HERE'S HOW TO HARNESS SPICE TO PRODUCE A REAL-WORLD SOLUTION TO A REAL-LIFE PROBLEM.

SIMULATE LASER-TRIMMED RESISTORS WITH SPICE

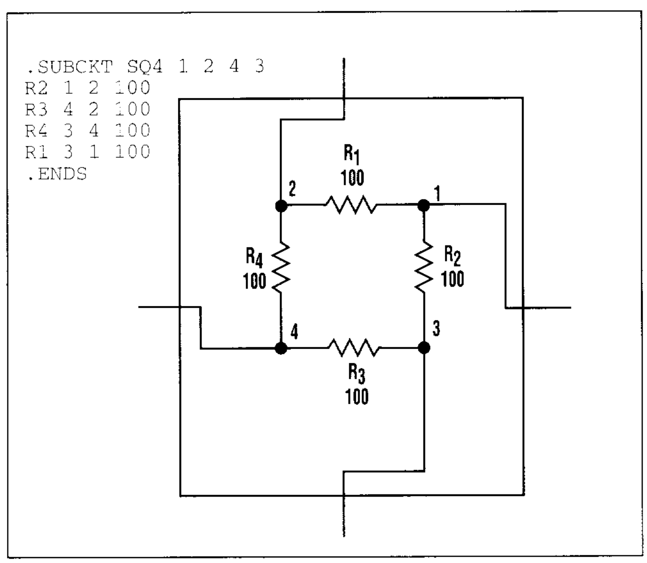
To simulate physical systems using Spice, engineers create electrical analogs of the physical parameters. The thermal analysis of a packaged MOSFET, for example, entails calculating the thermal capacitance and thermal resistance of various materials in the package. Adding ideal current and voltage sources to the analysis completes the circuit. Although the resulting schematic effectively simulates the physical system, it's merely a symbolic diagram. It doesn't enhance the physical view of the system's operation.

This article shows how a design engineer can use Spice to simulate thick- or thin-film resistors that have laser trims or complex shapes. The method employs a subcircuit technique to address this issue. Using any one of a number of Spice simulation software packages (which feature schematic capture, the ability to create subcircuits and symbols, and to copy these symbols into groups), a circuit schematic can be developed by the design engineer that also serves as a representative picture of the resistor as it would appear printed on a substrate.

The subcircuit technique is useful as a tool to help solve real-world problems in designing resistors. Moreover, with this technique, a designer using Spice can easily determine resistor values with variations in geometry or laser-trimmed values.

Recall that a square of resistor material is merely a chunk of the material with equal dimensions on each side and some specified thickness. If the resistance of the material is 100 Ω/square at the specified thickness, it really makes no difference whether each side measures 0.1 cm or 10 cm. The total resistance of the chunk still turns out to be 100 Ω.

Using the relations:
Squares = L/W, and
Ω = Squares × (Ω/Squares),
where L = length and W = width,



1. THIS SYMBOLIC representation of one square of resistor material is based on a schematic of a four-resistor square. A quick inspection shows that the equivalent resistance across opposite sides of the symbol is 100 Ω.

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the equivalent squares and resistance of a rectangular resistor may be calculated.

Unfortunately, the calculations for non-rectangular resistors aren't quite as simple. One common example is the top-hat geometry. Reference texts often refer to graphs with various curves for geometry ratios to specify the equivalent square count of the top hat. Other graphs show resistance variations as the laser-trim depth increases. But published graphs don't indicate how the value varies with laser-trimmed double-cuts, or "L"-cuts.

They also don't show effects with odd-shaped resistors. This is where building the resistor geometry in Spice shines. With the subcircuit technique, Spice not only determines rectangular and non-rectangular resistor values in a matter of a few seconds, but also displays the physical results as well.

A Building Block

As a basic Spice building block, consider a symbol created to represent one square of resistor material *(Fig. 1)*. Though the schematic of the 4-resistor "square" is shown inside the symbol, this needn't be done in practice. The schematic only serves to show the connections between the subcircuit and the symbol. By inspecting across opposite sides of the symbol, it's easily seen that the equivalent resistance of the square is 100 Ω.

A similar symbol and schematic uses 16 resistors to represent the square of resistive material *(Fig. 2)*. As might be expected, the more resistors used to simulate the square, the more accurate the results will be when simulating laser cuts or complex resistor shapes. The resistor matrix must be connected at the corners to properly simulate a square of material. After all, a real square of material could be considered as an infinite number of resistors arranged in an extended but similar fashion. The symbol also serves to convert the diagonal nature of the schematic to a rectangular format, which is much more convenient for building a resistor from many squares.

