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Research on Broadband Microwave Temperature Compensation Attenuator

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Abstract. This paper introduces a research process of a broadband microwave temperature compensation attenuator, including studying on materials and technics, designing of circuit structure, emulating with HFSS, trial-producing of samples, and analyzing the results. Finally, by sintering NTC and PTC pastes on 96% Al_2O_3 chip and using Thick-Film technics, we successfully design a broadband negative temperature compensation attenuator.

Key words: attenuator, temperature compensation, broadband, thermistor.

1. Introduction

Active devices in microwave circuits are usually silicon or gallium arsenide devices ,and its performance varies with temperature fluctuations, making the high and low temperature performance of microwave circuits volatile, and even making the product performance excessive. One way to suppress these fluctuations is to use temperature compensation circuit. There are two ways commonly used in temperature compensation. One way to compensate is using the principle that PN junction voltage drop decreases with increasing temperature (including diodes and transistors compensation), the other way is the use of thermal devices to compensate.

This paper uses thermal devices to compensate. Specific approach is based on the study the characteristics of existing thermistor paste [1], through deployment, testing, getting the slurry which was required for the design. Then using thick film technology [2], we can create a broadband temperature compensation attenuator with negative temperature characteristics. Experiments show that the indexes of this broadband microwave temperature compensation attenuator chip is close to practical standards, and it has great value to continue to explore.

2. Content and objectives of the study

2.1. Material

The substrate material of the attenuator uses 96% alumina ceramic substrate, and its thickness is 0.381mm. The core of the attenuator is negative temperature coefficient (NTC) thermistor and positive temperature coefficient (PTC) thermistor, which determines the device performance. The key performance indicators of thermistor slurry are sheet resistance, temperature coefficient and resistance range. The relationship that the resistance of PTC thermistor slurry changes with temperature is linear, and the temperature coefficient is a constant, material properties are also very stable.

The NTC thermistor slurry is generally based on semiconductor material, and its resistance changing with temperature shows non-linear characteristics. Generally we used to express resistance - temperature characteristics by B, and its expression is:

$$B = \frac{\ln R_2 - \ln R_1}{1/T_2 - 1/T_1} \qquad (1)$$

In equation (1) , B is material constant, T1 is reference absolute temperature (K), T2 is another absolute

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temperature (K) which is different from T1, R1 is the zero- power resistance when the temperature is T1 (kΩ), and R2 is the zero- power resistance when the temperature is T2 (kΩ). As the NTC thermistor slurry is difficult to sinter at the ordinary thick film sintering temperature (850℃), we should take its stability into consideration first. Therefore low-temperature glass must be encapsulated to ensure its stability. We use gold stuff as conductor material, and it is easy to gold bonding.

2.2. Technics

Thick-film technology is one of important technology means to achieve the miniaturization of electronic components. Using standard screen printing technology sintering process, on the alumina ceramic substrate, we produce PTC thermistor and NTC thermistor respectively, then create a microwave attenuator chip with a negative temperature compensation. The series of warming attenuator is small, leadless, adjustable resistance, reproducible, suitable for mass production, etc., and they aspects have a wide range of applications in the military and civilian.

2.3. Design

When materials and processes are identified, this paper focus on the design to study the realization ideas of temperature compensation attenuator, including analysis and selection of the circuit structural model, on-chip termination structure design and establishment of on-chip termination structure, simulation and comparison of design software and so on. Through trying and comparison of different design ideas, in the grasp of the advantages and disadvantages of each design ideas, we come to the optimal design at the same time.

2.4. Performance index

As different electronic equipment required for temperature compensation of the ever-changing, so when we first select the attenuation and temperature compensation coefficient which are in greater demand in actual scientific research and production as design goals. The design index of microwave temperature compensation attenuator chip are: Dimensions: 1.90 × 2.40 × 0.381 mm; Input and output impedance: 50Ω; Frequency range: DC ~ 15GHz; Nominal attenuation:3dB (Ta = +25℃); Attenuation accuracy:± 0.5dB; Temperature coefficient: 0.007 dB / dB / ℃; Port return loss (typical) ≤-14dB; Operating temperature: -55 ~ +85 ℃.

