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High-gain cavity backed patch antenna arrays at 140 GHz based on LTCC technology

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Research Paper

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140 GHz; patch antenna array; low temperature co-fired ceramic (LTCC); terahertz; high-gain

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Abstract

In this paper, high-gain cavity backed patch antenna arrays are proposed based on low temperature co-fired ceramic technology at 140 GHz. By introducing a substrate integrated cavity to the patch antenna element, the gain is enhanced by 3.3 dB. Moreover, a rectangular ring is loaded around the patch for better impedance matching and further gain enhancement. The final simulated maximum gain of the proposed antenna element is 9.8 dBi. Based on the proposed high-gain antenna element, a 4×4-element array and an 8×8- element array are presented. The 4×4-element array shows a measured maximum gain of 16.9 dBi with 9.5 GHz bandwidth (136.2–145.7 GHz) and the 8×8-element array shows a measured maximum gain of 21.8 dBi with 9.8 GHz bandwidth(136.7–146.5 GHz), respectively.

Introduction

A 140-GHz band or D-band (110–170 GHz) has been utilized for many applications by the Federal Communications Commission such as radio astronomy, satellite communications, and industry, scientific and medical (ISM) band (around 122 GHz) applications. For future high-rate wireless communications, the D-band is very promising among terahertz frequency bands. So far, several long-range D-band wireless communication systems have been successfully demonstrated [1, 2]. Traditional high-gain Cassegrain antennas are utilized to compensate the high propagation loss in these systems. However, this kind of antenna is bulky and not suitable for highly integrated systems.

In recent years, new types of high-gain antennas with low-profile properties are emerging [3–6] in the D-band driven from high-gain and high-integration requirements. Diffusion bonding technology is using several thin metal layers to construct hollow waveguide and radiating structures which shows high radiation efficiency. A 32×32-element array shows more than a 38 dBi gain with over 60% efficiency and a 64×64-element array shows more than a 43 dBi gain with over 50% efficiency [3]. Substrate integrated waveguide (SIW) uses via holes to construct a dielectric filled waveguide-like transmission line and electromagnetic wave can be confined in SIW by properly choosing the via diameter and spacing [7]. SIW can be easily implemented using low temperature co-fired ceramic (LTCC) technology which can be traced back to 1980s [8]. In the last two decades, antennas based on LTCC technology received much researchers' attention [9–12] promoted by the SIW structure. To date, LTCC technology is more mature than diffusion bonding technology and shows great vitality. However, the relatively high permittivity of LTCC will constrain the energy and reduce antenna gain. Several solutions have been used in literature to solve this problem. Open air cavities have been introduced in array design in [13], resulting in a 1–2 dB gain enhancement. In [14], electromagnetic band-gap (EBG) structure have been used to suppress surface waves yielding a 4-dB gain enhancement. However, EBG structure requires a large area to achieve its performance.

In this paper we firstly proposed a cavity backed patch antenna element using LTCC technology at 140 GHz. Substrate integrated cavity (SIC) is introduced to suppress surface waves and improve the gain performance. Furthermore, a rectangular ring is introduced around the patch for better impedance matching. Based on the high-gain antenna element, a 4×4 element array and an 8×8-element array are presented afterward. Finally, the comparison of simulated and measured results of the two arrays are shown.

Antenna configuration

Figure 1 shows the layer configuration of the proposed LTCC antennas. The antennas are constructed by eight substrate layers and five metal layers. The thicknesses of each substrate layer and metal layer are 0.096 and 0.01 mm, respectively. Ferro A6M is used as the substrate material with a permittivity of 5.9 and a loss tangent of 0.002. Metals are set to silver with a

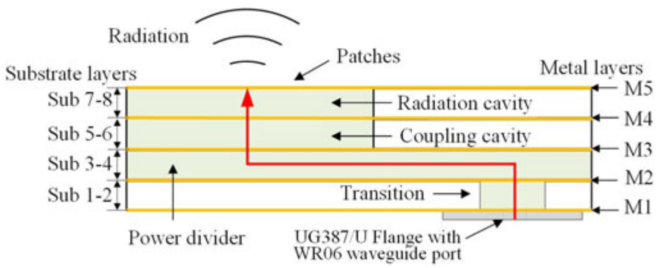

Fig. 1. Layer configuration of the proposed arrays in LTCC.

