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RESEARCH PAPER

Liquid crystal-based tunable CRLH-transmission line for leaky wave antenna applications at Ka-Band

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In this work, a liquid crystal based tunable composite right/left-handed transmission line for future leaky wave antennas working at the Ka-band is presented. The tuning of the liquid crystal is achieved by means of magnetic and electric biasing. For this purpose, different prototypes are fabricated for each biasing technique and their dispersive characteristics compared. Electric tunability is achieved by implementing highly resistive bias lines in the unit cell layout. Both techniques yield similar tuning capabilities at the operation frequency of 27GHz whereas the electric one has the advantage of being easily integratable in the layout.

Keywords: Antenna design, Modeling and measurements, Meta-materials and Photonic bandgap structures

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I. INTRODUCTION

The concept of leaky wave antennas (LWAs) was initially introduced in the first half of the 20th century but it was not until the past decades when the development of planar LWAs drew interest on this kind of structures due to their multiple advantages like narrow and high directive beams, inherently simple feeding network, and reduced unit cell length. The low profile and easy manufacturing [1] make them ideally suited for modern communication systems since they give high-quality performance at low cost [2]. A new approach to design and manufacture LWAs based on metamaterials [3], in particular composite right/left-handed (CRLH) unit cells, has been utilized combining the above mentioned advantages of LWAs with those of CRLH structures such as continuous radiation from backfire to endfire, including broadside direction [4–7].

Beam steering of LWAs can be achieved by frequency tuning due to the dispersive characteristic of the phase constant β of the propagating wave. The radiation angle with respect to broadside of an LWA is determined by [8]

$$\psi(f) = \sin^{-1}\left[\beta(f)/\beta_0(f)\right], \quad (1)$$

where β_0 is the free-space phase constant. Most CRLH LWAs with different topologies, applications, and manufacture technologies use frequency tuning in order to achieve beam steering such as the prototype presented in [9] which is based on substrate integrated waveguide technology. In [10], a CRLH LWA is used with the ability to steer the radiation beam from the backward to the forward quadrant by scanning the frequency from 3.4 to 4.3 GHz. Other authors have made use of the CRLH concept combining it with purpose-tailored materials such as ferrites [11]. However, for many applications beam steering is desirable at a fixed frequency. This can be done using tunable capacitors like semiconductor varactors [12, 13] or p-i-n diodes [14]. The poor performance of these semiconductor varactors at high frequencies has a big impact on the antenna efficiency and thus, limits the operation frequency to about 7 GHz. Another possibility for higher operation frequencies is the usage of liquid crystal (LC) at its nematic phase as a continuously tunable anisotropic dielectric [15]. By applying a static magnetic or electric field it is possible to orientate the LC molecules and hence vary its permittivity. The waveguide-based LWA prototype presented in [16] proves this concept at an operation frequency of 7.6 GHz using a magnetic biasing scheme. This type of biasing is also used in [17], where an LC-based tunable CRLH LWA shows a continuous beam steering of $\pm 20^\circ$ at 27 GHz. The bulkiness of the magnets used for a static magnetic biasing and the difficulty to manipulate them are the main drawbacks of this biasing technique. Hence, an electric biasing scheme that is easily integratable in planar tunable structures while offering the same performance as the magnetic one is desirable. In this work, both techniques are compared and evaluated. For this purpose, an LC-based tunable CRLH transmission line working at 27 GHz is designed and investigated.

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II. UNIT CELL DESIGN

Figure 1 shows the equivalent circuit of the proposed extended CRLH unit cell. It is formed by series and shunt capacitances and inductances that create the left- and right-handed propagation bands. On one hand, the right-handed band (RHB), which is that of traditional transmission line models, is created by the series inductance L_R and the shunt capacitance C_R. In this band, the phase constant β and therefore the phase velocity v_{ph} are both positive and the leaky wave is radiated into the forward quadrant. On the other hand, the series capacitance C_L and shunt inductance L_L are responsible for the left-handed band (LHB) where both, phase constant and phase velocity, are negative. In this case, the leaky wave is radiated into the backward quadrant [13]. This can be seen in Fig. 2, where the angle ψ is defined as in (1). For a seamless transition from the LHB to the RHB the unit cell has to be balanced [18], i.e. $\omega_{sh} = \omega_{se}$, where the shunt frequency is

