Wilkinson Power Divider

Part number PDW05758 - Overview

The Knowles PDW05758 from DLI is a surface mount, thin film power divider employing a three section Wilkinson topology.

This power divider utilizes a proprietary DLI temperature stable ceramic, low loss conductors, and integrated resistors. The device provides exceptional performance in a tiny package compatible with standard solder surface mount technology. The total package size measures 0.185 inch by 0.160 inch by 0.020 inch (4.7 mm by 4.06 mm by 0.5 mm). The power divider features excellent return loss on all ports as well as isolation between output ports. Return loss is typically better than 20dB and isolation is typically better than 25dB from 6GHz to 18GHz. The PDW05758 has a worst case excess loss of 0.7dB at 18GHz, over that of the nominal power split of 3.01dB. The nominal phase balance is 0 degrees. Typical measured S-parameters are plotted in Figure 2.

Excellent phase and amplitude balance is inherent to the PDW05758 due to the superior precision of the photolithography processes used to manufacture the device. Amplitude balance is ± 0.025 dB maximum and phase balance is ± 3.0 degrees maximum.

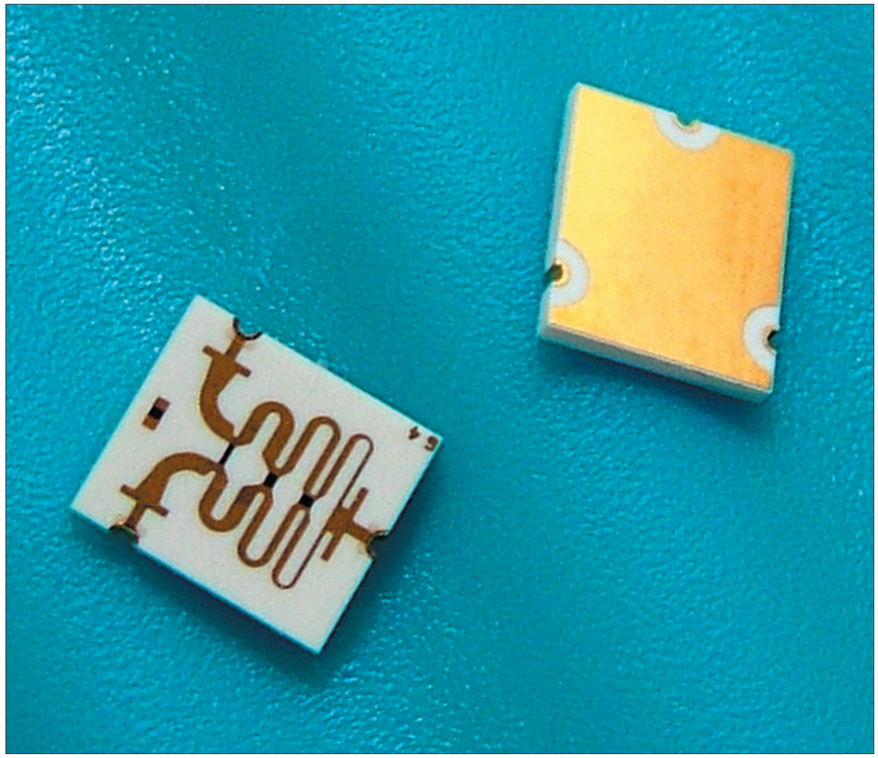
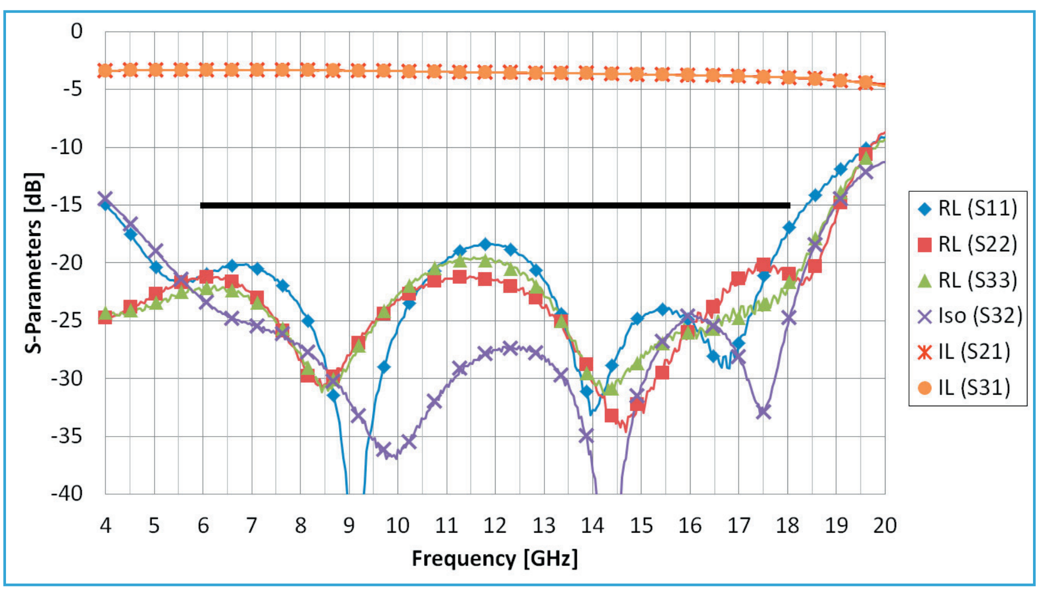


