# Materials Advances Enable Technical Improvements in Circulators, Filters and other Key Components Used in Commercial Wireless Technology

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# Introduction

Commercial wireless technology has undergone numerous transformations since its inception in the mid-1990s. These changes are expected to continue as we proceed into the later stages of 5G and 6G technology. And, as always, developments in materials technology and semiconductor devices have enabled many of these technological innovations.

This white paper will trace the evolution of materials technology. It will also describe materials advancements that have resulted in improved performance and dramatic reductions in SWaP (Size, Weight and Power) in commercial wireless applications.

## Ferrite Development for Circulators

A circulator is a non-reciprocal device acting as a rotary traffic circle for RF energy. Most commercial circulators consist of two ferrites biased by permanent magnets with a center conductor linking the ferrites and encased in a housing (Figure 1).


***Figure 1.*** *Image showing a typical commercial RF circulator.*

Circulators typically operate at magnetic field levels greater than those inducing ferrimagnetic resonance and are therefore generally small, narrow-bandwidth devices. At frequencies above approximately 4GHz, they operate at magnetic fields below the ferrimagnetic resonance. As a result, the saturation magnetization of the ferrite dictates the frequency of operation.

For below-resonance applications, microstrip circulators may be used. These devices, which do not need a housing, consist of a metal strip attached to the ferrite and a single permanent magnet on top. Because microstrip circulators cannot operate at higher frequencies (> 20 GHz) due to radiative losses, substrate integrated waveguide filters are used instead.

The following sections describe the two circulators typically used for commercial wireless technologies:

- ***Narrow Linewidth Garnets (CVG-TTVG).*** Operating in the 1-4GHz range for 1G through 5G generations, these circulators operate at magnetic fields greater than the gyromagnetic resonance. This allows for greater compactness but requires ferrite materials with ultra-low magnetic losses for effective operation of circulators. As a result, chemical formulations are developed to have very narrow magnetic resonant linewidths. The base material for all garnet ferrite materials is $Y_3Fe_5O_{12}$ or yttrium iron garnet (YIG). This material is chosen for its low dielectric loss, low electrical resistivity, and low magneto crystalline anisotropy energy ($K_1$). $K_1$ is a measure of how the magnetic response of a crystalline material to an applied magnetic field varies due to the crystallographic direction in which the field is applied. Low $K_1$ is directly related to sharp gyromagnetic resonance peaks, narrow resonance linewidths (3dB below the peak of the resonance) and reduced magnetic losses. The $K_1$ can be reduced even further by the substitution of non-magnetic ions such as $In^{3+}$ for $Fe^{3+}$ in the formulation.
  - ***Improvements in YIG Processing:*** The chemical formulations listed above have an insufficient Curie temperature for many applications. Having a high Curie temperature is desirable for better temperature stability of a circulator device. As a result, processing improvements have been made to reduce the resonance linewidth of yttrium iron garnet with a 280°C Curie temperature. These proprietary processing improvements lead to 3dB linewidths of less than 20 oersted for unsubstituted YIG.

- ***High Dielectric Constant Garnets.*** To enable miniaturization of devices, ferrites with dielectric constants greater than 13 for yttrium, iron garnet circulators are needed. With this breakthrough, dielectric constants up to 30 can be obtained, leading to a 25% reduction in footprint. This achievement resulted by substituting bismuth Bi3+ for yttrium in the YIG material. Bismuth compounds are notable for their high dielectric constant values. However, these materials are extremely challenging to process. With Trans-Tech's proprietary process, low-loss materials, trademarked TTHiE™ (Trans-Tech High Dielectric Constant), can be produced. These materials are available with saturation magnetization values from 400 gauss to above 1950 gauss and at dielectric constants from 25 to 31. When using devices containing one of the TTHiE™ compositions as a ferrite material, their high dielectric constant enables device miniaturization as well as higher fractional bandwidth and improved intermodulation performance.

## The Evolution of Microwave Dielectrics

The components used in wireless devices have evolved over time. For instance, 1G handsets first used large (typically on the order of two-inch-long) ceramic monoblocks as filters. The move to acoustic wave filters enabled a significant benefit since the speed of sound is 1/870000 that of the speed of light, at a given frequency, which means a half-wavelength resonator will be much smaller. This development has directly led to the miniaturization of handsets.

