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Frequency-Scanned Slot Antenna Array Fed by Boxed Stripline CRLH Series Network

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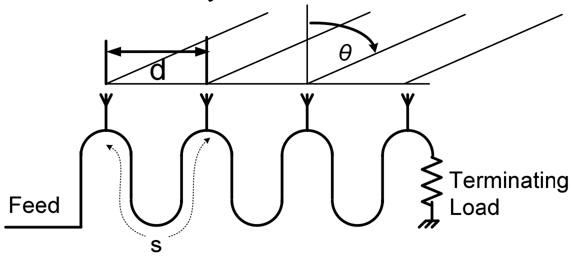
1. Introduction

Transmission line (TL) composite right/left-handed (CRLH) structures have already led to a large number of antenna and component applications [1]. However, most of the CRLH TLs reported to date were open structures and thereby structures supporting leaky-wave radiation due to the penetration of the CRLH dispersion curve into the fast-wave region of the dispersion diagram. Whereas leaky-wave radiation is a desired effect in antenna applications, it represents a parasitic effect corresponding to loss in guided-wave components. To overcome this problem, in [2] a boxed stripline structure was introduced and demonstrated to yield Q performance comparable to that of a microstrip line.

Here, we demonstrate this low-loss boxed stripline structure as a uniform (CRLH) series feeding network [3] to a slot antenna array [4]. The proposed CRLH feeding structure exhibits small size and allows arbitrary spacing between the radiators. Furthermore, it provides controllable dispersion for higher frequency scanning sensitivity (faster scanning). In contrast to the structure reported in [3], the boxed CRLH has much lower loss due to leaky-wave radiation suppression.

2. Scanning Array Configuration

Fig.1(a) shows the configuration of a typical series fed antenna array which employs a meandered feeding line (λ sections) to excite all elements in phase for broadside radiation. The relation between the direction of the main beam and frequency is given as $\sin\theta_m = (s\lambda_0/d)(1/\lambda_g - 1/\lambda_{gm})$, where θ_m is the angle of the main beam from broadside and λ_g is the guided wavelength of the feeding line, and λ_{gm} represents the feedline wavelength at the frequency where the beam is at broadside (θ_m=0) [4]. Fig.1(b) shows the proposed CRLH boxed stripline structure, which is used here to feed an array of resonant slots.



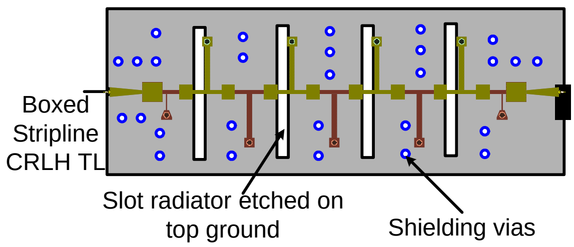


Fig.1 Possible series feeding network configurations for antenna arrays. (a) Conventional approach [1]. (b) Proposed boxed stripline CRLH TL approach, feeding a slot array.

Fig.2 shows the equivalent transmission line model for the series-fed slot antenna array. The variables α and β denote the attenuation constant and phase constant, respectively, of the feeding transmission line. S_1, S_2... S_n represent the lengths of the transmission line sections between the adjacent antenna elements, and $Z_{ant}{}^i = 1/Y_{ant}{}^i = 1/\left(G_{ant}{}^i + B_{ant}{}^i\right)$ is the active (self + mutual) impedance of each slot. If the array radiates toward broadside (βS_1=βS_2=βS_i=βS_n=$2\pi m$), the input impedance looking from the source into the whole array is:

$$Z_{in} = \sum_i Z_{ant}{}^i + Z_L \underset{\left(B_{ant}{}^i=0\right)}{\overset{\text{slot resonance}}{=}} \sum_i 1/G_{ant}{}^i + Z_L . \tag{1}$$

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This formula can thus be used to match the array for the broadside condition. At off-broadside directions, reached by frequency scanning, the $Z_{ant}^{\ i}$ will change due to the fact that the slots go off resonance, which will reduce the overall efficiency of the antenna. To overcome this problem, varactor diodes may be integrated along the slots and tuned with frequency to preserve the resonance condition of the slots.

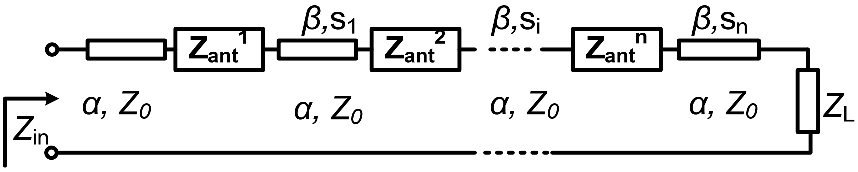


Fig.2 Equivalent TL model for the series-fed antenna array of Fig. 1(b).