Figure 1: 6GHz to 18GHz, Surface Mount, Power Divider

Figure 2: Measured performance of DLI PDW05758 Power Divider



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Conservation of Power

The schematic for an ideal three section Wilkinson power divider is shown in Figure 3.

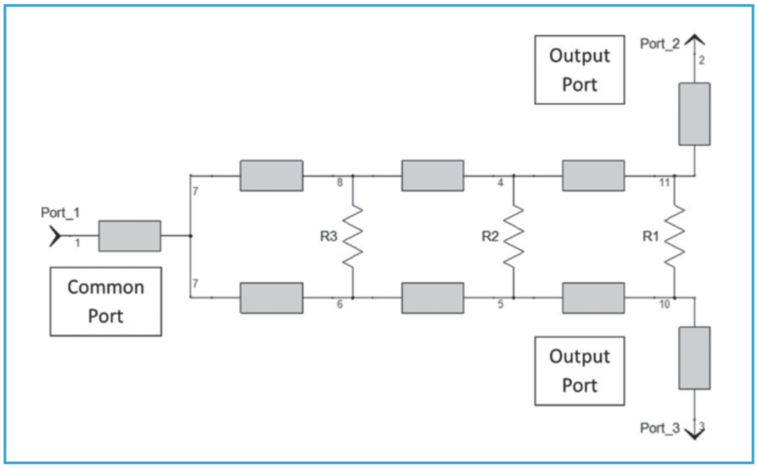

Figure 3: Multiple Section Wilkinson Power Divider

Even and odd mode analysis can be applied to this circuit. By definition the odd mode excitation consists of voltage sources at both output ports with equal magnitude but 180° out of phase with each other. It is known that for an ideal Wilkinson divider power will only be dissipated within the resistors with odd mode excitation. In fact theory tells us that in the odd mode 100% of the applied odd mode power is dissipated in the resistors and 0% is delivered to the common port.

For odd mode excitation one could utilize transmission line techniques to determine what percent of the total applied power is dissipated within each resistor of the ideal Wilkinson; however, for a physical component it is more prudent to utilize a commercially available 3D finite element simulation tool. With this tool we can analyze the distribution of the power dissipation by applying an odd mode excitation which consists of 0.5W of power at port two with phase zero and 0.5W of power at port three with phase 180°. The total possible power that can be accepted by the divider in this case is 1W.

