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RESEARCH ARTICLE

28 GHz metal cavity-backed twin arc slot antenna for high efficiency and thermal management

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Abstract
This article presents a metal cavity-backed antenna array with high gain and high radiation efficiency. The proposed antenna can be used for the purpose of thermal management. A 28 GHz linear polarized antenna is implemented on a low cost substrate with an aluminum structure that functions as a heat sink. Each antenna element is connected to integrated circuits with a stripline embedded in the printed circuit board. Each element is fed by a slot-coupled feeding structure and radiated through twin arc slots fabricated in circular metal cavity. The simulated antenna efficiency is over 80% including feeding structures. The simulated and measured radiation patterns show 17.2 dBi of peak gain. From the thermal simulation, temperature reduction can be expected.

KEYWORDS
5G communication, antenna arrays, slot antenna

1 | INTRODUCTION

Wireless communication systems are moving to its fifth generation (5G) for high throughput, huge data traffic and low latency. 5G system developments are being accelerated by the standardization activities of many research groups.[1,2] One of the new 5G radio interfaces uses millimeter wave (mmWave) frequencies, which have greater spectral availability.[3-5] Although many studies have been conducted on mmWave 5G, many technical issues must be overcome, such as propagation characteristics and thermal problems. Much of the research related to 5G systems has reported the results of extensive mmWave propagation measurements. These measurements were conducted around metropolitan areas in the United States and showed that the issues could be solved.[3] However, not much research has been made on thermal issues even though 5G techniques can have related problems. For example, the average efficiency of the power amplifier and digital circuits, which is the primary point of the energy consumption of a device, is still low at mmWave frequencies.[6] The module temperature can increase because of the high power consumption of the amplifier and digital circuits. As a result, the total performance of the radio module can deteriorate.

In this article, a metal cavity-backed antenna is proposed for high efficiency and thermal management, which can be used for both base stations and mobile terminals.[7] Figure 1 illustrates possible mmWave 5G front-end architectures. The transmitter/receiver antenna switch is used to minimize the antenna area for both configurations.[5] In this letter, a single polarized antenna scenario shown in Figure 1 is assumed. A 28 GHz linear polarized antenna is implemented on the FR4 substrate, which is suitable for mass production. Although its material cost is low, a high loss tangent must be overcome. A twin arc slot antenna is proposed to implement an antenna with a metal structure. As the proposed antenna is implemented in the air cavity, both higher gain and radiation efficiency can be attained. The proposed structure also mitigates thermal problems in the module. As thermal via holes on the printed circuit board (PCB) are connected from the integrated circuit (IC) to an aluminum heat sink, the temperature of ICs can be reduced.

This article is organized as follows. Section 2 summarizes the antenna configuration and design considerations. Section 3 presents its fabrication and measurement results. Section 4 provides thermal simulation results, and Section 5 gives the conclusion.

2 | ANTENNA CONFIGURATION AND DESIGN

2.1 | Proposed cavity-backed twin arc slot antenna

The radiation efficiency of a slot antenna is defined by:

