Antenna -in -Package Technology and Applications

Chapter 6 Antenna -in -package Designs in Multilayered Low - temperature Co -fired Ceramic Platforms

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LTCC, antenna, AiP, mmWave, SIW, Ferrite

Abbreviation

Radio Frequency (RF)

Integrated Circuit (IC)

System-on-Package (SoP)

Radio Frequency Integrated Circuit (RFIC)

Antenna-in-Package (AiP)

Printed Circuit Board (PCB)

Low-Temperature Co-fired Ceramic (LTCC)

Three-dimensional (3D)

Computer numerical controlled (CNC)

Substrate integrated waveguide (SIW)

3rd Generation Partnership Project (3GPP)

Wireless Personal Area Network (WPAN)

Federal Communications Commission (FCC)

Electromagnetic band-gap (EBG)

Section I Introduction

Over the past few decades, the evolution of radio frequency (RF) wireless systems has brought convenience to our daily life in the forms of communication through smart phones, navigation by GPS, information sharing through wireless sensor networks, and safety by automotive radar. Electronics in general, and wireless systems in particular, have been shrinking in size without losing functionality. In fact, more and more functionalities have been added in later versions. Traditionally, more focus has been on the miniaturization of transistors in the integrated circuit (IC) environment and this miniaturization has been well-governed by the famous Moore's law. However, ICs (commonly known as chips) form a small part of the system. The bulk of the system is formed by other components such as interconnects and discrete components such as resistors, capacitors, and inductors, etc. To miniaturize the bulk of the system, a concept known as system-on-package (SoP) was introduced a couple of decades ago [1]. It is well-known that all chips require packages for mechanical protection. Despite the fact that these packages take considerable space and cost money, they do not provide any functionality except protection from the environment. The idea behind SoP was to make the package functional by utilizing it for implementation of system components. This can help in overall system level miniaturization as well as in cost savings. Figure 7.1 illustrates the SoP concept where a radio frequency integrated circuit (RFIC) chip is placed inside a package cavity and connected to other passive components, such as filters, inductors, capacitors, and antennas, through bond wires, vias, and metal traces on each layer. It is also noted from Figure 7.1 that the antennas can be implemented on the package, leading to the antenna-in-package (AiP) concept, which is the focus of this chapter.

Fig. 7.1 An enlarged, 3D conceptual illustration of RF SoP to clearly demonstrate the embedded components and high level of integration possible in the SoP concept.

Consistent with the SoP concept, AiP is an antenna that is realized on the package of the driving circuit [2]. There are many advantages of AiP that are beneficial for RF systems, the most prominent being the ability of realizing multilayer (vertically integrated) antennas that reduce the overall size of the system. Further, no separate printed circuit boards (PCB) for antenna realization or connections to an external antenna board are required, increasing compactness and cost savings. Finally, efficient antennas can be realized in low loss packaging technologies, particularly at mmWave bands. These aspects are discussed in detail in the coming sections.

Low-temperature co-fired ceramic (LTCC) is one of the mainstream technologies for AiP designs. This chapter focuses on AiP designs in LTCC technology. Before moving on to details of AiP design, LTCC technology is introduced in the next section.

Section II LTCC Technology

LTCC is a multilayer ceramic tape system, which has recently gained popularity not only as a packaging technology but also as an efficient medium to realize passive components. In this section, we first briefly introduce the LTCC technology and then discuss the advantages and issues related to this technology. Later parts of the chapter focus on the LTCC process flow in detail. Finally, we list the major LTCC material suppliers and worldwide service foundries as a quick reference guide for readers.

1. LTCC Technology

LTCC has been the technology of choice for AiP designs due to its excellent electrical properties in addition to its suitable packaging properties for the driving circuits. For these reasons, LTCC technology has found a lot of use in many key application areas such as wireless communication and automotive radars, etc. LTCC technology has also been equally popular for military and space applications. Though the majority of the LTCC work has been in the research domain, commercial products, such as WLAN and GPS LTCC antennas from Digi-Key [3], are already available in the market, verifying the maturity of this technology. The core element behind the LTCC technology is the ceramic/glass dielectric tape (also known as GreenTape). Multiple GreenTapes can be stacked together and then co-fired to realize vertically integrated passive components in a compact fashion.

This technology is an attractive solution for realizing passive components due to the following advantages. Firstly, the capability of multilayered fabrication and metallization enables the integration of RFICs and all the other passive components including antennas as a three-dimensional (3D) integrated system. With LTCC technology, up to 100 layers can be stacked up together [4], thus a great deal of compactness can be achieved with this high level of vertical integration. Therefore, LTCC-based AiP designs can be considerably

