Compact multiplexer modules for multi-band wireless systems using LTCC technology

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Abstract: Recently, compact wireless modules are very significant parts for multi-band wireless systems such as mobile phones and compact personal computers. A low temperature co-fired ceramic (LTCC) substrate which has embedded passive components is effective technology for producing the compact modules, because this substrate is suitable for a multilayer structure and is also a low dielectric loss and a low conductor loss. Therefore, a lot of multi-band wireless systems use this technology. In the radio frequency circuits of the multi-band wireless systems, a multiplexer is one of the most important passive circuits, in order to achieve both a compact size and high performances. In this paper, we report the technology of the compact multiplexer modules using the LTCC substrate. This paper especially focuses on the multiplexer for ultra-wideband wireless systems. The multiplexer which is suitable for narrow band wireless systems is also described.

Keywords: low temperature co-fired ceramic (LTCC) substrate, module, multiplexer, multi-band wireless system, surface acoustic wave (SAW) filter, ultra-wideband (UWB)

Classification: Microwave and millimeter wave devices, circuits, and systems

References


1 Introduction

Wireless systems such as mobile phones, Bluetooth, a wireless local area network, and a global positioning system (GPS) have been used worldwide. New wireless technology including ultra-wideband (UWB) wireless systems has been studied actively [1]. Multi-band wireless systems including the many wireless specifications become widely used in order to achieve high speed wireless communications, low power consumption, and a wide communication area. The multi-band wireless systems require a lot of radio frequency (RF) components such as filters, switches, and multiplexers. The multiplexer is one of the most important circuits for miniaturization of the RF circuits and high-performance wireless communications [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13].

Compact implementation methods of high-performance RF circuits are significant for the wireless systems. A low temperature co-fired ceramic (LTCC) technology is very useful for the implementation method because many passive circuits and interconnections can be compactly fabricated in the substrate [3, 5, 6, 8, 10, 12, 13, 14, 15, 16]. Since the 1990s, modules using the LTCC substrate for the compact wireless systems have been actively studied and developed with the progress of the mobile terminal market [14]. Currently, this technology is adapted to the many compact wireless systems worldwide.

In this review paper, we describe the compact multiplexers using the LTCC substrate. Section 2 describes the overview of the modules using the LTCC technology and the role of multiplexer modules. In Section 3, we explain matching conditions of the multiplexer and the compact multiplexers for the multi-band UWB wireless systems. The multiplexer using surface acoustic wave (SAW) filters is also described in this section. Finally, conclusion is summarized in Section 4.
2 Compact wireless modules based on LTCC technology

2.1 Overview of a structure and processes

The compact wireless modules have been widely used in the wireless systems. Many of these modules use the substrate which can embed the some passive circuits. The LTCC substrate is one of the most effective methods, because high-performance passive circuits can be compactly embedded in the substrate. Figure 1 shows a general structure of the compact wireless modules using the LTCC substrate. The modules are generally composed of the LTCC substrate, surface mounting components, a shield, and passive components embedded in the LTCC substrate (e.g., filter, multiplexer, coupler, and matching circuits). The mounting components are integrated circuits (ICs), chip components, SAW filters, and so on. The embedded components in the LTCC substrate are fabricated by using the multilayer structure based on thin ceramic sheets and conductor patterns. It becomes possible to produce very compact modules compared to those with a general printed circuit board (PCB) substrate, because a number of passive components can be embedded in the substrate. The LTCC technology is suitable for not only the substrate for the modules but also very compact components [17, 18, 19]. Recently, LTCC components using a substrate integrate waveguide are also studied [20].

Figure 2 indicates a general procedure for making the compact wireless modules using the LTCC substrate. The process of the production can be separated into two major categories. One category is the production of the LTCC substrate embedded the integrated passive circuits. The other is the fabrication of the module using the LTCC substrate. The details of the procedure are explained in the following. In the first step, the sheets of the ceramics are made. The thickness of the sheets is very thin. For instance, the thinnest sheet is less than 20 µm. It is low dielectric loss. In a lot of cases, the relative permittivity of the sheets is less than 10.0. Via holes are formed in the second step. It is possible to make very small holes. For instance the diameter of the via holes is less than 100 µm. The conductor patterns are printed in the third step. Silver or copper is used for the conductor. The conductivity of the silver and that of the copper are ideally $6.1 \times 10^7$ S/m and $5.8 \times 10^7$ S/m, respectively. They are very high conductivity. In the fourth step, the sheets which have via holes and printed conductor patterns...
Fig. 2. General procedure for making compact modules using LTCC technology.

are stacked according to the design of the LTCC structure. The processes of pressing, co-firing, and coating are sequentially conducted in the step 5 through step 7. The LTCC substrate is built by the above processes.

