The Complementary Strip-Slot: From the Unit-Cell of Artificial Transmission Lines to the Basic Element of Novel Antennas

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***Abstract*— The complementary strip-slot radiating element and its applications are reviewed. The element is a modified version of the conventional microstrip-fed slot that presents very broad matching. Its inherent lattice equivalent circuit, its use as unit-cell of artificial transmission lines and its utility as radiating element are described. Promising experimental results for prototypes of a phased uniform array, a sequentially-rotated ring array and a log-periodic array based on the element for microwave frequencies are included.**

I. Introduction

Over the last decade, electromagnetic metamaterials have inspired numerous novel applications and concepts in communications engineering. Metamaterials are defined as artificial electromagnetic structures with unusual properties not available in nature. In this context, left-handed media (LH) are those media which simultaneously present negative electric permittivity and magnetic permeability, leading to novel phenomenons visioned by Veselago [1], like the reversal of the Snell's law or the reversal of the Vavilov-Čerenkov radiation.

Although LH media were not available in nature, it was thought that artificial LH transmission lines could be synthesized by periodically repeating the corresponding incremental equivalent circuit. However, due to unavoidable RH induced effects, the synthesis of LH media was not achievable and the unsuccessful attempt for building purely LH media came up as a novel concept called the Composite Right/Left-Handed Transmission Line (CRLH TL) [2].

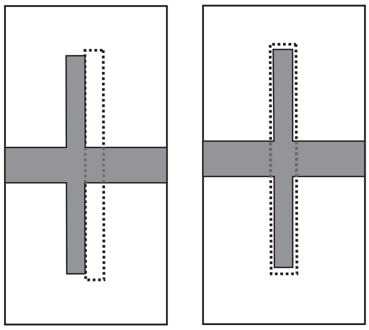
After the introduction of the CRLH TL, artificial TLs with different topologies were proposed. This way, a specific dispersion diagram can be synthesized by simply cascading the necessary unit-cells. The possibility of designing the phase constant of a TL using this concept was called 'dispersion engineering' and has given rise to numerous applications.

Until recently, the unit-cell of CRLH TLs was always built using T or Π topology networks. The use of these networks yields to the appearance of unavoidable stop-bands in the frequency response of the resulting artificial TLs. Moreover, as a consequence of the topology, the image impedance in the RH and LH pass-bands is frequency-dependent. Bongard *et al.* proposed a CRLH unit-cell using a lattice network [3]. This unit-cell does not suffer from stop-bands, thus presenting an all-pass behaviour when properly designed. The image impedance is then real (in the lossless case) and frequency independent.

In the search of unit-cells for building artificial TLs as part of the Consolider 'EMET' project, combinations of stubs and slots were investigated by the authors, in order to provide the required series and shunt immittances for CRLH TLs. These combinations were initially made by cascading both elements, as Fig. 1a shows, which resulted in a unit-cell in T or $\Pi-$ topology with its associated stop bands. However, it was found that when both elements were aligned, Fig. 1b, these stop-bands disappeared. This broadly-matched element was called the complementary strip-slot. Its natural equivalent circuit was shown to be a lattice network [4] and, this way, a lattice network-based CRLH TL could be obtained by cascading strip-slot elements, with no appearance of stop-bands. Nevertheless, the high radiation intrinsic to this element is not very convenient for guided application and this line of research has focused on its applications as an antenna element.

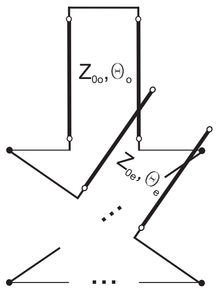
II. The Complementary Strip-Slot Element

As shown in Fig. 1b, the complementary strip-slot element is so called because it consists of a microstrip-fed slot, onto which its complementary strip is superimposed on the microstrip layer. The microstrip-fed slot is a resonant element, whereas the strip-slot results in a coupling structure that can be theoretically 'all pass' if properly designed. The equivalent circuit can be observed in Fig. 2 and consists in a lattice network with a series immittance given by the parameters of the odd mode and a crossed immittance given by the parameters of the even mode, where Z_M and Z_S stand for the characteristic impedances and $\epsilon_{eff,M}$ and $\epsilon_{eff,S}$, for the effective permittivities of such a microstrip line and a slotline, respectively. This way, under low coupling, the even and odd modes of the resultant microstrip-slotline coupling structure have the distinctive feature of being respectively similar to the modes propagating in the corresponding slotline and the microstrip line [4].



