25th ANNIVERSARY

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NOVEMBER 2014

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The company's new full line of 700 to 4200 MHz directional couplers ranges from 100W to 2000W CW, with coupling values of 20 to 60 dB. Model C10006 (shown above) is a 2000W solution and is designed to operate continuously into a 3:1 load VSWR at rated power. This low loss design will also operate into an infinite VSWR, at 700W CW, for 10 seconds.

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A new family of low and ultra-low PIM terminations features the company's new line of 50, 100 and 250W terminations with industry leading PIM performance of -160 to -165 dBc typical, while handling full rated power to +85ºC. All of the terminations cover 0.698 to 2700 GHz frequency bands, VSWR of 1.10:1 typical/1.20:1 minimum in 7/16 DIN, Type N and 4.1/9.5 (mini-DIN) connectors.

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MECA ELECTRONICS

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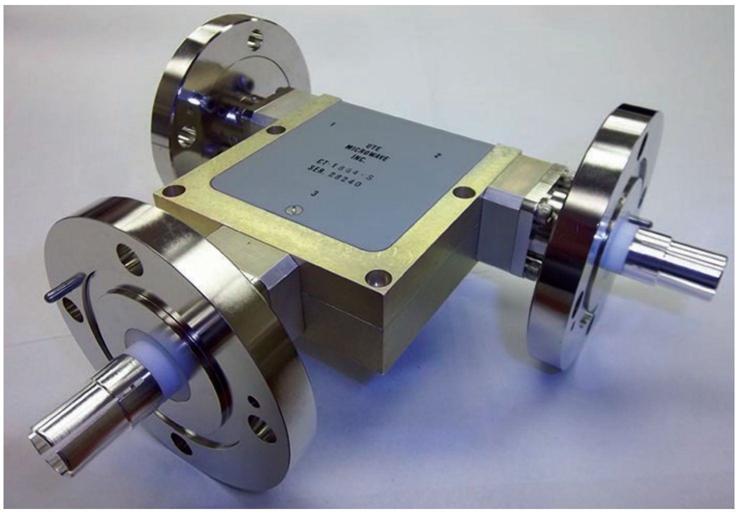

High Power Circulator

Model CT-1872-S is rated at 60kW peak and 600W average power at 325 MHz. The unit provides 20 dB minimum isolation, 0.2 dB insertion loss and 1.20:1 maximum VSWR. Its extremely compact design has flange to flange insertion length of only 6-3/4" and a height of 5-1/4". For use in radar applications, it has 1-5/8" EIA connectors. It is also available at other UHF frequencies and connector types.

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UTE MICROWAVE

Choosing Microwave PCB Materials for Wireless Communications Components

by John Coonrod, Rogers Corp.

