This catalog is intended for reference purposes only to aid in the understanding, design and use of microwave materials. It represents TRAK Ceramics, Inc. (Hagerstown, MD) at the time of their acquisition by NMG (Bethlehem, PA) in 2001. Not all of the materials and capabilities described are necessarily available today. Please call us to discuss your specific requirements with our engineers - we are here to help.

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TRAK Ceramics, Inc

tuned to the future

superior ceramic products for wireless applications

low-cost ferrite and garnet magnetic materials

the widest range of dielectric resonators in the industry

advanced ceramic materials

When you need advanced ceramic materials and components, and a business partner who has customer sensitivity, technical competence and the ability to innovate, look no further than TRAK Ceramics, Inc. (TCI) The company now offers the world's broadest range of low loss magnetic, dielectric and temperature compensated dielectric materials for RF and microwave applications.

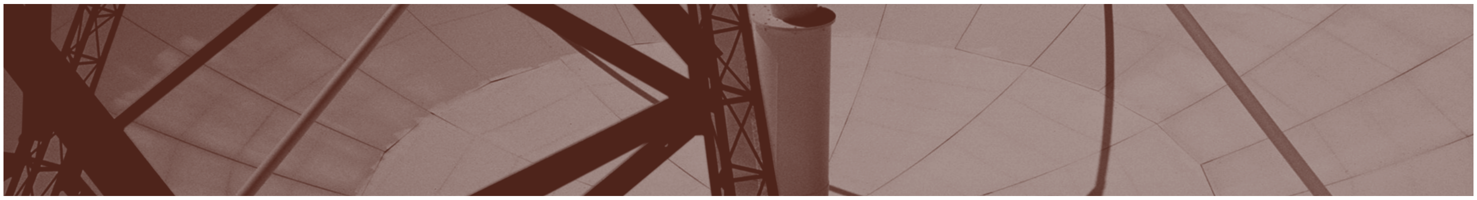
Operations in Hagerstown, Maryland enable the new TCI to provide customers with advanced materials and components, leading-edge research and development, and low-cost, high-volume manufacturing. With an eye toward reliability and each customer's bottom line, product quality is carefully monitored and controlled from receipt of raw materials through finishing of the end product.

Modern tools have armed today's designer of components and circuits with powerful means to model, optimize and improve new and existing products. Often, designs place stringent performance requirements on advanced materials such as low loss ceramics.

The new TCI management and development team includes recognized industry leaders and pioneers who are capable of meeting the demands of the market with timely development of innovative ceramics. Team members possess strong foundations in physics, electromagnetic theory, chemistry and ceramic processing. This expertise is applied throughout the production cycle to insure high quality and optimum performance of the final product.

TCI customers benefit from this unparalleled collection of experience in microwave technology and materials science combined with proven track records for launching new products from concept to full production.

From theory to finished product, the new TCI is the electronic designer's best resource ... exceeding customer expectations in performance, service and cost ... tuned to your needs now and into the future.



QUALITY

MISSION STATEMENT

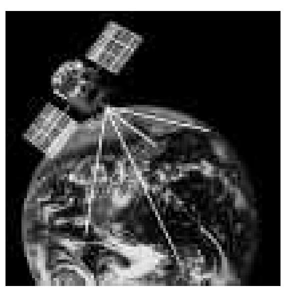
TRAK Ceramics, Inc. is dedicated to consistently providing the highest quality ceramics, powders, components, and devices in the world. We have dedicated ourselves to continuously improving our products, processes, and service and we make every attempt to exceed the quality expectations of our customers.

An Innovator in UHF/Microwave Materials and Components Serving the Wireless Market

Cellular Mobile Phones

Satellite TV

Base Station



Global Positioning

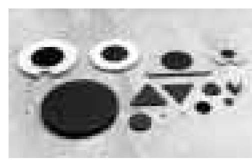
Custom R&D

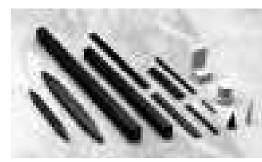
Defense

RF/Microwave and Non Microwave Materials and Products

Dielectric Resonators

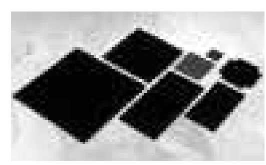
- Wide Range of Temperature Stable Materials
- Dielectric Constants Ranging from 10 to 80
- Extremely Low Loss





Magnetic Materials

- Garnets
- Ferrites
- Phase Shifter Elements

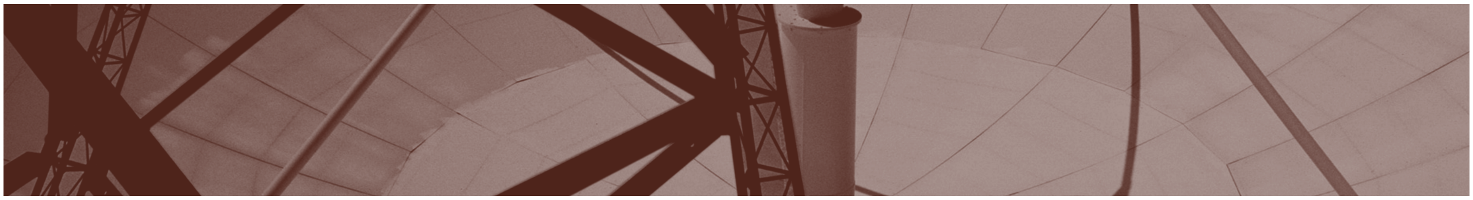


Substrates

- Broad Range of Dielectric and Magnetic Materials
- Dielectric Constants Ranging from 4.5 to 120
- Temperature Stable
- Low Loss

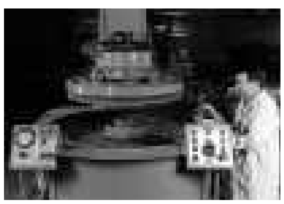
Advanced Materials

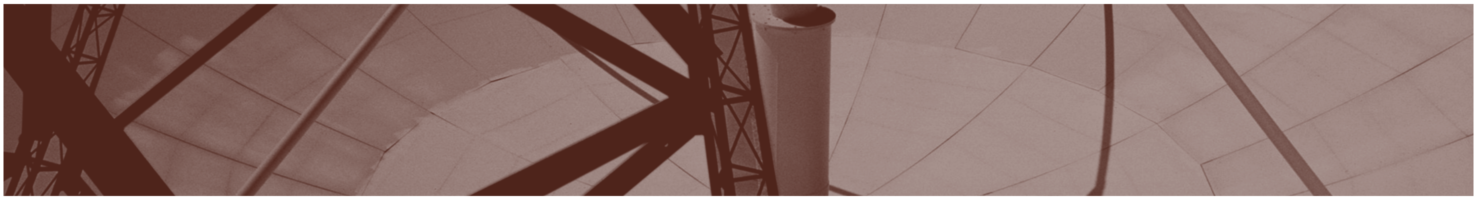
- Thermal Barrier Materials
- Custom R & D
- Sputtering Targets



PROCESS CAPABILITIES

TRAK Ceramics, Inc., an innovator in dielectric and magnetic materials specializing in UHF and microwave applications, maintains large scale manufacturing facilities in Maryland. TCI can handle small to large volume manufacturing requirements including non-standard, intricate shapes and sizes. Unmachined parts are available as bars, slabs, rods, disks and triangles. Machined configurations include phase shifter toroids, substrates, dielectric resonators, magnetic elements, and ferrite/dielectric composites.





MICROWAVE MATERIALS

Ferrite Materials

Garnets

The garnet family of microwave ceramics is based on the parent compound, $Y_3Fe_5O_{12}$, which has a minimum $4\pi M_s$ of about 1780 Gauss at room temperature and T_c near 280°C. More importantly, this family displays the lowest combination of dielectric (tanδ) and magnetic losses of all microwave ferrite-based materials regardless how the chemistry is adjusted using dopants (substitutional cations in the garnet structure) to alter the base properties.

Conventional garnet, polycrystalline ceramics typically have line widths characterized by ΔH (-3dB) in the 40–60 oe range. Well controlled processing of pure $Y_3Fe_5O_{12}$ ceramics, however, can produce line widths as low as 10-25 oe at room temperature. Major contributions to even these low level magnetic losses are pores, grain boundary chemistry and space charge characteristics, vanishingly small secondary phases (impurities, etc.), and magnetocrystalline anisotropy associated with the garnet crystal structure. Single crystals effectively eliminate the first three major causes and line widths lower than 1oe are easily obtained. Unfortunately, large single crystals at the size and configuration required by most microwave devices cannot be produced economically. On the other hand, substituting (doping) dopants such as In^{3+}, Zr^{4+}, etc. for Fe^{3+} in garnet can reduce magnetocrystalline anisotropy. This results in ceramics that can yield 3-20 oe line widths.

The $4\pi M_s$ of $Y_3Fe_5O_{12}$ can be adjusted downward by substituting Al^{3+} for Fe^{3+}, but the penalty is that T_c drops accordingly. Substitution of Gd^{3+} for Y^{3+} maintains a high T_c, but $4\pi M_s$ drops accordingly at room temperature. However, the established $4\pi M_s$ can be maintained over a broader temperature region above room temperature and this is important for applications that require power and generate heat. The combination of Gd^{3+} and Al^{3+} substitutions varies $4\pi M_s$ while providing $4\pi M_s$ stability in the high temperature region (0°-100°C) despite a systematic drop in T_c.

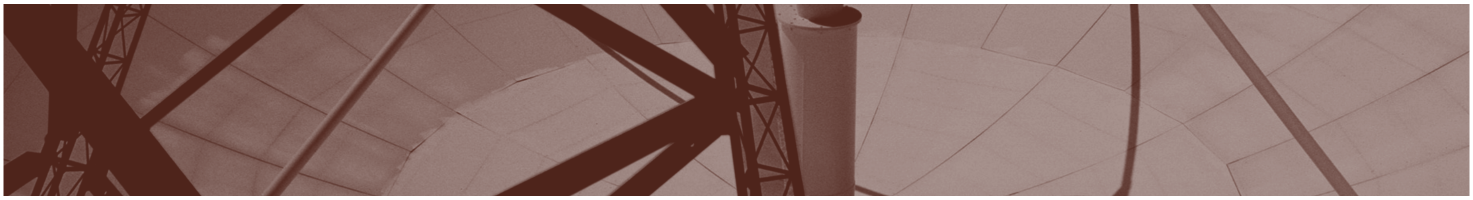
The intrinsic power handling capability (ΔH_K) of garnets is low, but it can be increased substantially by substitutions for Y^{3+} and/or for Fe^{3+}. The traditional approach is to substitute Ho^{3+} (or Dy^{3+}) for Y^{3+} in the crystal structure. Here, the penalty is somewhat larger magnetic loss as reflected in ΔH (-3dB). Alternatively, Co^{3+} can be substituted for Fe^{3+} without major increases in ΔH. Yet another approach is to maintain a small grain size in the ceramic.

Well processed garnet ceramics show excellent square hysteresis loops and small H_c needed for phase shifters, regardless of the bulk chemistry. Here, the key is to obtain a dense, but uniform microstructure in terms of grain size and actual distribution of porosity. In normal form, garnets are inherently magnetostrictive and, as such, their hysteresis loop properties can be significantly stress dependent. To overcome potential difficulties, their bulk chemistry can be modified and/or machined parts can be annealed to reduce magnetostrictive effects to low levels.

Spinels

The general formula AFe_2O_4 characterizes spinel-based ceramics, where A is typically Mg or Ni. This family also includes the lithium ferrites, which can be expressed as, $(Li_{0.5}Fe_{0.5})Fe_2O_4$. In general, spinel ceramics show somewhat larger dielectric and magnetic losses that are offset by other properties which are highly flexible. They are superior in applications where high T_c and high $4\pi M_s$ are needed. Intrinsic power handling capability is moderate, but can be increased substantially by controlling the grain size and/or by cobalt ion substitutions. Square hysteresis loops with small H_c are obtained from processing that maintains precise control over the crystal chemistry and the uniformity of grain size and pore distribution.

The $4\pi M_s$ of spinels is manipulated primarily by using combinations of Mn^{2+}, Mn^{3+}, Zn^{2+}, Al^{3+}, and Ti^{4+} substitutions, which also tend to progressively lower



T_c. Line widths of nickel spinel can be reduced by cobalt substitutions that decrease magnetocrystalline anisotropy, while controlled substitutions of Zn^{2+} in lithium ferrites reduce their ΔH (-3dB). Lithium ferrites are particularly versatile in that high and low line width variants with the same $4\pi M_s$ can be produced while maintaining high T_c and dielectric constants higher than garnet.

Spinels based on Mn, Zn are not commonly used as microwave materials. Provided that during processing the oxidation state of Mn is controlled and the loss of ZnO via vaporization is avoided, the properties of this spinel class can be manipulated for many lower frequency applications that require single crystals or ceramics. These materials feature high permeabilities. Power handling capability and loss characteristics can be tailored by substitutions, additives, and/or by precise control of the microstructures.

Hexaferrites are a unique class of magnetic materials that are not true spinels but do have spinel-like structural character. Most common are the so-called M-type based on the parent, $BaFe_{12}O_{19}$, although Sr^{2+} and Pb^{2+} easily substitute for Ba^{2+}. Substitutions for Fe^{3+} can be made to tailor the electromagnetic properties. The two primary ways (or their combination) can be expressed as, $BaFe_{12-x}Me_x^{3+}O_{19}$, and as, $BaFe_{12-2x}Me_x^{2+}Me_x^{4+}O_{19}$, where typically $Me^{3+} = Al^{3+}$; $Me^{2+} = Ni^{2+}$, Co^{2+}, Zn^{2+}; and $Me^{4+}=Ti^{4+}$. These ceramics offer high saturation magnetization and a large internal biasing field that may reduce or eliminate the need to saturate them with external, bulky, permanent magnets at millimeter-wave frequencies. Please consult factory for availablity of these non-standard materials.

General Design Considerations

From the standpoint of the microwave design engineer, ferrites fall into three classes based on the relationship of permeability, μ, and static field, H, relative to circularly polarized waves. In the low H region, circularly polarized waves are, by convention, positive and μ passes through an unsaturated zone centered around zero field. As H increases, μ decreases, but, finally, displays a rapid rise, commonly referred to as resonance or gyromagnetic resonance at H_r. Here, electromagnetic waves permeate the ferrite and their frequency is in step with electron spinning in the ferrite, giving rise to observed resonance. In actual applications, ferrite materials are used for operations (1) below H_r, (2) at or near H_r, or (3) above H_r.

1. Ferrites for operation below H_r

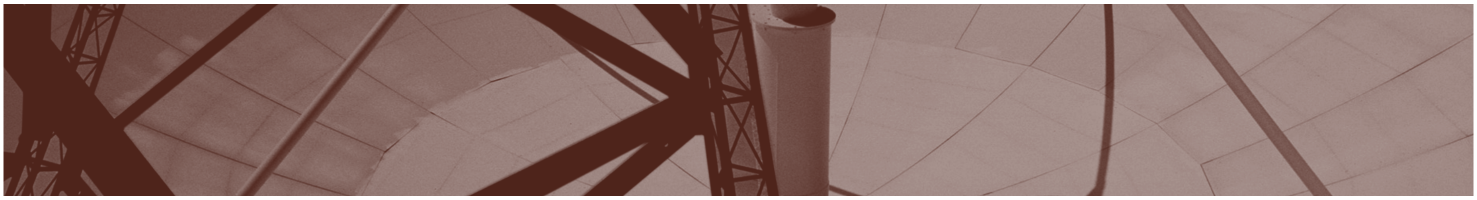
In the broadest sense, it may be correctly concluded that the temperature characteristics of the magnetic properties of a ferrite are always better when the Curie temperature, T_c, is higher. However, a higher T_c, can be obtained only at a higher $4\pi M_s$ which, in turn, increases the loss of the ferrite operating with low magnetic field. On the other hand, if the working microwave frequency is increased, low-field loss will diminish. Thus, higher T_c and higher $4\pi M_s$ ferrites become better candidates, especially for power applications. <u>A single material possessing all desirable properties for every frequency, bandwidth, power handling, etc. application, clearly is an impossibility</u>. For this reason alone, TRAK Ceramics, Inc. endeavers to meet the diversified requirements of designers by providing a wide variety of ferrite having a broad range of properties that can be selected. For example, NG-1000 could be used for 2 GHz circulators; however, if used in 1.7 GHz circulators, it would exhibit much greater loss than NG-900 despite the fact that both have very low and equivalent dielectric and magnetic losses.

2. Ferrites for operation at or near H_r

Invariably, ferrites operated in this range of static field are isolators. A material with $4\pi M_s$ best suited to the applied H and working frequency must be selected along with an optimal shape, pertinent to the field distribution. Since the bandwidth of an isolator is limited by the line width, ΔH, at resonance, TCI offers ferrite spinels that cover broad combinations of $4\pi M_s$, loss, T_c, and ΔH.

3. Ferrites for operation above H_r

Similar to ferrites used below H_r, materials operated in this range of H utilize the difference between the positive and negative μ tensor. However, they differ as low-field loss is not a factor since, for a given frequency, a difference in $4\pi M_s$ influences only the magnitude of H. Circuit elements of this type operate well even for very low working frequencies but care must be taken in selecting $4\pi M_s$. For example, in designing a conventional strip-line circulator, a $4\pi M_s$ that is too large will increase the demagnetization to such an extent that a very strong and unnecessary static field must be applied.



Intended Applications

Materials are designed to meet the demands of modern reciprocal (phase shifter), non reciprocal (isolators, circulators), and other applications that cover the frequency range, 100 MHz to 80 GHz. All performance requirements such as isolation, VSWR, midband frequency, bandwidth operating temperature, power handling, etc. are given high priority while addressing needs of optimal size, shape, and price.

Availability

Because of the numerous devices and design parameters to be considered, the selection of a microwave ferrite based strictly on given intrinsic and extrinsic properties is challenging. However, modern design capabilities can specify what properties are critical and optimal for a given device or circuit. A design also can be modified within constraints of target specifications to accommodate the performance capability of an existing material. Interactions between the designer and TRAK Ceramics, Inc. will hasten the required developments for the application and the material. While not intended to reflect lack of flexibility and ability to make improvements, some general selection guidelines are given below.

