Thick Film Temperature Variable Attenuators

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Abstract

Cost effective Temperature Variable Attenuators (TVA) for use up to 18 GHz are described. These devices maintain the signal level in amplifiers, switches, delay lines, and other microwave and RF signal processing devices. By combining Negative Temperature Coefficient (NTC) and Positive Temperature Coefficient (PTC) thermistors in "T" and "Π" configurations, the attenuation changes to compensate for temperature induced signal level changes. Judicious choice of resistance and TCR yields constant impedance over the operating range thus avoiding unwanted signal reflections.

While the temperature sensitivity of NTC and PTC chip thermistors is large, their use in TVAs requires a large and expensive inventory to provide the required resistance and TCR values. Thick film thermistor systems were developed to overcome these limitations. These include an NTC materials series with TCR values as high as -500,000 ppm/°C and resistance range coverage from 100 Ω/sq. to 1 MΩ/sq. The complimentary PTC system features linear TCR values of 3000 ppm/°C and greater with resistance values of 5 to 5000 Ω/sq.

Process variables for these new thick film thermistor materials are discussed. Attenuation and frequency curves are presented. Impedance match, as characterized by Voltage Standing Wave Ratio (VSWR) versus frequency curves are presented.

Key words: Attenuators, Temperature Compensation, Thick Film, Thermistors, PTC, NTC.

Introduction

Attenuators are used in microwave applications that require signal level control [1]. This can be accomplished by either reflecting a portion of the signal back to its source or by absorbing some of the signal in the attenuator itself. The latter case is often preferred because the mismatch which results from using a reflective attenuator can cause problems for other devices in the system such as nonsymmetrical two-port amplifiers [2]. It is for this reason that absorptive attenuators are more popular, particularly in microwave applications.

The Temperature Variable Attenuator (TVA) is an absorptive temperature compensating element which provides power dissipation that varies with temperature[3]. TVAs are constructed using at least two different resistors (thermistors). The temperature coefficients of these resistors are selected to produce an attenuator which varies in attenuation at a controlled rate with change in temperature while maintaining an impedance which is substantially constant.

To understand how a TVA functions, it is beneficial to review how a standard (non-temperature variable) attenuator functions. An attenuator is a network that reduces the input power by a predetermined ratio. The ratio of input power to output power is expressed in logarithmic terms such as decibels (dB), (Attenuation in dB = 10 log P_{out}/P_{in}).

Attenuators are built in two configurations; one, the "Pi Pad" configuration is illustrated in Figure 1. The other, the "Tee Pad" is represented in Figure 2 , which shows a plot of a family of constant attenuation curves , from 1 to 10 dB, with a constant 50 ohm impedance. The vertical axis on the plot represents the values of resistor R2 and the horizontal axis represents the values of R1. The point of intersection between the impedance curve and an attenuation curve gives the values for R1 and R2 that produce the desired attenuation and a 50 ohm impedance match. This figure is also useful for determining the proper design for a temperature variable attenuator.

The values of R1 and R2 for a TVA which will produce the proper attenuation at the high and low temperature extremes, can be determined from Figure 2. Once the values are selected, it is necessary to select a resistor material that will produce the resistance shift required. In order to address all of the possible combinations of attenuation values and temperature shifts that may be required, resistor systems with high TCR and wide resistance range capability are required.

This paper describes thick film NTC and PTC materials developed to meet these needs. The target of the effort was thermistor systems with ranges of material resistivities and temperature characteristics which could be blended together to produce varying resistivity and TCR as required. The functionality of the resulting TVAs is dependent on the intrinsic properties of the thick film thermistor materials and the compatible conductor and protective coating systems at the high operating frequencies required of these devices. These high frequencies require material formulations and component designs which minimize parasitic reactance.

Experimental

The large values of TCR required for both the NTC and PTC materials necessitate special considerations for evaluation of resistance characteristics. For a material with a TCR of 50,000, an error of 1 degree in temperature measurement translates to an error of 5.0% in resistance value. By using an environmental chamber and a platinum RTD, we have been able to achieve control to 1.0°C. Resistance values are therefore accurate to 0.02-0.5% in our reported results. This is particularly important in determining stability.

Although the properties of these materials are unusual, the processing conditions required are the same as those used for conventional thick film materials. Standard 850°C firing profiles are used on films printed to dried print thicknesses of 22.5μ. Pt/Au (ESL5837) metallizations were used in the evaluation of the thermistor compositions. Subsequent testing showed Ag/Pd (ESL 9635A) gave comparable results. Due to the very sensitive nature of these compositions, all resistance measurements up to 1000 Ω were done using four wire Kelvin probes. For higher resistance values, standard two wire measurements were made. All values were obtained from a Keithly 196 DMM with a Sun ECO1 environmental chamber.