more compact compared to the antennas realized on typical planar platforms such as single layer PCBs. Secondly, there is a variety of low loss and varying dielectric constant LTCC tape systems that are beneficial for passive component implementation. Most of the LTCC tapes have very low loss tangents (in the range of 10^{-3}), and many tapes maintain this low loss even at very high frequencies, such as Ferro A6M tape with a $\tan \delta < 0.002$ at 100 GHz [5]. The LTCC tape dielectric constants can vary from ~ 4 to ~ 70 . Some of the LTCC tape systems with high dielectric constants, such as CT765 LTCC ($\epsilon_r = 68.7$), can greatly assist in the miniaturization of passive components. For an antenna designer, the capability of co-firing ceramics with different dielectric constants brings flexibility from the antenna design perspective. In addition, LTCC technology can use low loss conductors for the metallization steps because the multilayered LTCC tapes are laminated and co-fired at relatively low temperature ($850 - 900^\circ\text{C}$), which is lower than the melting temperatures of the noble metals with excellent conductivities, such as Ag and Au. These low loss conductors can further improve the radiation performance of the AiP. Thirdly, LTCC has good packaging properties, such as high thermal conductivity ($\sim 3 \text{ W/mK}$), low thermal expansion (~ 4 to $\sim 7 \text{ ppm/K}$), and decent hermetic sealing capability (low water absorption). These properties are important for protecting the driving circuits and antennas when operating in high power conditions or harsh environments.

2. LTCC Fabrication Process

In general, the LTCC fabrication process comprises five main steps: tape preparation, formation of metal traces and vias, stacking, lamination, co-firing, and post-processing. Figure 7.2 shows the generalized LTCC fabrication process. In the first step (highlighted in pink), the LTCC tape is prepared. Raw materials composed of organic binders and inorganic recrystallized glass, ceramic powder and other solid or liquid additives are mixed and then ball-milled for more than 48 hours to produce the LTCC slurry [6]. Then, the slurry is cast and cut into LTCC tape with the required thickness. Commercial LTCC tapes are mainly fabricated by LTCC material suppliers who supply these to LTCC foundries.

The second step (highlighted in gray) is the formation of metal traces and vias. It starts with tape blanking, which is just the cutting of the LTCC tape into the required tape size for each layer. After tape blanking, the step of via punching can be done by either a laser source or through a mechanical method, such as punching through a computer numerical controlled (CNC) punching machine. The laser punching provides more precise punching locations and better via quality, while the mechanical method has higher efficiency by punching multiple vias simultaneously with a high-speed multi-head CNC punching machine [6]. After punching, the vias are filled with conductor paste through a screen printer. The mask of the screen printer has a precise map of all via holes, which is also well-aligned above the tape. In the screen printing process, the conductor paste is firstly

placed on top of the mask (screen), then the conductor paste is pushed through the mask openings by a squeegee. After via filling, the solid, conducting vias are ready to be connected to the various metal traces between the different layers. The metal traces on each layer are also realized by screen printing. Several non-contact masks are used to transfer the metal patterns to all tape layers.

Fig. 7.2 Generalized LTCC fabrication process

After the formation of metal traces and vias, all tape layers are aligned and stacked together in order. The alignment of the stacking is critical because a small alignment error can lead to disconnection of the whole system. Then, the stacked tapes are laminated according to the tape specifications from the manufacturer. For example, in the lamination step, the Ferro A6M tapes are pressed between two heated plates at 70 °C, 200 bar for 10 minutes.

After lamination, the tapes are co-fired according to a specific sintering profile (highlighted in blue). A typical sintering profile starts with temperatures slowly rising up to 450 °C at a speed of 2 – 5 °C per minute. Then the temperature rises up to 850 – 900 °C with a dwell time of about 15 – 30 minutes. Once the temperature cools down to room temperature, the sintered LTCC packages are ready for post-firing and electrical testing. In post-firing, steps such as chip attachment, wire bonding, flip chip assembly, or other back-

end processes can be performed. After the post-firing step, the samples are tested to characterize their physical and electrical properties.

Despite the advanced fabrication processes, there are still some technological issues in LTCC technology. The major issue is that of tape shrinkage during the co-firing step. For example, DuPont 951 tape shows 12.7% shrinkage along the x-y axis and 15% shrinkage in the z-axis after co-firing [4]. Though foundries provide the shrinkage information in advance, the precision of this information depends on a particular fabrication run and its conditions. Another issue is the alignment between multiple layers. This includes the layer-to-layer alignment and conductor-to-via alignment. Good alignment ensures a robust connection between each layer, which is critical for a reliable AiP design. However, the alignment accuracy also varies from foundry to foundry and one LTCC process to another. Having said that, LTCC fabrication processes have improved considerably since their inception and the above mentioned issues have become less severe as compared to the previous decades.

3. LTCC Material Suppliers and Manufacturing Foundries

There are several LTCC material suppliers in the market such as DuPont, Heraeus, Ferro, ESL, CeramTec, Kyocera, and KOA. They provide many commercial LTCC tape products. Some of the most commonly used LTCC tape systems from these manufacturers are DP 951 and DP 943 from DuPont, microwave tape A6M from Ferro, CT 2000 from Heraeus, and 41110 from ESL. The characteristics of the LTCC tapes mentioned above are listed in Table 7.1. It can be seen that there are many options for low loss LTCC tapes with different dielectric constants. In addition, most of the LTCC tapes shown in Table 7.1 have good thermal conductivity and low thermal expansion coefficient. The tape shrinkage issue can also be observed. For example, HL 2000 from Heraeus shows a z-axis shrinkage of 32%.

