

Complementary Split Ring Resonator Loaded Substrate Integrated Waveguide Leaky Wave Antenna

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How to cite this paper: Yousef, B.M., Attiya, A.M. and Shaalan, A.A. (2019) Complementary Split Ring Resonator Loaded Substrate Integrated Waveguide Leaky Wave Antenna. *Open Journal of Antennas and Propagation*, **7**, 1-11. https://doi.org/10.4236/ojapr.2019.71001

Received: February 28, 2019 **Accepted:** March 26, 2019 **Published:** March 29, 2019

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Abstract

In this paper we present the design of a leaky wave antenna based on Substrate Integrated Waveguide (SIW) loaded by Complementary Split Ring resonator (CSRR). The proposed antenna is designed for 5G application with a center frequency around 28 GHz. The antenna is implemented on Roger RT/Duriod 5880. The loading CSRRs are designed to resonate at 28 GHz. The design is simulated by using both High-Frequency Simulation Software (HFSS) and Computer Simulation Technology (CST) for verification. Experimental measurements are also presented.

Keywords

Leaky Wave Antennas, MM-Wave, 5G, SIW Antennas

1. Introduction

Leaky Wave Antennas (LWAs) can be described as a fast wave guiding structure with a complex propagation constant. LWAs can be classified into two main categories [1] [2] [3]; uniform guided wave structures [4] [5], and periodic guided wave structures [6] [7] [8] [9]. The uniform leaky-wave antenna can be scanned by varying frequency and its scanning range is extended from broadside to end fire, with the beam closer to end fire at higher frequencies [3]. Different antenna configurations can be used for leaky wave applications, substrate integrated waveguides (SIW) are quite suitable for these applications [10] [11]. On the other hand, in periodic leaky wave antennas, the beam swings up from backward direction towards the broadside and then through the broadside to

forward direction [3].

In [12], an LWA based on a periodic set of slots printed on a dielectric waveguide is introduced to obtain low side lope level (SLL). Different SIW leaky-wave antennas are proposed in [13]. The SIW long slot leaky-wave antenna is an example of SIW leaky wave antennas. In [13], a straight slot etched on the broadside of a meandering SIW exhibits SLL which can be acquired by tapering the aperture distribution of the centered slot. As the slot is designed to be symmetrical, the SIW straight long slot LWA can enhance cross-polarization level up to 30 dB. To decrease the cross polarization, a long slot is printed on the SIW centerline, and a sinusoidal ridge is applied to create a controllable asymmetric electric field around the long slot [11].

In this paper, a periodic LWA structure based on complementary split ring resonators (CSRRs) etched on the top of an SIW is proposed. Thus, an SIW structure with an equivalent effective negative constituent meta-surface can be obtained. Tapering line sections are designed to match the designed leaky wave structure to the feeding microstrip line. On the other hand, mm-wave leaky wave antennas are good candidates for different applications like radars [14], real time spectrum analyzers [15] and 5G mobile communications [16] [17]. In addition SIW is a good technique for implementing these mm-wave leaky wave antennas. The proposed CSRR-LWA can be used to steer the main beam from backward to forward direction through broadside at different frequencies. The effective width of SIW, diameter of via holes and rings are chosen according to operating frequency range. The proposed leaky-wave antenna in this paper has a wide bandwidth from 21 to 33 GHz with frequency steering from -60° to 60° . The use of CSRR introduces a large bandwidth and expands the range of frequency scanning. The gain of the proposed antenna is improved by approximately 2 dB compared with previously published results in [6] [9]. The size of the designed antenna is also reduced compared with these designs. The complete antenna structure is simulated by using both HFSS and CST for verification. In addition experimental measurements are presented, too.

In Sec. 2, the equivalent circuit model of a unit cell is discussed. The design simulation and experimental results of the proposed SIW leaky wave antenna are discussed in Sec. 3. Finally, Sec. 4 presents the concluding remarks.

2. Design of the Unit Cell

To introduce the wave leakage in the proposed SIW leaky wave antenna, periodic perturbations are added to the SIW. The proposed perturbation is CSRR as shown in **Figure 1**. The role of each perturbation is mainly to radiate a fraction of the guided wave. To introduce the required radiation, this CSRR should be nearly resonant at the proposed frequency of operation. In the present case, the required frequency is around 28 GHz.

In microstrip technology, a broadband negative μ media can be fabricated by using periodically etching series gaps on a microstrip transmission line [18]-[23]. The analysis of split ring resonator (SRR) and CSRR and their electromagnetic properties are discussed in [24]. In this analysis, SRRs and CSRRs behave as an equivalent LC resonator is excited by an external magnetic flux and electric flux respectively. Figure 1 shows the intrinsic equivalent circuit model of the CSRR. It is represented as dual of the SRR model. This equivalent circuit consists of a capacitance C_c of a disk of radius $r_o - c/2$ surrounded by a ground plane, where r_o is the average radius of ring and c is the width of the slot ring, and a parallel combination of the two inductances $L_o/2$ connecting the inner disk to the ground.

An analytical approximate expression for C_c , is presented in [24]. The final expression is

$$C_{c} = \frac{\pi^{3} \varepsilon_{o}}{c^{2}} \int_{0}^{\infty} dk \frac{\left[b\mathcal{B}(kb) - a\mathcal{B}(ka) \right]^{2}}{k^{2}} \left[\frac{1}{2} \left(1 + \frac{\varepsilon_{o}}{\varepsilon_{o}} \tanh\left(kh\right)}{1 + \frac{\varepsilon_{o}}{\varepsilon} \tanh\left(kh\right)} \right) \right]$$
(1)

where $a = r_o - c/2$ and $b = r_o - c/2$ are the geometrical parameters shown in Figure 1 and the function \mathcal{B} is defined as:

$$\mathcal{B}(x) = S_0(x)J_1(x) - S_1(x)J_0(x)$$
(2)

 S_n and J_n being the n^{th} order of Struve and Bessel functions respectively.