Since NTC compositions are based on high temperature semiconductor materials, the thick film firing process at < 1000°C yields a film which requires an overglaze to ensure stability. Therefore, a system of overglaze and stabilization treatment was developed for the NTC compositions. These are not necessary for the PTC compositions.

Results and Discussion

Characterizing parameters for the NTC and PTC thick film pastes developed for this application are shown in Tables 1 and 2. The properties of ESL D-NTC-2100 are given in Table 1 and those of ESL PTC 2600, ESL D-PTC-6200 and ESL D-PTC-2600A series are given in Table 2.

The NTC series of resistor materials, ranging from 100 Ω/sq to 1 Meg Ω/sq allows continuous range of resistance values from 10 Ω to 10 Meg Ω to be obtained since they are all blendable (Figure 3) and geometrically linear (Figure 4). Fractional squares down to 1/20 have shown little deviation from linearity and resistors as small as 1/100 square have been used with predictable results. The material constant β is also listed in the table.

Negative TCR materials, which are based on semiconductor materials exhibit a pronounced nonlinear variation of resistance with temperature (Figure 5); as a result the value for TCR is strongly dependent on the temperature range of interest. For example the TCR calculated from 25°C to -55°C is very different form the slope of the curve at any point on it. NTC materials, therefore are often characterized by the value [4]

$$\beta = (T_1T_0/\Delta T)*\ln(R_{T1}/R_{T2})$$

β is a material characteristic which is constant over a wide temperature range (Figure 6) and is used as a design parameter.

The combination of blendability and linearity allows the designer flexibility in meeting β or geometric constraints as shown in Table 3. This example shows three options to obtain a 400 Ω resistor with various geometries, β values and TCRs. Typical refire characteristics are shown in Figure 7. TCR and β are not effected by refiring at 850°C. Resistance shows a significant but predictable change after refire. Room temperature ageing characteristics are shown in Figure 8. The change in resistance noted is within current instrument capability (0.1-0.5%) for measuring temperature. These resistors are laser trimmable but care must be taken to account for change in resistance due to heating. Stability is not affected by laser trimming. All stability data has been taken on encapsulated and stabilized resistors. ESL overglaze D-4782 fired at 490°C followed by 16 hours at 150°C is recommended when encapsulation is needed.

The low resistivity compositions PTC-2650 and PTC-2611 have very high TCRs and have excellent stability at ambient and elevated temperatures (Figure 9). It is not necessary to encapsulate or stabilize these resistors to achieve these results. They show excellent linearity (Figure 10) and no hysteresis is observable. Resistors were cycled from 25°C - 125°C - 25°C - -55°C - 25°C three times and returned to their initial 25°C values. The higher values of resistance (100 Ω/sq -5000 Ω/sq) are provided by the D-PTC-6200 and D-PTC-2600A series of pastes. These are all blendable with adjacent members so that a continuous range of resistances are obtainable. Resistance vs. temperature is also linear over the entire range of resistivities. All the compositions are laser trimmable and stability is not affected by this procedure. All of the PTC compositions have been evaluated on Pd/Ag (ESL 9635A) metallizations as well as Pt/Au (ESL 5837) and exhibit excellent properties.

Significant improvement in the performance of the TVAs was achieved using the thick film materials developed for this program. Figure 11 shows the improvement in attenuation compensation of a 1 dB device. Most of the improvement comes for temperature below 40°C. Figure 12 shows improvements in the voltage standing wave ratio (VSWR) for a 10 dB device using the new thermistor materials compared to a 3 dB device using conventional materials. The improved RF performance results from the use of smaller geometries (0.1" x 0.l" vs. 0.122" x 0.145") in the 10 dB layout which is made possible because of the improved resistivities of the new materials. The attenuation performance shown in Figure 13 is modest for the 3 dB attenuator up to 6 GHz, however it degrades quickly due to reflections (VSWR) as shown in Figure 12. The overall performance improvement is quite good extending the frequency range of the 10 dB device up to 20 GHz (Figure 13).

Conclusions

1) Negative Temperature Coefficient thick film thermistor compositions covering a resistivity range from 100 Ω/sq to 1 Meg Ω/sq have been developed. β values up to 3100 and HTCRs as high as -9200 ppm/°C are achievable with these pastes.

2) Positive Temperature Coefficient thick film resistor compositions have been developed to provide a range of resistivities from 5Ω/sq to 5,000 Ω/sq. TCRs from 2200 ppm/°C to > 4000 ppm/°C are achievable with these products.