The next development was using of auto-tune combiners for 2G and 3G base stations. Originally, base stations relied on a mechanically tuned device called an auto-tune combiner for frequency selectivity. This approach required highly engineered ultra-low-loss dielectric materials that are often based on tantalum oxide.

In the mid-1990s, there was a push for microwave dielectric materials with higher Q values for 2G digital data transmission in the 2GHz range. Materials were required that exhibited a Q x f (Qf) product above 80000 at 2GHz, or more than double that of the current titanate materials. At that time, the best Q values known were the complex ordered perovskites barium magnesium tantalate Ba3MgTa2O9 (BMT) and barium zinc tantalate Ba3ZnTa2O9 (BZT). These materials had the perovskite structure with multiple cations on the B-site, with the B-site cations ordered in consecutive planes in the 111 directions (Figure 2).

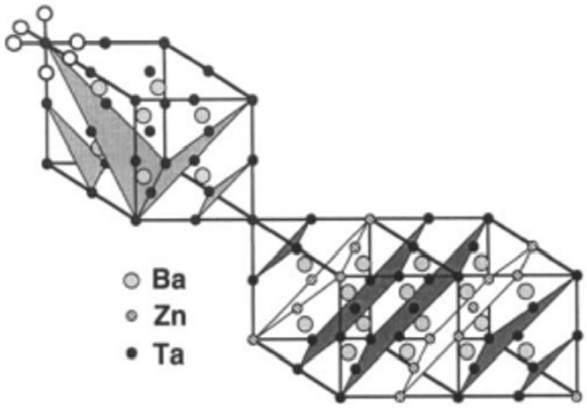



***Figure 2.*** *Illustration of B-site cations ordered in consecutive planes in 111 directions in BMT and BZT perovskites[1].*

As shown in Figure 2, the B-site cations have two consecutive rows of $Ta^{5+}$ ions followed by a row of divalent metal ions ($Zn^{2+}$ or $Mg^{2+}$) in BMT and BZT perovskites. These complex structures yield very high Qf product; often greater than 100000 with dielectric constants of 25 (for BMT) and 30 (for BZT). The Qf values of these perovskites are slightly positive but close enough to zero to be tunable with moderate amounts of substituent cations. The Q value is directly correlated with the degree of ordering in these materials. Perovskites with randomly distributed B-site cations show very low Q values as compared to the ordered variants. Above a critical temperature (the order-disorder transformation temperature), the material reverts to the disordered structure. It is desirable to sinter ceramic bodies of ordered perovskite materials below the order-disorder transformation temperature.

Fortunately, the order-disorder temperature in BMT and BZT is well above 1600°C, leaving a wide temperature window for ceramic processing.

***From tantalate to niobate super Q dielectrics***

When the price of tantalum skyrocketed in 2000-2001, Trans-Tech developed a cheaper material based on niobium for auto-tune combiners. Although tantalate compounds show excellent microwave dielectric properties, they have the inherent drawback of incorporating large amounts of very expensive tantalum oxide in their formulation. There is a drive in the industry for cost reduction, which has produced two new classes of high Q materials, including tungstate-based materials with dielectric constants in the niobate-based materials with dielectric constants in the 33-36 range.

Barium magnesium tungstate (BMW)-based perovskites have a 1:1 ordered perovskite structure and extremely high Q values (26). Tungsten is much cheaper than tantalum but more difficult to process by conventional ceramic techniques due to the tendency of tungsten oxide to react with water. In addition, because of the low-dielectric constant of the BMW material, a ceramic filter or combiner will require a larger puck than its tantalate equivalent, thus requiring a larger cavity resonator and a larger ceramic part.

Barium zinc niobate (BZN) is a 2:1-ordered perovskite isostructural with the corresponding tantalate. A solid solution with barium cobalt niobate produces a material (called BZCN) with a dielectric constant of 34 and a $Q_F$ close to zero. The high dielectric constant means that at a given frequency, the niobate-based ceramic resonator will be smaller than its tantalate-based counterpart (27). In addition, niobates do not react with water, making them amenable to aqueous ceramic processing techniques. However, the BZCN material has an order-disorder transformation temperature near 1400°C, which is below the typical sintering range from 1450-1550°C (28). This necessitates complicated processing and heat treatments, including lengthy annealing, to obtain the high Q ordered configuration. These niobates and tungstate-based materials will become increasingly important for commercial 3G high-power transmit filters and Wi-Max applications.

