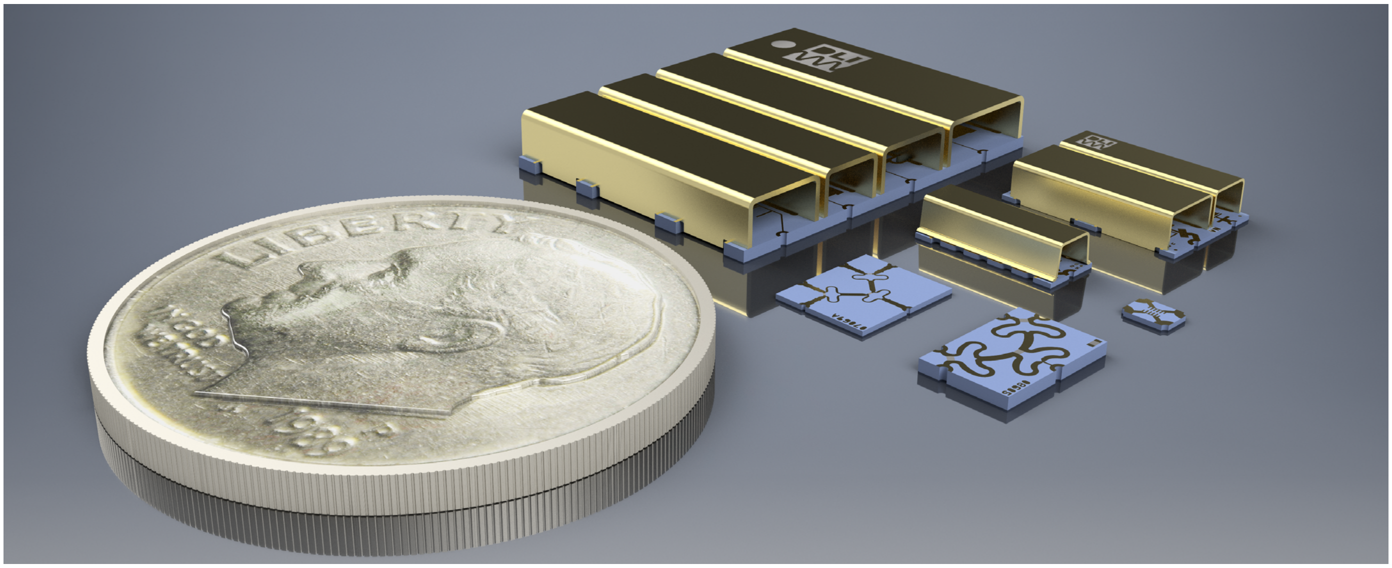
WHITEPAPER

Reduce RF Circuit SWaP with High K Materials and Precision Thin-Film Microstrip Technology



Whether an RF engineer is building a 5G antenna to mount on top of a street light or a satellite that will be launched into space, he or she is likely being told it needs to be smaller, weigh less, and use less power. As a result, companies developing RF and microwave applications are looking to vendors who can help them meet these demands by providing components that reduce size, weight, and power, or SWaP.

This is tricky, because even though wavelength and the corresponding critical dimensions decrease as frequency increases, RF circuits generally scale in size and complexity with the wavelengths supported. As a result, additional components may be required to process the increasingly complex signals. For example, consider the array spacing of a phased array structure at 28 GHz. If the supporting RF circuitry driving the antenna is to remain at a similar scale, innovative RF substrate materials are required.

This white paper covers how RF designers can reduce the SWaP of RF circuits while maintaining tight tolerances by processing Knowles Precision Devices' high K materials on high-precision thin-film microstrip technology. It also demonstrates techniques for reducing overall board space usage by integrating multiple RF circuits onto a single substrate.

A HIGHER DIELECTRIC CONSTANT CORRELATES TO A SHORTER WAVELENGTH, DRIVING COMPONENT SIZE

In general, wavelength is inversely proportional to the root of the effective K (Figure 1).

$$\lambda = \frac{c}{f\sqrt{\epsilon_r}}$$

$$\epsilon_e = \epsilon_r$$

Figure 1. This equation represents effective K used for microstrip where the height of the substrate is $s \ll \lambda$.