3) Thermopad® TVAs with improved performance were developed using these new materials. Attenuation compensation increased from 0.007 to 0.009 dB/dB/C and frequency range increased from 10 to 18 GHz.

References

[1] Joseph Mazzochette, "Passive Temperature Compensation for RF Amplifier Gain", Proceedings of the 1996 Microwave Theory & Techniques (MTD Symposium, 1996.

[2] Terry Edwards, "Foundations for Microstrip Circuit Design", J.Wiley Publishers, second edition, Chichester, Chapter 8, 1995.

[3] J.B.Mazzochette, J.R.Steponick, "Temperature Variable Attenuator" U.S.Patent 5,332.981, July 26, 1994.

[4] MIL-T-23648.

Table 1

Summary of NTC Compositions

Designation	Nominal Resistivity* (Ω)	Range** (Ω)	Cold TCR (PPM/°C)	Hot TCR (PPM/°C)	ß (-55 to 125C) (K)
D-NTC-2112	100	10 to 1K	-10,000	-5,000	850
D-NTC-2113	1K	100 to 10K	-100,000	-7,500	1700
D-NTC-2114	10K	1K to 100K	-160,000	-8,300	2125
D-NTC-2115	100K	10K to 1M	-300,000	-8,750	2500
D-NTC-2116	1M	100K to 10M	-550,000	-9,200	3100

*Measured on 0.040 X 0.040 resistors at 25°C and 22.5 µ DPT

**Resistive element geometry ranging from 1/10 square to 10 squares

Table 2

Summary of PTC Compositions

Designation	Resistivity (Ω)	Cold TCR (PPM/°C)	Hot TCR (PPM/°C)
PTC-2650	5	4,300	4,100
PTC 2611	10	4,000	3,700
D-PTC-6212	100	2,900	2,650
D-PTC-6232	300	2,750	2,450
D-PTC-2613A	1K	2,400	2,400
D-PTC-2653A	5K	2,200	2,200

Table 3

NTC Blend Characteristics

Blend Composition	(1) Resistivity	TCR CTCR/HTCR	ß	(2) Geometry	(1) X (2)
D-NTC-2112	100 Ω/sq	-10K/-5K	850	4 sq	400 Ω
1:2 D-NTC-2112 & D-NTC-2113	540 Ω/sq	-90K/-7.4K	1417	0.75 sq	400 Ω
D-NTC-2114	10K Ω/sq	-160K/-8.3K	2125	0.04 sq	400 Ω

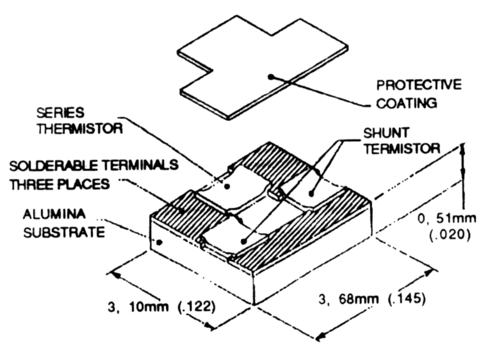

Figure 1. Pi Pad Attenuator.

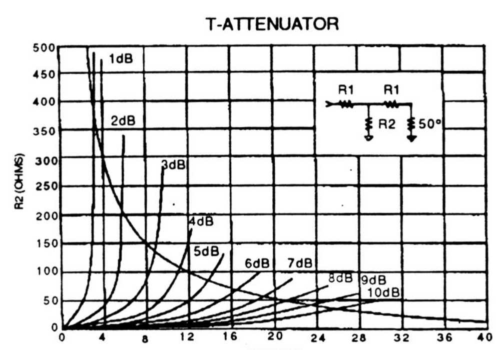

Figure 2. Series & Shunt Resistor Values with 50Ω Impedence Figure 2.

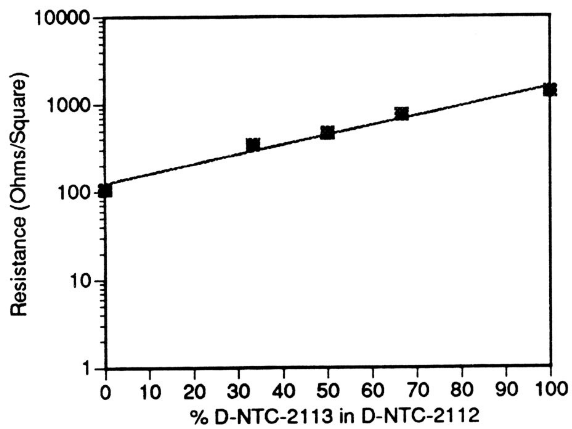

Figure 3. Thermistor Blend Curve.

