Wideband frequency-scanning phased-array feed network using novel composite right/left-handed unit cell

Bin-Feng Zong✉, Guangming Wang, JiangGang Liang, XuChun Zhang and D. Wang

Based on a novel composite right/left-handed unit cell, a wideband frequency-scanning network with a large scanning angle ranging towards both negative and positive elevation angles is proposed. The measured results show that the insertion loss variation of the designed frequency-scanning network is 7.2 ± 1 dB when the frequency ranges from 4.33 to 8.53 GHz and the phase differences of adjacent output ports scan from −50° to 50° when the frequency ranges from 4.76 to 8.26 GHz (53.8%). The proposed network can be used in wideband systems that require a large scanning angle range.

Introduction: Recently, the composite right/left-handed (CRLH)-based frequency-scanning phased-array feed network has attracted much attention because it can provide both negative and positive phase difference values, thus enabling the array system to direct the radiated beams in the entire upper hemisphere. Unlike the CRLH-based leaky-wave antennas, the frequency-scanning functionality is obtained through feed network design rather than the antenna design. Therefore, independent design controllability of radiation performance such as radiated polarisation type, polarisation orientation and cross-polarisation level can be provided. Unfortunately, few CRLH-based frequency-scanning phased-array feed networks have been reported until now. In [1], Choi *et al* first designed a dual-band frequency-scanning phased-array feed network using CRLH dispersive lines. In [2], frequency-scanning phased-array feed networks with equal and unequal amplitude output ports were designed by combining the CRLH dispersive lines with power dividers. However, the use of lumped elements limits their application in higher frequency and the tightness of lumped series capacitances and shunt inductances makes for a complex fabrication. Besides, the bandwidths of the feed networks in [2] are from 1.8 to 2.5 GHz (32.6%), making it unsuitable to be used in those systems that operate in wider bands.

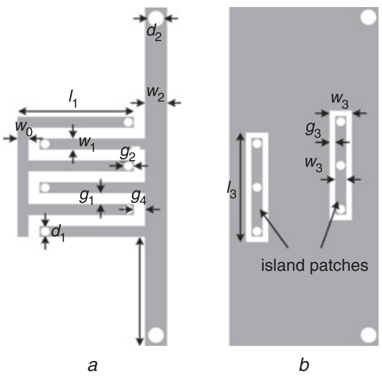


Fig. 1 *Layout of proposed CRLH unit cell*

a Top layer
b Bottom layer

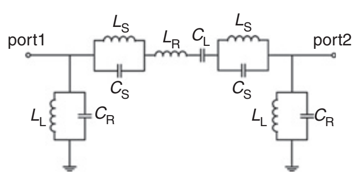


Fig. 2 *Lumped equivalent circuit model*

In this Letter, a novel CRLH unit cell with a wider operating band is initially proposed and analysed. Then, a frequency-scanning phased-array feed network, which is synthesised by combining the designed CRLH unit cells-based transmission lines with proper power dividers, is designed, fabricated and measured. The measured results show that the designed feed network has a wider operating band (from 4.76 to 8.26 GHz, 53.8%) and can provide a larger phase differences range (from −50° to 50°) between the adjacent output ports. Moreover, the designed feed network can be easily fabricated using the normal printed circuit board process.

Characterisation of proposed CRLH unit cell: Fig. 1 shows the layout of the proposed CRLH unit cell, which is composed of a novel interdigital capacitor (IDC) and two symmetrical short stubs. Unlike the conventional IDC, the proposed one has metallic via holes at the open ends of all capacitor fingers and two rectangular slot rings on the ground layer provide two island patches to connect the via holes of the alternate fingers at the same port. The CRLH unit cell was designed on a 0.8 mm substrate with a dielectric constant of 2.65 and a loss tangent of 0.005. The geometry parameters of the unit cell are $w_0 = 0.3$ mm, $w_1 = 0.3$ mm, $l_1 = 4.38$ mm, $g_1 = 0.12$ mm, $d_1 = 0.3$ mm, $w_2 = 0.3$ mm, $l_2 = 6.05$ mm, $g_2 = 0.4$ mm, $d_2 = 0.3$ mm, $w_3 = 1$ mm, $l_3 = 2.68$ mm, $g_3 = 0.2$ mm, $w_4 = 0.6$ mm, $g_4 = 0.12$ mm.

