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1–2 GHz dielectrics and ferrites: overview and perspectives

David Cruickshank

TransTech, a subsidiary of Skyworks Solutions Inc., 5620 Adamstown Road., Adamstown, MD 21710, USA

Abstract

Trends in the cellular communications industry are examined with reference to their likely effect on dielectric and magnetic ceramic materials currently used in 1–2 GHz devices. Cost pressures on dielectrics are likely to see the elimination of tantalate and even niobate based materials except for special devices. Titanate based ceramic compositions must compete with metal topologies in near antenna filters in Base Stations. Ceramic dielectric will continue to be used in coaxial form for resonators, filters and delay filters in this frequency range and higher for wireless infrastructure, but less so in high volume handheld products. Low temperature co-fired ceramics (LTCC) will be used increasingly for the latter in microwave multifunctional modules. Magnetic ceramics such as those based on yttrium iron garnets (YIG) will continue to be used in wireless infrastructure and some handheld products, where intermodulation effects (IMD) are the major remaining issue. Hexagonal ferrites have useful permeability close to the microwave region, and also are being used as absorbers at higher frequencies.

Keywords: Cellular communications; Dielectric materials; Hexagonal ferrite; IMD; LTCC; Magnetic materials; Microwave filters; YIG

1. Trends in the cellular industry

The cellular communication industry is experiencing a number of changes in direction that impact on the cost and technology employed in the microwave components used for infrastructure equipment. This review will confine itself mainly to technical ceramics for near-antenna components in the range 800 MHz to 2.5 GHz. These changes in direction are summarized below.

Phasing out of auto tuned combiners (ATCs), which have traditionally used large volumes of high Q dielectrics and connectorized isolators. These were used extensively in 1st and 2nd generation (1G and 2G) systems but are used less in 2.5G, and probably will not be used at all in 3G.

More extensive use of high Q ceramic resonator based filters in 2.5 and 3G because of size and performance advantages over air-metal filters, where cost permits.

The use of ultra linear power amplifiers for single (LPAs) and multicarrier (MCPAs) configurations, particularly in 2.5G and 3G.

Extreme cost reduction pressures to lower the overall base station equipment costs to the service providers, who lack the financial means to deploy new infrastructure in the current economic climate in Europe and North America.

In cellular handsets, the use of RF transceiver modules rather than discrete components, incorporating low temperature co-fired ceramics (LTCC).

This review will consider the effect of these changes on the microwave dielectric and ferrite materials made by the ceramic industry.

2. Dielectric materials

For microwave dielectrics for near antenna filter applications, we can specify some minimal characteristics:

Size constraints mean dielectric constants, ε_r, should exceed 30. Because of cost and Q considerations, this is further constrained to 35–55.

The 1st order temperature coefficient, T_f, needs to be tunable by composition from at least −5 to +5ppm/C. This is because of the effect the cavity, the resonator support, the tuner expansion coefficient, and the cavity size relative to the resonator have on the overall

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frequency drift of the filter. The tolerance on this value can be as tight as ±0.25ppm/C for the same reason, for narrow bandwidth filters.

The 2nd order temperature coefficient, T'_f, should not exceed ±0.01 ppm/°C/°C.for narrow band filters For similar reasons to T_f, the overall linearity of the frequency drift of a narrow band filter is impacted considerably by T'_f.

The Q for large unplated aluminum cavities, where the cavity diameter or cross section and height dimensions exceed the diameter of the TE resonator by 2/3 times, generally needs to be between 20 and 50 K at 2 GHz for practical applications. For small cavities, which approach the resonator in size, the ε_r has a strong influence on the available Q from the cavity, and may dominate the overall choice of material when the required Q is in the range 5–15 K at 2 GHz.

Taking all these factors into account, the practical range for ε_r is 35–50, with 55 only usable under special circumstances where Q and T'_f requirements permit.

If we look at available crystallographic systems, and apply the above criteria, we find we are constrained to a relatively small number of choices. Those most often used are discussed below from the point of view of electrical properties and cost.

