Substrate Integrated Coaxial Line Based Continuous Transverse Stub (SICL-CTS) Array Antenna for 5G Base Station Applications

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***Abstract*—In this paper, a coaxial continuous transverse stub (CTS) array antenna using substrate integrated coaxial line (SICL) is proposed, to address the antenna design requirements of low loss, high performance, and compact size for millimeter-wave applications. Different from conventional CTS antennas, the proposed SICL-CTS array antenna consists of SICL for transmitting TEM waves and parallel metal plates for radiation. A SICL-CTS array antenna with four elements is designed to verify the concept. From the simulated results, it can be seen that the reflection coefficient is below -10 dB from 19.64 GHz to 24.17 GHz, and the peak gain is about 6.8 dB at 20 GHz with the radiation efficiency of 94.34%. Moreover, the proposed array can maintain a ominidirectional pattern within a broadband performance. Due to the wide bandwidth and ominidirectional coverage ability, the presented SICL-CTS array antenna is a good candidate for 5G base stations.**

***Index Terms*—Continuous transverse stub array antenna, Millimeter-wave antenna, Substrate integrated coaxial line.**

I. INTRODUCTION

Originally invented by W. Milroy in 1990 at Hughes Aircraft Company, the planar continuous transverse stub (CTS) antenna represented a new category of low-cost antenna arrays [1]. The CTS antenna was fed conveniently by a rectangular waveguide and continuous stubs at the top of the substrate were cascaded for radiating power and realizing high radiation efficiency. Due to its its advantages of low return loss, high radiation efficiency, light weight, compact design, and low cost, CTS antenna is widely used in radar and wireless communication. Based on the design concept of a planar CTS antenna, coplanar waveguide (CPW) fed CTS and parallel-plate waveguide fed CTS antenna array were proposed with low profile and unidirectional radiation patterns [2], [3]. The traditional CTS antennas have a narrow bandwidth and typically operate in the microwave bands, while CTS arrays operating in the millimeter-wave (mm-wave) bands are very attractive. However, one of the key challenges to design mm-wave CTS antennas is finding reliable and suitable processing and assembly techniques. Recently, CTS array antenna that incorporated with substrate integrated waveguide (SIW) technology attracted great interest [3]–[6]. SIW is a fully shielded transmission line that can be used for mm-wave communications. In particular, SIW-CTS array antenna can obtain a good beam-scanning ability by some simple methods. However, SIW has its inherent shortcomings, such as narrow bandwidth and large size, etc. Therefore, it is important to design a planar, light-weight and broadband CTS antenna.

Coaxial CTS antennas offer more advantages than the planar ones, such as omnidirectional radiation pattern in the plane which is perpendicular to the transmission line. Magdy F. Iskander made good progress in this type of antenna, such as the multi-band coaxial CTS [7]–[11], which provided omnidirectional radiation patterns and relatively insensitivity to manufacturing tolerances. In order to further reduce the complexity of the antenna, triple-band operation was realized by using only two-element CTS antenna for satellite applications [12]. In addition, since the impedance matching of the coaxial CTS antenna can be tuned by adjusting the diameter of the coaxial line, the radiation efficiency can be greatly improved by loading the monopole at the end [13], [14].

The above coaxial CTS antennas had a relatively high profile and were not suitable for integration with planar circuits. To solve this problem, we use the substrate integrated coaxial line (SICL) instead of coaxial cables as the transmission line. SICL is one kind of planar transmission lines, which consists of a printed coaxial structure and then shielded by metallic vias [15]. Due to its unique structure, it presents a single-mode operation over a wide frequency band.

It can support the propagation of transverse electromagnetic (TEM) waves over a wide frequency band by adjusting the distance between the two rows of vias. It is shielded and not-dispersive, and can be produced by low-cost processing technology, such as the LTCC or PCB technology. Considerable studies of SICL technology have been reported in recent years, which realized compact-size structure and exhibited broad bandwidth making it very suitable for mm-wave applications [16], [17].

