly adjusted using the digital control circuit. Therefore, the complexity of the digital control circuits is also significantly decreased. In addition to these advantages, simplicity in the implementation of tapering algorithms is an interesting benefit of the structure.

This paper is organized as fallows. Section 2 describes the background theory including the calculations of radiated far fields of the conventional and the proposed phased array. Section 3 presents the simulation results in detail. Conclusions of work are presented in sections 4.

II. THEORY AND DESIGN

The main idea of the proposed scheme is the change in the phase reference of antenna array. In conventional RFICs phased array, phase shifts of ϕ, 2ϕ, 3ϕ… and Nϕ relative to first antenna element are implemented in the other elements [20-22] as shown in Fig. 1. This structure requires one phase shifter for each antenna element. If all elements have equal and in-phase current distributions, the electrical field at a far point can be obtained by

$$E(\theta) = 1 + e^{j\psi} + e^{j2\psi} + e^{j3\psi} + \cdots + e^{j(N-1)\psi} \quad (1)$$

where N is the number of antenna elements and $\psi = (2\pi a/\lambda)sin\theta - \phi$. Here, θ is the radiation angle, ϕ is the phase difference between two adjacent elements, and λ is the wave length. The summation in the equation (1) represents a geometric series, so it is equal to

$$E(\theta) = e^{j\left(\frac{N-1}{2}\right)\psi} \frac{\sin\left(\frac{N\psi}{2}\right)}{\sin\left(\frac{\psi}{2}\right)} \quad (2)$$

The far field array intensity pattern is then given by

$$|E(\theta)| = \frac{\sin\left(\frac{N\psi}{2}\right)}{\sin\left(\frac{\psi}{2}\right)} \quad (3)$$

The radiation angle can be calculated as

$$\theta = sin^{-1}\left(\frac{\phi\lambda}{2\pi d}\right) \quad (4)$$

where *c* is the light velocity and *d* is the elements spacing. For the more common case of d=*λ/2*

$$\theta = sin^{-1}\left(\frac{\phi}{\pi}\right) \quad (5)$$

Without loss of generality, assume N is an odd number. So, the phase reference can be moved to the center of the array as shown in Fig. 2. In this case, the desired phase shifts of the elements N_x and N_{-x} (N_{-x} is symmetric element of N_x) are identical. Thus, only one phase shifter can be used for both. In fact, for an N-element array, only (N-1)/2 phase shifters is required. By reducing the number of required phase shifters, the cost and the complexity of the system are reduced. The radiated field in this case can be written as

$$E(\theta) = e^{-j\frac{(N-1)}{2}\psi} + \cdots + e^{-j3\psi} + e^{-j2\psi} + e^{-j\psi} + 1 + e^{j\psi} + e^{j2\psi} + e^{j3\psi} + \cdots + e^{j\frac{(N-1)}{2}\psi} \quad (6)$$

Arranging the terms of the equation (6), we obtain

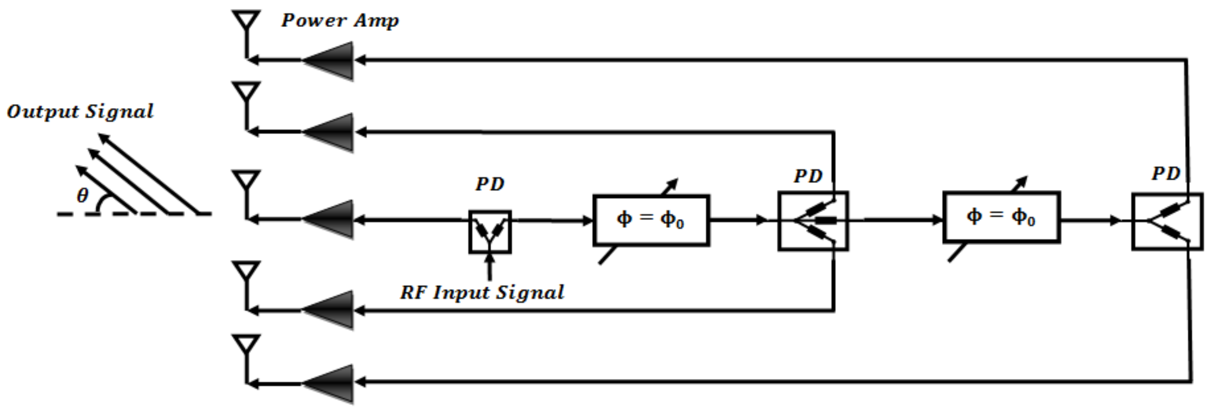

Fig. 3. Proposed phased array transmitter

$$E(\theta) = 1 + (e^{-j\psi} + e^{j\psi}) + (e^{-j2\psi} + + e^{j2\psi}) + (e^{-j3\psi} + + e^{j3\psi}) + \cdots + (e^{-j\frac{(N-1)}{2}\psi} + e^{j\frac{(N-1)}{2}\psi}) \quad (7)$$