2.1. $Ba_3ZnTa_2O_9$ based (BZT)

This material can be compositionally adjusted to give an ε_r of 30 when Zr is used to adjust T_f and ε_r, and, in combination with cooling rates, gives very tight control of all the above listed parameters.[1,2] However the high cost of tantalum pentoxide, even after its late 2000 peak, virtually precludes it from consideration for 2.5 and 3G fixed filters.

2.2. $Ba_3ZnNb_2O_9$ based (BZN)

This can be compositionally adjusted with Co[1–6] to give an ε_r of 33–35, Qs of >30K at 2GHz, and T_f. and T'_fs which meet the above criteria. A-site substitution using Sr raises ε_r (Fig. 1) but at the expense of T_f, T'_f and Q. Only Co has met the previously mentioned criteria so far. BZCN has a significantly better Q than BZT when cavity sizes fall below 50mm even when the large cavity Q of BZT is much higher (Fig. 2). BZCN was introduced commercially some time ago, but has been modified in recent years by Hill[1] using the 816 phase to raise the ε_r to ~35 in commercial products, while achieving Qs >45 K.

Other related perovskite niobate/tungstate/molybdates approaches may eventually successfully meet all the above criterion, plus cost requirements discussed later, but as far as is known this .has not yet occurred.

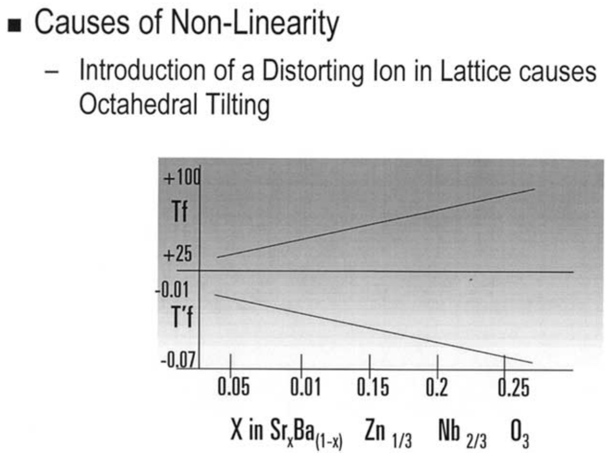

Fig. 1. Causes of non-linearity.

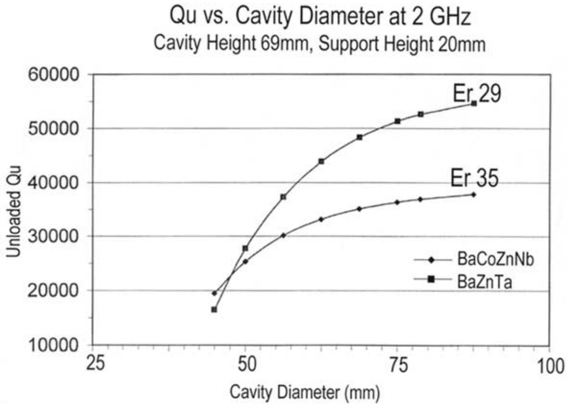

Fig. 2. Qu vs. cavity diameter at 2 GHz.

2.3. Titanate-based systems

In the ε_r range 35–45, available Qs from titanates in relatively large cavities (50×50×50 mm) barely exceed 20 K at 2 GHz, i.e. about half of what is available from BZT/BZCN. They are however, significantly cheaper, and in small cavities (e.g. 50 mm diameter ×25 mm height) offer advantages over BZT and BZCN because of higher available ε_r and therefore smaller resonators, such that the higher Q advantage of the latter is sometimes not realizable. Typical Qs in that situation are about 10 K for the best of all systems at 2 GHz., and the cheapest solution is often a titanate with ε_r in the range 43–46. However, ε_rs as high as 55 can be used with such small cavities even if their large cavity Qs are significantly lower, provided they meet the cost and T_f/T'_f requirements.