In this paper, a coaxial CTS array antenna based on the

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SICL technology is proposed for 5G base station applications. Using SICL as the transmission line, the proposed antenna can be achieved by stacking several substrates together. Thus the SICL-CTS array antenna has a very high integration level. From the simulated results, it is shown that the presented array antenna has a wide bandwidth, high efficiency and omnidirectional pattern, which makes it very suitable for mm-wave applications such as the 5G base stations.

II. ARRAY ANTENNA STRUCTURE AND DESIGN

The geometry of the SICL is shown in Fig. 1. As shown, the SICL is designed by a standard multi-layer PCB fabrication process. Two Rogers RT/Duroid 5880 substrates (dielectric constant of 2.2 and loss tangent of 0.0009) with a thickness of 0.787 mm are used to implement the antenna. They are bonded by the bonding film RO3003 (dielectric constant of 3 and loss tangent of 0.038) with a thickness of 0.127 mm. The thickness of the copper layer is 0.018 mm. Because of the frequency independence of the characteristic impedance Z_0 of the TEM mode, the value of Z_0 can be adjusted by changing the ratio between H_1 and W_1 [14]. A four-element SICL-CTS array antenna is designed and investigated. The configuration of the broadband SICL-CTS array antenna is show in Fig. 2. The yellow part in Fig. 2 indicates the metal plates, and the dielectric material filled in the stubs is Teflon (dielectric constant of 2.1). The proposed array antenna contains two parts, which are the TEM wave transmission lines and radiation part. The reactive transverse stub couples a longitudinal, z-directed displacement current across the parallel plate and SICL (see Fig. 2). An induced current is then generated which excites the TEM wave in the z-direction, wherein the electric field is linearly polarized in the y-direction to the stub element. The proposed SICL-CTS antenna is a traveling-wave antenna.

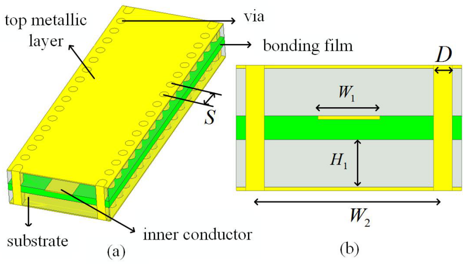

Fig. 1. Structure of SICL. (a) 3-D view. (b) front view. (D=0.3 mm, S=0.45 mm, W_1=0.7 mm, H_1=0.787 mm, and W_2=2 mm)

Antenna performance depends on the size of the continuous transverse stub and SICL. For example, the coupling values from the SICL to the radiating stubs are mainly dependent on the height (H_2), the inner conductor width between radiating elements (W_1), the distance (L_2) of the parallel plate stubs, and the transverse stubs width (W_3), which is used to adjust the coupling capacitance to compensate the inductance generated by the reaction of the stub elements. The array antenna is fed by a SICL transmission line and the height of substrate (H_1) and the width of inner conductor (W_1), and the dielectric constant (ϵ_r) can be adjusted to provide 50 Ω feed impedance.

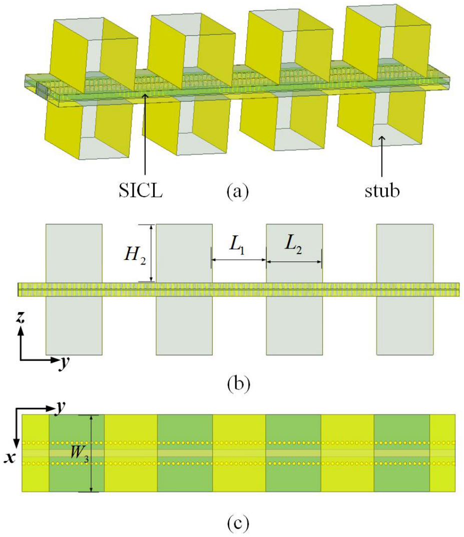

Fig. 2. Structure of SICL-CTS array antenna. (a) 3-D view. (b) front view. (c) top view. (L_1=5.053 mm, L_2=5.053 mm, W_3=7.45 mm, and H_2=6.2064 mm)

The substrate height (H_1) has a large effect on the radiation performance, and the proper choice makes it possible to improve the antenna gain without seriously affecting the incident transmission line mode and increasing the reflection. The distance (L_1) of the adjacent stubs needs to be far from the edge of the stub, which can maintain good impedance matching. Since the axis of the feeder is consistent with the E-plane radiation pattern, L_1 and L_2 are carefully chosen to achieve the desired radiation pattern.