Applying the recipe $e^{-jn\psi} + e^{jn\psi} = 2cos(n\psi)$

$$E(\theta) = 1 + 2cos\psi + 2cos2\psi + 2cos3\psi + \cdots + 2cos\frac{(N-1)}{2}\psi \quad (8)$$

Using trigonometric equations, $E(\theta)$ can be rewritten as

$$E(\theta) = \frac{sin\left(\frac{N\psi}{2}\right)}{sin\left(\frac{\psi}{2}\right)} \quad (9)$$

Equation (9) is similar to the equation (2) in magnitude. Thus, the far field array intensity pattern is calculated as (3). The maximum value of $|E(\theta)|$ is equal to N and occurs at $\psi = 0$. The "array factor" of an N-element 1-D array is then given by

$$AF(\theta) = \frac{1}{N}|E(\theta)| = \frac{1}{N}\frac{\sin\left(\frac{N\psi}{2}\right)}{\sin\left(\frac{\psi}{2}\right)} \quad (10)$$

The block diagram of the proposed phased array system (a 5-element phased array transmitter front-end) is shown in Fig. 3. By cascading two phase shifters, the phase shift range is doubled. Similarly, the larger ranges of phase shift can be achieved by cascading more phase shifters. So, it is not required to design a new large (typically large and lossy inductors are used in passive phase shifter) and complex phase shifter to reach higher phase shift. In addition, all phase shifters used in the system have same structure and make equal phase shift. Thus, they are controlled by a common digital control signal.

As another advantage, tapering the magnitude of the current across the array can be easily achieved. Amplitude tapering is a conventional method to create low sidelobes in the far-field pattern of an antenna array. In tapering, the largest current feeds the central element while the other elements are fed by the symmetrically tapered currents. By considering the loss of the phase shifters (note that all of the phase shifters have identical topology, equal phase shift, and hence equal loss), the required tapering can be easily obtained by adjusting the power dividing ratios of power dividers (PDs). Therefore, unlike the conventional phased arrays, there is no need to apply the high-cost high-complex gain control circuits. So, it can be said that the proposed symmetric structure is a "self-tapered" structure.

III. RESULTS AND DISCUSSIONS

To compare the performance of the proposed phase array with that of the conventional phased arrays, a 7-element array with λ=d/2 element spacing is considered. According to previous discussions, seven different phase shifters are required in the conventional 7-elemnt structure. Also, each phase shifter needs an exclusive control signal. On the other side, only three identical phase shifters with a common control signal are needed for the proposed symmetric 7-element structure. Fig. 4 shows the normalized array factor for these two scenarios. The first sidelobe is about 13 dB below the main lobe for the 7-element conventional array. It may be not sufficient for the most radar applications. For the 7-element proposed array, the difference between the main lobe and the first sidelobe can be easily adjusted to the desired value (it is adjusted to 17 dB in Fig. 4). In order to reach such a result in a conventional phased array, it is needed to use a separate gain control circuit (such as variable gain amplifiers or step attenuators) in each branch of the array. It leads to a more cost and complexity. Of course, reduction in the sidelobes level comes with decreased antenna gain and directivity. Therefore, the tradeoffs between these important parameters should be carefully considered.

Directivity is a key parameter in the antenna design. Antenna directivity in the direction of maximum radiation θ_0 is given by the relation [23]