Some titanate systems offer interesting advantages. Those based on $BaTi_4O_9/Ba_2Ti_9O_{20}$ (BT4/B2 T9) incorporating Zn, Ta and Nb,[7] although giving ε_rs of only 35, offer adjustable T'_f, depending on the ratio of BT4 (positive T'_f) to B2T9 (negative T'_f) This allows adjustment of the 2nd order coefficient to take account of all sources of non linearity in the cavity, assembly etc

(Fig. 3). By simultaneously adjusting the T_f, exceptionally stable frequency drift is possible, as little as 20 KHz over a 140 °C temperature range at 2 GHz (Fig. 4), corresponding to a total drift of 0.007 ppm/C. This was done with an ε_r of 35 in TE mode resonator form with a small +ve T_f and known T'_f, and an alumina support with large −ve T_f and opposing T'_f. By adjusting the volume of alumina in the cavity, expressed as a change in frequency loading in MHz, the T_f and T'_f of the overall assembly in the cavity could approach zero temperature drift.

Titanate systems based on the Zirconium Titanate with Zn and Nb substitution, which have the α PbO crystallographic structure, can produce good T_f ranges and useful T'_fs. They produce ε_rs up to ~44 when fired in a tunnel Kiln at 1.5–2 atmospheres of oxygen[8] to maximize density. Extending the ε_r by the use of 2nd phase rutile, however, will progressively adversely influence the T'_f as well as T_f. These systems, however have lower material and processing costs than the corresponding perovskite based $LnAlO_3/CaTiO_3$ system with similar ε_rs. Perovskite based materials are possible with $\varepsilon_r > 45$, but so far a practical material beyond an ε_r of about 50 has not emerged.

One approach to meeting high Q and high ε_r requirements is to accept the generalization that this usually comes with a high +ve T_f. This can be countered with support material in the TE mode assembly that has a large −ve T_f Alumina has this (−55 ppm/°C) but its low ε_r (9.8) means that a large volume is required, filling the cavity and raising the cost. Using slightly modified $ZnNb_2O_6$ (ZN) as in Refs. 9 and 10 will give high T_f (−70 ppm/°C), which when combined with its higher ε_r of 24 and Q of 45 K at 2 GHz, can give more practical solutions. When combined with a BZN based resonator, with an ε_r of 39 and a T_f. of +ve 25 ppm/°C, this will give a well compensated assembly with a combined $Q >$ 40 K in a 80 mm diameter×70 mm cavity (Fig. 5). By adjusting either the BZN/BZ ratio, or the physical size of the BZN resonator, it is possible to independently tune the overall T_f and the frequency of the cavity assembly. A similar structure also using the TE mode is shown in Fig. 6 in the same cavity size with a composite BZN/ZN resonator, an alumina support, and a BZT tuner which can be progressively inserted into the composite resonator. Again, the T_f is close to zero, the Qf product is >80 GHz, and the tuning range (Fig. 7) is around 60 MHz. In a small cavity, 50 mm in diameter by only 23 mm height, a similar approach with a BZN resonator and ZN supports will give a Q of >13 K at 2 GHz, compared with 9 K for a conventional ε_r 45 titanate with an alumina support at the same frequency. Combinations of ε_r 55 titanate materials with large positive T_f's could be compensated with ZN in the same way.

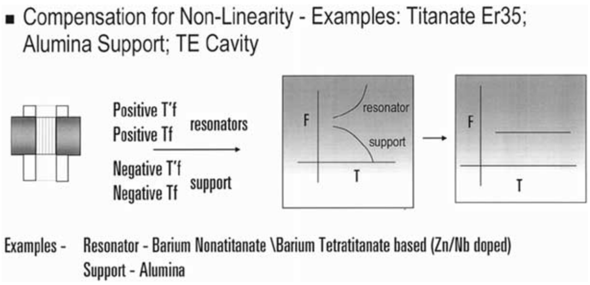

Fig. 3. Compensation for non-linearity (1).

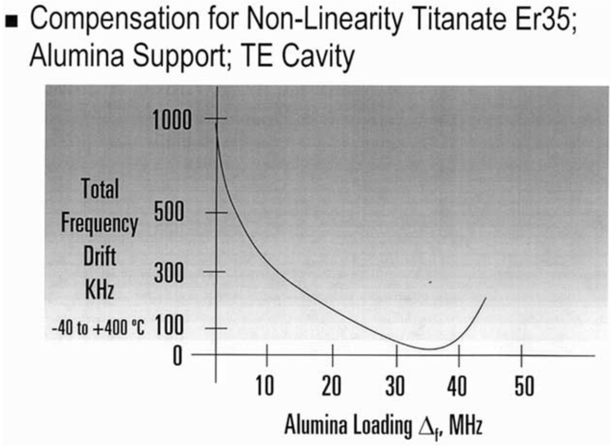

Fig. 4. Compensation for non-linearity (2).

