Microwave Journal

INVITED PAPER

How Hot Do Those Isolation Resistors Get?

Steve Huettner, Chris Hermanson, Andrew Gooden, Jonathan Lamb, Justin Sayres and Ben Cannon
Nuvotronics, Durham, N.C.

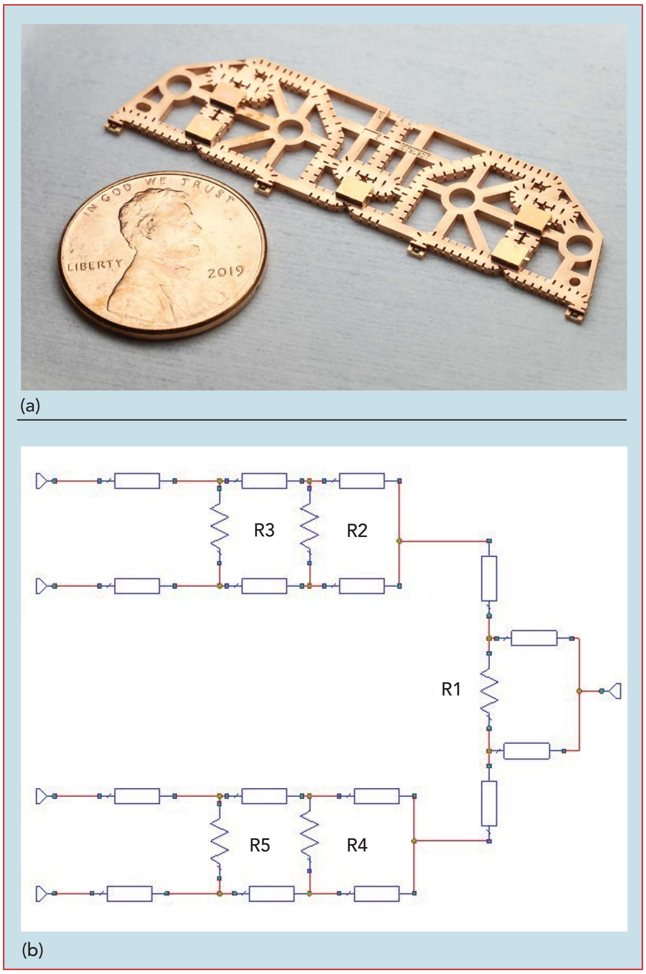

Fig. 1 **(a) Nuvotronics combiner. (b) Simplified combiner schematic.**

This article describes how isolation resistor temperatures are affected by phase imbalances in a real-world power combiner, followed by the results of power testing a modified back-to-back (B2B) combiner that stresses the resistors without causing a failure. A photo of a Nuvotronics 80 W, 6 to 18 GHz, four-way air-coax power combiner is shown in ***Figure 1a***. This network serves as the foundation for the examples presented in this article. As shown in the simplified schematic of ***Figure 1b***, the combiner is a cascaded Wilkinson design featuring five 100 Ohm isolation resistors that provide a minimum of 13 dB of isolation between inputs across the entire band. It is rated for temperatures up to 85°C and exhibits a loss of just 0.34 dB at the center frequency. This combiner uses the PolyStrata® manufacturing process to create its air-coaxial transmission lines.

In a Wilkinson power combiner, removing heat from isolation resistors can be a challenge. Typically, improving the thermal path adds capacitance to the structure, which can detune the RF performance. This is especially true in air-coax structures. In the 6 to 18 GHz combiner, the thermal resistance of the isolation resistors was evaluated to be 28°C/W using ANSYS software. Future designs have identified a path toward 3°C/W and these designs may become available in 2025.

The isolation resistors that are used in the PolyStrata combiners are CVD diamond thin film products from Smiths.[1] These resistors are typically configured in a 0402 package and rated to 20 W dissipation when attached to a suitable heat sink. According to the manufacturer, the resistors are rated to full power at a film temperature of up to 125°C, but they must be derated linearly to 0 percent power at 150°C. This derating curve is shown in ***Figure 2***. The temperature and power capability of the isolation resistors limit the allowable out-of-balance con-

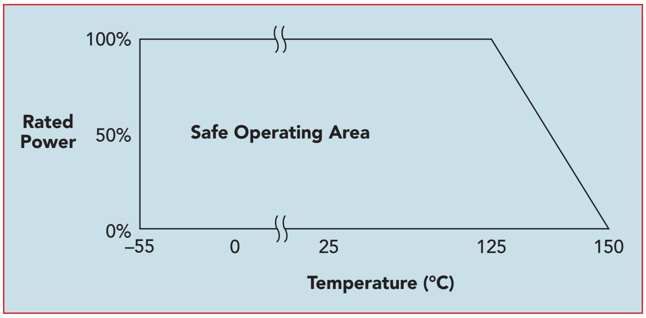

Fig. 2 Safe operating area for diamond thin film resistors.

