Novel Low-Cost Beam-Steering Techniques Using Microstrip Patch Antenna Arrays Fed by Dielectric Image Lines

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***Abstract*— This paper presents novel low-cost beam-steering techniques using microstrip patch antenna arrays fed by dielectric image lines (DIL's). Two approaches are designed and used. The first, DIL's without reflector plate, are used for feeding microstrip patch antenna arrays. Antenna array radiation beams are scanned when the operating frequency sweeps. The second, a dielectric image line with a movable reflector plate (DILWRP), is developed. The beam direction of the antenna array is controlled and steered by changing the perturbation distance between DIL and movable reflector plate at a given operating frequency. Both types of patch antenna array structures are simple, low cost, easily fabricated, stable, and reliable. Eight-element patch antenna arrays fed by DIL and DILWRP have been designed, fabricated, and tested. Experiments show good performance and results. Measurement results of scanning angles agree well with theoretical predictions.**

***Index Terms*—Beam steering, microstrip arrays.**

I. Introduction

THE rapid growth of wireless and satellite communication systems has caused an increase in the use of microwave and millimeter wave frequencies. The aperture-coupled microstrip patch antenna is a good candidate for these applications [1]. It is planar, conformal, easily fabricated using photolithography techniques, low cost, and fairly robust to environmental effects. Also, microstrip patch antenna has a good gain and an unidirectional radiation pattern. For high-frequency applications, microstrip feed lines have higher conduction losses and surface modes could also be excited. As a result, the gain of the antenna suffers. Recently, an aperture-coupled dielectric image line (DIL) feed was proposed for microstrip patch antenna arrays [2]–[4]. This array feed structure shows promise as an alternate feed method as it has lower losses at high frequencies.

Traditional phased arrays use a solid-state or ferrite phase shifter behind each antenna element. It makes beam-steering antenna arrays complicated and expensive. The dielectric image feed line is a traveling wave structure [5]. The electromagnetic signal travels mainly in the DIL and can be perturbed in several ways. The changing of the propagation constant of the electromagnetic (EM) field in DIL can be applied to steer radiation beam angles of patch antenna arrays. This paper presents two novel approaches for beam-steering applications. The first—DIL structure without reflector plate—is used for feeding microstrip patch antenna arrays. When the operating frequency sweeps, propagation constants in DIL change and antenna array radiation beams are scanned. The second, a movable reflector plate is applied on the back of the dielectric image feed line to form a dielectric image line with a movable reflector plate (DILWRP) structure. The beam direction of the antenna array is controlled by changing the perturbation distance between DIL and movable reflector plate at a given operating frequency. The beam-steering ability of patch antenna arrays fed by these two structures principally relies on the dispersion property of EM wave propagation constants in DIL's. Both types of patch antenna array structures are simple, low cost, easily fabricated, stable, and reliable.

A rigorous solution for the aperture-coupled microstrip patch antenna fed by dielectric image line (ACMADIL) is very difficult. Sufficiently accurate analysis and design for this antenna structure were given in [4] by making a few approximations. The DIL was analyzed in [4] using the effective dielectric constant (EDC) method [5]–[7]. It is an approximate calculation and is not accurate enough to theoretically compute the beam steering of patch antenna arrays fed by DIL. Furthermore, the EDC method cannot analyze dielectric image line structures with movable reflector plates (DILWRP).

In this paper, a rigorous hybrid-mode analysis is used for calculating the dispersion of electromagnetic field propagation constants in DIL structures with or without movable reflector plate. Then these theoretical results are used for designing frequency steering microstrip patch antenna arrays fed by DIL and beam-scanning patch antenna arrays fed by DILWRP. Angular scans of radiation beams are achieved by varying the operating frequency for DIL or by changing the perturbation distance of the reflector plate for DILWRP. Eight-element microstrip patch antenna arrays fed by DIL or DILWRP have been designed, fabricated, and tested. The patch antenna arrays show good match, high gain, wide frequency band, large scanning angles, low cross polarization, and low sidelobes. Experimental results of scanning angles in radiation patterns agree very well with theoretical predictions.