As the physical divider has good but not perfect return loss a small amount of this 1W of power will be reflected at the output ports but the majority of the power will be accepted into the divider. The amount of power accepted is defined as P_{in}. We integrate the Poynting vector at each excitation port to determine the total magnitude of P_{in}. We define the power that is delivered to the common port as P_{out}. The magnitude of P_{out} is zero for odd mode excitation for the case of both the ideal and physical device. We then define the power dissipated in each resistor as P_{R1}, P_{R2}, and P_{R3}, respectively. To compute the amount of power dissipated in each of the three resistors we integrate the surface loss density over each respective resistor. We define the sum of P_{R1}, P_{R2}, and P_{R3}, as P_{diss}. Lastly recall that we previously stated that in the odd mode 100% of P_{in} is dissipated in the resistors of an ideal Wilkinson. We know that in a physical device there will be other loss mechanisms such as conductor losses, dielectric losses, and radiation losses, and that these losses will account for some percent of the power P_{in}. We define the power dissipated in loss mechanisms other than the resistors as P_{loss}. We compute the amount of P_{loss} by using conservation of power. All of these power terms are plotted in Figure 4.

We see from Figure 4, that due to the good return loss of the Wilkinson divider that P_{in} is nearly 100% for the band of operation of 6GHz – 18GHz. Also as expected the total amount of power dissipated in the resistors P_{diss} is greater than 95%. This is due to the fact that the amount of loss in the conductors, dielectrics, and through radiation is small at less than 5% in the band of operation. Finally we see how the remaining applied power is distributed between the three resistors. This distribution

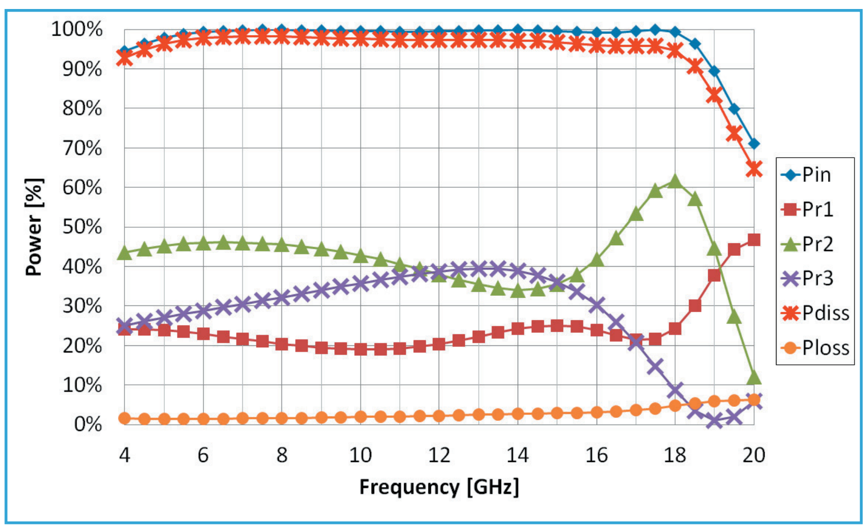

Figure 4: Power Budget for Odd Mode Excitation

of power is a function of the individual resistance values as well as the design of the Wilkinson divider transmission lines. For the majority of the 6GHz to 18GHz band, resistor two (R2) dissipates the most power at about 45%, resistor three (R3) dissipates the second most power at about 35% and resistor one (R1) dissipates the least amount of power at about 25%. At the worst case frequency of 18GHz the power dissipated in resistor two (R2) spikes up to 60%. In practice it is possible to more equally spread the power dissipation between the resistors through design modifications; however, this typically must be done at the expense of other performance parameters such as bandwidth, insertion loss, and physical size.

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Basic Thermal Modeling

As with all heat flow problems accurate analysis is complex and highly dependent upon the specific environment. In this section we discuss the application of a simplified one-dimensional thermal model and how it can be applied to the PDW05758 power divider. The nature of the model being discussed suggests that a relatively low thermal resistance path exists between the resistors on the top of the part and the system fixed temperature reference below the part. In this paper we define the system fixed temperature reference as the top of the printed wiring board upon which the divider is mounted. We refer to this temperature as the base temperature.