$$\omega_{sh} = \sqrt{\frac{1}{C_{DC}L_L} + \frac{1}{C_R L_L}}, \tag{2}$$

and the series frequency

$$\omega_{se} = \frac{1}{\sqrt{C_L L_R}}. \tag{3}$$

A DC blocking capacitor C_{DC} is added to the shunt branch of the CRLH unit cell for electric biasing purposes. In the present work, the CRLH unit cell is tuned both electrically and magnetically and its performance in both cases is compared. In order to study the influence of C_{DC} on the final design, it is always incorporated to the unit cell independently of the tuning method applied. C_{DC} creates an undesired stopband below

$$\omega_0 = \frac{1}{\sqrt{C_{DC}L_L}}. \tag{4}$$

Hence, C_{DC} has to be as large as possible in order to shift its stopband out of the intended frequency range of operation and thereby make its effect negligible. If C_{DC} is large enough, then the shunt frequency can be approximated by

$$\omega_{sh} = \sqrt{\frac{1}{C_{DC}L_L} + \frac{1}{C_R L_L}} \approx \frac{1}{\sqrt{C_R L_L}}, \tag{5}$$

and the presented unit cell works as a conventional CRLH structure at the frequency range of operation. Fig. 3a depicts the layout of the designed unit cell in microstrip technology based on the proposed CRLH equivalent circuit. The corresponding element dimensions are listed in Table 1. The series branch corresponds to the main interdigital capacitor (IDC), composed of six fingers. The meander line represents the shunt inductance while the IDC at its end is the DC blocking capacitor C_{DC}. The shunt capacitance is created between the complete unit cell and the ground plane below it. The microscope photo in Fig. 3b shows how the unit cell is periodically repeated to form the artificial transmission line. This scheme will be used for the magnetic biasing proof-of concept.

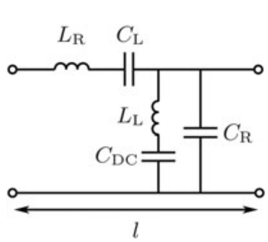

Fig. 1. Equivalent circuit of the modified CRLH unit cell.

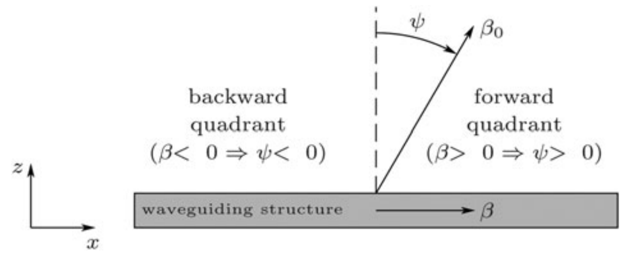

Fig. 2. Working principle of a leaky wave antenna.

III. TECHNOLOGY AND MANUFACTURE

The fabricated metamaterial transmission line consists of 16 CRLH unit cells. A cross-sectional view of the completely mounted structure is depicted in Fig. 4a and explained in detail in this section. All unit cells are printed on a borofloat (BF33) glass substrate with $\varepsilon_r = 4.65$ and $\tan\delta = 0.008$. This glass substrate is chosen not only because of its optimal behavior at microwave frequencies but also because its transparency enables easy alignment. The RF metalization is made of 2 μm thick gold on the bottom side of the glass substrate. A polyimide layer is spin coated with a height of 10 nm and subsequently mechanically rubbed with a velvet cloth. The aim of this is to anchor the LC molecules parallel to the polyimide grooves in the untuned state [19]. To provide mechanical stability to the complete structure, a brass block is used as a ground plane. A photo of the printed glass substrate and the metal block is shown in Fig. 4b. The complete transmission line with the tapers, all printed in the same glass substrate, has a length of 24.1 mm.

The glass substrate with the RF structure on the bottom side is then fixed with conducting glue on top of the metal block forming a cavity with a height of 100 μm between both of them. This cavity is filled with LC TUD-649 with $\varepsilon_{r\perp} = 2.43$, $\varepsilon_{r\parallel} = 3.22$, $\tan\delta \leq 0.0066$. $\varepsilon_{r\perp}$ represents the permittivity for the orientation, where the LC molecules are

Table 1. Unit cell elements dimensions.

l/μm	725
w/μm	161
f_l/μm	643
f_w/μm	21
gap/μm	7
$l_1 + \ldots + l_{10}$	1.9 mm
f_l'/μm	340
f_w'/μm	19
gap$'$/μm	10