TRAK Ceramics, Inc. offers the world's broadest range of magnetic materials for the designer. TRAK Ceramics, Inc.controls its processes from raw materials through finishing to assure repeatability and a consistent, high quality product at minimal cost.

Family Type	Description	Recommended Operating Frequency (GHz)	Temperature Stability	Power Handling Capability	Magnetic Loss	Loop Squareness	Catalog Pages
YG	Yttrium Iron Garnet	2.0 - 12.0	F	P to F	F to E	E	8
AL	Aluminum Garnet	1.0 – 8.0	P to F	P to F	F	E	8
GD	Gadolinium Garnet	2.0 - 12.0	F	F	P	E	10
GA	Gadolinium Aluminum Garnet	1.0 - 8.0	F	F to E	P	F to E	10
NG	Narrow Line Width Garnet	2.0 - 12.0	P to F	P	E	F	12
HG	Holmium Garnet	2.0 -12.0	P to F	F to E	P	E	12
NF	Nickel Ferrite – Spinel	2.0 – 29.0	E	E	P	F	14
MF	Magnesium Ferrite – Spinel	2.0 – 29.0	P	P	F	F	14
LF	Lithium Ferrite – Spinel	4.0 – 40.0	E	P to F	F to E	E	16

Legend: P = Poor; F = Fair; E = Excellent

Part numbering guide

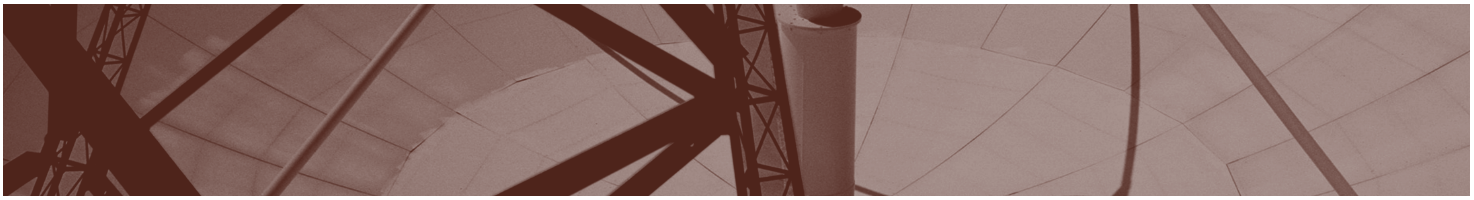
XX - XXXX - XXX

Line Width – Up to 3 places

Saturation Magnetization

Material Family

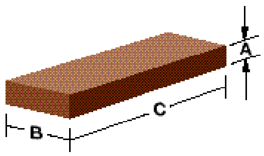
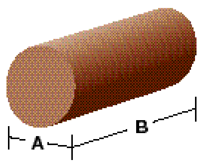
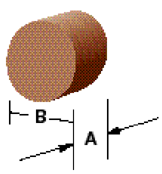
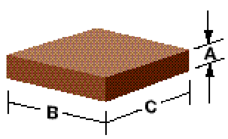
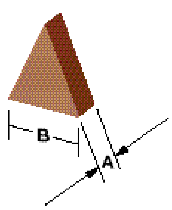
Example:
YG–1780–45 is Yttrium Iron Garnet, 1780 Gauss, 45 oe line width.



User Guide

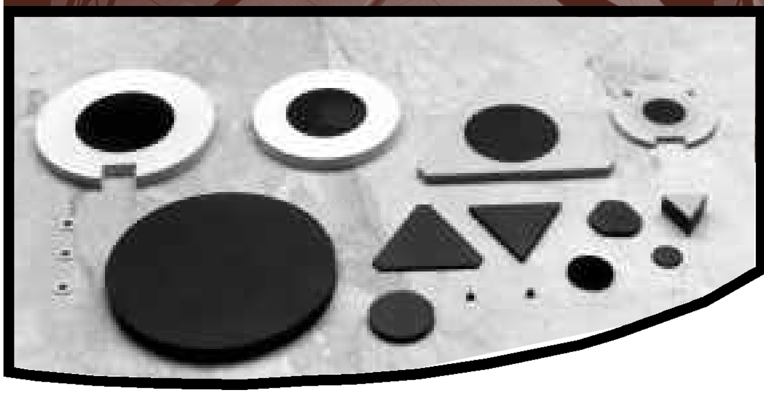
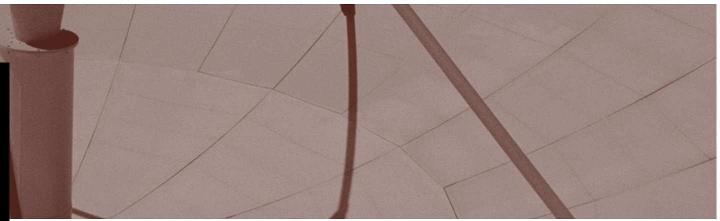
As fired materials are available in a variety of shapes and sizes as shown below. For further details please consult factory for availability.

Availability

		Minimum Size	Maximum Size
Bars		A = .25'' B = 1.00'' C = 6.00''	A = 2.00'' B = 2.00'' C = 6.00''
Rods		A = .25'' B = 6.00''	A = 2.00'' B = 6.00''
Disks		A = .05'' B = .50''	A = 2.00'' B = 4.00''
Substrates		A = .02'' B = 1.00'' C = 1.00''	A = 1.00'' B = 2.00'' C = 2.00''
Triangles		A = .05'' B = .50''	A = .15'' B = 4.00''

Machined Parts

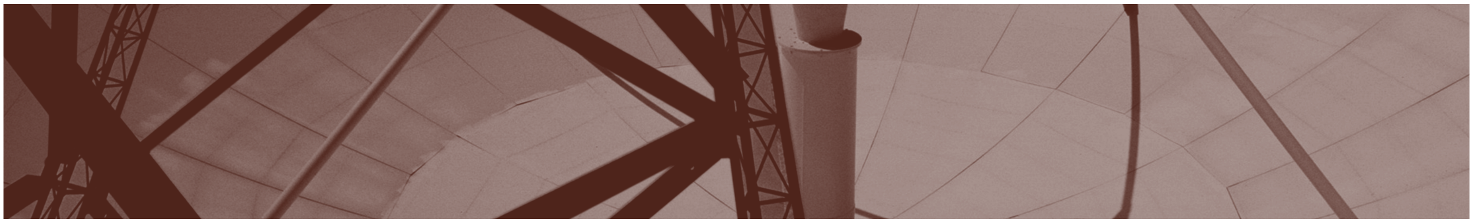
A wide variety of shapes and sizes can be machined to customer specifications. For further information please consult factory.

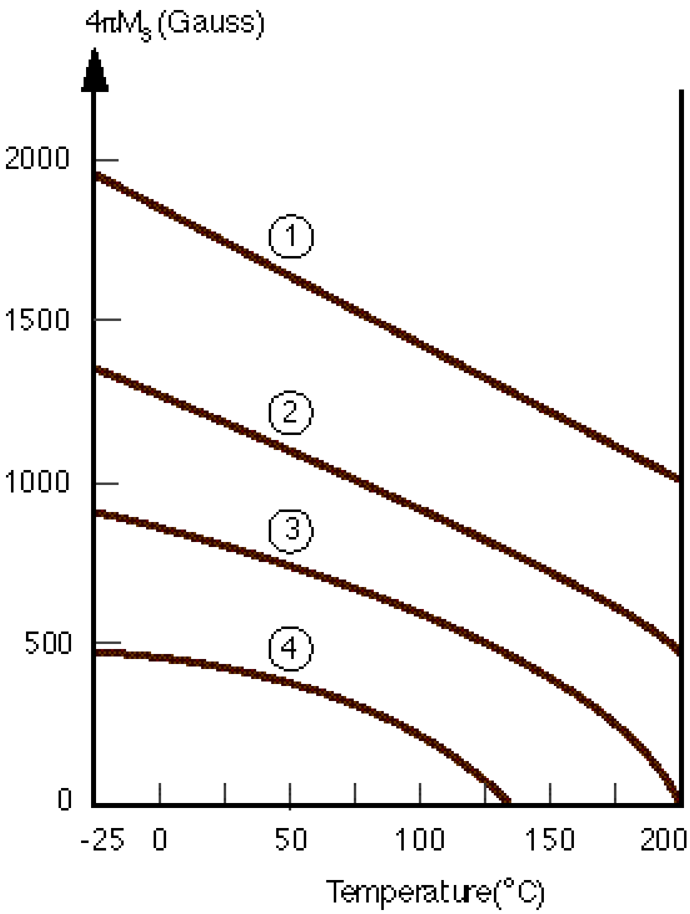
Low loss garnets are available with a broad selecti of saturation magnetization, covering a wide frequency range for most microwave applications. These materials are easily optimized to obtain reasonably low line widths, square hysteresis loop and good power handling performance.

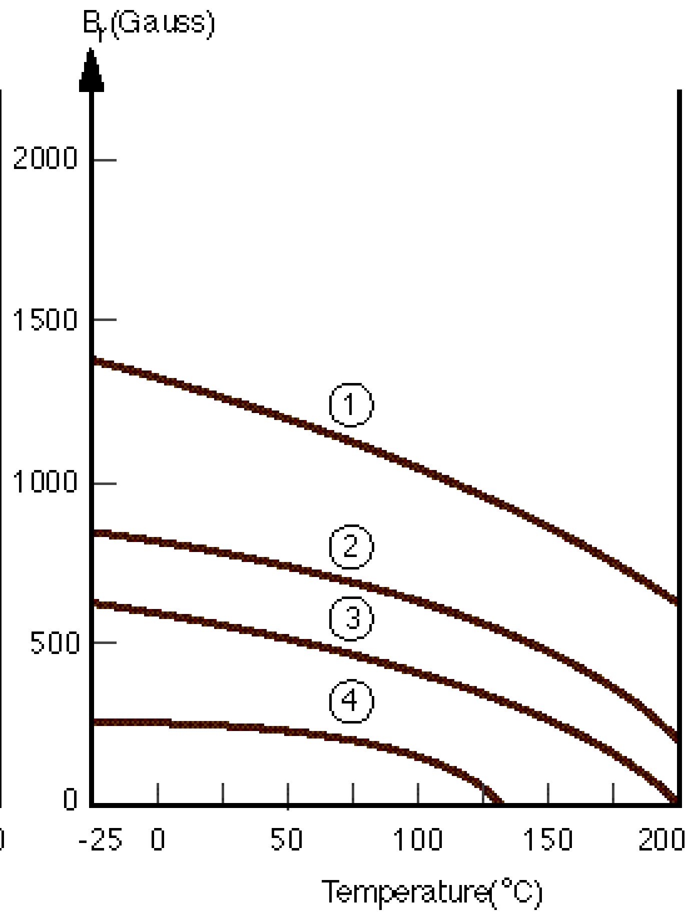
Family Type	Saturation Magnetization $4\pi M_s$ (Gauss)	Line Width ΔH (oe @ -3dB)	Dielectric Constant, ε'	Dielectric Loss Tangent Tan $\delta = \varepsilon''/\varepsilon'$ $\times 10^4$	Curie Temperature T_c,(°C), Nominal	Spin Wave Line Width ΔH_k (oe), Nominal	Remanent Induction B_r (Gauss), Nominal	Coercive Force H_c (oe) Nominal	α, $\Delta M_s/M_s\Delta T$ $\times 10^3$ Nominal	Comments (See page 36 for details)
GARNETS – Yttrium Iron Garnet										
YG – 1780 – 45			15.1	≤2	280	1.5	—	—	2.0	SG
YG – 1780 – 30			15.1	≤2	280	1.5	1275	0.5	2.0	NL
GARNETS – Aluminum Doped										
AL – 1510 – 45			14.9	≤2	255	1.5	—	—	2.3	SG
AL – 1510 – 35			14.9	≤2	255	1.5	—	—	2.3	NL
AL – 1400 – 45			14.8	≤2	245	1.5	—	—	2.3	SG
AL – 1380 – 45			14.9	≤2	240	5.0	—	—	2.1	NL, MPH
AL – 1210 – 45			14.8	≤2	230	1.5	780	0.7	2.4	SHL
AL – 1200 – 45			14.8	≤2	230	1.5	—	—	2.4	SG
AL – 1200 – 35			14.8	≤2	230	1.5	—	—	2.4	NL
AL – 1030 – 45			14.5	≤2	215	1.5	695	0.6	2.5	SHL
AL – 1000 – 45			14.5	≤2	210	1.5	—	—	2.5	SG
AL – 1000 – 35			14.5	≤2	210	1.5	—	—	2.5	NL
AL – 800 – 40			14.4	≤2	200	1.5	540	0.6	3.0	SG, SHL
AL – 650 – 40			14.4	≤2	175	1.5	435	0.6	3.3	SG, SHL
AL – 650 – 60			14.3	≤2	175	9.0	—	—	3.3	MPH
AL – 400 – 30			13.9	≤2	130	1.5	225	0.7	4.5	SG, SHL
AL – 210 – 25			13.7	≤2	100	1.5	120	0.6	5.0	SG, SHL

Notes:
[1] Intermediate $4\pi M_s$ members available.
[2] Landé factor, g_{-eff}, is ~ 2 for all garnets.
[3] Initial permeability (μ_o) of all garnets, except for narrow line width series NG, is in the range 10-135 depending on the $4\pi M_s$.
[4] All garnets can be specially processed to produce square hysteresis loops. Non-standard lot charges apply.
[5] All garnets can be custom formulated with cobalt doping to increase ΔH_k without increasing line width drastically.
Non-standard lot charges apply. Please consult factory for details.



Measurements and Tolerances

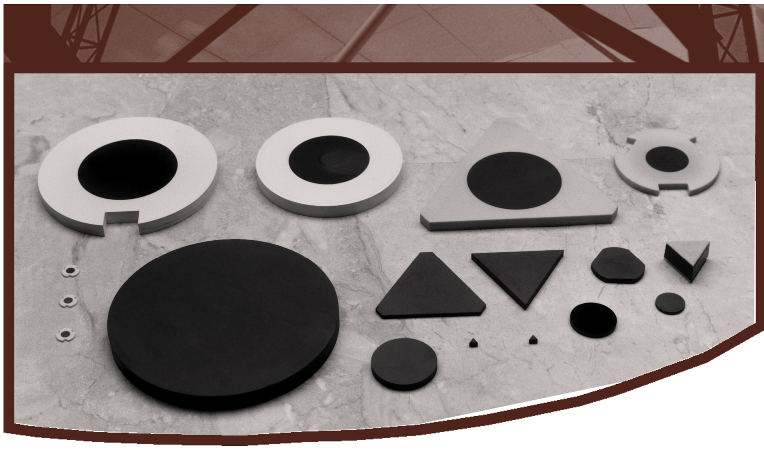




(1) YG-1780-30
(2) AL-1200-45
(3) AL-800-40
(4) AL-400-30

Saturation Magnetization, $4\pi M_s$ (Gauss)	± 5%
Line Width (ΔH oe @ -3 dB)	no greater than +20% of value given
Dielectric Constant, ε'	± 5%

Note:
[1] All data are nominal unless otherwise stated. Specifications subject to change without notice.



Low loss garnets are available featuring excellent temperature stability of saturation magnetization a modest to high power handling capability with minimal sacrifice of other intrinsic properties and square hysteresis loop characteristics. They are ea optimized to improve phase shifting performance (a wide frequency range.

Family Type	Saturation Magnetization $4\pi M_s$ (Gauss)	Line Width ΔH (oe @ -3dB)	Dielectric Constant, ε'	Dielectric Loss Tangent Tan δ = ε''/ε' x10⁴	Curie Temperature T_c,(°C), Nominal	Spin Wave Line Width ΔH_k (oe), Nominal	Remanent Induction B_r (Gauss), Nominal	Coercive Force H_c (oe) Nominal	α, $\Delta M_s/M_s\Delta T$ x10³ Nominal	Comments (See page 36 for details)
GARNETS – Gd doped Garnet										
GD	1600	45	15.1	≤2	280	4.0	—	—	2.0	SG
GD	1600	35	14.9	≤2	280	4.0	>1100	<1.0	2.0	SHL
GD	1300	75	15.0	≤2	280	6.0	—	—	1.3	SG, NL
GD	1200	75	15.2	≤2	280	7.0	—	—	1.0	SG, MPH
GD	1200	60	15.2	≤2	280	8.0	>800	<1.2	1.0	SHL, MPH
GD	1200	120	15.0	≤2	280	18.0	—	—	1.0	HPH
GD	1000	100	15.3	≤2	280	9.0	670	0.9	0.6	SG, MPH
GD	900	140	15.4	≤2	280	15.0	—	—	0.6	HPH
GD	725	200	15.4	≤2	280	10.0	365	1.5	0.9	SG, NL MPH
GARNETS – Gd, Al doped Garnet										
GA	1400	50	15.1	≤2	265	3.0	900	0.7	1.4	SG, SHL
GA	1300	30	15.1	≤2	225	7.0	—	—	2.5	SG, MPH
GA	1300	60	15.1	≤2	225	16.0	—	—	2.5	SG, HPH
GA	1200	50	15.1	≤2	250	3.0	790	0.8	2.5	SG, SHL
GA	1200	30	15.0	≤2	220	10.0	—	—	1.5	SG, MPH
GA	1150	30	15.1	≤2	230	7.0	—	—	1.7	SG, MPH
GA	1000	55	14.7	≤2	250	3.6	—	—	—	SG
GA	940	80	15.1	≤2	255	10.0	>650	<1.0	1.5	SG, SHL, MPH
GA	850	45	15.0	≤2	210	10.0	—	—	2.0	SG, MPH
GA	800	70	14.7	≤2	240	9.0	>500	0.5	1.0	SG, SHL, MPH
GA	650	45	14.8	≤2	180	13.0	—	—	2.0	SG, HPH
GA	600	60	14.5	≤2	200	14.0	—	—	—	SG
GA	550	55	14.5	≤2	175	8.0	>380	0.6	2.3	SG, SHL, MPH
GA	490	165	14.5	≤2	205	21.0	>310	0.7	1.2	SG, SHL, HPH
GA	450	40	14.5	≤2	140	13.0	—	—	2.5	SG, HPH
GA	400	90	14.5	≤2	160	13.0	—	—	2.5	SG, HPH

Notes:

[1] Intermediate $4\pi M_s$ members available.