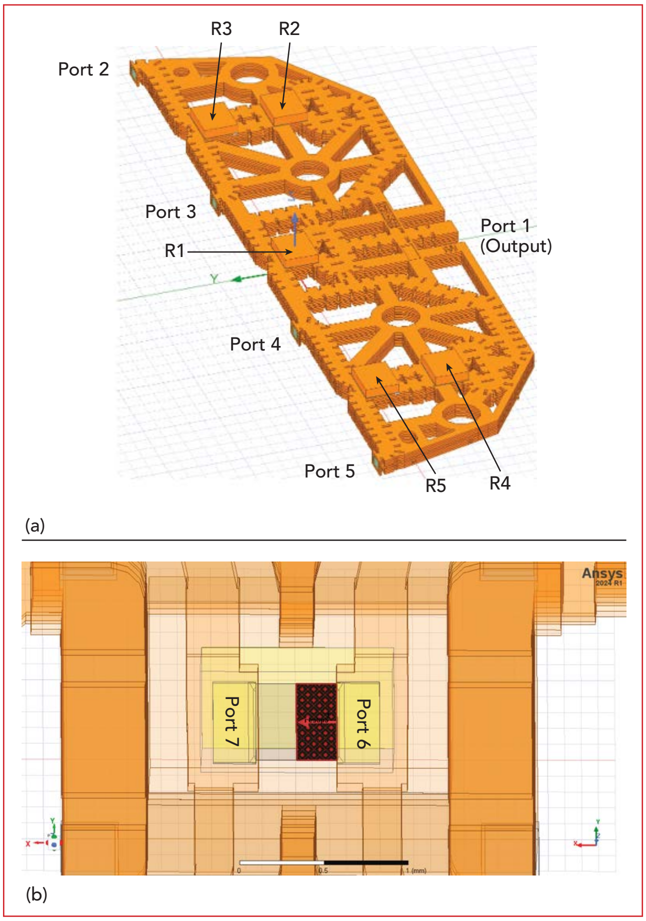

Fig. 3 (a) 3D circuit model showing Ports 1 to 5. (b) Port definition at R1 resistor interface.

ditions when a combiner is used in a solid-state power amplifier (SSPA).

HFSS/MWO "HYBRID" COMBINER MODEL

The 3D HFSS model for the five-port, four-way power combiner was reconfigured to remove the resistors. This was done to model the power combiner as closely as possible to the actual configuration while allowing access to resistors to evaluate their power dissipation under different configurations. RF ports were added to the resistor sites, resulting in a 15-port network. The HFSS model is illustrated in ***Figure 3a***, where Ports 6 through 15 are not depicted in the overall model. ***Figure 3b*** is an example resistor, showing where Ports 6 and 7 have replaced the resistor film.

Using Microwave Office (MWO), resistors were reintroduced into the network in a "hybrid" HFSS/MWO model. MWO enables the convenience of harmonic balance for quickly assessing power performance. An MWO schematic of the rebuilt combiner is shown in ***Figure 4a***. The block diagram in ***Figure 4b*** maps the positions of the five resistors within the network. For example, resistor R1 is closest to the common port or the output of the combiner.

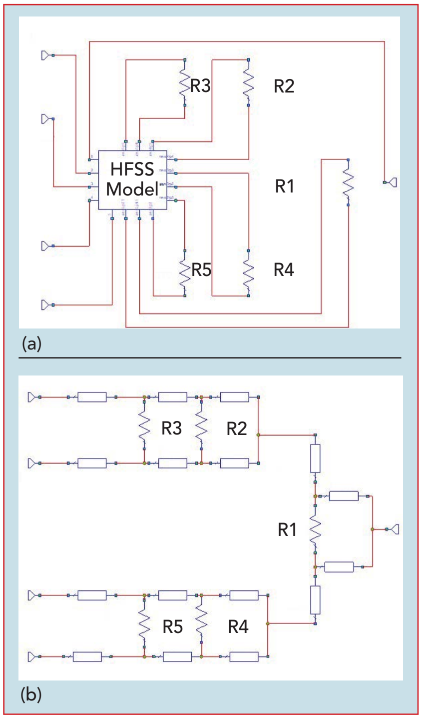

Fig. 4 (a) HFSS model with five external resistors. (b) Power combiner block diagram.