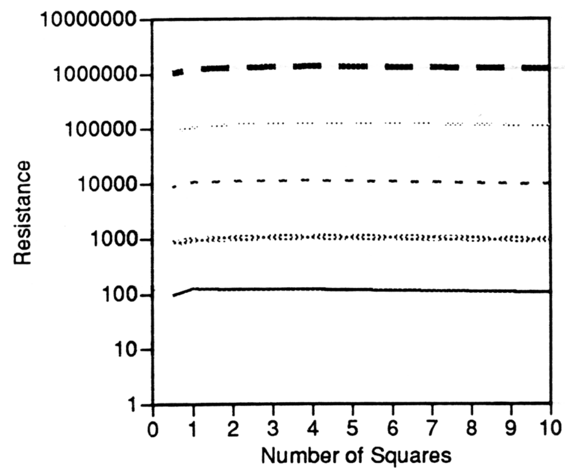

Figure 4. Geometry Effect.

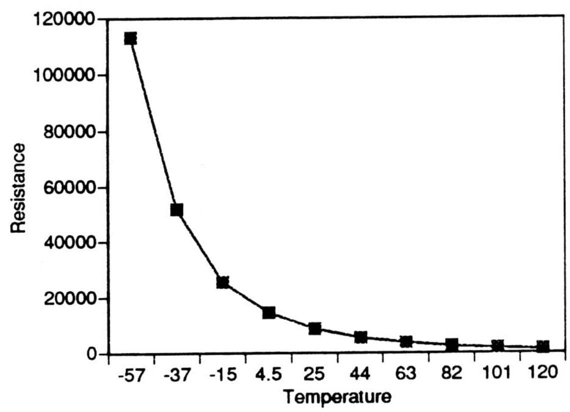

Figure 5. Resistance vs. Temperature.

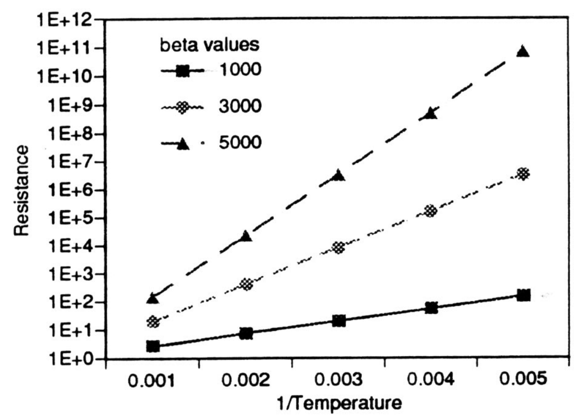

Figure 6. Resistance vs. 1/Temperature.

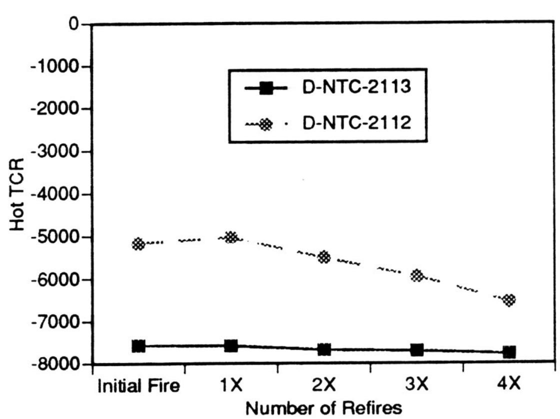

Figure 7. Effect of Refire on TCR.

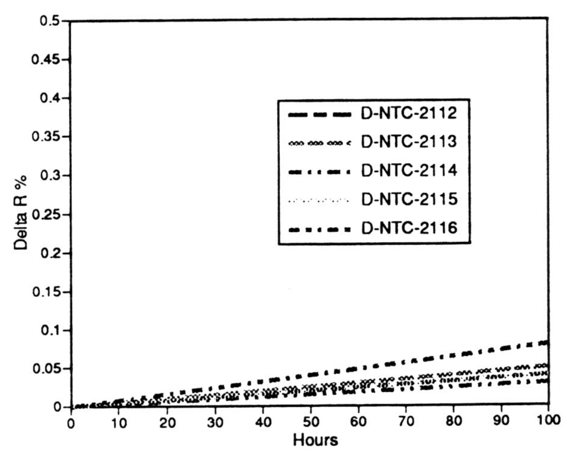

Figure 8. Room Temperature Ageing.

