Wide-Band and Low-Profile LTCC Conformal Antenna Array With Mixed Feeding Network

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ABSTRACT
As we know, the thickness mainly affects the yield of low-temperature co-fired ceramics (LTCC) device. There is a high risk of cracking for the thick structure in manufacture process especially for the curved one. In this paper, double-layer artificial magnetic conductors (AMCs), mixed feeding network and built-in wide-band laminated waveguide (LWG) with rectangular waveguide (RWG) transition are specially analyzed and designed. These structures all have low-profile characteristics. Thus, they are suitable for conformal LTCC process. The double-layer AMCs are presented to enhance the bandwidth and the gain of a Ka-band patch element. The thin mixed network consisting of microstrip line (MSL) and LWG is used to replace the thick multistage LWG network. An improved LWG-RWG transition integrated in LWG layer is designed to possess wider bandwidth. At last, the low-profile conformal 16 × 16 antenna array is designed, manufactured and tested. The measured results demonstrate that the low-profile conformal 16 × 16 antenna array has a good and stable performance with an enhanced impedance bandwidth of 12.17% and a high gain up to 26.9dB.

INDEX TERMS
Artificial magnetic conductor (AMC), low-profile conformal antenna array.

I. INTRODUCTION
Low-temperature co-fired ceramics (LTCC) processing has been regarded as a promising manufacturing technology for its light weight, compactness, easy integration, and excellent high-frequency performances [1] etc. However, the high permittivity of the LTCC material will entail strong surface waves and the deterioration of the radiation pattern of the antennas. Moreover, a conventional LTCC patch antenna usually has narrow bandwidth and low gain [2]. Therefore, it’s crucial to enhance the gain and the bandwidth of the antennas. In recent years, the artificial magnetic conductor (AMC) structure [3] not only has been proposed as the antenna ground plane to replace the perfect electric conductor (PEC) in terms of enhancing the radiation performances of antenna elements [4]–[8] but also has obvious advantages in low profile antenna designs [9], [10] on account of the in-phase reflection property. In addition, a conformal array antenna has an advantage in fitting to the shape of vehicles such as UVA, automobile and wide-range beam scanning [11]–[13], so it can be applied to a mobile communication system, a radar system and navigation etc.

Several planar or conformal LTCC antenna arrays based on the AMC structure are developed. A 26-layer integrated 4 × 4 planer antenna array is designed and fabricated with a measured bandwidth of 13.96% and a maximum gain of 19.1 dB [14]. In [15], a 29-layer 8 × 8 conformal array is presented, which is simulated by Ansoft HFSS, achieving good performances with a bandwidth of 17.4% and a maximum gain of 23.3dB.

However, the design of the conformal antenna array in millimeter frequency is still a challenge subject, since the intervals between two antenna elements are very small and even a subtle deviation of the size or the position would have large influences on the radiation features of the antenna arrays. In [16], as the curvature radius varies, the reflection factor of the conformal antenna is practically unchanged; however, the gain decreases with decreasing the curvature radius. As a result, the layout of the array and every element parameter must be taken into fully consideration in the design process. Meanwhile, the fabrication tolerance must be limited.

In this paper, it is shown that the thick structure is likely to bring about the cracking in the LTCC manufacture process. For this purpose, low-profile LTCC conformal antenna array with mixed feeding network is proposed. To guarantee
the patch element the enhanced bandwidth and high gain, a novel double-layer AMCs structure is designed. Afterwards, the low-profile conformal 16 × 16 antenna array with the thin mixed network used to replace the thick multistage laminated waveguide (LWG) network is manufactured. Ultimately, the measured results demonstrate that the antenna array has a good and stable performance.

This paper is organized as follows: the double-layer AMCs-based LTCC patch antenna is presented in Section II, where simulation results and comparisons are given. In section III, the design of mixed feeding network with the phase compensated structure is described. In Section IV, a wide-band and compact LWG-to-RWG transition is designed. Finally, a conformal 16 by 16 antenna array which only occupies 19 LTCC layers is shown. The simulated and measured results of the LTCC array are presented and discussed in Section V.

II. DESIGN OF ANTENNA ELEMENT FEEDING

The one-layer AMC structure was designed and discussed in [3], the frequency band, at which the reflection phase is within $-90^\circ$ and $+90^\circ$, defined as the in-phase band of the AMC structure. Because the reflection phase of the AMC structure varies continuously over a wide range, the impedance characteristic and the radiation performance of the patch antenna are significantly affected. One Ka-band antenna element with six LTCC layers and one AMC layer is shown in [7], its impedance bandwidth ($|S_{11}| < -10\text{dB}$) is widened to 26%, and the peak gain is enhanced to about 8.27dB.

In this paper, a novel interlaced double-layer AMCs structure instead of the single layer AMC structure placed under the antenna patch is proposed. Compared to the single-layer AMC, the proposed double-layer AMCs can achieve wider bandwidth and higher gain. Besides, the interlaced double-layer AMCs can decrease the ratio of the area of the surface metal to the total area, which is helpful to avoid possible deformation in the LTCC processing. Thus, it’s easier for the manufacturing process of LTCC. Last but not least, using the novel interlaced double-layer AMCs as the ground of the antenna element, we designed the layer of the element is 5. Compared to the single-layer AMC, the layer of the element is 6 in [7]. As a result, it is conductive to acquiring better antenna performance with thinner substrate.

