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Design of K-band Integrated Front-end Eight-channel T/R Module Based on LTCC Technology

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Abstract: A novel highly integrated front-end T/R module with eight RF channels for the application of a K-band transceiver is presented. The proposed T/R module is based on the LTCC package combined with embedded microwave passive circuits and a variety of microwave transistor dies. Due to the applied multi-layer LTCC technology, the overall size and weight of the designed module is greatly reduced. Furthermore, such design improves the overall performance of the T/R module with a lower cost and high efficiency.

Key words: T/R module, K-band transceiver, LTCC

INTRODUCTION

Driven by the significant worldwide demand for small-size, low-weight and high-integration satellite communication apparatus, the development of Transmit/Receive (T/R) modules become an inevitable trend. Numerous RF circuits based on Monolithic Microwave Integrated Circuit (MMIC) technologies have been introduced in the study articles Boles *et al*. (2010) and Masuda *et al*. (2011). On the other hand, Low Temperature Co-fired Ceramics (LTCC) technology used for RF module packaging and integration, especially in microwave frequency, has also been proposed by Ji *et al*. (2010) and Dai *et al*. (2006).

The Low Temperature Co-fired Ceramics (LTCC) packaging technology allows embedded passive components and mounted active transistor dies to be integrated in the same RF module. It is the reason that multi-T/R (transmitting/receiving) channels which typically include Power Amplifier (PA), Low Noise Amplifier (LNA), phase shifter and several other passive circuits, could be integrated together (Kopp *et al*., 2009). Such highly integrated T/R module which consists of several thousands of array components has important benefits such as a reduction of package size and higher integrated density.

Comparing to several other kinds of multi-layer package substrate such as High Temperature Co-fired Ceramic (HTCC), thick film, thin film and organic packaging, the LTCC technology has its own advantage, especially low dielectric losses and low material density. Based on the tested data, the loss of 50 Ohm line at 10 GHz is merely 0.01-0.02 dB mm^{-1} and the density of this material is only 2.6 g cm^{-3}. That is the reason why Multi Chip Modules (MCM) based on LTCC technology were widely used in automotive industry, especially in microwave band (Devlin *et al*., 2001; Sutono *et al*., 2009; Jantunen *et al*., 2003).

In this study, both MMIC and LTCC technologies are utilized in the proposed T/R module. All active chipsets are mounted on the bottom surface of a LTCC based housing cavity while passive components are embedded in the LTCC substrate. Such design arrangement allows the proposed T/R module to have the properties of high integration which leads to smaller size, low transmission loss that results a higher efficiency. Furthermore, high overall performance and low cost are achieved as well.

OVERALL DESIGN

The overall module system based on multilayer LTCC substrate includes eight T/R channels with microwave transistor dies buried in isolated cavities. Each channel consists of a phase shifter, a drive amplifier and a power amplifier for transmitting mode, a low noise amplifier, a drive amplifier and a vector modulator for receiving mode. Switch dies which controlled by digital controller are also buried in each channel used for transmitting/receiving transition. The block diagram of the designed T/R module is illustrated in Fig. 1.

