On the Phase Response and Radiation Efficiency of the Complementary Strip-Slot as an Array Element

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Abstract—The complementary strip-slot element is a broadly-matched microstrip radiator that has been used to design innovative series-fed arrays. It consists of a microstrip series-fed slot that have its complementary stub on the layer of the microstrip and aligned to the slot. In this contribution, the influence of the strip and slot geometry on its performance is studied through the analysis of four different designs. The obtained results highlight the possibility of controlling the radiation efficiency or the phase response, without compromising the broad matching. Therefore, potential series-fed arrays built with this element can exploit this feature to set the magnitude and phase of the excitations with certain flexibility.

Index Terms—array, microstrip, series-fed, strip-slot.

I. MOTIVATION

Recently, the authors proposed a novel planar radiating element based on a microstrip-centred-fed slot modified by adding its complementary stub on the microstrip layer and aligned to the slot (a prototype is shown in Fig. 1) [1]. An schematic of the radiating element is shown in Fig. 2, where the geometric variables are defined. This structure overcomes the narrowband response inherent in the resonant nature of planar radiators and has a very broadband impedance matching, whereas it behaves as a conventional microstrip-fed slot in terms of radiation.

Due to its series feeding and broad matching, the complementary strip-slot element has been used to build travelling-wave arrays with interesting features, such as linear arrays with full frequency scanning in several bands [2], log-periodic arrays with size reduction [3] and multiband sequentially-rotated arrays with circular polarization [4]. These arrays have been manufactured as proofs of concept, without any particular specifications. However, if arrays with a better control of the radiation characteristics, such as specifications of the side-lobe level, are pursued, it is necessary to analyse how the phase response and the power radiated by the element can be controlled. Therefore, this paper deals with a study of these parameters as a function of the element geometry.

II. THEORY

The resulting coupled structure formed by the strip and the slot has three conductors and, since it is symmetrical, an even and an odd mode propagate. Fig. 3 shows the electric field distributions of both modes in a cross section. This resulting coupled microstrip-slotline has been properly modeled by a lattice network [1], and the resulting image impedance can be obtained as

\[ Z_{im} = \frac{1}{2} \sqrt{Z_{0e} Z_{0o} \cot \theta_e \tan \theta_o}, \]  

where \( Z_{0e} \) and \( Z_{0o} \) are the characteristic impedances, and \( \theta_e \) and \( \theta_o \), the electrical lengths of the even and odd modes, respectively.
Table I

<table>
<thead>
<tr>
<th>Design</th>
<th>(w_M)</th>
<th>(w_S)</th>
<th>(l_M)</th>
<th>(l_S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design 1</td>
<td>0.22 mm</td>
<td>0.10 mm</td>
<td>9.13 mm</td>
<td>10.45 mm</td>
</tr>
<tr>
<td>Design 2</td>
<td>0.61 mm</td>
<td>0.47 mm</td>
<td>9.18 mm</td>
<td>10.76 mm</td>
</tr>
<tr>
<td>Design 3</td>
<td>0.90 mm</td>
<td>0.80 mm</td>
<td>9.04 mm</td>
<td>10.86 mm</td>
</tr>
<tr>
<td>Design 4</td>
<td>1.90 mm</td>
<td>1.8 mm</td>
<td>8.72 mm</td>
<td>9.99 mm</td>
</tr>
</tbody>
</table>

The parameters of the even and odd modes in the strip-slot structure were obtained from the ANSYS HFSS electromagnetic simulator. Parametrization of the widths \(w_M\) and \(w_S\) was done, in order to extract conclusions about how these geometric variables influence the performance. No coupling between elements in a potential array has been taken into account, since the array designs that have been already carried out showed good results when analysing the arrays with the isolated element model.

The isolines of the image impedance of the coupled microstrip-slotline section at 5.4 GHz, when \(\theta_e=\theta_o\) is assumed, are shown in Fig. 4 as a function of \(w_S\) and \(w_M\). The feed microstrip line was designed to have 50 \(\Omega\)-impedance level (i.e., \(w_M=1.83\) mm). Therefore, the line of 50 \(\Omega\) represents perfect matching. For this substrate, the results show that good matching is achieved when the slot and the strip have similar widths. It is also clear that a wide range of widths leads to a reasonably good matching for this substrate, since, for example, an image impedance of 40 \(\Omega\) corresponds to return losses of around 20 dB. This fact means that the structure is quite robust with regard to dimensioning, an important advantage for design and fabrication. In addition, it can be observed that the four designs (marked with black dots) present very good matching.