II. Configurations

Fig. 1 shows the structure of aperture-coupled microstrip patch antenna arrays fed by DIL's. This is a series-fed beam-

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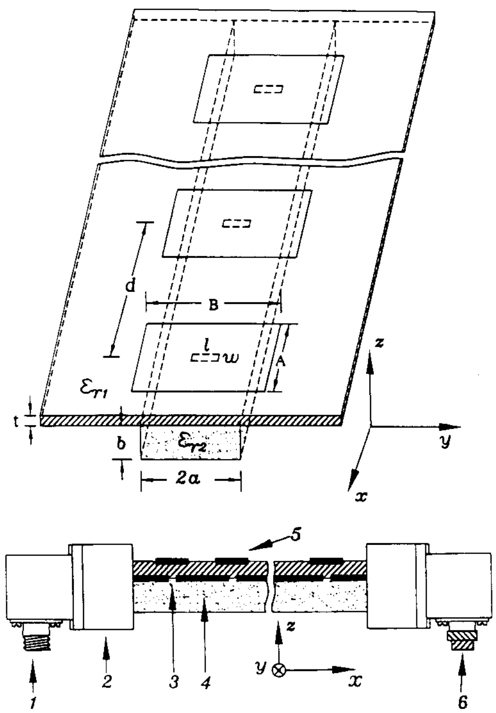

Fig. 1. Aperture-coupled microstrip patch antenna array fed by DIL. The waveguide components are only used for testing purpose. (1) N type to rectangular waveguide transition. (2) Waveguide to DIL transition. (3) Aperture. (4) DIL. (5) Patch. (6) Matched load.

steering antenna array. For testing purpose, the signal is coupled to the DIL from the waveguide through transitions. Proper design of DIL dimensions allows single-mode propagation for a considerable range of frequency [5]. For radiating patch elements fed serially along the DIL, there will be a phase delay between elements. This interelement phase delay is linearly progressive and is a function of the propagation constant in DIL. The radiation beam angle will steer when the propagation constant in DIL changes. To form a beam in the direction θ from broadside, the following has to be satisfied [8]:

$$\beta_0 \cdot d \cdot \sin\theta_n = \beta_g \cdot s - 2n\pi \tag{1}$$

where θ_n is the nth beam angle from broadside (normal), $\beta_0 = 2\pi/\lambda_0$ free-space propagation constant, $\beta_g = 2\pi/\lambda_g$ propagation constant in dielectric image feed line, d distance between radiating elements, s length of feed line between elements, and n integer

$$\sin\theta_n = \frac{\lambda_0}{d} \cdot \left(\frac{s}{\lambda_g} - n\right). \tag{2}$$

In this paper, s is chosen to be equal to d in the patch antenna array fed by DIL, as shown in Fig. 1. Under this condition, the beam scan (2) becomes

$$\sin\theta_n = \lambda_0 \cdot \left(\frac{1}{\lambda_g} - \frac{n}{d}\right). \tag{3}$$

Two approaches are applied in this paper to perturb propagation constants in DIL's and then to steer antenna array radiation patterns. When the operating frequency of the antenna array shown in Fig. 1 is adjusted, propagation constants in DIL change and antenna beam angles are steered. Fig. 2 shows the second approach. A movable metal reflector plate is installed in parallel on the back of the dielectric image feed line to form a DILWRP structure. The perturbation spacing between DIL and movable reflector plate is varied and controlled precisely using a micrometer head. The EM field in DIL is perturbed and propagation constants and λ_g in DILWRP will change. The radiation beams are scanned at a given operating frequency. Both approaches are simple, low cost, easily fabricated, and reliable. The beam-steering angles of patch antenna arrays can be controlled easily.

