Microwave Journal E-BOOK

Selection of PCB Materials for 5G

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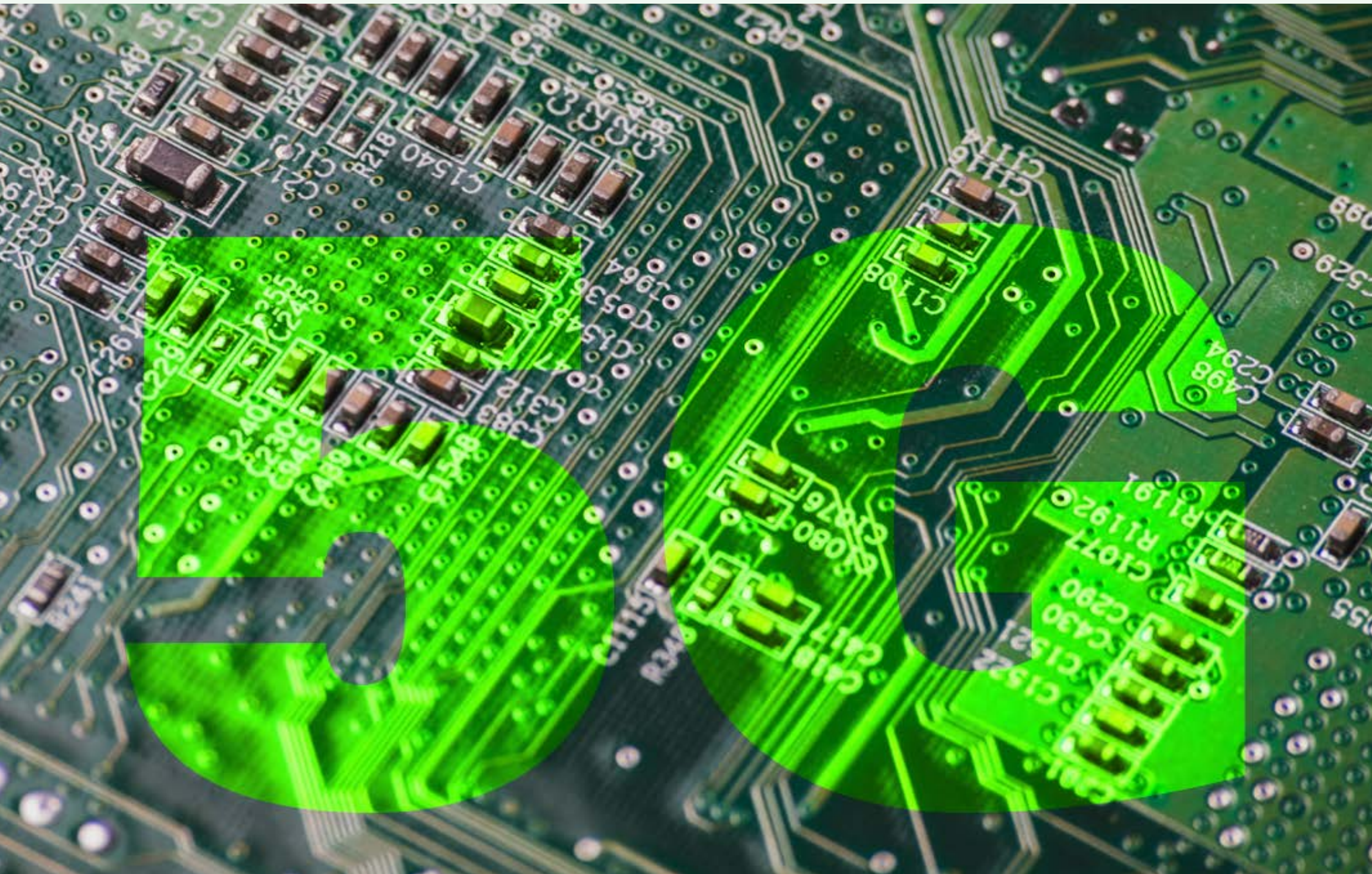

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PCB Materials Considerations for 5G

With the first 5G NR standard recently approved by the 3GPP at the end of 2017, many companies are racing to design 5G radio products that will demand wider bandwidths, higher frequencies, enhanced carrier aggregation and support of massive MIMO. AT&T and Samsung plan to launch 5G mobile services and Verizon plans to launch 5G Fixed Wireless Access in the US this year while South Korea will be demonstrating 5G at the upcoming Winter Olympics.

The demanding performance requirements of 5G will push the limit of PCB designs from antennas to control functions to amplifier circuits. PCB effects such as copper surface roughness, Dk variations, thermal dissipation, passive intermodulation, coefficient of thermal expansion and thickness variations, will affect 5G designs more than previous generations that had less stringent performance criteria. PCB designers will have to consider many of these effects in their designs so need to learn about the various tradeoffs with different types of PCB materials and processes.

5G mmWave applications will have very different materials needs than sub 6 GHz applications so these articles also address the requirements for higher frequency designs. At mmWave frequencies, the effects of small variations in material parameters will have even more affect on the circuit's performance. For higher frequencies into the mmWave range, designers typically need to minimize Dk, copper roughness and thickness variations as they can all negatively affect performance. These considerations must be incorporated into the design using accurate models and simulations in order to avoid costly iterations.

This eBook introduces 5G objectives and goals, opportunities for high frequency materials in 5G and IoT applications, materials effects for 5G designs, PCB antenna design considerations, and material selection for the different spectrum of 5G power amplifiers. The effects of various material parameters on loss, thermal dissipation and reliability are discussed in these articles to provide designers with the tools needed to account for these affects.

Microwave Journal has put together this collection of articles covering these topics. Rogers Corporation has contributed many of the articles as a leading PCB material manufacturer offering their expertise and experience in this field to educate designers and manufacturers about various PCB material considerations in 5G designs.

Pat Hindle, Microwave Journal Editor

5G: Is it Ready for Take Off?

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Never has there been so much hype and attention paid to a new wireless standard than with 5G. 5G has generated a lot of interest, due to its potential transformational impact on both consumers and businesses across the globe. Has the hype been overdone? Let's look at where we have come from, where we are today and speculate a bit as to what the future may hold.

HOW WE GOT HERE

A little over 10 years ago, Apple introduced the iPhone and opened our eyes to the potential of smart devices combined with wireless broadband data. In 2016, Cisco published their Global Mobile Traffic Forecast, estimating that over 1.5 billion smart devices were sold globally. The report also estimated that by 2021, the world will consume over 49 exabytes of data per month—a 7x increase over the usage in 2016. The acceptance, adoption and pervasiveness of smart devices astounds and has been, in and of itself, transformational. 5G aims to go further. Broadband wireless data will continue to draw attention, and the world's standardization bodies shaping 5G have taken notice.

At the outset of the 5G standardization kickoff, the 3GPP outlined three key performance metrics (see ***Figure 1***). The 3GPP defined the enhanced mobile broadband (eMBB) use case and attached a performance target of greater than 10 Gbps peak data rate to expand broadband data services. In response to several industry groups, the 3GPP also set key performance metrics for ultra-reliable low latency communications (URLLC) and increased connectivity, setting the stage for billions of connected devices for massive machine-type communication (mMTC).

Today's wireless standards do not and never have addressed latency and broad connectivity. Latency is quite important because lower latency will not only improve the common data experience for users but create new applications that rely on fast network response. Low latency and, specifically, deterministic low latency responsiveness provide the foundation for "control" applications over the network. Combining robots, drones, cars and other devices that "move" with low latency wireless communications makes controlling these devices from a remote location possible, potentially

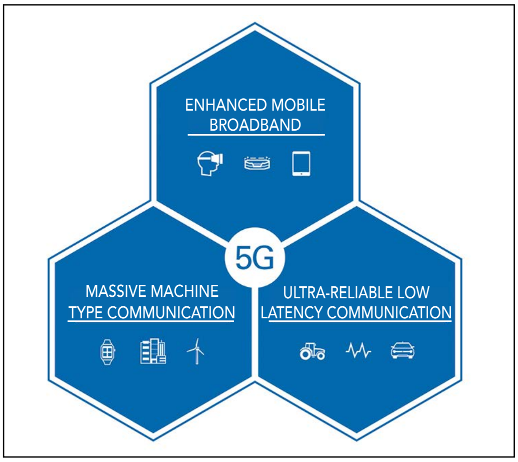


Fig. 1 **5G use cases defined by 3GPP.**

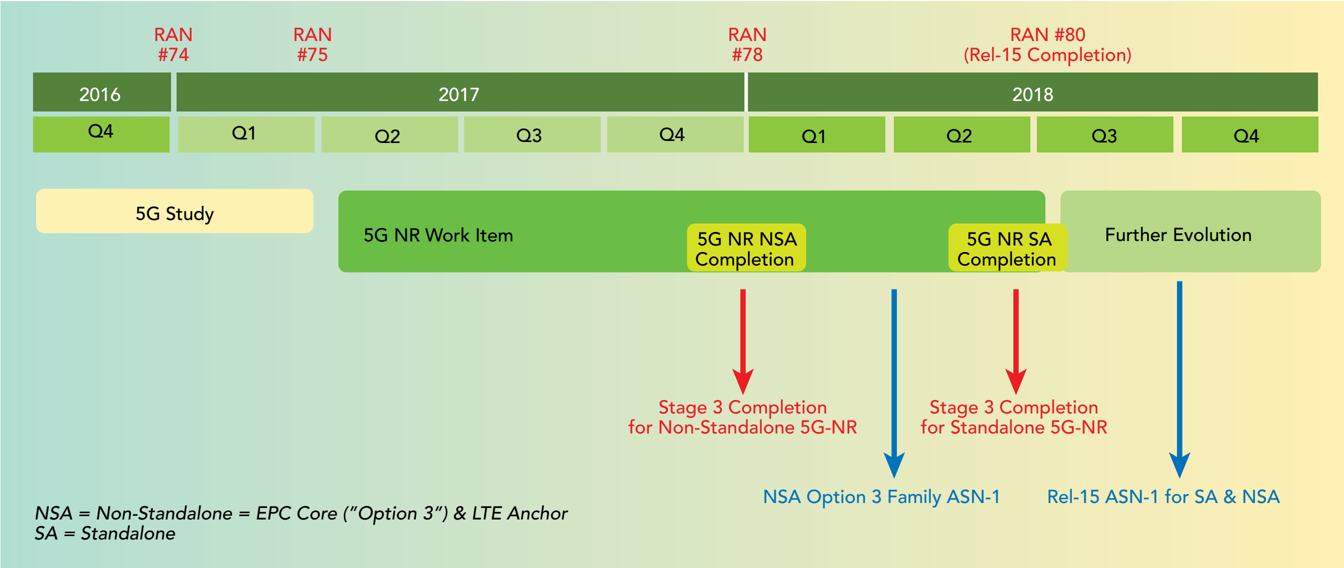


Fig. 2 Timeline for 5G radio access network standardization. The first NR specification release is scheduled for late 2017, with updates during 2018.

impacting construction, medicine, manufacturing, retail services and safety. Latency in this context also includes delivering timely information from the cloud or deployed sensors to the brains of these devices, so that decisions can be made on the fly to enhance safety. In this case, the data is delivered real-time, and the control mechanism is deployed on the device.