In this paper, L_2 is selected to be a half wavelength in the dielectric material (Teflon) that fills the stub, while L_1 is chosen to meet the distance and phase requirements between stubs. L_1 is set to be a half wavelength in the dielectric material that fills the SICL. In this way, it is possible to feed each stub in phase to increase the radiation gain.

III. PARAMETER STUDY

To further characterize the design, this section studies the effects of some key parameters on reflection coefficient when only one parameter is changed each time while others are fixed with the values shown in Fig. 1 and Fig. 2. Parameters that have production constraints and design requirements such as D, S, W_1, W_2, L_1 and L_2 are not mentioned here.

Fig. 3 shows the reflection coefficients versus frequency for different H_1, H_2 and W_3, respectively. It can be found from Fig. 3(a) that, increasing H_1 results in improved impedance bandwidth. To obtain good impedance matching and easy fabrication, H_1 should be set as 0.787 mm.

As can be seen from Fig. 3(b), the parameter H_2 mainly affects the impedance matching near 21 GHz while has slight effect near 23 GHz. Fig. 3(b) illustrates that as H_2 increases, the operating band shifts downward. It can be considered that increasing the size of the stub is beneficial to adjust the coupling between the stub elements. Hence, the value of H_2 is set to be 6.2064 mm

Fig. 3(c) shows the reflection coefficient in the case when W_3 is varied. It is found that the impedance bandwidth is slightly changed for various W_3. For good impedance matching performances, W_3 is selected as 7.45 mm. Therefore the width (W_3) and height (H_2) are selected to be approximately $0.72\lambda_g$ and $0.6\lambda_g$, respectively.

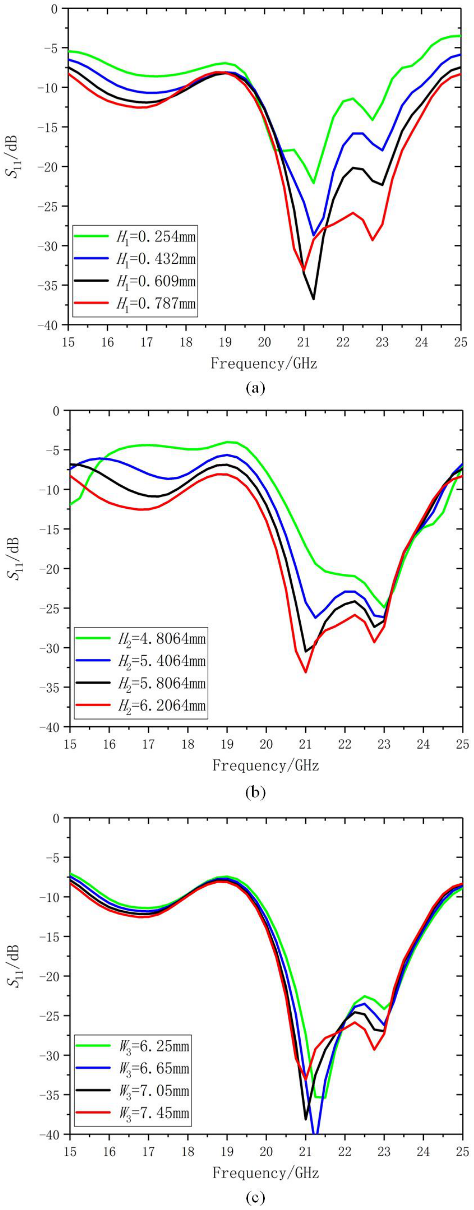

Fig. 3. Reflection coefficients against (a) H_1. (b) H_2. (c) W_3.