LTCC foundries are located all around the world, supplying manufacturing services that employ the commercial tape systems. Some foundries also develop their own LTCC tapes to meet their own needs regarding fabrication. As a quick reference for readers, Table 7.2 lists some of the major LTCC foundries around the world. All the foundries have their own design rules, which are available from the foundries. The design rules define the fabrication boundaries, such as the minimum conductor gaps, maximum package size, maximum layer number, and so on. These rules must be taken into consideration by the antenna or RF system designers at the design and simulation stages.

Table 7.1 Characteristics of LTCC material systems

Property	DuPont DP 951	DuPont DP 943	Heraeus CT 2000	Heraeus HL 2000	Ferro A6M	ESL 41110-70C
Dielectric Constant	7.85	7.5	9.1	7.3	5.9	4.3-4.7
$\tan \delta$	0.0045	0.001	0.002	0.0026	0.002	0.004
Breakdown Voltage (V/25 μm)	>1000	>1000	>1000	>800	>1000	>1500
Insulation Resistance (Ω/cm)	>10 ¹²	>10 ¹²	>10 ¹³	>10 ¹³	>10 ¹²	>10 ¹²
Thickness-Green (μm)	50, 112, 250	125	25, 98, 250	131	125, 250	125
Thickness-Fired (μm)	42, 95, 212	112	20, 77, 200	87~94	92, 185	105
Shrinkage x-y axis (%)	12.7 $\pm$ 0.3	9.5 $\pm$ 0.3	10.6 $\pm$ 0.3	0.16~0.24	14.8 $\pm$ 0.2	13 $\pm$ 0.5
Shrinkage z axis (%)	15.0 $\pm$ 0.5	10.3 $\pm$ 0.3	16.0 $\pm$ 1.5	32	27 $\pm$ 0.5	16 $\pm$ 1
Thermal Conductivity (W/mK)	3	4.4	3	3	2	2.5~3
CTE (ppm/K)	5.8	4.5	5.6	6.1	7	6.4
Flexural Strength (MPa)	320	230	210	>200	>170	NA

Table 7.2 Worldwide LTCC Foundries

	North America	Europe	Asia
Foundry	VisPro, ATC, C-MAC, CoorsTek, CTS, Johanson Technology	VTT, VIA Electronic, Selmic, IMST, MSE, Micro-Hybrid Electronic, EPCOS	ACX, Hitachi, Murata, Nikko, Taiyo Yuden, Yokowo

Section III LTCC-Based AiP

It can be seen from Section II that LTCC technology is highly suitable for AiP design due to its numerous advantages, such as vertical integration in multilayer substrates, low loss material especially at higher frequencies, and good thermal stability. For these reasons, a number of LTCC-based AiP designs have been shown in the last two decades covering various application spectrums. LTCC technology has peculiar advantages for certain types of AiP designs. For example, LTCC technology is highly suitable for substrate integrated waveguide (SIW)-based antennas. This is because LTCC is a multilayered technology where conductive vias are an integral part of the fabrication process. Because SIW technology requires many via holes in the design process and can benefit from the multiple layers, LTCC technology became a natural choice for SIW-based designs. Similarly, due to low loss at higher frequencies, LTCC is a suitable medium for mmWave antennas. Some AiP applications for harsh environments can also benefit from the good mechanical stability and thermal conductivity of LTCC tapes. Finally, LTCC, due to its excellent packaging capabilities, is highly suitable for active antennas where the antenna is realized on the package of the driving circuits. The above mentioned AiPs, due to their suitability for LTCC technology, are a special focus of this section. In addition, this section reviews various gain enhancement techniques for AiP designs. Towards the end of the section, Ferrite LTCC base reconfigurable AiPs—an emerging trend in this field—are also discussed.

1. SIW AiP

The traditional planar transmission lines, such as microstrip lines and coplanar waveguides, have the disadvantages of radiation losses and coupling to other RF components. It is well-known that metallic waveguides have the best transmission performance among most transmission lines, however they cannot be integrated in planar substrates due their bulky sizes and the fabrication complexity of the vertical metallic walls. The SIW concept was developed to overcome this problem [7]. SIW mainly consists of a dielectric with top and bottom metalized surfaces, while the two narrow walls on the sides are metallized through metallic via holes, thus realizing a waveguide in a substrate. The vias are arranged in a fashion that electromagnetic waves are confined inside the waveguide

with minimum leakage from the sidewalls, thus mutual coupling and radiation losses are minimized [8]. SIW can be integrated into antenna packages while preserving the advantages of low insertion loss and high quality factor associated with conventional waveguides. More importantly, the capability of multilayer integration, low dielectric loss, and easy via hole fabrication in LTCC technology makes it a perfect candidate for SIW-based AiP designs. In addition, the high permittivity of LTCC tapes can further miniaturize the SIW sizes for compact AiP designs.