The AMC cell is simulated using Floquet-port HFSS model [6]. It consists of 4 square metal plates located in two layers, a dielectric substrate ($\varepsilon_r=6$, $\tan\delta=0.002$) and a ground plane without grounded via (see Fig. 1a). As shown in Fig. 1b, the simulated reflection phase varies continuously from nearly $-180^\circ$ to nearly $+180^\circ$ over the frequency ranging from 20 to 50 GHz. Zero-reflection phase is achieved at about 38.5 GHz, and the in-phase band is from 35 to 42 GHz (18.2%).

As shown in Figs. 2a-2b, a Ka-band patch antenna element using AMCs is designed. The edge-fed patch antenna whose dimension is a × b is placed in the center of the structure on the top of the n-layer substrate. The interlaced double-layer AMCs are placed under the antenna patch to replace the PEC ground. The upper and the lower AMC are separately placed in the surface of the layer m and m+1. Furthermore, for reducing the spurious radiation and coupling effects from the
TABLE 1. Bandwidth and gain of antenna element for different m and n.

| m | n | Relative bandwidth | Maximum gain |
|---|---|-------------------|--------------|
| 3 | 2 | 5.4%(36-38GHz)   | 7.8dB(39.8GHz) |
| 4 | 2 | 17.8%(33.3-39.8GHz) | 8.7dB(39GHz) |
| 4 | 3 | 13.5%(37.1-42GHz)  | 7.8dB(41GHz) |
| 5 | 2 | 24.8%(28.26-36GHz) | 8.5dB(36GHz) |
| 5 | 3 | 30.4%(29.8-40.5GHz) | 8.6dB(37GHz) |
| 5 | 4 | 14.8%(35.5-41.2GHz) | 8.34dB(40.5GHz) |
| 6 | 2 | 26.1%(28.1-36.5GHz) | 8.2dB(33.2GHz) |
| 6 | 3 | 31.5%(28.2-38.8GHz) | 8.6dB(35.5GHz) |
| 6 | 4 | 26.9%(29.5-38.7GHz) | 8.5dB(36.5GHz) |
| 6 | 5 | 19.2%(33-40GHz)   | 7.5dB(39.5GHz) |

feedline, the ground of the microstrip line (MSL) is raised to the same height as the upper AMC to reduce the width of the microstrip line. The width of the microstrip feedline is 0.15mm, and the substrate thickness under the feedline is 0.288mm respectively.

The parameter m and n distinctly impact the bandwidth and the gain of the antenna element as shown in Table 1. The bandwidth and the gain of the antenna change as n increases from 3 to 6. The parameter m determines the location of the AMCs and significantly affects the antenna performance when n is given. Ultimately, the structure is optimized to be m=3, n=5, a=1.3 and b=2.1. In this way, the wide-band and low-profile characteristics are obtained.

In Figs. 3a-3b, the simulated results of the antenna using one-layer AMC and normal microstrip patch antenna (H=0.576mm) using PEC ground are compared to the antenna using interlaced double-layer AMCs. It is found that the bandwidth (|S11| <−10dB) of the antenna using interlaced double-layers AMCs (30.4%) is much wider than that of the two reference antennas (26% [7] and 9% [3]). Moreover, the peak gain of the antenna with the novel double-layer AMCs is 8.6dB (f=37GHz), while the other two are 8.27 dB(37.2GHz) [7] and 5.86dB (f=34.8GHz) [3]. It comes to the conclusion that the proposed antenna achieves the highest gain and widest bandwidth with lowest profiles.

III. DESIGN OF 2 × 2 SUB-ARRAY

In Ka-band or above, the substrate losses and conductor losses significantly deteriorate the performance of the antenna array in the microstrip line network. In [14], a 25-layer 2 × 2 sub-array consisting of 4 coaxial probe fed antennas, LWG power divider has a good performance with wide bandwidth and low loss.

However, the thickness of the divider is likely to cause fracture in the process of fabrication.

Therefore, the 19-layer and 4-way mixed network using the LWG and microstrip line feeding structure is presented in Figs. 4a-4c, which achieves low loss and compact structure. LWG is employed to form the main trunk of the feeding network. The vertical coupling probe passes through the LWG to the upper 2 × 2 microstrip line feeding network which is seated in the same layer as the antenna element. With the use of phase-delay line, the two patches fed on the opposite are in-phase.

For comparison, the 2 × 2 sub-array using 19-layer mixed network is simulated and compared to the 2 × 2 sub-array using 25-layer LWG network which is referred in [7], as shown in Fig. 5. It can be found that the impedance bandwidth of the sub-array using mixed network is almost the same as the referenced sub-array. But the peak gain of the proposed sub-array is 13.7dB (achieved at 36.5 GHz), 0.5dB higher than the sub-array using LWG network. In conclusion, although the MSL increases the insertion loss compared to the LWG, there are no upper LWG and vertical probe used in the mixed feeding network. As a result, the mixed network is more appropriate for a conformal LTCC process as its low-profile and wide-band and low-loss characteristics.