Next, the modules are fabricated by using the fabricated LTCC substrate. In the step 8, the surface mounting components and the shield are mounted on the substrate. The substrate is separated according to the size of each module in the step 9. The compact wireless modules using the LTCC substrate are completed.

2.2 Multiplexer for wireless systems

Figure 3 indicates a schematic of the multiplexer, which is widely used for the compact multiplexer modules based on the LTCC technology. It consists of the band pass filters (BPFs) and matching circuits. In some situations, a low pass filter, a high pass filter, and a band stop filter are used instead of the BPFs, and the multiplexer at the common port sets the matching circuits. The multiplexer can select each band and suppress frequency responses in the out-of-band region. Figure 4 shows examples of an RF front-end of the multi-band wireless system. Figure 4 (a) indicates the schematic using multiple antennas. This method requires a very large size due to the multiple
Fig. 3. Multiplexer.

Fig. 4. Examples of the multi-band wireless systems; (a) system using multiple antennas, (b) system using an RF switch, (c) system using a multiplexer.

Wires. Figure 4 (b) shows the system which uses a wideband antenna, an RF switch, and BPFs. This system is suitable for the compact-size implementation due to eliminate the multiple antennas. However, the system requires the RF switch. This system cannot receive high-frequency signals simultaneously. For instance, it is difficult to receive frequency signals from $f_2$ to $f_n$ at each system, when the high-frequency signal $f_1$ is passed between the wideband antenna and the BPF1 by the RF switch as shown in Fig. 4 (b). The RF circuit using the multiplexer is shown in Fig. 4 (c). This method can eliminate the RF switch and the multiple antennas. It can simultaneously receive the signals of each band and the RF circuit is also very simple. Note that the multiplexer cannot separate the bands which are the same frequency.
3 Multiplexer modules using an LTCC substrate

3.1 Matching conditions for multiplexers

We describe two matching conditions for the multiplexer, which are suitable for the wireless modules. Figure 5 (a) shows a diplexer using open conditions. Here, the diplexer is the simplest multiplexer for the two bands. The matching circuits of this method are transmission lines which act as phase shifters. The matching circuits of one BPF are designed using the open condition at the passband of the other BPF. Therefore, the lengths of the transmission lines between a common port and each filter are determined by

\[ Y_{o1} = 0.02 \quad \text{at} \quad f_1 \]  
\[ Y_{o2} = 0.02 \quad \text{at} \quad f_2 \]  
\[ Y_{o2} = 0 \quad \text{at} \quad f_1 \]

where, the reference admittance of each port is 0.02 S and input admittances of each BPF with a transmission line are \( Y_{o1} \) and \( Y_{o2} \). This design method is simple. Theoretically these matching conditions can be expanded to multiple bands. However, the transmission lines for the matching circuits are large in size. It is not suitable for wide passbands because the design of the open conditions in the wide bands is difficult.

The diplexer based on the matching conditions using arbitrary susceptances is indicated in Fig. 5 (b) [2]. In this method, the matching circuits between the common port and each filter are ideally determined by the conditions of (5)-(8) as follows:

\[ Y_{c1} = 0.02 + jX \quad \text{at} \quad f_1 \]  
\[ Y_{c1} = jY \quad \text{at} \quad f_2 \]
Fig. 6. UWB diplexer [10]; (a) schematic, (b) input admittance ($Y_{\text{low}}$), (c) input admittance ($Y_{\text{high}}$).

\[
Y_{c2} = 0.02 - jY \quad (\text{at } f_2) \quad (7)
\]
\[
Y_{c2} = -jX \quad (\text{at } f_1) \quad (8)
\]

where, the reference admittance of each port is 0.02 S and input admittances of each BPF with the matching circuit are $Y_1$ and $Y_2$. This method can achieve the compact size. It is suitable for the wide passbands.

### 3.2 Multiplexer for ultra-wideband systems

UWB wireless communication systems are researched worldwide. This systems use the ultra-wide band to achieve the high speed communications and low level signals. However, the design methods of the RF circuits for the wide band are difficult. Therefore, the RF circuits for the UWB systems are actively studied. In this section, we explain about the diplexer and a triplexer for the UWB systems. Figure 6 shows the UWB diplexer in the LTCC substrate [10]. The UWB systems are assumed for the band groups 1, 3, and 4 of the multi-band orthogonal frequency-division multiplexing systems [1]. It is comprised of two UWB BPFs and the matching circuits. The UWB BPFs [21] for the compact wireless module using the LTCC technology...
are chosen. The diplexer adapts the matching conditions using the arbitrary susceptances as shown in Figs. 6 (b) and (c). Simulations of Figs. 6 (b) and (c) are carried out by a circuit simulator (Ansoft Designer SV, ANSYS Inc.). The input admittance of the BPF for the low-frequency band is the inductive region at 3.88 GHz and acts as the inductor at 7.76 GHz. On the other hand, the input admittance of the filter for the high-frequency band is the capacitive region at 7.76 GHz and behaves as the capacitor at 3.88 GHz.