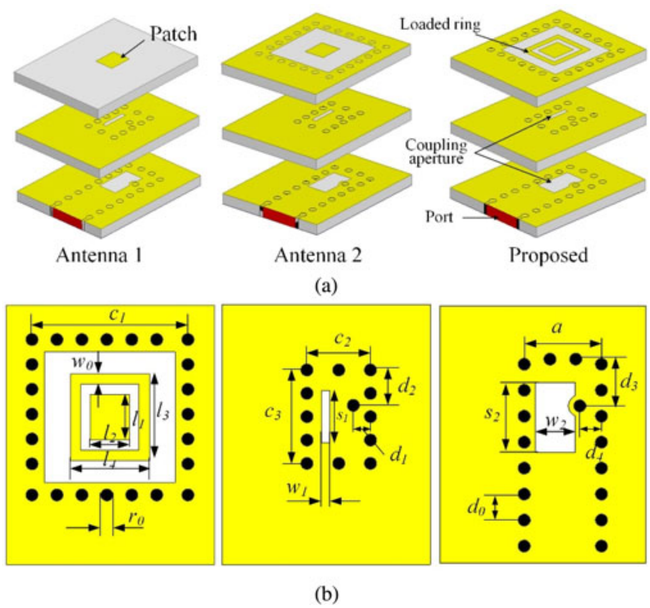

Fig. 2. Array element. (a) Exploded view of the models in HFSS (antenna 1, antenna 2, and the proposed antenna element). (b) Dimensions of the proposed antenna element.

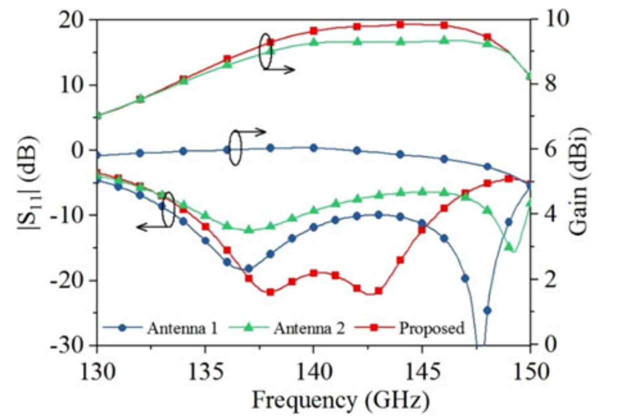

Fig. 3. Simulated $|S_{11}|$ and gains of the three antenna elements.

conductivity of 6.1×10^7S/m. All the simulations in this paper are taken in the full-wave simulation software Ansys HFSS.

Element design

An exploded view of the proposed element antenna model built in HFSS is given in Fig. 2(a). The element only uses Sub 3–8 substrate layers and M2-5 metal layers. A rectangular patch is placed on M5 layer with a rectangular ring loaded around it. A slot is etched on M4 metal layer to excite the radiation patch. The energy is fed by an aperture etched on M3. A SIC is constructed in Sub 5–6 layer for gain enhancement. Two reference antennas are also given in Fig. 2(a) for comparison. Antenna 1 is an antenna with only a patch on M5 layer. As compare to antenna 1, a SIC around the patch is added in antenna 2. Detailed dimensions of the proposed antenna element in Fig. 2(b) can be found in Table 1. All the three antennas are with the same total size of 2 mm × 2.5 mm.

Figure 3 shows the simulated results of the three antennas. Considering array design, we should keep the refection coefficient of an antenna element below −15 dB. Antenna 1 shows a narrow −15 dB bandwidth with the lowest gain of 6 dBi among these three antennas. This is mainly caused by surface waves due to the high permittivity. Surface waves are prevented by using the SIC [15–16], hence the maximum gain of antenna 2 is improved to about 9.3 dBi. However, antenna 2 shows a poor impedance matching. By introducing a rectangular ring, the proposed antenna gives a −15 dB bandwidth of 8.4 GHz (135.9–144.3 GHz). The ring loading shifts down the upper resonant frequency from 149.3 to 142.5 GHz and improves the impedance performance. On the other hand, the ring loading is also a radiating component which has the same current direction with the center patch. Thus, the maximum gain is further improved to 9.8 dBi at 145 GHz.