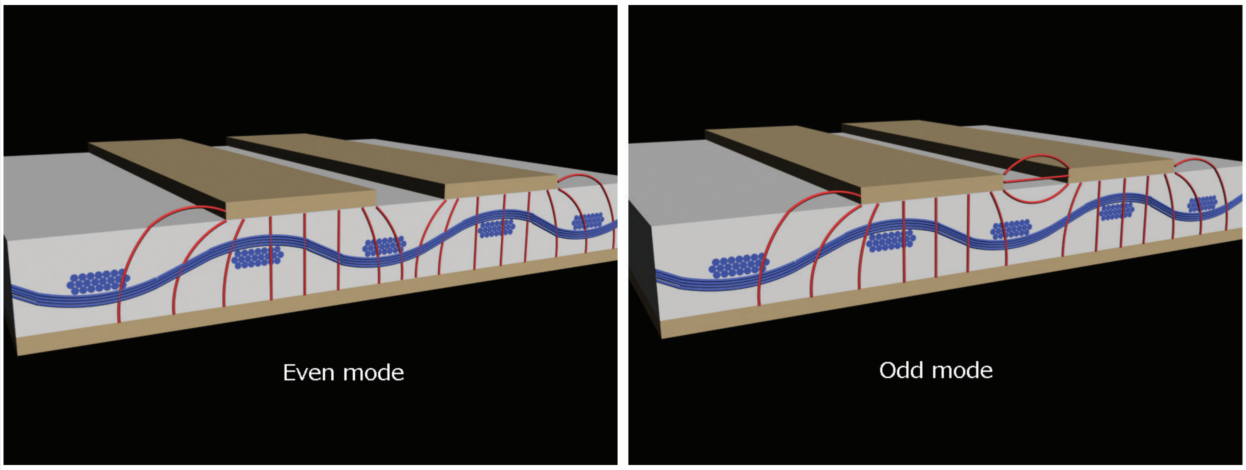

Figure 1: Microstrip even-and odd-mode electric field representations

Wireless communications systems operate because of many different electronic devices and components, and many of these components in turn rely on the printed-circuit-board (PCB) materials on which they are made of or mounted upon. The list of RF and microwave components for these systems is long, and includes baluns, couplers, filters, low-noise amplifiers (LNAs), power amplifiers (PAs), and frequency mixers. Each component has its own set of requirements for PCB materials for optimum performance, and the type of PCB material that may be most suitable for one type of component may not be the best choice for a different type of component. By understanding some of the basic PCB material properties and how they relate to the performance and operation of different RF and microwave components, it is possible to make the best match possible between component and PCB material.

For example, filters are passive components which can be designed for different signal-processing responses, namely, bandpass, band-stop, low-pass, and high-pass filter responses. Filters constructed from PCB materials employ several different configurations to realize the filter functions. Some filters use edge-coupled features, some work with stubs, some rely on stepped-impedance structures, and often filters are designed with a combination of these structures. Filters configured with edge-coupled features have different concerns for circuit material characteristics than filters formed with stubs or stepped-impedance features.

Edge-coupled structures are used for bandpass filters, directional couplers, and other passive components. Such structures provide different operating modes, with filters and couplers making use of their even and odd modes. In microstrip circuits, even- and odd-mode characteristics are described in many standard microwave texts,[1] with even-mode operation occurring when there is an even symmetry around the center line between two signal conductors. Most of the electric field in these two-conductor circuits is contained between each signal conductor and the circuit's ground plane. In even-mode operation, no electric-field coupling takes place between the two signal conductors. In contrast, in odd mode, the electric fields between the two signal conductors are coupled and there are electric fields between the conductors as well as between the conductors and the ground plane. Figure 1 shows a simple illustration of these different modes and their electric field configurations (red lines).

A high-frequency-laminate property critical for circuits with edge-coupled features is anisotropy, specifically, the anisotropic behavior of circuit material's dielectric constant (known as Dk, relative permittivity, or ε_r). Most laminates used in the high-frequency industry are anisotropic, where the Dk in the material's z-axis (the thickness axis) is different than the Dk in the material's x- or y-axis. Due to limits in test methods, it is typically easier to analyze circuit laminate anisotropy in terms of the x-y plane compared to the z-axis. In general, high-frequency laminates with lower nominal Dk values also exhibit lower anisotropy. In other words, the Dk value in the x-y plane has little difference compared to the Dk value in the z-axis of the circuit laminate; the resulting ratio is low between the sets of Dk values. For a circuit material with moderate nominal Dk values, such as 5 or 6, the anisotropy is higher. High-frequency circuit materials with higher nominal Dk values, such as 10 or higher, provide the most anisotropic behavior. There are a few exceptions to these general rules, where some circuit materials have been formulated to exhibit very low anisotropy, even with a relatively high nominal Dk value. Table 1 shows a list of materials commonly used in the microwave industry with z-axis Dk, x-y plane Dk, and anisotropy ratio values.

