Leaky-Wave Antenna with Modified Metamaterial Unit Cell for Narrowing Beam Steering Bandwidth

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***Abstract* – A novel unit cell of a composite right/left-handed transmission line has been proposed for application in leaky-wave antennas. It is shown that by the application of an open stub one can freely adjust the radiation frequency range in the right-hand region, and therefore, scanning of the main beam in the desired frequency range can be obtained. The results of theoretical analysis of the unit cell have been shown and confirmed by electromagnetic calculation of the proposed structure.**

***Index Terms* — Antennas, leaky-wave antennas, scanned-beam antennas, metamaterials, CRLH transmission lines.**

I. Introduction

The leaky-wave antennas are one of the possible approaches for designing high-gain and narrow-beam antennas [1]. Recently it has been shown that by utilization of composite balanced right/left handed (CRLH) transmission lines it is possible to achieve electronic beam scanning in a full angular range from -90° to +90° [2] – [4]. The disadvantage, however, of a classic balanced CRLH transmission line is its relatively wide frequency range needed to achieve full scan angle, moreover the typical dispersion characteristic vs. frequency is asymmetric with respect to the transition frequency i.e. the frequency at which the line changes its nature from left to right handed. This causes that the frequency range needed for scanning from -90° to 0° is much narrower than the frequency range needed for scanning from 0° to +90° [5]. One of the possible applications of leaky-wave antennas with beam scanning capability vs. frequency is in motion detection systems, where it is required to achieve a full scan angle in the desired (narrow) frequency range, typically symmetrical with respect to the transition frequency.

In this paper we propose a novel unit cell of CRLH transmission line designated for application in leaky-wave antennas. It has been shown that by adding an open stub to the classic CRLH unit cell one can arbitrarily adjust the upper cut-off frequency which in turn results in symmetrical frequency ranges for left and right handed regions. Such an approach allows for achieving a leaky-wave antenna having full scan angle in the desired frequency range, moreover the backward and forward scan angle is achieved within similar bandwidths. The theoretical investigation has been shown and the proposed concept has been validated by the results of electromagnetic calculations of the designed balanced CRLH section.

II. Theoretical Analysis

The proposed unit cell of a CRLH transmission line is shown in Fig. 1. The unit cell consists of a series capacitor and shorted transmission line section which correspond to the series capacitor and shunt inductor of a classic lumped element left handed transmission line [5], the series transmission line section represents the finite physical length of the unit cell and is responsible for the change of the cell's nature from left to right hand. In our proposed cell an open ended transmission line stub has been added, which introduces transmission zero at a finite frequency, and therefore allows to adjust the dispersion diagram in the right hand frequency region to be symmetrical with respect to the transition frequency f_T.

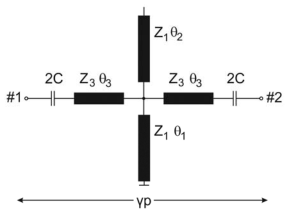

Fig. 1. Proposed unit cell of a CRLH transmission line.

The Bloch impedance and phase constant for the proposed unit cell can be expressed as follows:

$$Z_B = \sqrt{X_C\left(1 - \frac{Z_3}{X_C}\tan(\theta_3)\right)(-A)} \tag{1}$$

$$\beta p = \mathrm{Im}\left\{\operatorname{arccos}h\left[\frac{X_C\left(-1 + \frac{Z_3}{X_C}\tan(\theta_3)\right) - A}{-X_C\left(-1 + \frac{Z_3}{X_C}\tan(\theta_3)\right) - A}\right]\right\} \tag{2}$$

where:

$$A = X_C + Z_3\left[\frac{2Z_1 tg(\theta_1)ctg(\theta_2) + Z_3 tg(\theta_3)[ctg(\theta_2) - tg(\theta_1)]}{Z_1 tg(\theta_1)ctg(\theta_2)tg(\theta_3) + 2Z_3[ctg(\theta_2) - tg(\theta_1)]}\right]$$

In order to obtain a balanced structure the following two conditions must hold, from which two of the five values Z_1, Z_3, Θ_{01}, Θ_{02}, Θ_{03} and C can be found:

$$-1 + Z_3 \tan\left(\frac{f_T}{f_0}\theta_{03}\right)2\pi f_T 2C = 0 \tag{3}$$

$$Z_3 - \frac{2Z_1 tg(\frac{f_T}{f_0}\theta_{01})ctg(\frac{f_T}{f_0}\theta_{02})}{ctg(\frac{f_T}{f_0}\theta_{02}) - tg(\frac{f_T}{f_0}\theta_{01})} tg(\theta_{03}) = 0 \tag{4}$$

