WHITE PAPER

Superior TCR tracking in Resistor Networks and Dividers

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Introduction

Practitioners of conventional thick film technology are not accustomed to dealing with resistor requirements that involve matching to tolerances of the order of 0.1% or so. One of the reasons for this is that such tolerance levels require equivalent matching with respect to other characteristics such as Temperature Coefficient of Resistance (TCR). To illustrate, a pair of resistors trimmed to within plus or minus 0.1% initial room temperature match tolerances should have matching TCR to within about 20ppm/°C in order that a possible temperature excursion of, say, 50°C would result in a change in their relative values by no more than the amount of the initial tolerance itself (1000ppm). Other characteristics such as load life changes should be equally well matched.

TCR matching of ordinary thick film resistors to 20 ppm/°C over a limited temperature range is not an impossible requirement in the case of elements which are of equal or similar value and physical size. However, if either of their aspect ratios differ significantly or they are made from different ink compositions, close tracking is almost impossible to attain, other than by accident. The variation of TCR with aspect ratio is more correctly, a variation with resistor length due to interactions between resistor and termination which make disproportionate contributions to the total TCR, depending upon the length. This effect has been well documented. More importantly, the use of different ink compositions in separate printing steps usually produces resistors which differ radically in TCR.

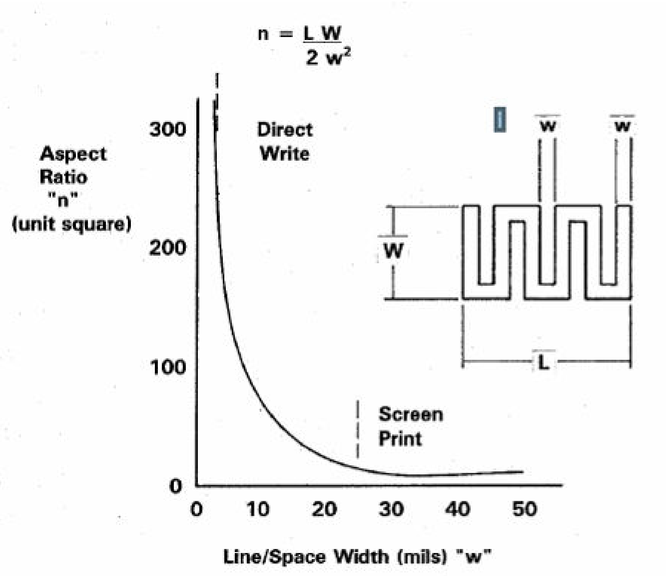


Figure 1
Maximum aspect ratio versus line/space width

In thin film technology, very close tracking is obtained by using a single, common film for all the resistors in a multi element network, and producing different values by designing with different aspect ratios. Variations in resistance, with excellent tracking, can be obtained in this way over a range of several decades. The critical enabling step is the ability to produce very narrow traces via photolithography.

The power of geometric multiplication of aspect ratio as a function of line width is illustrated in Figure 1, in which the aspect ratio attainable within a given area of substrate in a serpentine pattern as a function of line and space width is shown. For an area 100x100 mil in size, aspect ratios of many hundreds can be achieved through the use of pattern definition as small as a few mils.

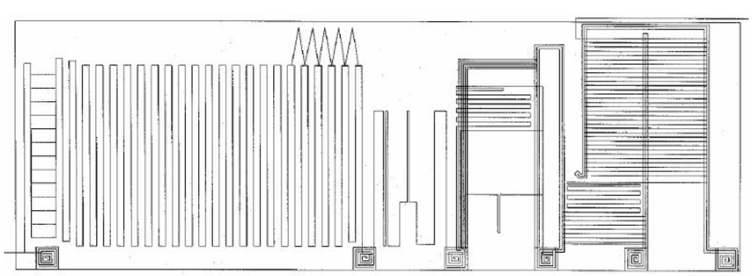
This report deals with a proposal to employ such an approach using thick films; that is, achieving a significant range of aspect ratio by deploying thick film inks in relatively fine line patterns, thereby resulting in multi value networks with close inter-element tracking. In principle, this concept has considerable appeal, but implementation based on conventional screen-printing deposition has major limitations, i.e. a line width below 20 mils or so is not readily done by that technique. An alternative technique that offers a variety of supplementary advantages is that of dispensing the ink under pressure through an orifice, in a direct write mode. This technique enables the deposition of lines as small as 4 mils, and spaces as narrow as 2 mils. Further, the lines produced by this technique are extremely uniform in cross section and edge regularity. Direct write also allows for very close control of film thickness. With lines of 4 mils and spaces of 2 mils, aspect ratios can be attained within the area referred to in Figure 1 up to a value of about 300 which is an improvement over screen-printing. The ability to do this with inks covering a wide range of sheet resistivity provides an enormous overall versatility; it is especially applicable to higher value resistors and networks. This design approach overcomes the other problem inherent in thick film resistor technology, mentioned earlier, and related to the resistor conductor interface reactions. Using longer traces reduces these phenomena, and thereby should contribute to improved tracking.

