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Fundamental Mode Leaky-Wave-Antenna (LWA) using Slot Line and Split-Ring-Resonator (SRR) Based Metamaterials

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***Abstract*—A new composite right/left-handed (CRLH) slot line leaky-wave antenna (LWA) is proposed. The antenna, implemented by loading a slot line with split-ring-resonators (SRRs), is designed to exhibit a balanced dispersion relation, with a continuous transition between the left-handed and the right-handed bands at 2.5 GHz. Since the periodicity of the structure is much less than a wavelength, the proposed LWA belongs to the family of quasi-uniform LWAs, and it radiates from the fundamental mode (contrary to periodic LWAs). Measured and simulated radiation patterns, gain and scanning angle are reported for a 17-cell LWA. The experimental results demonstrate the potential of the LWA to continuously radiate from backward (−50°) to forward (+60°) scanning angles, with maximum gains of 7.1 dB and 11.3 dB in the left- and right-handed bands, respectively, and specular radiation patterns.**

***Index Terms*—Leaky-wave antennas (LWAs), metamaterials, Split Ring Resonator (SRR), slot line.**

I. Introduction

LEAKY-WAVE antennas (LWAs) are known since the 1940s, when W.W. Hansen introduced the first LWA consisting of a slotted rectangular waveguide [1]. The basic working principle of LWAs is based on a wave propagating along a guiding structure and gradually leaking out a small amount of energy in the form of coherent radiation. Its advantages are the ability to offer sharp directional beams with a frequency scanning over a large bandwidth [2]. There are two different basic types of LWAs: uniform (or quasi-uniform) and periodic. In uniform LWAs the guiding structure is uniform along its length. In this case, the structure supports a wave that is fast with respect to free space. A quasi-uniform LWA operates in a similar way as does a uniform one, except that a periodic structure is used to guide the wave. However, the period is much smaller than the wavelength, and periodicity does not play an active role in the radiation phenomenon. In periodic LWAs, the guiding structure supports slow waves with respect to free space. However, the periodic modulation of the guiding structure produces infinite space harmonics, some of which may be fast, hence providing leaky-wave radiation [3],[4].

Specifically, planar LWAs have recently attracted much attention due to their structural simplicity, easy fabrication, and integration with other planar components [2],[3]. The interest in printed LWAs has increased significantly, mainly due to the advent of metamaterial transmission lines. Over the past years, metamaterial transmission lines have been proposed as backward, forward or backward-forward frequency scanning LWAs [5]-[13]. A very interesting property of these leaky-wave antennas is their capability to operate in the fundamental mode. This avoids the need for a complicated and costly feeding network, as typically used in a phased array. Moreover, most of these antennas can radiate at broadside [6],[10]-[13]. Despite the fact that these fundamental modes are fast in a certain region of the dispersion diagram, there is a cancelation of the leaky-wave radiation when open planar waveguides such as microstrip, coplanar waveguide (CPW) and coplanar strip (CPS) lines are used to design LWAs, due to the presence of antiparallel currents. Such antennas are usually treated as antenna arrays in which radiation is mainly achieved by virtue of periodically loaded radiating elements, which are excited by the fundamental propagating mode [5], [7],[14].

Planar left-handed metamaterials (LHMs) based on split ring resonators (SRRs) and wires (firstly introduced in [15]) can be tailored to produce backward (or left-handed) and forward (or right-handed) leaky-wave radiation, as it was shown in [8]. The original structure proposed in [15] consists of a set of SRRs periodically etched on the back substrate side of a CPW and a set of wires connecting the central strip and the ground plane, just above the SRRs. However, such structure, which supports fast-waves in a certain frequency range, results inefficient to produce leaky-wave radiation from the fundamental mode (CPW mode). Due to the symmetry of the line and excitation, a magnetic wall in the symmetry plane appears. The radiation properties can be obtained by considering the equivalent magnetic currents, which are antisymmetric by virtue of the presence of the magnetic wall. Therefore, a significant cancellation of the far field will take

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place, as occurs in a dipole antenna parallel to a tiny close electric conductor. In [8], in order to achieve efficient leaky-wave radiation, a strong asymmetry was forced in the SRR-loaded CPW by removing the set of SRRs present at one of the sides of the symmetry plane of the CPW. In this paper, a new slot line LWA, inspired by the structure presented in [15], with forward, backward and broadside leaky-wave radiation from the fundamental mode, is proposed.