Quite simply, materials with lower z-axis nominal Dk values have lower anisotropy. Materials with moderate Dk values, approximately 6, have higher anisotropy. Materials with higher nominal z-axis Dk values have the highest levels of anisotropy. To achieve a relatively low value of anisotropy,

	Dk		
Material	MDPL (x-axis)	SPDR (x-y plane)	Anisotropy Ratio
RO3003™	3.00	3.07	1.02
RO3006™	6.50	7.10	1.09
RO3010™	11.20	12.40	1.11
TMM®3	3.45	3.50	1.01
TMM4	4.70	7.81	1.02
TMM6	6.30	6.48	1.03
TMM10	9.80	10.75	1.10
TMM10i	10.16	10.30	1.01

Table 1: List of common materials used in microwave device applications and their anisotropic Dk values (where MDPL refers to microstrip differential phase length method[2] to determine Dk)

one of the materials (TMM®10i laminate) was specially formulated for that purpose.

Some materials which have higher anisotropy ratios can actually be beneficial to designers who are aware of the circuit properties and can make use of them. For RO3010™ materials, for example, the x-y plane Dk is much higher than the z-axis Dk, which can be beneficial for some edge-coupled circuit designs. To demonstrate, using an ideal isotropic material, the even-mode effective Dk will be higher than the odd-mode effective DK because the odd-mode behavior is impacted by the dielectric effects of the surrounding air (with Dk≅1). As Figure 1 shows, some of the electric fields propagate by using air in the odd mode, whereas in the even mode, the fields are mostly contained within the circuit substrate. However, if an anisotropic circuit material is used where the fields in the odd-mode use an x-y plane Dk which is higher than that of the z-axis, the effective Dk of the odd mode will increase. The effective Dk has a relationship to phase velocity and it has been shown[3] that matching even- and odd-mode phase velocities can minimize spurious harmonic responses in circuits with edge-coupled features. In addition, as in the RO3010 materials, having a high Dk in the x-y plane will cause the electric fields to condense and the edge-coupled features can be much more effectively coupled.

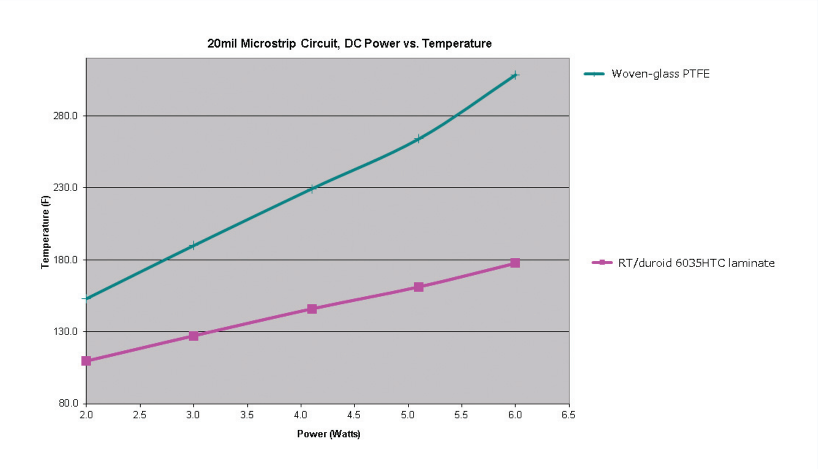

Figure 2: Comparison of circuits with the same geometry, mounted to a heat sink, with materials of different thermal conductivity and showing the difference in circuit heating

Circuit applications with stubs or stepped-impedance features are less concerned with material Dk anisotropy than those with edge-coupled structures. Stubs and stepped-impedance structures mostly use the z-axis properties of the circuit material, with x-y plane Dk properties having minimal effect on the fields of the circuit. Stepped-impedance configurations are mostly concerned with accurately knowing the impedances of the different circuit features. Many designers are sometimes surprised to learn that it is not circuit laminate Dk control that is most critical for characterizing the impedance of a microstrip circuit, but substrate thickness control (Table 2).

The RO4350B laminates used for this example (Table 2) have Dk tolerance, when tested per IPC-TM-650 2.5.5.5c test method, of ±0.05 which is considered quite good. The thickness tolerance for this material is also considered quite good, at ±10% or better, depending on the construction. However, even with such tight tolerances, normal lot-to-lot variations will exist and variations in circuit laminate thickness will have a much greater impact on circuit impedance variations than variations in Dk.