In 2015, when the 3GPP kicked off the 5G standardization effort, the group outlined the timelines and key performance objectives for this new standard. The 3GPP stated unprecedented guiding principles for the definition process to follow. First, 3GPP broke compatibility with prior releases, setting a goal of forward compatibility. By breaking with LTE and prior-generation standards, the 3GPP opened a path for innovation to meet these very difficult objectives. Second, the 3GPP divided 5G into phases. The first phase, or Phase 1, focused on mobile access below 40 GHz and set a framework for Phase 2 to investigate spectrum above 40 GHz. In all, the 3GPP has been working on 3GPP release 15, also known as 5G New Radio (NR) Phase 1, with an expected release date of June 2018 (see ***Figure 2***).

WHERE WE ARE TODAY

As I write this article, the 3GPP is closing in on the first draft of the physical layer of 5G NR Phase 1, targeted for December 2017. This first draft is critically important, as it establishes the foundation upon which semiconductor, device, infrastructure, test and measurement and other wireless ecosystem players will plan and build their businesses. Until this point, the development has evolved using system prototypes for field trails with service operators. With a firmer standard in place, the players can develop tangible plans and targets for product and service rollouts.

Interestingly, there have been announcements regarding the availability of 5G technologies—specifically by Intel and Qualcomm—and these early developments are intended to seed other companies to drive adoption. It may seem strange to announce products compliant with a standard before the standard is final, but the shape and structure of 5G NR has been crystalizing for several months. "Final" solutions will inevitably need some tweaking to meet the standard; however, progress toward the creation of the ecosystem has already started with a path toward commercialization.

Service operators have announced 5G plans in all shapes and sizes: SKT and KT are gearing up for 5G trial services to accompany the 2018 PyeongChang Winter Olympics in South Korea. In the U.S., Verizon has aggressively purchased spectrum in the 28, 37 and 39 GHz bands and driven the development of the 5GTF standard, primarily for fiber to the premises (FTTP) applications. Verizon has been trialing pre-commercial equipment in 11 cities in the U.S. since the beginning of this year and announced plans for initial commercial deployments in 2018. T-Mobile, the big winner in this year's FCC auction, won 31 MHz of spectrum around 600 MHz and announced plans to build a "nationwide" 5G network using their newly purchased spectrum. Sprint has approximately 120 MHz of spectrum in the 2.5 GHz band and has been working with Qualcomm and SoftBank, its parent company, to plan 5G rollouts in 2019. Meanwhile, AT&T has announced plans for IoT services in spectrum it currently owns and acquired FiberTower to obtain licenses at 24 and 39 GHz.

Since the 3GPP kicked off the 5G standardization effort in 2015, the mMTC use case has been deprioritized. The 3GPP continues to evolve LTE; in release 14, the 3GPP made several enhancements to LTE specifically targeting the mMTC use case, with development of the NB-IoT and LTE CAT-M standards. The mMTC use case elevates connectivity as a goal, driving device manufacturers to incorporate wireless capabilities into many devices not previously connected, expanding their utility. We have seen a glimpse of the possibilities with new IoT devices, but there are significant challenges: there is no pervasive or ubiquitous wireless IoT standard. As such, there are challenges with interoperability and seamless connectivity to infrastructure and smart devices. With the 3GPP addressing the mMTC use case in release 14 and delivering a comprehensive and widely supported standard, time will tell whether further enhancements are needed in a future evolution of 5G.

WHAT WILL 5G LOOK LIKE?

As noted, the 3GPP plans to finalize 5G NR Phase 1, 3GPP Release 15 by the end of 2017, with the ASN.1 ratification in June of 2018. The 3GPP has started on the path of defining the transformational radio access network by including wider bandwidths, essential for faster data rates. New spectrum has been identified to deploy these wider bandwidth systems. The 3GPP has also reduced the symbol timing compared to LTE, to enable shorter transfer time intervals (see ***Table 1***). In addition, the 3GPP has aligned on a self-contained subframe, which enables transmission and reception in a single subframe for time-division duplexing (TDD) systems. With this initial work, the 3GPP has addressed faster data rates and lower latency. Perhaps most importantly, a new, flexible numerology will enable operators to accommodate different types of devices and support diverse use cases.

For mmWave, the 3GPP has identified specific frequency bands and incorporated beam management and control for phased array antennas (PAA). Although the stage is set for mmWave deployments, many practical challenges remain for widespread adoption (more on this later).

The 3GPP defined two main network architectures for Phase 1. With the non-standalone (NSA) architecture, the 5G NR uses the existing LTE radio access network and evolved packet core or EPC (see ***Figure 3a***); NSA includes two additional options (see ***Figures 3b*** and ***3c***). The second main architecture, named standalone (SA), uses the 5G NR and a new 5G core (see ***Figure 4***). NSA enables operators to offer 5G services sooner, taking advantage of the existing infrastructure to deliver services in the short-term, since investments for SA are expected to be much larger and will take more time. In the standards meetings, NSA has been a focus because of the immediate opportunity and, perhaps, a narrower scope. SA will deliver more 5G benefits than

TABLE 1

LTE VS. 5G NR PHASE 1

	LTE	NR Phase 1
Number of Streams	SISO	SISO per Polarization per Antenna Panel
BW	20 MHz	800 MHz
Subcarrier Spacing	15 kHz	240 kHz (Maximum)
FFT Size	2048	2048, 4096
Number of Occupied Subcarriers	1200	~1600 (FFT Size 2048) ~3300 (FFT Size 4096)
Spectral Occupancy	90%	98%
Slot Duration	0.5 ms [7 Symbols]	125 µs [14 Symbols for 120 kHz Subcarrier Spacing]
Antenna	Omni	64 Beams (for SS Block)

NSA and will surely improve data rates and latency to be much closer to the 5G targets. The 3GPP is targeting December 2018 to wrap up Phase 1, release 15, which will include both NSA and SA.

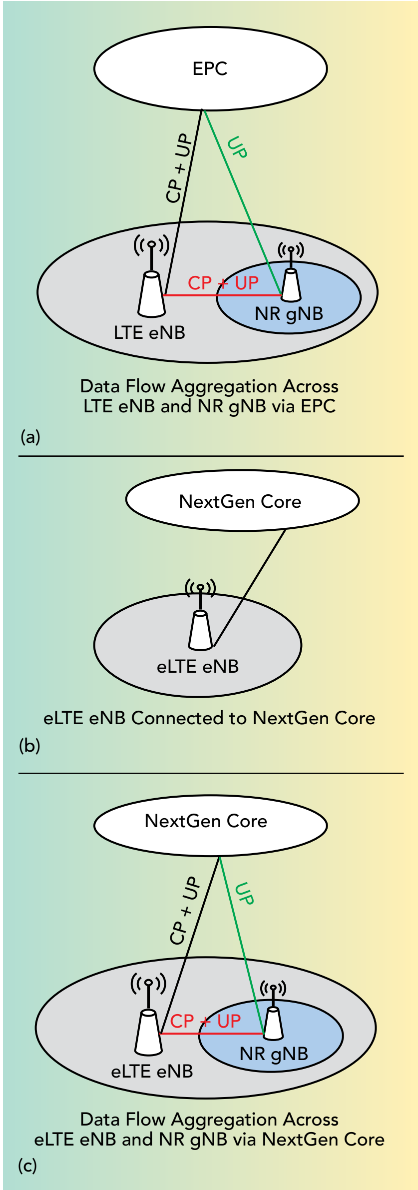
The 3GPP has accomplished much in a very short time. In the short-term, 5G deployments below 6 GHz may look a lot like LTE on steroids, i.e., faster data and lower latency. The first NSA deployments may provide noticeable performance enhancements over LTE, and the lightning fast data speeds will likely appear when network operators deploy mmWave technologies and the new 5G core network, needed for SA operation. What is clear is that this is just the beginning. Future evolutions and iterations seem inevitable.

CHALLENGES AHEAD

As the 3GPP finalizes the formative 5G specification, the path forward is not unimpeded. 5G has the potential to be a "game changer," but the transformational impact must come with extensive help from a diverse set of players. Potential challenges exist in three high level areas: mmWave, network topology and ecosystem.

mmWave

The 3GPP chose to incorporate mmWave technologies into the standard due to the scarcity of available spectrum below 6 GHz. More spectrum equates to faster data speeds. Although the 3GPP will specify 5G technologies for use in spectrum below 6 GHz, the 3GPP is relying on mmWave, with its copi-



▲ Fig. 3 Initial 5G deployments will use the existing LTE radio access network and EPC (a). The NSA specification includes architectural options using the new 5G core (b) and (c).

ous spectrum, to meet its goals for the eMBB use case. Over the last couple of years, several researchers have prototyped mmWave systems extensively, but the early prototypes were big, bulky and used very new technologies such as PAAs.

PAAs overcome the free space path loss associated with mmWave transmission and reception using multiple antenna elements and beamforming to enhance gain. With their benefits, PAAs also pose system challenges, as the control of the beams must be incorporated into the standard and, more practically, into the software deployed on these systems. To support mobility, the protocol software must switch the beams in less than 200 ns to maintain the link, requiring fast switching technology in the antenna assemblies and the software architectures that program them.