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.SUBCKT SQ16 2 8 9 10 11 5 6 7
R2 12 3 100
R3 1 4 100
R4 4 3 100
R5 5 4 100
R6 6 1 100
R7 6 5 100
R8 7 2 100
R9 2 12 100
R10 7 1 100
R11 12 8 100
R12 8 9 100
R13 3 9 100
R14 3 10 100
R15 4 11 100
R16 11 10 100
R1 1 12 100
.ENDS
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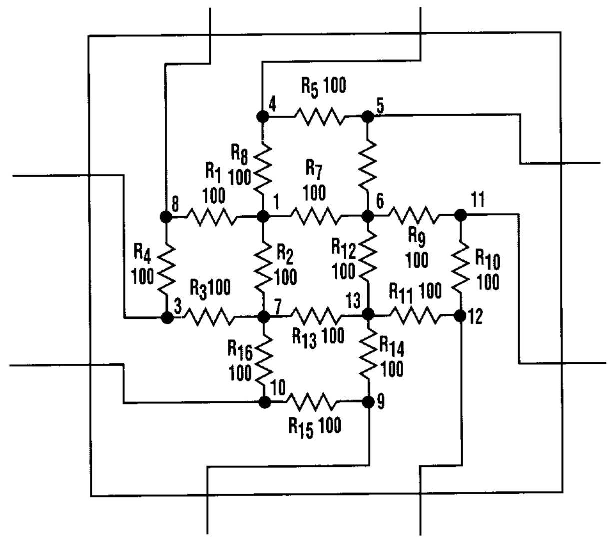


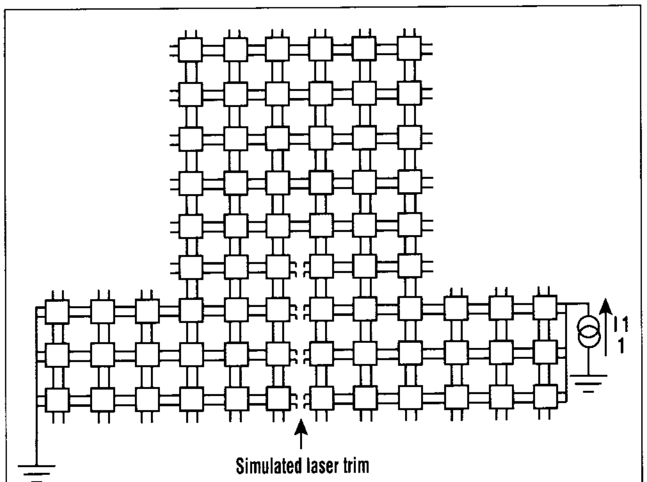
2. ANOTHER SQUARE of resistor material is modeled with 16 resistors to achieve greater accuracy when simulating laser cuts on complex resistor geometries. Each terminal pair must be treated as one (either connected or not connected to another symbol).

Although each side of the subcircuit has multiple terminals, they must be treated as one for the subcircuit to work correctly. In other words, if one terminal is opened or interconnects to a terminal of another symbol, then the others must do the same.

Once the symbol is created, it's retrieved from the Spice software library and a short wire segment is added to each terminal. This ensures that Spice will assign a node number to the terminal. It also allows connections between square symbols to be severed to simulate trims.

Next, the symbol with its attached wire segments is copied and joined to the original. The copying and joining of symbols should continue until the complete resistor geometry is constructed.

This method was used to construct a typical top-hat resistor shape *(Fig. 3)*. One end of the resistor is fed with a current source scaled for 1 A; the other end is grounded. All of the terminals at each end of the resistor must be tied together. Even though some terminals extending from some of the symbols appear to be open-circuited, the schematic of the symbol in Figure 2 shows they're not (Spice, of course, would not converge with open-circuited components).



3. A TYPICAL top-hat resistor is quickly and easily constructed using the copy and join steps in the subcircuit technique. While some of the terminals appear to be open-circuited, the schematic shows that they are not, Spice won't converge with open-circuited components.

The current source is scaled at 1 A so that the voltage read at its terminal will be the same as the total circuit resistance when each subcircuit symbol contains 100-Ω resistors. Other Ω/

square values could be handled by scaling the current-source for different values. If, for example, the resistor material was 3 kΩ/square, the current-source would be scaled for 30 A. Scaling the current-source is preferred to altering the subcircuit resistor values each time the resistor material changes. The 100-Ω/square subcircuit described previously is chosen only for convenience. Any value would do as well with the proper scaling applied to the current source. For instance, the subcircuit resistors could be scaled for 1 Ω. Then, the voltage read at the current-source terminal would be considered to be the equivalent square count.