Fine line/thick film technology has at least one limitation by comparison with thin film however, that the narrow thick film traces do, in fact, vary with the line width itself, unlike thin film traces. This is probably related to the thinning out of the thick film line at its edges. The conductivity in these thinner outer regions differs somewhat from that in thicker regions in the center of the trace and thereby contributes differently to various characteristics to a degree which depends upon the total width of the trace. This problem can be overcome by fabricating all the elements in a network with a single line width; those of lower aspect ratio can be made by combining a number of longer lines in a parallel arrangement. In addition, trim sections based on link cutting can be designed with the same common line width.

Experimentation

Different experiments were conducted to ascertain the level of tracking attainable with fine line thick film construction, measured primarily by TCR. The first example is a divider with variable aspect ratios, and the second is an array with fixed aspect ratios.

In the first case, a five-decade divider in a single-in-line format was prepared using a 1000-ohm per square ink and a 6-mil pen tip orifice. This variable aspect ratio line pattern is shown in Figure 2.



Some coarse trim features are included. Due to ink spreading, the traces were somewhat thinner than what would be recommended by ink manufactures and the resistor values correspondingly higher.

Figure 2
5 Decade Fine Line Divider

The pre-trim aspect ratios, resistance value and TCR obtained are shown in Table 1.

Variable Aspect Ratio Sheet Resistivity: 1KΩ / □ Pen Tip orifice: 6 mils			
Resistor	**Aspect Ratio**	**Resistance Value** (M ohms)	**TCR (25°C - 75°C)** (ppm/°C)
R_H	14,000:1	14.3	-9.6
R_2	1,300:1	1.3	-8.9
R_3	120:1	0.123	-10.1
R_4	12:1	0.0139	-9.6
R_L	1.5:1	0.00146	-9.2

Table 1
Variable Aspect Ratios of Elements in a 5 Resistor Divider

The absolute value of the TCR (on the order of –10ppm/°C) indicates that as the temperature increases these resistors undergo a significant change {a decrease in this case} in value. However, the differences among the TCR are an order of magnitude smaller than the absolute change. The relative resistance values, that is, their ratios, are preserved to a considerable degree. The resistors, even though differing greatly in value, are matched to within a few ppm/°C. To fabricate this same design, in line and space of 25 mil width, would have required a part approximately 16 times larger.

In a second example, an array of equal value 500K ohm resistors was prepared, also in sip format. Each element consists of a nominal 275 square trace and was made using 1000 ohms per square ink and a 4 mil per tip orifice. The pattern for a specific resistor array is shown in figure 3, however, for this trial, an entire plate of arrays was prepared consisting of 5 rows of this array. TCR values were determined among selected elements in the 25°C - 75°C range. The resistance values and TCR data are shown in Table 2.

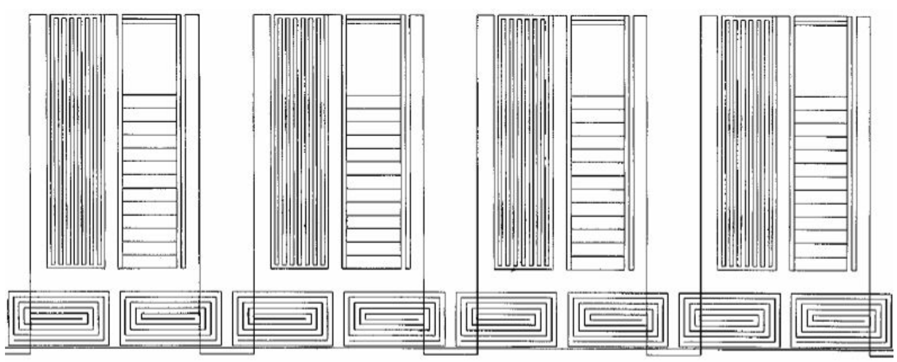


Figure 3
4 - 500MΩ Resistor Array

Fixed Aspect Ratio - As fired Resistance data Sheet Resistivity: 1KΩ / □ Pen Tip orifice: 4 mils (Resistance Values in K ohms)				
Resistor ► Row ▼	R_1	R_2	R_3	R_4
1	72.1	77.6	72.7	74.2
2	69.3	71	73.4	65.4
3	67.8	66.6	73.4	69.6
4	67.6	71	93.3	67.6
5	72.5	70.5	69.6	65.3

Fixed Aspect Ratio - As fired TCR data Sheet Resistivity: 1KΩ / □ Pen Tip orifice: 4 mils TCR is 25°C - 75°C (ppm/°C)				
Resistor ► Row ▼	R_1	R_2	R_3	R_4
1	39.8	36.9	42.2	44.6
2	41.1	42.6	40.7	45.1
3	43.7	42.5	42.3	41.7
4	45.6	45.5		46.5
5	42.2	43.5	45.1	46.1

Table 2
Ohmic Value and TCR data of elements in a 4 resistor array

The TCR differences between adjacent resistors in a given row indicate excellent tracking, within a few ppm/°C for the most part. The tracking data given are for a limited temperature range, 25°C - 75°C. Because the resistance temperature relationship of this type of film is so non-linear in nature, the TCR tracking over a wider range will be correspondingly greater. In fact, for a 25°C to 125°C range it will be approximately double that of the more limited temperature range.

Summary

Evidence confirms that multi value resistor networks fabricated from thick film resistor compositions in fine line patterns of common line width using a direct write deposition technique can be fabricated in a wide range of aspect ratios with excellent tracking characteristics. Other studies verify that such networks will also possess significantly lower current noise and voltage dependence than more conventional thick film products.