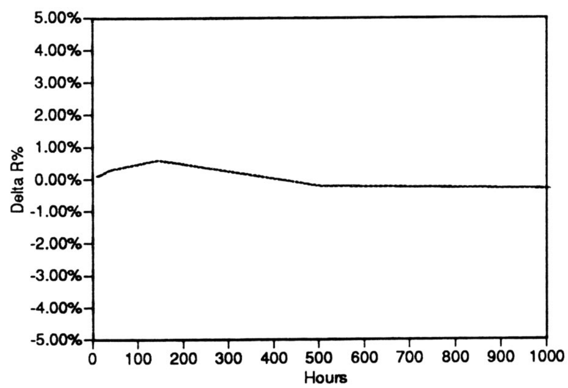

Figure 9. PTC 150°C Ageing.

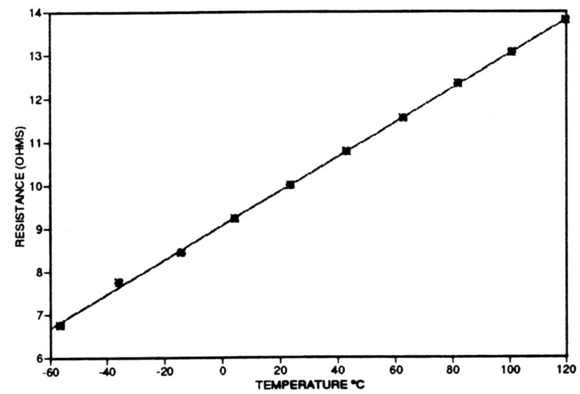

Figure 10. PTC-2611 Resistance vs. Temperature.

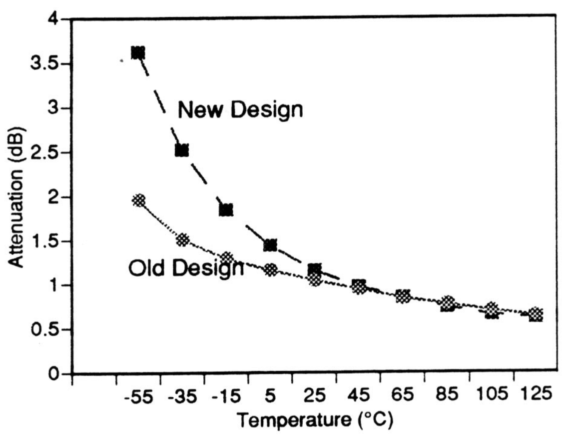

Figure 11. 1 dB Thermopad.

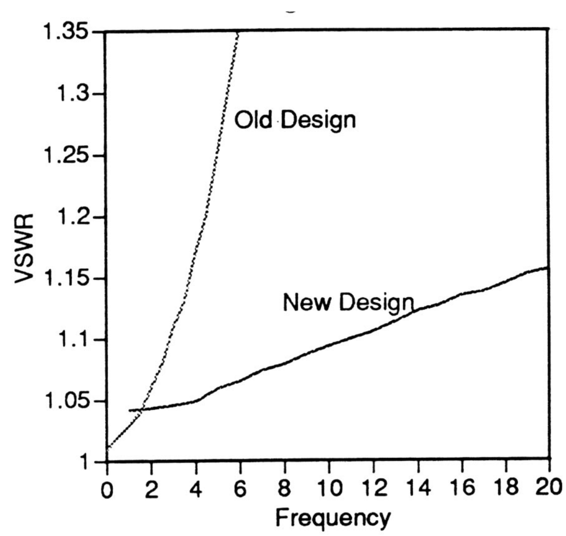

Figure 12. Thermopad Frequency Response.

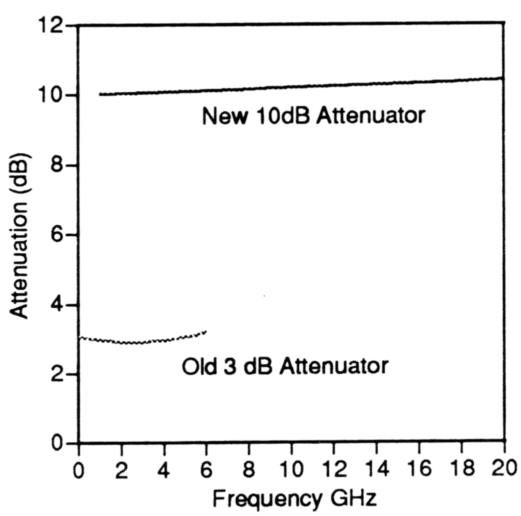

Figure 13. Thermopad Frequency Response.