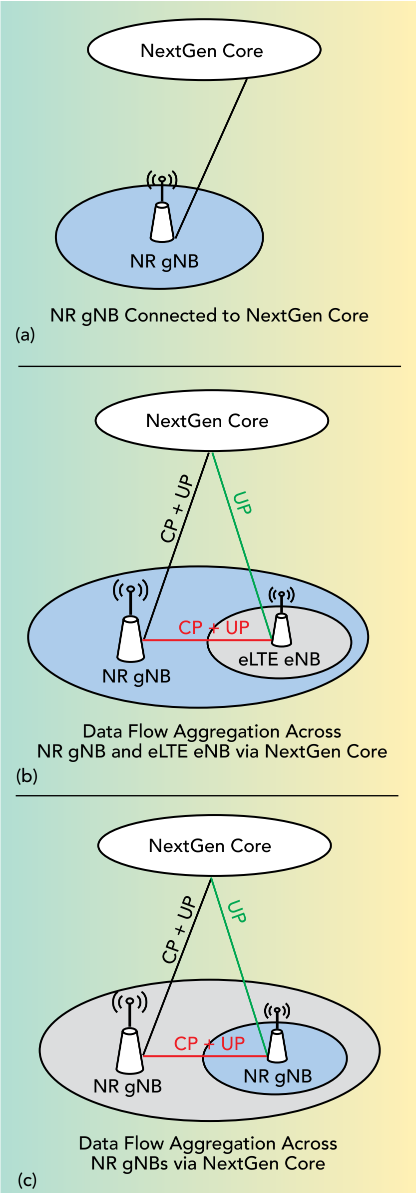


Fig. 4 The SA specification assumes the 5G NR and a new 5G core (a), with two additional options to handle deployment scenarios (b) and (c).

The testing of PAAs and the systems that incorporate them is being investigated and poses new challenges for the test and measurement industry. As PAAs are often integrated with their transceivers to minimize loss, cable access to these modules and the arrays that incorporate them will not exist. Over-the-air (OTA) techniques for testing PAAs are being explored by several companies, with proposals submitted to the 3GPP RAN4 working group for incorporation into the standard. OTA introduces new variables to the test equation; most significant is the need to minimize test time and test cost. Test and measurement companies must deliver fast, cost-effective solutions to the wireless industry to facilitate the development of the mmWave ecosystem.

Even with PAAs in both the user equipment (UE) and infrastructure (i.e., gNodeB), mmWave propagation is limited, even at the lower mmWave frequencies. Denser deployment of the infrastructure is a foregone conclusion that will likely signal more costly rollouts of the technology and systems. To address the density challenge, researchers are exploring new techniques for mesh and integrated access backhaul (IAB) to minimize the cost of denser deployments by utilizing the 5G gNodeBs already deployed. IAB would reduce the cost of running fiber to each mmWave access device; however, the technique may introduce more latency.

Network Slicing

One of the more impactful observations for 5G transformation is that the networks must morph and scale to optimize resources to support new applications and services. "Scalable" networks was not an explicit goal outlined by the ITU or the Next Generation Mobile Networks (NGMN) Alliance when the 5G standardization process was kicked off by 3GPP, but the implication was clear.

To describe this flexible network topology, the wireless industry defined the term "network slices." Network slices describes the ability of a service operator to "slice" the network to tailor a unique set of services for users, creating diverse applications and use cases and charging appropriately for the services. With network slices, a company or individual could purchase a service or a set of services to meet specific needs. For example, consider a company that outfits a factory with 1,000 connected sensors. The company may expect to pay less than $40 per month for unlimited data, since those sensors do not transmit or receive the type of data that we consume on our smartphones.

While the 3GPP has, indeed, made great progress toward defining a radio access network capable of achieving these lofty goals, network operators must be able to fairly charge for these services and conserve valuable network resources to sustain a healthy ecosystem and enable all contributors to prosper. To facilitate the creation of network slices, the 3GPP has enhanced the split architecture of the control and user planes to enable separate control and data paths. This is just the foundation. Network slicing also depends on implementing infrastructure elements beyond the physical layer of the protocol stack. Network technologies such as virtual EPC, network function virtualization (NFV), software defined networking (SDN) and mobile edge computing (MEC) are components and services necessary to move network slicing forward. Without these technologies, all data and control traffic must aggregate at the core network, potentially crippling the industry's ability to meet the goals of data throughput, end to end (E2E) latency and massive connectivity.

Creating the Ecosystem

5G's success or failure will depend on the creation of an ecosystem. The 5G ecosystem must extend beyond the traditional wireless value chain of usual participants: the service providers, semiconductor companies, infrastructure manufacturers and test and measurement companies, to name a few. Application software and service providers, cloud and cloud infrastructure, vertical integrators, software companies and even car, drone, appliance, medical device and construction manufacturers must be an integral part of the 5G landscape to realize the true economic potential. Creating an ecosystem does not occur overnight. The initial deployments of 5G services to enable the ecosystem to grow and evolve are critical.

A 5G FUTURE

Qualcomm recently commissioned a study by IHS Market to assess the economic impact of 5G. IHS Markit speculates that 5G will become a general purpose technology (GPT), a development so impactful that it becomes a catalyst for socio-economic transformation. For perspective, other examples in our history cited as GPTs include the printing press and electricity. IHS Markit expects 5G to contribute $12.3 trillion—yes, that is a "t"—to the global economy by 2035. IHS Markit is not alone in their prediction, as the world's economic leaders continue to invest in 5G with a myriad of funding and regulatory support. These global leaders are betting on 5G to catalyze GDP growth and create economic prosperity. While 2035 is 20 years away, the 5G foundation is being laid today. Creating an ecosystem for these applications will take investment, dedication and perseverance and, above all, time. The various ecosystem players must step up to the plate to realize the vast potential that 5G promises.

As noted, initial rollouts are scheduled for next year, and more meaningful deployments will begin in 2019. To realize 5G's potential, significant innovations must occur in semiconductors and packaging technology, system and network topologies and architectures and, of course, the important verticals that will take advantage of this new network of 5G capabilities and services. It will not be easy, but with the commitment of the industry and the world's government leadership, 5G has unstoppable momentum.

The industry has made great strides in moving the 5G agenda forward, achieving key milestones in both the standardization process and technology development. Demonstrable commitments from academia, industry and governments worldwide have created forward momentum, yet there remains much to do. 5G below 6 GHz may have a shorter runway to deployment, but mmWave is very important to the overall 5G vision. The next year should provide a better picture of the 5G timelines and potential, and the world will be watching the progress on the challenges outlined in this article. The major players have all anted up, but there are real and hard problems to solve for 5G to live up to its promise. 2018 should be an interesting year and this time next year, a clearer picture of the future should materialize.

The central question is not whether 5G will be impactful, the question is when?■

Opportunities for High Frequency Materials in 5G and the IoT

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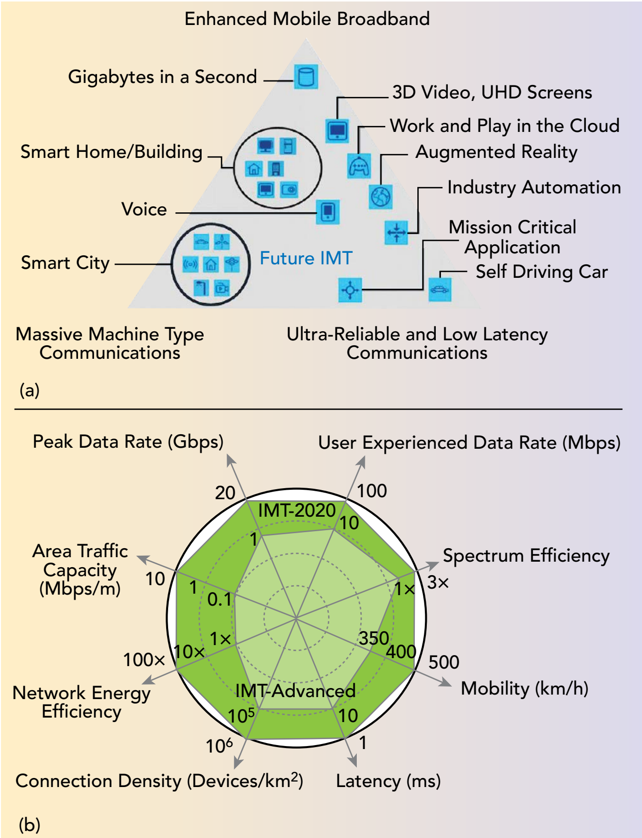

Fig. 1 ITU vision for IMT-2020, including usage scenarios (a) and enhancement of capabilities from IMT-Advanced (b).

Not a day goes by that we don't encounter the terms 5G and IoT (Internet of Things). Indeed, the future is about super-connectivity and the promise it gives us, once everything is "talking" with each other. Connected appliances to connected cars, making life easier as we prepare for smart homes, smart cities and smart everything. It is difficult to imagine this future—yet so was imagining 2015 when looking through the view of the internet in the year 2000.

There appear to be as many definitions of 5G and IoT as forecasts and opinions when discussing the potential benefits and relevant business cases of these technologies. The International Telecommunication Union (ITU) has been working on defining what 5G IMT-2020 will be from a technical perspective, or at least how it will differ in performance from 4G (IMT-Advanced). The term 5G IMT-2020 was coined in 2012 by the ITU Radiocommunication sector and means "international mobile telecommunication system," with a target date of 2020. Within that definition, we see how IoT will benefit. Parameters like peak data rates, mobility, latency and spectrum efficiency are important, as they help define what the user experience will be, key to enhanced mobile broadband (eMBB) and ultra-reliable and low latency communications (URLCC). ***Figure 1*** shows how the ITU envisions 5G.

IoT, on the other hand, will need different parameters to operate in a way that needs

TABLE 1

IoT APPLICATIONS

IoT Category	*Example Applications*
Massive IoT	Smart Building, Transport Logistics, Fleet Management, Smart Meters, Agriculture
Critical IoT	Traffic Safety, Autonomous Vehicles, Industrial Applications, Remote Manufacturing, Healthcare (including Remote Surgery)

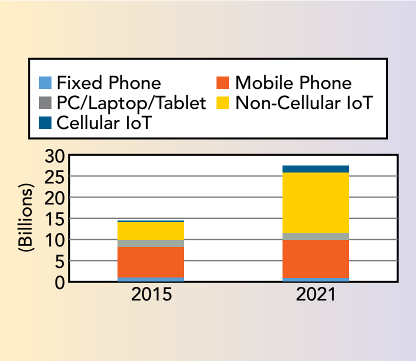

Fig. 2 Connected devices forecast, from 2016 Ericsson Mobility Report.

minimal to no user action on a day-to-day basis, after the initial setup. Today, we are seeing the beginning of the IoT market, an expansion of the M2M market that already exists and accounts for 600 million devices as of 2015.[1] The IoT can be divided into two segments.[2] The first represents massive IoT connections with high connection volume, low cost, low energy consumption and small data traffic. The second comprises critical IoT connections that require ultra-reliability and availability with very low latency. ***Table 1*** shows applications for each of the two classifications. ***Figure 2*** shows a forecast for the connected devices market, based on Ericsson's mobility report.[3] The traditional connected-device market of fixed, mobile phones and computer/tablets will increase slightly, while the overall number of devices associated with IoT, both cellular and non-cellular, will grow greater than 20 percent annually. The IoT space can also be viewed by how connectivity is achieved, particularly using low power technology. Various low power standards are summarized in ***Table 2***.

