Ku-Band Circularly Polarized Leaky-Wave Antenna based on Lateral Sparse Substrate Integrated Waveguide for Satellite Communication

Ming Yang
School of Information and Electronics
Beijing Institute of Technology
Beijing, China
Email: yangming_6@163.com

Cheng Jin
School of Information and Electronics
Beijing Institute of Technology
Beijing, China
Email: jincheng@bit.edu.cn

Meiguo Gao
School of Information and Electronics
Beijing Institute of Technology
Beijing, China
Email: gaomeiguo@bit.edu.cn

***Abstract*—This paper presents a user terminal leaky-wave antenna (LWA) for satellite communication system in Ku-band. The motivation is to propose a low-profile broadband high-gain receiving antenna with beam-scanning and circular polarization features. The antenna is based on a lateral sparse substrate integrated waveguide, which is constructed by a microstrip line shorted with two rows of sparse and abundant periodic metallic via-holes on both sides with periodic transverse slots etched on the upper side. To achieve good circularly polarized radiation and compact configuration, non-uniform SIW width configuration is used to realize effective phase shift over the relative broadband. Measured results show that the antenna presents experimentally expected broadband matched impedance with return loss $|S_{11}| > 10$ dB from 15.4 GHz to 19 GHz. The measured radiation pattern exhibits continuous frequency-scanning from 35^o at 15.5 GHz to 47^o at 18 GHz according to the broadside with maximum gain of 12.3 dBic. The measured axial ratio is within 3 dB from 15.9 GHz to 17.2 GHz. Measured results are in good agreement with predicted ones, and it is demonstrated that the proposed structure is a simple and compact candidate of high performance circularly-polarized antenna for satellite communications. Also the beam scanning capability of proposed antenna could find potential applications in inter-satellite communications.**

I. Introduction

Satellite technology is developing fast, and the applications for satellite technology are increasing all the time. Because of satellites increased use, number and size, congestion has become serious issue in the lower frequency bands. New technologies are being investigated so that higher bands can be used. Ku-band satellite antenna design is a challenging and circular polarization (CP) antennas are widely utilized to solve problems of polarization mismatch and multi-path interference in practical radar, satellite and various wireless communication systems [1], [2]. Low-profile CP antennas have been studied very extensively by numerous researchers in recent years and has become a widely applied technique in planar antenna design.

Leaky-wave antennas (LWAs) have been proposed with broadband, low-profile and high-gain properties. Menzel demonstrated a wider bandwidth phenomenon in microstrip leaky-wave antennas compared to resonator antennas [3], and Oliner further derived the leaky-wave theory thoroughly [4]. Several studies on leaky-wave antennas have been reported for the satellite communication systems [5], [6]. Most of these antennas have been designed to realize linearly polarized radiation.

A broadband beam-scanning antenna working in Ku band is designed based on the proposed LS-SIW in this paper. The design offers quite a few advantages. Firstly, the antenna is more compact, which is nearly half of the CP LWA with two-component slot pair CP radiator. Secondly, the matching network is much simpler. Thirdly, the phase velocity of leaky mode and the leakage rate can be controlled. Finally, CP LWA is realized based on the proposed low-profile LS-SIW structure.

II. Design Procedures

Fig. 1 shows the evolution process of the proposed LS-SIW LWA. Firstly, a periodically loaded broadband LWA with wide angle beam-scanning property is designed based on the SIW as shown in Fig. 1 (a) and (b). Periodic transverse slots with width of g are etched in the upper side of the waveguide to realize the linearly polarized LWA with E-field in xz-plane. Next, by tuning the space between the metallic via-holes of one side of the designed SIW LWA, a LS-SIW with a sparse row of metallic via-holes separated at a distance R_1 is obtained as shown in Fig. 1 (c) and (d) [7]. And then, a lateral wave with E-field in yz-plane radiates from the open-end of the truncated substrate. Finally, two more metallic inductive via-holes with pitch of R are introduced in the center of the LS-SIW to tune the phase difference of the radiation orthogonal waves as shown in Fig. 1 (f). Waves of orthogonal modes with 90^o phase difference are excited finally and a CP LWA is achieved.

$$k = \beta - j\alpha. \tag{1}$$

The amount of radiated power directly depends on the leakage rate α and the LWA length L_A, and the radiation efficiency is determined as [7]

$$\eta = 1 - e^{-2\alpha L_A} = 1 - e^{-4\pi \frac{\alpha}{k_0} \frac{L_A}{\lambda_0}} \tag{2}$$