The 6 to 18 GHz power combiner can use available 20 W GaN power amplifiers to achieve a 75 W SSPA power stage. A very simple linear model of such a power stage is shown in ***Figure 5***. In this model, the A1, A2, A3 and A4 amplifiers are fed from a lossless four-way divider, providing 20 dB of linear gain to feed power into the hybrid combiner model. With 29 dBm (800 mW) of input power to the network, the output power is predicted to be approximately 74 W at 10 GHz. This is slightly less than the available 80 W, as the combiner network has an insertion loss of 0.34 dB. Lossless phase shifter elements, Φ1, Φ2, Φ3 and Φ4, are in the model to vary transmission phases between amplifiers, as they will not be ideally matched in real-world conditions. In this study, amplitude imbalances are neglected because they create less mismatch.

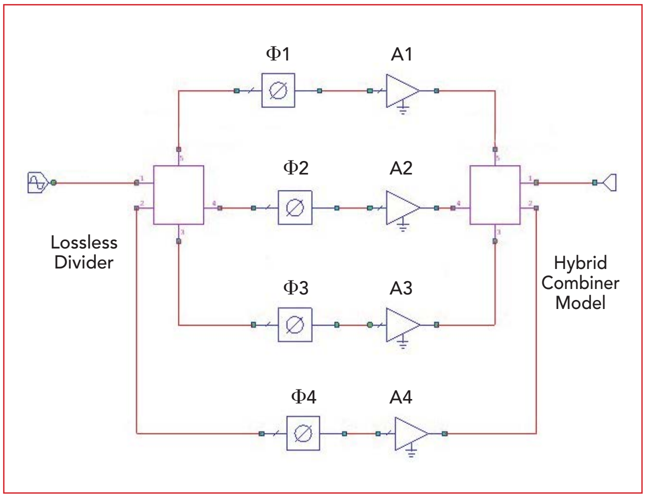

Fig. 5 75 W power stage model.