Recently, LTCC-based SIW structures have been widely used in AiP and feed network designs. However, most of the antenna designs are limited to higher frequencies (such as mmWave and above) to facilitate substrate integration. The slotted waveguide antenna array has been a popular choice, particularly for applications such as radar, navigation systems, and high power wireless systems, due to its small volume, high efficiency, and high power handling capability. Several slotted SIW antenna arrays in LTCC technology have been shown in the literature [8-10]. In [9], an SIW-based slotted antenna array was demonstrated, as shown in Figure 7.3. Five layers of LTCC tapes have been used to build the SIW structure and the radiating slots have been realized on the top metalized surface. Instead of a conventional straight slot, a bent slot shape in this example provides more degrees of freedom for the antenna design.

Fig. 7.3 3D view and slot geometry of the 79 GHz SIW 12-slot array antenna in LTCC [9]

Waveguide horn is another antenna type that can be realized in SIW technology. However, for ease in integration with the substrates, mostly H-plane horns have been realized. The first implementation of a horn antenna in LTCC-based SIW technology has been reported in [11]. In this example, a 140 GHz H-plane horn antenna has been demonstrated. This SIW horn antenna incorporates steps in the top and bottom flared walls while the side walls are realized with via (as shown in Figure 7.4). The design achieved a decent gain of 13.3 dBi in the end-fire direction. In subsequent work in this area, a vertical E-plane SIW horn antenna has been demonstrated for the first time in [12], as shown in

Other than the realization of antennas, SIW-based LTCC technology has also been attractive for feeding networks. Low loss feeding networks are highly desirable for antenna arrays, especially for large arrays. SIW, as a waveguide-like structure, has low radiation loss, which is a large issue with typical microstrip or CPW-based feed networks. By realizing SIW-based feed networks in LTCC technology, the dielectric and conductor

Fig. 7.5 Cross-section view of the 300 GHz SIW horn antenna in LTCC [12]

losses are also minimized due to excellent dielectric and conductive properties inherent in the technology. In addition, the multilayered integration possibility of LTCC technology to make 3D feeding networks results in extremely compact sizes, which resolves another major issue for typical large arrays. Many examples of SIW-based feeding networks in LTCC have been reported in the literature [13-15]. For example, in [13], a 4×4 slot antenna array at 60 GHz is fed by a low loss SIW-based feeding network. The feed network occupies the bottom seven layers as a folded butler matrix for beamforming, and the layer 8 to 15 as power divider, while the antenna array has been realized on the top five layers, as shown in Figure 7.6. This antenna achieves a high gain of 15.3 dBi at 60 GHz and a wide bandwidth of 4.2 GHz. This LTCC antenna array demonstrates a size reduction of approximately 80% as compared to a similar 4×4 planar design reported in [16].

Fig. 7.6 A 60 GHz 4×4 antenna array with multilayered SIW-based feeding network [13]

2. Millimeter wave AiP

With the rising interest in mmWave wireless communication systems, such as 5G communication systems, automotive radar, and imaging systems, high gain and high radiation efficiency mmWave antennas have become very important [17]. The mmWave is the frequency band from 30 to 300 GHz and corresponds to wavelengths from 10 mm to 1 mm. In the mmWave band, the antenna is small enough to be efficiently integrated in the

package. Hence, considerable AiP work has been done for mmWave applications. LTCC technology is considered a highly suitable platform for the mmWave AiP designs due to the benefits mentioned in Section II, particularly, its low loss aspect at these frequencies. In this subsection, LTCC-based mmWave AiPs are discussed and examples of different mmWave frequency bands and applications are demonstrated.

(1) 5G AiP

The upcoming 5G mobile communication systems have attracted equal interest from industry and the research community. According to the 3rd Generation Partnership Project (3GPP), there are several mmWave frequency bands that have been assigned for 5G mobile communications, such as 28, 37, 39, and 47 GHz bands [18]. The use of these mmWave bands for 5G systems can enable high data rates, and thus antennas with large bandwidths are required to support these high data rates. Several LTCC-based 5G AiP designs have been demonstrated in literature [19-23]. For example, in [20], two 38 GHz quasi-Yagi antennas have been implemented in one LTCC substrate to achieve two orthogonal horizontal polarizations, as shown in Figure 7.7. In order to improve the gain and isolation between the two antennas, the vertical via walls have been smartly designed around the radiating elements by making good use of the LTCC multilayered integration capability. This LTCC-based 5G quasi-Yagi antenna achieves a maximum gain of 6 dBi with over 80% radiation efficiency. The horizontally polarized antenna demonstrates a wide impedance bandwidth of 11.5 GHz (30.5 – 42 GHz), which covers the entire 37 and 39 GHz bands.

Fig. 7.7 Multilayered 3D structure of the 38 GHz LTCC quasi-Yagi antenna [20]

(2) WPAN (60 GHz) AiP

The unlicensed 60 GHz frequency band can be used for short range wireless communication systems with multi-gigabit data rates. One of the most anticipated application for this band is the high data rate wireless personal area network (WPAN) due to the large bandwidth (~ 7 GHz) dedicated for this band [24]. Most of these applications are for short range communication due to the large loss of approximately 15 to 30 dB/km from atmospheric absorption in this band [25]. Considerable work of AiP designs in the 60 GHz band has been presented in the literature [26-30]. In [27], a 60 GHz 4×6 stacked

circular patch antenna array has been demonstrated. As shown in Figure 7.8 (a)(b), this AiP design consists of ten LTCC layers, where the antenna array is realized on the top three layers and other layers have been used for the array feeding network. In addition, an RFIC chip has been attached to the LTCC substrate through flip-chip technology to feed the antenna array with different phase distribution, thus, the beam-steering ranges of 45° in both E-plane and H-plane have been achieved. A maximum gain of more than 14.5 dBi has been demonstrated at boresight. Moreover, as shown in Figure 7.8 (c), it realizes a wide bandwidth of 9 GHz from 57 to 66 GHz, which makes it suitable for high data rate WPAN applications.