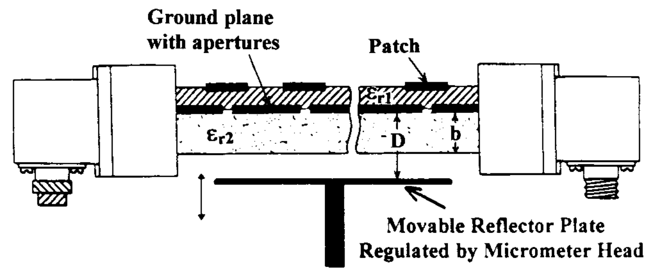

Fig. 2. Beam-steering patch antenna array fed by DIL with a movable reflector plate (DILWRP).

III. Rigorous Hybrid Mode Analysis

Accurate computation of propagation constants and λ_g in DIL's without or with movable reflector plate is required for theoretically predicting radiation scan angles and for designing beam-steering antenna arrays. A rigorous hybrid-mode analysis [9] is used in this paper for calculating the dispersion of EM field propagation constants in dielectric image lines without or with movable reflector plate (DIL or DILWRP).

A movable perfect electric reflector plate is placed at a distance D $(z = -D)$ parallel to the ground plane $(z = 0)$. The perturbation of the reflector plate on EM field properties in DILWRP can be adjusted by changing the distance D. DILWRP structures will become DIL when D increases to infinity. The cross-section region with DIL under the ground plane is subdivided into several subregions. A complete set of field solutions is derived for each subarea. The dependence of field components on x can be assumed to be an exponential function as $\exp(\pm j\beta_g x)$. β_g is the phase propagation constant and is the same in all these subregions. y and z dependencies of fields in subregions are formulated using eigenfunctions, so that boundary conditions are fulfilled on defined boundaries. All modes are classified as TM and TE with respect to z direction. Fields in every subregion can be expressed in terms of scalar potential functions for TM and TE to z modes, respectively. Boundary conditions are enforced independently. Finally, a complex matrix equation is derived. All matrix elements are functions of frequency f, perturbation spacing D, image line sizes, dielectric constant ε_{r2}, and propagation constant β_g. All data except β_g in these matrix elements can be calculated when f, D, image line sizes, and ε_{r2} are given. Propagation constants β_g in DILWRP are computed by solving the zeros of the determinant of the whole complex matrix equation. The effect of different perturbation distance

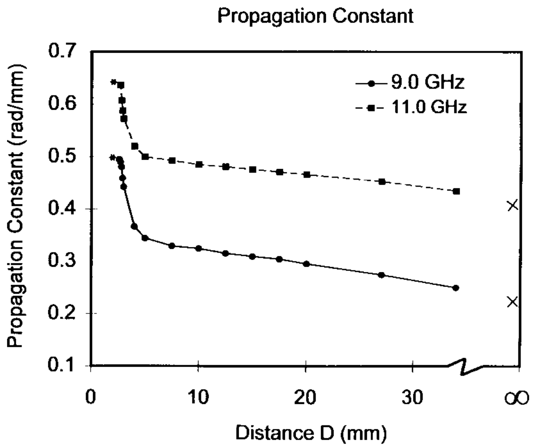

Fig. 3. Computed propagation constants β_g for X-band DILWRP with different distance D at 9.0 and 11.0 GHz. Image line sizes: 2.54 mm × 5.08 mm; $\varepsilon_{r2} = 10.5$ —●— 9.0 GHz, —■— 11.0 GHz; hybrid-mode analysis × EDC method; $*$ H-guide theory.

D on propagation constants β_g is then computed exactly. Propagation constants β_g in DIL structures are calculated by choosing a very large distance D.

For a given operating frequency and DILWRP structure characteristics, the determinant of the complex matrix is computed and examined for its zero crossing for β_g in the range between β_0 and $\beta_0\sqrt{\varepsilon_{r2}}$. Propagation constants β_g are then determined. The complex double precision is used in calculating the determinant. Sufficient number of imaginary roots has to be solved and used and the right imaginary roots have to be chosen in order to get convergent and accurate numerical results. The correct way to choose real and imaginary roots has been studied and found. A calculation accuracy better than 1.0% and fast convergence are achieved in this paper using only five TE modes and five TM modes, which include four real modes and one imaginary mode.

