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PHASING OF A MICROSTRIP REFLECTARRAY USING MULTI-DIMENSIONAL SCALING OF ITS ELEMENTS

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Abstract—The paper reports on investigations into new schemes for dimensional scaling of the elements of a microstrip reflectarray to obtain a slower slope of the reflected wave phase characteristic. First, the phase response as a function of various shape elements is investigated when only one of their dimensions is varied. Next investigations concern the case when two dimensions or features of the element are scaled in a certain manner simultaneously. In the latter case, it is shown that phase responses of lower slopes with a minimal range reduction can be obtained. The feasibility of this concept is illustrated for dipoles, rectangular patches, and square and circular rings. Comparisons of the obtained results show that two-dimensionally scaled square and circular rings offer much better phase responses than those observed for dipoles and patches.

1. INTRODUCTION

A microstrip reflectarray antenna [1, 2], being the mixture of a reflector antenna and a planar phased array antenna, uses a suitable phasing scheme for its elements to convert a spherical wave produced by its feed into a plane wave. One of the very popular phasing schemes involves varying dimensions of the elements such as printed dipoles or patches around their resonant size [2–4]. The phasing characteristics are obtained by determining the phase of the reflection coefficient of a plane wave of given polarization which is incident on a periodic array of identical elements. The assumption of perfect periodicity allows for reducing the phase determination task to the equivalent unit cell problem. In the equivalent unit cell problem, the phasing element is assumed to be positioned inside a short-circuited-at-one-end rectangular waveguide with an appropriate type side walls. The choice of walls depends on the type and angle of incidence of a plane wave. For the case of normal incidence of vertically polarized plane wave, the top and bottom walls of the equivalent waveguide are perfect electric conductors while its side walls are perfect magnetic conductors. Using this approach, the required phase is determined as the phase of the reflection coefficient of a TEM wave travelling inside the waveguide. The solution acquired for the normal wave incidence provides a good approximation for the case of TE and TM waves for an angle of incidence up to 30° from the reflectarray boresight direction.

Using the obtained phasing characteristics, the sizes of the individual elements in the reflectarray are adjusted to compensate for phase differences of the feed's spherical wave, which is incident upon them. To accomplish this task in an appropriate manner, the elements have to provide 360° phasing range at a given frequency. The requirement of 360° phasing range can be approximately fulfilled by dipoles or rectangular patches printed on a thin dielectric substrate. However, this is achieved at an expense of a sharply varying phase as a function of the phasing element size. As a result, the use of a thin substrate results in a narrow operational bandwidth of the reflectarray and a smaller tolerance to dimensional errors during the manufacturing process. An attempt to slow the phase slope by employing a thicker substrate results in the elements phasing range to be considerably smaller than 360°. This reduced phasing range leads to phasing errors of the reflectarray and thus to its reduced gain.

Because of the two opposite trends, of an increased phasing range and a lower phasing slope observed for printed dipoles and patches, the designers have shown a considerable interest in new types of phasing elements and methods, which could overcome this fundamental problem.

One method to increase the phasing range and to reduce the phase slope is based on the use of stacked patches and multi-layer dielectric substrates [5–7]. For moderately thick two-layer two-stacked patch structure, this method offers the phasing range of about 450° accompanied by a gentle phase slope as a function of the patches size. However, one undesired feature of this method is a more complicated manufacturing process. Individual patch layers need to be etched separately and then properly assembled to avoid adverse effects of misalignment. Because of these difficulties, many of new works in the field of microstrip reflectarray have returned to single layer structures involving new shapes of phasing elements. Examples include printed rectangular and square rings [8, 9] and advanced elements shapes such as a windmill ring [10] and Malta cross [11] and compound-cross-loop [12]. The goal of this activity is to achieve a wide phase range and a slow phase variation (slope) as a function of the element's variable size.

The present paper reports on investigations into new schemes for dimensional scaling of the elements shape in order to obtain more favourable characteristics of the phase response. These investigations commence with the phase response as a function of various shape elements when only one of their dimensions is varied. Next, the case when two dimensions or features of the element are changed in a certain manner simultaneously is considered. The goal is to have slower variations and thus smaller slopes for the phase response, with small reductions in the phase range. The investigations are focused on the equivalent unit cell with a vertically polarized TEM wave incidence.