Fig. 7.8 A 60 GHz 4×6 LTCC-based patch antenna array (a) side view of the AiP stack-up, (b) simulation model, (c) antenna array reflection coefficient [27]

(3) Automotive Radar (79 GHz) AiP

Another popular frequency band for AiP work is 79 GHz band (76 – 81 GHz), which has been allocated for automotive radar applications [31]. Antenna designs play an important role in functions such as collision avoidance and blind spot detection to improve driving efficiency and safety. LTCC technology has been widely used in the design of high-

resolution automotive radar systems [9, 32-35]. This is because LTCC materials have excellent thermal and packaging properties in addition to good electrical properties, thus it is a good medium for high performance AiP designs, particularly for harsh environments. In [32], ceramic filled cavity resonators have been designed in LTCC technology as an antenna array for 79 GHz automotive applications. As shown in Figure 7.9, this antenna consists of eight ceramic filled cavities which are excited by transverse slots on top of the laminated waveguide (between the B – B' and C – C' layers). The laminated waveguide is fed by the WR-12 waveguide at the bottom and divides the RF power into eight parts to feed each cavity resonator. This prototype shows a decent radiation performance with a gain of 13.1 dBi and a radiation efficiency of 65% at 79 GHz. More importantly, this antenna presents a stable E-plane radiation pattern with a 13° 3 dB beamwidth over the whole operating bandwidth from 76 to 81 GHz, while the sidelobe level stays 11 dB below the main radiation for the entire band. The features of high gain, sharp beam, and low-level sidelobe make this antenna a perfect candidate for automotive radar applications. This compact design of ceramic filled resonators has made good use of the high permittivity LTCC tapes and its capability of multilayer integration.

Fig. 7.9 Configuration of the 79-GHz cavity resonator antenna array in LTCC [32]

(4) Imaging and Radar (94 GHz) AiP

The 94 GHz band has also attracted research interest in the past decade because of the small wavelength and relatively low atmosphere absorption in this frequency band. According to Federal Communications Commission (FCC), the 94 GHz band (92 – 95 GHz) has been allocated for imaging and military radar and point-to-point communication systems [36]. For all these applications, high gain and compact designs are desirable

features from the antenna design perspective. Several examples of 94 GHz LTCC AiPs have been demonstrated in the literature [15, 37, 38]. For example, in [38], a dual polarized mesh array antenna has been designed in LTCC technology for 94 GHz band applications. As shown in Figure 7.10, this antenna consists of two grid arrays in two orthogonal directions with specially designed matching stubs to compensate the input impedance alteration, which is caused by the direct coupling of the complementary array of another polarization [38]. This mesh array antenna achieves a high gain of 13.3 dBi at 93.6 GHz, a 10 dB impedance bandwidth of 6.5 GHz, and a 3 dB gain bandwidth of 3.0 GHz, which can cover the whole 94 GHz band.

Fig. 7.10 A 94 GHz microstrip mesh array antenna (a) 3D exploded view, (b) radiator (top view) [38]

(5) Sub-THz (Above 100 GHz) AiP

The demand for massive data transfer has driven the rapid development of high data rate wireless communication systems in the above-100 GHz mmWave bands or sub-terahertz ranges, such as the D band (110 – 170 GHz), 270 GHz band, and 300 GHz band, in which the large bandwidth can be easily achieved. Recently, researchers have shown many high data rate wireless systems above 100 GHz employing LTCC AiP designs [12, 39-41]. For example, a 300 GHz step-profiled horn antenna realized in 27 LTCC layers achieved a high gain of around 18 dBi over 72 GHz bandwidth [12]. Other than high data rate wireless communications, the sub-terahertz frequency band is also attractive for imaging in which a sharp radiation beam is highly desired for better resolution. In [40], a radial waveguide is formed by utilizing vias as the sidewall in LTCC layers 2 and 3, as shown in Figure 7.11. The radiating slots are implemented on metal layer 2, loaded by metal strips on metal layer 1. Through this design of a radial line slotted antenna array, a high gain of 27.6 dBi is achieved at 275.2 GHz with a wide 3 dB gain bandwidth of 9.8 GHz. In addition, as shown in Figure 7.12, the antenna demonstrates a half power beamwidth of around 7° in the H-plane and around 4° in the E-plane.