Frequency band allocations for 5G focus heavily on available bandwidth, and they seem to center around three groups: sub 6 GHz, 15 to 40 GHz and greater than 60 GHz. Because much of 5G will be data intensive, the frequencies around 28, 39 and 77 GHz are gaining momentum because of the availability of spectrum within those bands. As many IoT applications are expected to be low data rate, most of the IoT activity is centering on the sub-6 GHz spectrum. An exception will be IoT for surveillance, where transmitting high definition video from remote areas may require the bandwidth found in the millimeter wave spectrum.

MATERIALS PERSPECTIVE

Printed circuit boards (PCB) are a building block in any electronic system. The choice of PCB material for RF applications depends on frequency, power level, circuit size and function. Designers have choices from basic epoxy/glass materials (FR-4), mid-loss materials and, ultimately, high end microwave/millimeter wave materials. The most common PCB material is FR-4, mainly developed for the mechanical properties key to multilayer circuit boards. Variations of these materials exist, offering dissipation factor (Df) or loss tangent values ranging from 0.01 to beyond 0.02 (see the tier 1 and 2 materials in ***Figure 3***). The focus of these materials has been low cost and ease of manufacturing for complex multilayer boards, with no real attention on repeatability of electrical properties, since the applications where these are used don't require that level of performance. The second set of materials use specialty resins, sometimes blended with epoxy, and achieve some improvement in loss. These materials have mainly been used in high speed digital applications up to 10 Gbps. The last group is defined as high frequency material (found in tiers 5 and 6), where the Df is less than 0.005.

Various parameters are considered in the selection process when deciding which type of PCB material to use: loss, dielectric constant, thickness, thermal conductivity and, let's not forget, cost. In the end, it is about selecting the appropriate material at the right cost. Much of the IoT market today is using traditional FR-4 in the transceiver or antenna portions of the radio. However, there is a subset of this market that requires a higher level of reliability, including industrial, medical, traffic control, automotive and smart meters. This subset is taking advantage of the higher performance materials and the increased focus on reliability that tier 5 and 6 materials can provide.

So what are the benefits of selecting a high performance material instead of FR-4? The first benefit a designer will notice is the impact loss tangent has on the loss of the circuit. Many times, this is the primary consideration. This

TABLE 2

LOW POWER IoT STANDARDS[4]

	Bluetooth, Wi-fi, RFID, ZigBee, Z-Wave	*NB-IoT*	*EC-GPRS*	*SigFox*	*LoRa*
Range	10 cm to 200 m	< 11 km	< 11 km	< 9 km	< 7 km
Maximum Coupling Loss (dB)	< 100	164	164	160	157
Spectrum, Bandwidth	Unlicensed 2.4 GHz	Licensed IMT, 200 kHz Shared	Licensed 800 to 900 MHz, Shared	Unlicensed 868 MHz, 600 Hz	Unlicensed 868 MHz, 125 kHz
Data Rate	< 100 Mbps	< 62 kbps UL < 26 kbps DL	<70 kbps	<1 kbps	< 50 kbps

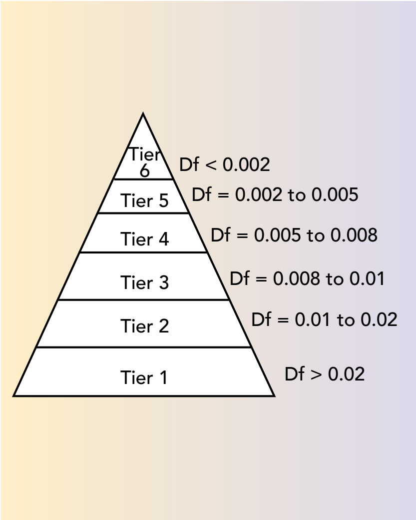

Fig. 3 PCB material classification by loss tangent (Df).

difference can be almost an order of magnitude greater with some materials. To keep it simple — and not include in the analysis the impact dielectric constant has as Dk of FR-4 is 4.4 and many high frequency materials options are lower — consider the simulated insertion loss for a 50 Ω transmission line on FR-4, with Dk = 4.4 and a dielectric thickness of 0.020". The 50 Ω width is calculated to be 0.038".[5] Comparing the change in insertion loss when Df varies from 0.02 to 0.004 at 2.4 GHz for this line width, the insertion loss is 0.24 dB/inch for a Df of 0.02; for a Df of 0.004 the insertion loss will only be 0.01 dB/inch. The benefit here is that if the circuit is an antenna, the lower loss improves the sensitivity and will extend the range of the antenna.

In some cases, it is not the loss of the material that is the main driver for selecting a high performance material; sometimes it is the variability of the dielectric constant. Most high performance materials have a tolerance of less than ±2 percent, even less for materials with low dielectric constant, while FR-4 materials can be greater than ±5 percent. The increased variability of the FR-4 may require the circuits to be tuned to ensure they operate within the frequency specified, while materials with tighter tolerance will not need such optimization.

Environmental changes can affect the dielectric constant of FR-4, yet have minimal impact on high performance materials. FR-4 has significantly higher moisture absorption than high performance materials. This leads to an increase in Dk (also Df). If the circuit needs to operate in a high moisture environment—tropical areas such as Malaysia—FR-4 materials have been known to drift, due to the change in dielectric constant. In comparison, moisture has minimal impact on the dielectric constant of the high frequency laminates. Changes in the temperature can also have a significant impact on the operation of a circuit: with FR-4, notably, dielectric constant changes with temperature (see ***Figure 4***). The change with FR-4 is close to an order-of-magnitude higher than with the more stable materials in the figure. FR-4 can change as much as 400 ppm/°C. With materials like RO3003™ and RO4350B™ laminate, the short-term change is close to 40 ppm/°C. Considering all these factors (i.e., tolerance, moisture absorption and temperature variation), selecting a high frequency material over FR-4 may be the best choice when a more consistent design is needed in the field.

In many cases, the IoT will be about having connectivity with a circuit as small as possible, due to limited space. In these cases, reducing the size of the antenna or circuit will be desired. By selecting materials with a dielectric constant of 6, 10 or higher, designs using FR-4 with a Dk of 4.4 can be reduced in size. Using a PCB with a Dk of 4.4, the wavelength at 1 GHz for 0.020" microstrip is about 7", while a material with a Dk of 10.2 (e.g., Rogers RO3010™ laminate), the wavelength is 4.4", close to a 40 percent reduction in size.[5] Higher dielectric constant materials allow designers to shrink the size of the circuit board, saving area compared to FR-4.

There will also be IoT applications that operate at higher frequencies, potentially in the 28 to 40 GHz range, and not necessarily on low power networks where the use of high frequency materials is a must. Managing losses is extremely important, so using materials with low dissipation factors is critical, as well as selecting copper foils that are smooth, to reduce the conductor impact on insertion loss. In the case of materials based on PTFE resin, this is often addressed by using rolled copper foil instead of traditional electrodeposited copper foil. However, for materials that use low loss thermoset resins, using smooth foil impacts copper peel strength, in many cases lowering the value to the limit specified by the industry. To address this, Rogers introduced LoPro® copper foil to go with Rogers RO4000® materials, allowing designers to reduce insertion loss while maintaining copper foil peel strength to the level of standard copper.

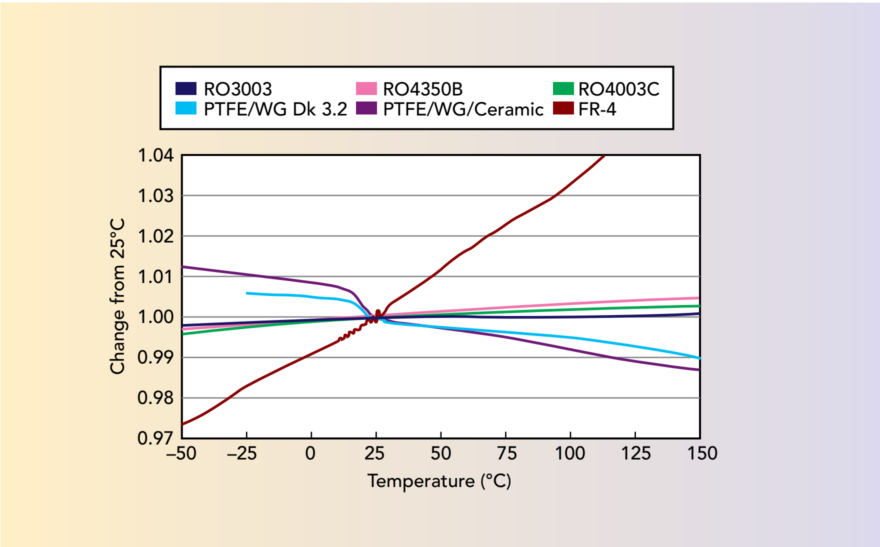

Fig. 4 Normalized dielectric constant vs. temperature.