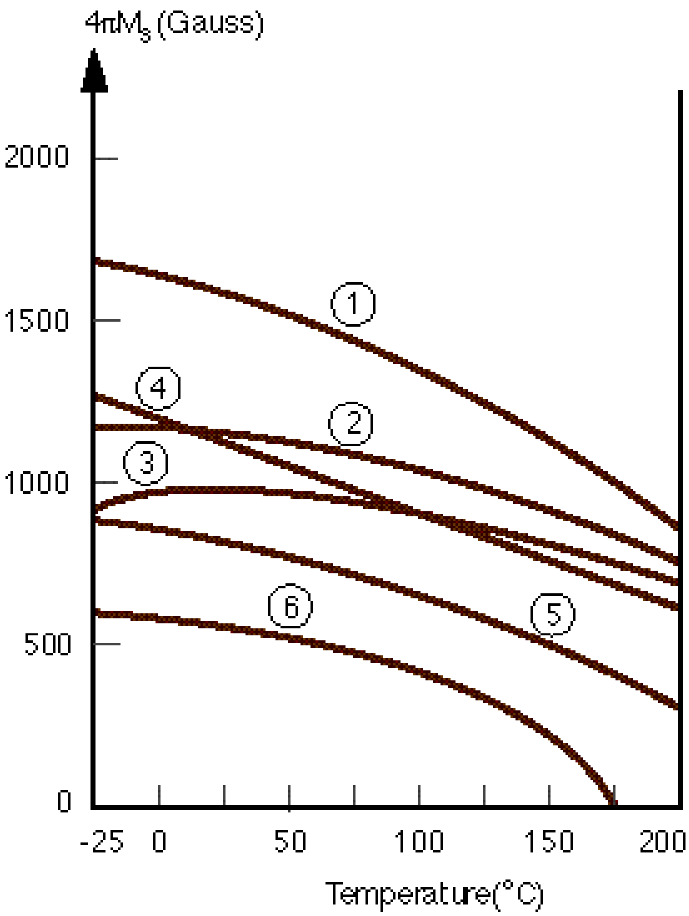
[2] Landé factor, g_{-eff}, is ~ 2 for all garnets.

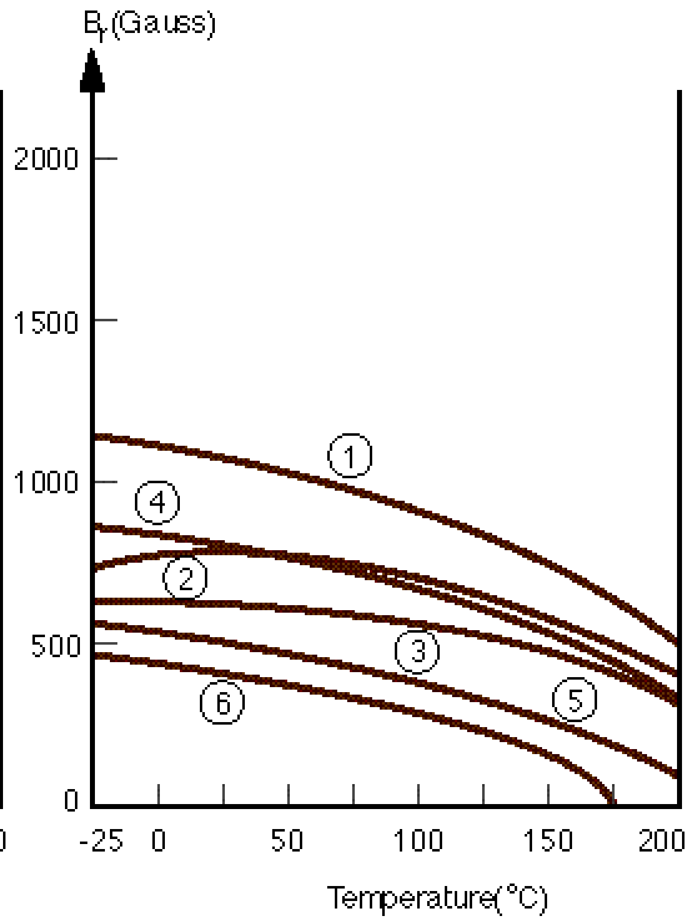
[3] Initial permeability (μ_o) of all garnets, except for narrow line width series NG, is in the range 10-135 depending on the $4\pi M_s$.

[4] All garnets can be specially processed to produce square hysteresis loops. Non-standard lot charges apply.

[5] Garnets may be custom formulated with cobalt doping to increase ΔH_k without increasing line width drastically. Non-standard lot charges apply. Please consult factory for details.

Measurements and Tolerances

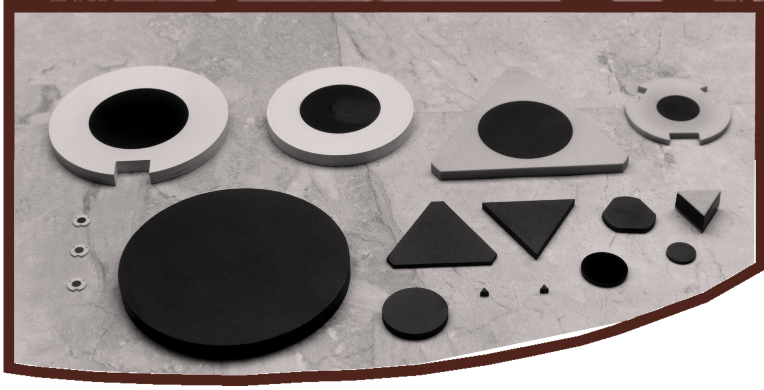




(1) GD-1600-35
(2) GD-1200-60
(3) GD-1000-100
(4) GA-1200-50
(5) GA-800-70
(6) GA-550-55

Saturation Magnetization, $4\pi M_s$ (Gauss) Line Width (ΔH oe @ -3 dB) Dielectric Constant, ε'	± 5% no greater than +20% of value given ± 5%

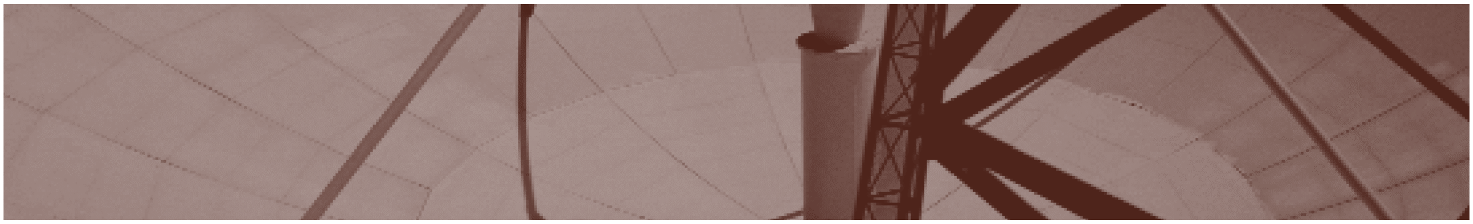
Note:
[1] All data are nominal unless otherwise stated. Specifications subject to change without notice.



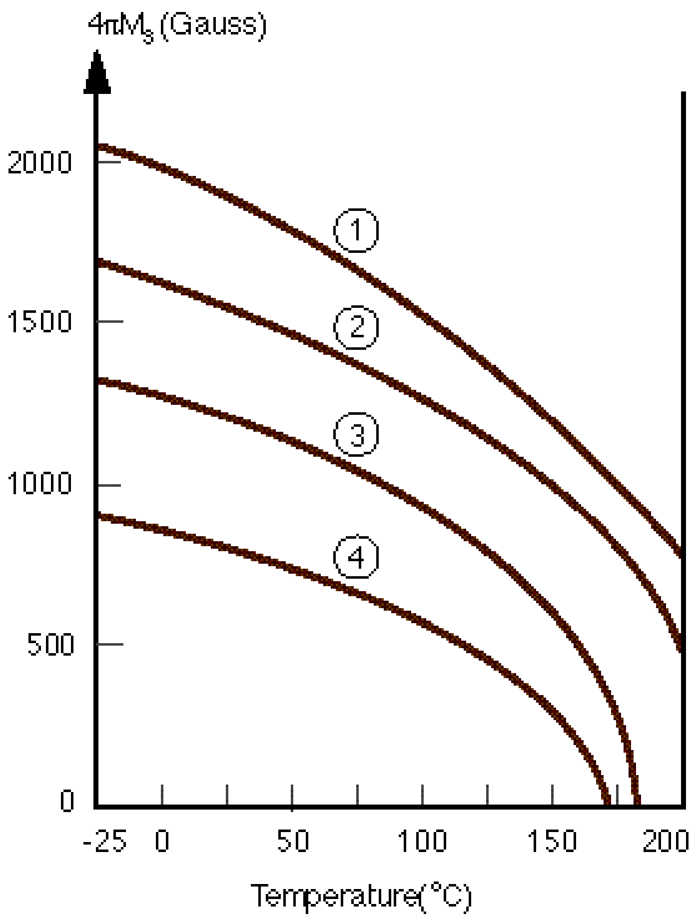
This garnet family offers outstanding narrow line widths with a broad selection of saturation magnetization for the most demanding low loss microwave devices.

Family Type	Saturation Magnetization $4\pi M_s$ (Gauss)	Line Width ΔH (oe @ -3dB)	Dielectric Constant, ε'	Dielectric Loss Tangent Tan $\delta = \varepsilon''/\varepsilon'$ x10^4	Curie Temperature T_c,(°C), Nominal	Spin Wave Line Width ΔH_k (oe), Nominal	Remanent Induction B_r (Gauss), Nominal	Coercive Force H_c (oe)	α, $\Delta M_s/M_s\Delta T$ x10^3 Nominal	Comments (See page 36 for details)
GARNETS – Narrow Line Width[1,2,3]										
NG – 1950 – 20			15.2	≤2	205	1.5	—	—	3.1	SG
NG – 1950 – 12			15.2	≤2	205	1.5	—	—	3.1	NL
NG – 1900 – 15			15.1	≤2	220	1.5	—	—	3.1	SG
NG – 1900 – 10			15.1	≤2	220	1.5	—	—	3.1	NL
NG – 1850 – 12			15.0	≤2	225	1.5	—	—	3.1	SG
NG – 1600 – 12			14.7	≤2	225	1.5	—	—	2.8	SG
NG – 1400 – 10			14.7	≤2	215	1.5	—	—	3.0	SG
NG – 1200 – 10			14.2	≤2	180	1.5	—	—	3.3	SG
NG – 1100 – 10			14.5	≤2	205	1.5	—	—	3.3	SG
NG – 1000 – 10			14.5	≤2	190	1.5	—	—	4.0	SG
NG – 900 – 10			14.2	≤2	180	1.5	—	—	4.0	SG
NG – 800 – 10			14.2	≤2	170	1.5	—	—	4.1	SG
NG – 520 – 10			13.3	≤2	120	1.5	—	—	5.5	SG
GARNETS – Holmium doped (Non-Standard, High Power Applications)[1,2,4]										
HG – 1600 – 90			15.2	≤2	280	6.0	980	0.8	1.5	SG
HG – 1200 – 120			15.1	≤2	265	8.0	715	1.0	1.0	SG
HG – 475 – 130			14.5	≤2	225	8.0	230	0.9	3.0	SG

Notes:
[1] Intermediate $4\pi M_s$ members available.
[2] Landé factor, g_{-eff}, is ~ 2 for all garnets.
[3] Initial permeability (μ_o) for the NG family is in the range of 130-400 depending on the $4\pi M_s$ value.
[4] Typical examples; dysprosium doped garnets also available.



Measurements and Tolerances



(1) NG-1900-15
(2) NG-1600-12
(3) NG-1200-10
(4) NG- 800-10

Saturation Magnetization, $4\pi M_s$ (Gauss)	± 5%
Line Width (ΔH oe @ -3 dB)	no greater than +20% of value given
Dielectric Constant, ε'	± 5%

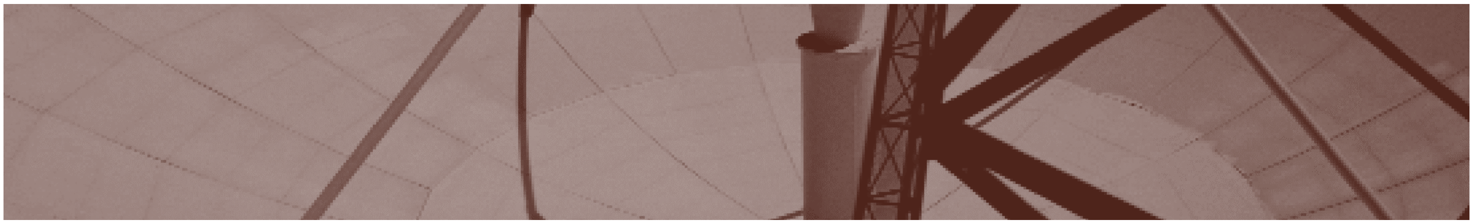
Note:
[1] All data are nominal unless otherwise stated. Specifications subject to change without notice.

The spinel family offers a broad range of intrinsic properties, including square hysteresis loops required for many devices from microwave to millimeter wave frequencies. Variants have excellent temperature stability of saturation magnetization plus modest to high power handling capability.

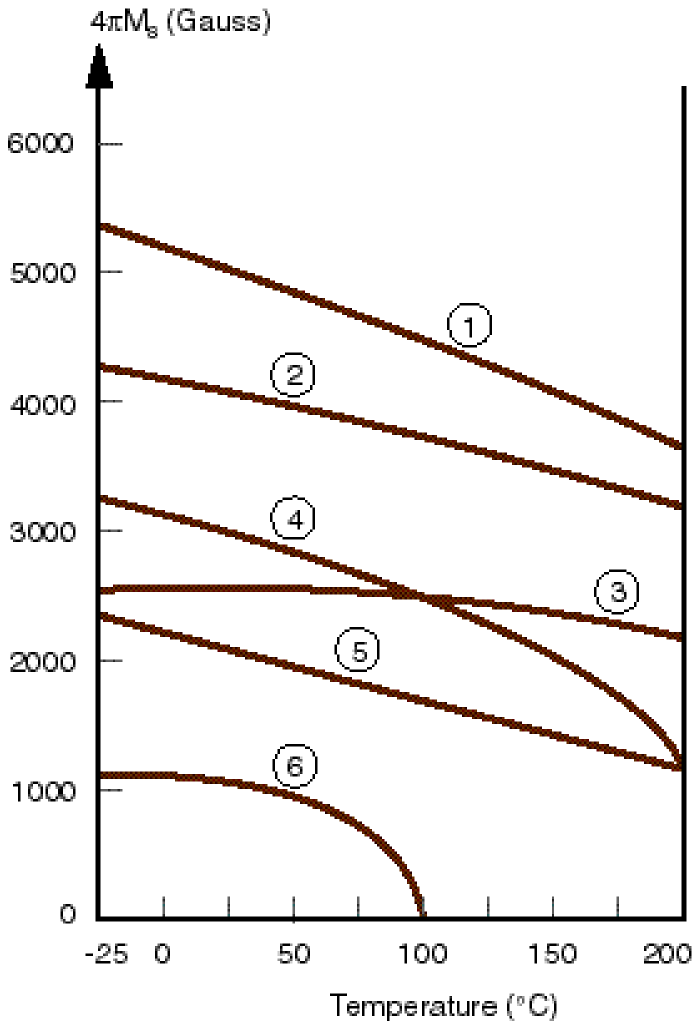
Family Type	Saturation Magnetization $4\pi M_s$ (Gauss)	Line Width ΔH (oe @ -3dB)	Dielectric Constant, ε'	Dielectric Loss Tangent Tan $\delta = \varepsilon''/\varepsilon'$ x10^4	Curie Temperature T_c,(°C), Nominal	Spin Wave Line Width ΔH_k (oe), Nominal	Remanent Induction B_r (Gauss), Nominal	Coercive Force H_c (oe) Nominal	α, $\Delta M_s/M_s \Delta T$ x10^3 Nominal	Comments (See page 36 for details)
SPINELS – Nickel Ferrites[1,2,3,4]										
NF – 5000 – 165			13.0	≤15	350	10	3500	1.5	1.8	SG, SHL, MPH, MM
NF – 4000 – 350			13.0	≤15	480	10	2400	1.9	1.0	SG, SHL, MPH
NF – 3000 – 300			13.0	≤15	560	>20	2000	3.0	0.9	SG, SHL, HPH
NF – 2500 – 500			13.0	≤15	530	>20	1100	3.5	0.7	SG, SHL, HPH
NF – 2100 – 480			13.0	≤10	500	10	—	—	1.2	SG
SPINELS – Magnesium Ferrites[5,6]										
MF – 3000 – 200			12.9	≤5	240	3	1950	0.9	3.0	SG, SHL
MF – 2650 – 180			13.0	≤3	250	3	1500	1.3	2.8	SG, SHL
MF – 2200 – 350			13.0	≤8	360	9	1300	2.0	2.0	SG
MF – 1450 – 130			12.0	≤4	140	4	—	—	2.0	SG
MF – 1000 – 120			11.6	≤3	100	3	600	0.6	4.5	SG, SHL

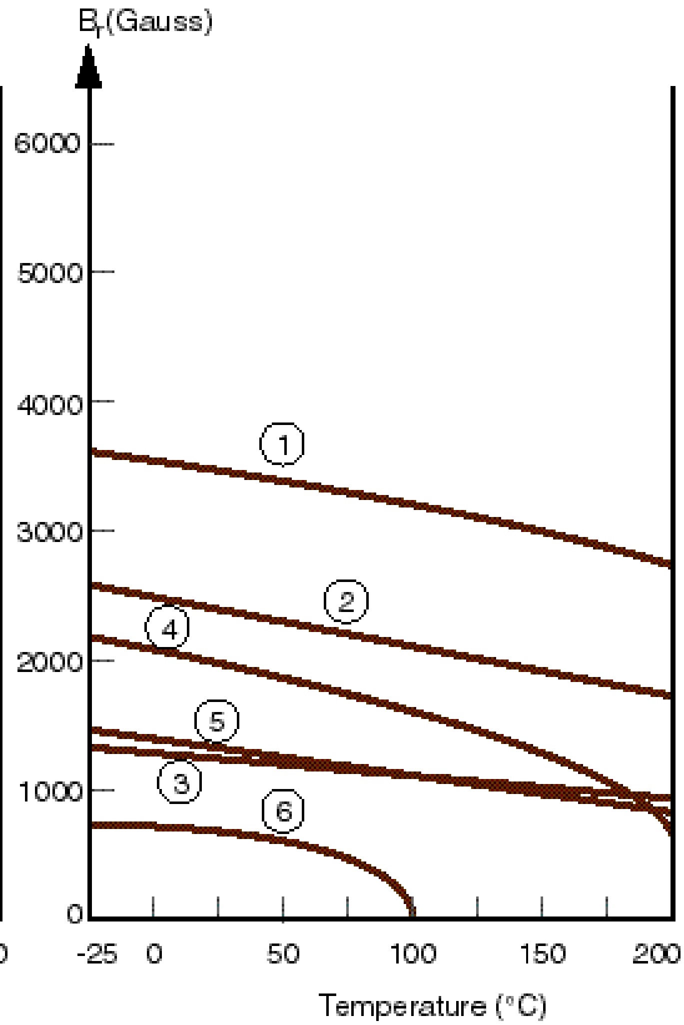
Notes:

[1] Intermediate $4\pi M_s$ members available.
[2] Average Landé factor, g_{-eff}, is ~ 2.35 for all nickel ferrites.
[3] Initial permeability (μ_o) is in the range of 4-100, except for NF-5000 which has >300.
[4] For some members, custom line widths well below 200 oe can be obtained by doping with cobalt. Non-standard lot charges apply. Please consult factory for details.
[5] Landé factor, g_{-eff}, is ~ 2.0 for all magnesium ferrites.
[6] Initial permeability (μ_o) is in the range of 25-150.