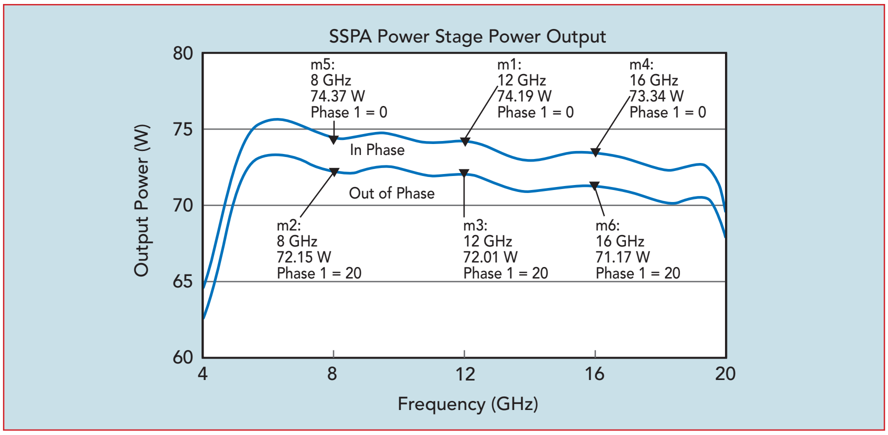

Fig. 6 **Example 1 power output response resulting from phase mismatches.**

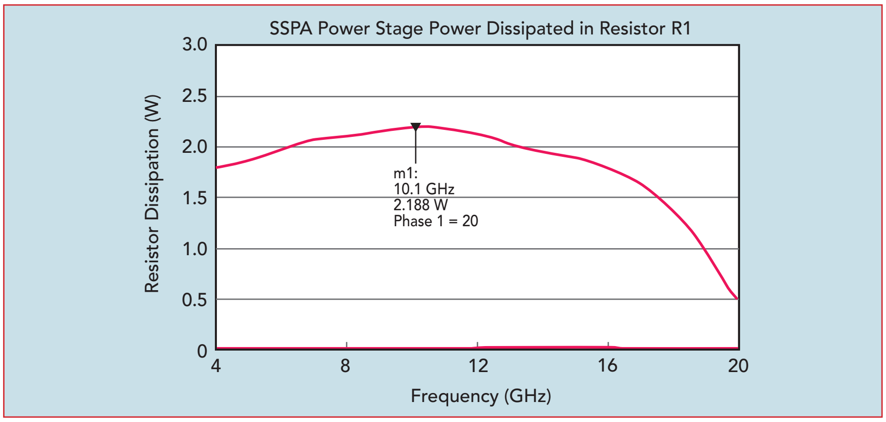

Fig. 7 **R1 power dissipation for the Example 1 phase mismatch conditions.**

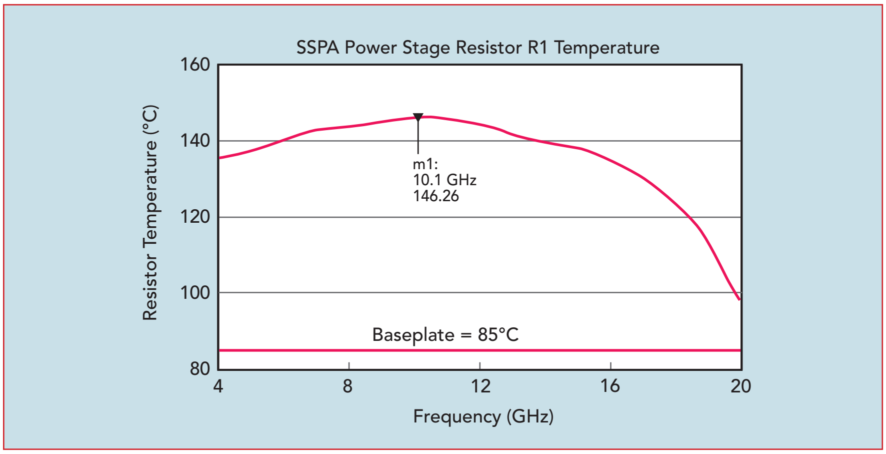

Fig. 8 **R1 film temperature profile caused by a 20-degree phase mismatch.**

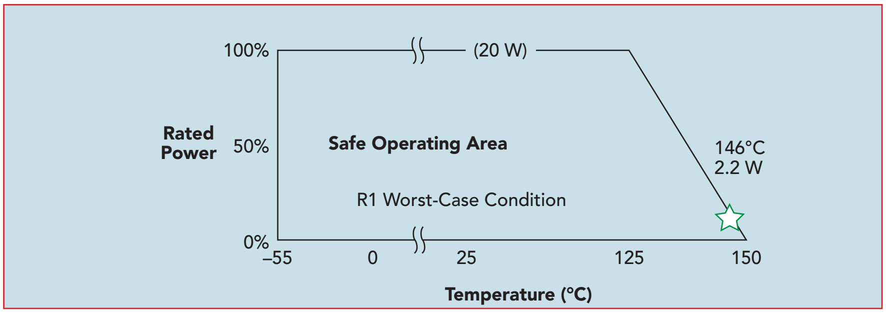

Fig. 9 **The worst-case condition for Example 1.**

PHASE MISMATCH EXAMPLE 1

In this example, amplifiers A1 and A2, as well as amplifiers A3 and A4, are assumed to be phase-matched pairs. When there is a phase difference between these pairs, all the mismatched power dissipates in a single resistor, R1, as shown in the schematic of Figure 4b. For this example, the phase difference between the pairs was set to 0 degrees for the in-phase case and then 20 degrees for the out-of-phase case.

The output power drop resulting from these phase conditions is shown in ***Figure 6***. When the phases are aligned and the phase difference between the amplifiers is 0 degrees, the output power is 74.2 W at the band center of 12 GHz. When the amplifier pairs are out of phase by 20 degrees, the output power decreases to 72 W.

Figure 7 illustrates the power dissipated in the R1 resistor during CW operation. For the in-phase condition, no power is dissipated in R1. However, in the case where the amplifiers are 20 degrees out of phase, R1 would dissipate 2.2 W at the worst-case value of 10.1 GHz over the 4 to 20 GHz frequency band.