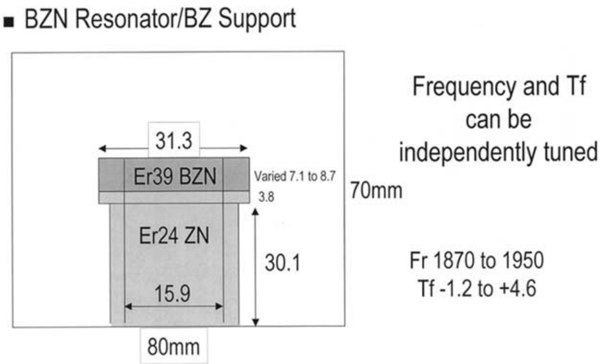

Fig. 5. BZN resonator/BZ support.

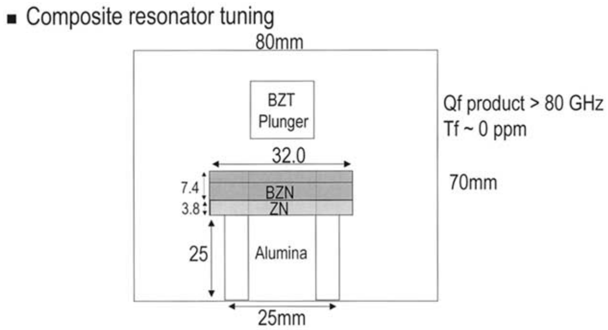

Fig. 6. Composite resonator tuning (1).

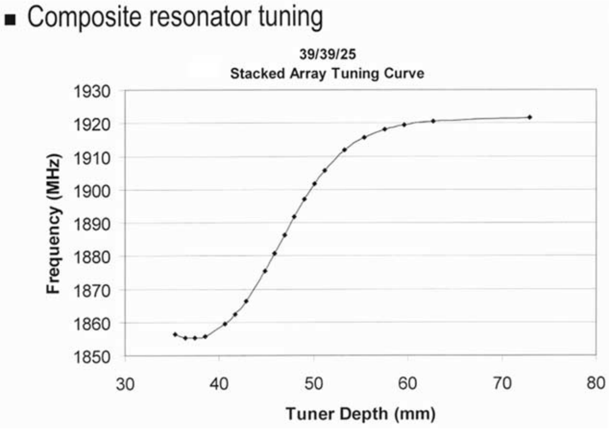

Fig. 7. Composite resonator tuning (2).

2.4. Applications and cost

The specification of 3rd generation filters at 2 GHz have bandwidths up to 60 MHz, and corresponding *Q*s can be as low as 5 K in small cavities. To compete with alternative filter designs using air/metal topologies, the additional cost of the dielectric resonator should not exceed the cost of the additional metal and silver plating etc. of the larger air/metal design, implying costs in the 1–3 euro range in very high volumes of TE resonators. These types of costs can be approached using the high volume automated assembly and test methods currently used in domestic satellite TV down converter resonators, and as fired resonator pucks and supports.

In this lower range of *Q*s, 5–10 K, an alternative is the use of the TM mode in cavities using ceramic tubes With a titanate of ε_r 35 in tubular form, in a 50 mm diameter 25 mm cavity, *Q*s at the lower end of this range can be achieved at 2 GHz. Using a BZCN niobate dielectric of the same εr will give a *Q* 50–70% higher for slightly less increase in cost. The cost of TM tubes is lower than the corresponding TE assemblies both because of the lower mass of the resonator tube and the elimination of the dielectric support, although methods of attaching the tube to the cavity can be more expensive.

Dielectric resonator dual mode filters have a significantly lower *Q* when compared with TE resonators in the same cavity size, because of the greater volume of the puck required to support both modes. Again, higher *Q* niobates can be used to offset this loss of *Q*, such that the saving in filter size is realized without loss of performance. Triple mode filters can be realized in the same way, where the shape factor is a cost issue. Triple mode filters can also be realized using all-ceramic metallised topologies, where the *Q* is a function of the metal losses, and relatively low ε_rs are necessary to minimize these losses.