Propagation constants β_g in DILWRP have been seen to be different when the perturbation distance D changes. This is useful for the beam-scanning application. Fig. 3 gives calculated results of β_g for X-band DILWRP with different distance D at 9.0 and 11.0 GHz. Results show that propagation constants β_g increase 64.6% at 9.0 GHz and 31.5% at 11.0 GHz when distance D decreases from 20.0 to 2.7 mm. Furthermore, results of propagation constants β_g are found to increase when the operating frequency increases. Two special cases are also considered in this paper: $D = \infty$ and $D = b$. The EDC method is an approximate method and can be used only for structures with an infinitive reflector plate distance D. H guide [5] is another special case of DILWRP when the distance D is equal to the thickness b of DIL. Calculated results using the EDC method and H-guide theory are also given in Fig. 3 for comparison. It can been seen that our theory agrees well with the results calculated using EDC method and H-guide theory for these two special cases.

IV. Design Criteria

Operating frequency range, propagation constants β_g in dielectric image feed lines, distance d between radiating patch elements, perturbation spacing D, and the effect of different D on β_g are several key parameters for designing steering microstrip patch antenna arrays fed by DIL or DILWRP. These values determine the beam angles of radiation patterns as seen in (1)–(3). Propagation constants β_g and its dispersion are determined by the operating frequency, DIL structure characteristics, and the perturbation spacing D. The rigorous hybrid-mode analysis is used to calculate precisely β_g and its dispersion. Ideally, DIL should be kept as large as possible at a given operating frequency range, especially for millimeter-wave applications, in order to ease fabrication problems and lessen the effects of size variations on the guide wave length and scan angle. At the same time, single-mode operation must be maintained in the propagation of signal in DIL with only a single radiation beam from an antenna array. The unit ratio of DIL size of $a/b = 1$ provides the maximum bandwidth [5]. For good field containment and single-mode operation, the following formula can be used to select unit aspect ratio a/λ_0 for DIL structures:

$$\frac{a}{\lambda_0} \approx \frac{0.32}{\sqrt{\varepsilon_{r2} - 1}}. \tag{4}$$

Relative dielectric constant ε_{r2} of DIL should be chosen not too small in order to get enough dispersion in dielectric image feed lines and then to realize wide scan ranges. $\varepsilon_{r2} = 10.5$ is a good choice from our experience. To obtain broadside radiation at a given center frequency, (3) shows that the distance d between patch elements must be chosen equal to the guide wavelength. In practice, it is nearly impossible to choose $d = \lambda_g$ due to impedance match problems of linear array feed structures. Therefore, the steering angle will not be equal to zero at the center frequency. In this paper, distances d between patch elements are optimized and chosen being slightly smaller than λ_g at its center operating frequency. Wide-frequency steering ranges and angle scanning ranges are obtained.

Design methods used in this paper for microstrip patch antennas, aperture sizes, and traveling wave arrays are identical to that of [4]. The cavity model is used for computing rectangular patch antennas and fringing field effects are taken into account [10]. Aperture sizes are designed using the theory based on the change in modal voltage of the image line at the aperture [4]. The electric field in the aperture is assumed to be a half-sinusoidal wave. The field inside the patch and, hence, the reaction at the aperture can be determined [11]. The normalized impedance of antenna at the aperture is then obtained by calculating the change in the modal voltage of DIL [12], [13]. The Dolph–Chebychev method [14] or Taylor's method [15] is used to find the required field amplitude distribution for antennas array elements. Well-known antenna array synthesis procedures [10], [16] are combined with the calculation method and theory developed in this paper and reference [4] to design steering linear traveling-wave antenna arrays.

