Modelling studies of microstrip reflectarrays

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Abstract: Modelling studies of microstrip reflectarrays are presented in this paper. A highly efficient full-wave analysis technique — a combination of the CG–FFT method and the complex discrete image technique — has been developed for the analysis of microstrip reflectarrays. Based on the technique, some trial designs have been implemented. Experimental and theoretical results are compared and found to be in good agreement.

1 Introduction

Mobile and satellite communication systems require high gain antennas which are compact in size and lightweight. Downsizing of antennas and associated technologies have recently become somewhat of a trend in the antenna community. Due to its compactness the microstrip reflectarray (MRA in short) has been suggested as a possible antenna for mobile and satellite communications [1].

The use of reflector antennas for beam forming is analogous to reflectors used in optics — the reflector surface is properly designed and fabricated to compensate for the phase differences of the fields travelling from the feed to different points on the reflector. A coherent phase-front for the reflected field is thereby generated. To reach the same goal, the microstrip reflectarray uses microstrip patches connected to open or short-circuited transmission lines to form a directional beam. The patches serve as re-radiators, and the connected microstrip transmission lines (we call them tails) are used as phase shifters. The tails are adjusted so as to generate a coherent field in a wanted direction.

Following the introduction of the concept of microstrip reflectarrays in 1987, only a few feasibility studies have been carried out. They have been primarily experimental in nature [2]. This is due to the fact that, as of yet, virtually no design tools have been developed for these types of structures. To add to this challenge, it should be noted that the structures are usually fairly large. As an analytical approach, basic antenna array theory combined with GTD, has been proposed by some workers [3]. This approach can only be used to derive a basic understanding and some rough predictions for the performance of these antennas. Another approach based on Method of Moment and Floquet theory of infinite large arrays has also been proposed in Reference 4. This approach can yield much more accurate results.

In this paper, we present our theoretical and experimental studies of MRAs. This work is carried out using a full-wave analysis technique which is a unique combination of the CG–FFT method and the complex discrete image technique. This technique is very efficient in terms of computer memory and computing time. It allows us to deal with very large MRAs (up to 1000 λ^2 area of 10 grids/λ) without any difficulty. Based on this full-wave analysis technique, we have studied the phase shift of the re-radiated field versus the length of microstrip tails, magnitude of current distributions versus the length of tails, the current distribution on the entire array and the radiation pattern of the MRA. To validate our model, several trial designs have been tested. The experimental results verify our theoretical studies.

2 Analysis

To accurately analyse a very large microstrip reflectarray, in particular, to accurately predict the backscattered fields from thousands of non-uniformly illuminated microstrip patches with un-equal lengths of microstrip transmission lines, a very complex analysis technique needs to be developed [3]. The conjugate-gradient fast Fourier transform method (CG–FFT) has a number of attributes that make it highly useful for analysing large microwave structures [5]. When combined with the discrete image technique [6], CG–FFT becomes a very robust technique for analysing very large microstrip antenna arrays [7]. In this paper, this technique is utilised to simulate large microstrip reflectarrays, as well as to predict the phase shifts of single patches with different lengths of tails, all in an array environment.

The general integral equation describing a microstrip antenna can be written as:

$$-\hat{n} \times \boldsymbol{E}^{\mathrm{inc}}(\hat{r}) = \hat{n} \times \int_S \bar{\bar{G}}(\hat{r}, \hat{r}') \cdot \boldsymbol{J}(\hat{r}')\, dS \tag{1}$$

with the conducting surface denoted by S, the current $\boldsymbol{J}$, the incident field $\boldsymbol{E}^{inc}$, the unit vector normal to the surface $\hat{n}$ and the dyadic Green's function $\bar{\bar{G}}$. If the equation is written into an operator equation form, then: $\boldsymbol{E} = L(\boldsymbol{J})$. The iterations of the CG algorithm minimise the functional $F(\boldsymbol{J}) = \langle \boldsymbol{r}, \boldsymbol{r} \rangle = \|\boldsymbol{r}\|^2$ where $\boldsymbol{r} = L\boldsymbol{J} - \boldsymbol{E}$. Because the integration in eqn. 1 is convolutional, an FFT can be used to compute the operation LV and L^*V (L^*: adjoint operator; V: $\boldsymbol{J}$ or $\boldsymbol{r}$). The CG–FFT method is very efficient in terms of computer memory ($O(N)$) and computing time ($O(4N(1 + \log_2 N))$).

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To overcome the difficulties of the Sommerfeld-type Green's function that is used to describe microstrip structures, the full-wave discrete image technique is integrated with the CG–FFT technique. This technique can convert the complicated Sommerfeld-type Green's function into a series of simple free-space-type Green's functions without losing any full-wave information. The computing time required for the generation of the discrete image is negligible compared to the CG–FFT procedure, and for a given substrate (single or multilayer), only one set of images has to be found regardless of the antenna's configuration and layout. The detailed description of the hybrid CG–FFT complex discrete image method can be found in References 7 and 8.