IV. SIMULATION RESULTS AND DISCUSSIONS

The array antenna operating at 20 GHz is simulated using Ansys HFSS. Fig. 4 shows the simulated reflection coefficient. It can be seen that the reflection coefficient (S_{11}) is below -10 dB from 19.54 GHz to 24.45 GHz with a 4.91 GHz bandwidth. Its radiated power ratio is calculated from [2]

$$P_{rad} = (1 - P_{ref} - P_{trans}) * 100\% \tag{1}$$

$$P_{ref} = 10^{(\frac{S_{11}(dB)}{10})} \tag{2}$$

$$P_{trans} = 10^{(\frac{S_{21}(dB)}{10})} \tag{3}$$

where P_{rad}, P_{ref}, and P_{trans} are the radiation, reflected, and transmitted powers, respectively. S_{11} and S_{21} are the reflection and insertion losses, respectively. P_{trans} represents the amount of power received at the end of the antenna. By calculating formulas (1)-(3), the array antenna radiates most of the incident power ($> 65\%$) within the passband. As shown in Fig. 4, the radiation efficiency is 94.34% with S_{11}=-14 dB at 20 GHz.

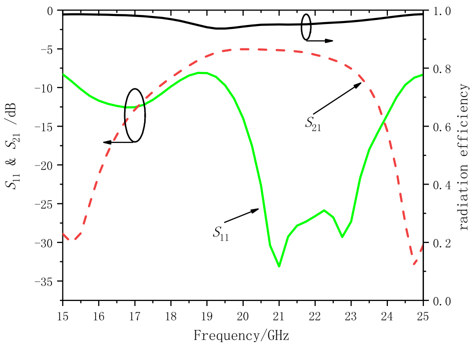

Fig. 4. *S*-parameters and radiation efficiency for coaxial SICL-CTS array.

Fig. 5 shows the simulated *XOZ*- and *YOZ*-plane radiation patterns at 20GHz. It can be seen that the radiation pattern is omnidirectional in horizontal plane and broadside directional in vertical plane, suitable for 5G base station applications. The simulated 3-dB beam width in *YOZ*-plane is 33.44° at 20GHz. At 20 GHz, the gain reaches 6.8 dB. It is found that the gain is not as high as expected. There are several reasons resulting this. On the one hand, the energy between two adjacent stubs is different. On the other hand, in order to obtain good impedance matching, each stubs cannot be fed exactly in the same phase, which may affect the far field gain. VSWR of the array antenna is shown is Fig. 6, and it is seen that the VSWR is smaller than 2 from 19.47 GHz to 24.53 GHz.

V. CONCLUSION

In this paper, a novel SICL-CTS array antenna has been descried, with the advantages of broadband bandwidth, low cost, compact size and omnidirectional radiation. A four-element SICL-CTS array antenna was designed and illustrated within the 15-25 GHz band. Both *S*-parameters and radiation pattern results were examined and illustrated. Specifically, the designed four-element antenna exhibited a well-formed broadside main beam at 20 GHz. Unlike the conventional CTS arrays, it provides a wide bandwidth and high integration level that can be applied to the 5G base stations.

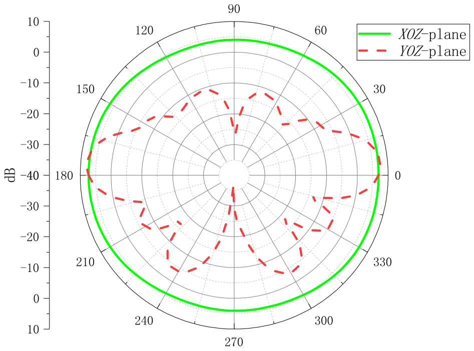

Fig. 5. Radiation pattern at 20GHz for the four-element coaxial SICL-CTS array antenna.

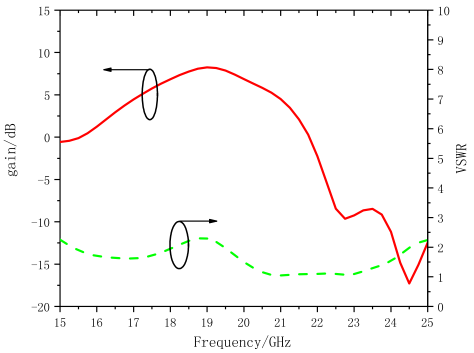

Fig. 6. Gain and VSWR for the four-element coaxial SICL-CTS array antenna.

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