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Millimetre-wave Planar Bruce Array Antenna

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Abstract—A tri-band mm-wave planar Bruce array antenna for fifth generation communications (5G) is presented. The 16-element planar Bruce array antenna is simulated and fabricated on Rogers RT/Duroid 5880 substrate with thickness of 0.254 mm. For a compact and simple structure, the antenna has a highly directional fan-beam radiation pattern at broadside and peak realized gain of 14.0 dBi.

Keywords— meandered structure, antenna array, 5G, mm wave, fan beam radiation pattern

I. INTRODUCTION

In 1927, Edmond Bruce proposed a meander line wire Bruce array antenna (BAA) [1]. The antenna is capable of moderate bandwidth and gain. Although being a very simple model and around for over nine decades, it has not drawn much attention from the research community. In 1996, Nakano et al. combined the performance of Bruce and Franklin array at 12.5 GHz [2] and most recent work on Bruce array was Chen's who designed a slot-type Bruce array antenna for 5-6 GHz band [3].

The global expansion of the wireless industry has increased the demand of low latency wireless communications. In order to develop next generation wireless communications, the scientific community has been working on quality research to accommodate more users and their demand for high data rate for which the introduction of 28 GHz 5G mm-wave frequency band is a strong and suitable candidate to meet the high data rate and low latency challenges. In the quest of achieving high gain and directive radiation patterns, several recent studies have emerged which include microstrip antenna arrays [4], sub-integrated waveguide (SIW) structures [5] and stacked patch arrays [6].

In this paper, the transition from wire Bruce array antenna to planar technology is discussed. The proposed planar Bruce array antenna operates in three frequency bands with optimization focus on 28.0 GHz band that has a directive fan-beam radiation pattern at broadside whereas the other two operating frequency ranges, i.e. 31.13 GHz to 31.99 GHz and 33.85 GHz to 34.85 GHz, have dual beam radiation patterns. A grid array antenna that supports single and dual beams at different frequency bands is presented in [7]. The spacing between the vertical elements play key role in the reduction of mutual coupling between the elements to avoid unwanted radiation in the mm-wave region. The paper is divided into three parts. Section 2 covers the working principle of conventional wire Bruce array antenna and its planar equivalent. The parametric effects, impedance bandwidth, realized gain, radiation patterns and other results of the rear-fed planar geometry are discussed in section 3.

Fig. 1. Twin-Line fed wire Bruce array antenna with 5 radiation elements

II. GEOMETRY OF BRUCE ARRAY ANTENNA

A. Review of wire Bruce Array Antenna

The original Bruce array was created by meandering a long wire for radio ham applications. The horizontal and vertical segments of the structure are approximately quarter wavelength long and fed using a twin line feed structure as shown in Figure 1. The size of arrows indicate the intensity of the currents. The segments at the end of the structure are half of quarter wavelength in length. The vertical segments of the wire operate as radiating elements as the currents add-up in broadside constructively whereas the horizontal segments are connecting elements in which the currents are out of phase therefore cancel the radiation in broadside. Meanwhile, for the inward bent end segments, the current flows in the same direction that would have cross-polarized radiation however the level of radiation remains low due to the small magnitude of current.

B. Planar Bruce Array Antenna Geometry

Figure 2(a) shows the geometry of planar Bruce array antenna with 16 radiating elements. The antenna is designed on the principles of wire Bruce array except for the horizontal and vertical lengths which are modified to $1.46\lambda_g/4$ because at 28.0 GHz, the gap between vertical

Fig. 2. (a) Geometry and (b) Prototype of co-axial fed planar Bruce array antenna with 16 elements

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Fig. 3. $|S_{11}|$ parametric variation of 'h' and 'v' together

elements 'v' with $\lambda_g/4$ becomes so small that mutual coupling occurs between these elements. The antenna is fabricated on $35.0 \times 9.0 \text{ mm}^2$ Rogers RT/Duroid 5880 substrate with thickness of 0.254 mm, relative permittivity of 2.2 and dielectric loss tangent of 0.0009 with copper cladding on both sides. The antenna is fed from the bottom using 50 Ω Southwest SMK 1014-33SF connector.