2. ANALYSIS

The analysis is carried out for a microstrip reflectarray operating in the X-band with the centre frequency of 10 GHz. The reflectarray is assumed to be formed by identical elements arranged in a square lattice with periodicity of 15 mm, which is equivalent to 0.5 wavelengths at 10 GHz. The elements are assumed to be printed on a 1.57 mm thick substrate of dielectric constant $\varepsilon_r = 3.2$, which is backed by a conducting ground plane.

In order to work out the phasing characteristics, the case of a vertically polarized (in Y-direction) TEM plane wave that is normally incident on an infinite periodic array of identical elements is assumed. The elements dimensions are varied linearly along the same direction. The equivalent waveguide side walls are formed by a perfect magnetic conductor while its bottom and top walls are composed of a perfect electric conductor. The element is positioned on the dielectric substrate that is backed by the waveguide short circuit. Using the unit cell approach, the phase of the reflected wave is determined as the phase of the scattering parameter S_{11} for the equivalent waveguide one-port. The structure is modelled using the commercial full-wave electromagnetic software CST Microwave Studio.

The investigations proceed as follows. First, fixed size square and elliptical patches with a variable size slot are considered. In this case, the slot size is changed to obtain variations of the reflected wave phase. Next, the behaviour of printed dipoles is investigated. Here, the phase changes as a function of length and width of the dipole are studied. The remaining investigation concerns the effect of variations in slot and outer size of rectangular and circular rings on the reflected wave phase behaviour. Two dimensions of these elements are scaled in an opposite manner so that the conflicting effects on the phase range and slope are appropriately tackled.

2.1. Variation of the Slot Size in Square and Elliptical Patches

Here, the effect of varying the slot dimension in a fixed size square patch is investigated. This phasing scheme preserves the distances between adjacent elements of the reflect array, and gives more freedom in selecting the separation between the array elements, or equivalently the unit cell size. Figure 1 shows the obtained phase responses for the family of slotted square patches. The considered square patch sizes are given by $L = 6.0, 6.5, 7.0$ and 7.5 mm. The phase variations are due to the variable size of the square slot inside the patch. It can be seen that a considerable reduction in the phase slope is obtained for the largest patch of 7.5 mm. However, this result is accompanied by reductions in the phase range. The extent of reductions in the slope and phase range depends on the outer size of the patch. Patch sizes that are not close to the resonant size offer smaller phase ranges and slopes. Note that for the chosen frequency of 10 GHz, the resonant size of the patch is 7.15 mm. As observed in Figure 1, the scheme with the slot

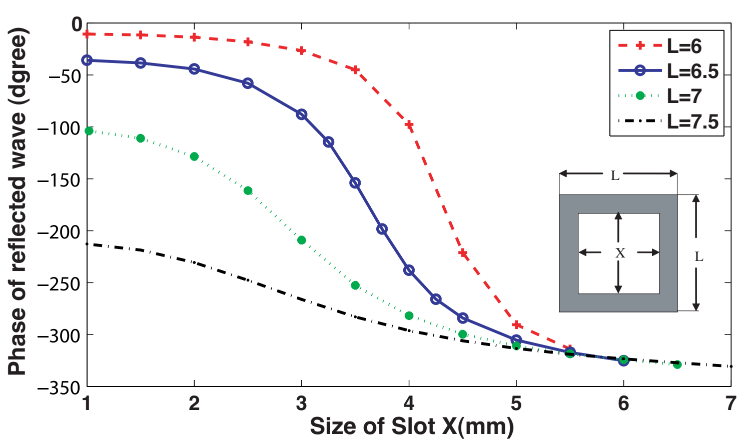

Figure 1. Phase response of fixed-size (L) square patches against slot size (X).

variation results in response curves with slopes ranging between 226 and 35 °/mm and ranges between 303° and 118° respectively. It has to be noted that the variable size square patch that resonates at the size of 7.15 mm offers the phase range of 303° with a slope of 266°/mm. Note that the slope is calculated here at the working size, which is defined here as the size of the patch corresponding to the centre of the phase response.