Arrays configuration

Two antenna arrays are built with a scale of 4 × 4 and 8 × 8 based on the proposed high-gain element antenna. Figs 4(a)–4(b) gives two explosion views of the arrays, respectively. Figures 4(c)–4(e) gives three top views of the radiation part of the 8 × 8-element array. These parts of the 4 × 4-element array are a quarter that of the 8 × 8-element array which are not shown here. WR-06 waveguide with UG-387 flange is used in both arrays to feed the energy. Figure 4(f) shows the transition part from WR-06 to the SIW feeding network. As shown in Fig. 4(e), some adjacent SIWs are sharing one via holes wall resulting in a compact feeding network [17]. The radiation elements are spaced with 1.5 mm (0.7- wavelength at 140 GHz) intervals and they are fed with equal phase and amplitude by the feeding network.

Table 1. Dimensions of the proposed antenna element (unit: mm).

Par.	a	c_1	c_2	c_3	d_0	d_1	d_2	d_3	d_4	l_1
Value	0.75	1.5	0.61	0.9	0.24	0.165	0.34	0.455	0.21	*0.44*
Par.	l_2	l_3	l_4	s_1	s_2	r_0	w_0	w_1	w_2	
Value	*0.38*	*0.84*	*0.76*	0.5	0.385	0.06	0.1	0.08	0.385	

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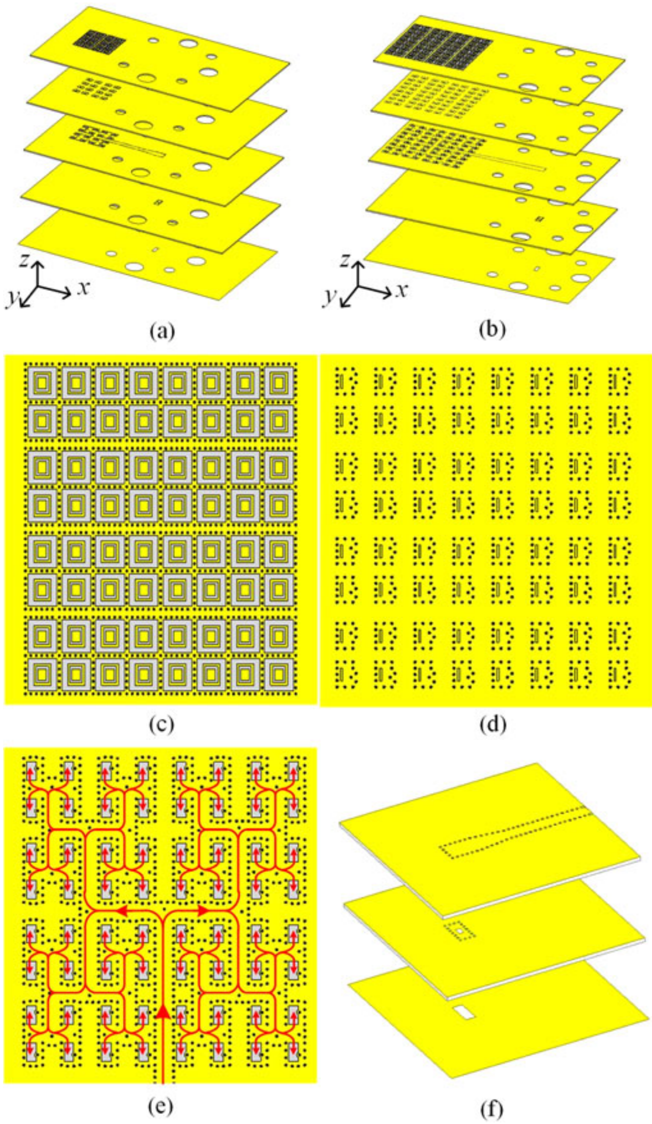

Fig. 4. Views of the 4 × 4-element array and the 8 × 8-element array. (a) Exploded view of the 4 × 4-element array; (b) exploded view of the 8 × 8-element array. (c) Top view of M5 and via holes in Sub 7–8. (d) Top view of M4 and via holes in Sub 5–6. (e) Top view of M3 and via holes in Sub 3–4. (f) WR-06 to SIW transition.