(a)

(b)

Fig. 7.11 Radial line slotted antenna array in LTCC (a) side view (b) top view [40]

(a)

(b)

Fig. 7.12 Measured and simulated radiation patterns at 276 GHz (a) H-plane (b) E-plane [40]

3. Active Antenna in LTCC

In the previous sections, the emphasis has been just on the AiP. However, another important aspect for AiP is its interface or integration with the circuits under the package. The true benefit of AiP is that the packaged circuits can be integrated with antennas in the same package for a compact system. Typically, the antennas that are integrated and characterized with the driving circuits are known as active antennas. Active antennas require additional routings for DC bias, which can be efficiently realized in the multilayered LTCC technology. LTCC technology is highly suitable for active antennas as it can provide excellent packaging characteristics (such as hermetic sealing, good thermal stability, and low thermal expansion) for RF chips as well as an efficient platform for high performance integrated antennas.

In terms of chip placement methods, there are two main approaches in LTCC technology. The chips can be mounted either on the top or bottom of the LTCC substrate (surface mount)

or they can be completed buried in the LTCC cavities. Examples for both cases have been shown and discussed later in this section. In addition to the chip placement methods, there are two main chip attachment techniques that have been widely adapted in LTCC technology. First is the traditional wire bonding approach where the bond pads on the chip are connected to the bond pads on the package through bond wires. A second is the flip chip approach where the bond pads on the chip are placed on specialized solder balls or bumps, so no wires are required for connection.

For the surface mounting method in LTCC, mostly flip-chip technique has been used to attach the RFIC chips to the surface of the LTCC substrate [28, 42, 43]. For example, in [42], a 2×2 circularly polarized patch antenna array is integrated with a 60 GHz Doppler CMOS radar chip in a LTCC substrate, as shown in Figure 7.13 (a). The CMOS radar chip is mounted on the bottom of the LTCC substrate through flip chip technology. In this LTCC substrate, a through-substrate via is smartly built as a coaxial cable with the help of six grounded multilayered vias to realize the vertical connection between the chip and the radiating elements on the top side of the substrate. Figure 7.13 (b) shows the LTCC active antenna array package mounted on a regular FR4 board. In the case of surface mount chips, the complete packaging is provided by a combination of LTCC as well as PCB technology.

Fig. 7.13 A 60 GHz active antenna in LTCC package (a) layer profile, (b) fabricated sample [42]

In the other approach, cavity structures have been utilized in LTCC for chips placement [26, 44-49]. By cutting the desired size hole in each layer and then aligning these holes in multiple layers, cavity structures can be easily realized in LTCC technology. More importantly, the cavity structures can be designed to have a step shape for different layers, thus providing more space for bond wire connections to different layers, as shown in the multi-step cavity in Figure 7.14. Placing the chips in buried cavities, instead of surface mounting, provides complete packaging to the chip. In [45], a 60 GHz grid array antenna is integrated with a receiver chip in LTCC. As shown in Figure 7.14, the chip is placed in a multi-tier cavity and connected to the metal traces in LTCC through bond wires. One of the important novelties in this example is that the antenna array and the receiver chip are designed on the opposite sides of the LTCC substrate and separated by a ground plane to

minimize the interference between the antenna and the chip, which is a well-known co-design issue for active antenna designs. It achieves a high gain of 13.5 dBi at 60 GHz.

Fig. 7.14 Grid array antenna in LTCC (a) top view, (b) bottom view [45]

4. Gain Enhancement Techniques in LTCC

With unprecedented proliferation in wireless communication systems, expanding to mmWave and THz bands, there is an increasing demand for the antenna designs with high gain and high radiation efficiency to enhance the communication range or compensate for high path loss in higher frequency bands. In addition, the signal-to-noise ratio can be significantly improved by the use of high gain antennas in the wireless communication systems. Though LTCC is a low loss medium that is suitable for efficient antenna design, gain improvements are still required in many cases, particularly in designs with relatively higher dielectric constants.

Several gain enhancement techniques have been investigated to achieve high gain antennas in LTCC technology. One of the most common methods has been to introduce open cavities around the radiating elements [50]. Compatible with the LTCC process, the open cavities can reduce losses caused by dielectric substrates to achieve better gains. In addition, this also helps with issues related to excitation of surface waves, which are common in typical high permittivity and thick LTCC substrates. Other than the open cavities, embedded cavities have also been demonstrated to improve gain performance [51-53]. For example, in [53], a 60 GHz antenna array is designed on a cavity embedded substrate, which achieves 2.8 dB gain enhancement without changing the antenna array structure, as shown in Figure 7.15. However, the embedded cavities require additional fabrication process in which, typically, a sacrificial volume material is inserted in the cavity before lamination and requires removal from a special escaping orifice during co-firing [54]. The additional process can increase the complexity and cost of fabrication.

Fig. 7.15 A 4×4 patch antenna array in LTCC with embedded cavity [53]

Another approach for gain enhancement is to focus the antenna radiation beam by using 3D structures in a multilayered LTCC, such as a superstrate layer or a lens structure [55, 56]. For example, an LTCC-based Fresnel lens structure has been demonstrated to enhance the antenna gain in [56]. As shown in Figure 7.16, the antenna array has been realized in a standard LTCC tape system (CT 707, $\epsilon_r = 6.4$), whereas to make a compact Fresnel lens, a very high permittivity LTCC substrate (CT765, $\epsilon_r = 68.7$) has been used. The 1×4 fractal patch array is fed through the apertures in the ground plane. The fractal patch has been used for bandwidth improvement. The Fresnel lens has been realized through four layers of planar grooved plates and provides 6 dB of gain enhancement. This design eventually achieves a gain of 15 dBi at 24 GHz, while maintaining a high level of compactness as compared to similar designs [57, 58].