Let's start by illustrating this with an example of how this is applicable for a single component. In this example, we compared the differences in size of a 6th order, half-wave resonator filter built using five different materials, which included the following:

- Rogers 4350b – A typical material used in PCBs
- Alumina – A common thin-film ceramic
- Three Knowles Precision Devices' proprietary ceramics, each with different dielectric constants

> Using high K materials results in a shorter wavelength and an overall reduction in component size.

To create an apples-to-apples comparison in this exercise, each filter was modeled to have the same bandwidth, rejections, and distance from the edge of the resonator to the edge of the ceramic. The detailed results of this experiment are shown in Table 1 and a visual representation of the difference in filter size using the various materials is shown in Figure 2.

Material	dK	Effective K	Wavelength @10 GHz (inch)	Percent Reduction	Size (inches)
RO4350b	3.7	2.8	0.707	--------------	0.320 x 0.450
Alumina, 99.6%	9.6	6.5	0.462	34.7%	0.328 x 0.323
PG	12.5	8.2	0.412	41.7%	0.336 x 0.295
CF	25	15.1	0.304	57.0%	0.347 x 0.246
CG	67	36.8	0.194	72.6%	0.360 x 0.177
**Values are for Freq. 10 GHz on 0.010” Substrate					

Table 1. This table shows how wavelength and size change as effective K increases.

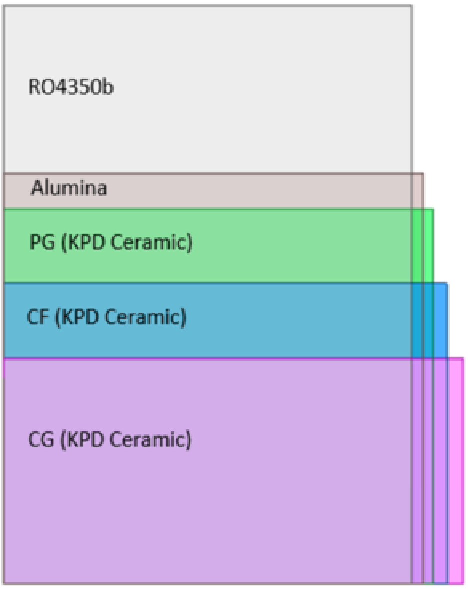


Figure 2. Based on this experiment, it is clear that using high K materials results in a shorter wavelength and an overall reduction in component size.

USING HIGH K MATERIALS ON MICROSTRIP TECHNOLOGY TO SIGNIFICANTLY REDUCE SWAP

If you are unfamiliar with microstrip technology, microstrip refers to a type of planar transmission line technology that consists of a conducting strip separated from a ground plane by a dielectric substrate. Entire components such as antennas, couplers, filters, and power dividers are formed from metallized patterns on the substrate. This means that in general, components built using a microstrip approach are lighter, more compact, and typically less expensive than alternative transmission line technologies such as waveguide. In other words, these components inherently help reduce SWaP.

To further reduce SWaP, RF component designers should consider using high K materials on high-precision thin-film photolithographic technology. Table 2 shows the dielectric constant and wavelength at 25 GHz for three common dielectric materials as well as three custom substrates developed by Knowles Precision Devices (PG, CF, and CG). Looking at this table, you can see that Knowles Precision Devices' CF has a dielectric constant of 25 compared to a dielectric constant of 4.8 for FR-4. As a result, the wavelength for the device using CF material is 2.5x smaller than the wavelength for the device using FR-4.

Material	Dielectric constant	~Wavelength at 25 GHz (inches)
PTFE	2.1	.327
FR-4	4.8	.217
Alumina, 99.6%	9.9	.150
PG	12.5	.134
CF	25	.094
CG	67	.059

Table 2. This table shows how wavelength and dielectric constant are inversely proportional.

In addition to affecting the size of less complex components such as filters, a change in substrate alone can lead to significant miniaturization for ultra-wideband (multi-stage) devices such as couplers or Wilkinson power dividers. Let's get a little more specific and look at a comparison demonstrating this for a broadband directional coupler at 10 dB and a frequency range of 2 – 18 GHz that we modeled on two different substrates. To get the bandwidth and desired coupling ripple shown in Figure 3, seven sections were needed.