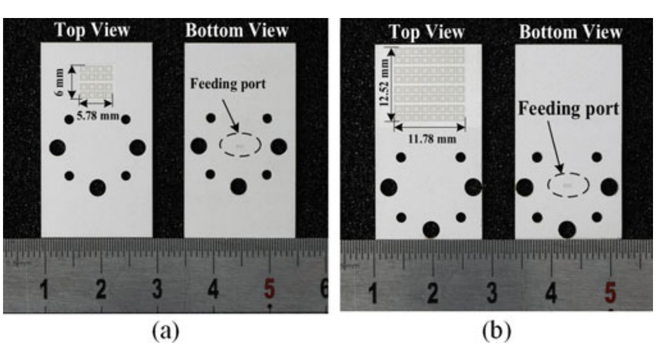

Fig. 5. Fabricated antenna arrays. (a) 4 × 4-element array. (b) 8 × 8-element array.

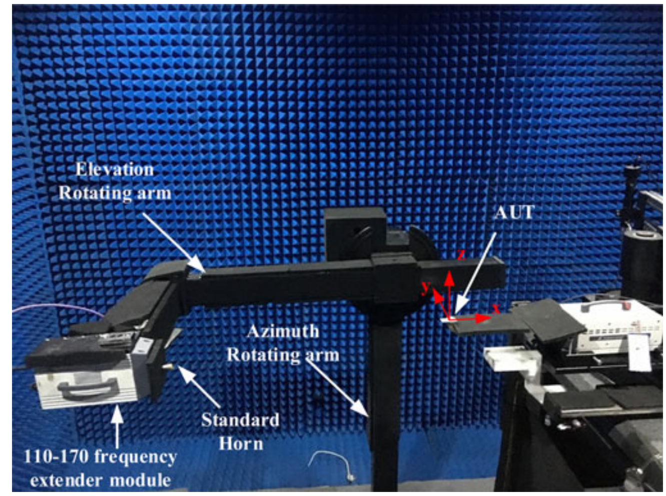

Fig. 6. Measurement setup.

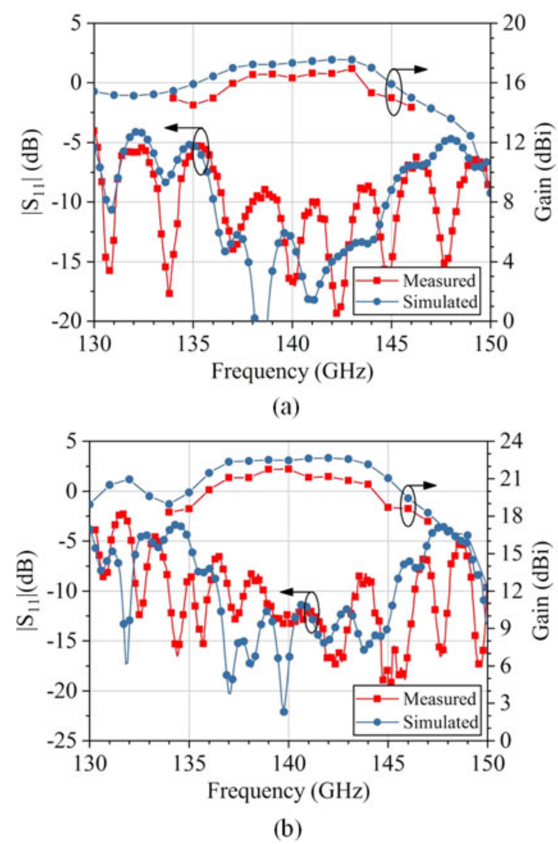

Fig. 7. Simulated and measured $|S_{11}|$ and gains. (a) 4 × 4-element array. (b) 8 × 8-element array.