Fig. 5 shows the isolines of the coupling coefficient, defined as \(k = \frac{Z_{0e}-Z_{0o}}{Z_{0e}+Z_{0o}}\), of the coupled microstrip-slotline section as a function of the slot and strip widths, \(w_S\) and \(w_M\), respectively. It can be observed that the four designs, which point out the line of good return losses, have very different coupling coefficients. In fact, for an isoline of 50 \(\Omega\) image impedance, the coupling coefficient can vary between 0 and 1. The wider the elements are, the lower the coupling coefficient is.

The coupling coefficient is closely related to the phase response in (4), since both parameters depend on the ratio between the mode characteristic impedances: \(\frac{Z_{0e}}{Z_{0o}}\). Then, the phase response can be controlled independently of the return losses. Since the four studied designs have been chosen to have the same phase at 5.4 GHz, \(\theta\) must be the same for the four designs at that frequency. Moreover, if low frequency
dispersion in the effective permittivities of the modes is assumed, the only parameter that is different in the phase of the four designs at any frequency is \( \frac{\omega}{c} \). According to (4), the phase response becomes independent of \( \frac{\omega}{c} \) when \( \theta = n\pi \). Therefore, it is expected that the phase factor of the four designs coincides at those frequencies at which \( \theta = n\pi/2 \) with a value of \( \phi = n\pi \) and differs out of them according to the coupling coefficient or \( \frac{\omega}{c} \).

Fig. 6 shows the comparison of the phase factor for the four studied cases. Measurements are only available for the Design 2. As predicted, the phase response becomes more linear for lower values of the coupling coefficient. This degree of freedom in the linearity between the points of phase linear for lower values of the coupling coefficient. This degree of freedom in the linearity between the points of phase linear for lower values of the coupling coefficient.

The designs of Table I are marked with black dots.

Fig. 7 shows the comparison of the phase response for the four designs of Table I.
IV. CONCLUSION

Four different designs of the complementary strip-slot radiating element have been studied, in order to show the influence of the geometric parameters in the matching, phase response and radiation efficiency. The four structures were properly designed to be broadly matched and have the same phase factor at a certain frequency (same slot resonance frequency). However, the widths were chosen very different, in order to highlight that the complementary strip-slot element is not only able to provide broad matching but also allows the control of the radiation efficiency or the phase response.

For good matching, the strip and slot widths must be chosen to make the microstrip-slotline coupling structure have an impedance level of 50Ω, as the feed microstrip line. Moreover, the strip and slot lengths must be designed so that they have the same electrical length, in order to cancel out the resonant behaviour of the image impedance. With these two conditions, ultra broad impedance matching is achieved. However, four variables are available to satisfy broad matching: \(w_M\), \(w_S\), \(l_M\), and \(l_S\), therefore two extra degrees of freedom are available. The width pair also determines the linearity of the phase response or the radiation efficiency in the region between two slot resonances. The length pair sets the value of the structure phase factor at a certain frequency. Therefore, by taking advantage of these two degrees of freedom, some control in the phase and radiation efficiency is possible. For example, if it is desired to build an array with a low number of elements, the widths of the elements must be chosen large, in order to radiate all the power with few elements. On the contrary, if the directivity is to be maximised, the element must be chosen very thin, in order to radiate low power amount and make the antenna aperture longer by placing many elements. In this way, this design freedom in the complementary strip-slot can be exploited for the construction of competitive broadly-matched series-fed arrays in which certain flexibility in the magnitude and the phase of the excitations is essential.

ACKNOWLEDGMENT

This work was supported by the Spanish Ministerio de Ciencia e Innovación (Programa Consolider-Ingenio 2010) under Grant CSD2008-00066, EMET, and by the Junta de Andalucía (Spain) under Grant P10-TIC-6883.

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