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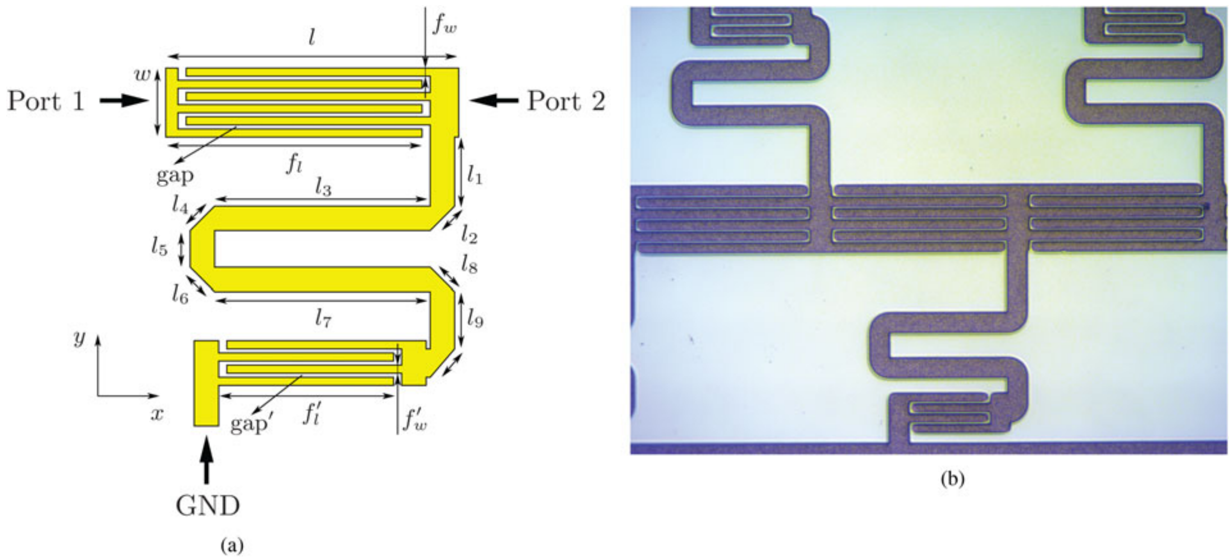

Fig. 3. (a) Proposed unit cell layout. (b) Detailed photo of the manufactured metamaterial transmission line without the biasing lines.

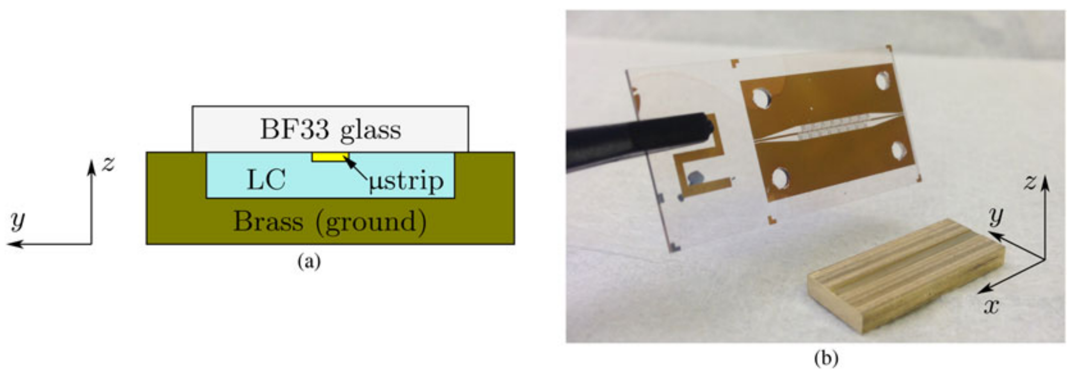

Fig. 4. (a) Cross-sectional view of the proposed structure. (b) Glass substrate with printed CRLH transmission line and ground brass block.