Designers of baluns, frequency mixers, and power dividers will have similar concerns with the circuit material properties detailed so far. In addition, LNAs and PAs will also face these concerns regarding circuit materials, along with the need to consider additional circuit material properties. LNAs and PAs are considered active devices, since they require bias power for operation. However, they are typically mounted on microwave PCB materials, and the attributes of the particular PCB material can impact the performance of an LNA or PA.

Although LNAs and PAs differ greatly in output power, power consumption, noise figure, and various other performance parameters, they do have some material concerns in common. Both types of amplifiers typically incorporate impedance-matching networks to make a transition from the impedance of the amplifier's active devices to the characteristic impedance of the circuit or system in which the amplifier will be used, typically 50Ω. So, designers of both types of amplifiers must be concerned with the impedance variables of circuit materials. In addition, thermal management is an important concern for designers considering different circuit materials for LNAs and PAs. In LNAs, thermal management is important since increased heat in a circuit can raise the noise floor and cause other performance problems, such as variations in gain. In PAs, removing the heat from an amplifier chip or packaged PA can be important not only to the reliability and operating lifetime of the PA, but to minimize the effects of high temperatures on the surrounding devices and components in the circuit.

A number of circuit material properties are related to thermal management. When RF power is applied to a micro-

Material	Substrate Dk	Substrate Dk tolerance	Substrate thickness tolerance	Impedance (Ω)					
				Lower end of Dk tolerance	Upper end of Dk tolerance	Lower end of thickness tolerance	Upper end of thickness tolerance	Range of impedance due to Dk tolerance	Range of impedance due to thickness tolerance
10mil RO4350B™	3.66	±0.05	±1mil	50.64	50.00	47.08	53.30	0.64	6.22
20mil RO4350B	3.66	±0.05	±1.5mil	50.31	49.71	47.62	52.27	0.60	4.65
30mil RO4350B	3.66	±0.05	±2mil	50.23	49.63	47.81	51.95	0.60	4.14
All models used MWI-2014 Software, 1/2 oz. ED copper and conductor widths were: 21mil wide for 10mil wide for 20mil circuit and 65mil wide for 30mil circuit									

Table 2: Comparison of Dk tolerance and thickness tolerance on the changes in impedance

Material	Thermal Conductivity (W/m/K)
Copper	400
Woven-glass PTFE	0.25
RO4350B™	0.64
RT/duroid® 6035HTC	1.44

Table 3: Thermal conductivity values of common materials used in the microwave PCB industry

wave PCB, it will cause heating in the circuit traces due to insertion losses in the circuit trace metal as well as dielectric losses in the circuit material. Using a PCB material with lower loss will result in less heat generated for a given applied power level. In addition, a circuit material with lower Dk allows the use of wider conductors for a given wavelength and frequency, with less insertion loss and heat generated in those wider conductors than in narrower conductors.

The most obvious circuit material property related to thermal management is probably the thermal conductivity of the substrate. When the heating of a PCB is due to trace heating from applied RF power, the only thermal path from the circuit trace to the heat sink is usually through the circuit substrate. Most microwave circuit substrates have thermal conductivity values that are closer to thermal insulators than thermal conductors (Table 3).

For achieving proper thermal management with active components such as LNAs and PAs, copper provides excellent thermal conductivity while PCB materials used for high-frequency circuits typically exhibit very low thermal conductivity. Thermal conductivity is directly related to the heat flow in a circuit. For example, comparing a 20-mil microstrip circuit fabricated on woven-glass PTFE with thermal conductivity of 0.25 W/m/K to an RT/duroid® 6035HTC laminate with a thermal conductivity of 1.44 W/m/K, the increase in thermal conductivity is more than 570% for the circuit material with the higher thermal conductivity, resulting in improved thermal flow through the circuit and a drastic reduction in the heating of a circuit fabricated on the RT/duroid® 6035HTC laminate versus the woven-glass PTFE material.

