Compact LTCC Diplexer With High Frequency Selectivity and High Isolation

Kewei Qian\textsuperscript{1} and Xiangru Chen\textsuperscript{1}

\textsuperscript{1}University of Electronic Science and Technology of China

May 31, 2023

Abstract

This paper proposes a design method of low temperature co-fired ceramic (LTCC) diplexer, which is used to separate GPS and ISM band signals, achieves high isolation and miniaturization, and can be used in electronic consumer products. The diplexer is composed of a low-pass filter and a band-pass filter. The antenna separates the received mixed signals according to frequency bands, and enters their respective processing modules through two output ports. The size of the diplexer is 1.6mm*0.8mm*0.6mm, the insertion loss is less than 0.6dB for GPS 1.575GHz application, the isolation is greater than 26dB, and the insertion loss is less than 0.6dB for ISM 2.4/5GHz application, the isolation is greater than 37dB. Compared with the reported LTCC diplexer, the features of this diplexer are that the lower channel occupies a smaller volume at lower frequency, and the higher channel maintains low insertion loss in a wider bandwidth, and the passbands of the two filters are close but still have high isolation.

Hosted file

Compact LTCC Diplexer With High Frequency Selectivity and High Isolation.rar available at https://authorea.com/users/624177/articles/646589-compact-ltcc-diplexer-with-high-frequency-selectivity-and-high-isolation
Compact LTCC Diplexer With High Frequency Selectivity and High Isolation

Kewei Qian\textsuperscript{1} and Xiangru Chen\textsuperscript{2}
\textsuperscript{1}University of Electronic Science and Technology of China, Chengdu, 611731, CN
\textsuperscript{2}University of Electronic Science and Technology of China, Chengdu, 611731, CN
Email: qiankewei@uestc.edu.cn

Abstract. This paper proposes a design method of low temperature co-fired ceramic (LTCC) diplexer, which is used to separate GPS and ISM band signals, achieves low insertion loss, high isolation and miniaturization, and can be used in electronic consumer products. The diplexer is composed of a low-pass filter and a band-pass filter. The antenna separates the received mixed signals according to frequency bands, and enters their respective processing modules through two output ports. The insertion loss is less than 0.6dB for GPS channel, the isolation is greater than 26dB, and the insertion loss is less than 0.6dB for ISM channel, the isolation is greater than 37dB. The size of the whole diplexer is 1.6mm×0.8mm×0.6mm. Compared with the reported LTCC diplexer, the features of this diplexer are that operating frequency of the diplexer is very low but it has small size, the higher channel maintains low insertion loss in a wider bandwidth, and the pass-bands of the two filters are close but still have high isolation.

Introduction: As one of the indispensable passive devices in the communication system, the diplexer is generally composed of two filters, which are mainly used for signal separation and spectrum isolation. Its performance directly affects the frequency response of the system. With the rapid development of microwave systems, passive devices are developing in the direction of high integration, high performance, low loss and low cost, which puts forward higher requirements for the design of diplexers.

Since 1982, the rapid development of LTCC technology has brought great economic benefits and also has broad market prospects in the future. LTCC diplexers are widely used, but they mainly appear in the form of commodities of monopoly enterprises. The relevant research reports and scientific achievements are far less than LTCC filters. The diplexer has a low operating frequency, and there are few designs that can achieve the package size of 1608 in the same frequency band. One of the diplexers that can achieve the package size of 1608 in the same frequency of diplexer can be summarized into the following three points:

1. The diplexer has a low operating frequency, and there are few designs that can achieve the package size of 1608 in the same frequency band.

2. The passband of the bandpass filter is very wide (2.4-5.9GHz), but it needs to maintain low insertion loss in the wide passband.

3. The center frequencies of the low-pass filter and the band-pass filter are very close, but they need to achieve high isolation, which means that both of them must have high frequency selectivity.

Theory: In order to meet the above requirements, we conducted many experiments, and finally determined the schematic of the diplexer as shown in Figure 1.