Measurements and Tolerances



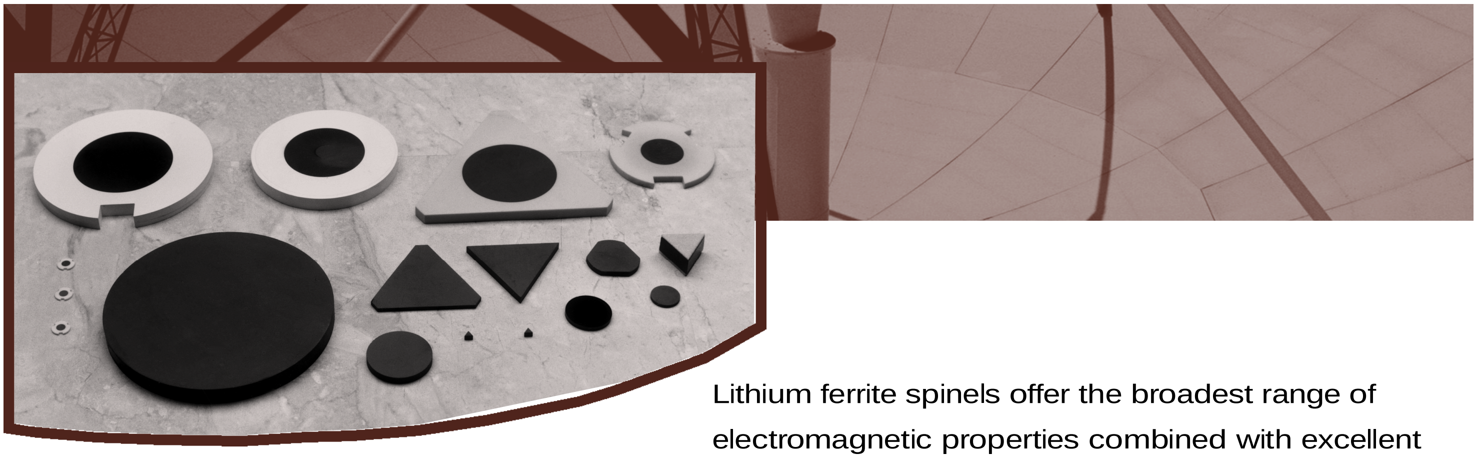


(1) NF-5000-165
(2) NF-4000-350
(3) NF-2500-500
(4) MF-3000-200
(5) MF-2200-350
(6) MF-1000-120

Saturation Magnetization, $4\pi M_s$ (Gauss)	± 10%
Line Width (ΔH oe @ -3 dB)	no greater than +20% of value given
Dielectric Constant, ε'	± 10%

Note:
[1] All data are nominal unless otherwise stated. Specifications subject to change without notice.

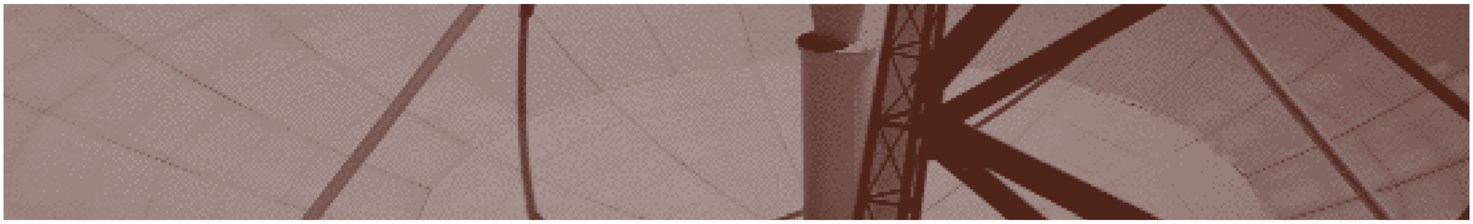
TRAK Ceramics, Inc. ■ 18450 Showalter Road, Box 112 ■ Hagerstown, Maryland 21742 ■ 301.766.0560 ■ Fax 301.766.0566



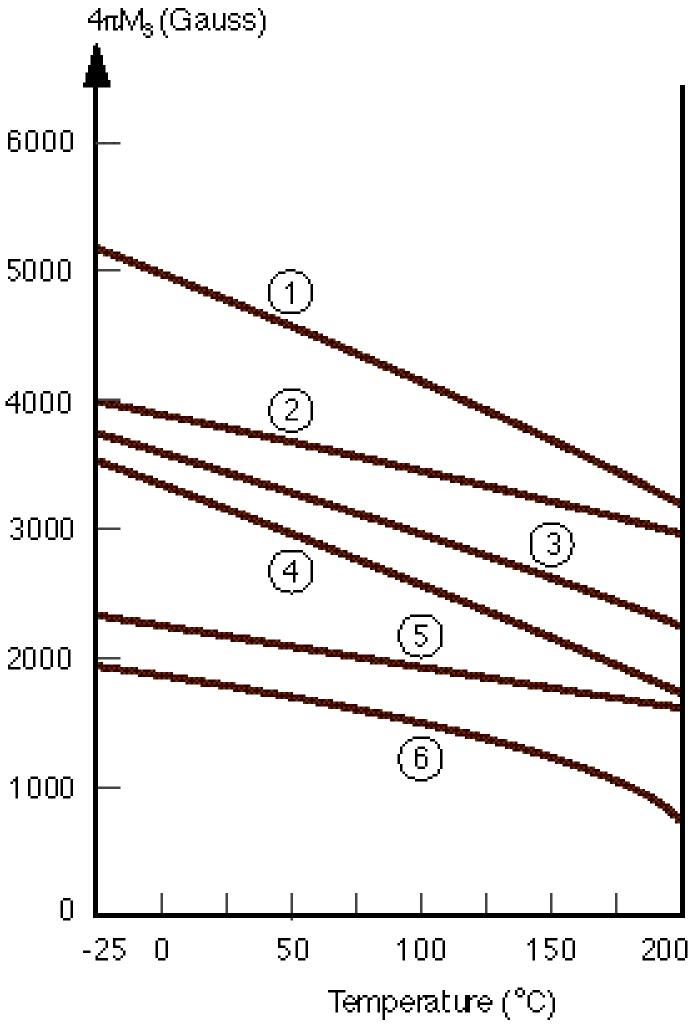
Lithium ferrite spinels offer the broadest range of electromagnetic properties combined with excellent temperature stability. They exhibit excellent performance near and above 9-10 GHz.

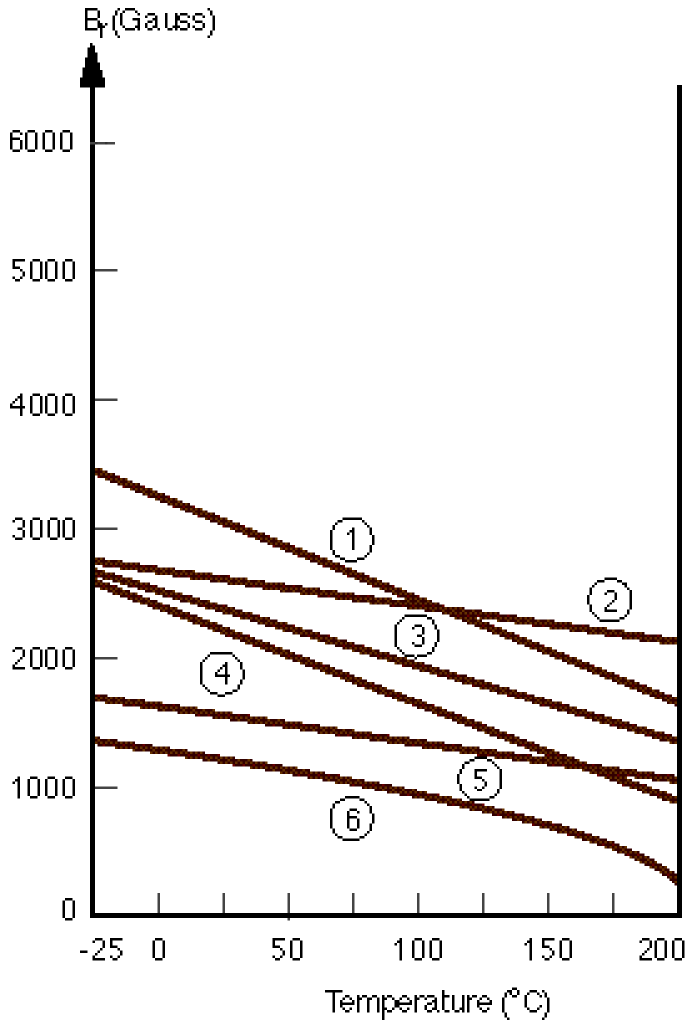
Family Type	Saturation Magnetization $4\pi M_s$ (Gauss)	Line Width ΔH (oe @ -3dB)	Dielectric Constant, ε'	Dielectric Loss Tangent Tan $\delta = \varepsilon''/\varepsilon'$ x10^4	Curie Temperature T_c,(°C), Nominal	Spin Wave Line Width ΔH_k (oe), Nominal	Remanent Induction B_r (Gauss), Nominal	Coercive Force H_c (oe) Nominal	α, $\Delta M_s/M_s\Delta T$ x10^3 Nominal	Comments (See page 36 for details)
SPINELS - Lithium Ferrites										
LF – 5000 – 200			15.0	≤10	450	2	>2800	0.7	1.6	SG, SHL, MM
LF – 4800 – 250			14.5	≤10	400	2	>3000	0.9	1.6	SG, SHL, MM
LF – 4100 – 550			14.6	≤10	570	2	—	—	1.1	SG
LF – 3750 – 650			15.0	≤10	630	2	>2600	2.4	1.0	SG, SHL
LF – 3700 – 400			16.0	≤10	560	2	>2500	2.0	1.0	SG, SHL
LF – 3400 – 600			15.0	≤10	570	2	>2400	2.4	1.0	SG, SHL
LF – 3400 – 350			15.5	≤10	470	2	>2500	1.1	0.9	SG, SHL
LF – 3200 – 150			16.1	≤10	325	2	>2200	0.6	0.8	SG, SHL
LF – 3000 – 450			16.4	≤10	550	2	>1950	1.2	0.8	SG, SHL
LF – 2500 – 250			16.8	≤10	390	2	—	—	0.9	SG
LF – 2200 – 450			16.5	≤10	520	2	>1500	1.3	1.2	SG, SHL
LF – 1700 – 400			16.1	≤10	460	2	>1150	1.2	1.2	SG, SHL
LF – 1700 – 150			17.0	≤10	240	2	>1150	1.2	1.2	SG, SHL
LF – 1300 – 150			17.5	≤10	210	2	—	—	1.2	SG
LF – 1200 – 350			16.5	≤10	390	2	>750	1.0	1.1	SG, SHL
LF – 1000 – 300			18.0	≤10	300	2	>675	1.0	1.2	SG, SHL
LF – 900 – 100			18.0	≤10	150	2	—	—	1.3	SG

Notes:
[1] Intermediate $4\pi M_s$ members available.
[2] Average Landé factor, g_{-eff}, is ~ 2 for all lithium ferrites.
[3] Custom line widths at fixed $4\pi M_s$ available.
[4] All lithium ferrites can be specially processed to produce custom square hysteresis loops. Non-standard lot charges apply.
[5] Initial permeability of lithium ferrites is typically >40.
[6] Power handling capability (larger ΔH_k) can be improved by appropriate doping.



Measurements and Tolerances

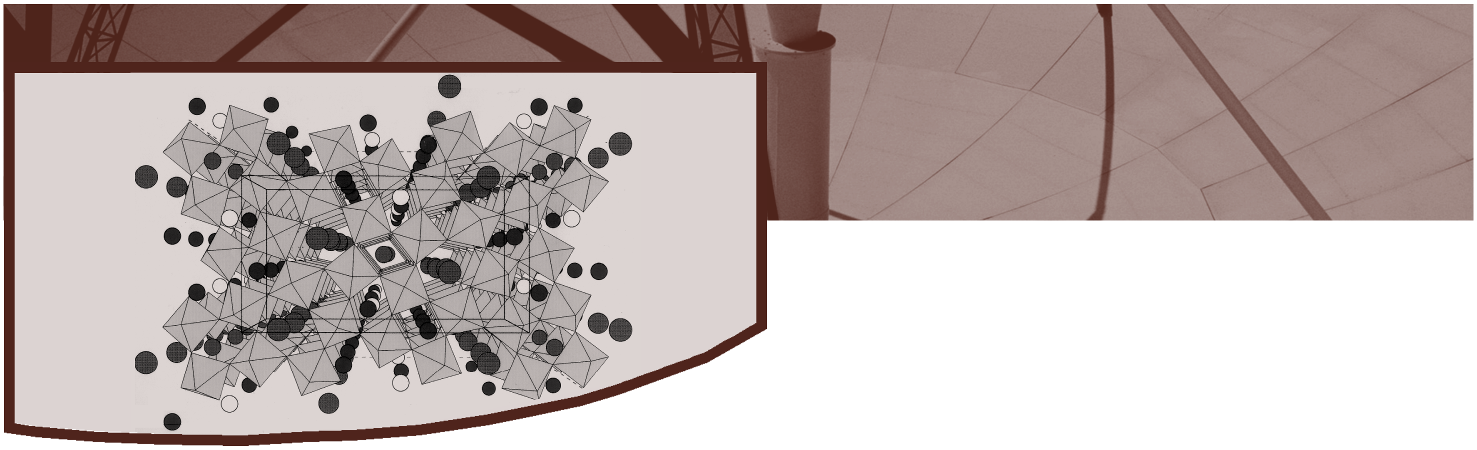




(1) LF-4800-250
(2) LF-3750-650
(3) LF-3400-600
(4) LF-3200-150
(5) LF-2200-450
(6) LF-1700-150

Saturation Magnetization, $4\pi M_s$ (Gauss)	± 5%
Line Width (ΔH oe @ -3 dB)	no greater than +20% of value given
Dielectric Constant, ε'	± 5%

Note:
[1] All data are nominal unless otherwise stated. Specifications subject to change without notice.



DIELECTRIC MATERIALS

Overview

TRAK Ceramics, Inc. produces a wide range of low loss dielectrics commonly used in conjunction with ferrite circulators, isolators, and phase shifters. Some are available as substrates for thin and thick film circuits or for high Q capacitor applications. Dielectric constants (ε') span from 4.5 to well above 100. Ceramics with low dielectric constants from 4.5 to 10 often are required as supports for our advanced dielectric resonators.

Thermal expansion and thermal conductivity for any given dielectric material cannot be varied significantly without altering the favorable electrical properties. The vast majority of all structural and electronic ceramics conduct heat very poorly. However, alumina (Al_2O_3, ε'= 9.5) is a modest conductor. Interestingly, it's temperature coefficient of ε' which is approximately +115 ppm/°C can be adjusted to near 0 ppm/°C. Magnesia (MgO, ε'=10) exhibits outstanding thermal conductivity combined with very high thermal expansion which matches more closely with that of metals. Thus, it is made available only as single crystal substrates to obtain enhanced performance.

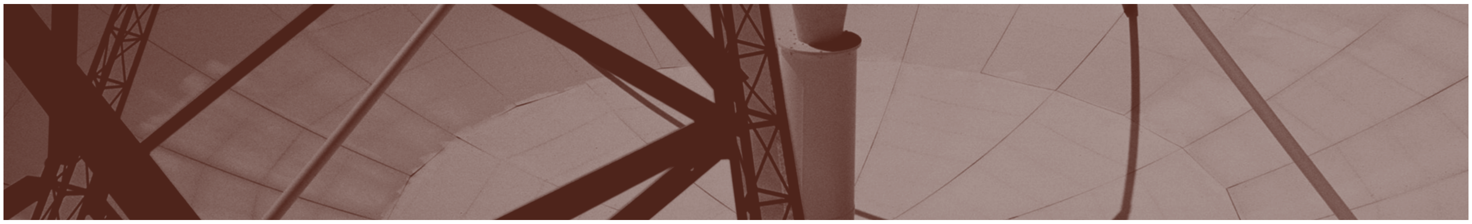
Dielectrics with ε' ranging from 4.5 to about 6 are typically based on magnesium aluminum silicate and magnesium silicate compounds, respectively. Dielectrics with ε' in the 13 to 16 range are based on the compounds Mg_2TiO_4 and $MgTiO_3$. Several routes can be followed to obtain low loss ceramics with ε'> 16. $CaTiO_3$ shows relatively modest loss but has a high ε' (150 - 160) and a very large, negative temperature coefficient of ε' (about -1600 ppm/°C). In turn, $CaTiO_3$ is chemically compatible with both Mg_2TiO_4 (ε'~13) and $MgTiO_3$ (ε'~16). Note that the magnesium titanates have moderately positive temperature coefficients of ε'. Thus, composite ceramics composed of Mg_2TiO_4 plus $CaTiO_3$ can cover ε' from 13 to about 150 at any desired value while composites of $MgTiO_3$ plus $CaTiO_3$ cover almost the same range, 16 to about 150. What has escaped both suppliers and users of such products over the years is that at some $CaTiO_3$ content in both series the temperature coefficient of ε' must traverse from positive through zero before becoming negative. For $MgTiO_3/CaTiO_3$ composite ceramics, this occurs at ε'~20-21. This particular temperature compensated ceramic is now standard for patch antennas and for coaxial resonator and filter applications.