II. LWA Design

We start by designing a balanced composite right/left handed (CRLH) CPW unit cell, with a sufficiently wide central strip to minimize field coupling between both slots. Then, one half of the structure is removed to obtain the unit cell of the LWA, which is expected to exhibit similar dispersion relation, as explained later. Finally, the length of the LWA is chosen such that almost all the incident power is radiated before reaching the antenna end termination.

The key point in our approach is that a CPW transmission line with the slots separated far enough can be thought of as two independent slot transmission lines sharing the same substrate, with a 180º phase shift between the magnetic currents in both slots. Thus, a symmetric CPW with a wide central strip should have similar propagation characteristics than the slot line resulting by removing one half of the CPW structure.

A. Design of a Balanced CRLH CPW Transmission line

The propagation characteristics of a CRLH CPW transmission line based on SRRs and wires can be obtained through the analysis of the dispersion relation. This can be inferred from the lumped element equivalent-circuit model of the elemental cell shown in Fig. 1, which is valid in the long-wavelength regime ($\beta d << 1$, where β is the phase constant for guided waves and d the unit cell length) [15],[16]. The lumped elements of this equivalent-circuit model are given by [16]

$$L' = \left(2 + \frac{L}{2L_p}\right)\frac{L}{2} - L'_s \tag{1}$$

$$L'_p = 2L_p + \frac{L}{2} \tag{2}$$

$$L'_s = 2\omega_0^2 M^2 C_s \frac{\left(1+\frac{L}{4L_p}\right)^2}{1+\frac{M^2}{2L_pL_s}} \tag{3}$$

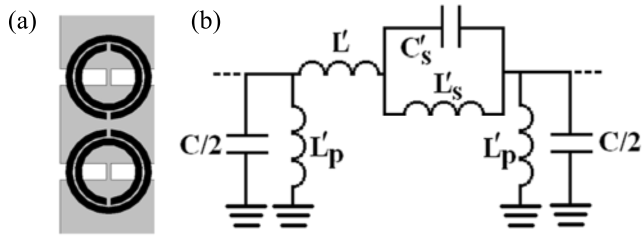


Fig. 1. (a) Layout of the unit cell of the considered CPW structures with SRRs (etched in the back substrate side) and shunt strips. (b) Simplified equivalent-circuit model. Figure extracted from [16]. The extracted parameters of the designed SRR-loaded CPW unit cell were found to be: $L' = 7.33$ nH, $C = 1.53$ pF, $L'_p = 5$ nH, $C'_s = 2.64$ pF, $L'_s = 1.97$ nH.

$$C'_s = \frac{L_s}{2\omega_0^2 M^2}\left(\frac{1+\frac{M^2}{2L_pL_s}}{1+\frac{L}{4L_p}}\right)^2 \tag{4}$$

where L and C are the per-section inductance and capacitance of the host CPW, L_p is the equivalent inductance of connecting wires and the SRRs are modeled as parallel resonant tanks [with inductance L_s, capacitance C_s and resonance frequency $\omega_0^2 = 1/(L_sC_s) = 1/(L'_sC'_s)$] which are inductively coupled to the line through a mutual inductance, M. The resulting dispersion diagram exhibits backward wave propagation at low frequencies and forward wave propagation at high frequencies. Typically, a frequency gap is present between the left-handed and the right-handed bands of the transmission line, unless it is designed to be balanced. In this case, the gap collapses and there is a continuous transition between the left-handed and the right-handed band at the so-called transition frequency, where the phase velocity is ideally infinity and the group velocity takes a finite value [17]. Following the indications described in [18], a balanced CRLH CPW unit cell with a wide central strip was designed. It was obtained by forcing the shunt resonance and the series resonance (that frequency that nulls the reactance of the series branch) of the π-circuit model of Fig. 1(b) to be equal, and by using the parameter extraction method reported in [19].