$$D = \frac{P(\theta_0)}{P(\theta)_{average}} \quad (11)$$

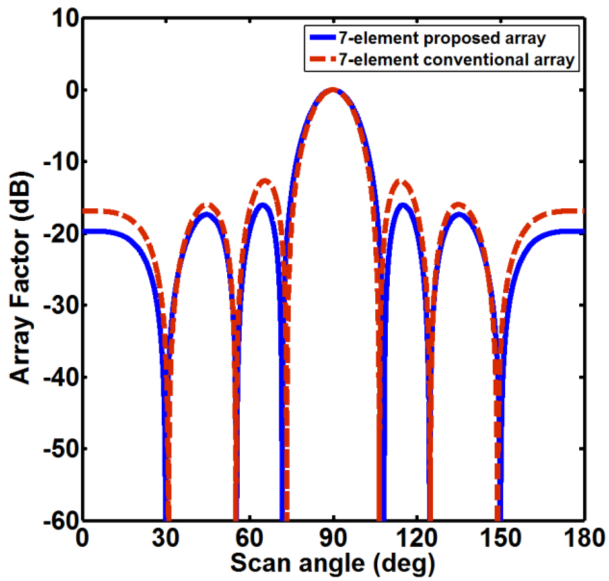

Fig. 4. Normalized array factor for a 7-element linear phased array

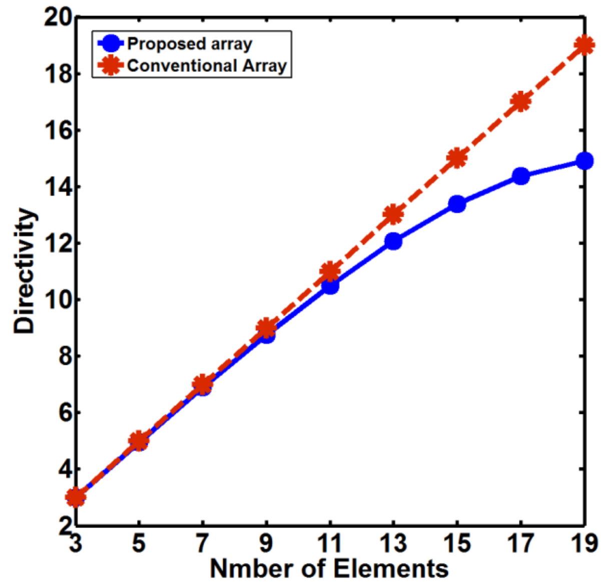

Fig. 5. Directivity as a function of the number of array elements

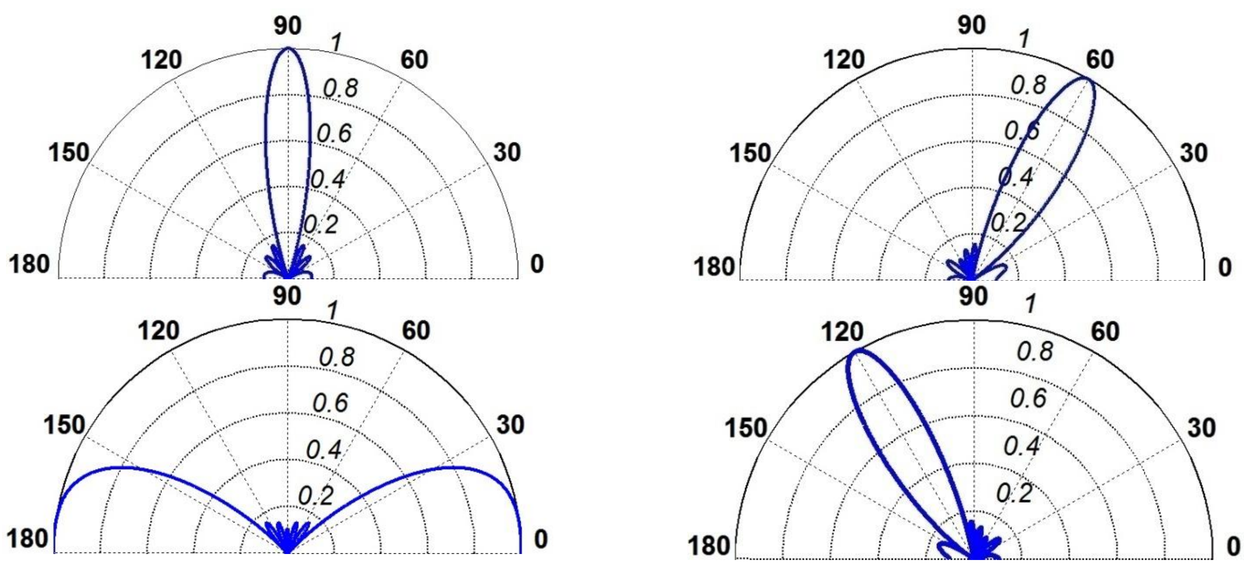

Fig. 6. Array patterns of the 7-element proposed phased array system. The antenna spacing is assumed to be half wavelength

where $P(\theta_0)$ is the maximum power density and $P(\theta)_{average}$ is the average power density (total power density divided by 4π steradians of a sphere surface) per unit solid angle. Knowing antenna beam area Ω_A, the antenna directivity can be given by

$$D = \frac{4\pi}{\Omega_A} \tag{12}$$

Taking into account the losses of the phase shifters and the other lossy elements such as power dividers, a typical plot of the directivity as a function of the number of array elements for $\theta_0 = 0$ (the array pattern gives a narrow beam broadside to the array axis) is shown in Fig. 5. As can be seen, the directivity of the proposed structure for a given number of elements is less than that of the conventional structure. It is not an unexpected result. In fact, tapering the magnitude of the currents across the array can increase the main-lobe beamwidth and hence the beam area. This can be properly seen in Fig. 4. According to the equation (12), increasing the beam area decreases the antenna directivity by an average of about 10%.

Finally, the simulated array patterns of the proposed 7-element phased array are shown in Fig. 6.

IV. Conclusion

A symmetric phased array structure is proposed and studied for RFIC processes. All phase shifters have identical structure. Also, a common control signal is used for all phase shifters in order to set required phase shift. So, in comparison with the conventional structure, the cost and the complexity of the system are effectively reduced. Unlike the conventional phased array in which each antenna element needs a separate phase shifter, the proposed structure requires up to N/2 phase shifters for an N-elements scheme. Moreover, the complex tapering algorithms are easily implemented without need to gain control circuits.

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