Fig. 7.16 Geometry of a 1×4 fractal antenna array with integrated Fresnel lens (a) schematic view (b) fabricated sample [56]

In addition to the gain enhancement techniques, there has been work focusing on surface wave suppression in LTCC. As mentioned above, this issue is relevant to LTCC AiP designs because LTCC substrates have relatively high dielectric constants and can be quite thick for some designs. One effective surface wave suppression method is to use the electromagnetic band-gap (EBG) structure, which is perfectly compatible with

multilayered LTCC fabrication [59-61]. The soft surface structure is one class of EBG structures that behaves as a perfect electrical conductor for the TE mode and as a perfect magnetic conductor for the TM mode, therefore, the soft surface has the stopband characteristics along the soft direction shown in Figure 7.17 (a) [61]. As can be seen in Figure 7.17 (b), the soft surfaces have been implemented between the LTCC-based patch antenna array to realize a stopband for suppressing the surface waves. Although the soft surface structures have been proven useful for surface wave suppression, the soft surface, as an anisotropic structure, only works along the soft direction. In contrast, the Sievenpiper EBG structure, as an isotropic structure, is able to suppress surface waves in all directions. Moreover, periodic and interlayered EBG structures are easily implemented in LTCC technology. In [60], a 60 GHz 2×2 patch antenna array is designed and fabricated in the LTCC substrate, where two five-row Sievenpiper EBG structures have been embedded on the two sides to suppress the surface waves. A 4 dB gain enhancement and 8 dB side lobe improvement has been achieved by the implementation of Sievenpiper EBG structures, as shown in Figure 7.18.

Fig. 7.17 (a) Geometry of the via-loaded strip soft surface structure (b) 4×4 patch antenna array with soft surfaces [61]

Fig. 7.18 Sievenpiper EBG embedded 60 GHz 2×2 antenna array [60]

5. Ferrite LTCC-Based Antenna

In the above sections, many examples of functional packages have been shown where the LTCC package acts as a substrate for the antenna and provides protection to the circuits. The next question is whether the components realized in the package, such as AiP, can be controlled. In other words, in addition to adding functionality to the package, can we also add control to it. The answer is yes, by mixing controllable materials with the ceramic powder, control can be added to the LTCC package. One example is mixing iron oxide with the ceramic powder, which has resulted in ferrite LTCC tape systems. Ferrite materials are magnetic dielectrics whose permeability can be altered dynamically by applying magnetic fields across them. For example, according to [62], the commercially available ferrite ESL 40012 shows a relative permeability tuning range from 100 to 370 when magnetic fields ranging from 100 to 2600 A/m are applied across it, as shown in Figure 7.19. The capability of tuning the permeability tensor through an applied magnetic field means that any RF component realized on this tape system can be tuned or reconfigured. For AiP, this reconfigurability can be in resonant frequency [63], radiation pattern [10], or even in polarization [64]. Such tunable and reconfigurable antennas are highly desirable for the modern wireless communication systems as they can provide diversity and flexibility in the use of available spectrum as well as radiation space.

Fig 7.19 Measured relative linear permeability of ESL 40012 [62]

Though the ferrite LTCC is a relatively new concept for AiP designs, some examples of tunable and reconfigurable AiP designs in this tape system can be found in the literature. In one of the first demonstrations of a tunable and reconfigurable AiP in ferrite LTCC technology [63], a 12 GHz microstrip patch antenna has been shown to vary its resonant frequency by 600 MHz when biased through an embedded winding, as shown in Figure 7.20. Two kinds of embedded windings, a solenoid and a toroid, have been explored in that

work. Though the antenna and the winding have both been implemented monolithically in the multilayer ferrite LTCC process, one issue was the interference of the RF fields with the embedded windings. In subsequent work [65], this problem has been resolved by moving the antenna ground plane above the embedded windings to restrict the RF fields to the ground plane while the DC magnetic fields from the windings can still influence the antenna substrate layers to achieve the required tuning. This is conceptually shown in Figure 7.21 (a). This antenna demonstrates a tunability of 1.25 GHz in resonance frequency, varying from 11.8 to 13.05 GHz when the bias current changes from 180 to 0 mA, as shown in Figure 7.21 (b). In another interesting design, the bias windings have been optimized to act as a helical antenna as well [66]. This means that the helical antenna/winding is not only providing the bias for tunability but is also the radiating element. Other than tunable AiP design, ferrite LTCC technology has also been widely used for other RF components, such as filter and inductor designs [67-69].