The dispersion diagrams of the designed CRLH CPW unit cell inferred from electromagnetic simulation (by using the *Agilent Momentum* commercial software) and from the circuit of Fig. 1 are depicted in Fig. 2. Perfect balance is achieved (the transition frequency is $f_0 = 2.5$ GHz), and good agreement between circuit and electromagnetic simulation results.

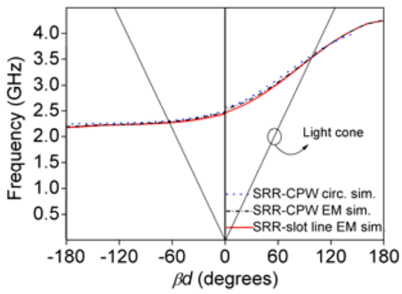


Fig. 2. Dispersion diagram of the SRR-loaded CPW and SRR-loaded slot line.

B. Proposed Structure

The proposed implementation of the CRLH slot line leaky-wave structure is shown in Fig. 3. The antenna is essentially a host slot line periodically loaded with SRRs and narrow metallic strips. The unit cell was obtained by removing one of the halves of the CPW unit cell designed in the previous subsection. The length of the basic cell is 23.5 mm, approximately 5 times smaller than the free-space wavelength ($\lambda_0 = 120$ mm) at 2.5 GHz. Fig. 2 shows the dispersion relation of the unit cell obtained from electromagnetic simulation. Good agreement between the dispersion diagrams obtained from the electromagnetic simulation of the SRR-loaded slot line and the SRR-loaded CPW results. As long as $|\beta| < k_0$ (the free-space wavenumber), radiation may occur, and the angle between the maximum of the radiation beam and the

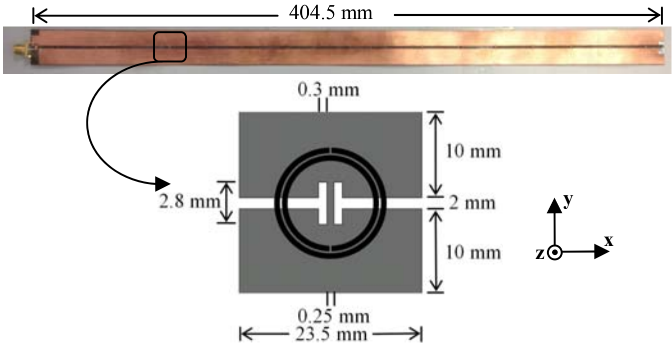


Fig. 3. Fabricated LWA and dimensions. The external radius, rings width and rings separation of the SRRs are 5.5 mm, 0.5 mm and 0.25 mm, respectively.

broadside direction, given by $\sin(\theta_m) = \beta/k_0$, can be either positive (forward wave radiation, $\beta > 0$) or negative (backward wave radiation, $\beta < 0$). Hence, the proposed structure allows for backward and forward leaky-wave radiation. Moreover, broadside radiation is also possible at 2.5 GHz since a continuous transition between the left-handed and the right-handed band is achieved at this frequency (see Fig. 2). As it is known, the analysis of a single unit cell is inaccurate for the determination of the attenuation constant α of leaky periodic structures. This is due to mutual coupling and edge effects. However, as the number of the considered unit cells increases, edge effects become less significant and the obtained attenuation constant is more accurate [7]. Therefore, in order to determine the required number of unit cells, N, the attenuation constant was computed by simulating an N-element two-port structure, using the *Agilent Momentum* commercial software. Fig. 4 shows the normalized attenuation constant α/k_0 at the design frequency of 2.5 GHz. It can be observed that more than 15 elements are required to achieve convergence to a value of $\alpha/k_0 = 0.076$. This value was used to obtain the length of the LWA from the expression for the power flow along a lossy periodic structure with periodicity d

$$P_n = P_0 e^{-2\alpha n d} \qquad (5)$$

where P_0 is the power delivered to the LWA and P_n is the power at the nth terminal of the periodic structure. For 95 % of the power dissipated before reaching the antenna termination and using the converged value of $\alpha/k_0 = 0.076$, we find that the needed number of unit cells is $N = 17$.