where Θ_{0x} is the electrical length of the line x specified at the frequency f_0, and f_T is the transition frequency between the left-hand and right-hand region, i.e. the frequency of boresight radiation. An exemplary dispersion diagram for the proposed unit cell is shown in Fig. 2, where the electrical length and attenuation of the unit cell vs. frequency have been presented for Z_1 = 120 Ω , Z_3 = 160 Ω , Θ_{01} = 6° Θ_{02} = 85.2° Θ_{03} = 44° (all @ 2GHz) and C =0.27 pF. Moreover, the lines enclosing the radiation region have been shown [5], and the frequencies f_1 and f_2 which limit the radiating frequency range can be seen. As it is seen the by adjusting the length of the open-ended stub one can adjust the position of the transmission zero f_3, and therefore, can modify the dispersion characteristics in the frequency range $f_1 - f_2$.

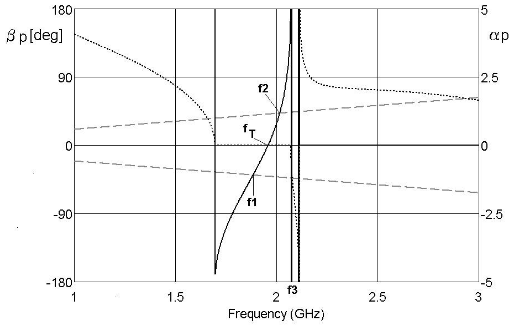

Fig. 2. Electrical length βp (solid line) and attenuation αp (dotted line) of the proposed CRLH unit cell. Dashed lines enclose the radiation region. Results of circuit analysis.

III. Antenna Design

The proposed unit cell has been designed and analyzed electromagnetically. For the design a dielectric structure shown as an inset in Fig. 3 has been chosen, which allows to easily incorporate the series capacitors between metallization layers. The results of electromagnetic calculations of the designed unit cell are presented in Fig 4, where an electrical length and attenuation of the unit cell are visible and fully correspond to the theoretical ones. The radiating frequency range can be found from 1.89 to 2.01 GHz. In Fig. 5 the S parameters of the antenna consisting of 10 unit cells have been presented showing the appropriate pass-band and impedance match in the radiating frequency range. The radiation pattern calculated near f_T has been shown as an inset in Fig. 5 and the boresight radiation is seen. The 3 dB beamwidth equals 36° and corresponds to the physical length of the designed antenna consisting of 10 unit cells.

IV. Conclusion

The novel unit cell of the CRLH transmission line for electronically scanned antenna has been proposed. By adding an open-ended stub one can freely modify the dispersion characteristic of the unit cell, hence, adjusting the radiating frequency range of the structure. The presented theoretical investigation has been confirmed by the electromagnetic calculations of the designed structure.

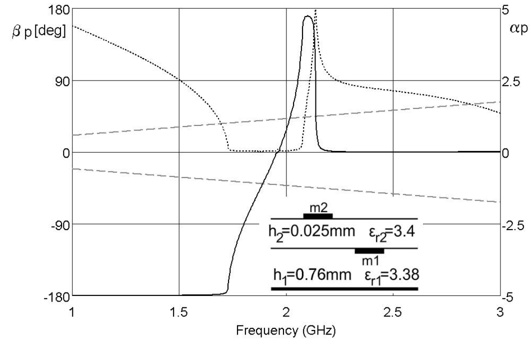

Fig. 3. Electrical length βp (solid line) and attenuation αp (dotted line) of the proposed CRLH unit cell. Dashed lines enclose the radiation region. Results of electromagnetic calculations. Cross-sectional view of the chosen dielectric structure is shown as an inset.

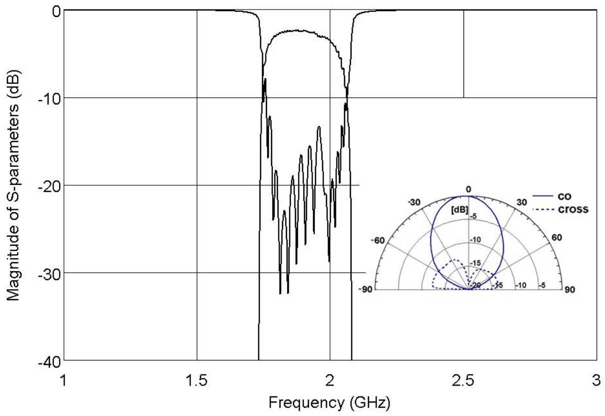

Fig. 4. S parameters of the balanced CRLH transmission line composed of 10 unit cells. Results of electromagnetic calculations. The radiation pattern calculated near f_T is shown as an inset.

Acknowledgment

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