Testing Corners

To determine the accuracy of the Spice simulation using this technique, a corner test circuit was designed to act as a calibrator *(Fig. 4)*. The test circuit has three squares, and each square is made up of 16 subcircuits. Each subcircuit contains 16 resistors. Although three squares are shown, the equivalent square count isn't three. The corner doesn't equal one square due to the current distribution in the material going around the bend. However, the circuit was constructed in this way because a corner can't exist in isolation. Also, the equivalent square count of the corner will vary slightly with the amount of material on each side of it. Yet, the value remains essentially constant when there's one or more squares at each end.

Corner test circuits were constructed and tested having total resistor counts of 64, 256, and 1024 per square. Spice reported the equivalent square counts as 0.591, 0.571, and 0.563, respectively. The actual equivalent square value for a corner is 0.559. These results give a feel for the accuracy values versus the resistor count. Several reference texts have reported the equivalent square value of a corner to be 0.65, but that's incorrect as is indicated by the Spice simulation. To relate the simulated resistor to the actual printed resistor, each symbol is assigned a physical dimension. The top-hat resistor of Figure 3, for example, was constructed with 12 symbols along the base. If each symbol (square) were assigned a dimension of 5 mils, then the base would be 60 mils long. The total height would be 45 mils and the resolution 5 mils. The resolution could then be increased by adding more symbols to increase the total symbol quantity.

For example, the total height of the top-hat could be boosted to 18 symbols (the other dimensions increased accordingly) and the resolution would increase to 2.5 mils (assuming the total height was still considered to be 45 mils).

The issue of resolution becomes important when investigating the laser-trimmed behavior of a resistor. Consider the top-hat resistor with a laser trim, where the connection between adjacent squares is opened by merely directing the short wire segments on the terminals down, instead of across *(Fig. 3, again)*. In the example, the total height of the top hat was 45 mils, with the resolution being 5 mils. This is equivalent to a laser trimming out 5 mils of the resistor with each bite. Assuming that all design requirements of the resistor are known, this analysis would be sufficient to properly design the resistor's geometry. Sometimes, though, the total requirements of the resistor design are best evaluated when compared with the operation of other circuit components that aren't precisely defined.

Many thick-film hybrid circuits need to be actively trimmed for various parameters. A case in point would be power operational amplifiers. Typical parameters that require laser trimming are offset voltage, offset-voltage drift, output-stage bias current and the thermal-shutdown temperature trip point.

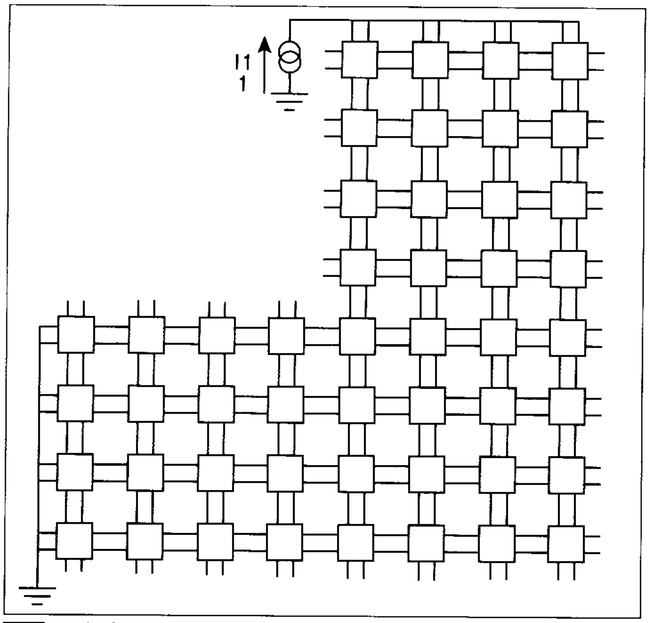
Using the technique described, the resistor models to be trimmed can be inserted into the Spice schematic of the circuit. A simplified circuit schematic of the Apex PA05 illustrates this point *(Fig. 5)*.