3. Theoretical basis and analysis

3.1. Circuit analysis

Commonly, attenuator circuit structures are the T-type and π –type [3-4] (as shown in Fig. 1). The two circuit structures are simple and practical, so they can be used as preliminary design of the circuit layout. Comparing the two circuits, the channel resistance of the T-type structure is very small, but in view of the thick-film technology's minimum critical size limitation, it need to occupy a larger area to achieve the corresponding small value in design. So this will increase the parasitic effects, and it can not meet the size by design requirements. However, in the π-type structure, the resistance is relatively so large in size that it eases the conflicts between the design dimensions and the technics dimensions. Moreover, as we all know, in the microwave band, good grounding can reduce parasitic effects, and reduce the phenomenon that port standing wave and other indicators' deterioration as the frequency increases. We can see from the above comparison, π-type structure is more suitable for the design requirements than the T-type circuit structure. So we chose a typical π-type circuit to design this broadband microwave temperature compensation attenuator.

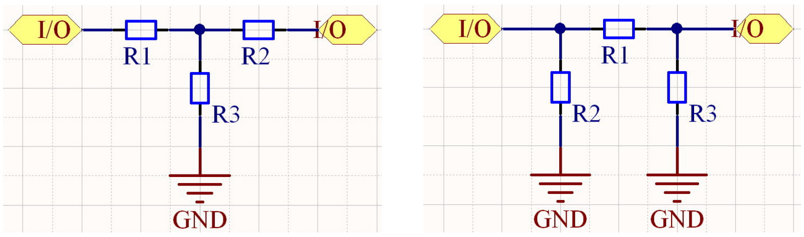


Fig.1: Common attenuator circuit structure

3.2. Resistance and material analysis

Note from the table that the circuit's resistance values of π-type structure in Figure 1 are respectively: R1：18Ω；R2～R3：292Ω. Thick-film resistor value is calculated as:

$$R = \rho \frac{L}{W} \qquad (2)$$

In equation (2), ρ is the surface resistivity of resistor paste, units of Ω / ■, and referred to as sheet resistance; L is the length of the membrane resistance; W is the width of the membrane resistance. From equation (2), thick-film resistor dimensions can be calculated.

As mentioned earlier, the attenuator designed in this paper is negative temperature characteristic compensation device. Membrane resistance value varies with the temperature, then the attenuation changes finally. So the temperature compensation function is realized. To achieve the negative temperature characteristics compensation, R1 should be a NTC thermistors, and R2 ~ R3 is a PTC thermistor.

The characteristic of material (resistor paste) mainly determines the changes in resistance with temperature. Sheet resistance and temperature coefficient of resistance are main parameters of resistor paste. Sheet resistance determines the square of the resistance, and temperature coefficient of resistance determines attenuation compensation range. Temperature coefficient of resistance (TCR) can be expressed as a mathematical formula:

$$TCR = \alpha = \frac{R_{T1} - R_{T2}}{R_{T2}(T1 - T2)} \times 10^6 \ \text{ppm/℃} \qquad （3）$$

3.3. Parasitics analysis

Although the thick-film technology has the advantages of miniaturization, due to the limitation of technics key size, the parasitic of device has bad effects on attenuator performance in microwave application, especially above X-band. This paper proposes appropriate theoretical analysis.

In the actual application process, there will be parasitic inductance and parasitic capacitance existed in High-frequency resistance. For microwave on-chip temperature compensation attenuator resistor, the equivalent circuit is shown in Figure 2.

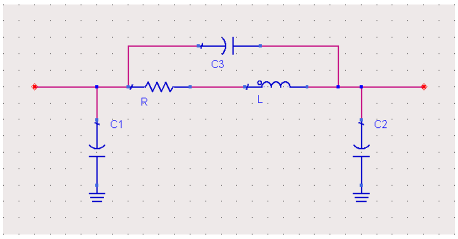


Fig.2: High frequency equivalent circuit of chip resistor

The formula for calculating the parasitic capacitance:

$$C = \varepsilon \frac{S}{d} \qquad (4)$$

Based on the actual size of the circuit, we can be calculated that the parasitic capacitance to ground (C1, C2) is larger, and the parasitic inductance and channel parasitic capacitance are smaller. Because the presence of parasitic capacitance, the circuit attenuation gets large and standing wave deteriorates at the high-frequency. Therefore, in the design process, based on the principle of high-frequency low -pass filter, we match the on-chip, making the frequency range in circuit applications wide, and meeting the bandwidth requirements to use in the microwave band.