Using the power dissipation response and the 28°C/W resistor thermal resistance of the resistive film calculated earlier, the temperature increase in the isolation resistor in the model can be calculated. Assuming an 85°C baseplate temperature, the 20-degree phase difference creates the thermal profile shown in ***Figure 8***. The maximum temperature increase is 146°C at 10.1 GHz.

Figure 9 superimposes this worst-case temperature increase for R1 onto the derating response shown in Figure 2. While the temperature/power point remains within the safe operating area for the resistor, there is not much room for error. This means the R1 resistor cannot be stressed much further while maintaining reliable operation.

PHASE MISMATCH EXAMPLE 2

In this second example, amplifiers A1 and A3 were paired together, as were amplifiers A2 and A4. In this case, the phase difference was set

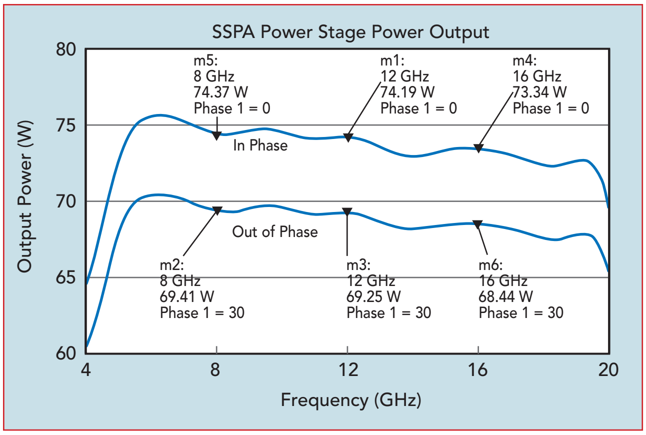

Fig. 10 **Power output profile from Example 2 phase mismatch.**

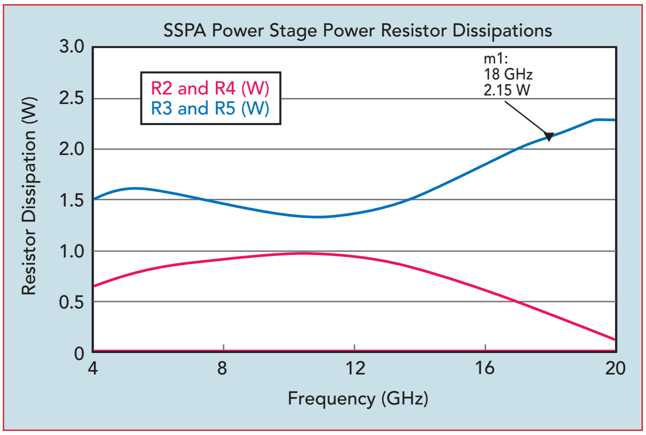

Fig. 11 **Power dissipated in resistors R2, R3, R4 and R5 from Example 2 phase mismatch.**

to 30 degrees, which is 50 percent higher than in Example 1. This results in a more severe power degradation scenario, as shown in ***Figure 10***. Now, the output power for the out-of-phase case decreases by approximately 5 W. Dissipating 5 W in a single resistor at an 85°C baseplate temperature in this combiner would result in failure. Fortunately, in this example, the dissipated power is spread across isolation resistors R2, R3, R4 and R5 as shown in the schematic of Figure 4b.

The power dissipation profiles for the four "hot" resistors are shown in ***Figure 11***. The power dissipation in these resistors is not equal. The worst-case dissipation across the 6 to 18 GHz operating band of the four-way combiner occurs at 18 GHz, where R3 and R5 dissipate 2.15 W. However, Example 1 has shown that this is a