3. Coaxial ceramic filters

Filters with Q in the range 100–2000 can be realized with coaxial ceramic resonators in the range 2 to 20 mm cross section or greater. Although initially used extensively in cell phone handsets, increasingly SAW is used for RF filters for those applications. Their prime application in cellular infrastructure is as band defining filters in base station transceivers, although increasingly they can be used as delay elements in error correction loops in LPAs, either as simple filters or in combination with hybrid couplers or circulators. Delays in excess of 50 ns have been achieved with compact circulator/filter combinations, with insertion losses less than 6 dB, competing favorably with coaxial transmission line cables.

In the frequency range around 2–4 GHz, coaxial filters are used for wireless local area networks, and wireless local loops, typically as Transmit/Receive diplexers and filters, and as high as 6 GHz for HyperLan. The frequency range has been extended by the use of low dielectric constant temperature stable material (ε_r 10) and the use of half wave instead of quarter wave resonators to preserve *Q*.

4. Low temperature Co fired ceramics, LTCC

It is not the intent to cover LTCC in detail here. The trend to RF modules is increasing the use of this technology in cellular handsets, where it is used to integrate passive components such as LC filters with semi-conducting switches and amplifiers. Higher performance filters such as SAW are often integrated as discrete devices, semi-packaged into the module. Ferrite devices are currently treated in the same way, in spite of their potential for integration as magnetic LTCCs.

5. Magnetic ceramics

As 3G applications slowly expand, ferrite based isolators continue to be used in amplifier chains in base station transceivers, usually as a ‘drop-in’ device in surface mount form onto a microstrip circuit. The current trends are to reduce insertion loss and intermodulation (IMD) products, while reducing costs.

Minimizing insertion loss is straightforward in the sense that in above resonance devices, which are used almost exclusively at 1–2 GHz to achieve small size and low IMD, the requirement is to minimize the ferromagnetic linewidth, generally expressed as ΔH_0 at the 3dB points. This will maximize the usable insertion loss bandwidth. Compositionally, this in turn means selecting materials with a low value of K_1, the first order magnetocrystalline anisotropy factor. This virtually precludes spinel ferrites, and garnets based on Yttrium

Iron Garnet (YIG) are universally used. YIG itself, and Al-doped compositions are one possibility, with linewidths as low as ~20 Oe. Another is combinations of V^{+5} on the tetrahedral site to lower magnetization (4πMs) with In^{+3}, Zr^{+4}, or Sn^{+4} on the octahedral site to reduce linewidth by raising Ms and reducing K_1, using Ca^{+2} to balance valencies. Sometimes both approaches are used in mixed garnets. In general the outcome of this is to produce a trade-off in linewidth, with a theoretical minimum defined by K_1/Ms, and Curie temperature, which is essentially a function of the total number of non-magnetic ions substituting for Fe^{+3} in the octahedral and tetrahedral sites, although V^{+5} has much less effect than the others. This is illustrated in Fig. 8 for the Ca/V/In and Zr garnets with 4πMs in the range 1200–1600 gauss. Linewidths of less than 5 Oersted are possible but with Curie temperatures of 150 °C or less, this is usually beyond the acceptable limit for practical devices, where Curie temperatures of close to 200 °C are desirable for reasonable temperature stability. As a result, linewidths of 10 or less are usually specified for CaVIn/Zr materials in the range 1000–1850 gauss 4πMs. For more temperature stable devices, YIG or Al-doped YIG are used. Gd-doped garnets are generally not used because of their higher linewidth and non-linear temperature behavior.

IMD is a much more complex problem. It is known to be influenced by the saturation state of the ferrite, which in turn is a function of applied field and field uniformity.[12] In thin discs and triangles, field uniformity can be difficult to achieve. Shaped pole pieces have been used. Composites of garnet discs and dielectric rings can be used to vary both the volume fraction of ferrite, the effective demagnetizing factor of the ferrite disc, and the field uniformity to optimize IMD contributions from these factors. Recent advances have been in co-firing the ferrite and dielectric at high temperatures to allow subsequent silver metallization of the composite.