***4G and 5G materials replace the ceramic auto-tuner with semiconductors***

In new 4G and 5G systems, the conventional auto-tune combiner was replaced by a semiconductor solution, which acted as a multi-carrier power amplifier. Ceramic filters needed for base stations had less stringent loss requirements. The earliest microwave dielectric materials were crystalline ceramics featuring tetravalent titania in octahedral coordination.

In the 1970s, O'Bryan and Thompson[2] thoroughly studied the titania-rich region of the $BaO-TiO_2$ system and identified two compounds that have become the staple materials for microwave dielectrics up to this day: barium tetratitanate ($BaTi_4O_9$) and barium nonatitanate ($Ba_2Ti_9O_{20}$). Each has a dielectric constant between 36 and 38 with slightly positive temperature coefficients. Their Q values are modest (Qf = 30000) by today's standards, but still useful for many applications. The temperature coefficients approach zero for a two-phase mixture of the components for reasons yet to be clearly established.

Figure 3 depicts the relationship between the temperature coefficient of the resonant frequency ($\tau_F$) and the relative contents of barium nonatitanate and barium tetratitanate. In the illustration, further improvements in the Q values[3] have been made by a coupled substitution of $Zn^{2+}$ and $Nb^{5+}$ or $Ta^{5+}$ for $Ti^{4+}$ in this material.

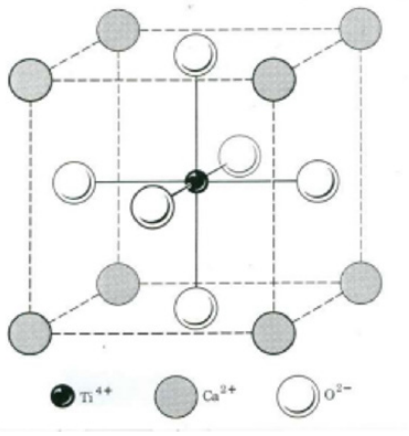



***Figure 3.*** *Illustration depicting the relationship between the temperature coefficient of the resonant frequency ($\tau_F$) and the relative contents of Ba2Ti9O20 and BaTi4O9.*

Another system containing $Ti^{4+}$ in octahedral coordination is the $ZrO_2$-$TiO_2$ system and, specifically, the compound $ZrTiO_4$ with the alpha-lead oxide structure. $Sn^{4+}$ doped $ZrTiO_4$ was one of the earliest microwave dielectrics used with a dielectric constant of 36[4]). The dielectric constant was improved into the 42-45 range by the coupled substitution of $Zn^{2+}$ and $Nb^{5+}$ for $Zr^{4+}$ in the structure[5]. Qf products above 40000 were obtained around 1GHz in this material. For both the $Sn^{4+}$ and the $Zn^{2+}$ and $Nb^{5+}$ doped systems, there is a substitution limit above which other cations cannot go into the alpha-PbO structure. Above this limit, a second-phase rutile forms with the $Q_F$ and the Qf, increasing dramatically.

Figure 4 shows the relationship between $Sn^{4+}$ substitution and the dielectric constant and temperature coefficient for the $ZrTiO_4$ material, from a paper published by Wolfram and Gobel in 1981[2]. By adjusting the atomic percent of the zirconia substituent, the temperature coefficient may be tuned.

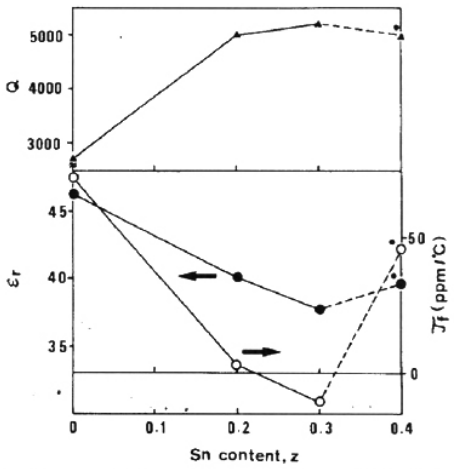



***Figure 4.*** *Line drawing showing the relationship between $Sn^{4+}$ substitution and the dielectric constant and temperature coefficient for the $ZrTiO_4$ material.*

## Advances in Materials Technology Reduce Circulator SWaP

One early drawback with circulator designs was that unless the permanent magnet had a significantly larger diameter than the ferrite, the ferrite would not be able to be completely saturated around the outer edge due to the relatively weak magnetic field (from the center). This led to losses and intermodulation distortion. One method for handling this issue was to glue a dielectric ring around the ferrite so that the magnet diameter was effectively larger than the ferrite diameter.