V. Experiments and Results

RT-Duroid material of relative dielectric constant $\varepsilon_{r2} = 10.5$ was used to make the DIL at X-band frequencies. The X-

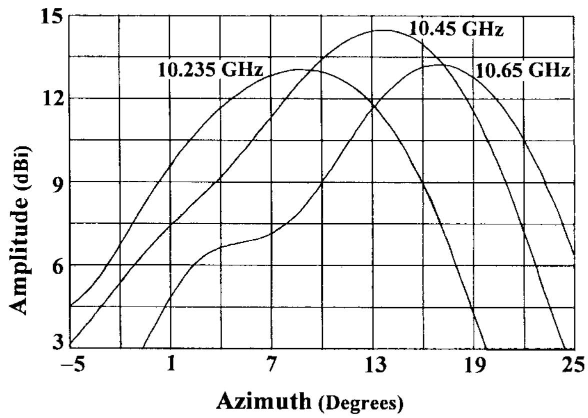

Fig. 4. X-band frequency beam-steering radiation patterns in E-plane for eight-element patch antenna array fed by DIL at 10.235, 10.45, and 10.65 GHz.

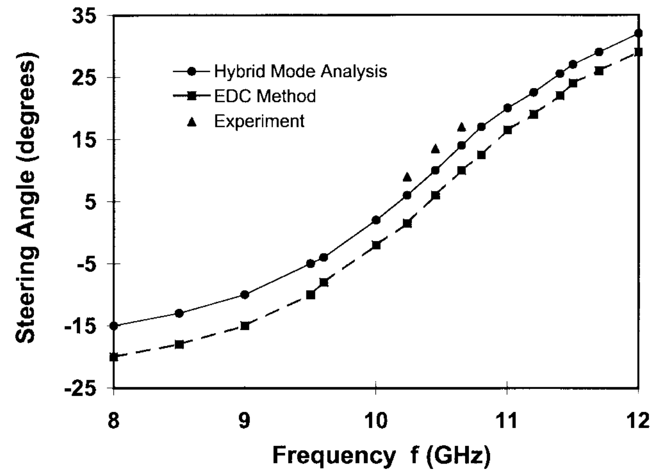

Fig. 5. Beam-steering angles versus operating frequencies for X-band patch antenna array fed by DIL.

band DIL had a width $2a = 5.08$ mm and thickness $b = 2.54$ mm. A micrometer head was used to control precisely the perturbation distance D to an accuracy of 1 mil.

RT-Duroid substrate of relative dielectric constant $\varepsilon_{r1} = 2.3$ and thickness $t = 1.524$ mm was used for X-band patches, which had a radiating length $A = 8$ mm and width $B = 10$ mm.

Eight-element Dolph–Chebychev arrays were designed for sidelobes of less than 30 dB. Using the theory developed, the normalized impedances of the elements were determined to achieve the required coupling and the aperture dimensions were decided. The X-band arrays were designed with the aperture length l for all the eight elements being 4.0 mm. The interelement distance d was chosen as 20 mm. The aperture widths to achieve the required distribution of the excitation are 0.31, 0.57, 0.95, 1.05, 0.83, 0.53, 0.3, and 0.12 mm from the load.

Patch antenna arrays with eight-elements fabricated showed good match, high gains, wide operating frequency ranges, large scanning angles, low cross polarization, and low sidelobes. The antenna efficiency of the array is estimated to be 70% [4].

The steering of the E-plane main beam angles with frequency for patch antenna arrays fed by DIL is shown in Fig. 4 for the X-band frequency range. The main lobes were steered from 9.0° at 10.235 GHz, 13.5° at 10.45 GHz, to 17.0° at 10.65 GHz. The gains of arrays were found not changing considerably with frequency. Fig. 5 gives experimental and theoretical results of beam-steering angles versus operating frequencies for the X-band eight-element patch antenna array fed by DIL. The hybrid-mode analysis and EDC method were used to compute theoretically the steering angles, respectively. The predicted results using the hybrid-mode analysis agreed very well with experimental data. Calculation results using the EDC method show a less accuracy due to its approximation.