III. PARAMETRIC ANALYSIS, RESULTS AND DISCUSSION

The effect of varying the lengths 'v' and 'h' simultaneously has been presented in Figure 3. The frequency response tunes down as the lengths increase and behaves otherwise as the lengths of radiating and interconnecting elements decrease. The variation in lengths has no considerable effect on the bandwidth of the antenna however the impedance matching improves as the lengths are decreased from $1.50*\lambda_g/4$ to $1.42*\lambda_g/4$ (2.94 mm to 2.78 mm).

Figure 4 shows the measured and simulated $|S_{11}|$ for the planar Bruce array antenna with 'v' and 'h' element lengths of $1.46*\lambda_g/4$ (2.87 mm) and 50 Ω matched width of 0.76 mm throughout the structure. The antenna is measured using Rhode and Schwarz Vector Network Analyzer (ZVA40). The antenna has $|S_{11}| < -10 \text{ dB}$ between 27.36 GHz to 28.50 GHz, 31.13 GHz to 31.99 GHz and 33.85 GHz to 34.85 GHz.

The total radiated power in all directions is defined as [8]:

Fig. 4. Simulated and measured $|S_{11}|$ of planar Bruce array antenna

Fig. 5. Total and radiation efficiency of planar Bruce array antenna

$$\eta = \frac{P_r}{P_{IN}} \quad (1)$$

where P_r is the radiated power in all directions and P_{IN} is the input power of the antenna. The simulated radiation and total efficiencies of the antenna are shown in Figure 5. The antenna has over 85% total efficiency in the operating frequency bands and has more than 90% efficiency at 28.0 GHz, 31.50 GHz and 34.30 GHz.

Figure 6 shows the realized gain plot of Bruce array antenna. The antenna has peak realized gain of 14.0 dBi at 28.0 GHz and 10.70 dBi at both 31.54 GHz and 34.34 GHz. In Figure 6, the gain drop in the latter two operating bands is observed because of the dual beam patterns.

The radiation pattern plots, simulated in CST Microwave Studio 2018 and measured in anechoic chamber, are presented in Figure 7. Figure 7(a) shows plot of yz-plane of the antenna. The antenna has a highly directive radiation pattern with half power beamwidth (HPBW) of 17° and sidelobe level (SLL) of -18.0 dB, thereby verifying the fan-beam radiation pattern. Dual beam patterns are observed at 31.54 GHz and 34.34 GHz with peak-to-peak angular separation of 34° and 62° , respectively, as shown in Figures 7(a) and 7(b). The antenna is symmetric to the substrate in xz-plane but the asymmetry in the feed position in yz-plane results in pattern tilt observed at 31.54 GHz and 34.34 GHz in Figure 7(b).

Fig. 6. Realized Gain of planar Bruce array antenna

Fig. 7. Simulated and measured xz-plane and yz-plane radiation pattern plots at (a) 28.0 GHz (b) 31.54 GHz (c) 34.34 GHz

Figure 8 shows the surface current distribution plots. As discussed in the wire Bruce array antenna theory in section 2, the vertical elements add in phase to give rise to radiation. The radiating vertical elements, at 28.0 GHz in Figure 8(a), have high distribution of current than the horizontal elements. This explains the highly directive radiation pattern shown in Figure 6. Figures 8(b) and 8(c) show the current distribution at 31.54 GHz and 34.34 GHz, respectively. It can be seen from these figures that the currents are equally distributed in vertical and horizontal elements, of which, the latter behaved as interconnecting elements at 28.0 GHz. Since the antenna is fed from centre, the currents travelling in opposite direction are giving rise to dual beams in either direction as shown in Figures 7(b) and 7(c).

Fig. 8. Surface current distribution (a) 28.0 GHz (b) 31.54 GHz (c) 34.34 GHz

IV. CONCLUSIONS

A compact, tri-band, 16-element planar Bruce array antenna of dimension $35.0 \times 9.0 \times 0.254 \text{ mm}^3$ for 5G, with peak gain of 14.0 dBi at 28.0 GHz, is presented. The analysis of the antenna is performed with rear coaxial feeding arrangement with a full ground plane. The antenna has a broadside fan beam radiation pattern at 28.0 GHz, split beam radiation patterns at 31.50 GHz, with 34° beam separation, and at 34.30 GHz with 62° beam separation.

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