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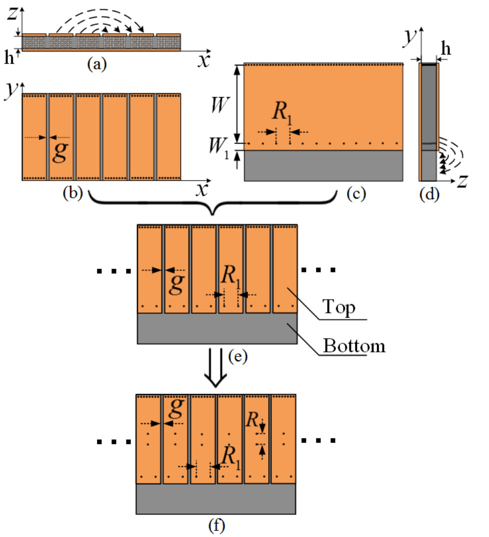


Fig. 1. The process of the evolution of the frequency beam-scanning CP LWA based on LS-SIW. (a) Side view of the SIW with periodic transverse slots. (b) Top view of the SIW with periodic transverse slots. (c) Top view of the LS-SIW. (d) Side view of the LS-SIW. (e) Combined LS-SIW with periodic transverse slots. (f) Combined LS-SIW with periodic transverse slots and middle via-holes.

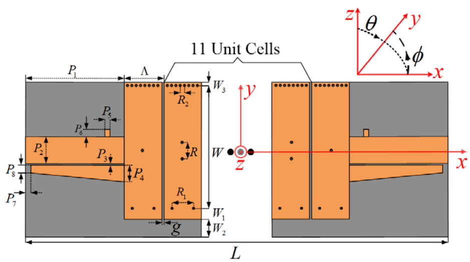


Fig. 2. Layout of the proposed structure. Substrate is Rogers RT/duroid5880: $\epsilon_r = 2.2$, $tan\delta = 0.0011$, thickness $h = 1.57$ mm. The diameter of the via-hole $d = 0.3$. $L = 124$, $W = 11.4$, $W_1 = 2.3$, $W_2 = 10$, $W_3 = 0.3$, $g = 0.16$. $P_1 = 9.5$, $P_2 = 2.6$, $P_3 = 0.127$, $P_4 = 1.6$, $P_5 = 0.5$, $P_6 = 0.68$, $P_7 = 0.5$, $P_8 = 0.8$. $R = 1$, $R_1 = 2.2$, $R_2 = 0.5$, and $\Lambda = 4.4$. All units are in mm.

The discussion of the two kinds of LWAs gives a potential approach to CP antenna design. Fig. 2 shows the configuration of the proposed CP LWA, which is based on the LS-SIW. An SIW with two rows of periodic metallic via-holes is designed firstly. The diameter of the via-holes d is 0.3 mm, and the spacing between adjacent via-holes R_2 is 0.5 mm. To get the radiation with E-field in x-direction, periodic transverse slots with width of $g = 0.16$ mm are etched in the upper side of the waveguide. To get the radiation with E-field in y-direction, one row of periodic metallic via-holes of the SIW are separated with a distance of $R_1 = 2.2$ mm and microstrip lateral edge with width of $W_1 = 2.3$ mm is designed. The radiation angle of waves based on the etched periodic transverse slots is upward. In order to get radiation from the periodic metallic via-holes also toward upside, the extended dielectric filled ground plane with $W_2 = 10$ mm is added.

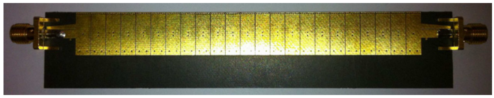


Fig. 3. Prototype of the fabricated antenna.

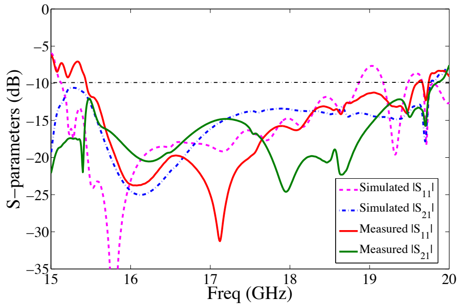


Fig. 4. Simulated and measured frequency responses of the LS-SIW CP LWA.