Figure 7 indicates an LTCC structure of the diplexer and measured results with electromagnetic simulated results. The relative permittivity of the LTCC substrate is 8.0. The material of the conductor in the substrate is the silver. It is composed of the three conductor layers inserted in the middle part of the LTCC substrate and the ground planes installed on the top and bottom layers. The size is compact \((7.2 \times 3.6 \times 0.384 \, \text{mm}^3)\). The UWB diplexer can separate the low-frequency band (3.168-4.752 GHz) from the high-frequency
(6.336-9.504 GHz) band. Insertion losses are less than 2.0 dB and isolation characteristics are 30 dB.

Figure 8 shows the triplexer for the UWB systems and 2.4 GHz wireless systems [13]. An LPF for the 2.4 GHz wireless systems consists of inductors and capacitors. The UWB diplexer has a strip line at the common port, in order to decrease the input admittance. The common port of the triplexer is equipped with matching circuits composed of a series inductor and a grounding capacitor. The dimension of the triplexer is $5.3 \times 5.3 \times 0.384$ mm$^3$. The insertion losses are less than 2.0 dB in the three passbands and the isolation characteristics are higher than 24 dB.

### 3.3 Multiplexer using SAW filters

The SAW filter is an important part for the wireless systems because it can obtain very sharp attenuation characteristics. The multiplexer modules which combine the SAW filters and the LTCC substrate have also been studied. Figure 9 shows an example of the triplexer using the SAW filters. This
prototype is for a universal mobile telecommunications system (UMTS) Band I, the UMTS Band II, and the GPS. The UMTS bands are assumed to be used for the downlink in which the SAW filters acts in the receive path at the mobile terminal. This triplexer consists of the SAW filters and matching circuits. The matching circuits which are set at each port of the SAW filters are a high pass filter type. Three SAW filters and two inductors are mounted on the substrate. The sizes of the inductor and the SAW filter are $0.6 \times 0.3 \times 0.3 \text{mm}^3$ and $1.4 \times 1.0 \times 0.5 \text{mm}^3$, respectively. These components
are produced by TAIYO YUDEN CO., LTD. The relative permittivity of the LTCC substrate is 7.1 and the conductor in the substrate is the silver. Interconnections, two inductors, three capacitors, and a strip line are embedded in the LTCC substrate.

It is confirmed that the prototype can separate the three bands. The insertion losses of the UMTS Band I Rx (2.11-2.17 GHz), the UMTS Band II Rx (1.93-1.99 GHz), and the GPS (1.574-1.577 GHz) are 3.1 dB, 2.7 dB, and 1.8 dB, respectively. The size is $3.3 \times 3.2 \times 1.0 \text{mm}^3$. The triplexer which combines the filters embedded in the LTCC substrate with the SAW filter has also been proposed [3]. The multiplexer for five bands can be fabricated by two duplexers and the triplexer [7]. This example uses a multilayer PCB substrate which can embed the passive components.

### 3.4 Future works of the multiplexer

Many wireless systems exist in our environment, and a number of applications using the multiple wireless specifications are rapidly increasing. Effective use of frequency resources is very important for the high speed wireless communications. For instance, multi-input multi-output wireless systems are implemented by some wireless systems. In LTE-advanced technology, carrier aggregation technology which uses some bands for the wireless communications is studied [22]. Therefore, the RF circuits will be complex and on a large scale in the future. In order to achieve high-performance RF circuits with a compact size, the multiplexer is one of the most important technologies. Main future works of the multiplexer for the multi-band wireless systems are the following items:
1) developments of miniaturization technology including the design methods and the process of manufacture;
2) developments of effective methods for separating multiple bands including both wide passbands and narrow passbands;
3) study of effective frequency selective methods using the multiplexer and the RF switch.

### 4 Conclusion

The wireless modules using the LTCC substrate are one of the most effective solutions for the multi-band wireless systems, because this technology enables us to make the system both in high performance and in compact size. In addition, the multiplexer has become increasingly important in the multi-band wireless systems. In this review paper, we report the compact multiplexers using the LTCC technology. The overview of the LTCC technology including the structure and the process is explained. The multiplexers which focus on the multi-band UWB wireless systems are reviewed. The compact multiplexer using the SAW filters is also described. We hope to the expansion of this field for the high speed wireless communications.
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