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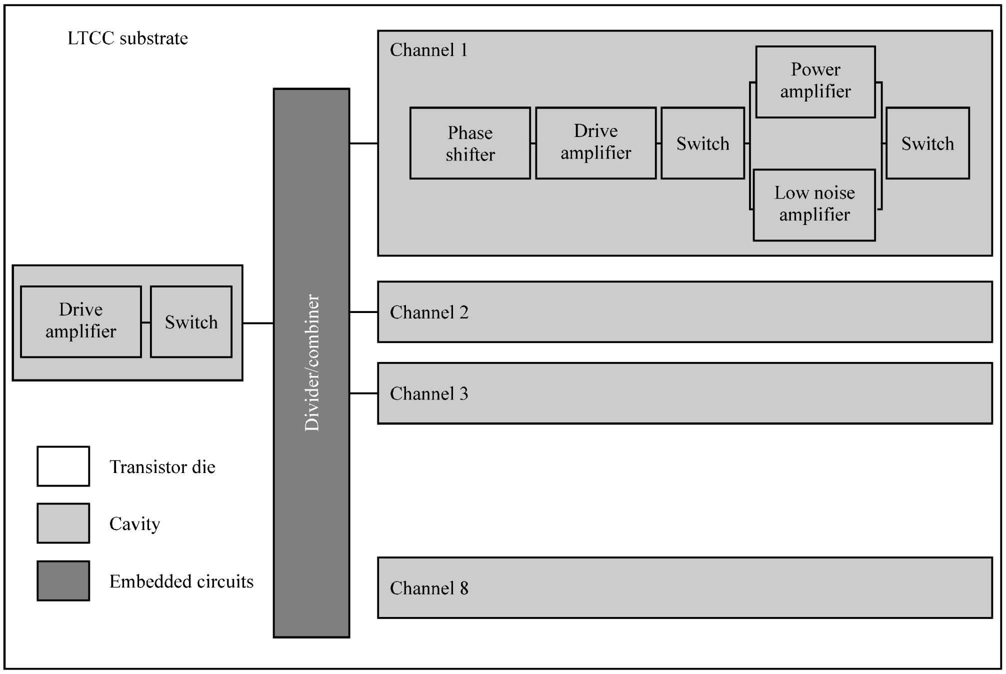

Fig. 1: Proposed T/R module

In Fig. 1, the transmitting signal which magnified by a drive amplifier in common path is distributed to different channels via an embedded passive power splitter. Then, the signal is phase shifted and amplitude modified by a vector modulator. Finally, the modified signal is amplified by drive and power amplifier. When the overall system works in receiving mode, the signal received via antenna unit is firstly amplified by the low noise amplifier and drive amplifier. Then, it is rectified by the vector modulator just as transmitting mode. Finally, the modified signals in each channel are combined by the embedded power combiner and amplified by drive amplifier. Each channel has a multifunction CMOS controller with responsibility for T/R transition, vector modulator control and amplifier bias signal modification. With such a highly integrated design method, multichannel could be integrated in one substrate board. Furthermore, the function of T/R transition and signal rectify are supported in each single channel.

CAVITY DESIGN

Placing a microwave circuit, no matter active or passive, in a cavity which works below the cut-off frequency, the unwanted signal radiation from the microwave elements can be well suppressed, in order to reduce the feedback and gain ripple effects. The cutoff frequency for the cavity can be estimated as:

$$F_C = \frac{C}{2b} \tag{1}$$

where, c denotes the speed of light, b denotes the longest width of the rectangular cavity. Although, in practical applications, the designed cavity contains other substrate which has a dielectric constant great than 1 (the dielectric constant of air), such as GaAs substrate (dielectric constant = 12.9), the contribution of the substrate can be neglected due to the negligible size comparing to the whole cavity.

In this design, the transistor die of one T/R channel is buried in single, isolated cavity which is surrounded by grounded via (Fig. 2). The width b of the cavity is 4 mm which is mainly limited by the size of filters in the T/R channel. Thus from Eq. 1, the cutoff frequency is about 37.5 GHz which is about twice of the operation frequency.

To validate the transmission effect in cavity, numerical simulation has been performed in two kinds of conducting environment which provide nearly the same frequency responses. One of the transmission conditions is within the LTCC cavity surrounded by grounded via and the other is within the metallic cavity, shown in Fig. 2 and 3, respectively. Furthermore, to evaluate the