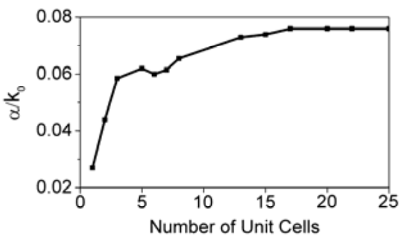


Fig. 4. Attenuation constant versus number of unit cells at 2.5 GHz.

III. Simulation and Experimental Results

An *Arlon Cuclad 250LX* substrate with dielectric constant $\varepsilon_r = 2.43$, loss tangent tanδ = 0.002 and thickness $h = 0.49$ mm was used to fabricate the designed antenna. According to simulation, the Bloch impedance of the loaded line around the transition frequency is about 150 Ω. This impedance was matched to the 50 Ω connector using a semi-lumped microstrip-to-slot line transition acting as an inductive transformer-based matching network. A photograph of the radiating structure terminated with a 150 Ω load, with the impedance matching network and with the input connector, is shown in Fig. 3. The simulated (by means of the *Agilent Momentum* commercial software) and measured return losses are depicted in Fig. 5. Although the simulated return loss shows good matching at the left-handed and the right-handed bands, with a matching level below –6 dB at the transition frequency (2.5 GHz), the measured return loss exhibits some frequency shift, and certain degradation of the matching level in the left-handed band as compared to the simulated results. This is mainly attributed to the critical dimensions of certain elements and to some uncertainty in the permittivity of the substrate (as reported in the datasheets).

The measured and simulated gains are depicted in Fig. 6. The maximum measured gains are 7.1 dB and 11.3 dB for the left-handed and right-handed bands, respectively. Antenna gain degradation at broadside is attributed to the fact that the fabricated structure is not perfectly balanced. The simulated radiation efficiency is higher than 70 % in the left-handed and the right-handed bands, with a maximum value of 80 % at 2.9 GHz. As expected, a degradation of the radiation efficiency is observed around 2.5 GHz with a value of 40 %. The angle θ_m as a function of frequency is also plotted in Fig. 6. The measured backward to forward scanning ranges from −50° to +60° while maintaining an acceptable gain level (above −2dB). The measured and simulated normalized radiation patterns are shown in Fig. 7. Backward, broadside and forward leaky-wave radiation is obtained as frequency increases from the left-handed to the right-handed frequency band. The measured radiation pattern of Fig. 7(b) shows that the main beam is quite wide at broadside. This is due to an imperfect balance (the existence of an evanescent mode at 2.5 GHz makes shorter the effective aperture length of the

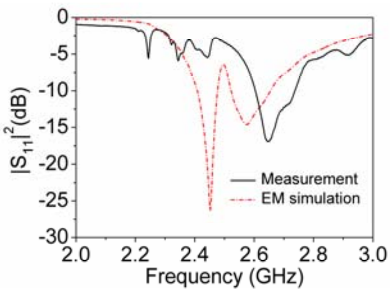


Fig. 5. Simulated and measured return losses of the proposed LWA.

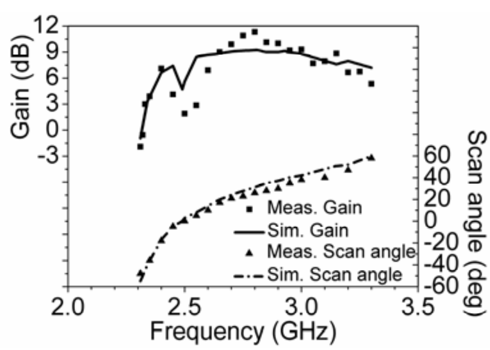
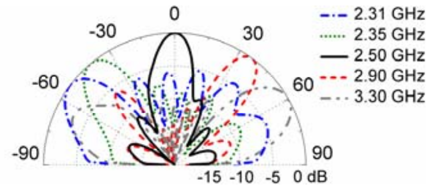


Fig. 6. Simulated and measured gain and scan angle of the proposed LWA.