Low loss ceramics covering ε' from about 37 to about 100 also can be produced from barium titanates. Typically, the low end of the series is the compound, $BaTi_4O_9$. Small increases in the TiO_2 content yield $BaTi_4O_9/Ba_2Ti_9O_{20}$ ceramic composites or pure $Ba_2Ti_9O_{20}$. However, the ε' remains in the 37-39 range and temperature coefficient of ε' remains very small but slightly negative. The region, ε'~39-100, is characterized by ceramics consisting of $Ba_2Ti_9O_{20}$ plus TiO_2. Both ε' and temperature coefficient of ε' rapidly rise in magnitude with increasing TiO_2 (ε'=100) content.

Temperature Compensated Dielectrics

This family of advanced dielectrics is characterized by high dielectric constants that are independent of useful frequency, high Q which is a function of frequency, and very low, but adjustable, temperature coefficients of resonant frequency, ε' and capacitance. High ε' permits miniaturization of substrates, antennas, resonant circuits, metal cavities, filters, and capacitors. Drift in frequency due to environmental fluctuations and/or to circuit heating is effectively eliminated by the small coefficients. High Q assures low insertion losses, especially for high power applications.

The cutting edge of science, technology, and manufacture of these remarkable ceramics has been advanced systematically by TCI engineers since the early 1970's. Theoretical considerations once suggested that



materials with small temperature coefficients and high Q simply were not possible if ε' was much greater than about 20. First, we pushed this frontier to ceramics with ε' in the 23–38 range and these have become industry targets and standards. More recent advances and improvements have demonstrated equivalent or better properties for ceramics in the ε'=42–46 range. Continued research with worldwide collaborations directed by TCI is focused on new generations of higher ε' ceramics without compromising Q.

Ceramics with ε' in the 36-46 range are based on $Ba_2Ti_9O_{20}$ or $ZrTiO_4$ parent compounds. Tuning of Q, temperature coefficients, and ε' is accomplished using substitutions of Sn^{4+}, Nb^{5+}, Zn^{2+}, Ta^{5+}, and Mg^{2+} combined with lower concentrations of manganese and/or cobalt.

High ε' ceramics in the 70–90 range, with modest Q, were developed for coaxial resonators, dielectric resonator filters, and substrate applications particularly for frequencies below about 2 GHz. More recently, increases in ε' to the 100-125 range have been proven without drastic reduction in Q. These ceramics consist of solid solutions within the complex series, $Ba_{6-3x}Ln_{8+2x}Ti_{18}O_{54}$, where Ln is La^{3+}, Nd^{3+}, Sm^{3+}, and/or Gd^{3+}. Substitutions of Sr^{2+} and Pb^{2+} for Ba^{2+} and of Bi^{3+} for Ln^{3+} are made to tune dielectric constants and temperature coefficients.

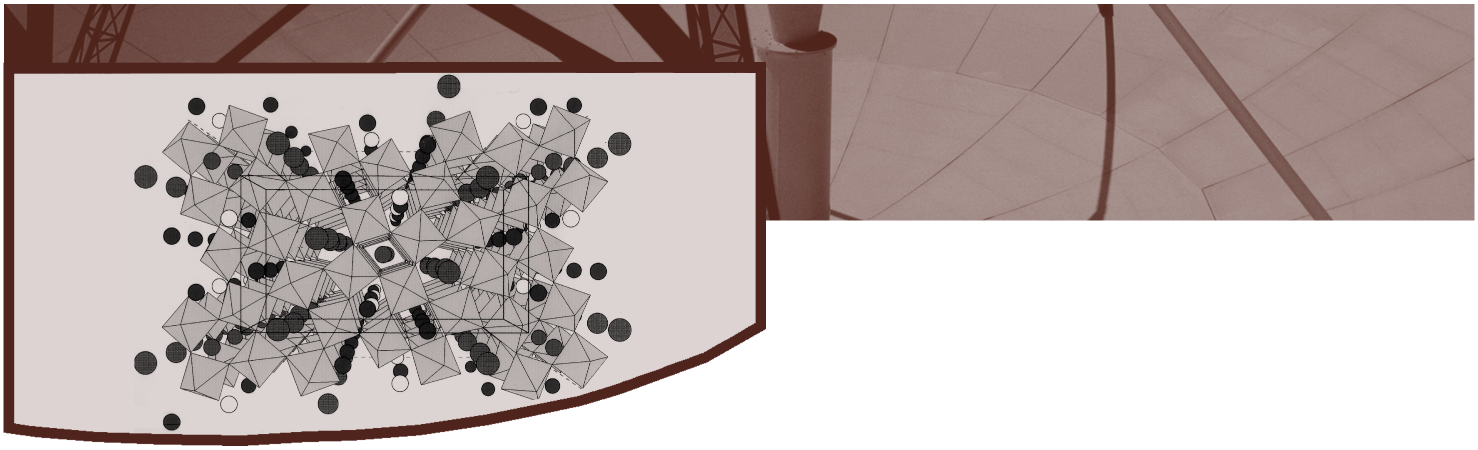
Super Q ceramics typically have ε' in the 21-30 range and, therefore, are useful for demanding Q applications above 1.5 GHz. These materials are based on solid solutions of parent compounds that include $Ba_3Ta_2MgO_9$, $Ba_3Ta_2ZnO_9$, $BaZrO_3$, and $BaCeO_3$. Cobalt, tungsten, manganese, nickel and lithium substitutions are used to tune Q and temperature coefficient.

Temperature compensated dielectrics with excellent Q but low ε'(10-21) are produced as three types of composites. The first (ε'=10) is based on alumina (Al_2O_3) and features modest thermal conductivity and small thermal expansion. The second is based on $MgAl_2O_4$ (ε'=10) which features ease of control over the temperature coefficient and ease of machining. The last is a $MgTiO_3$/$CaTiO_3$ composite (ε'=21) that allows for a size increase or decrease as needed for a given frequency.

The development of high ε' and high Q dielectrics with near zero ppm/°C temperature coefficient of ε', frequency, or capacitance has been driven largely by empirical studies and practical experience based on sound principles of solid state chemistry. While very rough approximations are available to predict ε' for any combination of cations and anions in a stable or postulated configuration at the atomic level, there has been minimal progress in predicting Q and especially temperature coefficients. To complicate matters, intrinsic Q of a crystalline material can be masked by impurities brought in from raw materials and/or from the processing. Typically, these degrade Q by forming lossy secondary phases and/or by creating lossy regions associated with pores and/or grain boundaries in the ceramic. TCI engineers, working with experts worldwide, have been demonstrating that high Q clearly depends on exactly how cations and anions are distributed within crystallites of a polycrystalline material over short and long distances measured in Angstroms (10^{-6}cm) at the atomic level. Principles have been developed, improved, and are being tested constantly to derive guidance for further advances and improvements in product.

Once high ε’ and Q are proven using theory, practical principles, and experiment, the next major hurdle is to tune the temperature coefficients via appropriate cation substitutions. Here, there is very little theoretical guidance despite recent, excellent work treating compounds having the so-called perovskite structure (e.g., $CaTiO_3$, $Ba_3Ta_2ZnO_9$, etc). Consequently, tuning is left to experience and experiment guided by the principles of crystal chemistry. Alternatively, temperature coefficients can be tuned by producing ceramic composites containing crystalline entities in correct proportion that have coefficients of opposite sign (without degrading ε' and Q). Finally, these demanding ceramics require levels of homogeneity that are not easily obtained via the conventional processing routes used by most suppliers. TCI uses proprietary mixing and gelling methods to manufacture reproducible product.

TCI engineers expect to work with designers to maximize and improve the properties of existing materials, as well as, to develop new materials for present and advanced applications. In addition, we welcome proprietary and confidential collaborations that require development of frequency tuning, attachment of supports, and thermal management design methodologies.



Introduction to Dielectric Resonators

Ceramic dielectric resonators have been used in place of metallic resonant cavities in RF and microwave circuits for several decades. Their widespread use, however, was delayed until the 1970's when the first low loss, temperature stable, high dielectric constant ceramic material was developed. Since then, many new and improved materials that exhibit a wide range of dielectric constant, extremely low loss, and excellent temperature stability have been developed. TRAK Ceramics, Inc. engineers are recognized pioneers in every major breakthrough in this material technology [1-6]. Typical applications for these new ceramic dielectric resonators include cellular telephones (PCS and GSM), satellite television receivers (TVRO and DBS), Global Positioning Systems (GPS), microwave oscillators, filters, speed guns, radar detectors, motion sensors, and transmitters.

Properties of Dielectric Resonators (DR's)

One significant advantage of using DR's is that the high dielectric constant (ε' or K) values of the ceramic afford size reduction of the circuit approximately equal to the square root of the ceramic's ε' value. Therefore, a resonant circuit using a dielectric material with a ε' of 36 can be ~6 times smaller than an equivalent circuit where an air filled resonant cavity is employed. A suitable first order working equation relating the dielectric resonator diameter (D_r) and resonant frequency (f_o) to the ceramic ε' is:

$$D_r = 12.873 / (f_o \times \varepsilon'^{1/2})$$

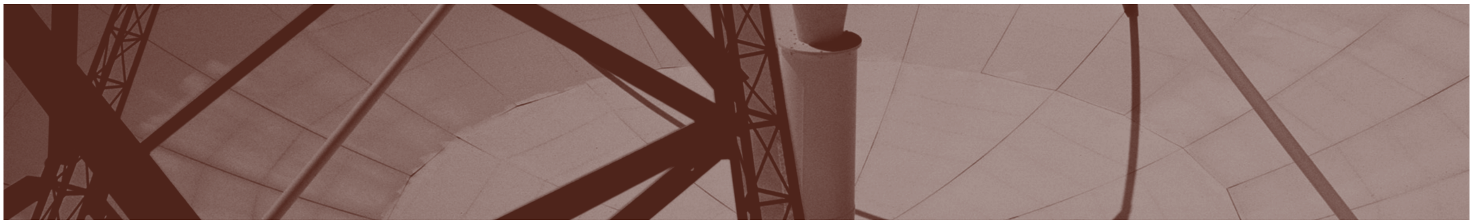
where D_r is the resonator diameter in inches, f_o is the frequency in GHz, and ε' is the material dielectric constant.

Additionally, the high ε' of the ceramic confines most of the electromagnetic fields within the resonator, which virtually eliminates radiation losses. This property combined with modern ceramic materials which exhibit very low intrinsic losses give the user an extremely high Q circuit element which reduces power drain and heat build-up while greatly improving insertion loss, filter selectivity, and interference from spurious modes. To further improve circuit Q, the metal resonator enclosure should be at least two times as large as the resonator itself.

Temperature stability is another significant advantage of ceramic dielectric resonators. The resonant frequency of a circuit will tend to shift over temperature as a result of environmental factors such as the size and linear thermal expansion coefficient of the metal DR enclosure, the position of the resonator within the enclosure, the type of resonator support, the temperature dependence of other circuit elements, etc. This shift in circuit resonant frequency can be greatly offset by the DR's intrinsic temperature coefficient of resonant frequency (τ_f). Each ceramic material type offers a wide range of DR temperature coefficient values expressed in parts-per-million per degree Celsius (ppm/°C). The circuit designer can select a specific DR temperature coefficient that will help compensate for the natural resonant frequency shift of the circuit, thereby, creating a circuit with excellent frequency stability.

Coupling and Modes of Operation

An infinite number resonant modes in four different categories TE, TM, EH and HE may be excited in an unmetallized cylindrical dielectric resonator. However, in the majority of applications, the $TE_{01\delta}$ resonant mode is employed, and we shall limit our discussion to this mode. Designing with hybrid modes is attractive but has been neglected to date.



Dielectric resonators may be magnetically coupled to circuits via a number of different methods. The coupling method of choice depends on several factors including the degree of coupling desired, the signal transmission medium employed (i.e. waveguide, coaxial cable, microstrip line), and the desired mode of operation. The $TE_{01\delta}$ resonant mode is most effectively coupled by the use of bent coaxial probes or microstrip lines as shown in Figure 1.

Figure 1 - Coupling Methods

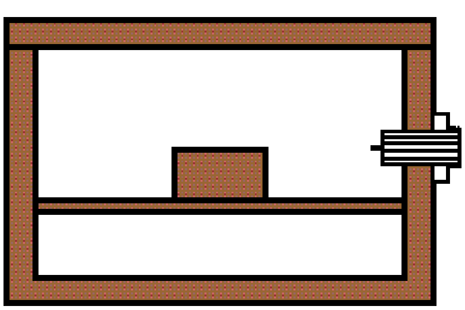
Loop Coupling   Microstrip Coupling

To prevent interference of the $TE_{01\delta}$ resonant mode by spurious modes, it is best if the DR's aspect ratio, or the ratio of DR thickness to DR diameter, is in the range of ~0.35 - 0.45.

Resonant Frequency

Of primary importance to the user is the resonant frequency (f_o) of the dielectric resonator. The f_o is dependent on the dielectric constant (ε') of the ceramic material, the physical size of the DR, and environmental effects such as the size and shape of the metal DR enclosure, the position of the DR within the enclosure, the type of DR support, and the method of coupling.

Figure 2 - Resonant Test Fixture



When measuring f_o, TRAK Ceramics, Inc. typically employs a cylindrical metal test fixture that is approximately 3-5 times larger than the DR to be tested (see Figure 2). A low loss, low ε' material is used to support the resonator in the center of the fixture. A bent coaxial probe is used for coupling.

When a test fixture such as the one described above is employed and the DR aspect ratio is ~ 0.35 - 0.45, the following equation may be used to estimate the $TE_{01\delta}$ resonant frequency of a given DR based upon its size and ε':

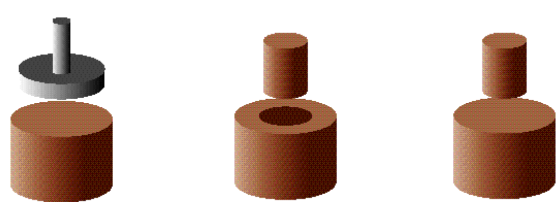
$$f_o = 8766 \; / \; ((\varepsilon'^{1/2}) \times (\pi/4)^{1/3} \times (D_r^2 T)^{1/3})$$

where f_o is the resonant frequency in MHz, D_r is the resonator diameter in inches, T is the resonator thickness in inches, and ε' is the dielectric constant of the resonator.

Resonant Frequency Tuning Methods

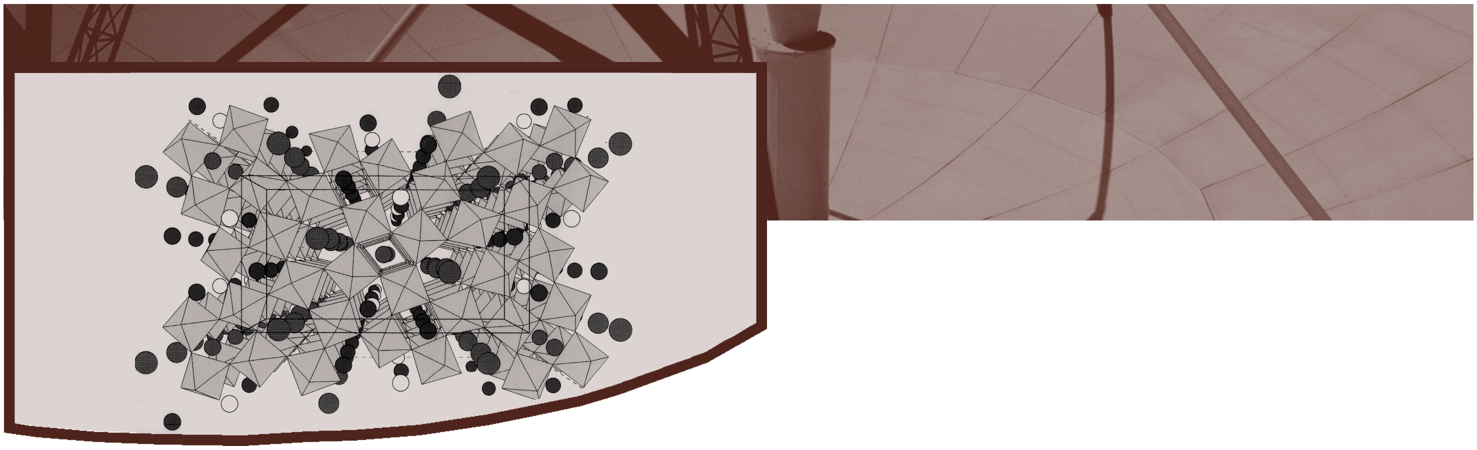
There are several techniques that can be used to "tune" or change the resonant frequency of a DR and these are illustrated in Figure 3. One popular method involves changing the physical position of a metallic or dielectric "tuner" within the DR enclosure which in turn causes perturbation of the fringe electromagnetic fields existing outside of the DR.

Figure 3 - Frequency Tuning Methods



Metal Tuner   Dielectric Tuner

TRAK Ceramics, Inc. ■ 18450 Showalter Road, Box 112 ■ Hagerstown, Maryland 21742 ■ 301.766.0560 ■ Fax 301.766.0566



If a metallic tuner is used, f_o will increase as the tuner approaches the DR; if a dielectric tuner is used, f_o will decrease as the tuner approaches the DR. A change in f_o of up to ~15% can be achieved using these methods. However, when using a metallic tuner, it is recommended that the tuning range be limited to only a few percent to avoid serious degradation of the Q-factor and/or temperature coefficient of the DR.

