Leaky-Wave Antenna in Multilayer Structure for Sensor Applications

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***Abstract* – A leaky-wave antenna has been analyzed and designed for application in smart motion sensors. The application of multilayer structure with a thin laminate layer allows for manufacturing the required capacitive elements without the need for SMD components' application. The theoretical expressions are derived allowing for initial unit cell design. The designed antenna structure consisting of 30 unit cells has been designed and verified electromagnetically. Finally the model of the antenna has been manufactured and measured.**

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

I. Introduction

The leaky-wave antennas offer the possibility of obtaining narrow-beam radiation patterns from a large aperture being a cascade connection of a large number of identical unit cells [1]. The drawback of such antennas is their beam squint with the change of the operational frequency, and therefore are not suitable for applications in which stable broadside beam is required in a broad frequency range such as in pulse radars or frequency modulated signal radars (FMCW). However, they can be useful in systems where a narrow operational bandwidth is utilized for a single measurement, and the broad frequency tuning is utilized to control the antenna beam. Examples of such radar sensors have been presented in [2] – [4]. In [2] a leaky-wave antenna designed in substrate-integrated-waveguide technique has been presented with the beam scanning in the frequency range of 8.5 – 11.5 GHz. However, in the presented design the beams are not evenly distributed along normal to the antenna plane, instead, the angular range 90° to 180° is better covered than the range 0 - 90°. In [3] and [4] exemplary results have been shown on radar sensors for tracking of humans, where leaky-wave antennas have been utilized operating in 5 – 8 GHz frequency range for azimuth tracking. The presented solutions are not optimized for narrow-bandwidth systems which could be commercially offered operating in e.g. 2.4 or 5.5 GHz frequency ranges, and offer beams not evenly distributed along normal to the antenna plane. Recently it has been shown that by utilization of metamaterial structures and in particular 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° [5] – [7].

In this paper we show our investigation result on the design of leaky-wave antennas which operate in relatively narrow bandwidth suitable for application in commercially available frequency bands and featuring evenly distributed beams along the normal to the antenna plane. The antenna has been designed in a multilayer microstrip technique in order to facilitate the needed lumped capacitors, which have been designed as layer-to-layer parallel plate capacitors. The antenna array has been analyzed electromagnetically and manufactured. The measured results confirmed the theoretical predictions.

II. Theoretical Analysis

The leaky-wave antenna is composed of a cascade connection of a large number of identical sub-networks called unit cells. The unit cell of a CRLH transmission line utilized is shown in Fig. 1 and consists of a series capacitor and a shorted transmission line section which correspond to shunt inductor of a classic lumped element left handed transmission line [8]. The additional sections of transmission lines connected in series with capacitors are added to obtain the transmission line having the composite right/left handed nature. Moreover, by appropriate choice of parameters of the series transmission-line section it is possible to meet the balanced conditions [8].

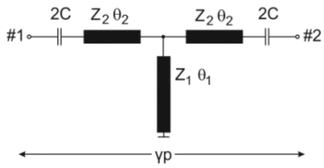

Fig. 1. Proposed unit cell of a CRLH transmission line.

The Bloch impedance and phase constant for the proposed unit cell can be explicitly expressed and are given at the top of the second page (1) – (4).

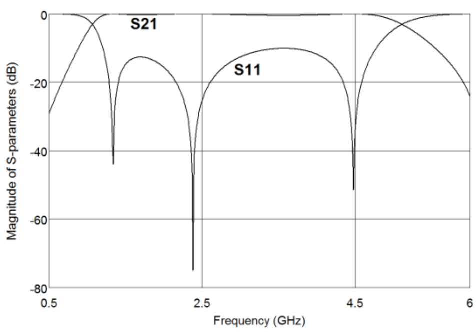

Fig. 2. The scattering parameters of the single unit cell shown schematically in Fig. 1.

