MATERIAL SELECTION FOR CERAMIC T/R MODULE PACKAGES

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Abstract

Multi-layer cofire ceramics technology offers the basis of package solutions for RF front-end, such as T/R modules, by embedding reliable 3-dimensional microwave transmission lines and transitions within the ceramic structure. The technology also offers an increasing number of materials with various electrical, mechanical, and thermal properties that create unique matches to specific applications. Choosing the right material is a fundamental step in package designing, which is an integral part of the module and system designing. The objective of this paper is to describe pros and cons of various ceramic materials for T/R module application.

1. Introduction

Phased array antennas have widely replaced mechanically scanning antennas in high performance radar and communication systems. By controlling 100s, 1,000s, or tens of 1,000s of radiating elements, each equipped with a transmit-and-receive (T/R) module, phased array antennas can achieve nano-seconds scan speed, higher resolution and accuracy, increased range, and higher overall system stability. Active electronically scanned array (AESA) is a common upgrade to its passive version of phased array and a significant improvement in terms of the efficiency and stability by installing MMIC amplifiers in each of its T/R modules. [1]

The objective of this paper is to compare currently available ceramic materials for T/R module packages that meet both performance and cost objectives of AESA beyond its prototype stage.

While the AESA concept has been proven for more than a decade by its development and prototype stages, the actual implementation of production-level systems is in the work for less than 5 years mainly due to the complexity of the final system and the prohibitive cost projections, which can go as high as $100 million per system. A significant portion of the antenna performance and cost belongs to those of its T/R modules. For AESA to be viable, T/R modules will need to be built at a lower cost for the current or a higher performance target. [2] [3]

2. T/R module package objectives

A T/R module is a self contained unit with RF amplifiers and a phase/gain controller, driving a single or group of radiating elements. The performance of this unit will be determined by the following module design characteristics; operating frequency, instantaneous band width, peak power output, receiver noise figure, pulse rise/fall time, case operating temperature and others. [4] Many of these characteristics are affected by the package design and material selection. The objectives of package design for T/R module can be summarized as follows:

1) Maintain high RF signal fidelity.
2) Minimize RF signal power loss.
3) Increase mechanical reliability.
4) Maintain operational temperature under the limit.
5) Minimize overall cost.
6) Minimize size and weight. [5]

In 1980's and 1990's when the modules are developed as prototypes, the package consisted of several planer substrates soldered onto a metal box brazed with also planer ceramic feedthroughs. This type of packages, called "discrete-substrate packages", was easy to design, but very difficult and expensive to assemble, requiring labor-intense RF tuning from feedthrough to substrate and vice versa. These packages tended to be 2-dimensional and long, forcing to have long microstrips. To avoid the difficult and expensive assembly process, the package design has evolved to an integrated approach which uses a monolithic ceramic body with brazed metal features. It has integrated the metal container, feedthroughs, and substrates together to eliminate the critical tuning process and reduce the cost of the module. The integrated packages have 3-dimensional routing with well shielded shorter striplines and weigh much less. Integrating RF connectors to the package for the module-to-manifold interfaces can also drastically improve the system reliability by insuring robust and efficient signal interfaces. This will significantly reduce the cost of antenna assembly and the maintenance down the way by eliminating a labor-intense and critical operation. [6]

Ceramic offers ideal characteristics to hi-reliability packaging. It is mechanically robust and chemically stable at a wider range of environmental conditions than organic materials; hence, it can protect the devices with a high level of reliability. Its dielectric property can, not only insulate the electricity, but also provide paths to high frequency signals without excessive energy loss. Co-fire technology can imbed circuits within and on the surfaces of the structure with relatively high precision. The physical features of a typical T/R module package (Fig.1) include cavities with or without heat sink metal, microstrips, striplines, transitions that are properly matched for the operating frequency, thousands of vias working as vertical shield, several routing layers for DC power and ground distribution, brazed seal ring for hermetic lid seal, and electrical interfaces, such as pins, leads, and connectors. As a manufacturer’s point view, these features demand the most advanced simulation tools and techniques to design, as well as they challenge the limit of feasibility with mechanical tolerances achievable by the advanced tools and years of production know-how. The difficulty is particularly evident as the module’s operating frequency goes higher than 10 GHz and the overall package size becomes smaller in order to avoid resonance and fulfill the half-wave-length spacing requirement. The package material needs to be ”easy to work with” to overcome all the manufacturing challenges while providing with superior electrical, mechanical and thermal properties.