LWA). The simulated and measured orthogonal patterns at 2.5 GHz are depicted in Fig. 8. It can be observed that, while the radiated beam is directive in the *xz*-plane (see Fig. 7), it is fat in the perpendicular direction (*yz*-plane), thus resulting in a fan beam. The highest cross-polarization level is −16.7 dB.

As compared to other planar CRLH one-dimensional LWAs that report experimental data on antenna performance [6],[9]-[13] the proposed implementation exhibits a good balance between size, gain and scanning capability (see table I). The scanning spans in the table are limited to threshold gains of –2dB, and f_0 is the transition frequency, except for the antenna of ref. [9], not balanced, where f_0 is the lower frequency of the right handed band. The proposed antenna produces specular radiation beams, contrary to those LWAs implemented in microstrip technology.

(a)



(b)

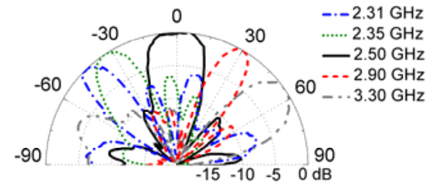


Fig. 7. (a) Simulated and (b) measured normalized radiation patterns of the proposed LWA at the longitudinal plane. Actually, the radiation patterns are specular, i.e., only the upper half semi-space of the *xz*-plane is shown.

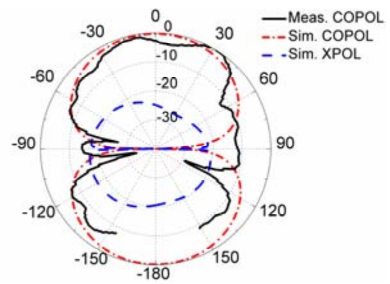


Fig. 8. Simulated and measured orthogonal radiation pattern at 2.5 GHz.

TABLE I
COMPARISON OF VARIOUS PLANAR CRLH LWAs

Ref.	Unit cell length	# cells (% rad. power)	Scan angle	Scan freq. (GHz)	Max. Gain
[6]	$\lambda_0/13$	24 (66%)	–20º,+20º	3.4-4.3	7dB
[9]	$\lambda_0/6$	20 (68%)	+11º,+67º	4.1-5.9	--
[10]	$\lambda_0/11$	41(95%)	–42º,+47º	4.0-5.5	15dB(a)
[11]	$\lambda_0/11$	12(--)	--	--	5.4dB
[12]	$\lambda_0/10$	16(--)	–60º,+25º	1.1-3.2	--
[13](b)	$\lambda_0/10$	10(70%)	–60º,+60º	2.2-2.8	3.2dB
This	$\boldsymbol{\lambda_0/5}$	**17 (95%)**	**–50º,+60º**	**2.3-3.3**	**11.3dB**

(a)Simulated value; (b)This LWA uses chip capacitors.

IV. CONCLUSION

In this paper, a new planar LWA that exploits the CRLH characteristics of a SRRs-loaded slot line is presented. The proposed antenna consists of a 17-cell CRLH slot line, designed to exhibit a continuous transition from the left-handed to the right-handed band at 2.5 GHz. The presented antenna is able to produce backward, broadside and forward leaky-wave radiation from its fundamental TE mode. The proposed prototype has been successfully tested, exhibiting a backward to forward scanning range from −50° to +60° with maximum measured gains of 7.1 dB and 11.3 dB for the left-handed and right-handed bands, respectively.

REFERENCES

[1] W. W. Hansen, "*Radiating electromagnetic waveguide*," U.S., Patent 2.402.622, 1940.

[2] T. Tamir, "*Leaky wave antennas*," in *Antenna Theory*, R. E. Collin and F. J. Zucker, Eds. New York: McGraw-Hill, 1969, ch. 20, pt. 2.

[3] A. Oliner, "*Leaky-wave antennas*," in Antenna Engineering Handbook, R. C. Johnson, Ed. New York: McGraw-Hill, ch. 10, 1993.