Radiation patterns of the X-band eight-element patch antenna array fed by DILWRP were measured for different perturbation spacing $(D-b)$. Fig. 6 shows the beam scanning of E-plane radiation patterns at the operating frequency of 10.45 GHz. The main beams were scanned from 3.5° at $(D-b) = 20$ mm, 6.0° at 5 mm, 8.5° at 2 mm, to 13.5° at

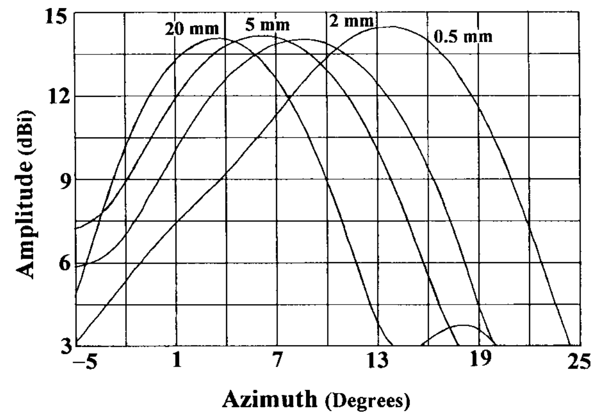

Fig. 6. Beam scanning of E-plane radiation patterns for X-band eight-element patch antenna array fed by DILWRP at 10.45 GHz with different perturbation distances $(D-b)$ of 20, 5, 2, and 0.5 mm.

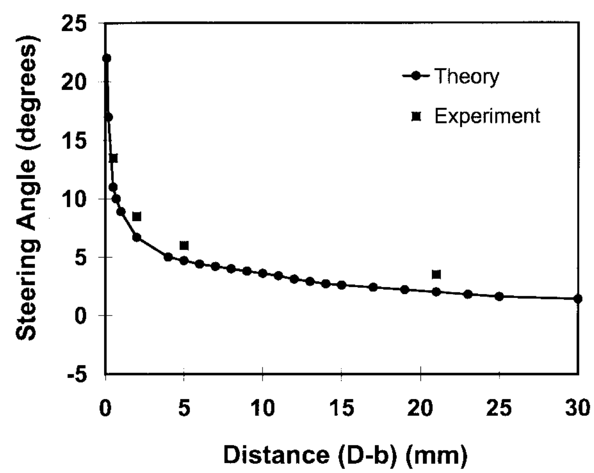

Fig. 7. Beam-steering angles versus perturbation distances for X-band patch antenna array fed by DILWRP at 10.45 GHz.

0.5 mm. Gains were found keeping closely the same level. The return loss is less than -10 dB for all these cases. Fig. 7 shows the experimental and theoretical results of beam scanning angles versus perturbation distances $(D-b)$ for the X-band eight-element patch antenna array fed by DILWRP. The computational steering angles using the hybrid-mode analysis matched well with experimental results.

VI. Conclusions

Novel low-cost beam-steering techniques using microstrip patch antenna arrays fed by DIL's have been presented in this paper. Two approaches have been designed and used. A rigorous hybrid-mode analysis has been used for calculating the dispersion of propagation constants in DIL's without or with movable reflector plate and then for designing beam-steering patch antenna arrays fed by DIL or DILWRP. Both types of patch antenna array structures are simple, low cost, easily fabricated, stable, and reliable. Eight-element patch antenna arrays have been designed and fabricated. Good return loss and radiation patterns have been measured. The movable reflector plate did not deteriorate the performance of the antenna array even when the perturbation distance $(D-b)$ was close to 1 mm. This property makes the antenna array to scan in a large angle range when the perturbation distance changes. The gains of arrays were found not changing considerably with frequency. Measurement results of scanning angles agreed well with theoretical predictions for all antenna arrays fabricated.

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