Planar Implementation of the Partially Overlapped Subarrays for Millimeterwave Beam Steerable Antenna Applications

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***Abstract* — Grouping the elements of a phased array into the partially overlapped subarrays with in-phase excited elements and using a single phase shifter per subarray has been studied in the past as an approach for reducing the number of phase shifters. Overlapped subarrays require complicated feeding scenarios, however, that cannot be easily implemented in planar technologies. This paper focuses on a planar implementation which is especially useful for compact millimeterwave arrays and facilitates integration of the antenna and electronics. This design uses a unique combination of series and parallel feeding schemes to form a standing wave array of microstrip elements. The proposed feeding scheme is theoretically insensitive to the mutual coupling between the elements.**

I. INTRODUCTION

With the growing interest in using millimeterwave radars as simple sensors in the automotive, collision avoidance, traffic control and robotic systems, as well as in a number of military applications, the beam steerable phased arrays have received an extraordinary attention as the economical alternatives of the bulky mechanical scanning systems. Even with using electronic scanning, the antenna array is still the final limitation in reducing the size, complexity and cost of the millimeterwave radar systems. The complexity of the phased arrays in turn is mainly due to the presence of the electronically adjustable phase shifters, which are used to control the beam angle. In a conventional phased array, the number of phase shifters is the same as the number of radiating elements, and the phase shifters should be accurately adjustable down to a few degrees, depending on the required angular resolution. However, the simplified phasing schemes may be used [1], which divide the elements of the array into a number of similar subarrays, each composed of only inphase elements and having a fixed array factor (primary array factor). The subarrays are then combined in a secondary array to form the overall array system. Each subarray is driven with a single phase-shifter in this scheme, so that the secondary array acts as a phased array with an electronically scanning beam. The total array factor is the product of the primary and secondary array factors. While the secondary array has the essential role in beam steering, it is normally a sparse array with grating lobes in its array factor. Unless the primary array factor is properly designed to suppress these grating lobes, they tend to raise the sidelobe level and lower the beam efficiency in the overall array. It is shown that the primary array factor can provide enough suppression only if the subarrays are arranged in an overlapping manner, i.e. with elements of one subarray placed between those of the adjacent subarray. This scenario has been proposed by a number of researchers in the past [1]-[2]. In a planar implementation of the partially overlapped subarrays one of the first issues is the intersecting feed network, which comes down to design of planar crossovers. Different techniques have been proposed to implement the partially overlapped subarrays by using spatial or constrained feed networks as reported for instance in reference [3]. However, most of the proposed designs are bulky and lossy, and do not lend themselves to the simple planar technologies. Moreover, none of these techniques may be effectively used for achieving the desired excitation coefficients, when a strong mutual coupling exists between the radiating elements. For this reason, use of the partially overlapped subarrays has been limited to the space borne and military radars, which use high gain elements with large spacing. In this paper, we describe a two layer planar design that simply avoids the difficulty of designing feed network crossovers by laying out the antenna and feed network in two separate layers. A new feeding scheme is introduced that uses resonant type transmission line sections in a combined series/parallel network to achieve a two dimensional excitation control which is insensitive to the mutual coupling effects. The performance of an 80 element microstrip phased array, designed based on this approach, will be examined.

II. A 2-LAYER MICROSTRIP IMPLEMANTATION OF THE ANTENNA ARRAY AND FEED NETWORK

The design example here is a two dimensional array of 16×5 elements with capability of scanning solely in the horizontal plane. This array, which is shown in Fig. 1, is composed of 16 identical vertical rows of five series fed

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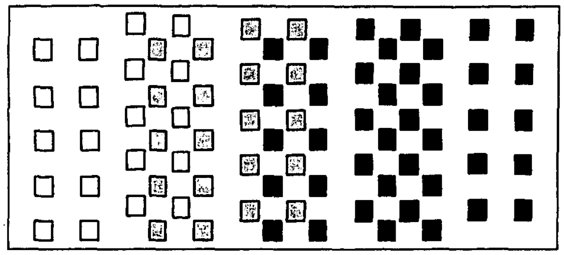

Fig. 1. Simplified layout of the 80 element array.: subarrays are shown in different gray scales.