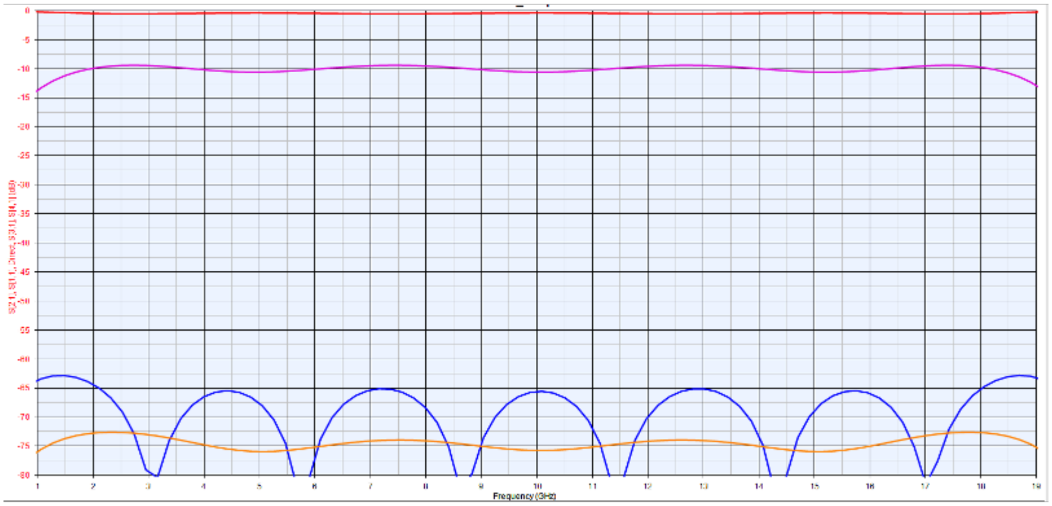


Figure 3. This graph shows the ideal performance across the frequency range used in this example.

In this example, when using Alumina with a K of 9.8, the coupler was .805 inches long, while the coupler using Knowles Precision Devices' CF material with a K of roughly 25 was .525 inches long. In this frequency range, this change in substrate alone resulted in .3 inch, or 35 percent, reduction in length.

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A REAL-WORLD EXAMPLE: REDUCING THE SIZE OF A WILKINSON POWER DIVIDER

In addition to reducing SWaP for components such as filters and couplers as already demonstrated, in this example, we look at how integration of a single-section Wilkinson power divider centered at 28 GHz can vary in size and performance in three different configurations. In Figure 4, the configuration on the left uses a thin-film 4-way on Knowles Precision Devices' PG material, the middle configuration uses three 2-ways on PG material integrated on a PCB, and the right uses a 4-way PCB with RO3003.

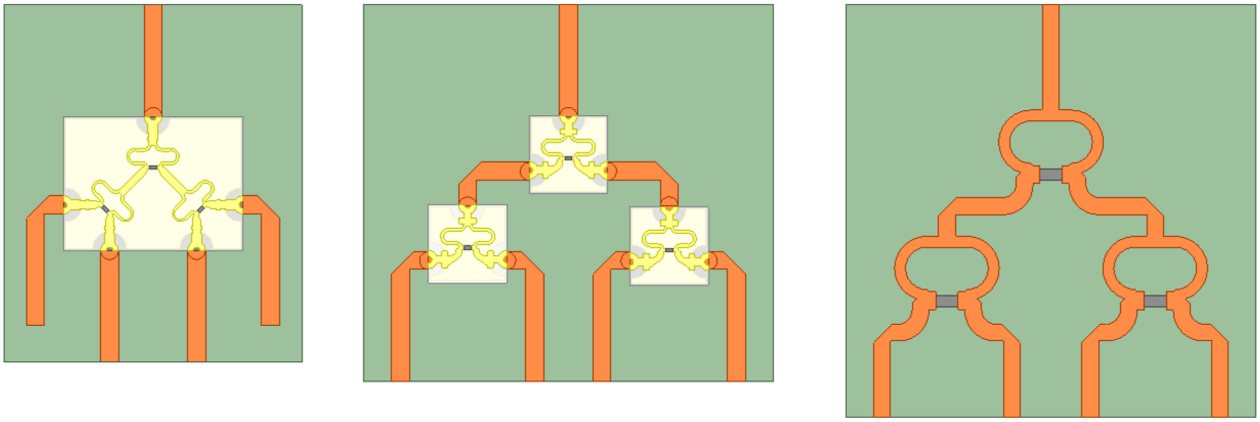


Figure 4. These diagrams represent three different configurations with different materials for a Wilkinson power divider.