$$Z_B = \sqrt{-Im(Ze)Im(Zo)} \quad (1)$$

where:

$$Z_o = j\left\{-\frac{1}{2\pi f 2C} + Z_2 \tan(\theta_2)\right\} = j\left\{\frac{-1+2\pi f 2C Z_2 \tan(\theta_2)}{2\pi f 2C}\right\} \quad (2)$$

$$Z_e = j\left\{-\frac{1}{2\pi f 2C} + Z_2 \frac{2Z_1 \tan(\theta_1)+Z_2 tan\theta_2}{Z_2-2Z_1 \tan(\theta_1)\tan(\theta_2)}\right\} = j\left\{\frac{-(Z_2-2Z_1\tan(\theta_1)\tan(\theta_2))+2\pi f 2C Z_2 (2Z_1\tan(\theta_1)+Z_2 tan\theta_2)}{2\pi f 2C(Z_2-2Z_1\tan(\theta_1)\tan(\theta_2))}\right\} \quad (3)$$

$$\beta p = Im\left\{arccosh\left[\frac{Ze+Zo}{Ze-Zo}\right]\right\} = Im\left\{arccosh\left[\frac{\left\{\frac{-(Z_2-2Z_1\tan(\theta_1)\tan(\theta_2))+2\pi f 2C Z_2(2Z_1\tan(\theta_1)+Z_2 tan\theta_2)}{2\pi f 2C(Z_2-2Z_1\tan(\theta_1)\tan(\theta_2))}\right\}+\left\{\frac{-1+2\pi f 2C Z_2\tan(\theta_2)}{2\pi f 2C}\right\}}{\left\{\frac{-(Z_2-2Z_1\tan(\theta_1)\tan(\theta_2))+2\pi f 2C Z_2(2Z_1\tan(\theta_1)+Z_2 tan\theta_2)}{2\pi f 2C(Z_2-2Z_1\tan(\theta_1)\tan(\theta_2))}\right\}-\left\{\frac{-1+2\pi f 2C Z_2\tan(\theta_2)}{2\pi f 2C}\right\}}\right]\right\} \quad (4)$$

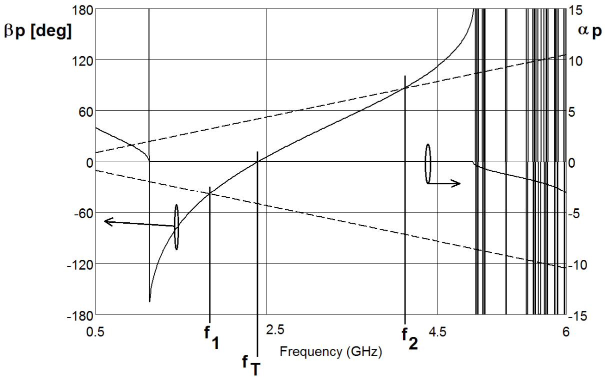

Fig. 3. Electrical length βp and attenuation αp of the proposed CRLH unit cell. Dashed lines enclose the radiation region. Results of circuit analysis.

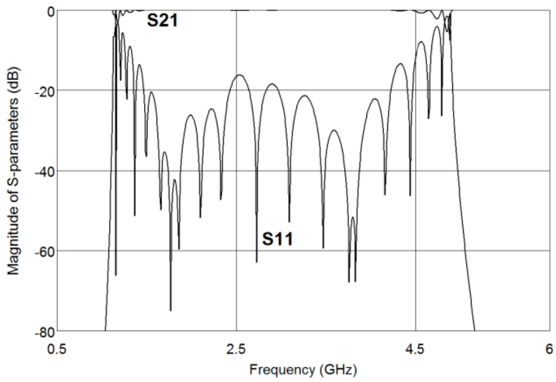

Fig. 4. S parameters of the balanced CRLH transmission line composed of 30 unit cells. Results of circuit calculations.