Fig 7.20 Measured relative linear permeability of ESL 40012 [63]

Fig 7.21 Tunable antenna on a Ferrite LTCC substrate with embedded windings (a) schematic view (b) measured frequency response with bias from 0 mA to 180 mA (from right to left) [65]

Ferrite LTCC has also been used for antenna designs with radiation pattern reconfigurability, in which the most important component is the embedded tunable phase shifter [70, 71]. Only a handful of radiation pattern reconfigurable antennas with embedded phase shifter in ferrite LTCC have been demonstrated in the literature [10, 72]. The concept of a phase shifter, which comprises an SIW section and embedded windings, feeding a

slotted SIW 4×4 phase array antenna has been demonstrated in [10] and shown in Figure 7.22. The insertion phase of the SIW can be tuned according to the strength of the magnetic field applied to the ferrite substrate. By applying different DC current values to the embedded windings, magnetic fields with tunable strengths are generated, leading to the change of SIW substrate permeability. As a result, signals with different phases are fed to each antenna subarray. Eventually, the proposed antenna array achieves the beam scanning function. Figure 7.23 (b) shows the experimental verification of a 2×3 Ku-band slotted SIW antenna array. It shows a beam scanning range of $\pm 19^\circ$ with embedded winding and an enhanced beam scanning of $\pm 28^\circ$ with an external winding. This design verifies that monolithic phased arrays can be realized in ferrite LTCC where the phase can be controlled through the applied magnetic field. In a subsequent work, a half-mode shifter has also been demonstrated for antenna radiation pattern reconfigurability, which does not need two solenoids for its operation [72].

Fig. 7.22 (a) Conceptual sketch of a monolithic slotted SIW phased antenna array in ferrite LTCC, (b) tunable SIW phase shifter with embedded windings [10]

Fig. 7.23 (a) Fabricated 2×3 antenna array prototype, (b) measured radiation pattern scanning range [10]

Although ferrite LTCCs show many good features for tunable antennas, there are some issues which need to be resolved for future advancement in this area. One of the main

drawbacks is that ferrite LTCC tapes have relatively higher loss ($\tan \delta > 0.001$) compared to conventional low loss LTCC tape. In addition, the existing ferrite LTCC tapes have decent operation up to ~ 20 GHz of frequency, as beyond that substantial loss restricts their use. One of the suggested solutions is to design the antennas on conventional low loss LTCC tapes and design tunable switches, such as a phase shifter, on the ferrite LTCC tapes. This solution ensures the high radiation performance of the antenna and good tunability of switches, but it requires the technique of LTCC fabrication with multiple tape types. In addition, the resistance of the embedded windings needs to be decreased to mitigate its self-heating effect if the windings are integrated for biasing [10].

Section IV Challenges and Upcoming Trends in LTCC AiP

For the foreseeable future, LTCC technology will continue to be one of the most attractive approaches to realize AiP designs due to all the above-mentioned advantages of LTCC technology. However, several challenges still remain for LTCC-based AiPs widespread use. One of the main challenges is the improvement of LTCC fabrication resolution and repeatability. The AiP designs, especially for mmWave frequencies and beyond, have very small feature sizes because of the small wavelength, so the fabrication accuracy becomes critical for the high frequency AiP designs. However, the LTCC technology has limited fabrication resolution. For example, according to VTT foundry design guidelines, it has minimum conductor line width of $100\ \mu\text{m}$ and spacing of $150\ \mu\text{m}$ [73]. But, the resolution on the order of tens of microns (or even lower) is required for AiP designs at sub-THz frequencies and beyond, so the LTCC fabrication resolution needs to be improved. There are other issues in the fabrication process that can affect fabrication accuracy. The tape shrinkage issue in LTCC package fabrication is a major concern for the fabrication accuracy. Though this aspect has been improved over time, some unpredictability remains. Tape shrinkage occurs during sintering, which causes variation in design dimensions. Therefore, the tape shrinkage issue should be taken into account during the design stage to obtain the desired design dimensions. Other than tape shrinkage issue, the layer-to-layer alignment is another important issue related to fabrication accuracy. Good alignment ensures a robust connection between each layer and is critical for a reliable AiP design. Researchers are currently exploring methods to realize fine line printing for more accurate fabrication, such as high precision screen printing, inkjet printing, and gravure offset printing.

With the rapid growth in LTCC-based AiP designs, there is need for LTCC tape systems with different functionalities. One of the development trends has been the implementation of multi-type LTCC tape systems, referring to integrating different types of LTCC tapes, including regular, ferrite, ferroelectric, and high permittivity LTCC tapes, in one single package to achieve some special functions, as shown in Figure 7.24. In addition to ferrite

LTCC, ferroelectric LTCC is another new LTCC tape system [74] that has the feature of tunable permittivity. So, both ferrite and ferroelectric LTCC can be used to build tunable components, such as ferrite-based tunable inductors, ferroelectric-based tunable capacitors, and tunable phase shifters, which are helpful for the realization of reconfigurable antenna designs. In addition, high permittivity LTCC tapes can be useful for compact AiP designs and the on-package realization of some special structures, such as a lens for antenna radiation beam shaping. However, stacking different LTCC tape systems on each other has the compatibility and adhesion issues because each LTCC tape system has its own laminating and co-firing conditions, which make the realization of multi-type LTCC tape system challenging.

Fig. 7.24 Conceptual drawing of multi-type LTCC tape system

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