Figure 5 shows a circuit placed over a ferrite assembly. The center black circle is the magnetic ferrite oxide, and the white ring around the ferrite circumference is the dielectric. The gray regions indicate the presence of metallization. The transformer sections can be placed on the magnetic ferrite material.

***Figure 5.*** *Illustration of a circuit placed over a ferrite assembly.*

Advantages of using a high dielectric ceramic include the following:

1. A high dielectric constant ring will reduce the physical size of the transformer.
2. A larger ratio of the magnet diameter to ferrite diameter helps to uniformly magnetize the ferrite material.
3. The dielectric ring reduces the operating frequency of the circulator.

***Shrink firing (Co-Firing) vs. polymer adhesives***

Initially, the circulator assemblies were made by gluing together rods of ferrite material and cylinders of non-magnetic dielectric material and slicing to create the ferrite assembly. However, with this process the polymer-based adhesive exhibits high dielectric losses, it is impossible to metalize using thick film silver. Metallization usually involves more cumbersome means, which will increase the losses.

However, certain combinations of materials may be bonded together with an inorganic ceramic bond by a process we call co-firing. With this process, the ferrite rod is initially fired separately.

Then, an unfired dielectric ring is pressed, and the sintered ferrite and unfired dielectric are fired together so that the dielectric "shrink wraps" around the fired ferrite material. This composite can then be sliced and used as ferrites in the circulator. The image in Figure 6 shows the different results using these two processes.

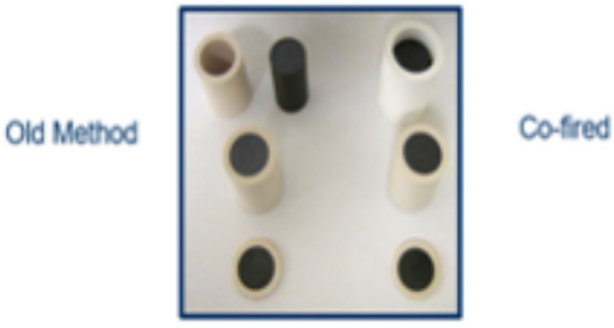



***Figure 6.*** *Image showing circulator polymer adhesive method (left) vs. co-fired assembly.*

There are a number of critical conditions for the material set that may be co-fired.

1. The ferrite must fire at a higher temperature than the dielectric material.
2. There should be minimal atomic diffusion between the dielectric and the ferrite at the dielectric sintering temperature.
3. The thermal expansion coefficients of the ferrite and the dielectric should be matched. A co-fired assembly does not contain lossy polymeric adhesives and is easily metallized with thick film silver, so the device insertion loss is reduced.

***Expanding the roster of materials***

Co-firing is currently done on a limited roster of compatible dielectric-magnetic combinations. Higher frequency use demands that the roster of materials available to be co-fired. In the case of some magnetic materials with lower sintering temperatures, dielectric materials sintered at lower temperatures than the ferrites with compatible thermal expansion coefficients need to be identified. An example of this type of material are spinel ferrites for X-Band and above. With high-frequency spinel ferrites and their lower firing temperatures, this makes the selection of low-firing-compatible dielectric materials challenging.

## Ferrite Developments for Modern Circulators

High-power applications require special ferrite compositions because at high power levels, much of the RF energy is converted to spin waves (or magnons). Magnons dramatically increase the insertion loss of a device and, therefore, a practical power level limit exists above which the device goes non-linear (due to spin wave formation) and the insertion loss increases dramatically. One commonly used design tactic is to dope the ferrite with a fast relaxor ion, such as $Ho^{3+}$ or $Co^{2+}$, to convert the RF energy at high power levels to lattice vibrations rather than spin waves. This approach increases the threshold power level before non-linearity sets in, but it also increases the low-power insertion loss.