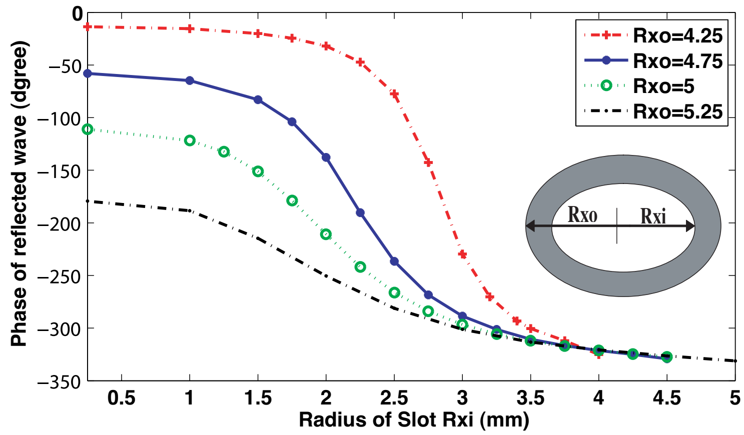

Figure 2. Phase response of fixed-size elliptical patches against slot radius R_{xi}, $(Dy/Dx = 0.8)$.

A similar trend can be observed for the elliptical patch when the size of an elliptical slot is varied. Figure 2 shows the results obtained for an elliptical patch of minor/major axes ratio $(Dy/Dx = 0.8)$, when its major axis is oriented perpendicular to the electric field of the incident wave. The phase response is plotted here against slot major radius R_{xi} for the shown values of patch major radii's R_{xo}. As observed in Figure 2, the scheme of slot variation results in response curves with slopes ranging between 174 and 33°/mm and ranges between 312° and 152° respectively. An elliptical patch of variable size and without the slot developed on the same substrate offers the phase response with a slope of 138°/mm, and range of 303°.

2.2. Variation of Length and Width of a Printed Dipole

Typically when printed dipoles are used to form a reflectarray, their width is fixed and thus only their length is varied. Here we present investigations that concern the changes in phase response when both the length and the width of a printed dipole are made variable. Figure 3

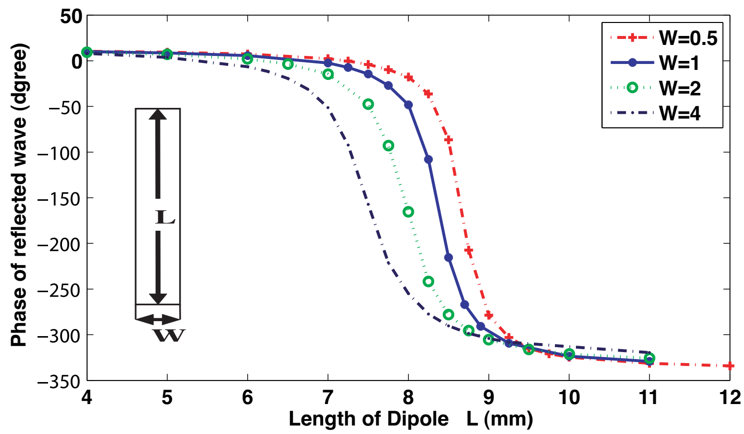

Figure 3. Phase response of dipoles for various fixed widths (W).

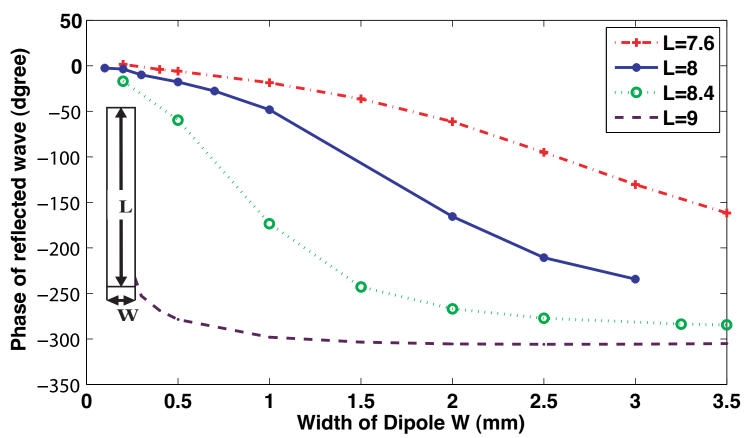

Figure 4. Phase response of various fixed-length (L) dipoles against the width (W).