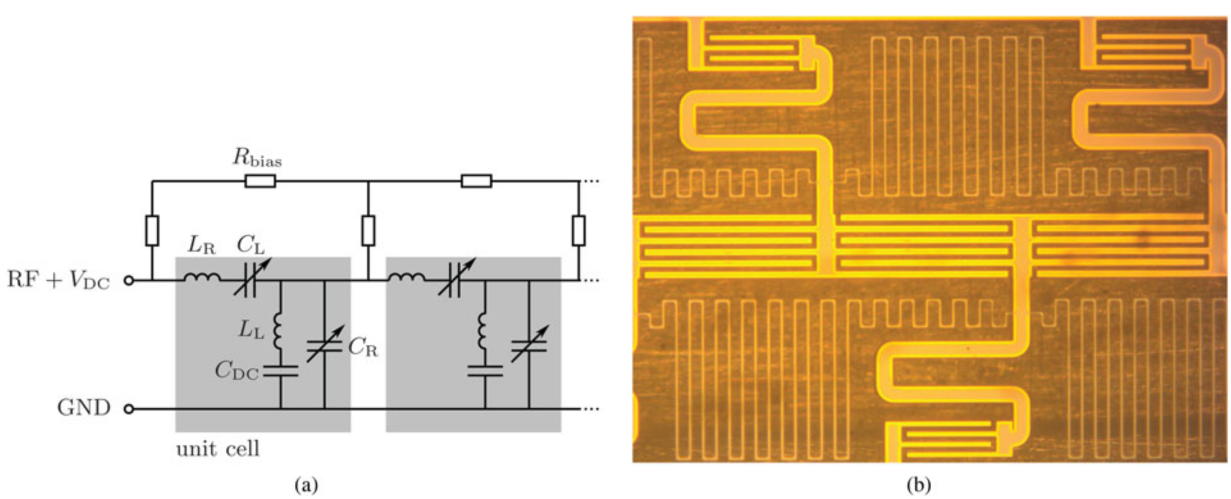

Fig. 5. (a) Electric biasing scheme. (b) Periodically repeated CRLH with highly resistive NiCr lines for electric biasing.

oriented perpendicularly to the RF field, the unbiased state, whereas for $\varepsilon_{r\parallel}$ the LC molecules are oriented parallel to the RF field, this is, the biased state. The orientation of the LC molecules and therefore its permittivity can be tuned either by applying a static magnetic or electric field.

For the magnetic biasing, a rare earth magnet with a field strength of 1T is used. For the electric biasing, highly resistive nickel chromium (NiCr) lines with a thickness of 20 nm and a width of 15 µm are implemented in the unit cell to distribute the tuning voltage along the structure. Figure 5 shows the

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modified unit cell including the NiCr biasing lines. The impact of these lines on the performance of the metamaterial transmission line is evaluated.

IV. DISPERSION CHARACTERISTICS

Advanced design system (ADS) is used for the fullwave simulations of the CRLH transmission line, taking into account metallic and dielectric losses as well as radiation effects. For the magnetic biasing configuration, simulations are carried out on the unit cell scheme represented in Fig. 3b. For the case of electric tuning the highly resistive lines are also included in the simulations in the form as shown in Fig. 5. Both configurations are simulated and measured for both tuning states. To obtain the dispersion diagram, scattering parameter measurements of the transmission line consisting of 16 unit cells are carried out in an on-wafer measurement setup with GSG probes with 250 μm pitch. In this configuration, the transmission line is turned upside down and placed on a layer of absorber. For antenna purposes, contacting with K-connectors directly mounted on the glass is also possible. From the obtained S-parameters, the phase shift and its corresponding radiation angle are extracted and compared for both biasing configurations.

A) Magnetic biasing

For the magnetic biasing, the structure is positioned directly on top of the magnet. The simulated and measured unit cell phase shift is presented in Fig. 6a for the biased and unbiased states. Simulations show a stopband between 23.5 and 25 GHz for the biased state and 25.8 and 27.3 GHz for the unbiased state. As expected, due to a higher permittivity of the LC, the dispersion curve is shifted downwards in frequency for the biased state. In the measurement, the stopband disappears due to the anisotropy of the LC which cannot be taken into account in the simulations. This effect shifts the shunt and series frequencies in opposite directions and thus, cancels out the stopband. For the biased and unbiased states, the frequencies for the broadside radiation, i.e. where the radiation angle $\psi = 0$, are 28.15 GHz and 25.6 GHz, respectively. Since both measured dispersion curves are balanced, it is possible to vary the unit cell shift between $\beta l = -0.04\pi$ and $\beta l = 0.05\pi$ for a fixed frequency of 27 GHz. If the presented transmission line is used for LWA purposes, the radiation angle extracted from the measured phase shift according to equation (1) corresponds to a nearly symmetrical beam steering of $\psi = -19.6^\circ$ to $\psi = 22.5^\circ$ with respect to the broadside direction. This can be seen in Fig. 6b, where the extracted radiation angle along the frequency is represented.