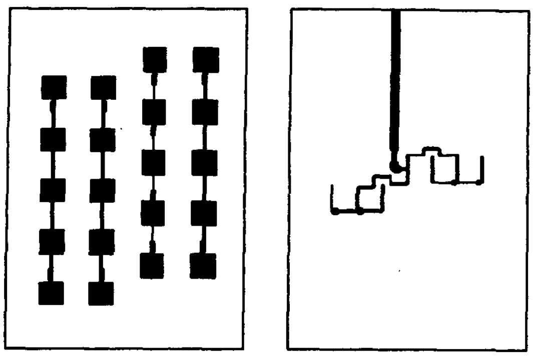

Fig. 2. Subarray layout. Left: antenna layer, right: feed layer.

rectangular microstrip patch antennas. Each row has a confined pattern in the vertical plane, and a broad beam pattern in the horizontal plane. These rows act like the elements of a horizontally extended array of 16 antennas that forms a two level phased array as described in the previous section. The 16 rows are divided into 4 similar groups. Each of these groups (5×4) is a subarray with inphase excitation. These subarrays are seen in different gray scales in Fig. 1. While the 5 elements within a row are amplitude locked through the interconnecting resonant transmission line sections [see sec. III], that lie in the same layer as the microstrip antennas (antenna layer), the 4 rows in each subarray are combined through a corporate feed which is similarly made of resonant line sections and locks the relative voltages between the rows. The corporate feed lies in a second layer of microstrip, which is isolated from the antenna layer by the common ground plane. Coupling between the corporate feed and the rows is through non-resonant slots on the ground plane, which are placed beneath the central elements of each row. Layouts of the antenna layer and the corporate feed have been shown in Fig.2 for an individual subarray. The resonant sections used in this design are simply two port microwave networks that provide a fixed voltage ratio between the input and output, independent of the loading conditions. Principle of operation and design procedure for these resonant sections will be described in the next section.

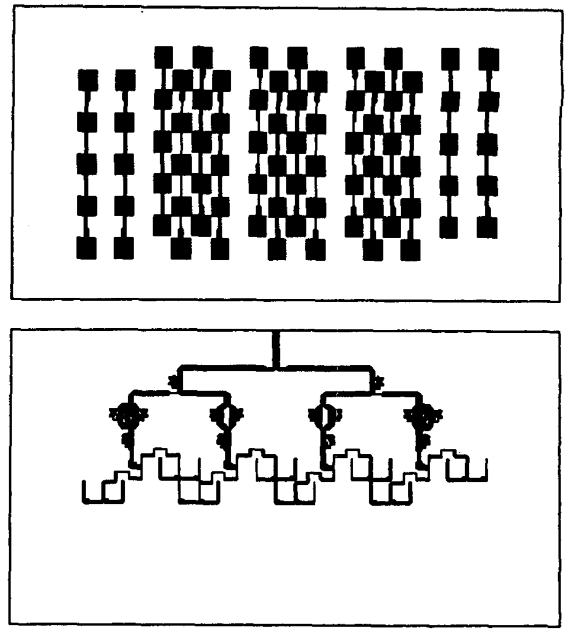

Fig. 3. Array layout. Top: antenna layer, Bottom: feed layer.

Each subarray is introduced to the secondary array through the input terminal of the corporate feed. Assuming that the subarrays are properly matched at these terminals, a conventional power divider along with phase shifters at its output ports is used to control the amplitude and phase of each subarray (here a 4 element Chebyshef distribution for SLL=−19dB). The power dividers and phase shifters are built on the second microstrip layer (feed layer).

Layouts of the antenna and feed layer for the full array have been shown in Fig. 3. In each subarray two of the rows are positioned with a vertical offset with respect to the other two. Such a displacement does not affect the radiation pattern in the horizontal plane and has a minor effect in the vertical plane pattern, which is not of primary concern in this design. With this offset arrangement of the rows: 1- the partially overlapped subarrays may be fed by non-intersecting feed networks, and 2- mutual coupling between the closely spaced rows of the overlapped subarrays is greatly reduced. As shown in Fig. 3-b, the subarray corporate feeds that have been modified for the offset subarray can reach the corresponding rows without crossing the neighboring feed networks. Considering the difficulty of implementing the RF crossovers in planar designs, this offers a considerable simplification. The effect of vertical offsetting in reducing the mutual coupling may be realized by a simple experiment. Fig. 4 shows the simulated value of S_{21} between the input terminals of two adjacent rectangular microstrip antennas, as a function of vertical offset h. The antennas are similar to those used in

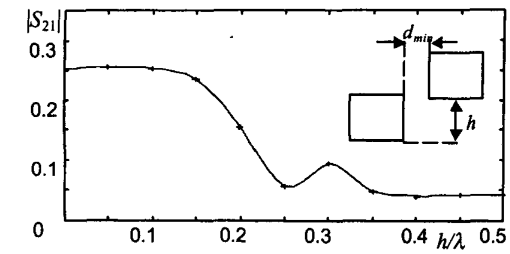

Fig. 4. Mutual coupling between two adjacent patch antennas vs. vertical offset.