IV. DESIGN OF CONFORMAL ARRAY

A. PHASE COMPENSATION STRUCTURE FOR CONFORMAL ARRAY

For cylindrical conformal structure, each element is distributed in different equi-phase surface. The schematic view of the phase between antenna elements is shown in Fig. 7. In far-field observations, the phase difference ϕ between the
element in the normal direction and others is

\[ \varphi = k \times (d_1 n - d_2 n) \]  

\[ d_{2n} = R (1 - \cos(\alpha_n)) \cos \theta \]  

where \( k \) is the propagation constant, \( R \) is the radius of the conformal surface, \( \alpha \) is the angle representing the normal direction of each element, and \( \theta \) is the angle between radiation direction and normal direction.

When \( \theta = 0 \), Equation (1) reduces to

\[ \varphi = k \times R (1 - \cos(\alpha_n)) \]  

It is necessary to design a phase compensation structure to counteract the phase differences \( \varphi \) which are related to the variables \( \alpha_n \).

**B. WIDE-BAND AND COMPACT LWG-TO-RWG TRANSITION**

Owing to the feature of no radiation loss and low insertion loss, LWG is considered as the main trunk of the mixed feeding network. A transition between an LWG and a standard air-filled RWG is required as the interface of the antenna array. As the dielectric constant of LTCC substrate is high, it is usually difficult to achieve the wide-band transition without any extra LTCC layers.
In this section, an improved wide-band and compact LWG-to-RWG transition evolve form the structure in [17] is shown in Figs. 6a-6b. The biconcave shape of the metallic wall is introduced to form two resonators with the changing profile. The dimensions of these two resonators are optimized and the transition 150% wider than the transition using a wall.

Simulated and measured S-parameters of the back-to-back transition are presented in Figs. 8a-8b. The measured results show that the whole frequency band was increased by about 0.8GHz. The difference is mainly caused by the dielectric constant tolerance and the machining error. Besides that, the simulated and measured results of bandwidth and insertion loss are in good consistence. As the measured bandwidth is 34.2-41.1GHz, a return loss is −10dB while the insertion loss is 0.5-0.7dB. It can infer that the relative bandwidth of the transition is more than 18% and the loss is less than 0.35dB.

C. OVERALL STRUCTURE
As shown in Figs. 9a-9b, the 16 × 16 antenna array is designed to conform to the radius R=200mm cylinder surface. The overall structure occupies only 19 LTCC layers.
FIGURE 10. Photographs of a) the fabricated conformal 16 × 16 antenna array and b) the test environment of radiation fields.

because of the use of the mixed feeding network. The antenna array element spacing is 6mm, about 0.7λ0. There is the patch antenna with AMC from the first to sixth layer. Each 2 × 2 antenna array is fed by the microstrip line, and the 2 × 2 array is transited to the LWG network by probe. Each two antenna elements are placed on opposite direction along X axis. Changing the length of bended MSL line (Figs. 4a-4c) and the position of T-type LWG divider (Figs. 6a-6b) can realize the phase compensation. A noteworthy feature is that the marginal antenna element has more phase compensation than the central one. The LWG network is from 7 to 19 layer. A compact LWG-RWG transition integrated with the LWG network whose relative bandwidth is 12.5% [14] avoids occupying extra layer. The input power is fed from the WR-28 rectangular waveguide (RWG) through a feeding aperture on the bottom of the substrate.

V. RESULTS
The conformal 16 × 16 antenna array was fabricated with the LTCC processing, as shown in Figs. 10a-10b. The simulated and measured results of the return loss |S11| and the radiation gains of these two antenna arrays are shown in Figs. 11a-11b. It is found that measured results agree with simulated results well. The simulated case has a slightly wider bandwidth than the measured because of the splice loss and the device loss during the period of measurement. The measured bandwidth (|S11| < −10dB) of the proposed array is 4.2GHz (32.4-36.6GHz), the relative bandwidth can reach 12.17%. In addition, the peak gain of the conformal array can reach 26.9dB at 35GHz, 3dB higher than the 16 × 16 plane array [18].

The measured radiation patterns of the proposed antenna array in E-H plane at the peak gain frequency are shown in Fig. 12. The normalized maximum side lobe is −11.5dB in E-plane and 3.5dB higher than H-plane because the electrical field radiated from the antenna elements located along the camber surface is not in the same direction.

FIGURE 11. Simulated and measured results of the proposed conformal 16 × 16 antenna array: a) |S11| and b) Gain.

FIGURE 12. Measured radiation patterns in the E- and H-plane at the peak gain frequency.

VI. CONCLUSION
In this paper, the edge-fed patch element using the double-layer AMCs structure has been designed to achieve wide band and high gain. An LWG and MSL mixed network with phase compensation has been proposed and used in 16 × 16 conformal antennal structure to reduce the profile dimension. The measured results demonstrate that the low-profile conformal 16 × 16 antenna array has a good performance with the wide band of 12.17% and high gain of 26.9dB.
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