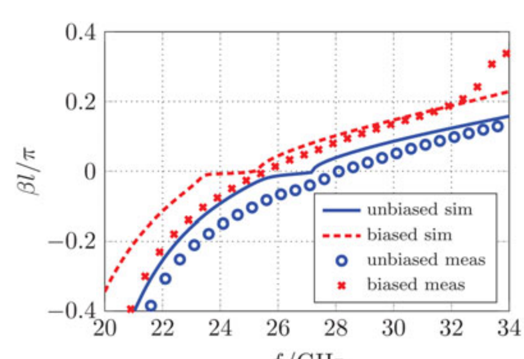
B) Electric biasing

For the electric biasing, DC voltages between 0 and 60 V are applied. In Fig. 7a, the simulated and measured dispersion diagrams are presented. Simulations show a stopband between 25.21 and 26.5 GHz for the biased state and from 26.8 to 28.23 GHz for the unbiased state. The stopband is shifted compared to the magnetically biased transmission line due to the highly resistive biasing lines. This effect is also present in the measured phase shift, where the stopband has almost disappeared. In the case of the measured phase shift at 60V the dispersion diagram shows a slight deviation compared to the simulated one. This is because an SOLT calibration is used during the measurements, so the effect of the taper between the designed transmission line and the probes is deembedded in a post-processing step using the simulated S-parameters of the taper. At 27 GHz, the measured phase shift per unit cell can be tuned between $\beta l = -0.040\pi$ and $\beta l = 0.049\pi$.

For the case the presented transmission line is used for LWA purposes, the frequency dependent radiation angle obtained from the measured unit cell phase shift using equation (1) is presented in Fig. 7b. Here the effect of the deembedding is also visible. At 27 GHz, the measured angles for the electric biasing correspond to a nearly symmetrical beam steering range of $\psi = -21.89^\circ$ to $\psi = 17.83^\circ$ with respect to the broadside direction.

Figure 8 shows the simulated and measured S-parameters for the electric biasing for different tuning voltages. By varying the biasing voltage, the transmission bands can be shifted by 2 GHz. For the different tuning states $|S_{21}|$ falls below −10 dB for frequencies corresponding to the stopband. This effect is also visible in $|S_{11}|$, since the structure is mismatched in the stopband and the input reflection increases up to −2.5 dB for 0V and −1.8 dB for 60V. The insertion loss is better than 0.9 dB per unit cell for the LHB and 0.37 dB per unit cell for the RHB, respectively.

The difference between the simulated and measured scattering parameters is caused by the effect of the deembedding



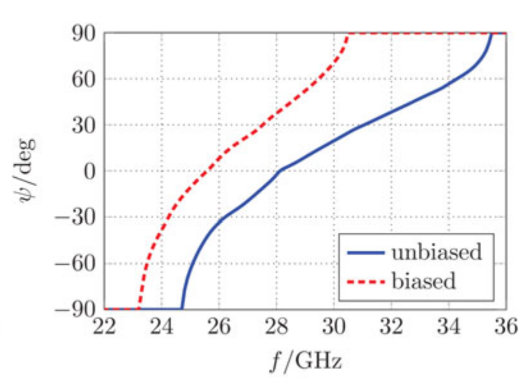


Fig. 6. (a) Measured and simulated unit cell phase shift with magnetic biasing. (b) Extracted radiation angle from the measured phase shift with magnetic biasing.

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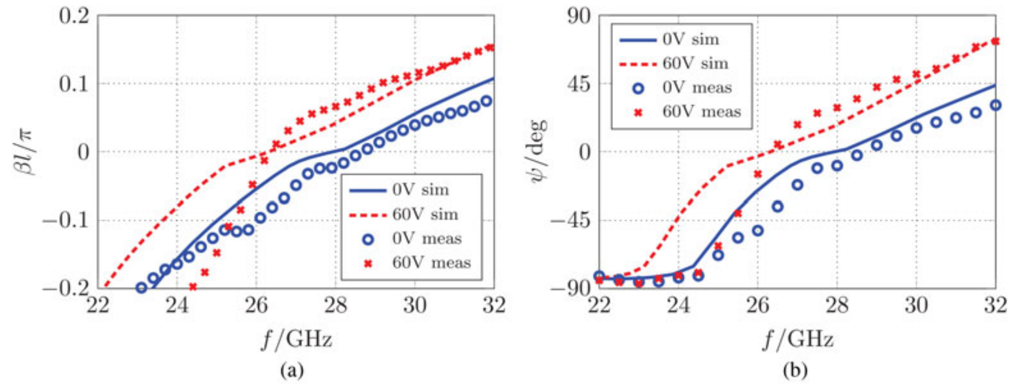

Fig. 7. (a) Measured and simulated unit cell phase shift with electric biasing. (b) Measured and simulated radiation angle with electric biasing.