CONCLUSION

5G and IoT have moved from if they happen to when they happen. It is likely that the applications that will revolutionize our lives may not yet have been thought of. What we do know is that many segments in the market will be undergoing significant change during the next few years. Smart homes, smart cities, remote health care monitoring, industrial controls and autonomous driving are topics of much interest. Many of these may benefit by using higher performance materials, especially for applications that use millimeter wave frequency bands. Much is yet to be defined about 5G and IoT, and we will no doubt see surprising use cases emerge. When asked, "Why did we connect a particular thing to the internet," we may find ourselves saying "because we could."■

References

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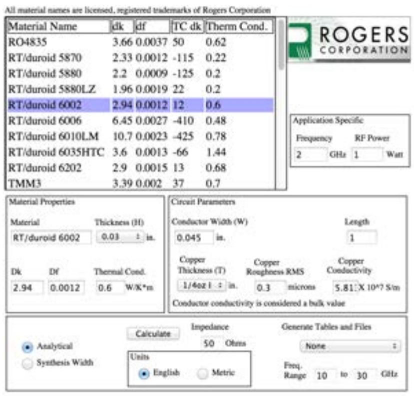
Microwave Impedance Calculator

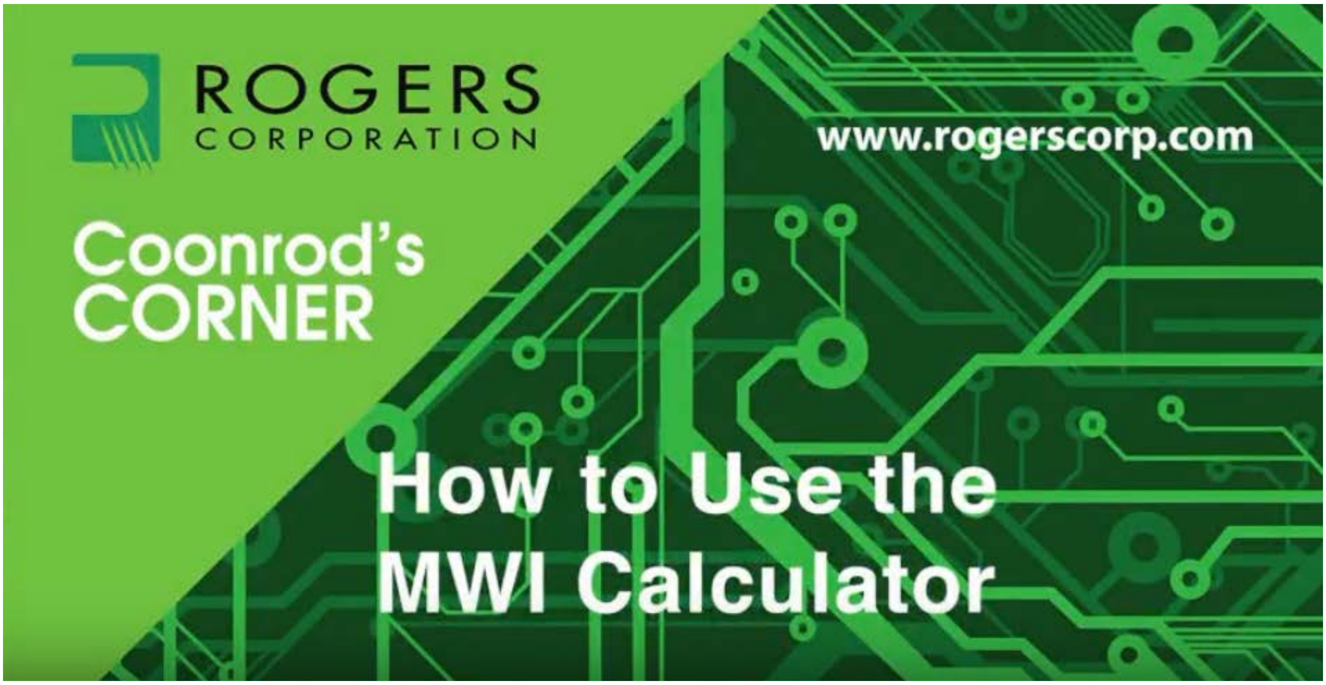
This software is intended to assist with microwave circuit design in predicting the impedance of a circuit made with Rogers High Frequency circuit materials. The software also has some capabilities for predicting transmission line losses as well. The user will select the circuit materials and the circuit construction, after which the software will determine the predicted impedance and other electrical information.



The calculator uses well known closed form equations to determine impedance and loss of a given circuit model. The loss calculation is divided into conductor loss and dielectric loss. With specific circuit designs, the calculator also predicts other properties such as wavelength in the circuit, skin depth and thermal rise above ambient.

Free (Requires Registration)

https://youtu.be/F_AeAUk7DuU



Paving the Way for 5G Wireless Networks

The ROG Blog is contributed by John Coonrod and various other experts from Rogers Corporation, providing technical advice and information about RF/microwave materials.

Growing demand for mobile wireless communications services has quickly eclipsed the capabilities of Fourth Generation (4G) Long Term Evolution (LTE) wireless networks and created a need for a next-generation mobile wireless network solution. Fifth Generation (5G) wireless networks promise more capacity and capability than 4G LTE systems, using wider channel bandwidths, new antenna and modulation technologies, and higher carrier frequencies even through millimeter-wave frequencies. But before 5G wireless networks can become a reality, systems and circuits will be needed for higher frequencies than current 2.6-GHz 4G LTE wireless networks.

Standards are still being formulated for 5G wireless networks, with goals of achieving data rates of 10 Gb/s and beyond with low latency, using higher frequencies than in traditional wireless communications systems. In the United States, for example, last year the Federal Communications Commission (FCC) approved the use of frequency bands at 28, 37, and 39 GHz for 5G.

PCB MATERIALS FOR MILLIMETER WAVES

For circuit designers, one challenge will be in knowing where to start, which means, for millimeter-wave frequencies, knowing what types of printed-circuit-board (PCB) material characteristics are the most important at higher frequencies. Millimeter-wave frequencies (above 30 GHz) were once used almost exclusively by the military and for research experiments, but 5G represents an opportunity to "popularize" millimeter-wave frequencies and make them part of everyday life, not just for exotic electronic devices in the limited quantities used in research and by the military, but for potentially billions of electronic devices for people and things, as in how Internet of Things (IoT) devices will use 5G networks for Internet access.

Designing circuits at millimeter-wave frequencies starts with the right PCB material, and knowing how different PCB characteristics affect circuit performance at millimeter-wave frequencies. Variations in certain circuit material parameters, such as dielectric constant (Dk), can have greater impact on performance as the operating frequency increases. For example, signal power is a valuable commodity at millimeter-wave frequencies, requiring circuit designers to minimize loss in their circuits as much as possible. This begins with the choice of PCB material, since a PCB material not meant for use at millimeter-wave frequencies can result in excessive signal losses when operated beyond its intended operating frequency range.

PCB materials can degrade signal power in three ways: radiation losses, dielectric losses, and conductor losses. Losses through radiation of EM energy largely depend on the circuit architecture, so even the lowest-loss PCB material may not save a circuit configuration that has a tendency to radiate energy.

A thoughtful choice of PCB material can help minimize dielectric and conductor losses at millimeter-wave frequencies. A circuit material's dielectric loss is closely related to its dissipation factor (Df) or loss tangent, which increases with frequency. The Df is also related to a material's dielectric constant (Dk), with materials that have higher values of Dk often have higher Df loss, although there are exceptions. Attempts to minimize dielectric losses for millimeter-wave circuits can be aided by considering circuit materials with low Df values.

CONTROLLING CONDUCTOR LOSS

Finding a material with low conductor losses at millimeter-wave frequencies is not as straightforward, since conductor losses are determined by a number of variables, including the surface roughness and the type of finish. As the name suggests, millimeter-wave signals have extremely small wavelengths, mechanical variations in a circuit-board material can have significant effects on small-wavelength signals. Increased copper surface roughness will increase the loss of a conductor, such as a microstrip transmission line, and slow the phase velocity of signals propagating through it. In microstrip, signals propagate along the conductor, through the dielectric material, and through the air around the circuit material, so the roughness of the conductor at the interface with the dielectric material will contribute to the conductor loss. The amount of loss depends on frequency: the loss is greatest when the skin depth of the propagating signal is less than the copper surface roughness. Such a condition also degrades the phase response of the propagating signal.

The impact of copper surface roughness on conductor loss depends on the thickness of the PCB material: thinner circuits are more affected than thicker circuits. The effects of copper surface roughness on loss become apparent at millimeter-wave frequencies. For example, two circuits based on 5-mil-thick RT/duroid® 6002 circuit material from Rogers Corp. but with two different types of copper conductor and surface roughnesses were tested at 77 GHz. The circuit with rolled copper and root mean square (RMS) conductor surface roughness of 0.3 μm exhibited considerably lower conductor loss than the same circuit material with electrodeposited (ED) copper conductor having 1.8-μm surface roughness.

Propagation of the small wavelengths at millimeter-wave frequencies can also be affected by the type of finish used on a PCB's conductors. Most plated finishes have lower conductivity than copper, and their addition to a copper conductor will increase the loss of the conductor, with loss increasing as the frequency increases. Electroless nickel immersion gold (ENIG) is a popular finish for copper conductors; unfortunately, nickel has about one-third the conductivity of copper. As a result, ENIG plating will increase the loss of a copper conductor, with the amount of loss increasing as a function of increasing frequency.

ENVIRONMENTAL EFFECTS

Environmental conditions can also impact the amount of loss exhibited by a PCB material, especially at millimeter-wave frequencies. Many network scenarios for 5G predict the need for many smaller wireless base stations than used in earlier wireless network generations, in part because of an increased number of expected users and the use of millimeter-wave frequencies and their shorter propagation distances than lower-frequency carriers. Where 5G base stations cannot be maintained in climate-controlled environments, circuits may be subject to changing environmental conditions, such as high relative humidity (RH). Water absorption can dramatically increase the loss of a PCB material, and the loss of circuit materials with high moisture absorption will be greatly affected under high RH conditions.

Testing on 5-mil-thick RO3003™ circuit material from Rogers Corp. for two different operating environments showed how loss at millimeter-wave frequencies can increase with RH. One circuit was maintained at room temperature and the other was subjected to +85°C and 85% RH for 72 hours. At 79 GHz, the room temperature material had about 0.1 dB/in. less loss than the material subjected to higher humidity and temperature. When testing was performed on a third, thermoset circuit material from a different supplier, the increase in circuit loss at 79 GHz was even more dramatic.

For those interested in learning more about the nuances of selecting PCB materials and designing circuits for 5G, in particular at millimeter-wave frequencies, Rogers has created a number of tutorial videos in their "The Road to 5G" series. The videos guide viewers on what different circuit material parameters mean at millimeter-wave frequencies, and which material characteristics make the most difference at those higher frequencies. The videos offer quick and easy ways to learn how to specify PCB materials for 5G, and to get ready for this next revolution in wireless communications.

Do you have a design or fabrication question? Rogers Corporation's experts are available to help. Log in to the Rogers Technology Support Hub and "Ask an Engineer" today.

Transformation to 5G: PCB Advantage

Tony Mattingly
Rogers Corp., Chandler, Ariz.