(a) Alternate (b) Superimposed

Fig. 1. Unit-cells based on the combinations of strip and slot fed by a microstrip line.



$$Z_{0e} \approx 2Z_M$$

$$Z_{0o} \approx \frac{Z_S}{2}$$

$$\epsilon_{eff,e} \approx \epsilon_{eff,M}$$

$$\epsilon_{eff,o} \approx \epsilon_{eff,S}$$

Fig. 2. Equivalent circuit of the complementary strip-slot element.

In this way, the design of the element is as simple as designing the slot and the strip so that the image impedance of the corresponding lattice network is constant with frequency, which means that the strip is designed to resonate at the same frequency as the slot and, since the behaviour of its impedance is complementary to the slot, an 'all pass' response is obtained [4]. As an example, a design has been carried out with slot length $\lambda/2$ at 5.4 GHz. Fig. 3 shows an impedance bandwidth from 1 to 16 GHz with $|S_{11}|$ better than -10 dB.

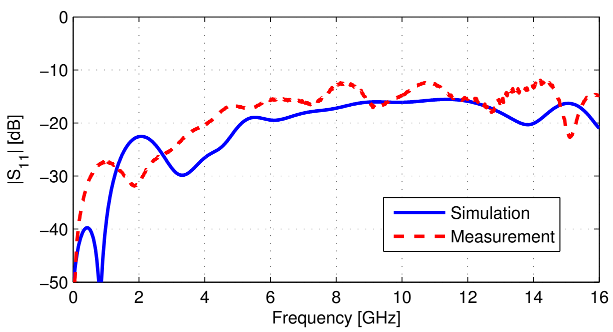


Fig. 3. $|S_{11}|$ of a prototype of the complementary strip-slot.

In radiation, the element behaves as a conventional microstrip-fed slot with radiation into both half-spaces [4].

III. Lattice Network-Based CRLH TL

The resultant lattice network of the complementary strip-slot element is a key feature for building artificial transmission lines, since a CRLH TL without the unavoidable stop bands of ladder networks can be built. Other lattice unit-cells have been built by physically reproducing the lattice topology, leading to complicate circuits. The advantage of this element is that its simple structure naturally behaves as a lattice network. Fig. 5 compares the reflection coefficient of three concatenated unit-cells with the elements shown in Fig. 1 (superimposed and alternate) with a slot length that resonates at 2.4 GHz and a unit-cell length of 10 mm.

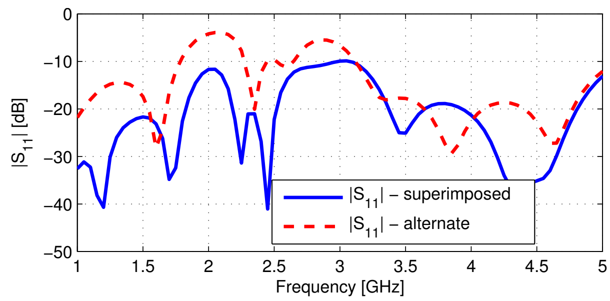


Fig. 4. Phase factor for different unit-cell lengths.

In Fig. 5, the phase factor of the unit-cell is plotted. There is no appreciable difference in the dispersion diagram between the superimposed and the alternated versions. From the point of view of artificial transmission lines, the element is the unit-cell of a high-order CRLH TL. It alternates RH and LH behavior with a non-linear dispersion diagram. This non-linearity can be controlled by the coupling between the strip and the slot. The advantage of having a unit-cell with a lattice circuit (the complementary strip-slot element) compared to a ladder network is here clear: the transitions between RH and LH are matched.

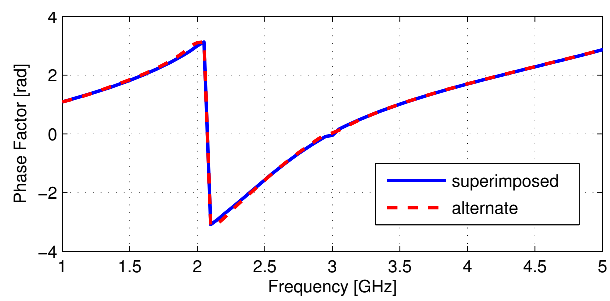


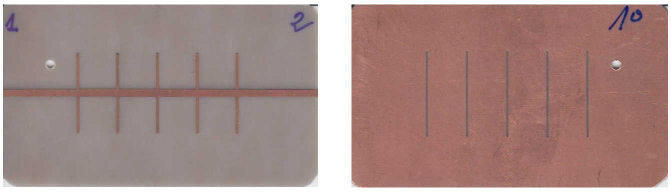
Fig. 5. Phase factor for the superimposed and alternate strip-slot element.