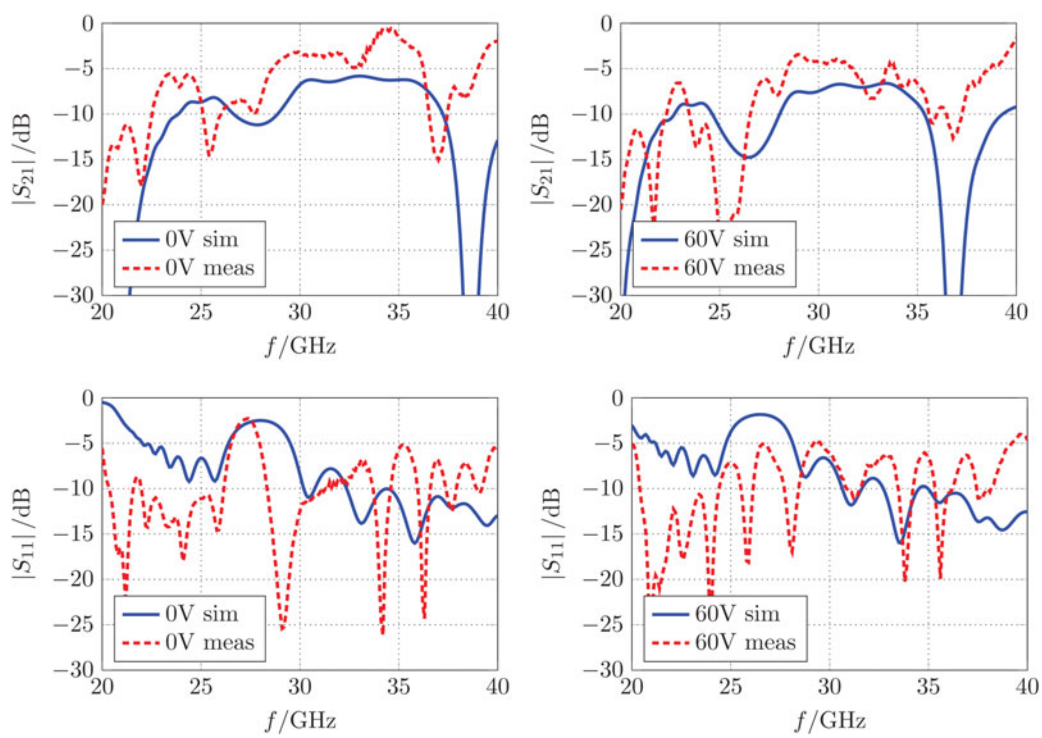

Fig. 8. Measured and simulated scattering parameters of the CRLH line consisting of 16 unit cells for different bias voltages.

of the taper after the SOLT calibration. However, the highly resistive biasing lines have minor impact on the phase shift of the unit cell.

V. CONCLUSION AND OUTLOOK

In this work, an LC-based tunable CRLH transmission line for future LWAs working at 27 GHz has been presented. The tuning of the LC is achieved by magnetic and electric biasing techniques specifically designed for planar structures. Different prototypes have been designed and manufactured for each biasing technique. For the electric biasing, highly resistive NiCr lines are integrated in the unit cell layout. The tuning of the LC and comparison of both prototypes has been done by simulation and measurements of the *S*-parameters and dispersion characteristics. From the obtained *S*-parameters, the corresponding radiation angles are extracted and a beam scanning range of $\pm 20^\circ$ at 27 GHz is achieved with both techniques. The electric biasing provides similar tuning behavior as the magnetic one with the advantage of being easily integratable in the unit cell layout. This electric biasing technique can be easily applied to different types of planar voltage tunable components such as LWAs with continuous beam scanning capability but also tunable phase shifters and filters.

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REFERENCES

[1] Jackson, D.; Caloz, C.; Itoh, T.: Leaky-wave antennas. Proc. IEEE, **100** (7) (2012), 2194–2206.