Similar to the earlier coupler example discussed, Table 3 shows that by using a high K substrate, either in a single 4-way or three different 2-way configurations, ultimately lets RF designers develop a Wilkinson power divider that is smaller than what someone can do without using high K materials on a PCB.

> Beyond decreasing the size of the power divider, using either the 4-way or three 2-ways built on Knowles Precision Devices' custom ceramics improves performance as well.

Material	Quarter Wave @ 28 GHz Inch	Percent Reduction Wavelength	Dk	Area (inch²)	Percent Reduction Area
4-Way (RO3003)	0.069	-----------	3.0	0.061	-----------
Three 2-Way (PG Ceramic)	0.036	47.8%	12.5	0.039	36.1%
4-Way (PG Ceramic)	0.036	47.8%	12.5	0.019	68.9%

Table 3. This table shows the reduction in wavelength and surface area possible when using Knowles Precision Devices custom substrates.

Beyond decreasing the size of the power divider, using either the 4-way or three 2-ways built on Knowles Precision Devices' custom ceramics improves performance as well (Table 4).

Performance Metric	Four-Way (PG Ceramic)	Three Two-Way (PG Ceramic)	Four-Way (RO3003)
Excess Insertion Loss	0.6dB	0.9dB	0.6dB
Amplitude Balance	0.03dB	0.2dB	0.05dB
Phase Balance	0°	1.5°	0°

Table 4. This table shows RF performance at 28 GHz for the three different configurations used in this example.

We also looked at worst-case etching tolerances due to manufacturing variability to compare expected performance over multiple builds. Table 5 shows that the thin-film tolerances used were ± 0.0001 inches, while the PCB tolerance was ±.002 inches For the three 2-way configuration we also looked at a ±.001 inches variation for XY location placement.

Performance @ 28 GHz	4-Way (PG Ceramic)	Three 2-Way (PG Ceramic)	4-Way (RO3003)
Amplitude Matching	± 0.1dB	± 0.2dBzz	± 0.3dB
Phase Matching	± 1.5°	± 10°	± 13°
Worst-Case Return Loss	18dB	14dB	12dB

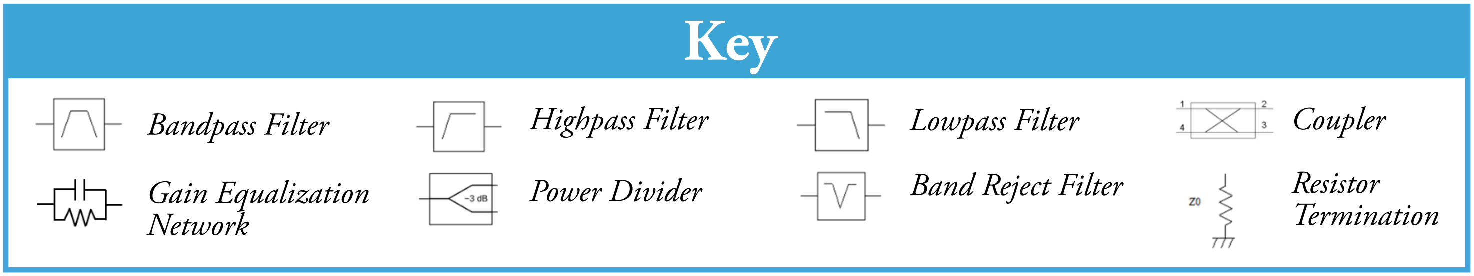
Table 5: This table shows simulated part-to-part worst case scenarios for RF repeatability.

DESIGN SMALLER CIRCUITS WITH KNOWLES PRECISION DEVICES PASSIVE RF COMPONENT INTEGRATION EXPERTISE

In general, integration of passive functions is not overly difficult at lower frequencies, but, at higher frequencies, developing these circuits is quite challenging. Since Knowles Precision Devices is not trying to be a typical commodity component manufacturer, we welcome this challenge. We are well positioned to address the current and future design challenges associated with component integration as we have material scientists on staff who are constantly working to innovate on our custom high K ceramics for thin-film development.