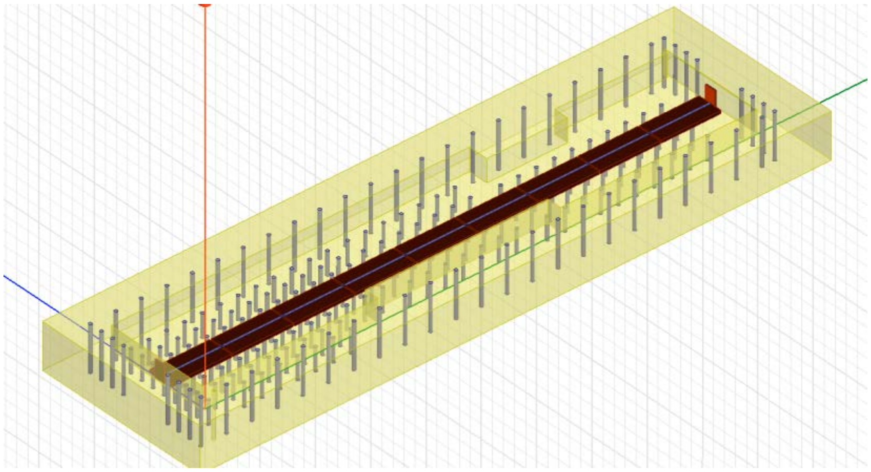

Fig. 2: Microwave signal transmitted in LTCC cavity which surrounded by grounded via

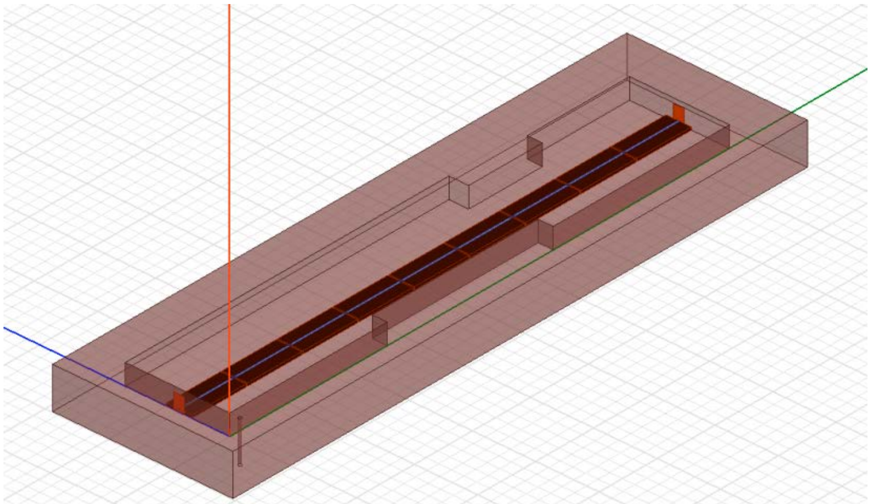

Fig. 3: Microwave signal transmitted in metal cavity

discontinuousness effect to the microwave signal transmission, the influence of different gap sizes between transistor dies has been compared when operated in the channel. The results are shown in Fig. 4-6, respectively. We can conclude that smaller gap between transistor dies could obtain better reflection, especially in the operation band. All the numerical simulations are conducted with the commercial finite element simulation software HFSS.

For the microwave circuits with a high gain or with a high isolation requirement such as the multichannel module in this design, a good rule of thumb is to make the reverse isolation of cavity as strong as possible. Equation 2 can estimate the attenuation of the microwave signal as it travels through the waveguide channel:

$$\text{Alpha} = \text{sqrt}\left(\left(\frac{\pi}{b}\right)^2 - \left(\frac{2\pi f}{c}\right)^2\right) \tag{2}$$

$$\text{Attenuation} = 20\times\log(\exp(\text{Alpha}\times Z))\ \text{dB} \tag{3}$$

where, Alpha represents the attenuation constant and z denotes the length of the channel.