When heat is generated due to power dissipation in the resistor film there will be a temperature difference between the resistor film and the base temperature. This temperature difference will be proportional to the thermal conductivity of the divider's substrate, thickness of the divider's substrate, and physical area of which the heat flows. We define the thermal conductivity of the substrate as k with units of Watts per meter Kelvin. We also define the thickness of the substrate as d. The relationship between the power dissipated within any of the resistors and the associated rise in temperature of that resistor is given by Equation 1:

(1): $Q = (k\,\Delta t\,A)/d$

where Q is the power dissipated within the resistor with units of Watts, Δt is the associated rise in temperature between the base and film with units °C or °K, and A is the cross sectional area of the heat flux channel between the film and base temperature. It is known that as the heat flows through the substrate it spreads laterally. This lateral spreading effectively increases the cross sectional area of the heat flux channel as compared to physical area of the resistor film. A common assumption is that the heat spreads with a spreading angle of 45 degrees relative to the plane of the resistor film and the effective area which the heat flows is the area of the 45 degree projection in the center of the substrate. We define the physical width and length dimensions of the resistor film as $w_{physical}$ and $l_{physical}$. The area of the heat flux channel, assuming a 45 degree spreading angle, is calculated in terms of the physical dimensions of the resistor and substrate thickness:

(2): $A=(w_{physical}+d)(l_{physical}+d)$

The final assumption required of this simple one dimensional model is that the resistors are sufficiently isolated from each other such that there are no thermal interactions between them. This is rarely the case in actual applications. In cases where there is significant thermal interactions more precise solutions for complex, multi-heat source circuits will require the application of finite element thermal analysis tools or actual thermal measurements.

The physical sizes of R1, R2, and R3 are respectively 0.0148″ x 0.004″, 0.0094″ x 0.007″, and 0.0069″ x 0.0088″. Recall that the substrate thickness is 0.020″. The thermal conductivity of the DLI ceramic substrate is approximately 9.0 Watts per meter Kelvin.

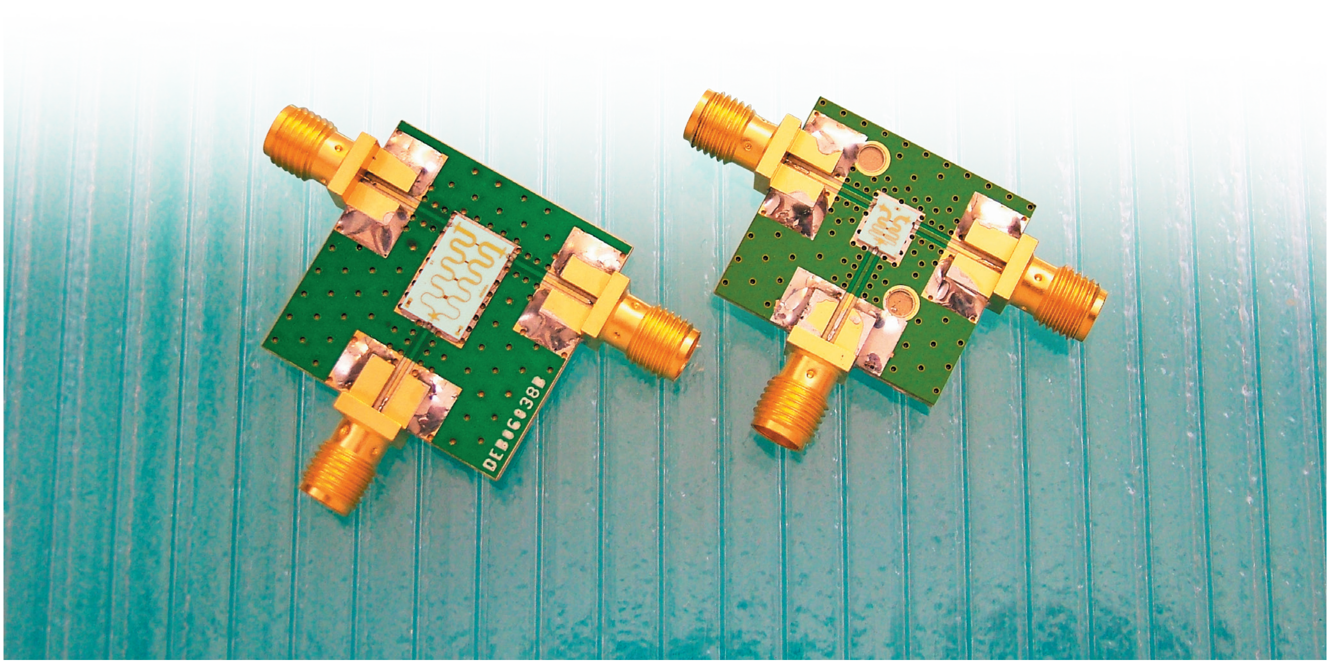
Using Equation 1, and 2 we compute the rise in temperature in each resistor ΔT_{R1}, ΔT_{R2}, and ΔT_{R3}, as:

(3): $\Delta T_{R1} = 113.04°C/Watt$

$\Delta T_{R2} = 118.94°C/Watt$

$\Delta T_{R3} = 121.88°C/Watt$

where we have assumed 1 Watt of dissipated power in each resistor. The usefulness of computing the temperature rise of each resister normalized to 1 Watt of dissipated power is that Equation 3 can be used in conjunction with the P_{R1}, P_{R2}, and P_{R3} data of Figure 4 to predict each resistor film temperature for any magnitude of odd mode applied power at any frequency.



Film Temperature Measurement

Until this point all data presented was obtained from electromagnetic finite element software and simple thermal models. In order to validate this approach we measure the resistor film temperatures of the PDW05758 while applying RF power to the output ports in the odd mode. We measure the resistor film temperature with an IR camera as a function of applied RF power level and frequency. An image from the IR camera of the PDW05758 under test is shown in Figure 5.

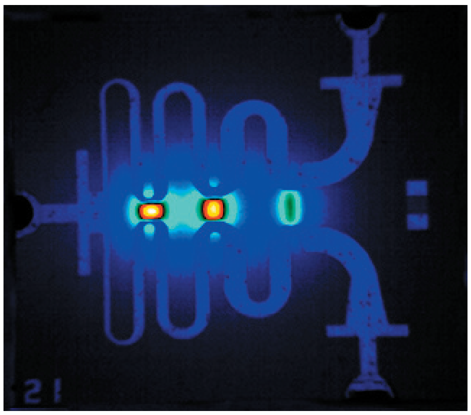


Figure 5: Thermal Image with 1Watt Applied in Odd Mode

This image was taken for a total applied power in the odd mode of 1 Watt at 12GHz. We see from this image that the temperature rise of each resistor is different with resistors two and three being much hotter than resistor one. In addition we see the heat spreading laterally between the resistors with some overlap especially between resistors two and three.

As mentioned previously we utilize Equation 3 and Figure 4 to compute the predicted temperature rise of each resistor normalized by the total applied power. We compare the measured temperature rise of each resistor with the predicted values. These comparisons are shown in the plots of Figures 6, 7 and 8. We see excellent correlation between the measured and predicted resistor film temperatures thus validating the use of a finite element, electromagnetic simulation tool in tandem with a simplified thermal model for accurately predicting film temperatures relative to an applied odd mode power.

One way that the data in Figures 6, 7, and 8 could be used is to determine the maximum applied odd mode power for a given maximum base temperature and given maximum allowed film temperature. For example at 18GHz the R2 film temperature rise per Watt of odd mode applied power is a worst case 70.75°C/Watt. In this case the maximum odd mode applied power as a function of maximum base temperature is plotted in Figure 9 for four maximum allowed film temperatures 85°C, 100°C, 125°C, and 150°C. For reference, a bold line is placed at the base plate temperature of 85°C, a typical commercial and military maximum system operating temperature. At the base plate temperature of 85°C the corresponding maximum applied odd mode powers are 0W, 0.22W, 0.57W, and 0.93W for maximum allowed film temperatures of 85°C, 100°C, 125°C, and 150°C respectively.