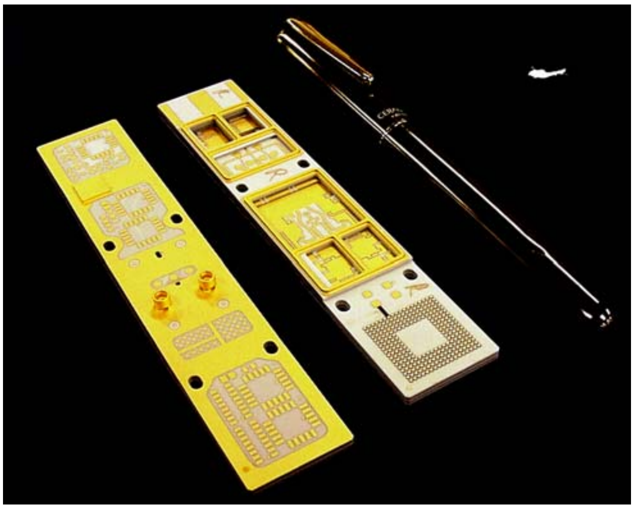


Fig. 1: A typical integrated T/R module package with deep cavities, heat sink, seal rings, and RF connectors. Material is alumina. Courtesy of EADS Astrium, UK.

3. Key material characteristic considerations

(1) Electrical evaluation

Loss budget is the central part of the electronic system design from top to bottom. The loss budget of package is specified after considering both system requirements and physical capability. Sometimes it is one of the highest priorities of the package spec, and sometimes it is more of a target. The choice of the material can be a significant factor from loss budget point of view, particularly, if the system has uncompromised performance specs where the designer would try to save extra 0.1 dB even with a large cost increase. The electrical properties critical to this discussion are dielectric constant, loss tangent of the ceramic, and conductivity of the conductor. These values have been measured and well documented as a basis of microwave engineering. These 3 physical properties can be converted to an attenuation constant by a number of theoretically and experimentally deduced formulae for each of transmission line types; microstrip, stripline, and coax. [7] [8] The attenuation constant has a unit of a loss-per-length. These attenuation constants can be used to estimate the loss of RF signal power along particular geometries of complex RF paths (Fig 2) by multiplying with the length of the path segment of applicable transmission line type, then, adding altogether. This indicates that the loss is also a strong function of the geometry, such as the line width and length. The loss can be minimized even more effectively by creatively re-designing the package with wider and shorter RF lines.

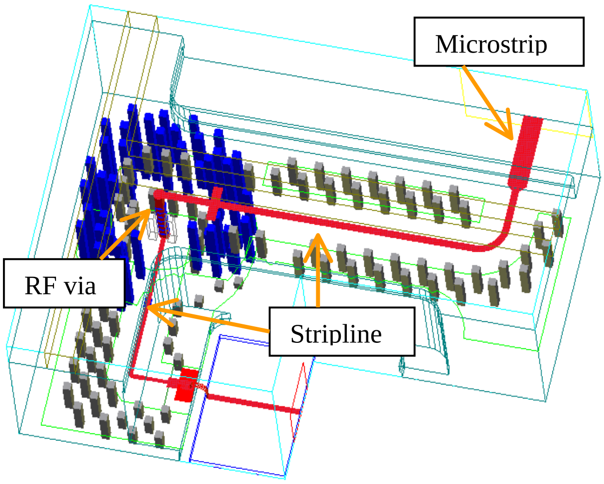


Fig. 2: A typical 3-D RF path in the integrated T/R module. The path (transmission line) has microstrip, stripline, RF via (coax mode) segments.

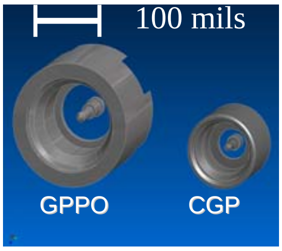
The passive integration is another factor to the material selection. Low temperature cofire ceramics (LTCC) can imbed resistors, capacitors, and inductors within or on the surfaces of the structure with varied tolerances. [9] Both LTCC and high temperature cofire ceramics (HTCC) can incorporate filters even though they take relatively large areas. The key factors are again dielectric constant, loss tangent, and conductivity. In addition, the availability of thin ceramic tapes, such as 2- or 3-mil thick, is a necessary condition to realize meaningful capacitors. Due to the compromised tolerances of internal features, where the laser trimming is not an option, the internally embedded resistors are not often considered. The surface resistors are the most common passive devices on T/R module packages. They can be substituted with the alternative discrete devices, which require extra assembly, but offer a larger range of resistor values and a more flexible implementation.