IV. Antenna Applications

Applications of the complementary strip-slot element have been found mainly in the antenna field, since it is an efficient radiating element. Planar antennas are mostly built using patches or slots, which both are resonant elements. Therefore, antennas based on the complementary strip-slot have the special feature that do not need to work at the resonance frequency because the planar radiating element is broadly-matched and this allows multiband behavior and design flexibility. Moreover, the element has series-feeding, which is appropriate for traveling-wave arrays. Different prototypes of antennas have been analysed and manufactured.

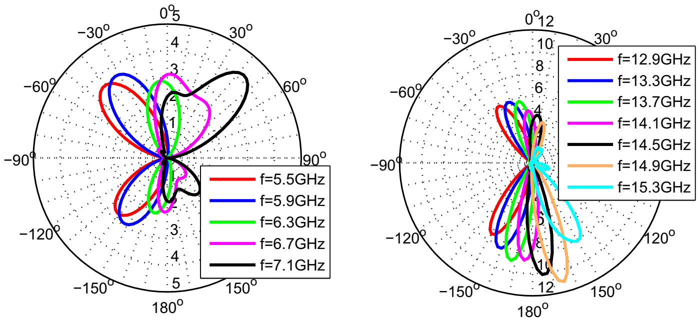
A. *Phased Array*

A uniform phased array has been built by cascading five elements, in order to perform frequency scanning in the whole space [5]. Fig. 6 shows the manufactured prototype, with the slot resonating at 5.4 GHz. Since the dispersion diagram has LH and RH behavior, beam scanning is obtained from backward to forward directions, shown in Fig. 7, with multiband behavior.



(a) Strip view (b) Slot view

Fig. 6. Uniform phased array.

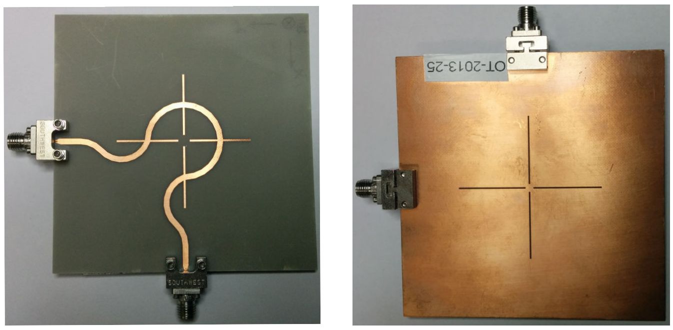


(a) First band (b) Second band

Fig. 7. Radiation patterns of the proposed uniform phased array.

B. *Ring Sequentially-Rotated Array*

A ring array with four complementary strip-slot elements has also been designed and manufactured for providing polarisation agility and multiband behavior with a very simple structure [6]. The prototype is shown in Fig. 8. The polarization can be configured (circular or linear and the sign) with the excitations at the two ports. Sequential rotation technique [8] has been applied to provide circular polarisation (CP) with linearly-polarised elements when singly fed. The series feeding configuration allows the implementation of the required phase shifts between elements with just a microstrip line. Single feeding leads to CP, whereas dual feeding can generate LP, when the same signal is introduced by the two ports, or two orthogonal CP waves when different channels must be transmitted. In addition, since consecutive operating bands possess different signs of CP when single feeding, two bands with the same sign of CP can be diplexed through the two ports. Fig. 9 shows the axial ratio with single excitation, with several bands with good CP purity (AR<3 dB). The antenna radiates broadside in the operating bands, as Fig. 10 shows.



(a) Strip view (b) Slot view

Fig. 8. Layout of a manufactured antenna.

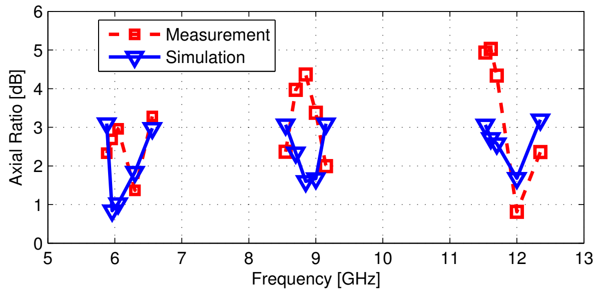
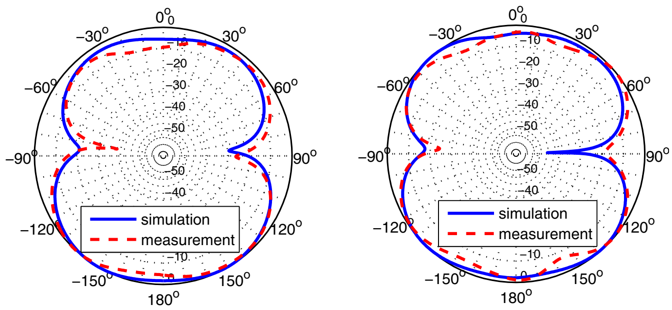


Fig. 9. Axial ratio of the proposed ring array.