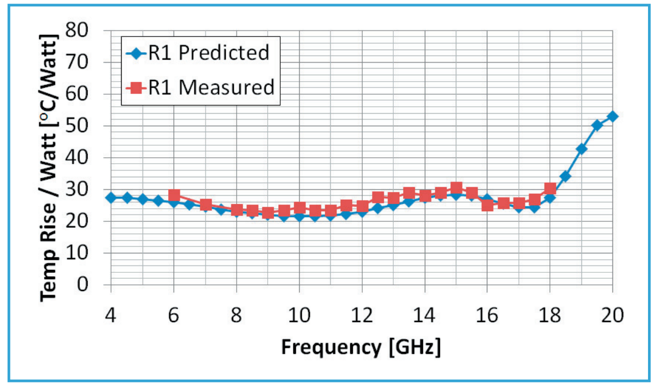


Figure 6: R1 Temperature Rise per Watt

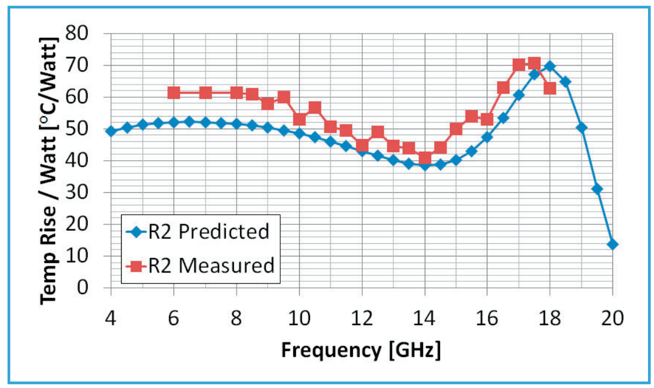


Figure 7: R2 Temperature Rise per Watt

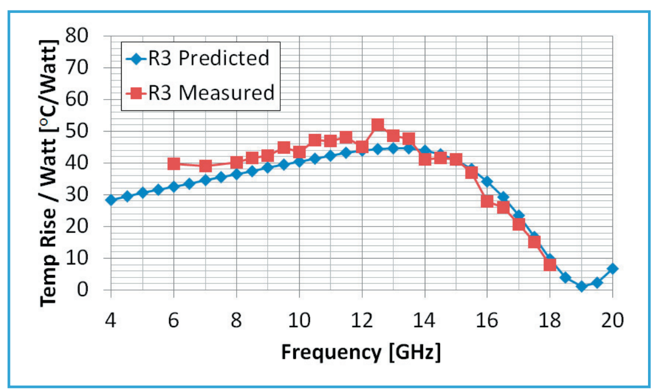


Figure 8: R3 Temperature Rise per Watt

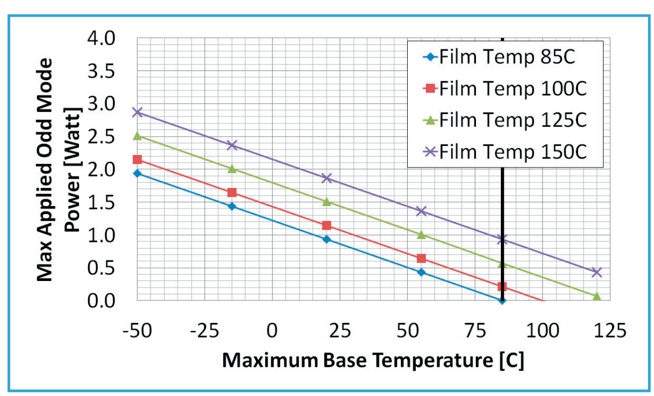


Figure 9: Maximum Dissipated Power vs Base Temperature vs Maximum Film Temperature at 18GHz

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Implications of Resistor Heating