For the leaky-wave antenna the following parameters of the unit cell have been found: $C = 1.5$ pF, $Z_1 = 50\ \Omega$, $\Theta_1 = 70°$, $Z_2 = 110\ \Omega$, $\Theta_2 = 22°$. Results of circuit calculations of the S parameters of the unit cell are presented in Fig. 2, whereas, the calculated propagation constant of a structure of infinite number of unit cells is presented in Fig. 3. As it is seen the transition frequency between the left-handed and right-handed frequency range equals $f_T = 2.4$ GHz, and around f_T the attenuation is 0, i.e. the periodic structure has propagating properties. Fig. 4 presents the S parameters of 30 unit cells connected in cascade, and the structure features good return losses and low attenuation around the transition frequency. The number of 30 unit cells has been selected to achieve narrow beamwidth antenna radiation pattern.

III. Antenna Design

The antenna has been designed using Ansoft Designer CAD software for electromagnetic calculations of 2.5D structures. The proposed unit cell has been designed and analyzed electromagnetically in the dielectric structure shown in Fig. 5, in which the series capacitors have been realized as metallization pads between two different metallization layers. The dimensions of the capacitors have been found to be 2.8 x 2.3 mm. The following dimensions of transmission line sections have been obtained after optimization: 1.7 x 10.8 mm and 0.3 x 3.3 mm for shunt and series sections, respectively. The electromagnetically calculated S parameters of the designed antenna array around the f_T frequency are presented in Fig. 6. As it is seen the $f_T = 1.9$ GHz obtained from electromagnetic calculations is lower than the initially assumed one and another design iteration is required for frequency tuning.

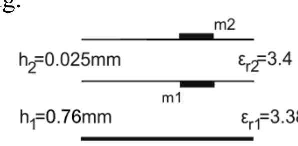

Fig. 5. Dielectric structure selected for the leaky-wave antenna design.

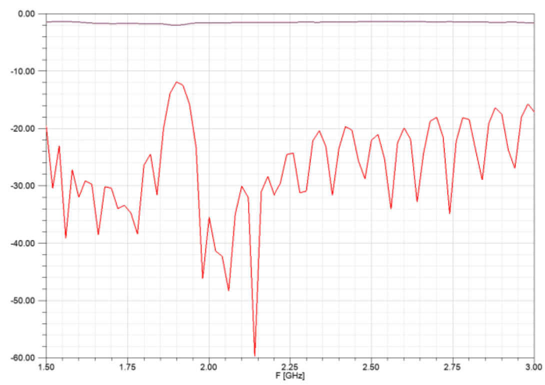

Fig. 6. S parameters of the balanced CRLH transmission line composed of 30 unit cells. Results of electromagnetic calculations.

The electromagnetically calculated radiation patterns are presented in Fig. 7 and Fig. 8, and prove the concept of frequency dependable radiation pattern. Also the broadside beam is obtained for the frequency f = 1.9 GHz and agree with the f_T frequency obtained from scattering parameters. The obtained radiation patterns are evenly distributed along the normal to the antenna plane, moreover, the frequency range for the full scan is narrow and close to the requirement for ISM band allocations.

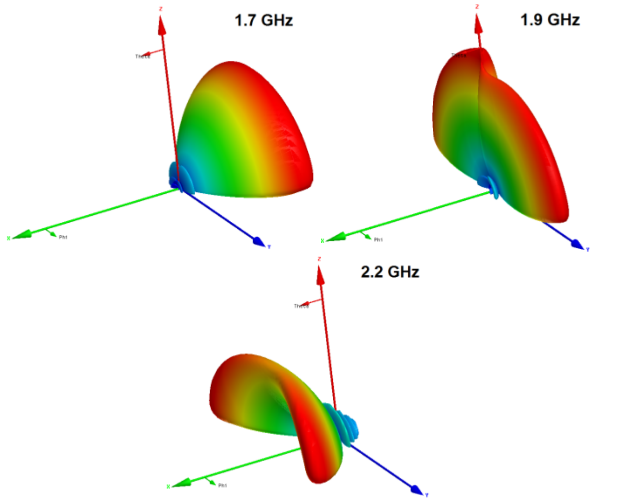

Fig. 7. Radiation patterns of the 30-unit-cell leaky-wave antenna. 3D results of electromagnetic calculations shown for three different frequencies.