It is not yet clear whether composition has an effect on IMD. Two factors which may shed some light on the influence of the material on IMD are;

1. Reported IMD contributions from material of the same composition[11] but with different porosity. Porosity increases resonance linewidth and spin wave linewidth through spin wave scattering, and only resonance linewidth was reported. No details were given about grain size, which influences spin wave linewidth, but not resonance linewidth.
2. From the same reference, at low power, porosity, through the resonance linewidth, increased the IMD products, but the effect was diminished at higher power and there was convergence of the slopes of IMD against power as a result.

One interpretation of these results is that at higher powers, spin wave scattering reduces non-linearity processes, such that the higher spinwave linewidth associated with more porous and possibly finer-grained material had a reduced IMD dependence with increasing power. Associated with this type of result is the observation that IMD products rise with temperature. Because both resonance and spinwave linewidth both fall with temperature as K_1 falls, this would suggest that the spinwave linewidth could come into play more at higher temperatures. Some care is required in interpreting these results as the applied field may vary in strength and uniformity at temperature.

At present, the optimum approach is to eliminate porosity. Because different materials have different K1/Ms, there is no special absolute value of linewidth for low IMD for all materials. As an example, the absolute K_1/Ms value for YIG is thought to be 17 Oe from both the theoretical values from single crystal and polycrystalline data, and the lowest actual values obtained

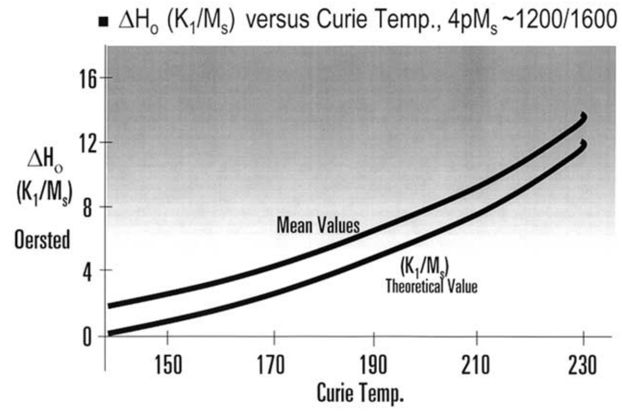

Fig. 8. ΔH_o (K_1/M_δ) vs. Curie Temp.

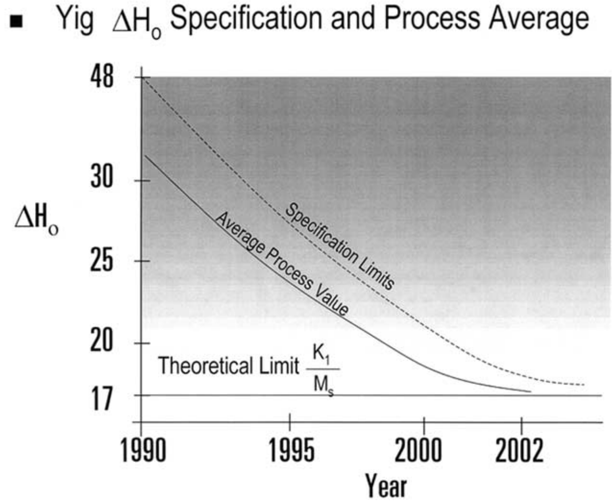

Fig. 9. Yig: ΔH_o specification and process average.

by any fabrication technique, e.g. hot pressing of exactly stoichiometric material. For YIG, specifications from device requirements and observed processing average values are now converging on 20Oe, implying very low levels of porosity and second phase materials, of around 0.2% total (Fig. 9).

A corresponding figure for CaVIn/Zr, with a K_1/Ms of close to 0 and a Curie temperature of 170–200 °C, would be close to 3 Oe, depending on 4πMs (Fig. 8). This would be difficult to achieve in practical manufacturing because of the relatively complex chemistry of this type of material, and so they may not be the best choice for low IMD, even if their lower resonance linewidth is an advantage for insertion loss.