In this design, a narrow, compact, isolated cavity for single T/R channel has been proposed, b = 4 mm,

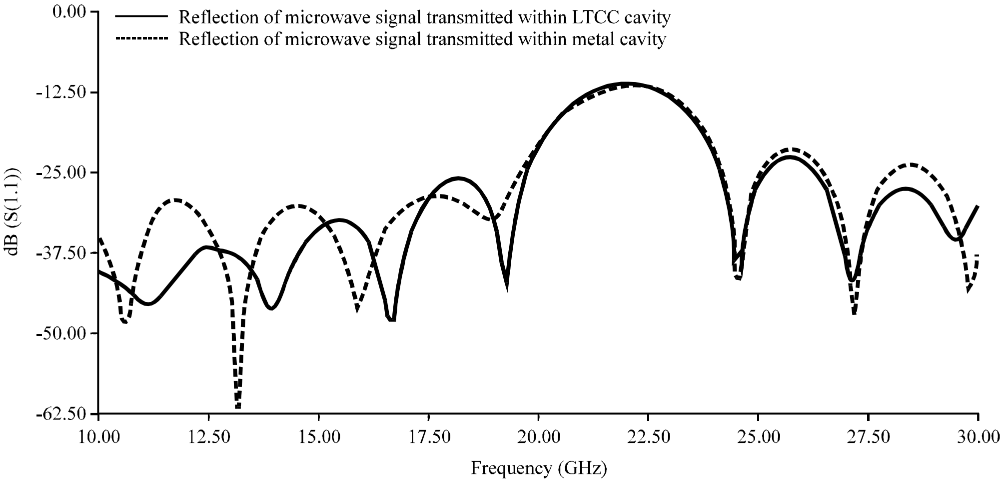

Fig. 4: Reflection of microwave signal transmitted within different cavities when the gap of transistor is 50 μm

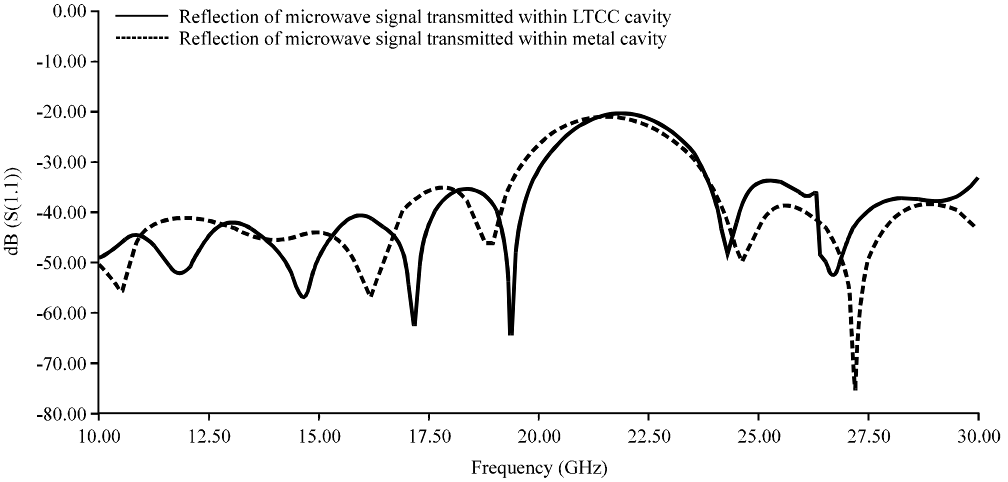

Fig. 5: Reflection of microwave signal transmitted within different cavities when gap of transistor die is 20 μm