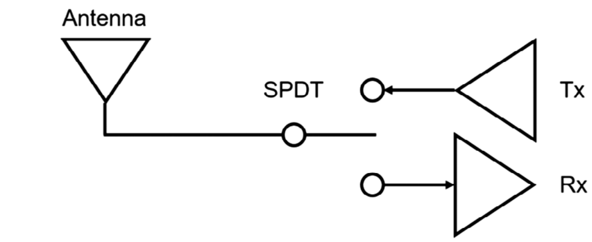

FIGURE 1 Possible mmWave 5G front-end configuration

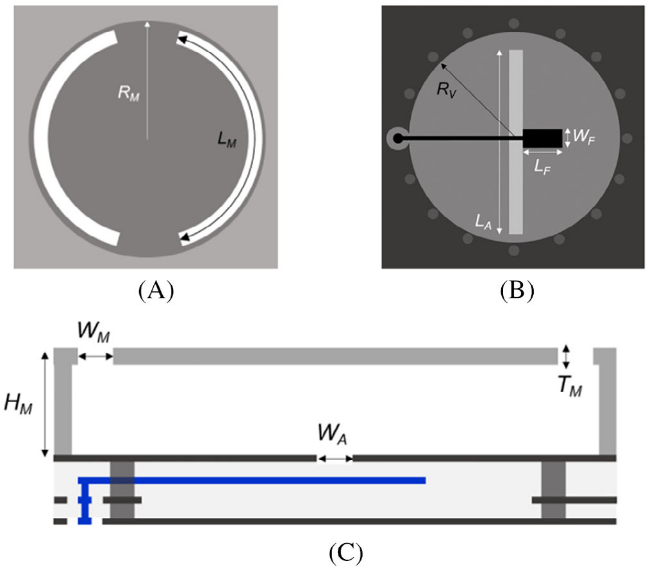

FIGURE 2 Geometry of the proposed antenna element. A, Twin arc slot antenna embedded in the metal cavity. B, Aperture coupled feeding structure in the PCB. C, Side view [Color figure can be viewed at wileyonlinelibrary.com]

$$\eta_{rad} = P_{rad}/(P_{rad} + P_{sw} + P_{back}) \quad (1)$$

where P_{rad} is the power radiated into the whole free-space, P_{sw} is the power of the surface wave, and P_{back} is the power radiated into the back side of the antenna.

In References 8 and 9, the twin arc slot antenna is fed by microstrip lines printed on the top side of the same substrate. As an electrically thin substrate is assumed, the surface wave is ignored. Although a reflector is placed on the back side of the substrate to block the direct back radiation, the parallel plate TEM mode is excited between the ground plane and a reflector. To minimize the TEM power, the optimum radius of a twin arc slot, R, is chosen, $R = 0.293\ \lambda_0$. In this case, the maximum radiation efficiency reaches 99%. However, the radiation efficiency can be deteriorated, if the optimum radius is not used.

Figure 2 illustrates the geometry of the proposed aperture coupled twin arc slot antenna element. As shown in Figure 2B, an aperture-coupled feeding network is printed on a substrate with a relative permittivity ε_r and thickness h. The circular cavity can be excited through the slot with width W_A and length L_A. A twin arc slot is located at the top of the metal cavity, and it has a radius of R_M and a length of L_M. The surface wave, P_{sw}, in Equation (1) can be minimized, as radiators of the proposed antenna is implemented with an aluminum. Moreover, P_{back} can be minimized with the cavity-backed structure. Whereas the radius of the twin arc slot is restricted for maximum efficiency in previous studies, the radius of the proposed antenna can be changed without affecting the radiation efficiency.