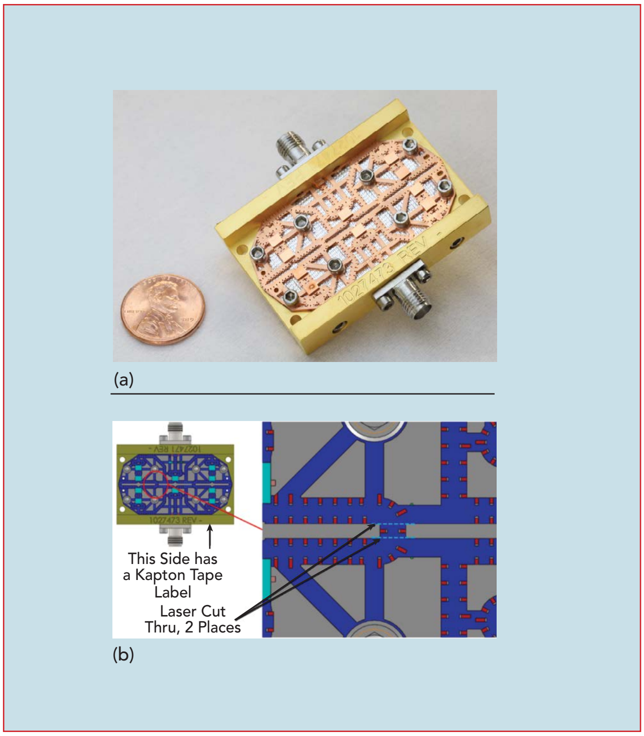

Fig. 12 **(a) B2B combiner with cut path. (b) Laser-cut circuit diagram to replicate failed amplifier.**

safe level of dissipation at an 85°C baseplate temperature.

These results suggest several key conclusions. First, phase mismatches should be minimized. This is especially true for phase mismatches that affect R1. This is most critical because R1 does not share its thermal load with a second resistor, unlike the R2/R3 and R3/R4 resistor pairs.

EXPERIMENTAL VERIFICATION OF RESISTOR SURVIVAL

Mismatching the phase of the high-power amplifiers needed to test the resistor temperature model could be a costly and complicated endeavor. Additionally, measuring resistor temperatures inside a combiner would require removing the isolation lids, which would negatively impact RF performance. As a result, a simpler, indirect method was developed to stress the combiner resistors to the edge of their safe operating area and demonstrate survivability.

This method involved modifying a B2B combiner to simulate a graceful degradation of a failed amplifier. The B2B combiner is illustrated in ***Figure 12a***. The

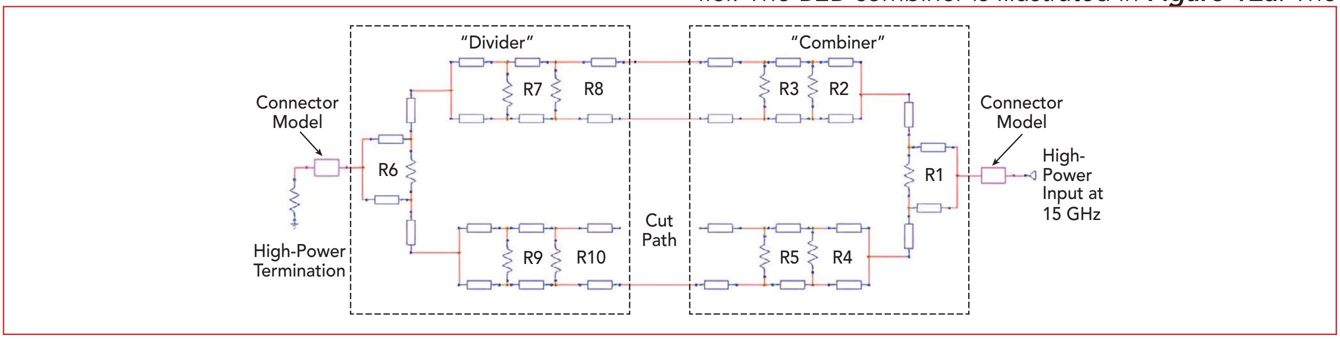

Fig. 13 **Schematic of B2B combiner with cut path.**

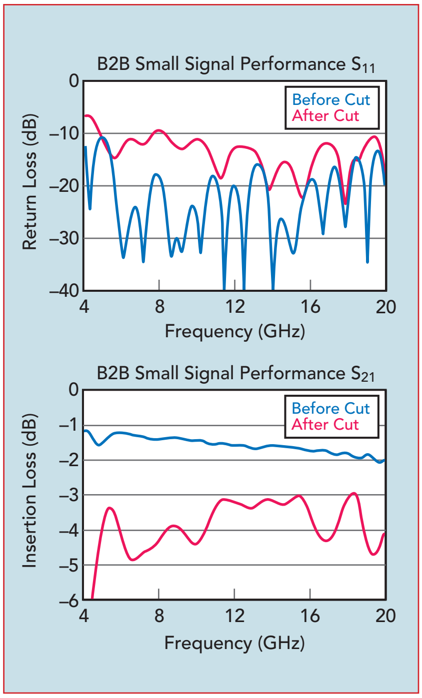

Fig. 14 B2B S_{11} (top) and S_{21} (bottom) combiner performance before and after cutting the path.