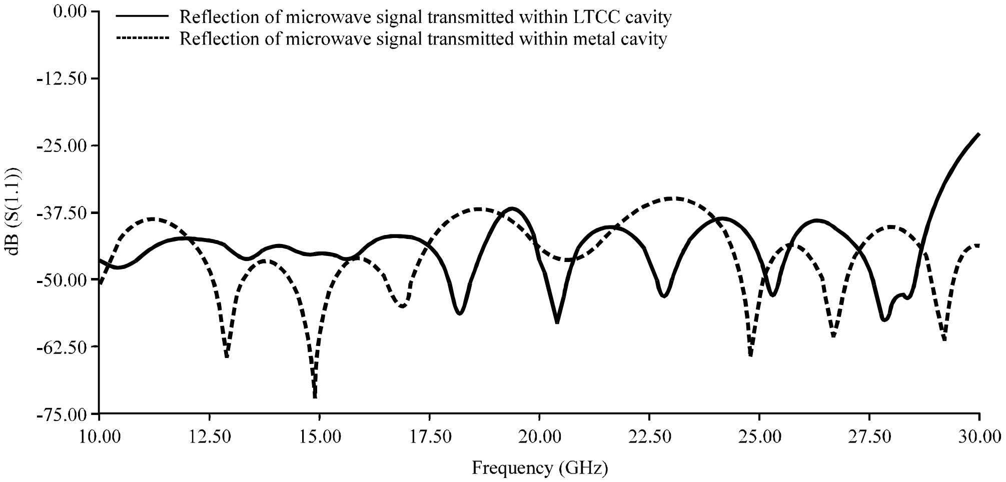

Fig. 6: Reflection of microwave signal transmitted within different cavities when gap of transistor die is 0 μm

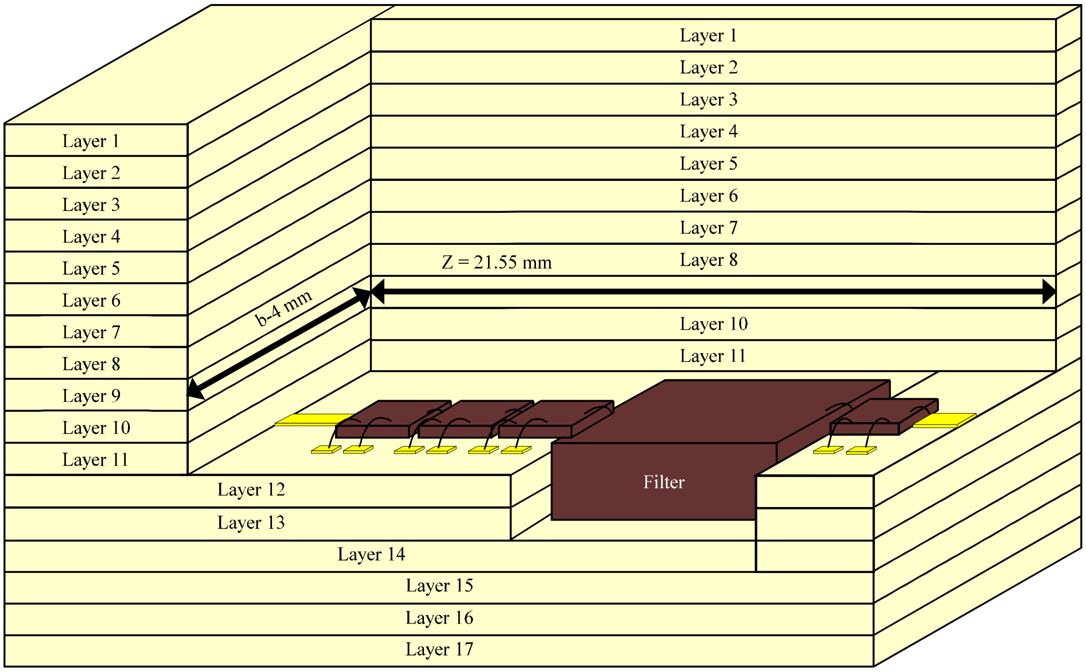

Fig. 7: Cavity structure of single channel

z = 21 mm which determined by the total length of the transistor dies in one channel and the gaps between dies. From Eq. 2 and 3, we obtain Alpha = 635.7, Attenuation = 119 dB which proved that high reverse isolation could be realized. The LTCC cavity structure is depicted in Fig. 7.

LAYOUT ARRANGEMENT DESIGN

The overall layout design can be divided into two parts, the microwave part and the control/power part. Consequently, a reasonable, high-isolated, high-integrated overall arrangement will significantly affect the Electro Magnetic Compatibility (EMC) performance and module cost. In this design, all control signals, including switch signal for T/R transition, bias and power signal for active amplifiers, interface signal for channel communication, are distributed from layer 1 to 8. At the same time, all microwave paths, including embedded power splitter, active amplifier transistor die and microwave transmission line are placed on layer 12 which been shielded by upper (layer 9) and bottom (layer 16) grounded plane. As depicted in Fig. 8a.