As previously mentioned, thin film is a layer of material used to fabricate electronic components. This approach helps reduce the size of components because thin film generally ranges from fractions of a nanometer to several micrometers in thickness. When using this development approach with our high K ceramics, we reduce SWaP by making components much more compact versus using other material options.

Since we have in-depth expertise in ceramics materials science and have developed proven precision thin-film techniques, we can build pretty much anything an RF designer can draw. With our custom thin-film solutions, our in-house RF designers can help customers address their toughest challenges, especially when it comes to putting multiple circuit elements into a compact single surface-mount package. Figure 5 shows eight diagrams of custom circuits we developed using these techniques while Figure 6 shows how small these circuits actually are once developed.



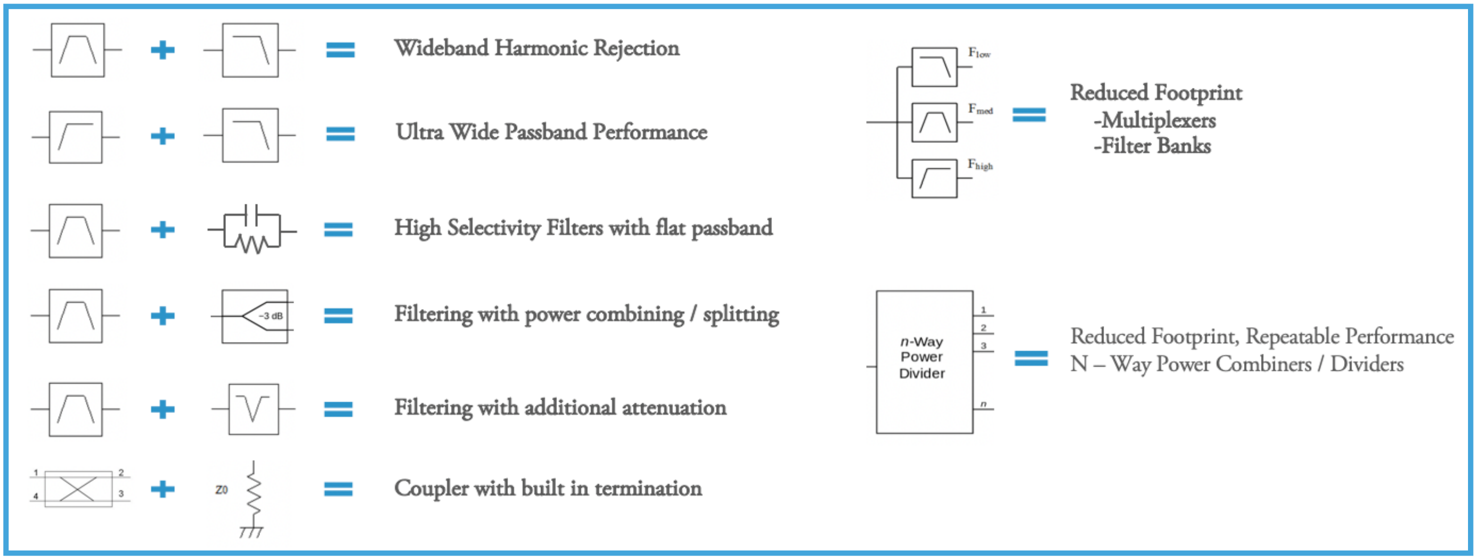


Figure 6. Our high K ceramics and experience with thin-film development allows our experts to integrate multiple RF components into a single surface-mount device.