shows a family of phase responses when lengths of various width dipoles are changed. The curves are obtained for the dipole width of $w = 0.5, 1, 2$ and $4\,\text{mm}$. As observed in Figure 3, dipoles with larger widths have phase responses, with respect to the varying length, shifted to the left (smaller lengths). This means that at a fixed dipole length, the increase of width results in reducing the phase of the reflected wave. This is confirmed by results illustrated in Figure 4, which shows phase responses when the dipole width is varied while keeping the length constant. Although much smaller slopes are achieved in this way, they are obtained at the expense of a very large phase range reduction. When the dipole fixed length L is away from resonance (as for $L = 9$), then there is a very small variation in the phase. Consequently, around the resonance condition, the increase in the length and that in the width have similar effects on the phase response. This finding can lead to devising a phasing scheme offering a lower phase slope.

The new scheme would simply rely on increasing one parameter while decreasing the other one at the same time, so that the net effect would be the reduction of phase changes. The scheme could start with wide and short (thick) dipole and then by reducing the width as the length is increased one would move towards thinner dipoles. The decrease in width would reduce the effect on phase due to increasing the length resulting in slower slope. This is illustrated by the results shown in Figure 5, which demonstrates various dimensional scaling schemes suggested for varying the dipole width and length according to the given relation ($W = f(L)$). The three schemes shown here are of fixed, ascending and descending widths as the length is increased. The last two schemes produce lower slopes as compared to the fixed width scheme. When the width is varied according to the relation ($W = 19\,\text{mm} - 2L$), the slope is down to about 40% of its value for the relation ($W = 0.1L$). The latter relation is for normal scaling of shape, where both dimensions of the dipole are changed in a similar manner.

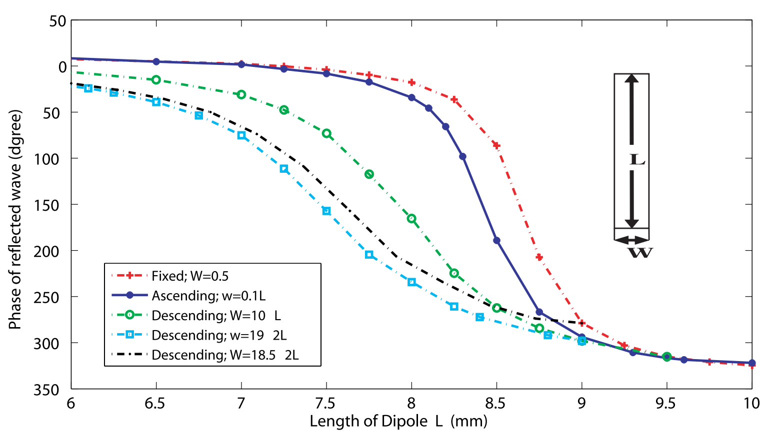

Figure 5. Phase response for a dipole of length (L) for various schemes of width (W) variation.

2.3. Variation of Width and Length of a Rectangular Patch

The above considerations concerning the dipole can be extended to the rectangular patch. The only difference is that the width of this structure is comparable with its length. For the dipole, the usual assumption is that its length is much greater than its width. Figure 6 shows a family of phase characteristics for the rectangular patch where the patch X-dimension perpendicular to the electric field is increased while its Y-dimension is decreased according to the shown relations $(Y = f(X))$. In all of the presented dimensional scaling schemes, the size along the electric field of the incident wave is decreasing and this is responsible for the increasing phase response. Thus starting with a rectangular patch normal to the electric field, then moving to a square patch, one finally ends with another rectangular patch aligned with the electric field. In Figure 6 the intersection point for various schemes of dimensional scaling represents the case of a square patch having a working size of $7.15 \times 7.15\,\text{mm}^2$. The phase response of a square patch is also shown for comparison. It can be seen that by scaling the two dimensions of the rectangular patch in opposite manner, phase responses of much lower slopes are achieved. The shown slopes range between 194°/mm and 38°/mm. The reduction in the phase range is moderate here as it varied between 315° and 205° as compared to 303° for the square patch. The overall phasing trend for the rectangular patch is similar to that of the dipole, but with larger reductions in the slopes and less sacrifices in the phase range.