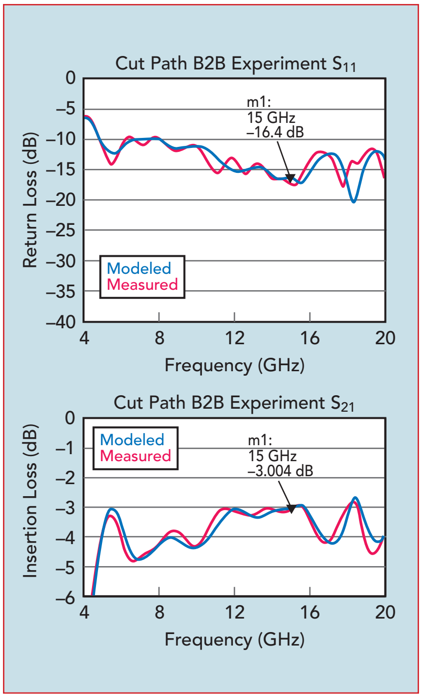

Fig. 15 Small-signal modeled and measured S_{11} (top) and S_{21} (bottom).

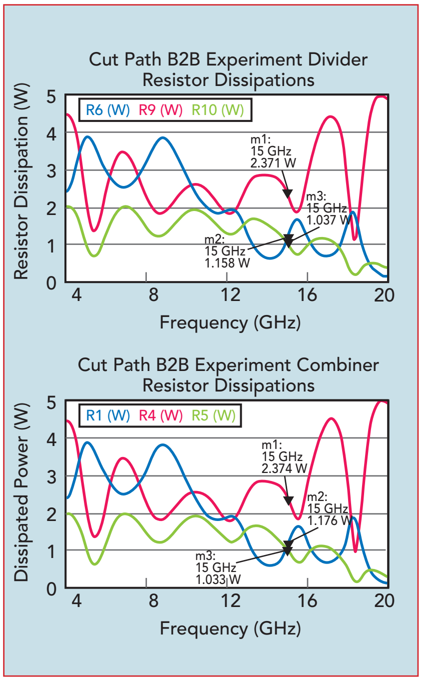

Fig. 16 Predicted resistor dissipations in cut B2B combiner for divider resistors (top) and combiner resistors (bottom).

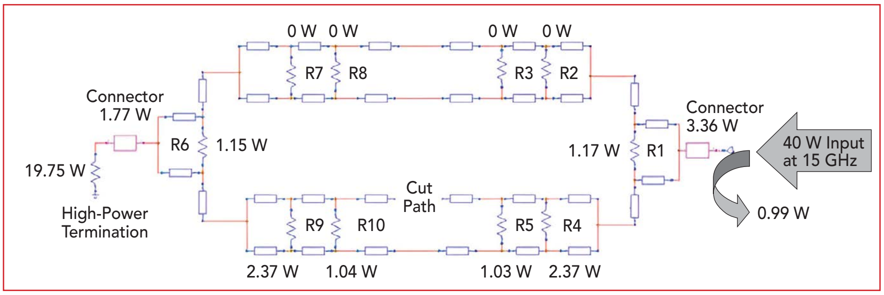

Fig. 17 Predicted cut B2B combiner power dissipation.

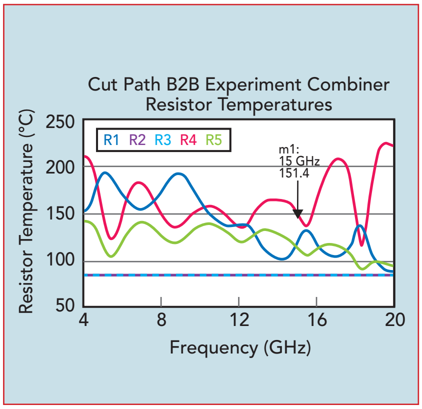

Fig. 18 Predicted combiner resistor temperatures.

diagram in ***Figure 12b*** illustrates an RF path that has been laser-cut to create an open circuit, simulating a failed amplifier.