Trim Stability

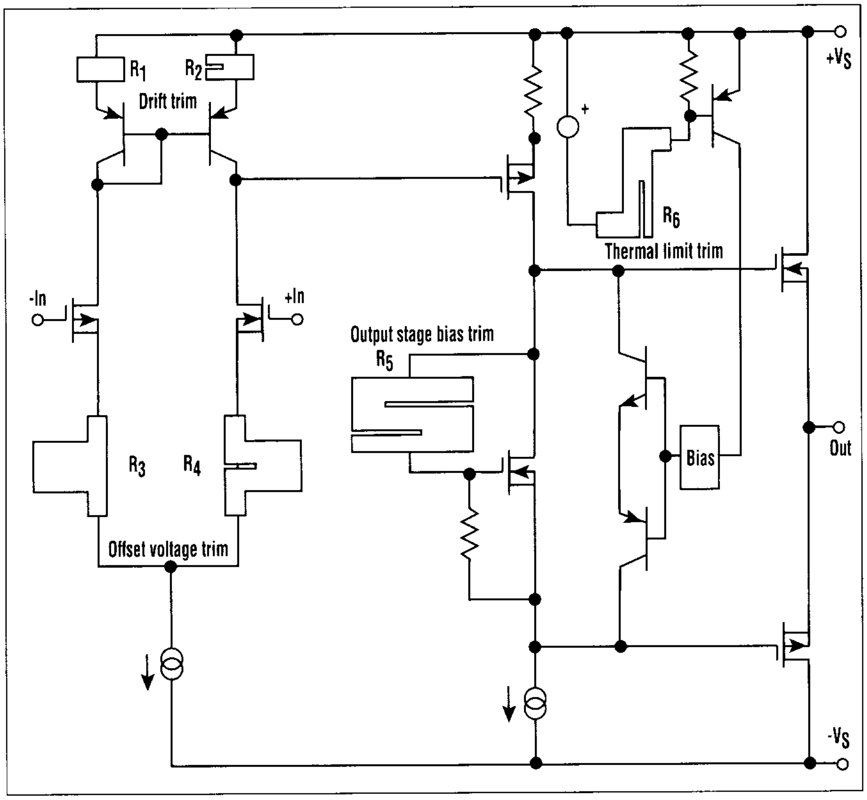
Laser-trimmed resistor stability is related to, among other things, the distance from the end of the laser cut to the edge of the resistor. Microcracks left in the resistive material at the end of the cut are prone to change the resistor value during temperature cycling and burn-in. This shift can be quite significant if the micro-crack length is large compared to the remaining uncut width of the resistor.

For trimming accuracy, the rate of change of parameter variation with laser cut bite size also must be considered. It's possible, for example, to achieve a total change in the trimmed resistor that's the required size. But, the rate of change of the trimmed parameter may be so great that with each laser bite, the parameter simply changes too fast to achieve the required accuracy. In other words, gross overtrim could result from having trimmed one bite too many.

Whenever the drift-resistors, R_1 or R_2, are trimmed, the output offset voltage also is affected. Thus, the



4. A CORNER CIRCUIT, used for calibration purposes, could represent some circuit interconnecting metal path or a section of a "snake" resistor. Although the circuit appears to be made up of three identical squares, the square in the corner actually has an equivalent square value of 0.559.



5. A SIMPLIFIED SCHEMATIC of the Apex PA05 illustrates how the models of laser-trimmed resistors can be inserted into the Spice circuit schematic.

offset voltage must be trimmed back to zero. This interaction causes R_3 or R_4 to be trimmed more than would be otherwise expected. However, by inserting the trimmed-resistor models into the circuit, it's possible to see how much of the trim resistors remains once the circuit is trimmed to maximum.

Output-stage bias current is adjusted by trimming R_5. In this particular circuit, R_5 needs to have a wide range of possible values. In fact, the trim range is 4 to 1. This wide range is due to the variations in resistor tolerances and MOSFET threshold values. Consequently, the trim resistor was designed so that a maximum of two laser cuts would cover the range and still produce a stable resistor with acceptable trim resolution.

Fixing A Problem

Resistor R_6, with its odd shape, was designed to solve a particular problem. The resistor's original design was unacceptable due to trim sensitivity and range. However, the problem wasn't discovered until after work had begun on the second substrate production lot.

This particular shape was developed by employing the methods described in this article, and it solved these problems using the available space on the substrate. The newly designed resistor was inserted into an iteration of its resistor layer, thus saving the cost of scrapping the substrate run and designing new metal masks.

Although purely mathematical means could be used to solve the particular problems of thick-film resistor shapes, trim ranges, and trim sensitivities, the method described here offers accurate solutions to what's essentially a geometrical problem. Furthermore, the visual aid is helpful in both designing and evaluating the performance of the resistor design.□

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How Valuable?	Circle
Highly	530
Moderately	531
Slightly	532