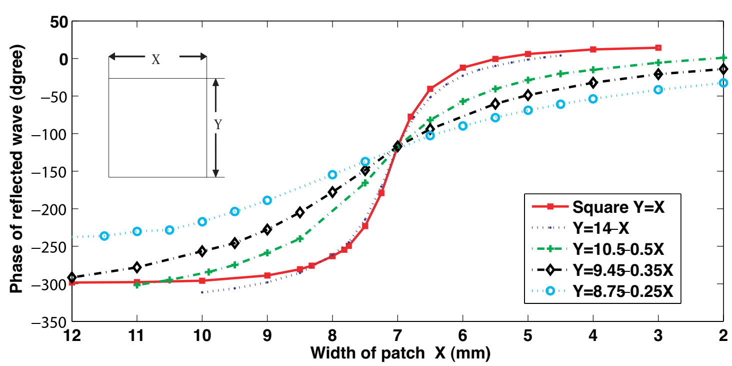

Figure 6. Phase response for square patches against dimension perpendicular to the electric field for the various schemes of length variations.

2.4. Variation of Inner and Outer Size of Square and Circular Rings

The previously considered elements are suitable for phasing of a vertically polarized wave. In many applications, a reflectarray is required to operate with waves of dual (vertical and horizontal) polarization. In this case, phasing elements having dual symmetry such as square patches or rings are the preferable choice for forming a reflectarray. The difference between the patches and the rings is that the latter ones offer two degrees of freedom with respect to the change of their dimensions. These are their overall size (L_o) and arm width (w), or equivalently the surrounded slot size (L_i). Here we investigate phasing characteristics of square and circular shaped rings.

We start the investigation with a square ring of outer dimensions or size $L_o \times L_o$ and inner dimensions (slot size) $L_i \times L_i$. Next, the slot size L_i, is scaled in the way that is not similar to that for scaling the outer dimensions Lo. In such scaling the shape of slotted patch remains, but the ratio L_i/L_o of slot to the patch dimension is changed as the patch size is scaled up. The obtained results of the phase response against the outer dimension Lo of the patch for various schemes of varying the slot size ($L_i = f(L_o)$) are shown in Figure 7. Three schemes for the slot size or ring width variation are considered here:

- the constant width $W = 0.5\,\text{mm}$, or increasing slot size $L_i = L_o - 0.5$.
- the proportional width $W = 0.025L_o$, or increasing slot size $L_i = 0.95L_o$, and
- the case of increasing width for the increasing ring size, or decreasing slot size for increasing patch size.

The phase response of a square patch is also plotted for comparison. It can be seen in Figure 7 that the obtained phase responses have working sizes and slopes that are different for the three schemes. The schemes of fixed and proportional width ($W = 0.025L$) have the largest slopes and range since they represent thin rings. When the arm width is increased while the outer dimension is increased (or the slot size is decreased as the outer size is increased), then the phase response has a smaller slope. The scheme of ($W = L_o - 5\,\text{mm}$) has a minimum slope of 111°/mm, and its range is reduced to 236°. Moreover, most of this range is of linear shape. Compared to the square patch, the slope is reduced by 51% with range reduction of 22%.