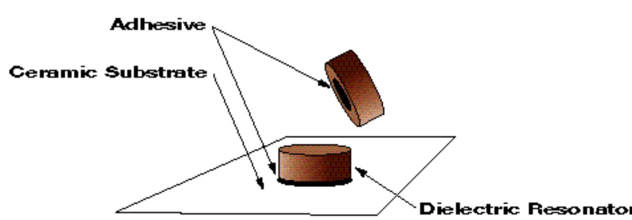
Another common method of frequency tuning DR's involves changing the physical size of the DR as previously discussed. Typically, the diameter (and inside diameter, if applicable) of the dielectric resonator is held constant within machining tolerances, and the thickness of the resonator is adjusted to compensate for small lot-to-lot and/or sample-to-sample f_o variations. Other machining methods, such as changing the DR's diameter or removing small quantities of ceramic from the resonator by scoring, drilling, slicing, or sanding, may also be employed. This method of tuning is often used when extremely tight f_o tolerances (±0.05% to 0.50%) are required. A virtually unlimited f_o tuning range may be achieved, and the Q-factor or temperature coefficient characteristics of the DR remain practically unchanged.

Frequency tuning without Q-factor or temperature coefficient degradation may also be accomplished on larger DR's by effectively increasing the overall size of the resonator by attaching small "tuning chips" or pieces of ceramic material to the DR with a low loss glue or epoxy. By varying the size of the added chip, one can incrementally vary the amount in which the f_o of the resonator is lowered. Additionally, f_o may be adjusted very slightly by varying the position of the tuning chip on the DR. Practical f_o tuning range is limited to minus 1 to 2%.

Mounting Considerations

When mounting a resonator to a ceramic substrate, dispense a small drop of low loss adhesive (i.e. thixotropic type adhesive – cyanoacrylic) to the center of the resonator. Each drop should be approximately .9mm in size for a .500'' diameter resonator. Take care not to apply excessive amount of adhesive, otherwise it may affect the performance. Larger resonators will need proportionally more adhesive for attachment. Place resonator lightly on substrate, align and then press firmly. Read adhesive manufacturers directions for further details.

Figure 4

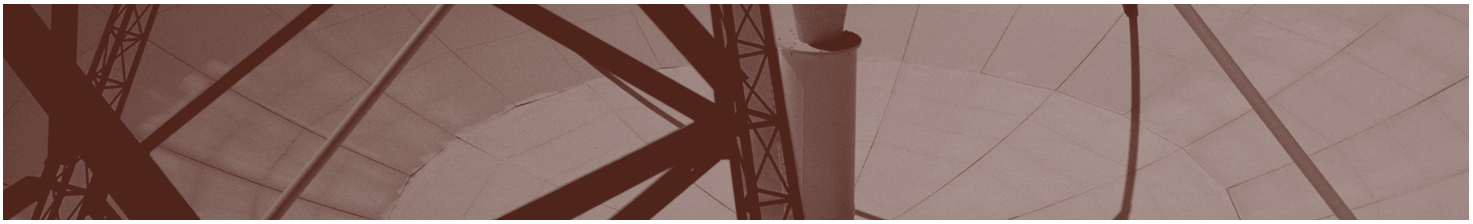


Product Selection

Choosing the correct TRAK Ceramics, Inc. product for your intended application is a multi-step process, which requires the user to consider many potential variables and product offerings. Our sales and engineering staff are available to assist in the selection process. If you have any questions, concerns or need additional help please contact our sales department for assistance.

1. Select the best TCI material type for your intended application. Refer to "Material Specification Summary", page 29. If you are not sure which temperature coefficient of resonant frequency (τ_f) value to select, we suggest starting with 0±2 ppm/°C.

2. If you already know the correct resonator size based on your previous experience, or you have a resonator which is close to your desired resonant frequency, one which you can provide as a correlation sample, proceed to step 5.



3. Using the equation for Dr given earlier, determine the approximate resonator thickness (T) by multiplying D_r by 0.4 (for example, for a desired frequency of 4.3 GHz using a material with a ε' of 36, the approximate diameter (D_r) would be .499'' and the approximate thickness (T) would be .200'').

4. Select the nearest standard material diameter from our list of standard sizes, in this case, .505”. Determine the difference in diameter between our standard material diameter size and the approximate resonator diameter (D_r) by subtracting D_r from the standard diameter (i.e. .505''-.499''=.006''). Now subtract this difference from the approximate resonator thickness T (i.e. .200''-.006''=.194''). This exercise gives you the proper resonator size to order for frequency correlation purposes. Contact TRAK Ceramics, Inc. and ask for a sample based upon these calculations.

5. Measure the resonant frequency (f_o) and temperature coefficient (τ_f) of the correlation sample in your circuit. Compare the measured frequency and τ_f to the desired or target values for your circuit. Contact TCI and notify us of the following information: the TCI lot number, the material type, the sample size, the measured frequency in your circuit, the desired or target frequency for your circuit, the measured τ_f in your circuit, and the desired or target τ_f in your circuit. Or, you may return the correlation sample to us with your frequency and τ_f information. Based on this correlation sample, we can usually provide a second iteration sample which resonates within 0.5% of your desired target frequency and which will meet your desired τ_f.

6. At TRAK Ceramics, Inc. we understand that the needs of each customer are unique, and we are committed to providing optimal solutions including custom products for the most demanding requirements. Please consult the factory for product selection if required.

References

[1] T. Negas, G. Yeager, S. Bell, and R. Amren, “Chemistry and Properties of Temperature Compensated Microwave Dielectrics”, NIST Special Publication 804, Chemistry of Electronic Ceramic Materials, Proceedings of the International Conference, pages 21-37 (1991).

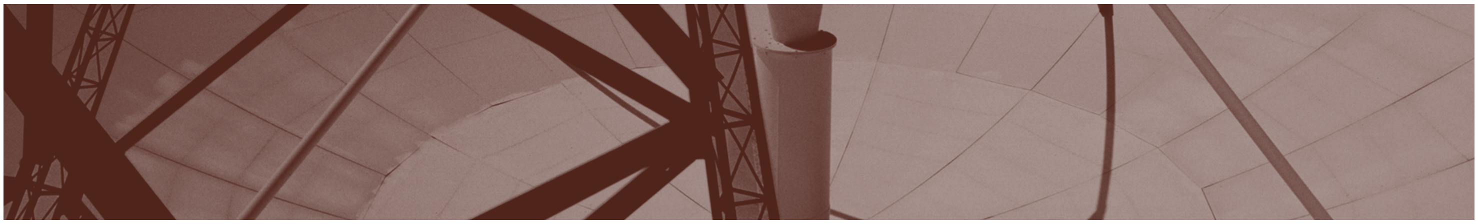
[2] T. Negas, G. Yeager, S. Bell, N.Coates and I. Minis, “$BaTi_4O_9/Ba_2Ti_9O_{20}$ – Based Ceramics Resurrected for Modern Microwave Applications”, American Ceramic Society Bulletin , vol. 72 (1), pages 80–89 (1993).

[3] R. Christoffersen, P. K. Davies, X. Wei and T. Negas, “Microstructure and Properties of Sn-doped $ZrTiO_4$ Microwave Ceramics”, Journal of the American Ceramic Society, vol. 77(6), pages 1441-1451 (1994).

[4] T. Negas and P. K. Davies, “Influence of Chemistry and Processing on the Electrical Properties of $Ba_{6-3x}Ln_{8+2x}Ti_{18}O_{54}$ Solid Solutions”, Ceramic Transactions, vol. 53, edited by T. Negas and H. Ling, pages 179-196 (1995).

[5] M. Valant, I. Arcom, D. Suvorov, A. Kodra, T. Negas and R. Frahm, “EXAFS Study of Incorporation of Bi and Pb Atoms into the Crystal Structure of $Ba_{4.5}Nd_9Ti_{18}O_{54}$”, Journal of Materials Research, vol. 12(3),pages 799-804 (1997).

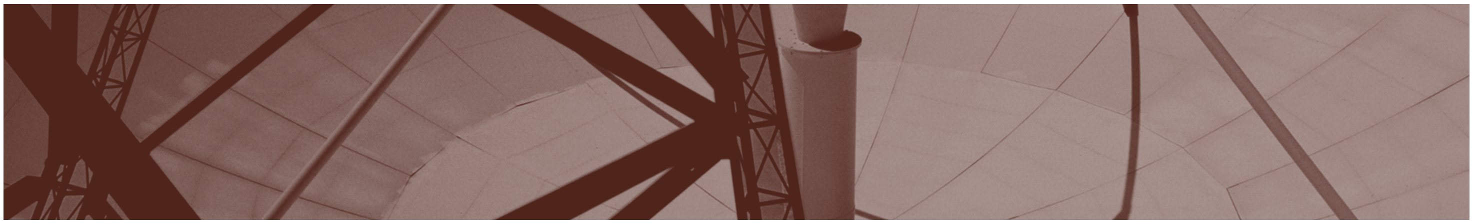
[6] P. K. Davies, J. Tong and T. Negas, “The Effect of Ordering Induced Domain Boundaries on Low Loss $Ba(Zn_{1/3}Ta_{2/3})O_3$-$BaZrO_3$ Perovskite Microwave Dielectrics”, in press, Journal of the American Ceramic Society(1997).



TRAK Ceramics, Inc. offers conventional RF/microwave dielectrics that cover a broad range in dielectric constant while maintaining low loss and high density. These materials were developed for use as matching media in microwave ferrite devices, but are suitable generally where a high dielectric constant, low loss material is required. They can be supplied in complex shapes and various sizes with precision dimensional tolerances.

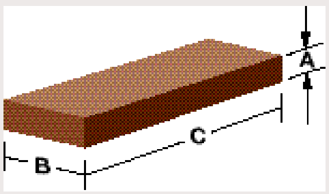
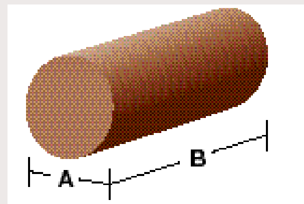
Family Type	Dielectric Constant ε'	Temperature Coefficient of Dielectric Constant (ppm/°C), Nominal	Dielectric Loss Tangent Tan $\delta = \varepsilon''/\varepsilon'$ x10^4	Thermal Expansion (ppm/°C), Nominal	Thermal Conductivity (cal/(sec)(cm)(°C))x10^3 Nominal	Comments
MS – 4	4.3	+ 55	≤ 2	2.4	7	Cordierite
MS – 6	6.3	+ 107	≤ 2	10.0	9	Forsterite
MA – 8	8.0	+ 100	≤ 2	7.0	33	Spinel
A – 9	9.5	+ 115	≤ 2	6.0	45	Alumina
MA-10	10.0	+ 100	≤ 2	7.5	25	
MA –12	12.0	+ 100	≤ 2	7.5	25	
MT – 13	13.0	+ 120	≤ 2	8.0	10	Spinel
MT – 16	16.0	+ 120	≤ 2	7.5	10	Ilmenite
MC – 18	18.0	+ 80	≤10	8.0	10	Composites
MC – 20	20.0	+ 10	≤10	8.5	10	
MC – 25	25.0	- 125	≤10	9.0	10	Composites
MC – 30	30.0	- 370	≤10	9.2	10	
BT – 37	37.0	- 25	≤ 5	9.4	10	Ba Polytitanate
BT – 50	50.0	- 250	≤ 5	8.0	10	Composites
MC – 50	50.0	- 700	≤10	9.7	10	Composites
MC – 70	70.0	- 950	≤10	10.0	10	Composites
TI – 100	100.0	- 600	≤10	7.5	10	Titania
MC – 100	100.0	-1100	≤15	10.3	10	Composites
MC – 125	125.0	-1150	≤15	10.5	10	Composites
MC – 140	140.0	-1200	≤15	10.7	10	Composites
ST – 250	250.0	-2600	≤50	10.0	10	Strontium Titanate

Notes:
[1] Some members are available with larger and intermediate dielectric constants. Please consult the factory for details.
[2] All dielectrics are > 95% of theoretical density and, therefore, absorption of moisture is nil.
[3] Other materials available upon request. Please consult factory for details.
[4] Dielectric constant tolerance ± 5%.
[5] Dielectric loss is quoted at 6 GHz for material with dielectric constant >20.
[6] Dielectric loss is quoted at 10 GHz for material with dielectric constant ≤20.



As Fired Material Availability

TRAK Ceramics, Inc. can manufacture a wide variety of shapes and sizes as fired.

	Bar			Rod	
					
Dimension	A	B	C	A	B
Min.	.25''	1.00''	6.00''	.25''	6.00''
Max.	1.00''	2.00''	6.00''	3.00''	6.00''

Units (inches)

Note:
[1] Custom shapes and sizes available upon request. Consult factory for details

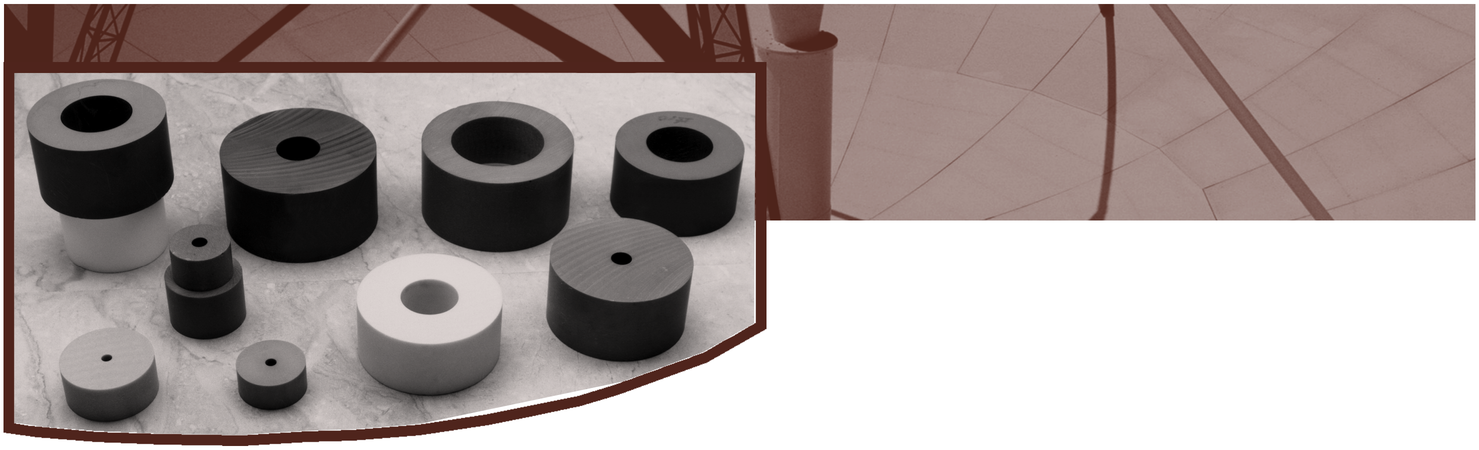
Machined Parts

TRAK Ceramics, Inc. maintains a precision diamond grinding facility in Maryland to custom shape and size materials to customer specifications. Our expertise in producing low loss dielectric materials with tightly controlled electrical properties combined with precision machining is well suited to low cost, high volume commercial applications. A variety of shapes and sizes are offered including disks, cylinders, triangles, substrates, bars, rods and others. Please consult the factory for details or send specification to TRAK Ceramics, Inc.

In addition, contract thick film metallization and assembly is available upon request.

Other Applications

- Patch Antennas for Automotive and GPS
- Dielectric Rod Antennas
- Ceramic Transformers
- Ceramic Supports
- Sleeves for Ferrites
- Waveguide Filters
- Phase Shifters and Tuning Elements
- Sputtering Targets



DIELECTRIC RESONATORS

General Overview

TRAK Ceramics, Inc. offers a broad range of high dielectric constant resonator materials that are temperature compensated with high Q. Dielectric resonators are used in microwave oscillator and filter applications where miniaturization, temperature stability and low loss are required.

Typical Applications

- Cellular Base Station Filters and Combiners
- PCS/PCN Base Station Filters and Combiners
- Direct Broadcast Satellite LNB
- TV Receive Only Satellite LNB
- Radar Detectors
- LMDS / MMDS Wireless Cable TV

Part numbering guide

DRXXX - XXX - X - X

Frequency Tuned=F; Mechanical=M

τ_f Tolerance 1= ±1 ppm/°C, 2= ±2 ppm/°C

τ_f PXX=Positive, NXX=Negative; where XX=one or two digit τ_f

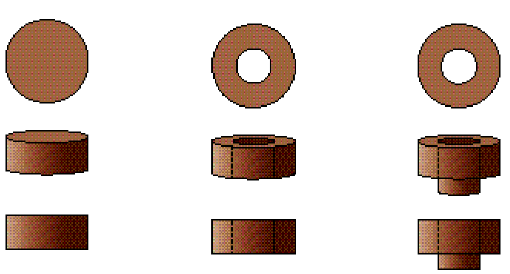
Material Family

Example: DR36-P9-2F

Material Family DR36; τ_f = +9; τ_f Tolerance = ± 2ppm/°C; Frequency Tuned
List product dimensions as description under part numbers.

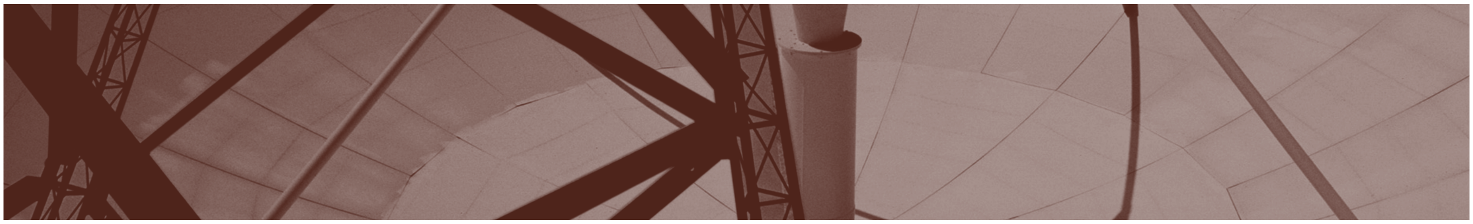
Note: TRAK Ceramics, Inc. can work with you to determine the correct frequency in your device, or the part may be ordered to mechanical dimensions-tolerances.

Standard Cofiguration - Disks/Cylinders/Assemblies



Disks Cylinders Assembly

Note:
[1] Assemblies are non-standard.



Standard Diameters Availability - Disks/Cylinders/Assemblies

Disks/Cylinders/Assemblies Standard Outside Diameter						
2.475	1.400	.840	.505	.305	.190	.120
2.275	1.300	.785	.470	.285	.180	.112
2.100	1.210	.730	.435	.265	.170	.104
1.940	1.125	.675	.405	.245	.160	.096
1.790	1.045	.630	.375	.230	.150	.089
1.650	.975	.585	.350	.215	.140	.082
1.520	.905	.545	.325	.200	.130	.076

Units (inches)

Cylinders/Assemblies Outside Diameter	Std. I.D.
.785 < 1.400	.162
.585 < .784	.122
.245 < .585	.083

Units (inches)

Note:
[1] When determining the dielectric resonator size, use the nearest standard diameter and adjust the thickness for frequency. Calculate resonator dimensions as discussed under the section “Product Selection” on page 22.