III. Experiment and Measurement

Based on the discussion of the proposed LS-SIW with periodic transverse slots, it is noted that proposed structure will contribute a good CP radiation behavior. To demonstrate this concept, a CP LWA is designed, simulated using the numerical full-wave simulation tool, and measured. Fig. 3 shows the fabricated CP LWA with the same dimensions indicated in Fig. 2. The substrate Rogers RT5880 with a dielectric constant $\epsilon_r = 2.2$, thickness of 1.57 mm and loss tangent of $tan\delta = 0.0011$ is used to enhance the fringing fields and hence to get higher radiation efficiency.

The simulated and measured transmission and reflection coefficients of the designed CP LWA are shown in Fig. 4. It is shown that the typical radiation occurs from 15.4 GHz to 19 GHz with both return loss and insertion loss larger than 10 dB, and the bandwidth is 3.6 GHz. The measured scattering parameters have been slightly shifted due to the material and manufacturing tolerances, as well as the SMA-connector loss and mismatch with the circuit.

Fig. 5 shows the frequency dependence of the simulated and measured peak gain, and simulated radiation efficiency in the corresponding radiation region. The measured gain is about 12 dBic from 15.5 GHz to 16.5 GHz. The simulated

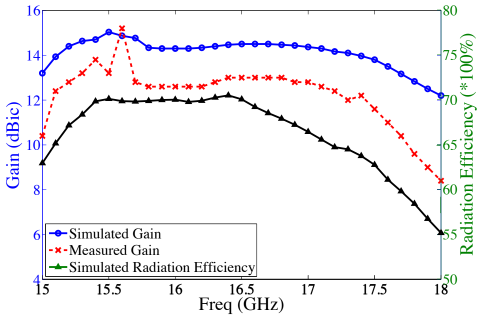


Fig. 5. Simulated and measured gain and simulated radiation efficiency of the LS-SIW CP LWA at 16 GHz.

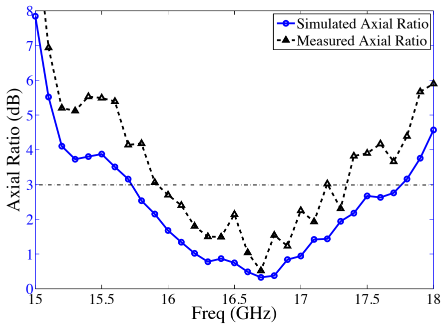


Fig. 6. Simulated frequency dependent axial ratio of the LS-SIW CP LWA at 16 GHz.

radiation efficiency is around 72% from 15.5 GHz to 17.5 GHz, and it also reduces as the frequency goes higher. The lower radiation efficiency at higher frequency should be the reason why the gain is smaller at the relative frequency. Fig. 6 shows the simulated and measured frequency dependent axial ratio. The minimum measured axial ratio is 0.92 dB, and the minimum simulated axial ratio is 0.68 dB. The measured 3 dB axial ratio bandwidth is 1.3 GHz from 15.9 GHz to 17.2 GHz.

The radiation patterns are simulated and measured to confirm the radiation behavior of the proposed CP LWA. Fig. 7 shows the simulated 3D far-field radiation pattern at 16 GHz. It is shown that a typical fan beam is achieved in the yz-plane with main lobe radiating at direction of $\theta = -17^o$, and high directivity is in the xz-plane with direction of $\theta = 36^o$, where θ is defined as shown in Fig. 1 (g). Fig. 8 shows the measured radiation patterns comparing with the simulated ones at different frequencies. Both the right handed circularly polarized (RHCP) and left handed circularly polarized (LHCP) radiation patterns are given. The measured radiation patterns in xz-plane show that the antenna radiates in the direction with

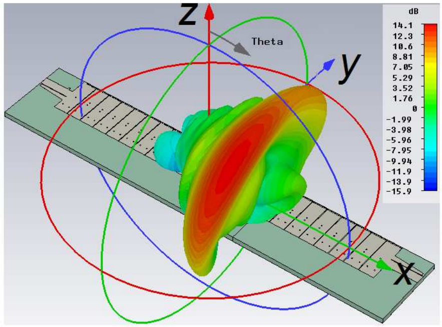


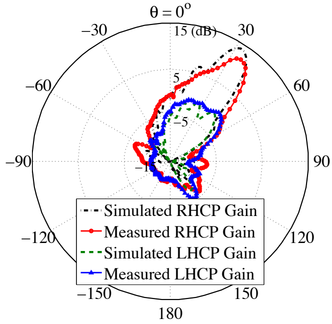
Fig. 7. Simulated 3D radiation pattern of the LS-SIW CP LWA at 16 GHz.