the array design and are separated with a horizontal distance d_{min}, corresponding to the shortest horizontal separation occurring between the adjacent elements of two neighboring subarrays. This simple observation shows that offsetting can considerably reduce the undesirable coupling between the two antennas. Since in a scanning array, the amount of mutual loadings are not constant and depend on the state of the beam, in principle it is impossible to account for the mutual couplings in designing the feed network, and therefore it is important to minimize the mutual coupling and reduce its effect on the array coefficients. Together, *Offsetting* and *Resonant Feeding* address both of these requirements to provide a robust amplitude control in the array.

III. Resonant Feeding and Standing Wave Microstrip Arrays

While the standing wave type designs are standard for waveguide fed slot arrays, they have not been reportedly attempted for many other types of the antenna arrays. A class of standing wave feed networks may be developed for the microstrip arrays, which are especially useful when an exact account of the mutual coupling is not possible. The basic assumption here is that in a moderately strong mutual coupling environment, the mutual effect between two microstrip antennas changes only the amplitude of the current over each patch, not the form of the current distributions. This assumption is justified to a great extent by the resonant nature of the patch antennas, for which the form of current distribution is mainly determined by the modal field under the patch. Based on such a premise, the excitation coefficient of a patch is controlled by the voltage established across the input terminal as a result of input signal sources as well as the coupling to the other elements. Therefore if the feed network can establish the correct voltages across these terminals, proper excitation of the array is insured.

Fig. 5 shows a two-section transmission line with electrical lengths $\beta_1 l_1$ and $\beta_2 l_2$, and Characteristic impedances Z_1 and Z_2. The *ABCD* matrix for the two-port is obtained by multiplying the *ABCD* matrices of the

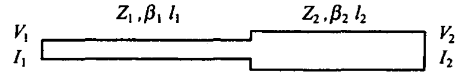

Fig. 5. A two part transmission line feed section.

individual sections:

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} = \begin{pmatrix} \cos\beta_1 l_1 & jZ_1 \sin\beta_1 l_1 \\ j/Z_1 \sin\beta_1 l_1 & \cos\beta_1 l_1 \end{pmatrix} \times \begin{pmatrix} \cos\beta_2 l_2 & jZ_2 \sin\beta_2 l_2 \\ j/Z_2 \sin\beta_2 l_2 & \cos\beta_2 l_2 \end{pmatrix} \quad (1)$$

By imposing the condition b=0, we have:

$$V_1 = a V_2 \quad (2)$$

This establishes a fixed ratio between the input and output voltages which does not depend on the loading (input/output currents). In a real problem, the total length l_1+l_2 is fixed and equal to l. For a given voltage ratio K, these conditions may be rewritten as:

$$l_1 + l_2 = l \quad (3\text{-a})$$

$$\cos(\beta_1 l_1) = K \cos(\beta_2 l_2) \quad (3\text{-b})$$

$$Z_1 / Z_2 = -\tan(\beta_1 l_1)/\tan(\beta_2 l_2) \quad (3\text{-c})$$

Solving (3) for l_1, l_2 and Z_1/Z_2, one can design the section that gives the desired voltage ratio. However, not for all values of K and l do these equations have a solution, and since the values of characteristic impedance are typically limited to 50 to 150 ohms for microstrip lines, even when they have a solution it may not be realizable. Nevertheless, for values of K between 1/3 and 3, and $\beta_1 l_1 + \beta_2 l_2$ between $p/2$ and $3p/2$, one can normally find a realizable solution. As for a 2-port network with b=0 the impedance matrix is singular, we call such a two-segment transmission line as a *resonant section*. The relative voltage of all the excitation nodes in a subarray now may be fixed by successive locking of the voltage amplitudes using these resonant sections. Such a feed network is called the *resonant feed network* and has the property that its nodal voltage distribution is independent of the loading. Now, since the mutual coupling among the elements of the array is modeled by a term in the *active* loading admittances of the elements, it cannot affect the nodal voltage distribution in a resonant feed network.