Hard to believe it has been over 30 years since 1G was introduced to the world, back when there were no official requirements and analog technology was being used. The 1990s brought 2G, with the introduction of digital technology and the ability to transmit text messages via your cellular device. Ten years later, in 2000, an upgrade to 3G brought IEEE WiMAX standards that were designed to support 30 to 40 megabit per second (Mbps) data rates. Then, 4G was introduced a mere seven years ago and, although it brought to the world a much higher spectral efficiency, exponential consumer demand for wireless data is now driving a need for substantially higher mobile network capacity and performance. Let's take, for example, the primary driver for data usage on smartphones: video streaming. Just an hour a day of mobile video at 1 Mbps throughput—which is typical of applications supporting streaming video like YouTube or Netflix—consumes 13.5 GB per month. The demand for data will continue to grow as the 5G and IoT ecosystems are created in the coming years (see ***Figure 1***), and we will all eventually live in a world that depends on billions of devices communicating with one another. The connectivity of these devices will be expected to be instantaneous and without interruption.

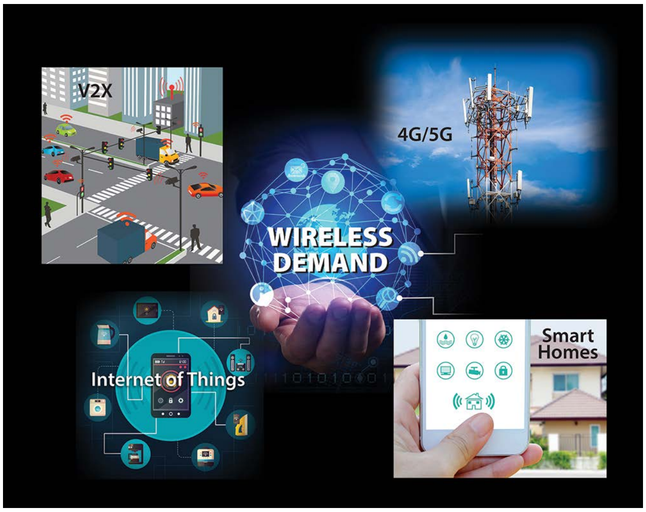


Fig. 1 Our world is increasingly connected, which is driving the growing demand for wireless data.

Adding capacity is not cheap, and space for additional antenna towers is limited. In the U.S., most towers are not owned by carriers, rather companies such as American Tower, Crown Castle and SBA. Carriers lease space on these towers and, as strict permitting processes make it difficult to build new sites, carriers are forced to replace antennas with newer and more efficient ones. Arguably, the cost for operators to deliver data is proportional to the spectral efficiency of the wireless technology. LTE networks have the highest spectral efficiency of any technology to date, but it is not going to be enough to serve consumer desire to always be connected. So how is capacity added in an already saturated wireless infrastructure? One answer is advanced antenna designs employing new technologies that operate within current frequencies. Another answer is adding wireless infrastructure that operates at new and higher frequencies, where plenty of spectrum exists. Early in 2015, U.S. carriers spent more than $40 billion

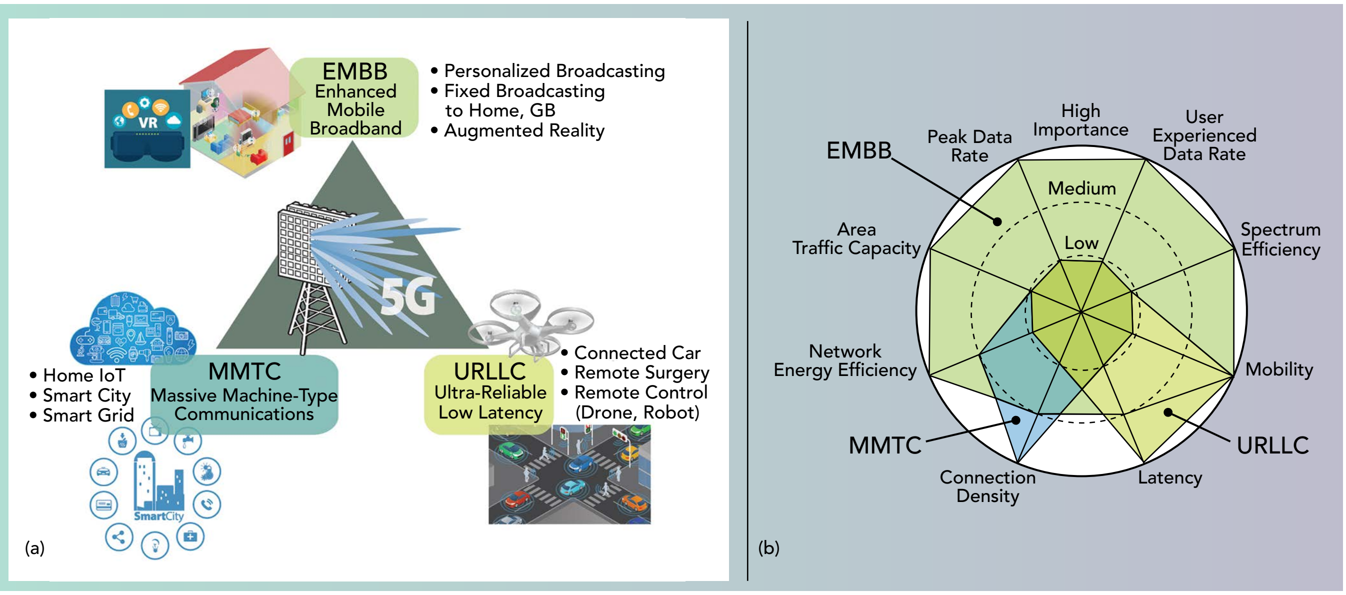


Fig. 2 5G is envisioned to support three general use cases: high data rate, low latency and massive numbers of connections (a), and these use cases define the performance requirements of the network (b).

on spectrum! Because much of the spectrum below 2.5 GHz is limited, frequency bands around 3.5, 28, 39 and 77 GHz are gaining interest because of the availability of bandwidth.

5G COMING SOON

We should start by clarifying the conceptual goals for 5G (see ***Figure 2***). Cost to deliver data is crucial to the success and survivability of the carriers, so the 5G infrastructure will need to support a greater number of devices at lower average revenue than with 4G systems. The infrastructure must also provide peak data rates of multi-gigabits per second (Gbps), facilitate a user experience that is uniform throughout the coverage area—no matter the device density—support numerous frequencies (including cellular bands and frequencies above 6 GHz), use both licensed and unlicensed bands and follow advanced spectrum sharing rules.

The 5G networks of the future will require infrastructure that has a wide range of capabilities and operates both below 6 GHz and at millimeter wave frequencies. These networks will use massive MIMO antenna structures and massive carrier aggregation and will need to operate "lightning fast" with very low latency. Massive MIMO comprises hundreds of antennas at the base station that enables spatial multiplexing and beamforming. These systems provide three times the spectral efficiency of today's LTE-Advanced antennas. Carrier aggregation, which is a key LTE-Advanced feature that operators are deploying globally, uses spectrum more effectively, increases network capacity and user throughput rates and provide new ways to integrate unlicensed spectrum. Frequency band allocations for 5G focus heavily on bandwidth availability and seem to center around three groups: below 6 GHz, 15 to 40 GHz and above 60 GHz. The combination of lower and higher frequencies is crucial for 5G operation. Lower bands can be devoted to coverage and control, while the higher bands enable high data rates. While millimeter wave frequencies suffer from characteristics such as higher propagation loss—even with line-of-sight conditions and no obstructions—this challenge can be overcome with beamforming antenna arrays or massive MIMO.

Regulatory policies around the world are striving to keep pace with these changing technologies. Some of the complex issues to be addressed: allocating and managing the new spectrum, maintaining neutrality within the networks and preserving privacy. Spectrum is considered a precious commodity within the industry. This could be seen during the U.S. auction for the 3.5 GHz small cell band last year, spectrum the FCC is now enabling. As advancements in technology provide a path for small cell operation between 6 and 100 GHz, a vast amount of available spectrum is introduced. Wider radio channels operating at higher frequencies enable much higher data rates. Small cells offload data from macro cells, inherently increasing capacity, and can offer improved signal quality in places with a higher concentration of users or where the signal from a macro tower is weak. Millions of small cells will eventually be deployed, leading to massive increases in capacity. The industry is slowly overcoming challenges that have impeded small cell deployments. These include government regulations, acquiring real estate for the antennas and managing and preventing interference. Another challenge relates to spectrum sharing. Future wireless systems may interface with a planned spectrum access system that manages spectrum among primary users—government agencies, in some cases—and secondary or tertiary users. This will enable more efficient use of spectrum for scenarios in which incumbents use spectrum lightly.

Many countries have started 5G trials, focusing on various applications and using different frequencies. Major carriers in the U.S. are conducting trials in 2017 with a focus on fixed broadband at 28 GHz. South Korea is also conducting trials at 28 GHz to prepare for the 2018 Olympic Games in Seoul. Japan plans to start trials in Tokyo during 2017, using both sub-6 GHz and 28 GHz, and they will likely scale up the trials significantly during 2018 and 2019. China has announced ongoing 5G trials at 3.5 GHz, with a major carrier testing seven experimental base stations in several cities throughout 2017. Additionally, the European Commission recently published their 5G action plan, with preliminary trials starting in 2017 and pre-commercial trials in 2018; they will use 3.4 to 3.8 and 24.25 to 27.5 GHz. However, all these trials will be very targeted and limited in scale, constrained by the pace of 5G standards, technology development and economic justification. This view has also been confirmed by the November 2016 forecast from ABI Research, estimating 5G subscribers will reach 4 million in 2020 and 349 million in 2025, accounting for only 0.04 percent of all subscribers in 2020 and 3.6 percent in 2025.

PCB ANTENNAS

With all that said, there is no doubt antennas for next-generation wireless systems (e.g., LTE-Advanced and 5G) are becoming more complex. With demand for mobile data projected to grow at approximately 53 percent compound annual growth rate through 2020, active antennas and small cells will continue to be deployed to handle the data throughput. These trends and the associated growth are expanding the use of printed circuit board (PCB) materials in antenna designs. The material requirements will be different from the traditional cellular network. At the same time, 5G designs are completely new to the designers of wireless infrastructure. These designers need to overcome the many challenges and understand what performance properties are needed to meet their design goals.