Three considerations are made for such a layout arrangement: (1) To avoid control and power signals destroying the grounding integrality of active transistor dies which have back via inside to the bottom of substrate, (2) To isolate the high frequency digital signal (10 M) from the microwave transmitting path and (3) To construct deep, isolated cavity to bury microwave transistor dies for better isolation and stability.

For the purpose of reducing the channel insertion loss as much as possible, in this design method, the microwave signal path is transmitted in a plane. Thus, a transition structure from microstrip (MS) to stripline (SL) has been designed and optimized in the operation band. As depicted from previous section, the layer 12 was used to implement a 50 ohm microstrip transmission line with the dimension W1 = 0.61 mm, the ground plane for MS is placed four layers below. The SL used was also designed for a characteristic impedance of 50 ohm with the dimension W2 = 0.23 mm and was implemented on layer 12. The ground planes for SL were implemented on layer 9 and 16. A top view of the transition structure can be seen in Fig. 8c. Grounded via fencing was designed to prevent resonance between grounding planes. Furthermore, several via fencings also are designed between plane 1 and 9 to prevent resonance in these layers.

The spacing between two via is compromised considering isolation, module cost and fabrication accuracy. A linear tapered transformer structure was used in this design to achieve a better matching. In general, the longer the taper section, the better the reflection performance. In this design, a taper section with the dimension D2 = 0.5 mm is optimized by simulation tools.

