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Recent Developments in the Analysis and Design of Printed Phased Array Antennas

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I. Introduction:

Printed antenna array design is a rich and fascinating subject that has attracted the interest of antenna practitioners and analysts alike. This is partly due to the fact that printed arrays have a number of practical advantages, such as low cost, light weight, and conformability that make them preferred over other antenna types for a variety of applications. But another reason for the interest in this subject is the fact that printed antennas offer more flexibility and variety in their design than probably any other class of antenna. The large number of possible permutations of element types, feeding methods, and substrate configurations has led to a wealth of novel and useful designs, and this trend shows no sign of diminishing [1]. This wide variety of printed array configurations also provides a fertile supply of challenging problems in analysis and modelling.

This paper will summarize some of the key developments in the design and analysis of printed phased array antennas that have occurred in the last three years. We will begin with a summary of the wide variety of printed array geometries and configurations that have been developed or suggested, and make some general comments on the analysis of printed antenna arrays. The majority of the paper will involve the discussion of several specific printed array geometries that have been proposed, fabricated, or analyzed in recent years.

A. General Discussion of Array Configurations

Printed antenna array designs can be categorized according to the array geometry and the array performance specifications. The table shown below categorizes most of the possible array geometries in terms of the type of substrate material, the substrate configuration, the radiating element type, and the feeding technique. This table can be used as a menu, making one selection from each column (although not all combinations result in practical arrays). The examples discussed in Section II will cover several of these array configurations that have received attention in recent years, but there are obviously many possibilities that have yet to be studied. These configurations include both parallel substrate "tile" architectures, as well as "brick" architectures that use perpendicular substrates.

Menu of Printed Array Geometries			
Substrate Material	Substrate Configuration	Element Type	Feeding Method
Isotropic Anisotropic Ferrite Chiral	Single layer Multiple layers Perpendicular substrates	Microstrip patches Printed dipoles Stacked patches Tapered slots	Coaxial probes Microstrip feed Aperture coupled Proximity coupled

Further array definition involves the performance specifications of the array, as listed in the table shown below. These options and those listed above for the array geometry clearly have an intimate impact on each other, so choices from these two tables can seldom made independently.

Menu of Printed Array Specifications				
Type	Configuration	Phasing	Amplitude	Polarization
Linear	Non-subarrayed	Broadside	Normal SLL	Linear
Planar	Subarrayed	Squinted	Low SLL	Dual
Conformal		Scanning		Circular

B. General Comments on Array Analysis

A completely rigorous analysis of most printed antenna problems is very difficult because of several factors, including the presence of dielectric inhomogeneities, high-Q elements, and complicated and varied feed structures. Arrays introduce further complexity in the form of mutual coupling, spurious radiation, and scan blindness effects. In practice, however, useful design data can often be obtained using very simple models, while more sophisticated modelling is required for higher order effects.

Thus, we can divide printed array analysis into two categories, as shown in the table below:

Array Properties Requiring Only a Simple Model:

* isolated element impedance
* isolated element pattern
* element excitations
* array patterns (excluding mutual coupling effects)
* feed network design and feed losses

Array Properties Requiring Full-Wave Modeling:

* effect of mutual coupling on element impedance
* scan blindness effects
* effect of mutual coupling on array patterns
* feed network radiation
* surface wave effects
* diffraction effects

For example, the simplest and most straightforward analysis of a microstrip patch array uses cavity-model formulas for element patterns combined with an array factor; microwave circuit CAD may be used to design the feed network. Such a model often gives excellent results for many cases of practical fixed-beam array design, even though mutual coupling effects are ignored in this model, as are surface waves and a number of other second-order effects. If a large scanning array of microstrip patches is to be designed, however, mutual coupling and surface wave effects may be critical, thus requiring the use of full-wave analysis techniques. In addition, techniques such as full-wave solutions are often the only cost-effective way to optimize the design of a large array, or to define the limits of performance for a given array design.

Mutual coupling effects in arrays can be treated in two quite different ways, using either the finite array model or the infinite array model. The former requires mutual coupling terms for each pair of elements in the array in the presence of all other elements, while the infinite array approach utilizes periodicity to account for all mutual coupling effects through the consideration of a single unit cell. Edge effects can be modeled in the finite array approach, but not with the infinite array model. The infinite array model is much more computationally efficient, however, especially for large arrays.