The same trend is also observed for circular rings when various schemes of scaling the inner radius as a function of outer radius are adopted. Figure 8 shows the obtained results, along with the

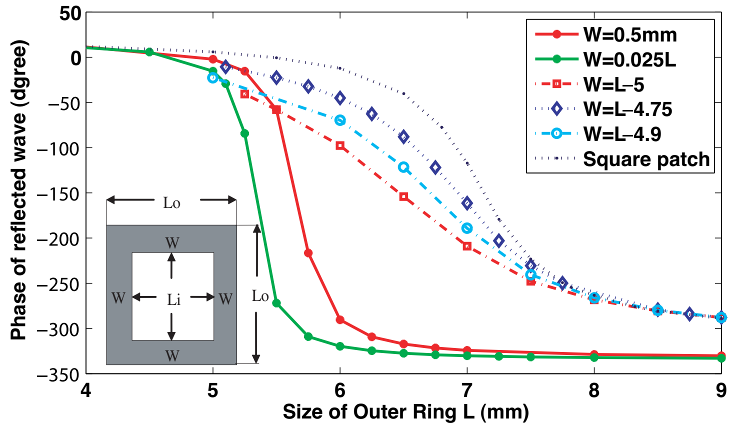

Figure 7. Phase response for square rings against outer size (L) for various schemes of varying the width W.

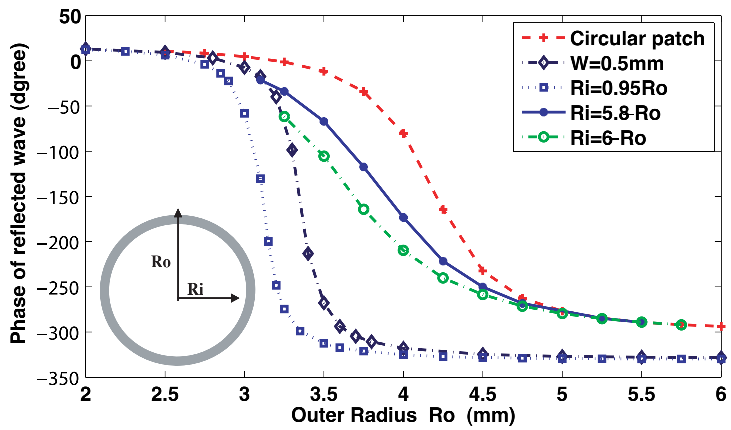

Figure 8. Phase response for circular rings against outer radius (R_o) for various schemes of varying the slot size.

response of a circular patch for comparison. The slopes of the phase responses for the fixed arm width and that for ($W = 0.05R_o$) are high because they represent thin rings. The scheme of ($R_i = 6\,\text{mm} - R_o$) and ($R_i = 5.8\,\text{mm} - R_o$), where the widths are ($2R_o - 6\,\text{mm}$) and ($2R_o - 5.8\,\text{mm}$) respectively have considerably lower slopes of $106°/\text{mm}$ and $105°/\text{mm}$. The respective ranges are $268°$ and $231°$. In these schemes the width increases by twice the rate of increasing the outer radius. The rings become thicker as they grow larger. Compared to the circular patch, the slope is reduced by 37% with range reduction of 14%. The introduction of a slot in the square and circular patches and the proposed scheme of scaling offer a reduced phase slopes. These are accomplished at the expense of moderate reduction in the phase range. One can observe that changing outer size and slot size have similar effect on the phase response. When one of these dimensions is scaled up while the other is scaled down, their net effect is the reduction in the phase variation or the slope value.

By closely inspecting these results it can be noticed that when varying the outer and inner dimensions of each of the square and circular rings in opposite manner there is a minimum value of slope that is reached at a certain relation between the two dimensions. These relations are ($W = L_o - 5\,\mathrm{mm}$) for the square ring and ($2R_o - 5.8\,\mathrm{mm}$) for the circular ring. No such minima can be found for the dipole or rectangular patch when their length and width are varied. Also from the comparison between circular shape patches and rings to dipoles and rectangular patches one can find that the circular shapes give lower values for the slope. This may be attributed to the gentler variation of their dimension parallel to the applied electric field.

3. CONCLUSION

Conventional schemes for phasing of fixed-beam reflectarrays rely on scaling only one dimension of their elements. In the work presented in this paper, it has been shown that an alternative multi-dimensional scaling can provide better phase responses. For example, varying two dimensions of a given element can yield phase responses of lower slopes with minimal reduction of the phase range. The feasibility of this concept has been illustrated for dipoles, rectangular patches and square and circular rings. From comparisons of the obtained results, it has been found that two-dimensionally scaled square and circular rings can offer much better phase responses than those observed for dipoles and patches.

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