[2] Podilchak, S.; Freundorfer, A.; Antar, Y.M.M.: Broadside radiation from a planar 2-d leaky-wave antenna by practical surface-wave launching. IEEE Antennas Wirel. Propag. Lett., **7** (2008), 517–520.

[3] Liu, L.; Caloz, C.; Itoh, T.: Dominant mode leaky-wave antenna with backfire-to-endfire scanning capability. Electron. Lett., **38** (23) (2002), 1414–1416.

[4] Caloz, C.; Itoh, T.; Rennings, A.: Crlh metamaterial leaky-wave and resonant antennas. IEEE Antennas Propag. Mag., **50** (5) (2008), 25–39.

[5] Hashemi, M.; Itoh, T.: Evolution of composite right/left-handed leaky-wave antennas. Proc. IEEE, **99** (10) (2011), 1746–1754.

[6] Otto, S.; Rennings, A.; Solbach, K.; Caloz, C.: Transmission line modeling and asymptotic formulas for periodic leaky-wave antennas scanning through broadside. IEEE Transact. Antennas Propag., **59** (10) (2011), 3695–3709.

[7] Paulotto, S.; Baccarelli, P.; Frezza, F.; Jackson, D.: Full-wave modal dispersion analysis and broadside optimization for a class of microstrip CRLH leaky-wave antennas. IEEE Transact. Microw. Theory Tech., **56** (12) (2008), 2826–2837.

[8] Johnson, R.C.; Jasik, H.: Antenna Engineering Handbook, McGraw-Hill, New York, NY, 1984.

[9] Liu, J.; Jackson, D.; Long, Y.: Substrate integrated waveguide (siw) leaky-wave antenna with transverse slots. IEEE Transact. Antennas Propag., **60** (1) (2012), 20–29.

[10] Hashemi, M.; Itoh, T.: Dispersion engineered metamaterial-based transmission line for conformal surface application, in 2008 IEEE MTT-S Int. Microwave Symp. Digest, 2008, 331–334.

[11] Kodera, T.; Caloz, C.: Uniform ferrite-loaded open waveguide structure with CRLH response and its application to a novel backfire-to-endfire leaky-wave antenna. IEEE Transact. Microw. Theory Techn., **57** (4) (2009), 784–795.

[12] Lim, S.; Caloz, C.; Itoh, T.: Electronically-controlled metamaterial-based transmission line as a continuous-scanning leaky-wave antenna, in 2004 IEEE MTT-S Int. Microwave Symp. Digest, vol. 1, June 2004, 313–316.

[13] Lim, S.; Caloz, C.; Itoh, T.: Metamaterial-based electronically controlled transmission-line structure as a novel leaky-wave antenna with tunable radiation angle and beamwidth. IEEE Transact. Microw. Theory Tech., **53** (1) (2005), 161–173.

[14] Huang, L.; Chiao, J.-C.; De Lisio, P.: An electronically switchable leaky wave antenna. IEEE Transact. Antennas Propag., **48** (11) (2000), 1769–1772.

[15] Mueller, S.; Goelden, F.; Scheele, P.; Wittek, M.; Hock, C.; Jakoby, R.: Passive phase shifter for w-band applications using liquid crystals, in 36th Eur. Microwave Conf., 2006, September 2006, 306–309.

[16] Damm, C.; Maasch, M.; Gonzalo, R.; Jakoby, R.: Tunable composite right/left-handed leaky wave antenna based on a rectangular waveguide using liquid crystals, in 2010 IEEE MTT-S Int. Microwave Symp. Digest (MTT), May 2010, 13–16.

[17] Roig, M.; Maasch, M.; Damm, C.; Karabey, O.H.; Jakoby, R.: Liquid crystal based tunable composite right/left-handed leaky-wave antenna for ka-band applications, in 2013 European Microwave Conf. (EuMC), 2013, 759–762.

[18] Caloz, C.; Itoh, T.: Novel microwave devices and structures based on the transmission line approach of meta-materials, in 2003 IEEE MTT-S Int. Microwave Symp. Digest, vol. 1, 2003, 195–198.

[19] Goelden, F.; Gaebler, A.; Mueller, S.; Lapanik, A.; Haase, W.; Jakoby, R.: Liquid-crystal varactors with fast switching times for microwave applications. Electron. Lett., **44** (7) 27 (2008), 480–481.

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