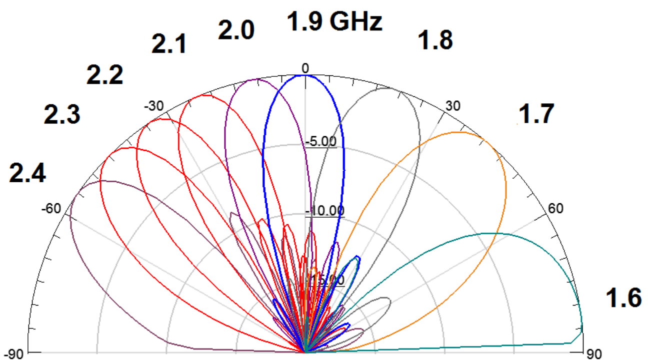

Fig. 8. Radiation patterns of the 30-unit-cell leaky-wave antenna – cut-plane for phi = 0 and theta = (-90°; + 90°). Results of electromagnetic calculations shown for nine different frequencies.

IV. Experimental Results

The designed 30-cell leaky-wave antenna has been fabricated and measured. The multilayer structure has been obtained by thermal bonding the upper and lower dielectric layer with bonding material having dielectric constant equal $\varepsilon r = 3.38$, thus corresponding to the dielectric constant of the main substrate (the bonding temperature T = 140°C and the heating time equals 20 minutes after reaching the bonding temperature). The measured S parameters are presented in Fig. 9 and correspond well with the calculated ones. There is a full agreement in f_T frequency between electromagnetic calculations and measurements. The measured radiation patterns are presented in Fig. 10 and correspond with the calculated ones validating the designed leaky-wave antenna.

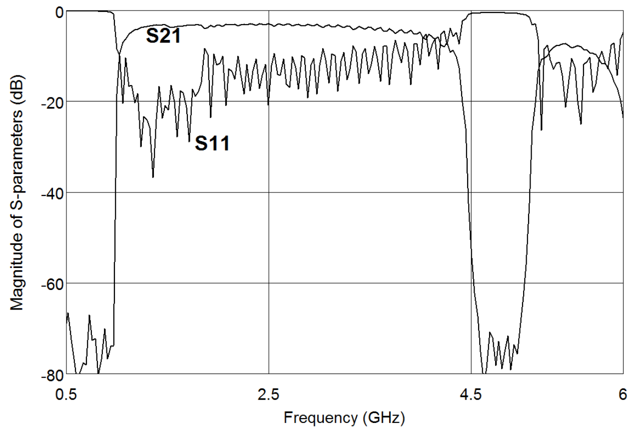

Fig. 9. S parameters of 30-unit-cell leaky-wave antenna composed of 30 unit cells. Results of measurements.

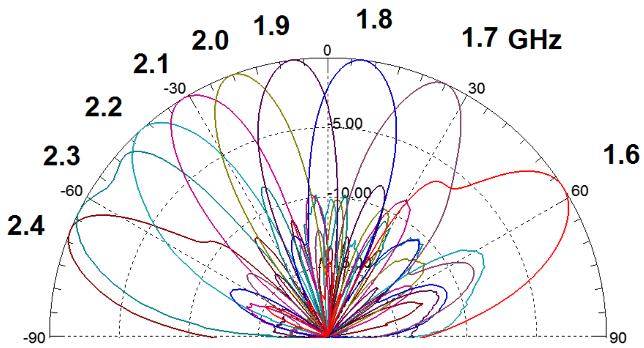

Fig. 10. Radiation patterns of the 30-unit-cell leaky-wave antenna – cut-plane for phi = 0 and theta = (-90°; + 90°). Results of measurements for nine different frequencies.