Dielectric Supports - Material Characteristics

Material Type..MS–4

Composition...Cordierite

Dielectric Constant (ε')..4.3 ± 5%

Dielectric Loss (tanδ) .... ≤ 0.0002

Temperature Coefficient of Resonant
Frequency (τ_f) (ppm/°C, 25° to 60°C)....................................+55

Volume Resistivity (ohm - cm) @ 20°C ....10^{14}

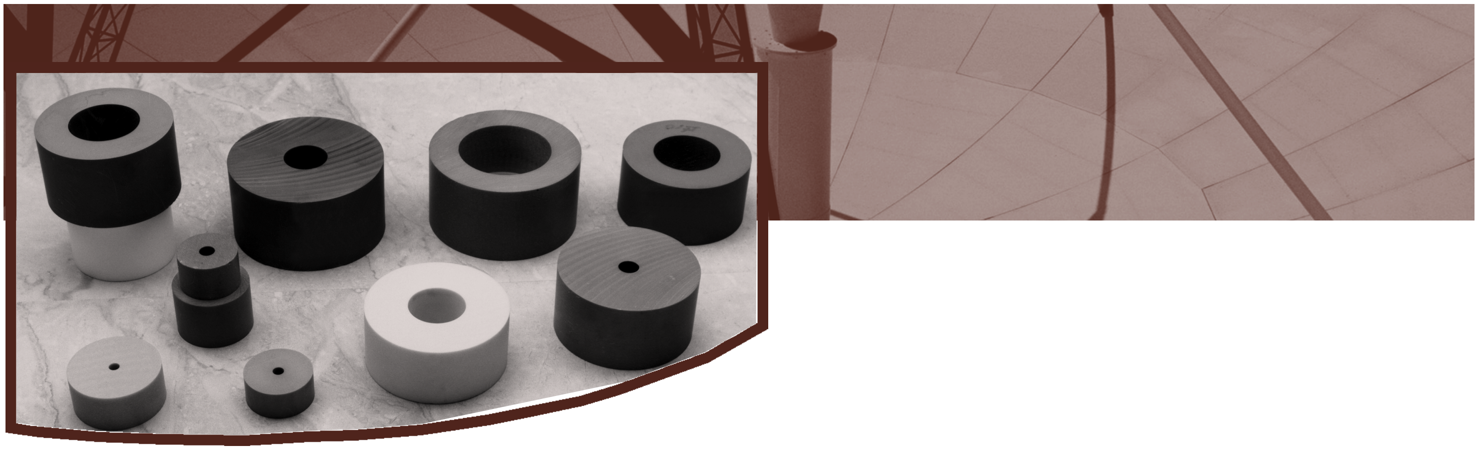
Thermal Expansion (ppm/°C)..2.4

Thermal Conductivity (cal/(sec)(cm)(°C)) x 10^{3}.........................7.0

Dielectric Supports - Available Configurations

Dielectric supports can be used with both cylinders or assembly type resonators to improve coupling and temperature stability while reducing phase noise and cavity losses. Supports can be supplied in either disk or cylinder form. Please consult the factory for details. Support material specifications are shown above. Consult factory for alternative support materials and sizes.

Note:
[1] Length of support available in two sizes per diameter range.



Materials Overview

Features

- High ε'
- High Q
- Temperature Compensated
- Excellent Frequency Stability

Benefits

- Reduced Size
- Reduced Weight
- Low Loss
- Close Channel Spacing

DR30 This product offers the user the ultimate in a high Q resonator along with a very linear temperature coefficient. It is an excellent choice for the most demanding circuit requirements, especially in high frequency applications.

- Extremely high Q (> 10,000 @ 10 GHz)
- Very linear τ_f
- Excellent high frequency performance
- Typical uses include satellite communications, military ECM, high frequency filters and DRO's

DR36 This product offers excellent overall performance at a very affordable price for all applications from 800 MHz to 20 GHz. Q is extremely high in the cellular & PCS frequency bands (800MHz-2.0GHz) and the temperature coefficient linearity is excellent over a wide temperature range.

- High ε' (36) for circuit miniaturization
- Excellent τ_f linearity
- Very high Q (> 35,000 @ 850 MHz; > 10,000 @ 4 GHz)
- Typical applications include GSM, PCS, TVRO, DBS, DRO's, microwave filters

DR45 This material offers a higher dielectric constant for further circuit miniaturization while maintaining an excellent Q value, making it ideal as an alternative to DR36 for cellular and PCS applications when small size is important. It performs well over a wide frequency range.

- Very high ε' (45) for greater circuit miniaturization
- Very high Q (> 35,000 @ 850 MHz; > 10,000 @ 4 GHz)
- Typical applications include GSM, PCS, TVRO, DBS, DRO's, microwave filters
- Wide range of τ_f available

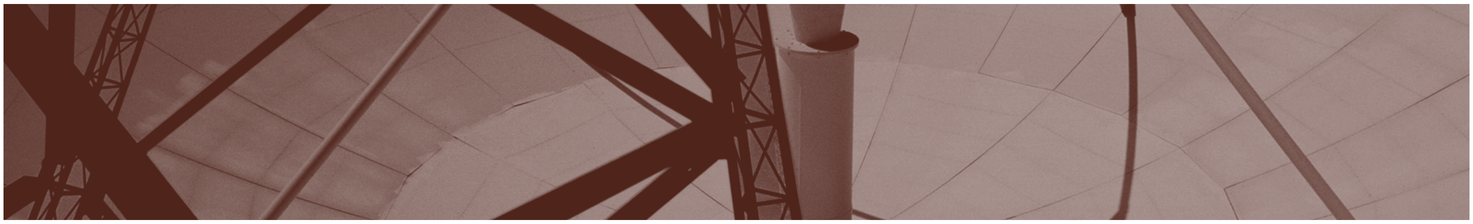
DR80 Our highest dielectric constant standard resonator material offers the benefit of greatly enhanced circuit miniaturization while maintaining a good Q. Available in a wide range of temperature coefficients and sizes.

- Extremely high ε' (80) for a very high degree of circuit miniaturization
- Wide range of τ_f available
- High Q (>3000 @ 3 GHz)
- Typical applications include filters, duplexers, TVRO, and cellular radio

Non Standard, Available Upon Request

DR38 This material is made available for applications requiring a direct replacement for products with a dielectric constant of 38 and positive τ_f values. Except for members in the τ_f = 6-8 ppm/°C range, these materials are not as linear as the τ_f for DR36.

- Broad range of positive τ_f, +4 to +14
- High Q (> 10,000 @ 4 GHz)
- Typical applications include DBS, DRO's and microwave filters



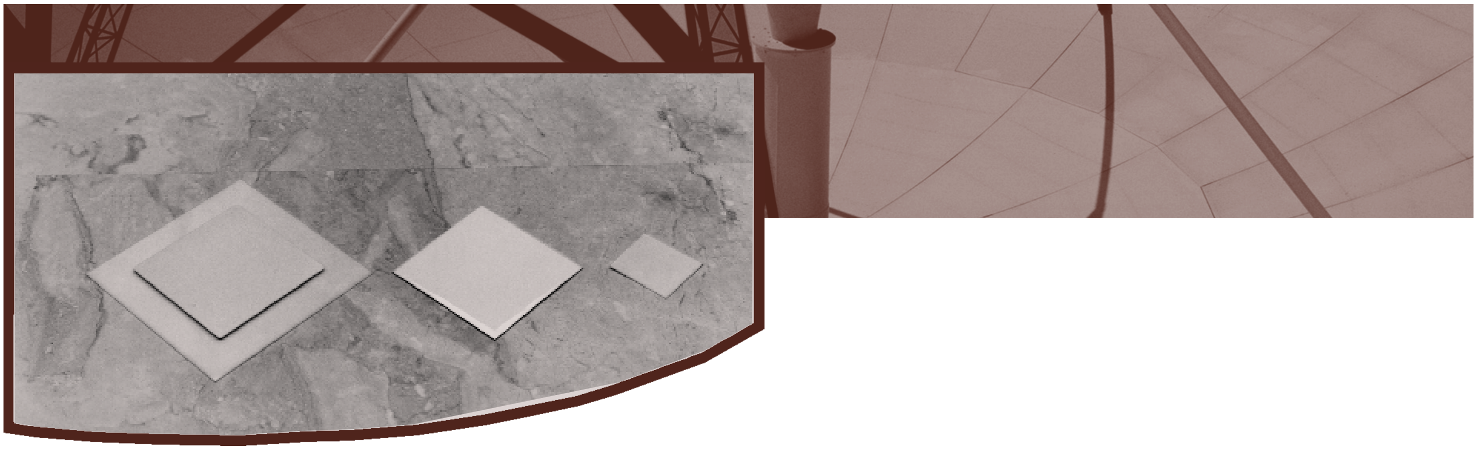
Material Specification Summary

Material Family	Resonators DR30	DR36	DR45	DR80
Dielectric Constant (ε') Nominal	30±1	36±1	45±1	80±2
Temperature Coefficient of Resonant Frequency (τ_f) (ppm/°C, 25° to 60°C)	+4 to -2	+9 to –3	+6 to –3	+9 to -3
Insulation Resistance (ohm-cm)	$>10^{14}$	$>10^{13}$	$>10^{13}$	$>10^{12}$
Thermal Expansion (ppm/°C) Nominal	10.0	9.0	6.0	8.5
Thermal Conductivity (cal/cm^2/cm/sec/°C) x 10^3 Nominal	6	5	5	5

Notes:
[1] Other temperature compensated dielectrics available upon request (i.e., ε'=10, 20, 36, 38, 90-120). Consult factory for details.
[2] All material densities are > 95% of theoretical and, therefore, moisture absorption is nil.
[3] Customized properties are available upon request.

Material Code	Dielectric Constant	τ_f	Unloaded Q	Diameter Range Available	Recommended Frequency
DR30 – P4	31.0 ± 1	+4	≥ 10,000 @ 10GHz	.076'' to 1.500''	1.5 – 20.0 GHz
DR30 – P2	30.5 ± 1	+2		"	"
DR30 – 0	30.0 ± 1	0	"	"	"
DR30 – N2	29.5 ± 1	-2	"	"	"
DR36 – P9	36.5 ± 1	+9	≥ 10,000 @ 4GHz	.160'' to 3.500''	0.8 – 13.5 GHz
DR36 – P6	36.0 ± 1	+6	35,000 @ 850 MHz		"
DR36 – P3	35.7 ± 1	+3	"	"	"
DR36 – 0	35.5 ± 1	0	"	"	"
DR36 – N3	35.0 ± 1	-3	"	"	"
DR45 – P9	46.5 ± 1	+9	≥ 10,000 @ 4GHz	.160'' to 3.500''	0.4 – 13.5 GHz
DR45 – P6	45.5 ± 1	+6	35,000 @ 850 MHz	"	"
DR45 – P3	45.0 ± 1	+3	"	"	"
DR45 – 0	45.0 ± 1	0	"	"	"
DR45 – N3	45.0 ± 1	-3	"	"	"
DR80 – P9	80.0 ± 2	+9	≥ 3,000 @ 3GHz	.405'' to 1.125''	0.4 – 4.0 GHz
DR80 – P6	80.0 ± 2	+6	"	"	"
DR80 – P3	80.0 ± 2	+3	"	"	"
DR80 – 0	80.0 ± 2	0	"	"	"
DR80 – N3	80.0 ± 2	-3	"	"	"

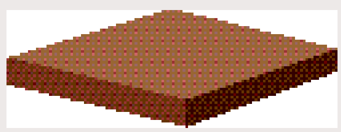
Notes:
[1] All τ_f specifications are measured between 25° to 60°C using a TRAK Ceramics, Inc. standard cavity.
[2] All materials are available in ±1ppm/°C and ±2 ppm/°C tolerance, except DR80 which is available only in ±2ppm/°C tolerance.



DIELECTRIC SUBSTRATES

General

TRAK Ceramics, Inc. offers substrates exhibiting high Q, excellent temperature stability, and high density. They are ideally suited for microwave integrated circuits and high Q capacitors. Surface finishes for these materials can be optimized for either thick or thin film metallization. Temperature coefficient of dielectric constant can be custom tailored based on customer specifications. Test



Material Type	S10	S20	S38	S90
Dielectric Constant (ε'), nominal	10±1	20±1	38±1	90±2
Temperature Coefficient of Dielectric Constant (τ_k) (ppm/°C)	0±30	-20±30	-25±30	0±30
Q factor = 1/tanδ Measured @ GHz	>10,000 9.0	>6,000 6.0	>10,000 4.1	>1,500 3.0
Thermal Expansion (ppm/°C), nominal	7.1	8.7	9.2	9.0
Thermal Conductivity (cal/(sec)(cm)(°C)) x 10^3, nominal	33	10	10	5
Available surface finishes	A/B/C	A/B/C	A/B/C	A/B/C

Notes:
[1] All dielectrics are > 95% of theoretical density and, therefore, absorption of moisture is nil.
[2] Consult factory for custom dielectric constants and temperature coefficients.

Surface Finish Specifications

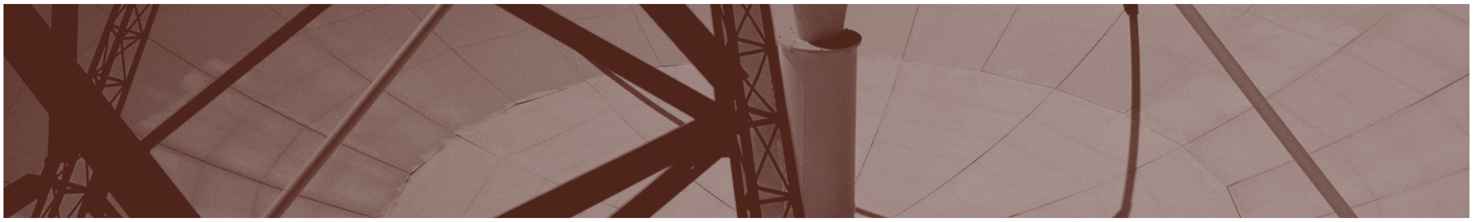
Surface Finish	Units	Grade A	Grade B	Grade C
Uniform Surface Roughness	µ''(RMS)	4 – 8	12 – 22	< 40

Available Sizes and Tolerances

Standard Sizes	Minimum Thickness
1 x 1	.010 min.
1 x 2	.010 min.
2 x 2	.020 min.
3 x 3	.020 min.

Units (inches)

Notes:
[1] Custom sizes and tolerances available on request.
[2] Contract thick film metallization is available upon request.



Available Surface Finishes

TRAK Ceramics, Inc. offers three standard grades of surface finish for substrates to insure optimum thick and thin film metallization. Other surface finishes may be requested. Please consult the factory for details.

Grade A

Designed for thin film MIC applications that require superior surface finish and dimensional control. Grade A substrates are 100% inspected for visual specifications.

Grade B

Designed for both thick and thin film MIC circuits where cost combined with performance is required.

Grade C

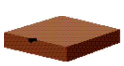
Designed for thick film applications where good surface perfection and low cost are required. Ideally suited for thick or thin film capacitor applications.

Inspection Guidelines

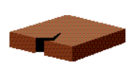
Visual Criteria	Grade A	Grade B	Grade C
Surface Finish (RMS)	4-8 µ''	12-22 µ''	< 40 µ''
Camber	< .0005''/inch	< .001''/inch	< .002''/inch
Hole, Pit, Pock	.010 Max. Dia.	.015 Max. Dia.	.025 Max. Dia.
Perpendicularity	.005"/inch	005''/inch	005''/inch
Parallelism	.001''/inch	.001''/inch	.001''/inch
Radius of Concern	<.010'' max.	<.010'' max.	<.010'' max.

Notes:
[1] No single chip to exceed .040" along the edge or < .020" deep.
[2] Substrate tolerance: length, width = ± .010"; thickness = ± .001".
[3] Blemishes: maximum diameter .030''; maximum 6 per side or 2 per inch.
[4] No cracks or ridges permitted.

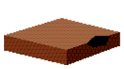
Visual Defects



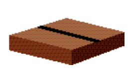
Chip – An area along an edge or corner where the material has broken off.



Crack – A line of fracture without complete separation.



Hole, Pit, or Pock – A deep depression or void.



Ridge – A long narrow protrusion on the surface.