II. Analysis and Design of Specific Printed Phased Array Antennas

A. Probe-fed Microstrip Patch Arrays

Coaxial probe feeds are one of the most common ways of feeding microstrip patch antennas. They are simple to fabricate, and can be used as interconnects between different substrate layers. The rigorous analysis of probe-fed patch antennas is difficult, however, due to the rapidly varying current near the probe-patch junction. A number of researchers in recent years have developed accurate feed models for isolated probe-fed patches [2], but there has been very little work on the application of such models to finite array analysis. Infinite array modeling has met with more success, with the development of full-wave solutions for infinite arrays of rectangular or circular patch elements having one or two probe feeds [3],[4]. These solutions use a special attachment mode to model the current flow from the probe to the patch, and have been found to be accurate for thick and/or high dielectric constant substrates; they have been verified with measurements from waveguide simulators. They have also been extended to cases of stacked patches and multilayer substrates. Several examples demonstrating these solutions will be presented during the talk.

A recent example of probe-fed patch array development is a 64 element S-band conformal microstrip patch phased array developed by Raytheon [5]. Each element uses two pairs of probe feeds in a balanced configuration for circular polarization, and is driven with an MMIC T/R module containing a 5-bit phase shifter.

B. Aperture Coupled Microstrip Patch Arrays

Aperture coupled microstrip patch elements have a number of advantages over direct contacting feeds, including the use of separate substrates for radiating elements and feed circuitry, isolation of spurious feed radiation, and the elimination of soldered connections. Both full-wave and cavity-type solutions for isolated aperture coupled microstrip antennas have been available for several years, and a solution for infinite arrays of aperture coupled microstrip antennas has recently been published [6]. There has only been preliminary work on the mutual coupling between pairs of aperture coupled elements.

More recently, arrays of multilayer aperture coupled elements have been studied [7],[8]. These geometries include stacked patches (for increased bandwidth), radome layers, and the use of multilayer feed lines such as inhomogeneous stripline or coplanar waveguide. A fairly general CAD analysis routine capable of handling all of these variations has been developed and tested [7], and some examples from this work will be shown.

Several planar and series-fed aperture coupled microstrip arrays have been successfully designed and tested without consideration of mutual coupling effects [9]-[11], and aperture coupled elements are being considered in a number of advanced phased array systems. One such system that is near completion is the 30 GHz monolithic phased array being developed as part of the NASA ACTS satellite program. This antenna is being developed by Texas Instruments, and uses a 4x4 array of aperture coupled microstrip elements with MMIC phase shifters and variable gain amplifiers at each element to provide beam switching in conjunction with a large reflector [12].

C. Proximity Coupled Microstrip Patch Arrays

Proximity coupled microstrip patch antennas use microstrip feed circuitry on one substrate layer with open-circuited stubs to couple to microstrip patch elements on a superstrate layer. The feed circuitry thus sees a relatively thin substrate, which results in low spurious radiation and unwanted coupling, while the bandwidth of the antenna elements is improved because of the effectively thicker antenna substrate [2]. A full-wave solution for infinite arrays of proximity coupled patches has been completed [13]. This solution was verified with waveguide simulator experiments, and used for the optimization of arrays of proximity coupled patches for wide bandwidth and wide scan angles. Designs were obtained having bandwidths of up to 18% over a 60° scan range.

D. Arrays of Dipoles or Tapered Slots on Dielectric Sheets Perpendicular to Ground Plane

Arrays of printed dipoles or tapered slot antennas on dielectric substrates protruding perpendicularly from a ground plane are examples of the "brick" array architecture, which has advantages of unlimited space for active circuitry, a high degree of modularity, and good isolation between the radiating aperture and the feed circuitry. Disadvantages are that the configuration does not retain the simplicity of a monolithic geometry, does not have a low-profile, and dual or circular polarization is very difficult to obtain. A rigorous analysis of such arrays is quite complicated because of the fact that the dielectric substrate is finite in two dimensions, but infinite array solutions have recently been developed for printed dipoles [14] and tapered slot antennas [15]. These solutions predict that scan blindness effects can occur due to guided waves along the substrates and, in the case of dipoles fed with balanced transmission lines, blindness can also be caused by the feed lines.