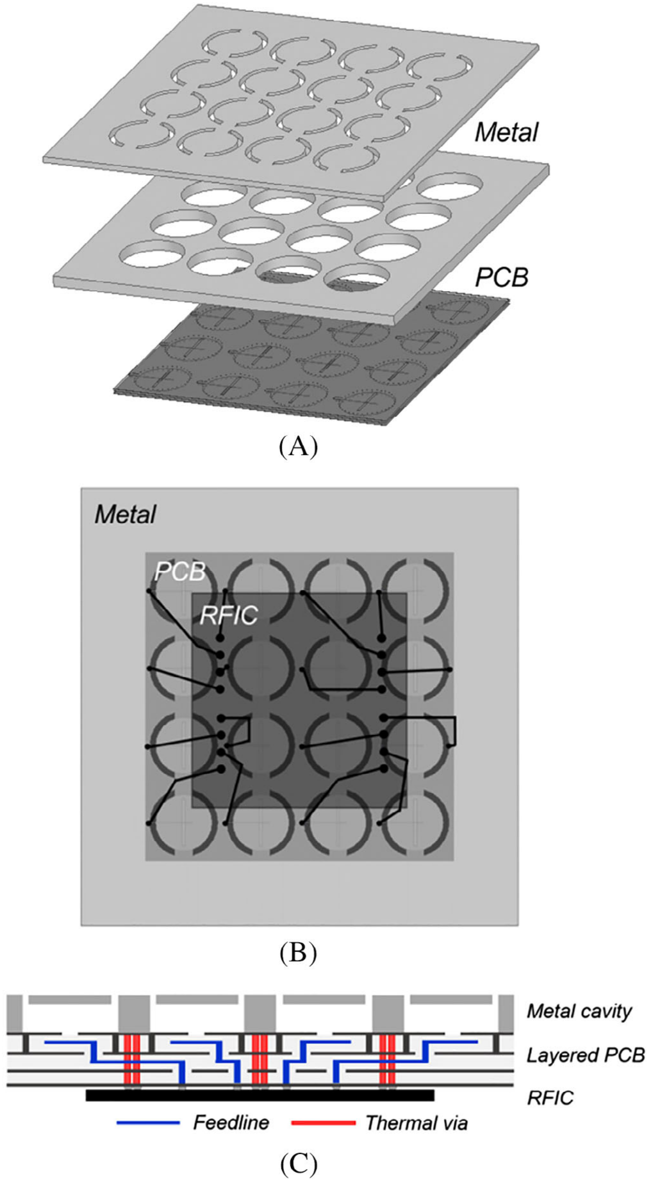

FIGURE 3 Configuration of the proposed metal cavity antenna array. A, An exploded simulation model. B, Top view of the conceptual illustration. C, Layer structure [Color figure can be viewed at wileyonlinelibrary.com]

2.2 | Antenna design

Figure 3 provides the configuration of the proposed metal cavity antenna array. As the illustrated layer structures in Figure 3C, the FR4 PCB consists of stacked layers, each

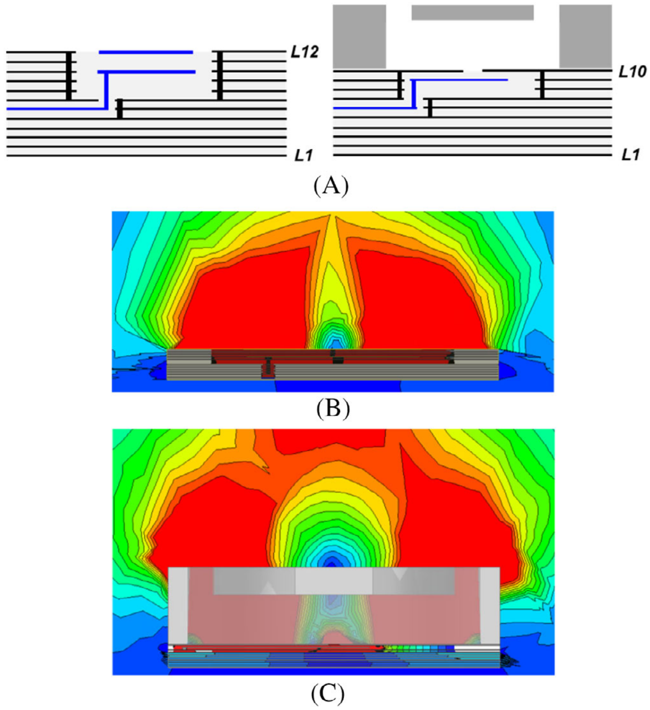

FIGURE 4 A, A Comparison of layer structures. B, The field distribution of a conventional stacked patch antenna. C, The field distribution of a proposed antenna [Color figure can be viewed at wileyonlinelibrary.com]

with a permittivity of 3.8 and a loss tangent of 0.013. The dielectric layers have a thickness of 30 μm, and the metal layers have a thickness of 15 μm. The 28 GHz radio frequency integrated circuits (RFIC) are flip-chip mounted on layer 1. The power line and signal routings for an RFIC are positioned from layers 1 to 5. Each of the RFIC chains is connected to the antenna elements with striplines, which are located from layers 5 to 7. The proposed antenna is implemented with four layers from layers 7 to 10. It is two layers less than a conventional stacked patch antenna, and this reduced number of layers is related to the cost of mass production.[4] In Figure 4A, layer structures of the antennas are compared.

The geometry of the antenna element and its design parameters are shown in Figure 2. An aperture-coupled structure is devised for a feeding network. A clearance is realized by via holes with a radius R_V. The resonant frequency can be mainly adjusted with parameters such as L_M, L_A, and R_M. The feeding structure can be optimized with parameters such as W_F and L_F.[10] A parametric study to satisfy a 28 GHz test band is performed using Ansys HFSS. The finalized design parameters of the antenna are $R_M = 2.65$ mm, $L_M = 15.2$ mm, $R_V = 2.2$ mm, $W_A = 0.2$ mm, $L_A = 3.65$ mm, $W_F = 0.1$ mm, $L_F = 0.75$ mm, $W_M = 0.5$ mm, $H_M = 1.4$ mm, and $T_M = 0.5$ mm. Figure 4B,C presents simulated field distribution of a conventional stacked patch antenna and a proposed antenna. A simulated radiation efficiency of the conventional stacked patch antenna is 61% due to high loss tangent of the FR4 substrate. Whereas a