Part numbering guide

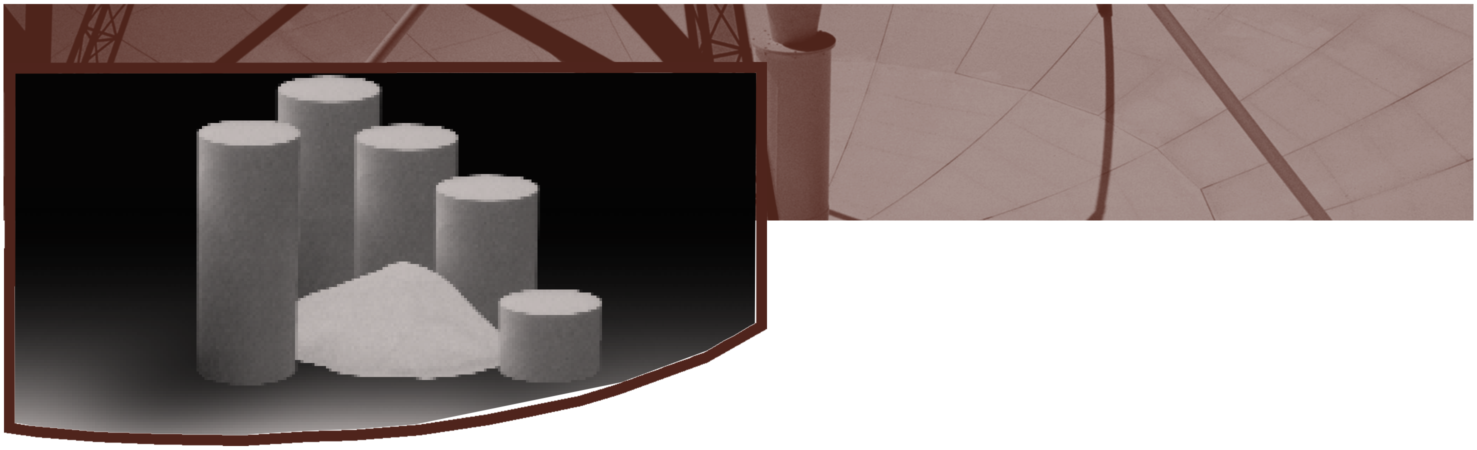
SXX - X

Surface Finish Grade (see page 30 “Surface Finish Specifications” for availability)

Material Type

Example: S10-A

Material Type S10; Surface Finish Grade = A
List product dimensions as a description under part numbers

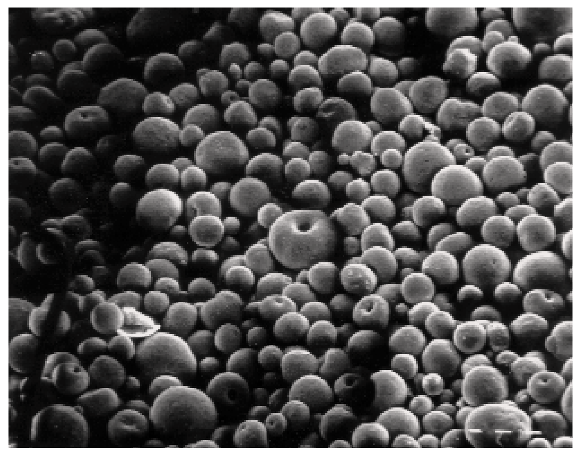


ADVANCED MATERIALS

Ceramic Materials for Thermal Deposition

General Overview

TRAK Ceramics, Inc. thermal deposition materials are composed of yttria-zirconia and other material families, typically used as thermal barriers, as well as, wear and resistant coatings. TCI deposition materials have uniform grain and pore size distributions that assure satisfaction and meet the highest standards for purity and flowability. TCI ingots minimize spitting while providing rapid evaporation rates for PVD applications.



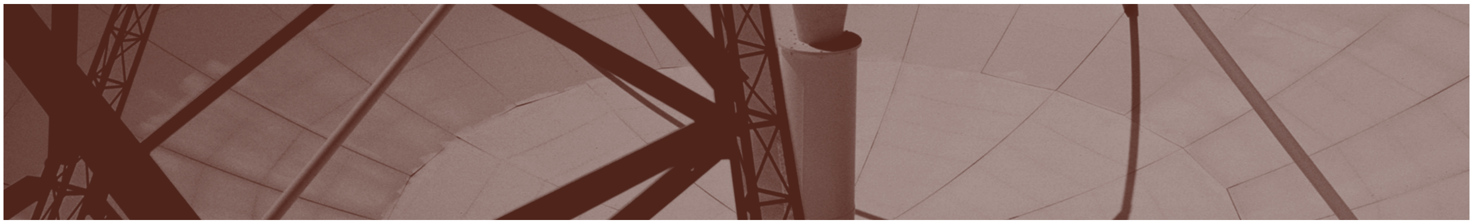
Spherical, flowable powder

Typical Applications

- Aircraft Turbine Blades
- Automotive Components
- Industrial Turbine Engines
- Wear Resistance for Pump Components
- Medical Coatings

Features and Benefits

	Features	Benefits
Powders	• Sintered Spray Dried Powder • Controlled Composition • Fully Reacted • High Spherical Uniformity	• Improved Process Repeatability • Consistent Mechanical and Chemical Performance • Improved Deposition Efficiency • Easily Incorporated into Polymers
Ingots	• Controlled Density • Controlled Composition • Fully Reacted • Uniform Grain and Pore Size Distribution	• Uniform Melting • Improved Process Repeatability • Consistent Mechanical and Chemical Performance • Improved Deposition Efficiency • Minimum Degassing and Spitting • Improved Process Yields • Efficient Feedstock Loading



Specifications

The TRAK Ceramics, Inc. product line includes both powders and ingots based on the following material families:

- Yttria-Zirconia
- Neodymia-Zirconia
- Ytterbia-Zirconia
- Zircon (Zirconium Silicate)
- Ceria-Yttria-Zirconia
- Lanthana-Zirconia

Actual chemistry is custom formulated to the customer's requirements. Other material families available upon request. Please consult factory for details.

General

The powder shall be capable of producing thermal sprayed coatings which are smooth, uniform and free from lumps. The powder will be uniform in color and chemistry and will be supplied dry and free from foreign materials.

Chemical Analysis

The chemical analysis shall be conducted in accordance with ASTM standards or industry practice.

Packaging

All materials shall be packed in sealed, moisture proof containers to prevent contamination or loss during handling, shipment or storage.

Certificate of Test

A certificate of test will accompany each shipment of material showing results in accordance with the customer's specifications, purchase order and part number. The test results will include lot identification, quantity, class and revision.

Custom Services and Specialty Materials

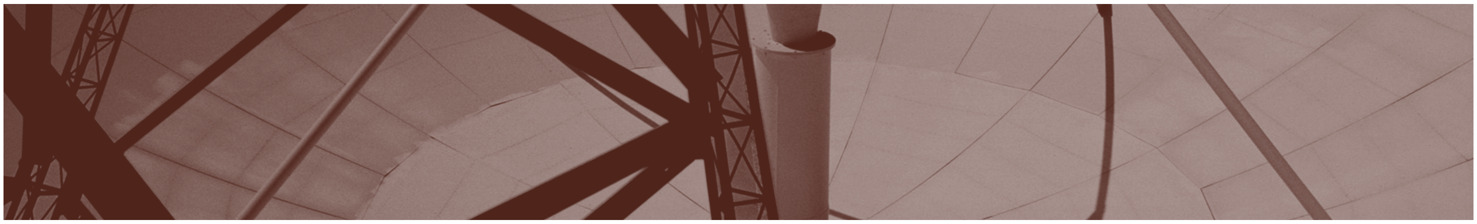
In addition to materials for coating processes, TRAK Ceramics, Inc.offers other specialty compounds in powder and in consolidated ceramic configurations. These include:

- Lithium aluminate ($LiAlO_2$) porous breeder rods and ingots for tritium production; other lithium compounds also are available.
- Synthetic "bone" material, hydroxyapatite, [$Ca_{10}P_6O_{24}(OH)_2$], as powder for medical applications.
- Conductor perovskites (doped rare earth chromites) as powder for high temperature fuel cells.
- Dielectric powder as filler material to control ε' and improve loss of polymer composites.
- Ferrite powders to control absorption of electromagnetic energy and as fillers.
- Sputtering targets.

Specialized processes are also available upon request and include:

- Custom Synthesis
- Pelletizing
- Milling
- Spray Drying
- Forming
- Sintering

TRAK Ceramics, Inc. engineers are material specialists. We welcome technical discussions regarding your application and specifications for your powder needs. We can manufacture and provide custom chemistry/phase content and controlled cuts in crystallite/agglomerate size without sacrifice in requested purity levels.



APPENDIX A

Basic Test Methods

Dielectric Constant Measurement

Also known as relative permittivity, K or ε', dielectric constant is tested primarily in one of two ways. For garnet, ferrite, and dielectric materials with dielectric constant values less than ~20, a rectangular waveguide resonant cavity operating in the TE_{10X} mode (where x is odd) at approximately 10 GHz is employed. A dielectric rod sample approximately .050" in diameter is introduced into the center of the cavity perturbing the electromagnetic fields within the cavity. Dielectric constant and loss tangent (1/Q) may then be calculated based on the change in resonant frequency and Q due to the introduction of the sample. This technique is based upon ASTM D-2520, Method B.

For other dielectric materials with higher dielectric constant values, the Courtney "parallel-plate" dielectrometer[1] is employed. With this method, a cylindrical rod resonator sample is placed between two parallel conducting plates. Resonant frequency of the sample in the TE_{011} resonant mode is measured as are the sample dimensions, and from these values dielectric constant is calculated.

Another accurate and reliable method which may be employed for measuring the dielectric constant of thin dielectric substrate specimens is the Resonant Mode Dielectrometer or RMD[2,3]. With this technique, a thin substrate specimen is inserted on the central transverse plane of a cylindrical waveguide RMD cavity. Dielectric constant is calculated based upon the thickness of the sample specimen and its resonant frequency in the H_{011} mode.

Very low frequency (~1 KHz - 1 MHz) capacitance methods may also be used for determination of dielectric constant. Dielectric constant is calculated using very well known relationships among the measured capacitance, area, and thickness of a sample specimen. Care must be exercised to assure complete contact of the conductor to the ceramic surface and to avoid being misled by certain intrinsic low frequency phenomena exhibited by some materials.

Quality Factor (Q) or Loss Tangent Measurement

The quality factor, or Q, is equal to 1/loss tangent. Either method of expression is correct, although quality factor is more commonly associated with microwave circuit design. For the purposes of this catalog, we will refer only to the unloaded quality factor.

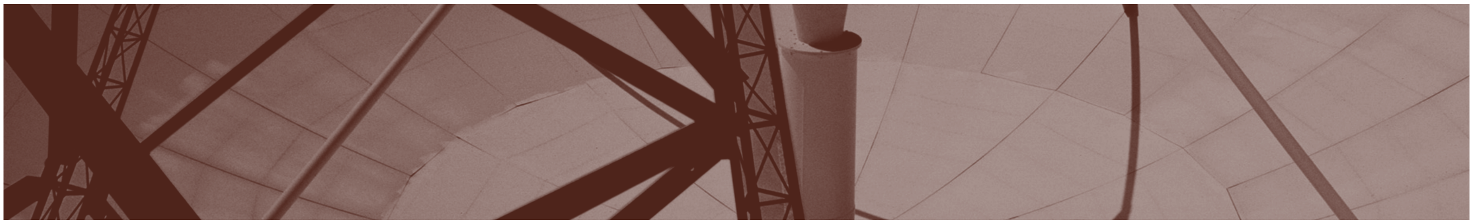
When considering quality factor, one must always bear in mind that from a practical standpoint the measured value of this parameter is highly dependent not only on the intrinsic quality of the ceramic material, but also on the method of measurement, the measurement environment, and the frequency at which the sample is measured. A given material sample may exhibit greatly differing Q values when tested in different test fixtures and environments which may vary in size, shape, conductor quality, coupling, type of sample support, ambient temperature, relative humidity, etc.

Additionally, the intrinsic Q of any given material sample will vary with the frequency of measurement. Often, manufacturers will state that Q vs. frequency is an indirectly proportional linear function such that Q times frequency (often referred to as the $Q*f$ product) is equal to a constant. This concept, however, is overly simplistic and is only suitable for use as a rough first approximation or for use over an extremely narrow range of frequency space. Characterizing Q is further complicated by the difficulty in making electrically identical test fixtures for use at different test frequencies. Therefore, actual measurement of Q, performed under near identical circumstances and at or near the frequency of interest to the end-user is the best way to compare the relative benefits of one material versus another and/or to determine the suitability of a material for a given application.

The method employed for Q measurement of low dielectric constant materials as well as ferrite and garnet materials is discussed above.

Quality factor for higher dielectric constant materials is tested primarily by using a cylindrical resonant cavity made of high conductivity metal with interior dimensions approximately 3-5 times larger than the dimensions of the test sample. The test sample is placed inside the cavity upon a low loss, low dielectric constant support and inductive coupling to the resonator sample is achieved via a coupling loop or bent probe. The S_{21} or transmission characteristics of the $TE_{01\delta}$ resonant mode is measured, and quality factor is calculated using the formula: $Q = (f_0/\Delta f) / (1\text{-}10 \wedge^{(-I.L./20)})$ where f_0 is the resonant frequency, Δf is the -3dB bandwidth, and I.L. is the insertion loss expressed in dB.

Quality factor at very low frequencies (~1KHz -1MHz) may also be measured using various commercially available capacitance or L.C.R. meters and fixtures which give a direct reading of Q. This technique, however, often results in Q data which are extremely inaccurate and potentially misleading unless all variables are properly accounted for, especially for high Q materials. It is best used only for relative comparisons of similar samples.



Temperature Coefficient Of Resonant Frequency (τ_f) Measurement

Temperature coefficient of resonant frequency is measured by using a cylindrical resonant cavity made of high conductivity metal with dimensions approximately 3-5 times larger than the dimensions of the test sample. The test sample is placed inside the cavity on a low loss, low dielectric constant, low thermal expansion support and inductive coupling to the resonator is achieved via a coupling loop or bent probe. The cavity is then placed inside of a temperature chamber and the temperature is cycled over the desired range (usually 25°-60°C). The resonant frequency of the $TE_{01\delta}$ mode is measured at each temperature. Temperature coefficient is calculated as follows and is expressed in parts-per-million-per-degree Celsius (ppm/°C.): $\Delta f_0 / (f_0 \Delta T)$. For more precise applications, polynomials are fitted to the data which can include temperatures below 25°C.

Temperature Coefficient Of Capacitance (τ_c) Measurement

Temperature coefficient of capacitance at ~1KHz - 1MHz is usually measured on samples which have been metallized using a fired-on or electro-deposited high conductivity conductor such as silver or copper. Specially designed and built test fixtures are employed to hold the sample during testing. Capacitance is monitored as the temperature of the samples is cycled and τ_c is calculated as follows and is expressed in parts-per-million-per-degree Celsius (ppm/°C.): $\Delta C_o/(C_o \Delta T)$.

Temperature Coefficient Of Dielectric Constant (τ_k) Measurement

Temperature coefficient of dielectric constant is of primary interest to users of dielectric substrate materials. In most cases, the substrates are tested for temperature coefficient of resonant frequency (τ_f) as if they were a dielectric resonator, and τ_k is calculated using the equation: $\tau_k = -2(\tau_f + \alpha)$, where α is the linear thermal expansion coefficient of the ceramic material.

Ferromagnetic Resonance Line Width (ΔH) Measurement

The sample for this measurement is a polished sphere ~.050" in diameter. The sphere is placed into a TE_{10x} mode waveguide cavity (resonant at ~9.2GHz) which is located between the poles of an electromagnet. A gaussmeter is used to measure the changes in the magnetic field necessary to produce a -3 dB resonance attenuation.

Saturation Magnetization ($4\pi M_s$) Measurement

A sample disk of material is placed between the poles of an electromagnet which is set to produce a field of sufficient strength to completely saturate the sample material. A gaussmeter is used to measure the change in field strength with the sample present as compared to when the sample is not present. The $4\pi M_s$ is calculated based on the change in the field strength reading and the volume of the sample disk.

Hysteresis Loop Characteristics

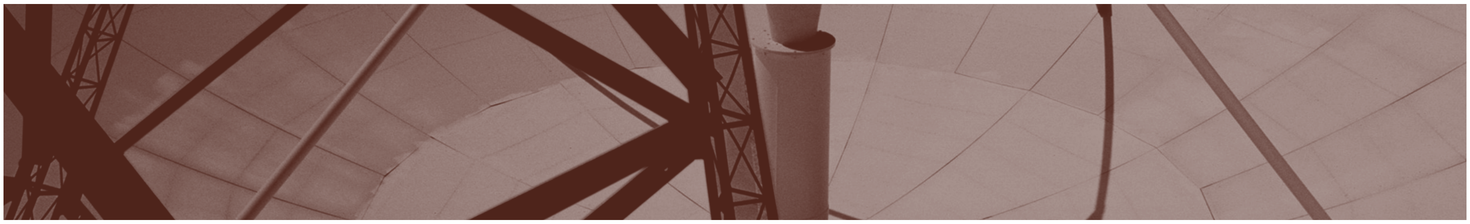
A toroid sample fitted with a double winding is used as a transformer for measuring the hysteresis loop characteristics B_r (remanent induction), B_m (maximum induction) and H_c (coercive force). The primary winding magnetizes the sample with a low frequency AC signal and the applied H field is proportional to the primary current. The signal, which is then induced in the secondary winding, is proportional to the magnetic flux variation and is integrated to obtain the B_r. The induction value B_m is measured at an applied field of 5 times H_c.

References

1. W.E. Courtney, "Analysis and Evaluation of a Method of Measuring the Complex Permittivity and Permeability of Microwave Insulators", IEEE Transactions on Microwave Theory and Techniques, Volume MTT-18, August 1970.

2. G. Kent, "Nondestructive Permittivity Measurement of Substrates", IEEE Transactions on Instrumentation and Measurement, Volume 45, February 1996, pp 102-106.

3. G. Kent and S.M. Bell, "The Gap Correction for the Resonant-Mode Dielectrometer", IEEE Transactions on Instrumentation and Measurement, Volume 45, February 1996, pp 98-101.



APPENDIX B
Symbol Glossary

Symbol	Description
τ_f	Temperature Coefficient of Resonant Frequency
B	Magnetic Induction
B_m	Maximum Induction
B_r	Remanent Induction
B_r/B_m	Squareness Ratio
ΔH	Ferromagnetic Resonance Line Width @ - 3dB
ΔH_k	Spin Wave Line Width
$\tan\delta$	Dielectric Loss Tangent $\varepsilon''/\varepsilon'$
ε'	Relative Permittivity – Real Part
ε''	Relative Permittivity – Imaginary Part
f_o	Resonant Frequency
γ	Gyromagnetic Ratio

Symbol	Description
$g_{\text{-eff}}$	Landé Factor
H	Applied Magnetic Field
H_c	Coercive Force
$4\pi M_s$	Saturation Magnetization
Q	Q Factor = $1/\tan\delta$
T	Tesla
T_c	Curie Temperature
$\tau_{\varepsilon'}$ or τ_k	Temperature Coefficient of Dielectric Constant
D_r	Outside Diameter
d_r	Inside Diameter
T(°C)	Temperature, Degree Celsius
dB	Decibel
α	Temperature Coefficient of M_s

Other Abbreviations

DBS	Direct Broadcast Satellite
DR	Dielectric Resonator
DRO	Dielectric Resonator Oscillator
ECM	Electronic Counter Measures
GPS	Global Positioning System
GSM	Global Specialized Mobile
HPH	High Power Handling
MM	Millimeter Wave
MPH	Moderate Power Handling
NL	Narrow Line Width
PCN	Personal Communication Network
PCS	Personal Communication System
PVD	Physical Vapor Deposition
RMS	Root Mean Square
SG	Standard Grade
SHL	Square Hysteresis Loop
TVRO	TV Receive Only
VSWR	Voltage Standing Wave Ratio