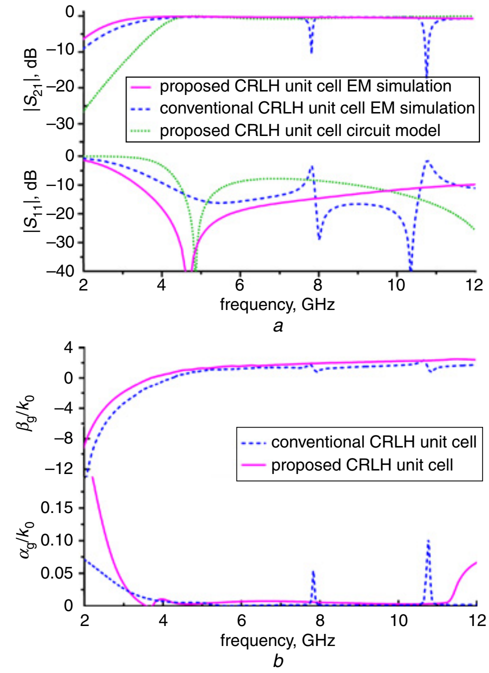


Fig. 3 *Characteristics comparison between novel CRLH unit cell and its conventional counterpart*

a S-parameters
b Normalised attenuation and phase constants

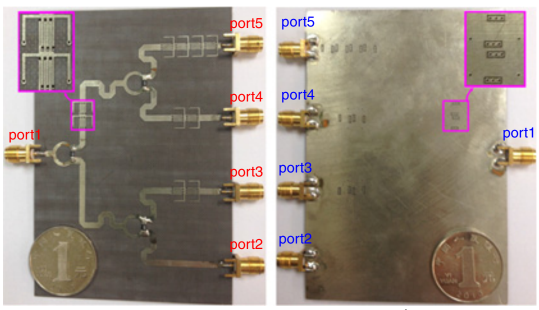
Fig. 2 shows the corresponding lumped equivalent circuit model of the proposed CRLH unit cell. It consists of a Π network of the conventional IDC and two parallel LC tanks. The parallel LC tanks, which are composed of L_S and C_S, represent the rectangular slot rings on the ground. In [3], it has been pointed out that the *S*-parameter curves are nearly the same for a slot with or without an island patch. Therefore, the slot with an island patch can also be modelled as a parallel LC tank [4]. The fingers connected by via holes on the island patches are modelled as a serial LC tank composed of L_R and C_L on the host line. The symmetrical short stubs provide parallel LC tanks composed of L_L and C_R. In this model, the parasitic elements are neglected for the sake of simplicity. The extracted circuit element values are $L_S = 0.04$ nH, $C_S = 0.09$ pF, $L_R = 0.11$ nH, $C_L = 0.655$ pF, $L_L = 0.85$ nH, $C_R = 0.178$ pF.

Fig. 3*a* compares the *S*-parameters of the CRLH unit cell based on the proposed and the conventional IDCs. It can be observed that the CRLH unit cell based on the novel IDC has a wider transmission band than its conventional counterpart. This is due to the spurious spikes at 7.8 and 10.7 GHz being removed. Besides, good agreement between the results of the circuit model and the EM simulation indicates the correctness of the circuit model. Fig. 3*b* compares the normalised attenuation constant (α_g/k_0) and the normalised wavenumber (β_g/k_0) of the unit cells. Both of them were extracted based on the expression, which has been reported in [5]

$$e^{\gamma_g L} = e^{(\alpha_g + j\beta_g)L} = \frac{1 - S_{11}^2 + S_{21}^2 + \sqrt{(1 + S_{11}^2 - S_{21}^2)^2 - (2S_{11})^2}}{2S_{21}} \quad (1)$$

where L is the total length of the proposed unit cell. It can be observed that the novel CRLH unit cell has a wider flat phase characteristic within the operating bandwidth, because sudden abrupt changes at the spurious spikes of the conventional one are removed by using the new design method. Although the attenuation constant of the novel unit cell is larger than that of the conventional one in some bands, it still has a lower level within the whole operation band. As a result, the novel CRLH unit cell can be applied to design devices with a wider phase response.