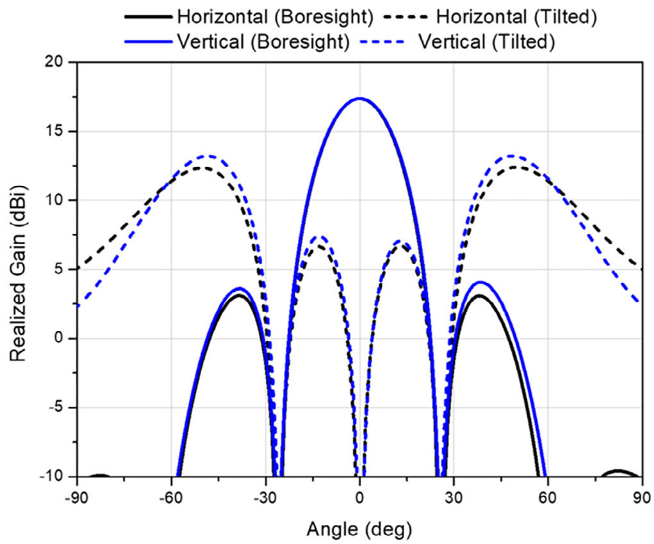

FIGURE 5 Simulated radiation patterns on the horizontal and vertical axis [Color figure can be viewed at wileyonlinelibrary.com]

simulated efficiency of the proposed structure is enhanced to 82% including feeding structures since electric fields are concentrated on the air cavity. Figure 5 illustrates simulated radiation pattern of 4 × 4 proposed antenna array. The simulated results show 5.4 dBi of a single element gain and 17.4 dBi of 16 chain array gain. The horizontal and vertical beam pattern shows similar gain and beam width.

3 | FABRICATION AND MEASUREMENTS

The overall dimension of the presented module is 34 mm × 34 mm × 2.2 mm. An array spacing of 6 mm (0.56λ @ 28 GHz) was selected. In Figure 6, photographs of the fabricated antenna array are shown. Figure 6A presents the top view of the PCB, which has feeding slot structure. A metal cavity is implemented using a computerized numerical control (CNC) process, as shown in Figure 6B. Due to the limitations of the milling machine, the thickness of the metal cavity is restricted to 0.5 mm. The simulated and the measured return loss are presented in Figure 7A. The −10 dB return loss is from 27 to 30 GHz, which satisfies the 5G test band requirements. The mismatch in the results is due to the gap between the metal cavity and the PCB, which can be overcome by a more elaborate assembly.

Two types of 16-chain power dividers are designed to measure the radiation pattern of boresight and 50° tilted beams. A maximum gain and −6 dB coverage of the antenna array can be measured, respectively. Figure 7B presents the simulated and measured radiation patterns of the proposed linear polarized antenna array, which shows well matched results. The measured results show 17.2 dBi of peak gain at 28 GHz and approximately 25° of a half-power beam width. The tilted beam performance shows −6 dB coverage of

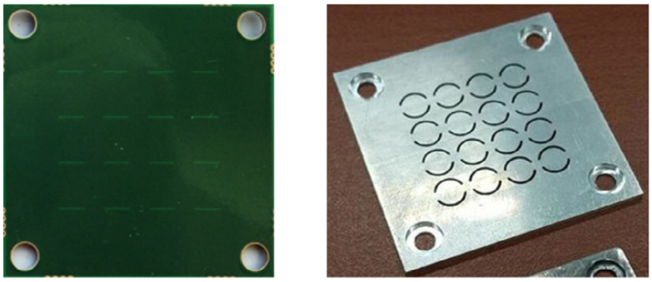
(A) (B)

FIGURE 6 Pictures of the fabricated antenna array. A, Top view of the PCB. B, Fabricated metal structure [Color figure can be viewed at wileyonlinelibrary.com]