[4] D.R. Jackson, C. Caloz and T. Itoh, "*Leaky-Wave Antennas*," *Proceedings of the IEEE* vol. 100, no. 7, pp. 2194–2206, July 2012.

[5] A. Grbic, G.V. Eleftheriades, "Experimental verification of backward-wave radiation from a negative refractive index metamaterial", *J. Appl. Phys*., vol. 92, no. 10, pp. 5930–5935, Nov. 2002.

[6] Liu, L., Caloz, C., and Itoh, T., "Dominant mode leaky-wave antenna with backfire-to-endfire scanning capability", *Electron. Lett*., vol. 38, no. 23, pp. 1414–1416, Nov. 2002.

[7] A. Grbic, and G.V. Eleftheriades, "Leaky CPW-based slot antenna arrays for millimeter-wave applications", *IEEE Trans. Antennas Propag.*, vol. 50, no. 11, pp. 1494–1504, Nov. 2002.

[8] I Arnedo, J. Illescas, M. Flores, M.A.G. Laso, F. Falcone, J. Bonache, J. García-García, F. Martín, J.A. Marcotegui, R. Marques and M. Sorolla, "Forward and backward leaky wave radiation in split-ring-resonator-based metamaterials," *IET Microw. Antennas Propag.,* vol. 1, no. 1, pp. 65–68, Feb. 2007.

[9] M. A. Antoniades and G.V. Eleftheriades, "A CPS leaky-wave antenna with reduced beam squinting using NRI-TL metamaterials," *IEEE Trans. Antennas Propag*., vol. 56, no. 3, pp. 708–721, March 2008.

[10] S. Paulotto, P. Baccarelli, F. Frezza and D.R. Jackson, "Full-wave modal dispersion analysis and broadside optimization for a class of microstrip CRLH leaky-wave antennas," *IEEE Trans. Microw. Theory Tech.,* vol. 56, no. 12, pp. 2826–2837, Dec. 2008.

[11] R. Siragusa, E. Perret, P. Lemaitre-Auger, H. Van Nguyen, S. Tedjini and C. Caloz, "A Tapered CRLH Interdigital/Stub Leaky-Wave Antenna with Minimized Side-lobe Levels," *IEEE Antennas and Wireless Propag. Lett.*, vol. 11, pp. 1214–1217, Oct. 2012.

[12] O. Losito, M. Gallo, V. Dimiccoli, D. Barletta and M. Bozzetti, "A tapered design of a CRLH-TL leaky wave antenna," *IEEE Proceedings of the 5th European Conference on Antennas and Propagation (EUCAP),* pp. 357–360, April. 2011.

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

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

[15] F. Martín, F. Falcone, J. Bonache, R. Marqués and M. Sorolla, "Split ring resonator-based left handed coplanar waveguide," *Appl. Phys. Lett.*, vol. 83, pp. 4652–4654, Dec. 2003.

[16] F. Aznar, J. Bonache and F. Martin, "Improved circuit model for left-handed lines loaded with split ring resonators", *Appl. Phys. Lett.*, vol. 92, no. 4, paper 043512, Feb. 2008.

[17] A. Sanada, C. Caloz, and T. Itoh, "Characteristics of the composite right/left-handed transmission lines," *IEEE Microwave Wireless Comp. Lett.*, vol. 14, pp. 68–70, Feb. 2004.

[18] J. Selga, M. Gil, F. Aznar, J. Bonache and F. Martín, "Composite right/left-handed coplanar waveguides loaded with split ring resonators and their application to high-pass filters," *IET Microw. Antennas Propag.*, vol. 4, no. 7, pp. 822–827, July 2010.

[19] F. Aznar, M. Gil, J. Bonache, L. Jelinek, J. D. Baena, R. Marqués and F. Martín, "Characterization of miniaturized metamaterial resonators coupled to planar transmission lines through parameter extraction", *J. Appl. Phys.,* vol. 104, no. 11, pp. 114501 (1–8), Dec. 2008.