Frequency-scanning phased-array feed network and results: The wide magnitude and phase responses of the novel CRLH unit cell can be applied to design a wideband frequency-scanning phased-array feed network. In this Letter, a frequency-scanning phased-array feed network, which is composed of two conventional microstrip lines, four CRLH lines and three power dividers, is proposed. Among the CRLH lines, three of them are designed by cascading two proposed CRLH unit cells and one of them is designed by cascading four unit cells. Photographs of the fabricated prototype of the network are depicted in Fig. 4. As shown in Fig. 4, there are 0, 2, 4 and 6 proposed CRLH unit cells in series of the paths from port1 to port i ($i = 2, 3, 4$ and 5), which results in the progressive phase shifting between the adjacent output ports in the passband. This is an essential property required in continuous frequency scanning. The lengths of the normal microstrip lines, which have less influence on the transmission coefficient, can be used to optimise for required output phase responses. In this design, all of the shunt stubs of the unit cells are folded to reduce the occupied size of the network.



a b

Fig. 4 *Photographs of proposed frequency-scanning phased-array feed network*
a Top view
b Bottom view

The simulated and measured results, which are in good agreement, are shown in Fig. 5. The simulation was accomplished using the Ansys HFSS and the measurement was carried out by an Anritsu ME7808A network analyser. In Fig. 5*a*, *S*-parameters of the designed frequency-scanning phased-array feed network are given. From the measured results, it can be observed that the designed network exhibits a −10 dB reflection coefficient ($|S_{11}|$) bandwidth ranging from 4.01 to 9 GHz and the transmission coefficients ($|S_{21}|$, $|S_{31}|$, $|S_{41}|$ and $|S_{51}|$) bandwidth with 7.2 ± 1 dB ranging from 4.33 to 8.53 GHz. In Fig. 5*b*, the phase differences of the adjacent output ports are given. As can be observed, the phase differences of adjacent output ports ($P_i - P_{i-1}$, $i = 3, 4, 5$) are 0° at 6.16 GHz and the phase differences range towards −50° to 50° from 4.76 to 8.26 GHz. The variation is <10° at every specific frequency point. As a result, the operation band of the proposed frequency-scanning phased-array feed network ranges from 4.76 to 8.26 GHz when both the magnitude and phase responses are taken into consideration. Compared with the bandwidths of the networks (32.6%) in [2] (to our best knowledge, they are the widest designed CRLH-based frequency-scanning phased-array feed networks with a scanning angle ranging towards both positive and negative angles), the designed network has a wider operation band (53.8%). Here, it should be pointed out that the acceptable deviations between the measured and the simulated results appear because of the fabrication and calculation error. The proposed feed network can be used to synthesise frequency-scanning phased-array antenna for wideband systems.

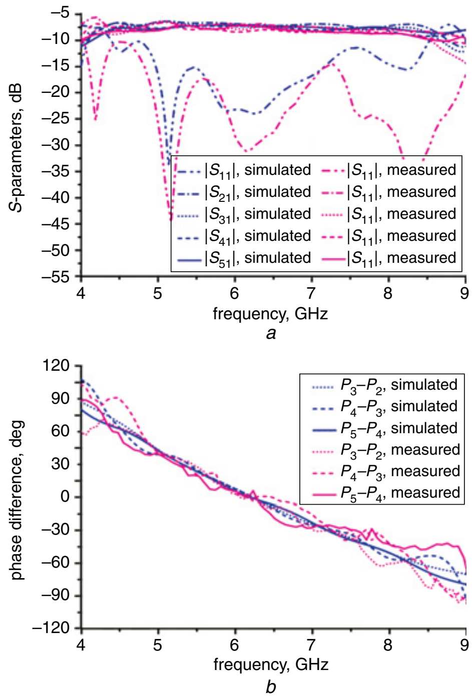


Fig. 5 *Results of proposed frequency-scanning phased-array feed network*
a *S*-parameters
b Phase differences between adjacent output ports

Conclusion: In this Letter, a wideband frequency-scanning phased-array feed network based on a new type of CRLH unit cell has been presented. Its insertion loss variation is 7.2 ± 1 dB and the scanning angle is from −50° to 50° between the frequencies 4.76 and 8.26 GHz. The designed network has good potential in wideband frequency-scanning phased-array antennas.

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One or more of the Figures in this Letter are available in colour online.

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