Four-Channel X-band T/R Front-end Design Based on LTCC Technology

Abstract: With the phased array radar’s further control of the volume and weight, high performance and miniaturized transceiver components based on the LTCC technology are currently an important development direction of the transceiver components. Based on Ferro A6 LTCC process technology, this paper studies the design technology of X-band transceiver front-end components. The designed transceiver front-end can be implemented on a multilayer LTCC substrate. The design specifications meet the application requirements.

Key Words: LTCC substrate, X-band, T/R front-end, four-channel

1 Introduction

X-band transceiver module is widely used in radar, electronic countermeasures, satellite communications and other fields, and is one of the core components of antenna array elements in airborne, shipborne, spaceborne active phased array radar and synthetic aperture radar. According to the requirements of the overall lightweight and miniaturization in the application field, the X-band transceiver front-end module is required to complete the duplex control of transmission and reception functions in a very small volume, to achieve the transmission and reception of microwave radio frequency signals, to achieve a certain transmission power and reception sensitivity, and to reduce the electromagnetic interference between the modules to ensure signal quality. As an advanced multilayer substrate for microwave and radio frequency, LTCC substrate is widely used in transceiver module, its dielectric constant is appropriate, the use of metal materials with high conductivity makes it have excellent high-frequency, high Q performance, its single layer thickness is small, high printing accuracy, easy to make multilayer substrate, improve the assembly density.

2. Analysis of receiving and transmitting component index

The main functions of the X-band four-channel transceiver front-end module include: feeding the transmitted signal to the antenna radiation unit after shunting, phase modulation and high-power amplification; sending the received signal to the back-end receiver after low-noise amplification, phase shift and attenuation.

The main specifications of the X-band four-channel transceiver front-end module circuit are as follows:

1) Operating frequency 8-12GHZ
2) Transmit signal input power: 0dBm
3) Output power $\geq 35$dBm
4) Receive gain $\geq 27$dB
5) Receive noise figure $\leq 4$dB
6) Isolation between receiving channels: $\geq 15$dB
7) The standing wave of the input and output port of the receiving channel: $\leq 2$
8) Numerically controlled phase shifter bits: 6
9) Receive Numeric Control Attenuator Digit: 6 bits
10) Transceiver conversion time $\leq 400$ ns
11) Working voltage: $+8.5V, -5V$

According to the requirements of the transceiver front-end circuit, the device is decomposed, including: low noise amplifier, numerical control attenuator, numerical control
phase shifter, driver stage amplifier, last stage amplifier, limiter, power divider, microwave switch, circulator and other devices.

The circuit schematic design is shown in Figure 1:

![Fig. 1 Single Channel Circuit Schematic (without power divider)](image1)

LTCC substrate design

Based on LTCC multi-layer ceramic substrate technology, the X-band four-channel transceiver front-end module adopts bare chips, surface-mount resistors, capacitors and other devices to be mounted on the surface of the substrate, and realizes the functions of chip grounding and chip heat dissipation by adding grounding holes and heat conduction holes; chips with larger power consumption are directly bonded to metal carriers through the opening of the substrate cavity, so as to achieve better heat dissipation effect. The surface conductor material uses the gold, the silver mixing system, satisfies the component the adhesion, the welding, the bonding and so on many kinds of assembly request.

The X-band four-channel transceiver front-end module mainly realizes the functions of transmitting power amplification, receiving low-noise amplification, phase-shifting switch gating and the like of the radio frequency signal, in addition, the power supply control circuit is needed to provide stable power supply and the digital signal processing unit circuit is needed to provide control signal. In the small space of the substrate, there must be mutual interference between analog signal, digital signal and radio frequency signal, in order to avoid mutual interference between various lines, it is necessary to realize partition management. By taking advantage of the multi-layer wiring of LTCC substrate, the traces of each part of the module are reasonably distributed to each layer of the substrate, and the interference is reduced by adjusting the line direction and increasing the stratum.

In the layout of the multi-layer structure, the radio frequency signal transmission lines are arranged on the surface layer to avoid the extra loss caused by the transition of the multi-layer traveling lines; through setting multi-row grounding holes, signal ground and other structures on both sides of the transmission line, and supplemented by metal partition walls between channels, good isolation between each signal transmission line is realized to meet the requirement of the isolation degree of the signal path; the fifth layer is a radio frequency signal stratum, the influence of the control signal and the power signal on the radio frequency signal is reduced; the sixth to tenth layers are the control signal line layers, and the eleventh to thirteenth layers are the power line layers. Through the layering wiring and the middle stratum arrangement, may the effective reduction between each line mutual interference.

![Fig. 2 Schematic diagram of substrate layout](image2)
4 Simulation of Transceiver Component
4.1 Passive Simulation of Transceiver Front-end

The passive circuit part of the transceiver front-end is mainly about the optimization of transmission line discontinuity, the design of power divider and the simulation of wire bonding, as shown in Figure 3.