![Fig. 1 Schematic of the diplexer](image)

On the basis of the fourth-order prototype low-pass filter, the transmission zeros are introduced through the resonant unit, which can effectively improve the out-of-band suppression at high frequencies. The design requires extremely low insertion loss and the Butterworth filter has a passband with maximum flatness and it is therefore suitable. The order of the filter affects both the size and the performance. Low order leads to poor performance, and too high order will increase the size. The choice of 4 order low-pass filter is a compromise for miniaturization and high performance. The cut-off frequency is about 2GHz, the characteristic impedance is 50Ω, so L1=L2=3.045nH, C2=C3=2.941pF. The other element values can be calculated using Formula 1.

\[ \omega = \frac{1}{\sqrt{LC}} \] (1)

The first transmission zero should be located near 2.5GHz, controlled by L2 and C1, and the second is located near 4.5GHz, controlled by C2 and L3. C1=1.33pF, L3=0.43nH can be obtained according to Formula 1. After the circuit optimization, L1=3.67nH, L2=3.71nH, L3=0.56nH, C1=1.04pF, C2=0.76pF, C3=2.27pF.

The simulation result of LPF is shown in Figure 2.

![Fig. 2 Simulation result of LPF](image)

Design: In this paper, we propose a design method of LTCC diplexer based on lumped-element for GPS 1.575GHz/ISM 2.4GHz/5GHz band RF application. By analyzing the design indexes, the design difficulties of diplexer can be summarized into the following three points:

1. The diplexer has a low operating frequency, and there are few designs that can achieve the package size of 1608 in the same frequency band.

2. The passband of the bandpass filter is very wide (2.4-5.9GHz), but it needs to maintain low insertion loss in the wide passband.

3. The center frequencies of the low-pass filter and the band-pass filter are very close, but they need to achieve high isolation, which means that...
introduces a transmission zero on the basis of the third-order high-pass filter, and the low-pass module has no attenuation index, using a capacitor and inductor is enough to meet the design requirements.

The cut-off frequency of the bandpass filter is located near 2GHz, and the cut-off frequency of the bandpass filter is located near 6.5GHz. Then the transmission zero introduced by adding C5 should be set at 1.5GHz, the element value after the circuit optimization is that C4=1.27pF, C5=2.49pF, C6=1.11pF, C7=0.3pF, L4=4.37nH, L5=1.51nH.

The simulation result of BPF is shown in Figure3.

![Simulation result of BPF](image1)

**Fig. 3** Simulation result of BPF

The topological structures of both low-pass and bandpass filters can be represented by network structures, as shown in Figure4.

![Network structure of filters](image2)

**Fig. 4** Network structure of filters

According to the definition of Y matrix, the expression of Y12 is

\[ Y_{12} = \frac{-Y_1 \times Y_2}{Y_1 + Y_2 + Y_3} \]

(2)

For the low pass filter,

\[ Y_1 = \frac{1}{j \omega L_1}, \quad Y_2 = \frac{-\omega^2 C_1 L_2 + 1}{j \omega L_2}, \quad Y_3 = \frac{j \omega C_2}{-\omega^2 C_1 L_2 + 1} \]

(3)

For the band pass filter,

\[ Y'_1 = j \omega C_4, \quad Y'_2 = \frac{j \omega C_6}{-\omega^2 C_6 L_5 + 1}, \quad Y'_3 = \frac{j \omega C_5}{-\omega^2 C_5 L_4 + 1} \]

(4)

Substituting equations (2) and (3) into equations (1), the numerator of the denominator of Y12 is respectively

\[ Y_{12} = (\omega^3 C_1 L_2 - 1) (-\omega^2 C_2 L_3 + 1) \]

(5)

Therefore, it can be deduced from the formula (4) that C1 and L2 control the position of the first transmission zero in the low-pass filter, and C2 and L3 control the position of the second transmission zero. The position of transmission zero in the second module is controlled by C5 and L4, which is consistent with the simulation results of ADS.