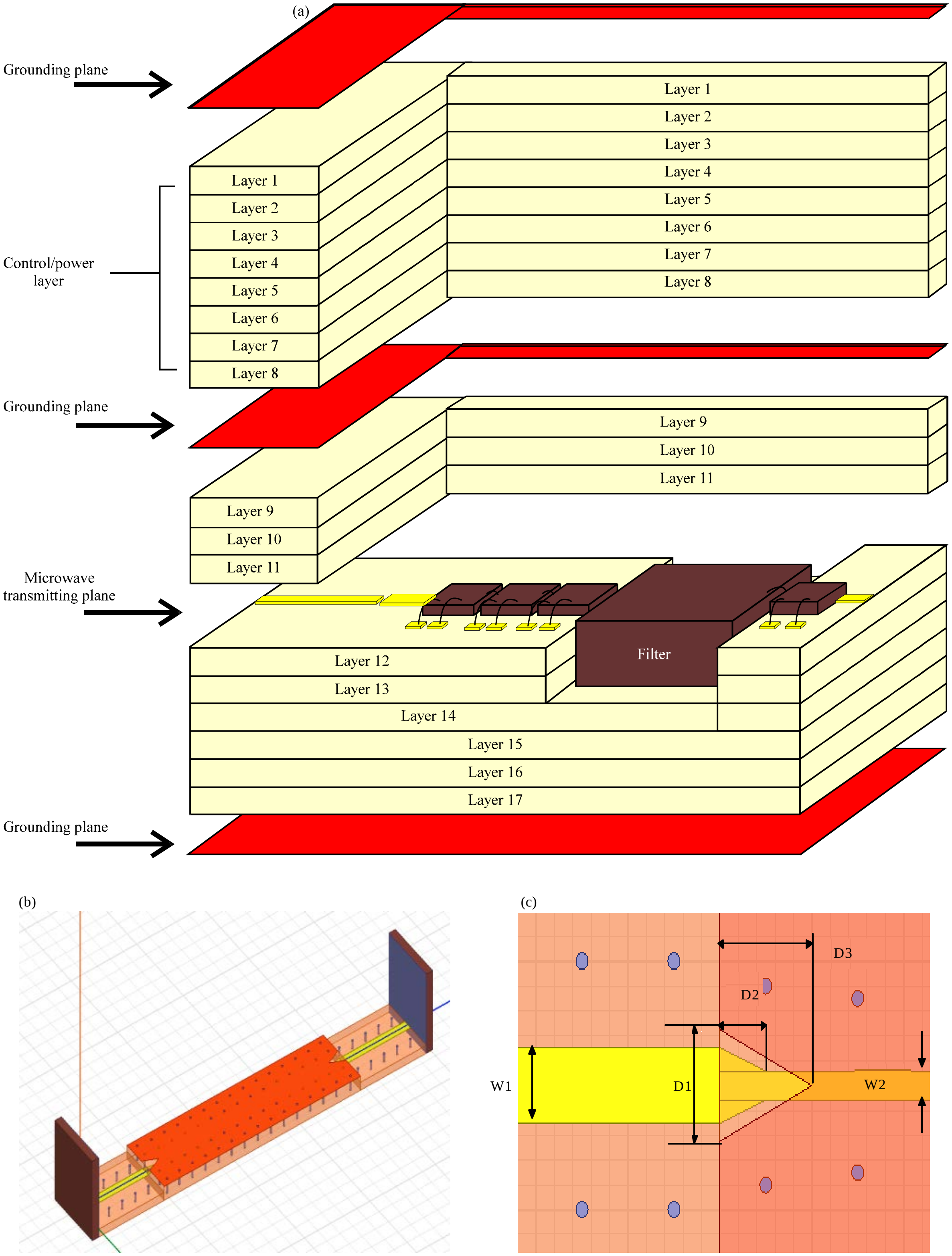

Fig. 8(a-c): (a) Layout arrangement of the overall design, (b) 3D simulation model of transition structure from microstrip to stripline and (c) Dimension of transition structure and optimized simulation results of reflection

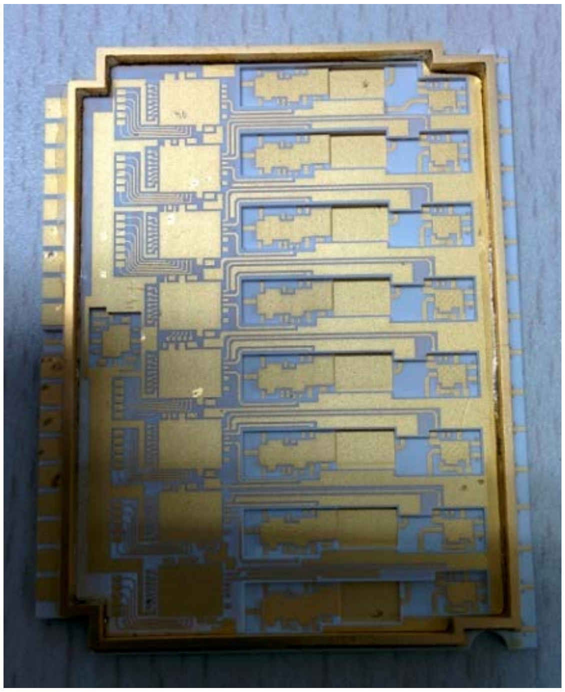

Fig. 9: T/R module with LTCC technology

A triangular section was dig out on the upper grounding plane (layer 9) to compensate the discontinuousness caused by different width of transmission lines. Figure 9 presents the photo of T/R module based on LTCC technology.

CONCLUSION

In this study, a highly integrated T/R module for K-band phased array radar is introduced. The LTCC based housing cavity design contains of 16 layers for the RF signal path and power supplies to the active chipset and the control signal. Extra ground layers are used for protecting the analog control signal from other interference. Through-holes connected with RF ground are used to construct a shielding wall for reducing the RF signal interference. Such arrangements allow the designed T/R module has a smaller size which leads to the improving of efficiency, reducing of size, weight and cost. The simulation results of the embedded passive RF devices demonstrate that the design well fit with the requirements. Furthermore, the future work will be the testing of the T/R module with all the active chipset assembled.

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