With the use of additional frequency bands and consumer demand for better performance and lower latency, PCBs have advantages compared to competing technologies, such as bent metal and cable. Designers at antenna original equipment manufacturers (OEM) find that PCB-based designs shorten the design iteration cycle and enable the development of complex, multilayer board (MLB) designs. However, PCB-based designs have challenges: integration of the power amplifier (PA) and antenna into one structure for active antennas and higher fabrication and assembly costs of MLB approaches using PTFE materials. While thermoset high frequency materials are ideal for MLB designs, there are limited thermoset materials that have low loss, low passive intermodulation (PIM) and are flame retardant, meeting the sought after UL 94 V-0 designation.

To address these challenges, PCB materials companies like Rogers have launched new antenna grade laminates. Rogers' solution combines a flame retardant, low loss thermoset dielectric with low profile copper foil and incorporates a proprietary filler system. The material has a dielectric constant (Dk) of 3.0, a popular choice for antenna designers, and a dissipation factor (Df) of 0.0023 at 2.5 GHz. The laminate possesses a low thermal coefficient of dielectric constant (TCDk), which gives consistent circuit performance over a range of temperatures. It has low passive modulation (PIM < -160 dBc), because it is constructed using a patented LoPro copper foil, and it incorporates low density microspheres, yielding a laminate that is 30 percent lighter than PTFE materials. The coefficient of thermal expansion (CTE) is matched to copper in the X and Y directions, which minimizes bow and twist and allows for hybrid MLB construction, and the material has a low Z-axis CTE of 30.3 ppm/°C from -55°C to +288°C, for reliable plated through holes (PTH) in multilayer circuit assemblies. These laminates offer a practical, cost-effective circuit material for active antenna arrays and PCB antennas, whether for current wireless systems or those on the horizon. With the right combination of materials, these laminates provide the optimum blend of price, performance and durability.

Rogers, like other PCB materials companies, continues to focus on market trends and material needs of the future. Under development is a whole family of thermoset laminates with multiple thicknesses, low dielectric constant and low insertion loss for emerging PA and small cell point-to-point backhaul radio applications operating at millimeter wave. Rogers will soon add a thermoset solution designed to meet the growing RF needs within the carrier grade Wi-Fi and distributed antenna system (DAS) markets, where better loss, improved Dk over frequency and more controlled thickness tolerance are desired. These product offerings will only serve to enhance an already comprehensive portfolio of the highest reliability and highest quality product offerings. PCB manufacturers are meeting the needs of the antenna market with new products aimed at the performance criteria needed to meet 5G performance goals.■

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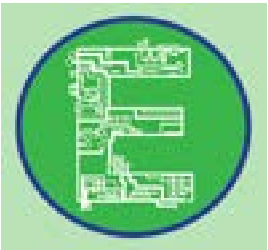

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Selecting Circuit Material for the Different Spectra of 5G Power Amplifiers

John Coonrod
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Several bands of frequencies (spectra) are expected to be used for 5G applications. Most cellular-communications-network operators have allocated several frequency bands for 5G. Some of these are in the lower microwave range (300 MHz to 30 GHz), some are at higher microwave frequencies, and yet other bands are within the millimeter-wave frequency range (30 to 300 GHz). With previous cell-phone technology, a power amplifier was typically designed for use at lower microwave frequencies and there would not be a lot of difference in behavior at higher frequencies. But wireless communications networks based on 5G technology will be considerably different than traditional cellular communications systems, and designers of 5G power amplifiers will be expected to deal with microwave and millimeter-wave frequency considerations.

Design considerations for microwave circuits can be very different than those of millimeter-wave circuits. Also, the type of high-frequency circuit materials needed for microwave circuits can be very different than those required for millimeter-wave applications. This article will give information for which materials are best suited for power amplifier applications at microwave and millimeter-wave frequencies.

In general, most 5G applications operating at microwave frequencies will be at sub-6-GHz frequencies. Also, these lower-frequency applications will probably be at higher power levels than those at millimeter-wave frequencies. Microwave 5G power amplifiers will depend on circuit materials for a number of key traits, including good thermal management, low insertion loss, and consistent RF performance over a wide range of temperatures. As for the material properties specifically important for microwave power amplifiers, they include a well-controlled dielectric constant (Dk or εr), high thermal conductivity, low TCDk (Thermal Coefficient of Dk), low dissipation factor, and tightly controlled substrate thickness.

Let's look at each of the material properties and why these are critical to microwave power amplifiers. Many 5G microwave power amplifiers will use a Doherty amplifier configuration and these types of circuit designs require quarter-wavelength circuit elements on the PCB. The PCB conductor element, which is intended to be a quarter-wavelength circuit structure, will perform as expected assuming the variables related to wavelength on the PCB are well controlled. These variables are the material Dk and the substrate thickness. PCB fabrication variables can also impact the quality of quarter-wavelength circuit elements, such as the conductor definition and conductor copper thickness.

Typically a high frequency circuit material with a Dk tolerance of ± 0.05 is considered good and should be used for these types of applications. Additionally, the substrate thickness control for the material of choice should be ±10% or better.

Another topic important for microwave power amplifier design is the impedance tuning network that varies the impedance presented to the power amplifier chip. Impedance control employs the same variables as wavelength; however, the variables behave differently for impedance than for wavelength. Many designers assume that Dk variation is a major influence for impedance variation; however, that is typically not true. A very simple experiment can be done using any reliable impedance software, showing the hierarchy of influence for the different variables regarding impedance variations. A summary of such an experiment is shown in ***Table 1***.

The information in Table 1 is based on a microstrip transmission-line circuit, with a high-frequency circuit material that is 20 mils thick with nominal Dk of 3.50 and Dk tolerance of ± 0.05. The first row of information serves as the baseline or reference. That row shows the impedance model obtaining an impedance value of 50.07 ohms.

TABLE 1

MICROSTRIP TRANSMISSION LINE CIRCUIT USING 20 MIL THICK HIGH FREQUENCY LAMINATE

The most significant variables for impedance are:
1. Substrate thickness 2. Conductor width 3. Copper thickness 4. Dk

Dk	*Substrate Thickness (mils)*	*Copper Thickness (mils)*	*Conductor Width (mils)*	*Characteristic Impedance (ohms)*	*Difference of Impedance (ohms)*	*Comment*
3.50	20	2	43	50.07		Baseline for comparisons
3.50	18	2	43	46.86	3.21	Substrate is 10% thinner than baseline
3.45	20	2	43	50.39	0.32	Dk lower by 1.4% from baseline
3.50	20	1	43	50.70	0.63	Copper thickness reduced by 1 mil from baseline
3.50	20	2	42	50.78	0.71	Conductor width reduced by 1 mil from baseline

Results from a simple experiment, using impedance software, to show the most significant variables on impedance.

▲ **Table 1 Results from a simple experiment, using impedance software, to show the most significant variables on impedance.**

The other rows in Table 1 show the response to impedance, with a change of one of the variables. The most influential variable for impedance variation is the substrate thickness control. After that, conductor width and copper thickness control are most meaningful, with Dk the least impactful variable on impedance variation.

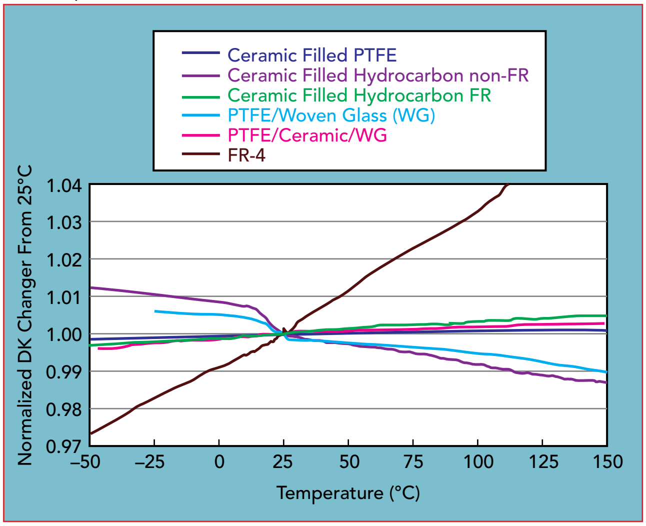
Another issue of concern when designing microwave power amplifiers is thermal management. A material property which can help minimize this concern is thermal conductivity. Most high frequency circuit materials have a low thermal conductivity, typically in the range of 0.2 W/m·K to 0.3 W/m·K. A thermal conductivity which is considered good for a PCB material is 0.5 W/m·K or higher. Higher thermal conductivity allows better heat flow from the power amplifier chip, through the high frequency circuit material, which allows for more efficient cooling of the circuit.

Along with the thermal management issue is the fact that many microwave power amplifiers will be required to handle a wide temperature range during their normal operation. Circuit materials are characterized by a property referred to as temperature coefficient of dielectric constant (TCDk) which is an indicator of how much the Dk will change with a change in temperature. As noted, the Dk variation is not as concerning for impedance variation; however, Dk variation does have impact on wavelength variation and that can certainly cause issues with the quarter-wavelength circuit elements often used in Doherty power amplifier designs. As a rule of thumb, a TCDk of |50| ppm/°C or less is considered good, where 0 ppm/°C or no change of Dk with a change in temperature would be ideal. ***Figure 1*** includes a chart which gives the TCDk behavior for several different types of materials.

The dark purple curve for PTFE / Ceramic / WG shows a pretty large swing in Dk change around room temperature, which is normal for PTFE. If the PTFE substrate is formulated correctly, this room temperature Dk swing can be minimized or eliminated which is the case for the dark blue curve which represents a ceramic-filled PTFE material, Rogers RO3003™ laminate, with a TCDk value of -3 ppm/°C. The yellow curve shows thermoset material (non-PTFE) and it also have very good TCDk behavior, about 50 ppm/°C, and that curve shows results for Rogers RO4350B™ (or RO4835™) material.

The brown curve presents data for FR-4 and that is included in the chart as a reference. FR-4 is not formulated for good TCDk, but it is a good example of a material with poor TCDk. An ideal TCDk would a flat curve centered at 1.00 on the y-axis.

Finally, a material property that impacts many different circuit properties and thermal management, is dissipation factor (Df or Tanδ). Basically, a circuit built on a material with a lower Df will have lower insertion loss and lower loss translates to less heat generated. For microwave power amplifier applications which are sub 6 GHz, a material with a Df of 0.005 or less is considered adequate.