6. Spinel and hexagonal ferrites

At 1–2 GHz, spinel ferrites are not used for junction or linear devices because of their high Ms below resonance, creating low field losses, or above resonance because of their high linewidth. NiZn spinels are, however, used as absorbers from 100 MHZ to 10 GHz in the broad absorption peak associated with domain resonance and the drop in permeability from lower frequency, usually referred to as low field loss. These absorbing properties can be used for both RF and high speed digital applications at Gigabit rates. Their use as inductors is limited to a few hundred MHz because their permeability approaches unity just above 1 GHz, referred to as the Snoek limit.

Hexagonal ferrites, because of internal anisotropy fields, have significantly higher limits, opening up the possibility of ferrite inductors in the 1 to 2 GHz region,[13,14] and special types of antennas, where $\mu > \varepsilon_r$, allowing impedance matching into free space, provided the magnetic losses can be pushed out of the frequency of interest by compositional adjustment of the relaxation induced absorption peaks. These materials have become known as a class of meta-materials, although not strictly meeting that definition. Absorbers with absorption peaks well above 10 GHz can be realized from the same type of materials.

These materials in powder form are being used in absorber paints, or when incorporated into plastics, as moldable shapes, for example sheets of RF and high speed data circuit leakage absorbers.

7. Summary and conclusions

High *Q* dielectrics face significant cost challenges to replace metal filters in 3G near antenna filters. TE mode resonators using ε_r 43–45 titanates are suitable for low cost high volume situations where cavity *Q*s in the range 10–20 K are required. For some applications, higher *Q* temperature stable niobates may be necessary, although their lower ER can be a disadvantage. BZN/ZN solutions may be a viable alternative in some situations. TM mode resonators in tube form can be used for very low cost, lower *Q* applications. Without such low cost approaches, the application of ceramic high *Q* dielectrics in 3G near antenna filters will be unsuccessful.

Ceramic coaxial filters are becoming less common in cellular handsets, and are used more in infrastructure applications, including as delay line filters, and as Transmit/Receive filters in WLL and WLAN and many other wireless application in and around the 1–2 GHz range. They offer cheaper and more compact solutions compared with metal filters.

Magnetic ceramics, invariably garnets, continue to be used extensively in cellular infrastructure integrated isolators, with the emphasis on cost, insertion loss and IMD. IMD is the most intractable in terms of understanding all of its causes, and is the subject of ongoing research. Hexagonal ferrites may have a part to play as microwave inductors, absorbers and antenna elements.

Acknowledgements

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References

1. Hill, M. D., Cruickshank, D. B. ACERS AMA.1-A-01-2002, April 2002.
2. Webb, S. J., Breeze, J., Scott, R. J., Cannell, D. S., Iddles, D. M. and Alford, N., *J. Am. Soc.*, 1753, **85**, 2002.
3. Cruickshank, D.B. ACERS AMA A3A-01-2001-1, April 2001.
4. Endo, K., Fujimoro, K. and Murakawa, K. J., *Am. Ceram. Soc.*, 1987, **70**, C215.
5. Ahn, C.-W., Nahm, S., Lim, Y.-S., Choi, W., Park, H.-M. and Lee, H.-J., *Jpn. J. Appl. Phys.*, 2002, **41**(8), 5277–5280.
6. Hughes, H., Iddles, D. M. and Reaney, I. M., *J. Appl. Phys. Letters*, 2001, **79**(18), 2952–2953.
7. US patent No 5,262,370.
8. US patent No 5,635,121.
9. Lee, H.-J., Kim, I.-T. and Hong, K. S., *Jpn. J. Appl. Phys.*, 1997, **36**(10A), 1318–1320.
10. Kim, D.-W., Ko, K. H., Kuon, D.-K. and Hong, K. S., *J. Am. Ceram. Soc.*, 2002, **85**, 1169–1172.
11. Miura, T., Hasegawa, M. IEEE IMS 2000 WMD-10.1, June 2000.
12. How, H. and Fang, T. M. C., *Vittoria IEEE Trans MTT*, 1997, **45**, 245–252.
13. Matsumoto, M. and Sakakura, M., *Am. J. Ceram. Soc.*, 1995, **78**(10), 2857–2860.
14. Nakamura, T. and Hatakeyama, K., *IEEE Trans. Mag.*, 2000, **36**(5), 3415–3417.