4. Software design and simulation

According to the above analysis, in combination with thick film process design rules, and in order to optimize the circuit and carries on the contrast, this paper firstly established in HFSS a without internal matching circuit structure model, the initial layout of the circuit and its simulation results as shown in Figure 3 and Figure 4.

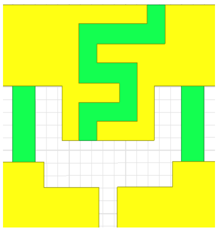


Fig.3: A preliminary layout

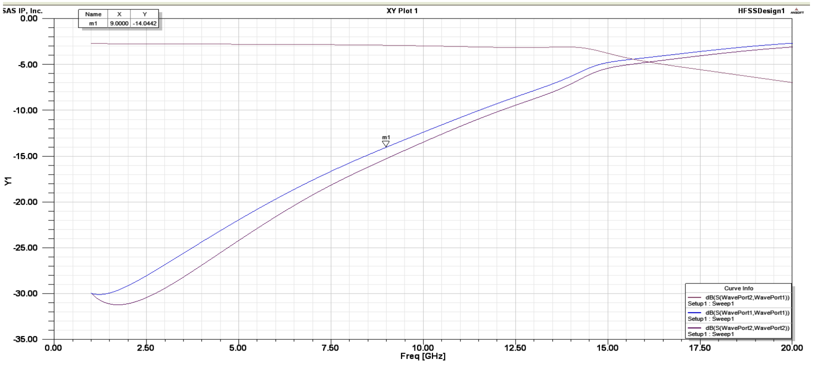
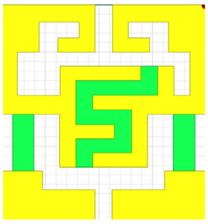


Fig.4: simulation results

From the simulation results, as we can see, because of parasitic effects of the circuit metal pressure and resistance, the standing waves at the 11.6GHz or so has been very poor, and this can not meet the design requirements.

Through the design of internal matching, using high frequency low pass filter circuit principle, the circuit structure and equivalent circuit show in Figure 5 and Figure 6.



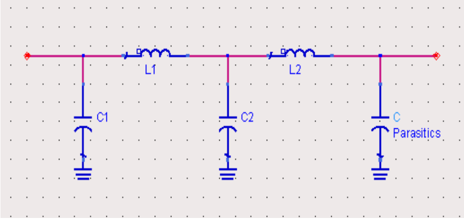


Fig.5: The optimization of circuit

Fig.6: The matching equivalent circuit

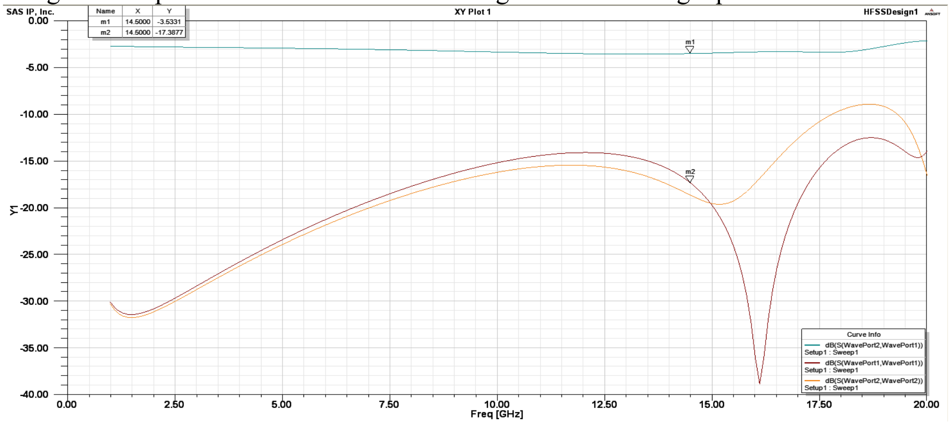


Fig.7: simulation results of the optimization of circuit

By the graph 7, we can see, the optimized circuit has better simulation results. From the full band simulation data, the maximum of the attenuation is 3.5dB@15GHz, return loss⩽14dB, and Obviously, the circuit layout meets the design specifications.