**Realization of diplexer:** Since the diplexer operates at a lower frequency band, large inductors and capacitors are required to implement the circuit. Due to the flexibility of the LTCC technology, both large inductance and large capacitance can be easily realized in small-sized dielectric substrates. Figure5 shows the 3D structure of LTCC large inductance and large capacitance. The inductance is wound by 4-5 layers of conductors, and the layers are connected through vias. Increasing the width or length of the condenser increases the inductance value. Compared with metal-insulator-metal(MIM) capacitors, vertically-interdigitated capacitors(VIC) connect the odd-layer and even-layer through vias respectively, which dominates in realizing miniaturization and large capacitance value. In the case of the same area, the capacitance value of VIC is about 3 times that of MIM[8], and the capacitance value is determined by the length, width and distance of the parallel plate.

![3D structure of elements](image3)

**Fig. 5** 3D structure of elements

- **a** 3D structure of inductance.
- **b** 3D structure of capacitance.

To accommodate the operating frequency, we choose a dielectric substrate with a dielectric constant of 9.8. In order to realize the miniaturization of the capacitor, the layer distance is selected as 0.02mm. In order to reduce the capacitance parasitic effect of the inductor, the width of the conductor is 0.05mm, and the silver thickness is 0.01mm.

On the basis of the schematic, the three-dimensional models of inductors and capacitors are designed through the inductor empirical formula[9] and the plate capacitor formula, but this is far from enough. Under the condition of high frequency, the coupling effect between elements is relatively serious, and small-sized packaging is required, so the reasonable layout of elements is critical to filter performance. The solution we give is to reasonably partition the dielectric substrate to achieve physical isolation between elements. In the horizontal direction, the two filters are placed on the left and right sides of the substrate respectively. In the vertical direction, the substrate is divided into three areas - inductive area, capacitive area and grounding area, and the distance between the areas can effectively reduce the coupling. Inductive and capacitive regions alternate in both vertical and horizontal directions, as shown in Figure6.

![Structure of the diplexer](image4)

**Fig. 6** Structure of the diplexer

After completing the circuit layout, we simulated the 3D models of the two filters separately. Although we refer to the empirical formulas of capacitance and inductance when designing the circuit to make the equivalent values of three-dimensional inductance and capacitance close to that of ideal components, there are some differences due to parasitics. This is because the inductance and capacitance values of the 3D model vary with frequency, while ideal lumped components do not. Therefore, the simulation results of the filter may not exactly match expectations. In general, 3D circuits are inferior to ideal circuits with out-of-band rejection, but, fortunately, changes in 3D inductance and capacitance values have almost the same effect on the circuit as an ideal lumped component value change. Therefore, we need to use this regularity to guide the debugging process to meet the design requirements of the filter. Figure7 shows the simulation results of the low-pass filter and the band-pass filter under the three-dimensional structure.
**Performance of LTCC diplexer:** Combining the two filters, the package size is only 1.6mm*0.8mm*0.6mm. The two filters are only connected by a T-junction, and there is mutual interference between the filters, resulting in poor performance of the diplexer. In order to increase the isolation between the filters, it can be achieved by tuning the element values around the T-junction. The performance parameters of the LTCC diplexer are obtained through simulation. As shown in Figure 8: the insertion loss in the 1.57-1.61GHz is less than 0.6dB, the isolation in 1.57-1.61GHz is greater than 26dB, the insertion loss in the 2.4GHz-2.5GHz and 4.9-5.9GHz is less than 0.6dB, isolation in 2.4GHz-2.5GHz and 4.9-5.9GHz is greater than 37dB. In summary, this filter has a compact size, low insertion loss, and high isolation.

**Fabrication and measurements:** The model was processed into a LTCC diplexer, and the test figure is shown in Figure 9.

**Conclusion:** In this paper, we propose a design method of LTCC diplexer based on lumped-element for GPS 1.575GHz/ISM 2.4GHz/5GHz band RF application. We use lumped elements to achieve miniaturization, and high isolation can be achieved by introducing transmission zeros and controlling transmission zeros position. A detailed schematic design, simulation and optimization have been given, good performance of the diplexer is obtained. Then the diplexer has been fabricated and measured, and the measured results are in good agreements with the designed.

**References**