In the simulation, the incident field $\boldsymbol{E}^{inc}$ is defined by the characteristics of the feed antenna. When the type and the location of the feed is decided; it is not difficult to calculate the incident fields precisely (magnitudes, phases and glazing angles) at every position within the reflectarray. After calculation of the current distribution $\boldsymbol{J}(\hat{r}')$ on the conducting surface, the Fourier transform of $\boldsymbol{J}$ on a single patch with tail can be carried out to give the phase information of the re-radiated field from the patch:

$$I_{\xi}(\theta, \phi) = \int dx' \int dy' \boldsymbol{J}_{\xi}(x', y') e^{-jk_s \hat{r}'} \tag{2}$$

with $\hat{r}' = x'\hat{x} + y'\hat{y} + z'\hat{z}$, $\xi = x$ or y and $\boldsymbol{k}_s = k(\sin\theta \cos\phi\hat{x} + \sin\theta\sin\phi\hat{y} + \cos\theta\hat{z})$.

3 Numerical results

Based on the simulation approach described above, combined with conventional optics, reflector antenna and array theories, different types of MRAs can be designed. These include the parabolic, elliptical, hyperbolic, circular, triangular corner, flat sheet type, etc. The feed can have a large offset from the centre of the array, as long as the phase shifts from each patch are predicted accurately before designing the layout of the complete array.

We have simulated and tested some trial X-band linear microstrip reflectarrays, with different numbers of patches. Each patch is resonant at 12 GHz. The ε_r of the substrate used is 2.2, and its thickness is 1.59 mm. We give one design example to verify our simulation model, 1×23 linear array with $1/2\lambda$ spacing. A scheme for the improvement of the MRA is proposed.

First, the relationship between the phase shift of the field-re-radiated from a single patch and the length of the connected tail is investigated. This is presented by the solid line in Fig. 1*a*. To show the effect of mutual coupling, a single patch in the array environment has been analysed, and the phase shift relation is shown in Fig. 1*a* (dashed line). To study the effect of different shaped patches, the phase shifts of patches with indented tails, which can be used to match the impedance of the tail with that of the patch, are also simulated (Fig. 1*a*, dotted line). The indentations are 1.2 mm vertically and 0.9 mm horizontally. It is worth mentioning that the field described in the above figures consists of only the field that is re-radiated from the patch. The total field is the vector summation of the field mentioned above and the field reflected from the grounded substrate without the presence of the microstrip patches. The reflected field can be calculated easily using plane wave theory.

The whole linear array is analysed using CG–FFT. In the simulation we found that the current distributions on the patches are effected by the attached tails. This behaviour is due to the fact that the impedance looking into the tail at the junction between the patch and tail is

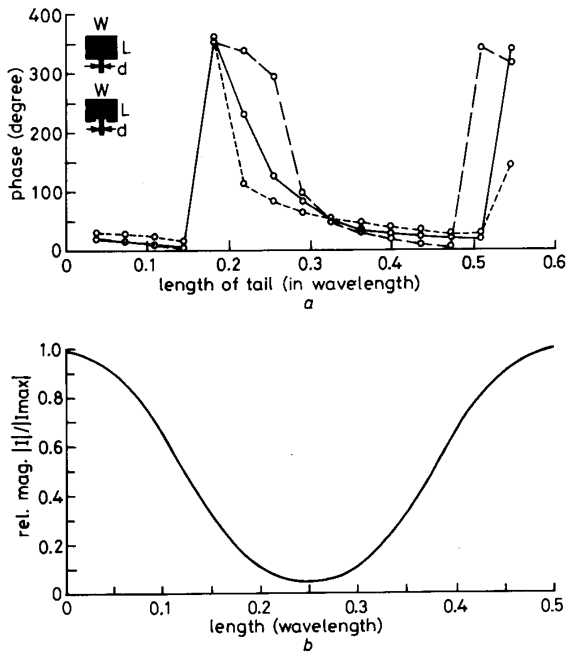

Fig. 1 *Re-radiated field*
a Phase shift
b Current magnitude on a single patch versus the length of the tail
$W = 9.8$ mm, $L = 7.2$ mm, $d = 0.7$ mm
O—O Single patch
O--O Single patch within an array
O···O Single patch with indented tail

varying with the length of the tail. For instance, the impedance should be near zero when the tail length is $\lambda_g/4$. The current distribution on the patch for this case should be close to zero because of the short-circuiting effect of the tail. As the length of the tails either increases or decreases with respect to $\lambda_g/4$, the current increase monotonically. This is known as $\lambda_g/4$ effect. These relationships are shown in Fig. 1*b*.