Reducing the grain size of the ferrite material is another method of increasing the power threshold with no effect on the low-power insertion loss. However, this process is difficult to achieve consistently without special ceramic processing techniques.

***Materials for 4-10 GHz operations for miniaturized stripline circulators***

The range of 4-10 GHz is of special interest since the only method of reducing the size of these devices is using a high dielectric constant ferrite material, such as Trans-Tech's TTHiE series described earlier. In this frequency range, circulators operate at a magnetic field below the ferrimagnetic resonance of the device. Therefore, each frequency range needs to have a material with a specific saturation magnetization (Figure 7).

| Frequency | Saturation Magnetization |
|---|---|
| 2.0-2.5 GHz | 700-800 gauss (TTHiE-700) |
| 3.0-3.5 GHz | 900-1000 gauss (TTHiE-950) |
| 4.0-4.2 GHz | 1100-1200 gauss (TTHiE-1000) |
| 5.0-5.5 GHz | 1400 gauss (TTHiE-1400) |
| 6.0-6.5 GHz | 1600 gauss (TTHiE-1600 or TTVG-1600) |
| 7.0-7.5 GHz | 1800 gauss (TG-113 or THiE-1800) |
| 8.0-8.5 GHz | 1850-1900 gauss (TTVG-1850, TTVG-1900 or TTHiE-1950) |
| 9 GHz | Spinel Ferrites |

***Figure 7.*** *The table shows the saturation magnetization values of specific ferrites that may be used at the defined frequencies for below-resonance circulators.*

## Using Flat-Temperature-Response Ferrite Materials for High-Temperature Applications

The temperature dependence of the saturation magnetization of ferrite materials is highest near absolute zero and steadily decreases as the Curie temperature of the material is approached. The Curie temperature is the temperature above which the material loses its magnetic properties. The highest Curie temperatures for the garnet materials are in the 278-300°C range.

While many materials operate at room temperature, which is far away from the Curie temperature of most ferrite materials, there is a decrease in the saturation magnetization of the ferrite if the material warms up due to increasing ambient temperatures or the application of high power. This can be offset over a limited temperature range with the use of gadolinium substituting for yttrium in the garnet structure. Gadolinium has 7 unpaired 4f electrons and a magnetization that counters the magnetization of the 3d electrons in trivalent iron. The magnetic interaction between gadolinium ions is very strong at low temperatures yet decreases as room temperature is approached. If the gadolinium content is chosen judiciously, one can get a flat-temperature response over a specific temperature range due to these competing effects.

***Ku Band and Above***

- Ferrite Materials for high-frequency latching devices. Latching devices take advantage of the two-state nature of hard ferroelectrics. There is a relationship between the frequency of operations and the saturation magnetization of the latching ferrite. The optimal saturation magnetization for a given frequency is dictated by identifying the region where the dielectric losses and magnetic losses are minimized. For applications in the Ku band and above, high-saturation magnetization spinels, such as nickel zinc ferrite materials, are required, as illustrated in Figure 8.

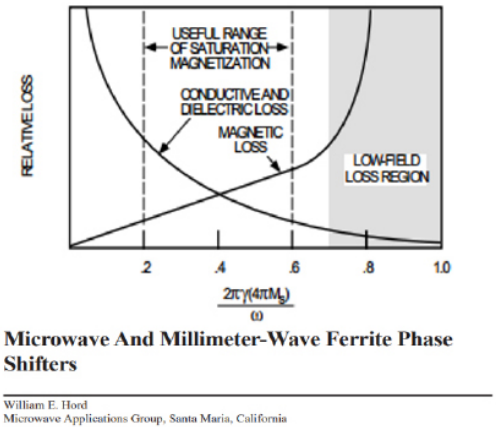



***Figure 8.*** *Graph showing the region of minimum loss (optimal operating parameters) for latching ferrite designs. The minimum loss corresponds to an x axis value near ".4," which is a function of the operating frequency and the saturation magnetization of the ferrite[6].*

- Thin film ferrite solutions for microstrip and SIW circulator designs.

  For applications in the Ku band and above, microstrip or substrate integrated waveguide circulators are needed. These may require thin film magnetic ferrites or these magnetic cross sections.

- Advanced processing techniques and materials.