Results and discussions

The proposed 4 × 4-element and 8 × 8-element antenna arrays were fabricated by LTCC process. Photographs of the fabricated prototypes are shown in Fig. 5. The overall dimensions of the 4 × 4-element array and the 8 × 8-element array are 20 mm × 35 mm and 18.2 mm × 33.15 mm, respectively. Actually, the overall size of the two arrays is designed in the same dimensions. However, due to the fabrication area limitation, there is a little change in the 8 × 8-element array which does not effect on the array performance.

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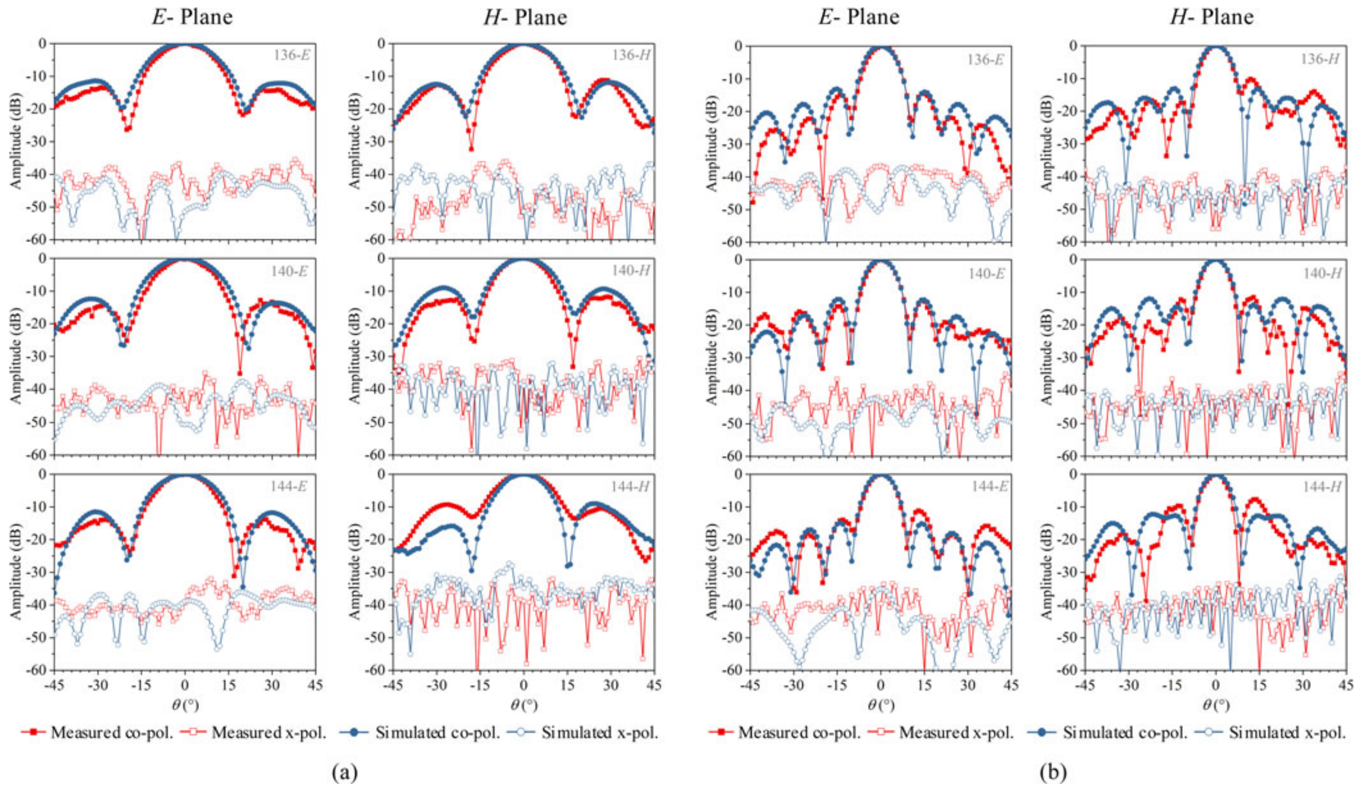

Fig. 8. Simulated and measured radiation patterns in the *E*-plane and the *H*-plane at 136, 140, and 144 GHz. (a) 4 × 4-element array. (b) 8 × 8-element array.