▲ **Fig. 1 TCDk curves for several different types of circuit materials.**

TABLE 2

MATERIALS USED IN MICROWAVE POWER AMPLIFIER PCB APPLICATIONS

	Dk and Tolerance	Df	Thermal Conductivity	TCDk ppm/°C
Woven Glass PTFE	2.50	0.0012	0.25	-180
PPE Based Material	3.00	0.004	0.33	50
RO4350B™ (RO4835™) Laminate	3.48±0.05	0.0037	0.66	50
RO3003™ Laminate	3.00±0.04	0.001	0.5	-3
RT/duroid® 6035HTC	3.50±0.05	0.0013	1.44	-66

As a quick summary of the material properties considered key for microwave power amplifiers, table 2 lists the different materials and their parameters related to microwave power amplifier performance, especially for minimizing generation of heat.

The topic of millimeter-wave applications for 5G has similar material concerns as those at microwave frequencies; however, at these higher frequencies, there are several other issues to consider. Typically, insertion loss is higher at millimeter-wave frequencies and, with the smaller wavelengths at those higher frequencies, Dk and TCDk control is more important.

It is very common for the RF portion of a millimeter-wave power amplifier PCB to use a very low-loss, high-frequency material which is relatively thin. At millimeter-wave frequencies, the thin substrate helps avoid spurious wave modes and resonances. In general, 10-mil-thick substrates are used for applications from 30 GHz to about 60 GHz, with a transition to 5-mil-thick substrates common for frequencies beyond 60 GHz. There are certainly exceptions to this general rule.

The most commonly used RF structures for millimeter-wave applications are microstrip and Grounded Coplanar Waveguide (GCPW). When microstrip is used and there are impedance transitions, such as the signal launch from an RF connector to the circuit, GCPW is typically used in those areas only and the remainder of the circuit is microstrip. There are drawbacks to microstrip, such as its structures being more prone to radiation loss than GCPW and it is dispersive. Additionally, few design options are available with microstrip to assist in suppression of spurious modes. If GCPW is used at millimeter-wave frequencies, the proper design could drastically reduce or eliminate radiation loss and dispersion effects. The drawback with GCPW is that its RF performance is more susceptible to PCB fabrication variations [1] and this can result in greater circuit-to-circuit performance variations for the same design produced in GCPW.

Due to the need of a thin substrate at millimeter-wave frequencies, minimizing insertion loss gets a little more complicated than at microwave frequencies. For microwave applications and their larger wavelengths, the circuit materials are typically thicker and the component of insertion loss that is related to the conductor--conductor loss--is much less significant. Conductor loss and specifically copper surface roughness, can be a significant factor for insertion loss at millimeter-wave frequencies.

For example, using a thin microstrip circuit, the copper surface roughness which is a concern is at the substrate-copper interface. Copper surface roughness can have a significant impact on conductor loss when the skin depth is thinner than the roughened surface of the copper. [2] ***Figure 2*** shows the difference in insertion loss at millimeter-wave frequencies as a function of copper surface roughness, for a microstrip transmission line circuit which is using a material that is commonly used in millimeter-wave applications.

Additionally, a rougher copper will cause a slower phase velocity which will cause the circuit to behave as if it were fabricated on a higher Dk material. A simple experiment was done to prove this concept, using the same substrate material. However, copper-clad laminates were made with different copper types, with significantly different copper surface roughnesses. The surface roughness of each copper type was measured with a non-contact laser profileometer prior to making the laminates. After the laminates were made, 50-Ω microstrip transmission line circuits were made on the laminates. The circuits were tested for phase response and their effective Dks were plotted vs. frequency as shown in ***Figure 3***.

In Figure 3, it can be seen that the circuits which used the laminate with the smoothest copper (red curve), having an average surface roughness of 0.5 μm RMS, had the lowest effective dielectric constant. The trend in the chart is apparent: as the surface roughness increases, the effective Dk increases. Basically, rougher copper will result in slower phase velocity more and a slower wave is perceived by the circuit as a higher dielectric constant medium. The difference of the effective Dk from the circuits using the laminate with the smoothest copper to the laminate using the

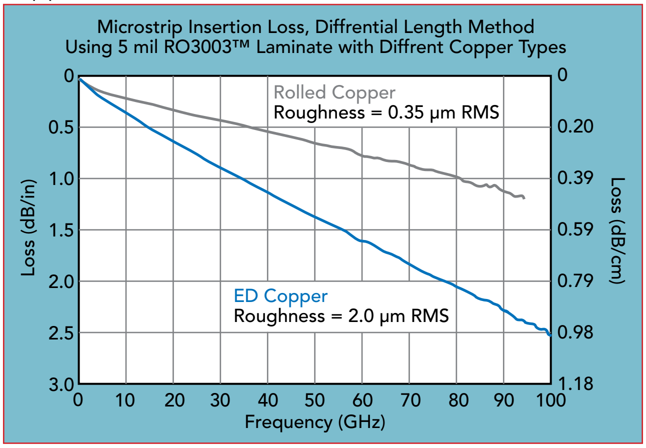


Fig. 2 Insertion loss comparison of a microstrip transmission line circuit, using the same dielectric substrate material, but comparing copper metals with two different surface roughnesses.

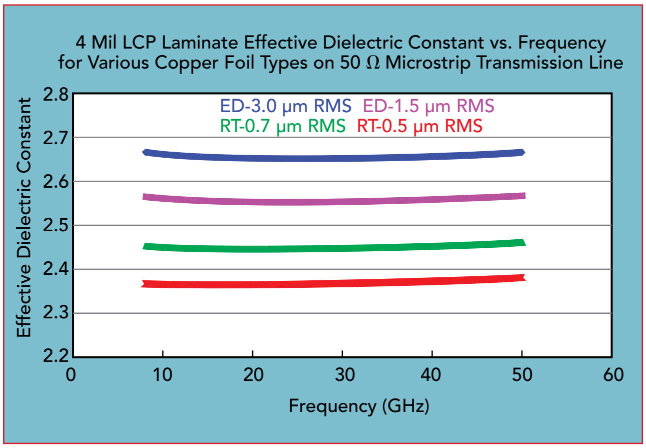


Fig. 3 **Several 50 ohm microstrip transmission line circuits, built on the same substrate, but with different copper types, each having different copper surface roughness, were evaluated for the impact on effective Dk.**

roughest copper is about 0.3. That is a very large difference in effective dielectric constant, when considering all of the circuits used the same substrate and it is the copper surface roughness difference which is causing the big difference in effective Dk.

The same circuits which were tested for insertion loss differences due to copper surface roughness differences, shown in Figure 2, were also tested for phase response. Using the microstrip phase response formula and special software (MWI-2018) which is free for download from Rogers Corporation Technology Support Hub, a chart of extracted Dk vs. Frequency is shown in Figure 4.

The extracted Dk shown in ***Figure 4*** is the circuit-perceived-Dk or the Design Dk. The high frequency circuit material used in Figure 4 has an intrinsic Dk value of 3.0. When the circuit is clad with a copper which has a rough copper surface, the wave is slowed the Dk is increased. That is the case for the circuits using the ED copper. In the case of the circuits using the rolled copper, which is extremely smooth, the phase velocity is not slowed much and because of that the Dk is lower and closer to the intrinsic Dk value of the substrate. In theory, if the copper was perfectly smooth, the Dk curve would approach the 3.0 equaling the substrate material's intrinsic Dk value.

Conductor effects are much more significant on thin circuits as compared to thicker circuits. If the same experiment is done, the curves in figure 4 would be different and less difference between the circuits of different copper roughness when using a thicker substrate. For circuits using 20mil thick substrate, the Dk at 20 GHz would be slightly closer to the intrinsic 3.0 Dk value at about 3.005 for circuits using the very smooth rolled copper and the circuits using the ED copper which is much rougher would have a Dk value at 20 GHz of about 3.060. So the difference between the Dk values is less for a thicker substrate, because a thicker substrate is not impacted by conductor effects (in this case copper surface roughness) as much as a thinner circuit as shown in Figure 4.

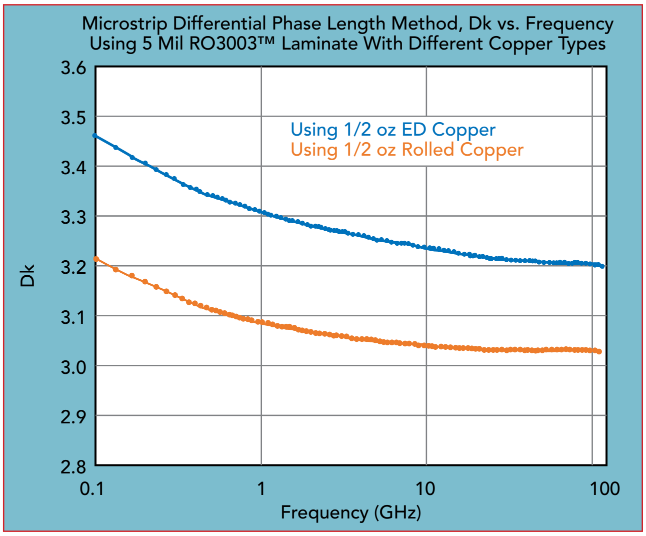


Fig. 4 **Extracted Dk vs. Frequency charts for microstrip transmission line circuits, using the same substrate but different copper types and with different copper surface roughness.**

Since a thinner circuit is more sensitive to conductor effects, the copper surface roughness should be considered for the overall insertion loss but also for Design Dk. Also, consistency for circuit phase response and Design Dk is also dependent on the copper surface roughness. The copper foil used to make the high frequency laminates will have a surface which has a normal variation of roughness. All copper foils have copper surface roughness variation from batch-to-batch or even within-sheet surface roughness variations. However, the smoother the copper, the less copper surface roughness variation. And since copper surface roughness will affect the Design Dk and phase response, a smoother copper with less surface roughness variation means the circuit performance will be much more consistent when looking at circuit-to-circuit evaluations.

The world of wireless communications is quickly moving to its Fifth Generation (5G) of technology, requiring the widespread use of higher, millimeter-wave frequencies. Power amplifiers will be needed for those wireless networks, and circuit materials for those amplifiers, but selecting optimum circuit materials for millimeter-wave circuits involves even more concerns than for circuit materials at microwave frequencies. Overall, the critical material properties for a microwave power amplifier is insertion loss, Dk consistency, substrate thickness consistency, thermal conductivity, and TCDk. These same material properties can apply to millimeter-wave power amplifiers, although the materials will be thinner and more susceptible to the effects of copper surface roughness.

References

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