θ increased from 36^o, 38^o to 42^o, corresponding to 16 GHz, 16.5 GHz, and 17 GHz, respectively. However, the main lobe of the measured radiation pattern in the yz-plane is slightly deceased.

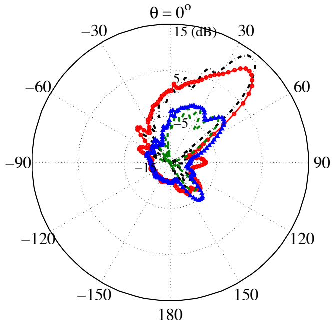
The frequency dependence of simulated and measured beam directions are shown in Fig.9. The beam directions are simulated in the reasonable leaky-wave region from 15.5 to 18 GHz. The simulated results show that the scanning angle scans from $\theta = 28^o$ to $\theta = 59^o$ in the xz-plane, and $\theta = -26^o$ to $\theta = -12^o$ in the yz-plane. It should be pointed out that the angle of beam direction in yz-plane is negative based on the coordinate system as shown in Fig. 1 (g). For simplicity and easier comparison with the beam direction in the xz-plane, the absolute value of the beam direction is shown in the Fig. 9. The beam direction is only measured in xz-plane, because the direction in yz-plane is not sensitive to be experimentally checked. The measured beam direction in xz-plane scans from $\theta = 35^o$ to the $\theta = 47^o$ with frequency increasing from 15.5 GHz to 18 GHz. In addition, since the measurement system is not sensitive enough and because of the fabrication tolerance of the structure, a little angle shift occurs.

IV. Conclusion

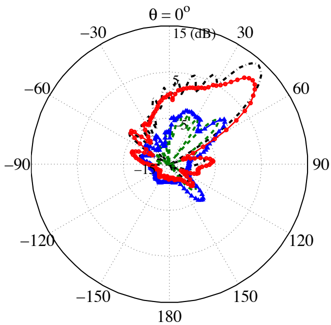
A LS-SIW has been introduced in this paper and a CP radiation property is obtained with broad bandwidth. The proposed structure is expected to contribute a low-profile high-gain broadband LWA with circular polarization and beam-scanning for the satellite communication system. The evolution process and the radiation mechanism of the proposed LS-SIW has been discussed at first. By combining the periodic transverse slots etched in the upper side of the waveguide and a sparse row of metallic via-holes at lateral side of the structure, a LS-SIW is obtained. Orthogonal polarized waves are radiated from the etched slots in the upper side and sparse metallic via-holes in the lateral edge of the structure. Then, a CP LWA has been designed at Ku band for the satellite communication system. Two metallic inductive via-holes were introduced to tune the phase difference of the orthogonal waves to get the best performance of CP radiation. Finally, the designed LWA



(a)



(b)



(c)

Fig. 8. Measured and simulated radiation patterns of the LS-SIW CP antenna. (a) 16 GHz, in xz-plane. (b) 16.5 GHz, in xz-plane ($\phi = 0^o$). (c) 17 GHz, in xz-plane.

has been fabricated, and its radiation characteristics have been demonstrated. Both the simulated and measured results have shown that the proposed LS-SIW is a promising candidate of high performance circularly-polarized antenna for satellite communications. In addition, the beam scanning capability of

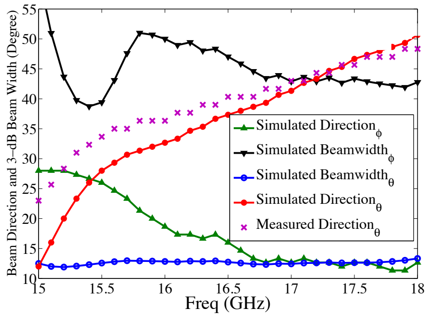


Fig. 9. Simulated and measured radiation characteristics of the LS-SIW CP LWA.

the proposed leaky wave antenna could be exploited in potential application of inter-satellite communications by assigning different frequencies within the available broadband.

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