The dimension of the surface layer transmission line with impedance of 50 ohms can be obtained by the transmission line calculation formula or the software aided design, and the transmission line dimension can be adjusted and optimized by the simulation software. According to the simulation and optimization results and the limitation of LTCC processing accuracy, the medium layer height is set as 0.376 m, and the line width of microstrip transmission line is selected as 0.52 mm. Because the input and output position of the module is not in a straight line, and to adapt to the requirements of the connection between the components, the surface layer transmission line can not be straight, there is signal transmission line discontinuity in the transmission process, mainly including transmission line bending, transmission line width change, oblique travel line and so on, in the case of transmission line discontinuity need to be based on the actual circuit layout design requirements for targeted simulation and optimization. The design of power divider can also be calculated, simulated and optimized by software, which will not be detailed here. The gold wire bonding is used to realize the connection of chip and signal transmission line, which is another key technology affecting the signal transmission performance, and its performance directly affects the overall performance of the module. Through theoretical analysis, the parasitic inductance and resistance generated by 25um diameter gold wire in X-band is the main factor affecting the signal transmission performance. The key performance indicators of gold wire bonding are the arch height, span and the number of gold wires bonded at the same bonding point. The key indicators are simulated by modeling in HFSS, as shown in Figure 4 and Figure 5.
According to the simulation results, the lower the arch height and the smaller the span, the less the influence of gold wire bonding on signal transmission performance, but in fact, these indicators are affected by processing technology, layout design, chip bonding point size and location, etc.

4.2 Simulation of Active Circuit for Transceiver Front-end

X band transceiver front-end module in each channel mainly includes two functional parts: a receiving branch and a transmitting branch, and the working state is selected and switched through a switch and a circulator. When the transmitting branch of the transceiver front-end is in operation, the input excitation signal is amplified through a phase shifter and a switch, a drive stage amplifier and a final stage amplifier, and is fed to an antenna through the circulator to an output port. In the design of the transmitting branch, the power amplifier is the core device of the transmitting branch, which is responsible for the amplifying function of the transmitting signal, and its selection requires high gain and efficiency, good signal quality, stability and reliability. First, according to the output power requirements, the output power of the final stage amplifier should be more than 35dBm, because there are transmission line circulators, connectors and other parts that can bring transmission loss after the final stage amplifier, there should be a certain margin when selecting devices. Combining with chip selection and circuit stability, matching and other indicators, the transmission branch uses three-stage amplifier structure for circuit design and simulation.

The gain and output power of the entire transmit path are calculated based on the loss and gain values of each part of the circuit, as shown in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>功率(dBm)</th>
<th>输入过载</th>
<th>功率放大</th>
<th>第一级 PA</th>
<th>第二级 PA</th>
<th>外部 PA</th>
<th>限幅器</th>
<th>输出过载</th>
<th>输出功率</th>
<th>输出增益</th>
</tr>
</thead>
<tbody>
<tr>
<td>功率(dBm)</td>
<td>0</td>
<td>-0.15</td>
<td>-7.15</td>
<td>3.85</td>
<td>16.85</td>
<td>37.85</td>
<td>37.25</td>
<td>37.1</td>
<td>37.1</td>
<td></td>
</tr>
<tr>
<td>增益(dB)</td>
<td>0</td>
<td>-0.15</td>
<td>-7</td>
<td>11</td>
<td>13</td>
<td>21</td>
<td>-0.6</td>
<td>-0.15</td>
<td>37.1</td>
<td></td>
</tr>
</tbody>
</table>
The calculation results show that the device selection can meet the requirements of component circuit design indicators, and leave a certain margin.

When the receiving branch of the transceiver front end is in operation, the weak signal fed by the antenna is sent to the low noise amplifier by the limiter, and the signal is amplified by multi-level and then reached the receiver by the phase shifter and switch. In the design of the receiving branch, the selection of the low noise amplifier is the core of the design, which requires low noise figure, high gain, good flatness, large dynamic range, stable and reliable, especially the noise figure and gain of the first stage low noise amplifier have the greatest influence on the performance of the whole receiving branch. In order to control the whole gain of the receiving branch and improve the inter-stage matching of the LNA, an adjustable attenuator is added between each stage of the LNA.

According to the calculation results, it can be seen that the device selection can meet the requirements of the index, and there is a certain design margin.

5 Layout Design

According to the LTCC process parameters of the Ferro A6 material, the layout of the front-end of the X-band four-channel transceiver module is carried out.

1) The minimum line width and line spacing of the conduction band are 0.075 mm, and the maximum line width is 1.5 mm;

2) that minimum distance between the conduction band is 0.075 mm;

3) that size of the common through hole are 0.100mm, 0.150mm, 0.200mm and 0.300mm;

4) in that same layer, the minimum through hole spacing is \(2.5 \times \Phi\), or 0.5 mm; in two adjacent layer, the minimum through hole spacing of the offset through hole is \(2.0 \times \Phi\); the minimum distance from the center of the through hole to the edge of the ceramic tape layer is \(3 \times \Phi\), or the edge of the hole is 0.38 mm from the edge;

5) The distance between the edge of the through hole and the edge of the conduction band is 0.25 mm;

6) Large area conductors such as ground layer and power layer in the multilayer substrate shall adopt grid-like structure as far as possible, with a conductor coverage area of about 50% and an optimal line width of 250 µm to 400 µm.

The final layout is shown in Figure 6.
Summary

X-band four-channel transceiver front-end module is an important component in the radar system. With the development of phased array radar system, miniaturization, lightweight, high performance, high consistency and high reliability are the focus of the development of transceiver front-end module. Based on the design experience, the circuit is designed by using HSS and other advanced simulation software technology, and combined with LTCC substrate processing technology, an X-band four-channel transceiver front-end module based on LTCC substrate technology is designed, the design results show that the design index can meet the performance requirements of transceiver front-end, product substrate design LTCC processing requirements, the transceiver front-end module products can be applied to radar communication system.