To evaluate the heat flow of microstrip circuits fabricated on two different circuit materials, a surface-mount termination resistor was mounted on each circuit and DC power applied to evaluate the heat flow path. The circuit materials were woven-glass PTFE and RT/duroid 6035HTC laminate, and the geometry of the 20-mil-thick microstrip circuits was the same, where the top or signal side had the resistor soldered in the middle of the circuit as the heat source. The ground plane (the bottom side of the circuit) was in direct contact with a water-cooled heat sink. A thermal imaging camera was used to monitor the temperature of the various circuits in the evaluation (Figure 2).

As this analysis showed, much improved heat flow was achieved through the use of the circuit material with increased thermal conductivity (RT/duroid 6035HTC). It should be emphasized that RF/microwave heating issues can be quite complicated because of the use of different circuit structures, materials, modulation formats, and other issues, and this analysis was performed purposely with DC power to heat the termination resistor in order to simplify the thermal analysis of the circuit materials as much as possible.

Many microwave devices have thermal management issues and the manner in which the circuit is attached to the heat sink can be important. Typically, a heat sink is attached to a microwave PCB by mechanical screw-down, sweat soldering, or the use of thermal and electrically conductive adhesive (TECA). TECA bonding to a heat sink can minimize the chance of air gaps in the material/thermal interface, which can be a limitation for the other heat-sink attachment options. Assuming the other options are free of air gaps, they offer higher thermal conductivity because the thermal path consists of metal, whereas TECA is an adhesive system with lower thermal conductivity. One exception is the COOLSPAN® TECA film from Rogers Corp., which features impressive thermal conductivity of 6 W/mK.

An issue that can be a concern with some heat sink attachment approach is how it will impact the ground return path (and the RF/microwave performance). In addition, some TECA materials have suffered rises in insertion loss when operating at higher temperatures. To better understand these TECA characteristics, a simple study was performed to evaluate the insertion-loss performance of simple microstrip transmission-line circuits when COOLSPAN TECA was used to bond the circuits to thick copper as the heat sink. The insertion-loss performance of the circuits was checked at both room temperature and at +65°C, along with evaluating any difference due to lead-free solder reflow cycles. Table 4 shows a summary of this study, with 8" long microstrip transmission line circuits built on RO4350B™ circuit laminate and bonded to 6 oz. rolled copper with 4-mil-thick COOLSPAN TECA.

Very little differences were found when comparing the circuits after heat sink attachment compared to after two lead-free-solder reflow cycles (Table 4). In addition, very little difference was found for the circuits tested at room temperature and at +65°C. Still, there will always be some differences in the insertion loss of circuit materials at room temperature and at elevated temperatures due to the circuit material temperature coefficient of dissipation factor (TCDf) and the fact that the connectors and cables used in the testing may change electrical characteristics with temperature. But the differences in this

	Room temp insertion Loss (dB)				65°C Insertion Loss (dB)			
	5 GHz	10 GHz	15 GHz	20 GHz	5 GHz	10 GHz	15 GHz	20 GHz
After heat sink attach	1.878	3.177	4.464	5.617	1.937	3.315	4.726	5.863
After lead-free reflow 1	1.851	3.117	4.384	5.503	1.88	3.199	4.508	5.661
After lead-free reflow 2	1.904	3.245	4.536	5.68	1.911	3.304	4.629	5.853
Maximum difference	0.053	0.128	0.152	0.177	0.057	0.166	0.128	0.202
Testing was done with 8" long microstrip transmission line circuit bonded to thick copper heat sink with COOLSPAN TECA and using 2 end launch connectors.								

Table 4: Comparison of insertion loss between room temperature performance and 65°C operating conditions, include the impact of multiple lead-free solder reflow cycles

analysis, with 8" long transmission line circuits, were minimal.

In summary, different RF/microwave devices and components have different circuit material requirements. Choosing a circuit material for a particular type of component, whether active or passive, can depend on evaluating various key material parameters, such as Dk and thermal conductivity, to achieve the best possible performance from that active or passive component.

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