  Advanced processing techniques, such as thin film deposition (e.g., sputtering), may be used for high-frequency devices. Surface finish and metallization quality are mundane but critically important parameters as the frequency goes up.

***Ferrite considerations***

- Supply Chain Risk.

  Many ferrite devices are based on yttrium iron garnet materials. Yttrium is among the rare-earth materials almost exclusively sourced through China. Geopolitical considerations have the potential to disrupt the supply of yttrium. Spinel and hexagonal ferrites, however, do not typically use yttrium or other rare earths.

- Trends in circulator manufacturing.

  Like so many other industries, automation is a megatrend for circulator manufacturing. Many of these factories are in China or Vietnam, potentially resulting in supply chain risks. A trend is to try to establish circulator manufacturing in the U.S., particularly for military and aerospace applications.

## Microwave Dielectrics for Devices Enable SWaP Reduction

***High-dielectric constant materials for miniaturized devices***

- BSTO for tunable materials.

  Tunable filters are the holy grail for device applications. However, the best material, BSTO (Ba1-xSrxTi03), is a high-dielectric constant paraelectric subject to issues with temperature drift and high-dielectric loss. Along with the high-dielectric constant at microwave frequencies, the material will adjust its dielectric constant in response to an applied electric field, making it interesting for tunable filter applications. But this promise has been tempered since these materials also have high-dielectric losses and the dielectric constant varies greatly with temperature.

- Temperature-compensating high dielectric constant materials.

  The miniaturization of devices requires materials with a higher dielectric constant. However, as a general trend, higher dielectric constant materials have higher loss tangents and poor temperature stability. The highest-temperature-stable dielectric at TransTech is the D-125 material. The material with the best combination of high dielectric constant, Q and temperature stability is the 73XX material, which has a dielectric constant of 73 and a Qf product approaching 12000 at 1GHz. High dielectric constants enable miniaturization in resonator diameters proportional to 1/(e)1/2 since the speed of light in a high dielectric medium is slowed by a factor of 1/(e)1/2. For a given frequency, a higher dielectric constant will lead to a smaller size resonator, and the dielectric resonator dimensions need to be multiples of ½ of the wavelength for the field to propagate through.

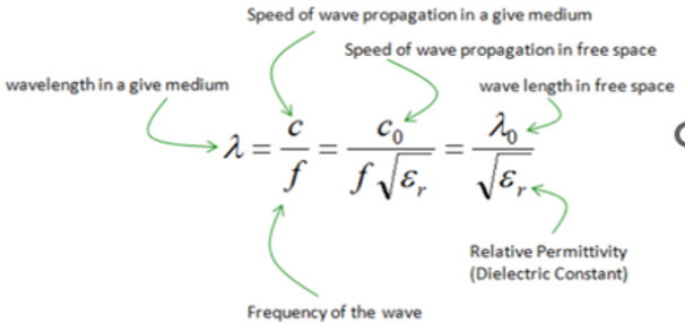
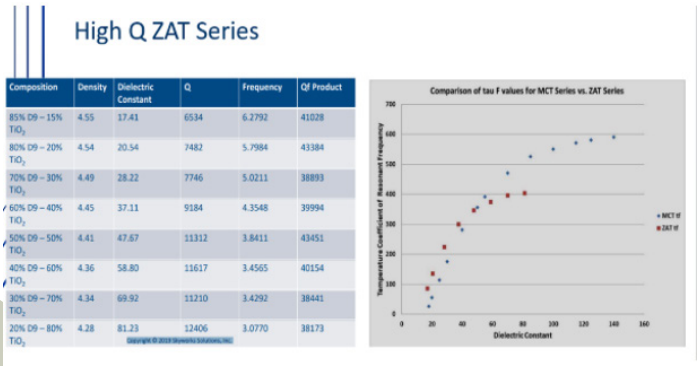



***Figure 9.*** *Equations for how the speed of electromagnetic wave propagation and the wavelength decrease in a medium with a dielectric constant greater than 1.*

- Low-dielectric constant materials

  Low-dielectric constant materials are suitable for mm-wave devices. For high-frequency resonators (> 20GHz), a low dielectric constant material is needed to achieve a resonator large enough to be machined to precise dimensions. In addition, for 5G and 6G applications, reducing the latency or time delay becomes a paramount consideration. The time delay Td = L(e)1/2/c, where L is the signal transmission distance, e is the dielectric constant and c is the speed of light in a vacuum. The time delay is smallest in materials with low dielectric constants. The ceramic materials with the lowest dielectric constants include forsterite (Mg2SiO4) and Willemite (Zn2SiO4), with a dielectric constant of 6. Low-loss and temperature-stable versions of these materials are an active area of research at Trans-Tech.