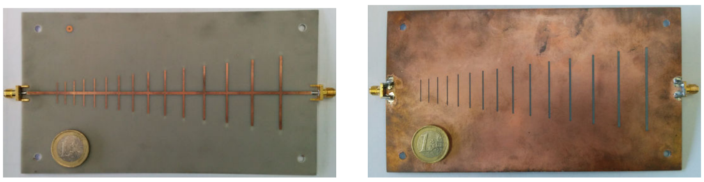
(a) f=5.88 GHz (b) f=8.85 GHz

Fig. 10. Radiation patterns of the proposed ring array.

C. *Log-periodic Array*

Log-periodic arrays are wideband antennas built out of resonant elements (dipoles or patches). Thanks to the log-periodic progression in its geometry, a log-periodic array is suitable to cover wide bandwidth. The design methodology of these arrays has been established taking into account the resonant nature of the basic element. For instance, the scale factor τ ($\tau = \frac{l_n}{l_{n+1}}$, where l_n is the length of the n^{th} element) is restricted by the resonant behaviour of the element, since if τ is very small, the adjacent element resonances are too far from each other and not enough elements are able to radiate all the power at a certain frequency. However, a size reduction would be achieved if τ could be lowered. Moreover, since the elements are mismatched out of their resonant frequency, the relative spacing between elements (σ) must be set so that the reflections from the mismatched-elements are canceled.

Log-periodic arrays with the complementary strip-slot element have been analysed [7]. Since the complementary strip-slot is a broadly-matched element, low scale factor (τ) with high radiation efficiency is possible, since the element radiation efficiency is not resonant and the relative spacing does not have to be selected for good matching, because the element is intrinsically matched. A design example with $\tau = 0.909$, $\sigma = 0.17$ and 15 elements that are designed to cover from 2.7 to 8.6 GHz has been manufactured and analysed [7]. Fig. 11 shows the prototype. It can be observed in Fig. 12 that $VSWR < 2.5$ in the designed bandwidth and no power is arriving to the termination port, since no difference is found between loading with matched load and open circuit. Two radiation patterns at different frequencies are shown in Fig. 13, in order to illustrate that the array maintains the radiation pattern over frequency.



(a) Strip view (b) Slot view

Fig. 11. Layout of a manufactured antenna.

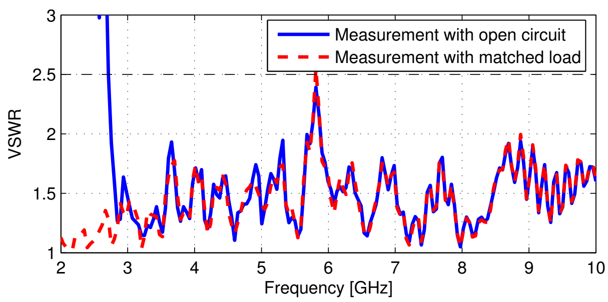
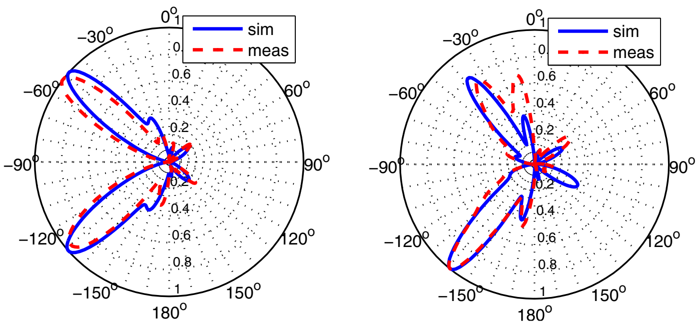


Fig. 12. VSWR of the log-periodic array prototype.



(a) f=5.85 GHz (b) f=8.65 GHz

Fig. 13. Radiation patterns of the log-periodic array.

V. Conclusions

A novel planar radiating element and its applications have been reviewed. Its special feature is that it is a conventional microstrip-fed slot with broad matching. It can be properly modeled with a lattice network and its radiation performance is similar to that of a conventional microstrip-fed slot. The element, initially conceived for artificial transmission lines, has demonstrated its excellent performance and capabilities for planar antenna arrays. Both applications as unit-cell of artificial transmission lines and antenna arrays have been highlighted with simulated and experimental results. Its broad impedance bandwidth allows designing planar structures with different properties to those obtained with classical resonant element (e.g., multiband behavior)s. It is expected that its versatility, simplicity and easy design, due to the available equivalent circuit, make it a good candidate for novel antenna designs.

Acknowledgements

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