A simplified schematic of the B2B network with the circuit cut is shown in ***Figure 13***, which identifies the resistor nomenclature. The left side of the structure is designated the "divider," while the right side is the "combiner" function. To measure the heating effects, a high-power CW signal was injected into the combiner input port on the right side of the diagram. RF connectors on the evaluation board introduce loss, but this is accounted for using a connector model with loss proportional to the square root of the frequency.

Two-port S-parameters of the B2B network were evaluated before and after the modification, as shown in ***Figure 14***. Disconnecting one path reduced return loss and increased insertion loss as expected. Much of the increased loss is due to power being dissipated in the isolation resistors.

Figure 15 compares the small-signal response of the cut B2B network with that of the hybrid HFSS/MWO model. There is a close correlation between the modeled and measured S_{11} and S_{21} magnitudes. This serves to illustrate the accuracy of the hybrid modeling approach.

Resistor dissipation is strongly dependent on frequency. For this experiment, a 40 W signal was injected at 15 GHz and the HFSS/MWO model was used to predict resistor dissipation. ***Figure 16*** shows the modeled results, with R4 and R9 dissipating 2.37 W at 15 GHz. This is more than double the dissipation seen in R1, R5, R6 and R10. Resistors R2, R3, R7 and R8 are not in line with the cut path and therefore do not dissipate any power.

A summary of the modeled power dissipation during the cut B2B experiment is shown in ***Figure 17***. The total power dissipation for the resistors is 9.13 W, while the connectors dissipate 5.13 W. Accounting for a reflected power of 0.99 W, since S_{11} is not perfectly matched and 19.75 W power output, this means 5 W is dissipated in the PolyStrata coax transmission lines. These lines can easily handle this thermal load.

The network was heated to a baseplate temperature of 70°C and subjected to increasing power lev-

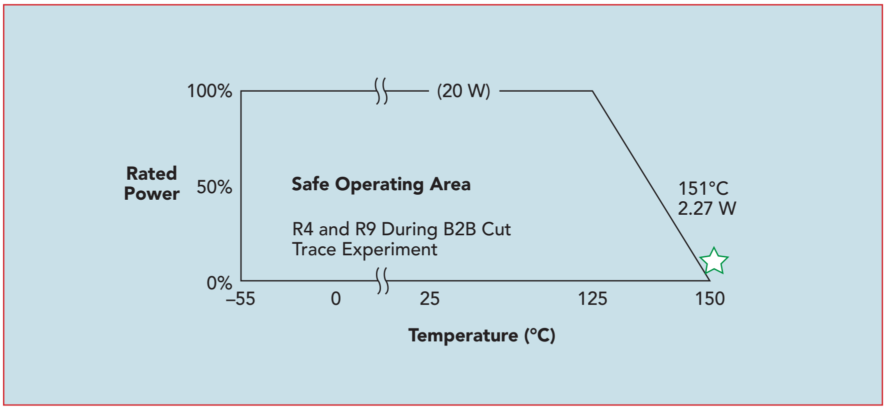

Fig. 19 **R4 and R9 results are just outside the safe operating area.**

els at 15 GHz. The resulting resistor temperatures, subjected to an input power of 40 W CW to the cut path B2B combiner for 30 minutes, are shown in ***Figure 18***. R4 in the combiner and R9 in the divider sections dissipate an equal amount of power and these two resistors show a worst-case temperature of 151°C in response to the 40 W input power.

Performing the same analysis as earlier, ***Figure 19*** plots the R4 and R9 temperature and power conditions against the safe operating area. At 150°C, the resistor is rated at zero power, so the cut B2B operating condition of 151°C is outside the safe operating range of the resistor. After the power exposure, the part was re-evaluated and no change in performance was observed. Although it did not fail, continued operation at this point would constitute a reliability concern.

SUMMARY

This article examines the impact of phase imbalances on power dissipation in Wilkinson power divider and combiner architectures. Using a Nuvotronics PolyStrata combiner as an example, a straightforward, inexpensive method is presented for predicting the temperature increase of an isolation resistor using a physical model of a power combiner. The article also presents the modeled results when the PolyStrata combiner/divider is subjected to various input powers and phase imbalance relationships. Rather than an exercise in modeling and matching modeled results to actual results, the experiments described in the article highlight constraints and potential challenges that arise when isolation resistors are stressed to the limit of their safe operating range.

References

1. "Diamond RF Resistives® Family," *Smiths Interconnect*, pp 69–70.