Several prototype phased arrays of this type are currently being proposed or studied. A 60 GHz dipole array on protruding ceramic substrates with MMIC phase shifter and amplifier modules is being developed by General Electric [16] for SDI satellite-to-satellite communications, and a small array of linearly tapered slot antennas has been evaluated by JPL for spatial power combining with a Cassegrain reflector antenna for a limited scanning application in satellite communications [17].

E. Low Sidelobe Microstrip Arrays

Practical implementation of arrays with sidelobe levels lower than 25 or 30 dB is very difficult because of random phase and amplitude errors introduced by the feed network, tolerances in element positioning, and imperfect impedance matching or feed network isolation; deterministic errors may be introduced by mutual coupling and diffraction effects. Low sidelobe printed arrays suffer from further difficulties due to spurious feed network radiation, surface wave diffraction and, most importantly, potentially large phase errors that can result from the narrow bandwidth of most microstrip antennas.

A quantitative study of the factors affecting the performance of low sidelobe microstrip arrays has been recently completed [18]. It is found that spurious feed network radiation precludes the use of a coplanar feed network if sidelobe levels lower than about 25 dB are to be attained. It is also found that very tight tolerances on the size (or resonant frequency) of the microstrip elements must be maintained in order to reduce phase errors resulting from the rapid variation of the input reactance with patch size that is typical of narrow bandwidth elements. Mutual coupling effects, however, were found to be relatively insignificant for most low sidelobe microstrip arrays. These findings were verified through tests with a 16 element microstrip patch array fed with an off-board divider network; sidelobe levels of 35 dB were measured.

F. Infinite Arrays of Subarrays

Grouping array elements into contiguous subarrays offers potential cost savings for large phased array antennas, as well as allowing simpler feed networks. Arrays with parasitic elements and arrays of circularly polarized synchronous subarrays [19] can also be treated as subarrayed arrays. Since there are several tradeoffs between array performance measures and the type and degree of subarraying, it is useful to have some analytical model for such antennas. This has recently been achieved for several types of infinite arrays of printed antenna subarrays [20], and results from this work showing the tradeoff between subarray size and power lost to grating lobes will be shown, as will results for circularly polarized synchronous subarrays. Another interesting result of this work is that scan blindness effects can be reduced or eliminated by subarraying, and examples of this effect will be discussed.

G. Microstrip Arrays on Ferrite or Chiral Substrates

Most printed antenna work to date has used ordinary dielectric substrates, but more exotic materials offer the possibility of enhanced performance or totally novel effects. Ferrites are particularly interesting because they are readily available, and offer an anisotropy that can be controlled through a DC magnetic bias field. Recent analytical work has considered the performance of microstrip patch antennas and infinite arrays on normally biased ferrite substrates [21], and several unique features were found to be achievable with this geometry. These include generation of circular polarization from a square or circular patch with a single feed point, frequency tuning and/or polarization switching by varying the strength or polarity of the magnetic bias field, wide-angle impedance matching for phased arrays by dynamic adjustment of the bias field with scan angle, and the capability to switch the substrate into a cutoff mode whereby the radar cross section of a microstrip antenna can be reduced by 20 - 30 dB. Examples of these effects will be presented during the talk.

Another interesting possibility is the use of chiral materials for printed antenna substrates. Radiation and scattering characteristics of chiral materials have been the topic of much study in the past few years, even though it is not clear that such materials are economically practical. We have recently completed an analytical study [22] of microstrip antennas and arrays on chiral substrates, and have found that, in terms of antenna performance, there does not seem to be any advantages to be gained from the use of chiral substrates. In fact, there are several disadvantages that may result from the use of chiral substrates, including increased surface wave excitation and significantly degraded cross-polarization levels. Previously published claims that the use of chiral substrates lead to reduced surface wave power and mutual coupling levels do not appear to be valid for microstrip antennas.

III. Conclusion

Significant progress has been made in the last three to five years in the analysis, design, and development of printed phased array antennas. This paper has reviewed some of these developments, providing summaries of evolving printed array architectures as well as several specific phased array design types. Several examples of these different designs will be discussed during the talk.

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