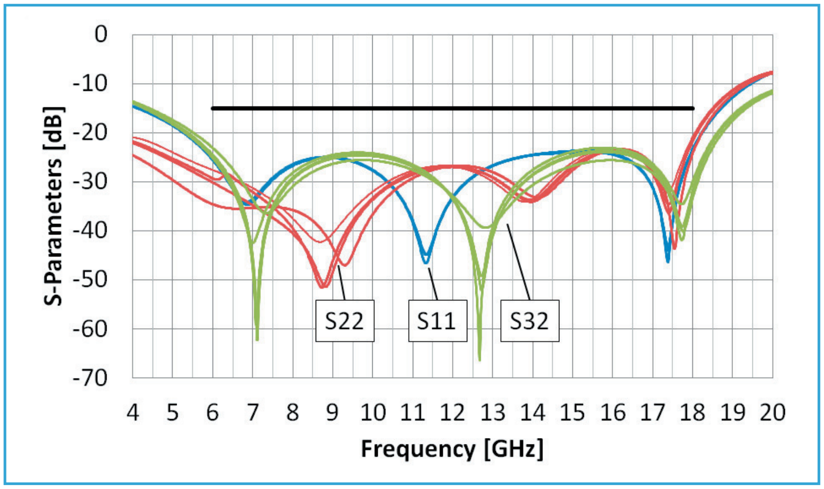

Figure 10: Simulated Effect of Resistor Aging

In general there are two concerns associated with the heating of thin film resistors: resistor aging and the heating of the bond attaching the divider to the printed wiring board. The former is typically associated with long term continuous power handling while the latter is a short term heating issue that may result in a failure mode.

Resistor aging is a phenomenon which causes tantalum nitride thin film resistor to continue to oxidize when operated at elevated temperatures. Depending upon the temperature of the film and the length of exposure, the resistance will increase at a different logarithmic rate. Typically the film temperature needs to be significantly higher than 85°C to see appreciable resistance increases in reasonable time durations. For example oven aging experiments on DLI manufactured resistors indicate a resistance increase of about 1.2% in 250 thousand hours (28.5 years) at 85°C. When the film temperature is increased from 85°C to 100°C the same is resistor is predicted to increases by 2.5% in the same 250 thousand hours. Increasing the temperature further to 125°C corresponds to a predicted increase of 7.3% again in 250 thousand hours. Reducing the time of exposure in all of these cases reduces the resistance increase.

In the case of the Wilkinson divider we are not so concerned with a change in resistor values but rather the potential change in the S-parameters due to the resistor increase. In Figure 10 we plot the simulated S-parameters of the Wilkinson divider for nominal resistance value, a 1.2% increase, a 2.5% increase and a 7.3% increase. These values are taken from the previous example.

As we see in Figure 10 the change in S-parameter performance due to aging is minimal even for a resistance increase of 7.3%. The temperature of the bond between the divider and the printed wiring board may also define the maximum power handing of the divider. In most customer applications the bond is formed of epoxy or solder. The solder between the Wilkinson divider and customer PWB must be maintained under the melting temperature of the solder. The epoxy also needs to be kept under the maximum continuous operating temperature specified by the epoxy vendor. In most cases the maximum temperatures of commonly used bond layers will be between 180°C and 250°C. Typical industry practice is to limit this mounting temperature to 125°C maximum for continuous operation.

Conclusion

Proper application of a finite element, electromagnetic, simulation tool combined with a simplistic heat flow model has been demonstrated to be useful in predicting the film temperature of each resistors of the three section PDW05758 Wilkinson power divider with odd mode applied power. We have validated these resistor temperature rise predictions by way of thermal IR measurements of the resistors with RF power applied.

The total amount of power actually dissipated in a Wilkinson divider under normal operation in a classical application will most likely be significantly less than the levels discussed above. The actual power dissipated is dependent upon the magnitude and phasing of the source and load reflection coefficients connected to the divider ports; however, it is common to analyze the odd mode as this represents the absolute worst case scenario albeit unlikely. For further details of the operation of a Wilkinson power divider, and the power dissipation within the divider in different applications other than the odd mode, please contact the Dielectric Laboratories facility of Knowles.

In addition to the DLI PDW05758, Knowles also offers several other off-the-shelf Wilkinson power dividers utilizing both surface mount as well as wire bondable interfaces with varying bands of operation. Moreover, DLI welcomes all opportunities to review all custom power divider specifications.

Within Knowles Corporation, DLI is a manufacturer of high frequency, high Q, multi-layer and single layer capacitors with a global reputation. In recent years, DLI has emerged as a comprehensive manufacturer of custom and off the shelf specialty ceramic components for microwave and millimeter wave applications serving customers in fiber optic, wireless, medical, transportation, semiconductor, space, avionics, and military markets.