  An ultra-low-loss, temperature-stable family of materials with a dielectric constant below 14 was recently developed at Trans-Tech based on the Zn1+xAl2-2xTixO4 system. This material has a temperature-compensated dielectric constant of 12.8 and may be used for high Q (low loss applications) for dielectric constants between 9 and 100 (Figure 10). The figure shows that as the dielectric constant increases, the temperature coefficient of the dielectric constant increases as well.




| Composition | Density | Dielectric Constant | Q | Frequency | Qf Product |
|---|---|---|---|---|---|
| 85% D9 – 15% $TiO_2$ | 4.55 | 17.41 | 6534 | 6.2792 | 41028 |
| 80% D9 – 20% $TiO_2$ | 4.54 | 20.54 | 7482 | 5.7984 | 43384 |
| 70% D9 – 30% $TiO_2$ | 4.49 | 28.22 | 7746 | 5.0211 | 38893 |
| 60% D9 – 40% $TiO_2$ | 4.45 | 37.11 | 9184 | 4.3548 | 39994 |
| 50% D9 – 50% $TiO_2$ | 4.41 | 47.67 | 11312 | 3.8411 | 43451 |
| 40% D9 – 60% $TiO_2$ | 4.36 | 58.80 | 11617 | 3.4565 | 40154 |
| 30% D9 – 70% $TiO_2$ | 4.34 | 69.92 | 11210 | 3.4292 | 38441 |
| 20% D9 – 80% $TiO_2$ | 4.28 | 81.23 | 12406 | 3.0770 | 38173 |

***Figure 10.*** *Table showing the dielectric constant, Q, and temperature coefficient of the $Zn_{1+x}Al_{2-2x}Ti_xO_4$ series of microwave dielectric materials.*

***Dielectric materials for antennas***

- High-performance patch antennas.

  Trans-Tech has perfected a process to tightly control the dielectric constant for high-performance patch antennas for military and aerospace applications. These are low-loss materials that can operate in extreme environments where polymer-based patch antennas cannot.

- Medical RFID antennas.

  The medical RFID frequency for subcutaneous transponders and in vivo implants is 13.56MHz. Trans-Tech has developed a magnetic antenna material with the magnetic Q and permeability optimized at this frequency.

- Magnetodielectric antennas.

  Miniaturization is desirable for antennas for many applications. Indeed, using a patch antenna with a high-dielectric constant may reduce the antenna dimensions by the familiar $1/(e)^{1/2}$ factor. However, this comes at a significant cost in antenna performance. Magnetic insulating material may be advantageous to use for antenna applications since you may derive the benefit of miniaturization without the loss of efficiency or bandwidth. In the case of a magnetic material, the miniaturization factor becomes $1/(em)^{1/2}$, where e is the dielectric constant and m is the magnetic permeability of the material. If a magnetic material has a permeability of 10 and a dielectric constant of 10, then one could achieve the same miniaturization as a non-magnetic material (permeability = 1), with a dielectric constant of 100. Furthermore, the achievable bandwidth and efficiency is proportional to $(m/e)^{1/2}$. For $m \geq e$, there is no penalty in efficiency for miniaturization.

The problem is that there are very few insulating materials that have a permeability above 1 at 500 MHz or above, much less at above 1GHz. Trans-Tech's TTZ-500 material is used for applications at 500 MHz, and it has a dielectric constant > 11 and a permeability > 11. Recently, Trans-Tech has developed a material with a dielectric constant near 11 with a permeability close to 7 at 1GHz. Although there is interest in magnetodielectric antennas operating at higher frequencies, the materials are not yet there.

# Conclusion

Material advances have driven substantial improvements in performance and SWaP of commercial RF components and systems.

Trans-Tech continues to develop ceramic materials for wireless technology applications over a wide range of frequencies. As new technologies develop, Trans-Tech will continue to create innovative materials for current and future applications.

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