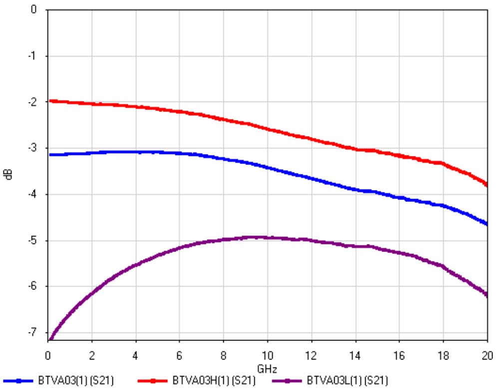
5. Sample preparation, testing and analysis of results

The appearance size of the actual production of a temperature compensation attenuator is 1.90×2.40×0.381mm.Its appearance as shown in Figure 8.

Fig. 8: The temperature compensation attenuator's size and physical appearance

By using the self-made test fixture, we test the samples, and obtain experimental data collated into

Figure 9 and Figure 10. In the Figures, the blue line expresses the attenuation with the temperature change curve attenuation at +25℃, the red line expresses the attenuation with the temperature change curve attenuation at +85℃, and the purple line expresses the attenuation with the temperature change curve attenuation at -55℃.



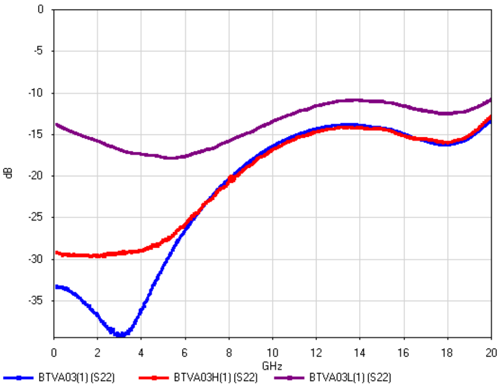


Fig. 9: Attenuation VS Frequency in three temperatures Fig. 10: Return Loss VS Frequency in three temperatures

Through the collation of data, the result of temperature compensating variation at 5GHz is shown in Fig. 11.

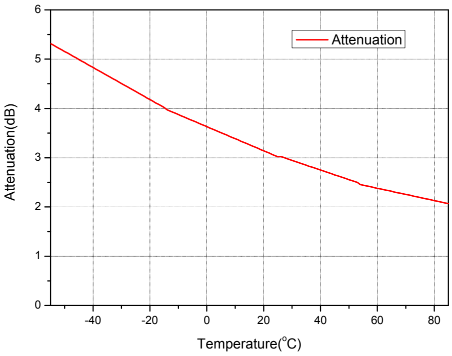


Fig. 11: High and low temperature compensating variation at 5GHz

Based on the analysis of results, the actual test result and simulation result are compared. However the simulation software only estimates in the ideal case, and the measured results of deviation analysis is as follows: the test fixture loss leads to the deviation of the measured attenuation; The simulation results are so nearly by the design target that lead the return loss near the 9GHz can not meet the design requirements; NTC resistance at low temperature is bigger than that at room temperature and high temperature, which leads compensation beyond the design expectations index in low temperature.

6. Conclusion and Prospect

This design process of the broadband microwave temperature compensation attenuator explains that through the circuit layout optimization design, the use of HFSS component model simulation and thick-film technology, it is feasible to develop the microwave temperature compensation attenuator and the indicators have been close to the practical standard. In addition, theory and design experience also suggests that such products are particularly suitable for microwave equipment. Various technical indicators and the appearance can be customized according to user requirements flexibly.

Based on the work carried out in this paper, we will further improve the broadband microwave temperature compensation attenuator, optimize the structure and resistance paste ratio, improve the technology standard, verify the reliability of products, and grope for product indicators limit exploration.

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