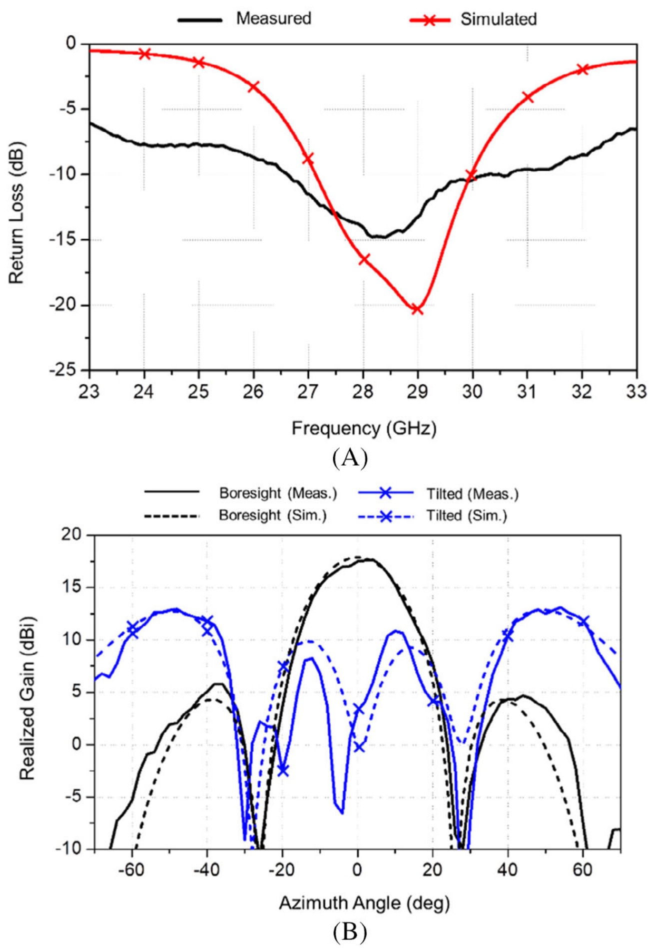

FIGURE 7 Comparison of the measured and simulated results. A, Return loss of a single element. B, Radiation pattern of the 16-chain antenna array [Color figure can be viewed at wileyonlinelibrary.com]

±58°. The efficiency of the proposed antenna array is approximately 78%, which is calculated by comparing simulated and measured results.

4 | THERMAL SIMULATION

To verify the thermal managing effects of the proposed antenna array, the proposed structure is analyzed with the Icepak computational fluid dynamics solver. The structure in Figure 3A is embedded in a simplified mobile phone model for the simulation. Figure 8 represents the simulated IC temperature against a dissipated power in the RFIC. The results of the conventional stacked patch antenna without a heat sink show huge increases in temperature. In comparison, the proposed antenna shows more alleviated results. A temperature drop of approximately 70°C occurs with a dissipated power of 1 W. Because the aluminum structure is contacted to a top layer of the PCB and connected through thermal via holes as illustrated in Figure 3C.

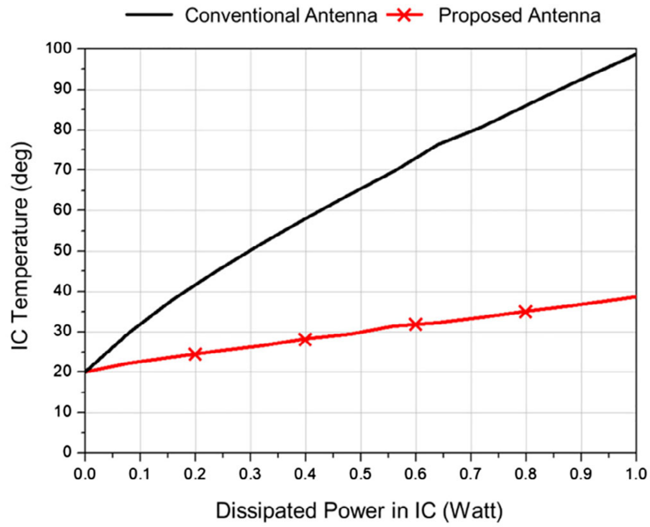

FIGURE 8 IC temperature vs dissipated power in an RFIC [Color figure can be viewed at wileyonlinelibrary.com]

5 | CONCLUSION

A metal cavity-backed twin arc slot antenna array topology, which is expected to be beneficial to the thermal management of an RFIC, is proposed and investigated. The antenna-in-package is simulated with a full structure. The structure is verified with a 16-chain array. The proposed antenna exhibits higher performance than a conventional patch antenna array.

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