V. Conclusion

The leaky-wave antenna operating in relatively narrow frequency range has been designed. For easy fabrication of the antenna structure a multilayer microstrip technique has been selected allowing for easy fabrications of layer-to-layer parallel-plate series capacitors. The designed antenna features broad scanning range in the frequency range of 1.6 - 2.4 GHz and can be applied for smart sensor applications. It is possible to design Doppler motion sensors with tunable operational frequency for estimation of the angular location of the detected target. Further development will be conducted aiming at frequency adjustment to the desired operational frequency and further bandwidth decrease. It is worth underlining that the research focused at simplification of the antenna layout to remove the necessity of via connections and multilayer substrates is justified for future low-cost applications.

Acknowledgment

This work has been supported by the National Science Centre, decision no. DEC-2011/01/D/ST7/00789.

References

[1] A. Oliner, "Leaky-wave antennas," in Antenna Engineering Handbook, Third Edition, edited by R. C. Johnson, McGraw Hill, 1993.

[2] F. Kozak, V. Jenik, P. Hudes, „Microwave radar sensor based on CRLH SIW leaky-wave antennas," in proc. *11th European Radar Conference*, pp. 53 -56, Rome, Italy, Oct. 2014.

[3] S-T. Yang, H. Ling, "Design of a microstrip leaky-wave antenna for two-dimensional bearing tracking," *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 784 – 787, 2011.

[4] S-T. Yang, H. Ling, "Application of a microstrip leaky wave antenna for range azimuth tracking of humans," *IEEE Geoscience and Remote Sensing Letters*, vol. 10, no. 6, pp. 1385 – 1388, June 2013.

[5] S. Lim, C. Caloz, T. Itoh, "Metamaterial-based electronically controlled transmission-line structure as a novel leaky-wave antenna with tunable radiation angle and beamwidth," Microw. Theory Tech., IEEE Transactions on , vol.52, no.12, pp. 2678- 2690, Dec. 2004.

[6] Y. Chi, F. Chen, "CRLH Leaky-Wave Antenna Based on ACPS Technology with 180° Horizontal Plane Scanning Capability," Antennas and Propagation, IEEE Transactions on, vol.61, no. 2, pp. 571-577, Feb. 2013.

[7] C. Caloz, T. Itoh, "Array factor approach of leaky-wave antennas and application to 1D/2D composite right/left handed (CRLH) structures," *IEEE Microw. Wireless Compon. Lett*., vol. 14, no. 6, pp. 274-276, June 2004.

[8] C. Caloz, T. Itoh, "Electromagnetic metamaterials: Transmission Line Theory and Microwave Applications", New York: Wiley, 2006.

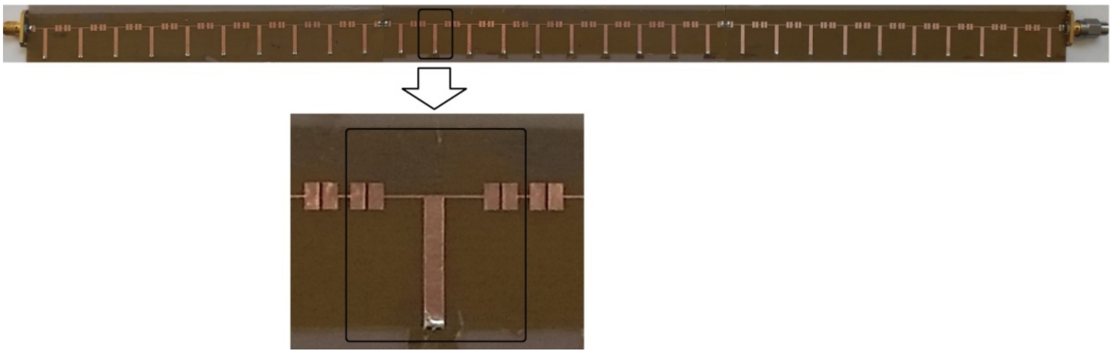

Fig. 11. Picture of the developed leaky wave antenna consisting of 30 unit cells with one unit cell enlarged for detailed view.