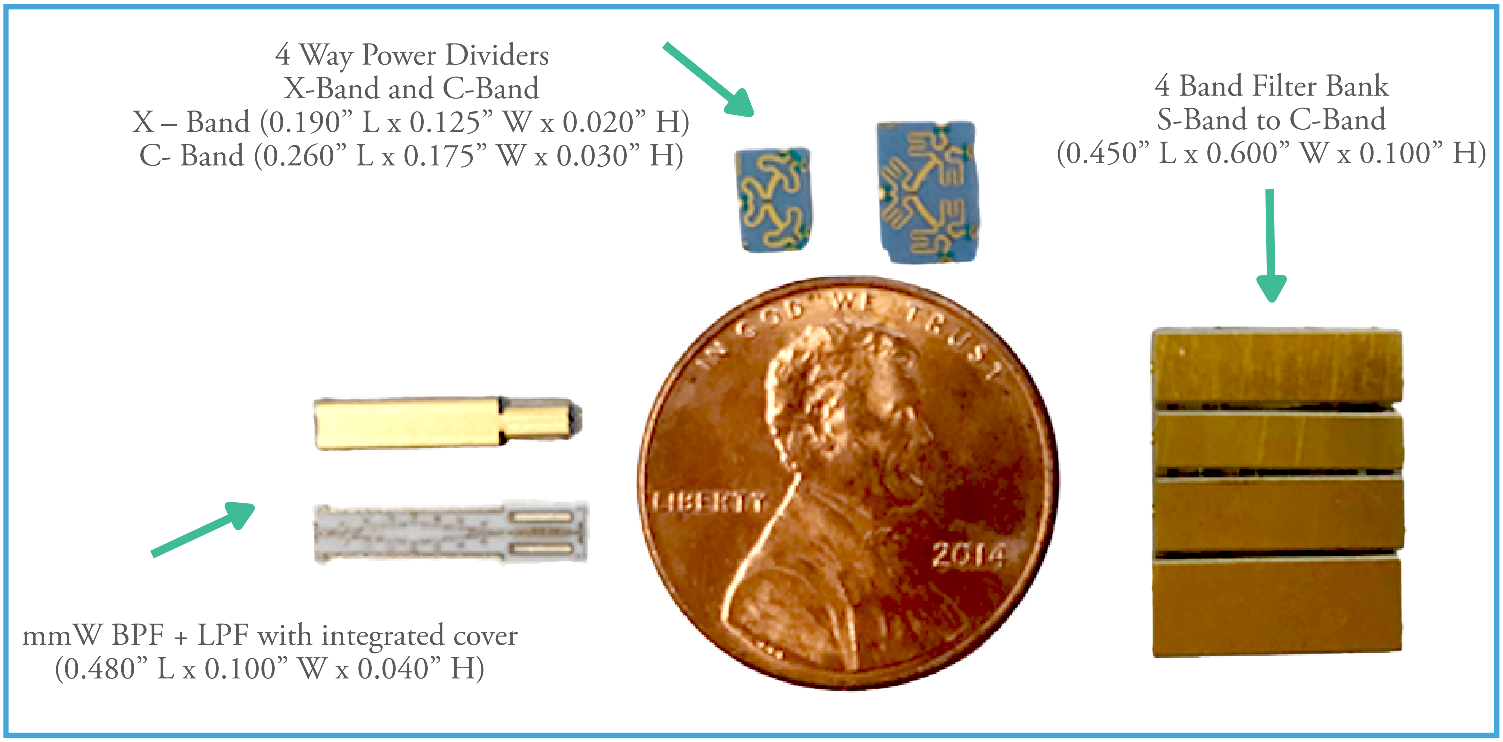


Figure 6. Using our high K ceramics, we consistently significantly reduce the size of circuits, even the complex ones, that we build for customers.

In addition to reducing size, components we build with our high K ceramics using a precision thin-film approach also offer the following performance benefits:

- Temperature stability
- Low loss
- CTE similar to many common PCB materials
- High quality

LET US SOLVE YOUR TOUGHEST DEVICE MINIATURIZATION CHALLENGES

In general, developing high-performance and reliable mmWave circuits is not an easy task. Add in the additional demand to continuously reduce device size, and circuit development becomes even more challenging. Thus, it can be really difficult to find companies who are up for a challenge like this.

At Knowles Precision Devices, we are not only up for it, we encourage RF designers to bring us their most difficult challenges. With the combination of our custom high K dielectrics, our experience working with high-precision thin-film photolithographic technology, and our ability to seamlessly integrate multiple passive components into a single circuit, we constantly have new and innovative ways to miniaturize RF components available. As a result, we are helping RF designers meet industry demands to continuously improve the SWaP of their devices.

Learn how Knowles Precision Devices can help you reduce the SWaP of your RF circuits with our high K materials and precision thin-film technology.

Learn More

Contact Us