Each inductance of the two parallel can be considered as $L_o/2$ where h = 0.508mm and L_{pul} is the per unit length inductance of the CPW connecting the inner disk to the transmission line [25]. The total CSRR inductance can be calculated as $L_c = L_o/4$. After calculating the total CSRR capacitance C_c and inductance L_c , the resonant frequency can be obtained from Equation (3) as

$$f_{o,CSRR} = \frac{1}{2\pi\sqrt{l_c c_c}} \tag{3}$$

Using Equations (1)-(3) the initial values for a specific resonant frequency of a, b and r_o can be obtained. The proposed unit cell is designed to operate at frequency 28 GHz. The substrate is Roger/RT Duroid 5880 (tm) with a permittivity of $\varepsilon_r = 2.2$ and a substrate thickness h = 0.508mm. According to the previous steps and resonance frequency of 28 GHz, the initial values of a, b and r_o are obtained as follows 1.2 mm, 1.5 mm and 1.35 mm respectively.

These initial values are used to simulate a unit cell inserted inside periodic boundary conditions and terminated by input and output wave ports. The unit cell structure is shown in **Figure 2**. **Figure 3** shows the scattering parameter of unit cell over the frequency range from 21 to 33 GHz. The complex propagation constant can be recovered from these transmission and reflection coefficients (S-Parameters) according to theses Equations (4-a) and (4-b) [26] [27]:

$$\beta = \operatorname{Re}\left[\cos^{-1}\left(\frac{1 - S_{11}S_{22} + S_{12}S_{21}}{2S_{21}}\right)\right]$$
(4-a)

$$\alpha = \operatorname{Im}\left[\cos^{-1}\left(\frac{1 - S_{11}S_{22} + S_{12}S_{21}}{2S_{21}}\right)\right]$$
(4-b)

The results of dispersion diagram for a unit cell are shown in **Figure 4**; **Figure 4(a)** shows the real part of complex propagation constant (β), while **Figure 4(b)** shows the imaginary part of complex propagation constant (the attenuation constant *a*) normalized to the free space propagation constant k_0 .



Figure 1. The intrinsic equivalent circuit model of the CSRR.



Figure 2. The unit cell structure.



Figure 3. S-Parameters of the unit cell.



Figure 4. The results of dispersion diagram for unit-cell, (a) β/K_0 and (b) α/K_0 .

3. Complete Antenna Design

The proposed antenna is designed based on substrate integrated wave guide (SIW) consisting of two horizontal metal plates, the ground plane and the transmission line plate with etching CSRR, printed on dielectric substrate. The two metal plates are connected together by using metal vias in both sides of the substrate. These vias act as side walls of the wave guide as shown in **Figure 5**.

The designed leaky wave antenna consists of ten unit-cells. The separation between the adjacent unit-cells is 0.2 mm. The overall antenna size is 6.6×41.4 mm², which is printed on grounded Roger/RT Duroid 5880 (tm) substrate. To match the designed antenna to 50 Ω feed line, the two ends of the designed antenna are terminated by tapering matching sections. Figure 6 shows a parametric study of outer radius of the CSRR*b*. The outer radius of 1.7 mm is the optimum one for the required application around 28 GHz. In Figure 7, a parametric study of the ring width *c* is introduced and 0.285 mm is chosen to be the accepted one. The gap between the two rings is assumed to be equal the ring width. Figure 8 shows the fabricated antenna and its measurements. Figure 9 shows a comparison between the simulated and measure *S* parameters of the designed leaky wave antennas. Good agreements between the two results are obtained. These reflection and transmission coefficients are used to determine the normalized radiated power as follows:

$$P_{rad} / P_{in} = 1 - \left| S_{11} \right|^2 - \left| S_{21} \right|^2$$
(3)

Figure 10 shows a comparison between the simulated and measured normalized radiated power as a function of the operating frequency. It can be noted that the maximum radiated power occurs at around 28 GHz, which it is expected from the results of complex propagation constant.

Figure 11 shows the radiation pattern along E-plane at the designed frequency of 28 GHz. The maximum radiation pattern can be obtained at more than one frequency. Frequency scanning from angle -60° to 60° is achieved around the resonant frequency as shown in **Figure 12**.

The radiation efficiency of this antenna is shown in Figure 13 which gives good efficiency.



Figure 5. Leaky wave antenna of a SIW loaded by periodic CSRR.



Figure 6. Parametric study of outer radius of the CSRR.



Figure 7. Parametric study of the ring width.



Figure 8. Fabricated Antenna.



Figure 9. (a) Comparison between the simulated and measured S11 of the designed leaky wave antenna; (b) Comparison between the simulated and measured S21 of the designed leaky wave.



Figure 10. Comparison between the simulated and measured normalized radiated power of the designed leaky wave.



Figure 11. Radiationpattern at frequency 28 GHz.



Figure 12. Frequency scanning radiation pattern.



Figure 13. The radiation efficiency of the CSRR leaky wave antenna.

4. Conclusion

In this paper the design of a leaky wave antenna based in CSRR loaded SIW is presented. The proposed antenna is designed at a frequency 28 GHz. The ob-

tained antenna can be used in the frequency range from 21 to 33 GHz. Frequency scanning is also obtained. This property makes the proposed antenna be suitable for scanning radar application, in addition to the proposed application of 5G communication. Tapering sections are used to terminate the two ends of the proposed antenna to be matched with the feeding network. Good matching is obtained by using this technique. The impedance matching, radiation pattern and radiation efficiency are studied for this antenna.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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