The current distribution for the MRA example are shown in Fig. 2. The radiation pattern is calculated from

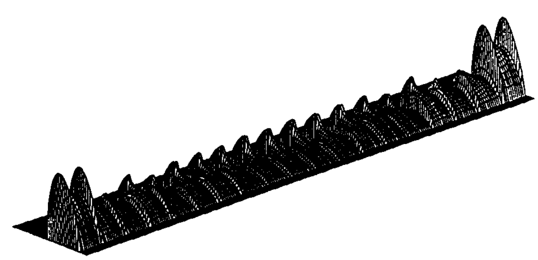

Fig. 2 *Co-pol current distribution on the microstrip reflectarray (on some central patches)*

the current distribution. The H-plane pattern is shown in Fig. 3 (solid). Only the H-plane is shown here because it is the plane in which the antenna is focused for this specific MRA example. The main beam direction was usually chosen to be consistent with those used in practical systems. The measurements for the array are carried out in our anechoic chamber. The measured pattern (dotted line in Fig. 3) is compared with the simulated pattern. Reasonably good agreement is shown. Due to

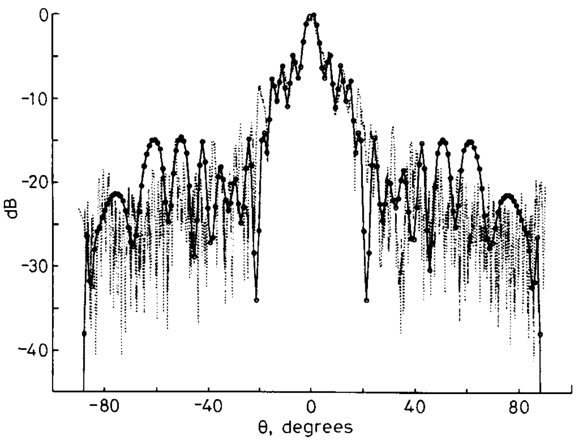

Fig. 3 *Radiation pattern (H-plane) of the microstrip reflectarray*
——— Simulation result
– – – – Measurement

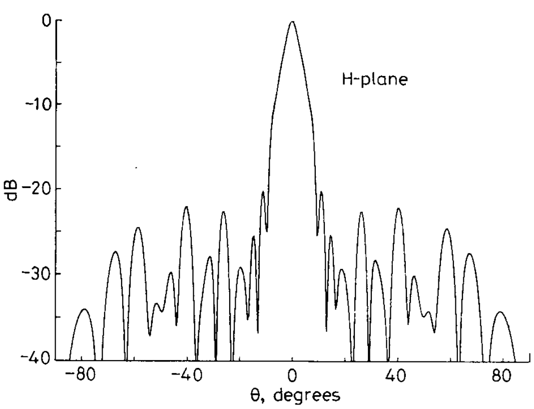

Fig. 4 *Radiation pattern of the MRA after optimal adjustment*

the absence of a proper 12 GHz low-noise amplifier, the pattern measured outside of 50° is dominated by noise. We find that the currents on the central patches are smaller than those on the side patches (V-shape) which results in a relatively high side-lobe-level (SLL). This is because of (1) the edge effect of the backscattering field from the arrays, and (2) the effect that the patch tail lengths have on the current magnitude along the array.

To overcome the destructive edge effect and tail effect, we propose the following scheme:

(*a*) Add some dummy elements at both sides of the array. In our studies, we found that if we put some patches with $\lambda_g/4$ tails on both sides of the array, the short-circuit effect and the edge effect effectively cancel one another.

(*b*) Combine two methods of tuning. It was reported [4] that the phase of the re-radiated field can be controlled by changing the length of the patch. We propose that by combining the two techniques for tuning the patches, i.e. by changing the length of tails and/or the length of patches, we can achieve an optimal current distribution as well as the desired phase shifts to obtain a MRA with low SLL as well as an accurately focused beam.

Fig. 4 gives the simulation result of the microstrip reflectarray after the implementation of the above optimal adjustment. We can find the obvious improvement of the SLL of the modified MRA compared with the previous one (Fig. 3). Further research is needed to test the optimal adjustment technique for designing and constructing large 2D MRAs.

4 Conclusions

According to our modelling and experimental studies of MRAs, we conclude the following. To achieve accurate focusing of the microstrip reflectarray, one key factor to be considered is the precise phase shift that must be imposed on the signal re-radiated by each of the patches in the array. This phase is controlled by the length of the short transmission lines that are used for tuning. Intuitively, a linear relationship between the phase shift and the length of the tails is expected. This can be proven true if the equivalent transmission line model is used. But at higher frequencies (e.g. X-band) and in array environments, the tail cannot simply be treated as a pure transmission line. The effects of re-radiation, surface waves and mutual coupling between neighbouring patches and tails, etc. have to be considered. This is true in the analysis of a complete array as well as in the prediction of the phase change for each patch. The simulation results in this paper show that phase shift versus tail length does not follow a simple linear relationship. In order to achieve high performance, the destructive edge and tail effects have to been considered. By putting some dummy elements at the edges of the array and by using two tuning approaches, we can improve the performance of MRA. The simulation results have verified these ideas. Continuing experimental research is needed to further improve the design of microstrip reflectarrays.

5 References

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