Although resonant feed network is very useful for realizing the desired array coefficients, it does not provide any control on the array input impedance. As a result one cannot design the feed network to simultaneously achieve amplitude control and input matching. A practical solution is to design the feed network for the required array coefficients, simulate or calculate the input impedance of the entire array and then add a matching network at the array input. In our case, the subarrays use resonant feed networks and are matched at their input terminals. Aside from the mismatch losses, input matching is crucial for

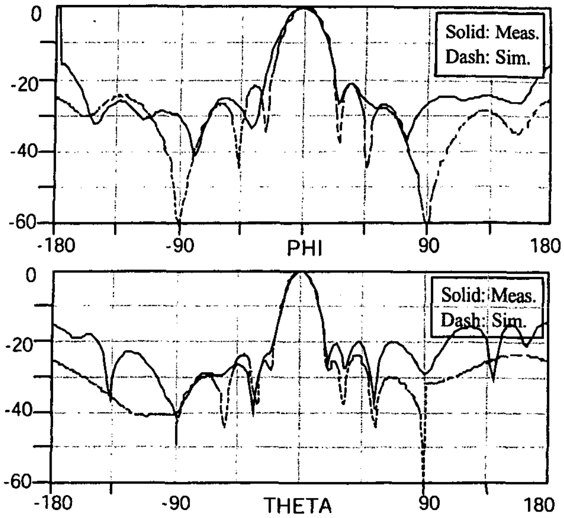

Fig. 6. Measured and simulated radiation patterns for a subarray. Top: horizontal plane, bottom: vertical plane.

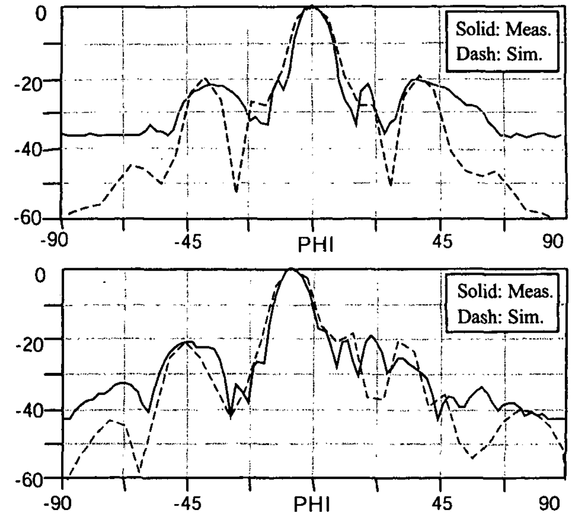

Fig. 7. Measured and simulated radiation patterns of the full array. Top: centered beam position, bottom: scanned.

proper operation of the phase shifters and the input power divider. The matching network can be simply made of a two or three section transmission line. As patch elements are normally narrowband elements, the overall bandwidth of the resonantly fed array is comparable to the one using standard feeding schemes and is basically limited by the element bandwidth.

IV. SIMULATION AND EXPERIMENTAL RESULTS

The 5×4×4 element array described in section II has been designed for a millimeterwave traffic control radar operating at 60GHz. A scaled prototype of this array has been fabricated and measured in X-band. Figs. 6 show the measured radiation pattern of an individual subarray along with the full wave simulation. In both principal planes, both simulated and measured patterns are similar to what expected from a Chebyshef array with a cosine type element factor, which shows that the resonant feed network has successfully set the excitation coefficients to the targeted values. The measured sidelobe level is better than –20dB in both principal planes as expected and S_{11} is less than –10dB over a 4% bandwidth. Figs. 7 shows the measurement and simulation results for the 80 element phased array, in the centered and scanned beam positions. As in the vertical plane, pattern is identical to that of a subarray, only the horizontal plane patterns have been shown. Sidelobe level was measured at –20dB and –19dB for the centered and scanned beam positions. With a measured beamwidth of ~8 and ~16 degrees in horizontal and vertical planes, the estimated directivity is 25dB. The measured gain is 20.6 dB, however, which is corresponding to an efficiency of 33%. A –10dB bandwidth of 6.3% and 8.5% was measured in the centered and scanned cases, respectively.

V. CONCLUSION

A planar implementation of the beam steerable phased arrays with partial overlapping was proposed which is suitable for millimeterwave applications. Issues like feeding the overlapped subarrays without using the crossovers, as well as the layout concerns for reducing the mutual coupling have been addressed for a particular design example. The concept of resonant feeding has been developed and utilized to achieve a highly tolerant amplitude control. The proposed techniques may be used for developing simple beam steerable phased array systems with moderately low sidelobe level. Such planar designs may be considered for wafer level integration with the phase shifters and front end electronics.

ACKNOWLEDGEMENT

Authors would like to thank Mitsubishi Electronics, Osaka, Japan, for sponsoring this research.

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