Table 2. Comparison with other published 140-GHz LTCC antenna arrays

Ref.	Type	No. of Elements	BW (GHz) (%)	Size	Gain (dBi)	Efficiency (%)
[5]	Slot array	4 × 4	130.2–158.8 (19.8)	n.a.	16.3	55
[18]	Slot array	8 × 8	126.8–147.8 (15.3)	15.1 × 10.8	21.3	35
[19]	Grid array	240	137–147 (7)[a]	n.a.	17.6	65[b]
This work	Patch array	4 × 4	136.2–145.7 (6.67)	6 × 5.78	16.9	46.1
This work	Patch array	8 × 8	136.7–146.5 (6.9)	12.52 × 11.78	21.8	38.3

[a]$|S^{11}| \leq -5$ dB.
[b]simulated.

The impedance matching performance of the proposed antennas was measured by Ceyear AV3672B vector network analyzer with frequency extension module AV3646A. The radiation characteristics were measured in an anechoic chamber with a far-field measurement system (As shown in Fig. 6). The simulated and measured reflection coefficients are compared in Fig. 7. The simulated −8 dB bandwidth of the 4 × 4-element array is 9.5 GHz (135.8–145.3 GHz) while the measured bandwidth is 9.5 GHz (136.2–145.7 GHz). The simulated −8 dB bandwidth of the 8 × 8-element array is 9.4 GHz (136.2–145.6 GHz) while the measured bandwidth is 9.8 GHz (136.7–146.5 GHz). The measured $|S_{11}|$ shows more ripples and larger reflection than the simulated ones, this may be due to some fabrication errors.

The simulated and measured gains are also compared in Fig. 7. For the 4 × 4-element array, the maximum simulated gain is 17.5 dBi at143 GHz, while the measured maximum gain is 16.9 dBi at 143 GHz. For the 8 × 8-element array, the maximum simulated gain is 22.7 dBi at 142 GHz, while the measured maximum gain is 21.8 dBi at 140 GHz. The simulated gains of the 4 × 4-element array and 8 × 8-element array at 140 GHz are 17.5 and 22.7 dBi with radiation efficiency of 60.8 and 47.2%, respectively. The measured gain of the 4 × 4-element array at 140 GHz is 16.3 dBi. The measured radiation efficiencies can be calculated by comparing the simulated directivity and the measured gains. It can be estimated that the measured efficiencies are 46.1 and 38.3% at 140 GHz for the 4 × 4- and 8 × 8-element array, respectively.

The simulated and measured normalized radiation patterns in the *E*-plane and the *H*-plane of the two antennas are shown in Figs 8(a)–8(b). In most cases, the measured beam patterns match well with the simulated ones and the cross polarizations stay at almost the same level of the simulated ones in both the *E*-plane and the *H*-plane for both arrays. However, there exist some differences in the side lobe level of the 144-GHz *H*-plane

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for both arrays. In such high frequencies, this is primarily because of the feeding setup near the antenna in measurement.

The characteristics and performances of the proposed arrays and other published 140 GHz LTCC antenna arrays are listed in Table 2 for comparison. As compared to [5], the proposed 4×4-element array gives a higher gain for the same scale. As compared to [18], the proposed 8×8-element array gives a higher gain and higher radiation efficiency. The proposed arrays merit high gain property and are suitable for 140 GHz wireless communications.

Conclusion

This paper proposed a 4×4-element and an 8×8-element cavity backed patch antenna array at 140 GHz based on LTCC technology. By introducing a SIC and a rectangular ring load to the antenna element, a high gain of 9.8 dBi is achieved. Measured results show that the 4×4-element array possesses 9.5-GHz bandwidth (136.2–145.7 GHz) with a maximum gain of 16.9 dBi and the 8×8-element array possesses 9.8-GHz bandwidth (136.7–146.5 GHz) with a maximum gain of 21.7 dBi. In general, the proposed antennas have the potential to be used for 140 GHz wireless communications.

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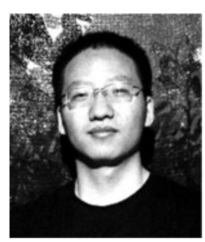

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