3. Resonant Slot Radiators

Fig. 3(a) shows a transverse slot radiator etched on the ground plane of a stripline, and representing each of the slots in Fig. 2(b). The loading of the stripline due to the magnetic energy coupled to the slot may be modelled as an equivalent RLC anti-tank, shown in Fig. 3(b), series-connected to the main transmission line. The coupling level is controlled by the stripline width, slot width and offset of the slot center from the axis of the stripline. A formula for the self-conductance of a centered transverse slot was proposed in [5]:

$$\frac{G_{ant}}{Y_0} = \frac{16}{3\pi}\frac{b}{w+(2b\cdot\ln 2)/\pi}\left(\frac{a}{\lambda}\right)^2\cdot\left[1-0.374\left(\frac{a}{\lambda}\right)^2+0.13\left(\frac{a}{\lambda}\right)^4\right], \tag{2}$$

where the parameters a, b and w are defined in Fig. 3(a). However, this formula is restricted to centered slots, whereas the array of Fig. 1(b) will require off-centered slots for matching, and does not account for possible mutual coupling (mainly from the air for thin substrates) between the slots in the array. In addition, no formula have been found for the susceptance of the slot. Therefore, we have to resort to full-wave analysis (MoM) to obtain the active (self and mutual) self-admittance (conductance and susceptance) of the the slot radiators of the array. Using Fig.3(b), the exact slot self-admittance can be extracted from two-port full-wave simulation results as

$$G_{ant} + jB_{ant} = Y_0\frac{S_{21}}{2(1-S_{21})}, \tag{3}$$

where S_{21} is the transmission coefficient of the 2-port network after numerical calibration to reference plane TT'. This extracted conductance was verified (not shown here) to agree well with the theoretical prediction of Eq. (2). It was also found from that for a thin substrate a spurious TEM parallel-plate waveguide mode was strongly excited between the top an bottom plates of the structure, and significantly degraded the radiation efficiency. Excitation of this parasitic mode is a consequence of the unbalanced voltage generated between the top and bottom ground planes due to the asymmetric configuration of the slot in the structure. To suppress it, the two grounds are shorted by arrays of vias enforcing the same potential on the top and bottom plates, as illustrated in Fig. 3(a).

Fig.3(c) shows the admittance extracted by Eq. (3) versus frequency for different slot widths (b) and slot-center offsets (d). At the resonance frequency, the feeding line is not perturbed by the slot because the slot is then a purely resistive load. The position of the vias also significantly affects the resonant frequency and the radiation impedance of the slots. In addition, the active admittance, depending also on the coupling to the other slots, was also found to be significantly different from the self admittance [Fig. 3(c) and (d)] and the design subsequently needs to be adjusted for optimal performances. If the vias are too close to the slot, the resonant frequency may be strongly increased as a result of the of a cavity mode excitation. On the other hand, the array of vias can reduce the surface-wave and coupling between the slot elements.

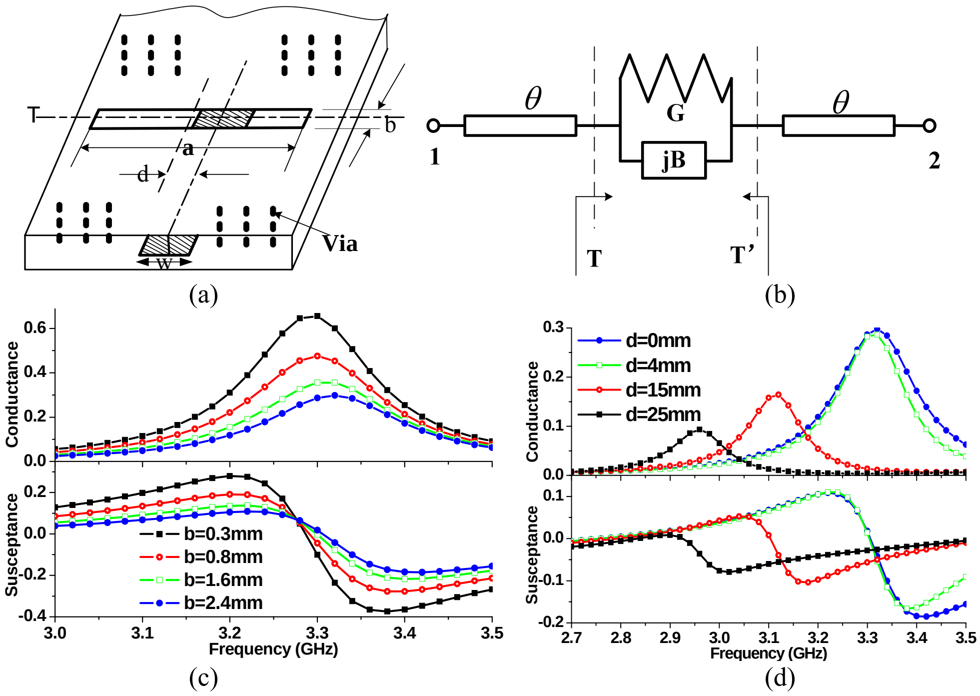


Fig.3 (a) Unit cell stripline-coupled slot configuration. (b) Equivalent circuit model. (c) Full-wave simulated self-admittance versus slot widths *b*. (d) Full-wave simulated self-admittance versus slot offset *d*.

4. CRLH Series Feeding Network

A CRLH TL is strongly dispersive, a characteristic that may be exploited in the design of many microwave components. A large $d\beta/d\omega$ design used here to achieve high angle-frequency scanning sensitivity.

As the CRLH dispersion curve penetrates into the fast-wave (or leaky-wave) region of the dispersion diagram, an open CRLH TL structure always radiates to some extent. Leakage radiation is a parasitic effect in guided-wave structures since it lowers the quality factor. Therefore, the CRLH boxed stripline configuration introduced in [2] is used here to totally suppress this leakage, and thereby make the structure more practical to act as antenna feeding network.

Fig. 4 shows a picture of the fabricated prototype of the boxed stripline CRLH structure. The series capacitance and the shunt inductance required for the left-handed transmission are implemented by MIM capacitors and stub inductors, respectively.

Fig.4 Prototype of a non-radiative CRLH boxed stripline structure.

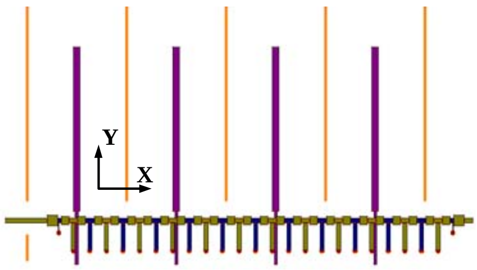


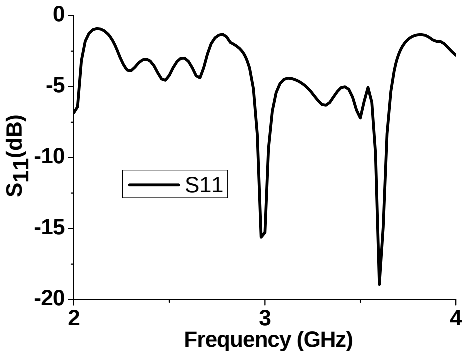
Fig.5 Top view of the array.

5. Complete Array

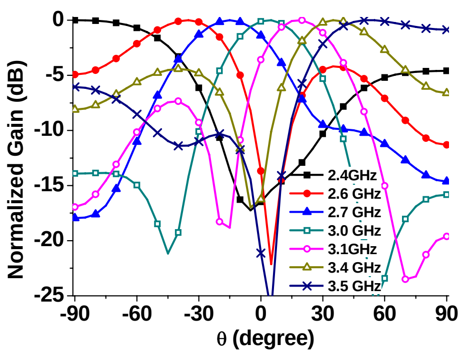
A 4-element slot array is designed, as shown in Fig.5. At the transition frequency (uniform field distribution) of the CRLH feeding network, all the slots of the array illuminated in phase and exhibit therefore the same active admittance if the coupling among the slots could be neglected. The distance between adjacent slots is a quarter of the free-space wavelength at the slot resonant frequency. The structure consists of a three-layer substrate with dielectric constant of 2.94 and overall height of 65 mil.

6. Results

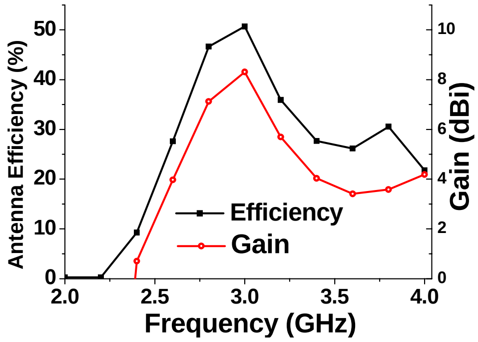
The antenna array is simulated with IE3D (2.5-D MoM simulator). Fig.6 (a) shows its return loss. As expected, the overall antenna is matched only at 3 GHz which is the resonant frequency of the slots, which, as discussed in Sec. 3, may be remedied by using tuning varactors. Fig. 6(b) shows the normalized co-polarization radiation patterns in the X-Z (scanning) plane and reveals that this array is capable to perform full-space scanning (from -90 to 90 degrees) as the feeding CRLH line is fed from its left-handed to its right-handed ranges. It is also observed that the beam scanning sensitivity, $d\theta/df$, decreases as frequency increases, as a consequence of the increasingly non-dispersive (right-handed) response of the CRLH structure with increasing frequencies. The radiation efficiency and gain of the array vs. frequency are shown in Fig. 6(c). Due essentially to mismatch and slots narrow bandwidth, efficiency quickly decreases away from the resonant frequency of the slots. This problem will be solved in future by implementing varactors as discussed above.



(a)



(b)



(c)

Fig. 6 Simulated performance of the antenna array. (a) Return loss. (b) Antenna efficiency and gain. (c) Radiation pattern.

6. Conclusion

A frequency-scanned slot antenna array fed by a boxed stripline CRLH network has been demonstrated. Both the design approach and simulation results have been presented. The antenna array will be fabricated and measured soon.

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