(2) Mechanical evaluation

The most important aspect of any hardware is the reliability, assuming it is already proven manufacturable. Ceramics are strong and hard, but also brittle. T/R module packages require, as a minimum, the standard MIL-spec-level reliablity conducted by thermal shock and temp cycle and subsequent hermeticity test to guarantee its structural integrity. For the package application almost all ceramic materials show much more than sufficient flexural strength and hardness. The brittleness, often indicated as low fracture toughness, negatively contributes to the integrity of stressed points, such as brazing joints, sharp cavity corners, and thin wide ledges. The substrate materials have been tested until the reliability is proved with statistical confidence before they are available in the commercial market.

Metal components, such as seal rings, heat sinks, and connectors are attached to metallized ceramic surfaces by brazing operation where a choice of copper-silver, gold-germanium, and gold-tin eutectic alloys, typically, is melted and re-solidified as a bonding medium. High temperature braze, such as copper-silver, is more reliable than low temperature braze, such as gold-germanium and gold-tin. The thermal expansion mismatch between the ceramic and any of these metals adhered will cause a permanent stress after cooling. It is up to the ceramic material, the ceramic-to-metallization interface, and the braze alloy to withstand the residual stress as well as additional stresses caused during subsequent heat processes. Seam sealing requires local welding between the seal ring metal and a metal lid. Keeping the hermeticity of the sealed area after seam sealing is a general requirement of packages. The hermeticity is a proof of flawless braze joints and the consistency in achieving hermeticity is a proof of brazing reliability from the material and process points of view.

The reliability of braze joints is a crucial subject of connector integration. (Figs 3 and 4) As it is mentioned earlier, RF connectors can be a key feature to drastically improve the antenna assembly quality and cost. Due to a limited contact area, brazing connectors reliably is more difficult than brazing a seal ring or a heat sink. It is regarded as one of the key material characteristics to have a reliable brazing system for this type of small features. The reliability needs to be proved statistically.



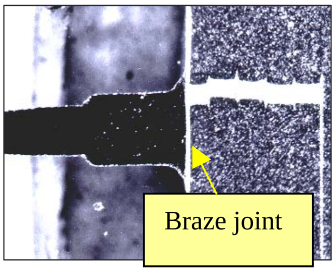


Fig. 3 (left) : Brazable RF connectors [3]
Fig. 4 (right) : Braze joint of the connector pin on the ceramic. [3]

(3) Thermal evaluation

A typical T/R module requires a use of high power amplifier (HPA) that releases heat more than ceramics can usually dissipate. A use of heat sink, such as copper moly, copper tungsten, often satisfies the heat flow requirement of the package; hence, the issue goes back to the mechanical reliability of brazing. It is not common that T/R module package material to be chosen based on its thermal property for this reason. Heat flow requirement will only increase in the future when gallium nitride based MMIC HPA comes out at which time far more highly conductive heat sinks are required. Use of thermal vias is an option to dissipate the heat of low power amplifiers. A ceramic with a high thermal conductivity, such as aluminum nitride, will be used if the geometry of package doesn't allow heat sink attachment. A good example is found in a tile-shape antenna architecture where radiating elements, T/R modules, and manifolds are vertically interconnected. [6] [10] The heat dissipation is inevitably co-worked with the cooling mechanisms outside of the package. A liquid cooling system or a forced air flow system is a standard feature to cool T/R modules. The thermal requirement is often reduced to the requirement of the temperature that this outside cooling system can maintain.

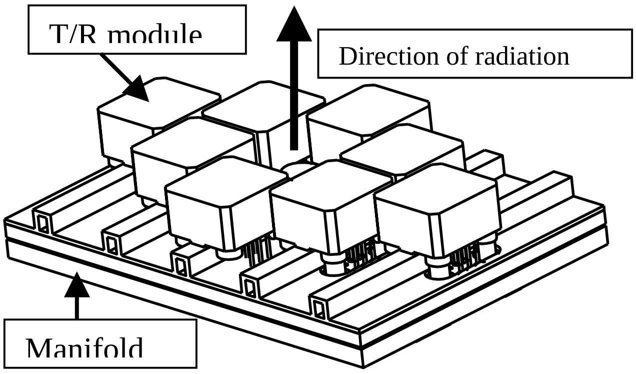


Fig. 5: A sketch of a tile-shape antenna architecture. The module (package) may not have heat sinks. [6]

4) Cost evaluation

Along with the hardware reliability, the cost is an absolutely critical factor for T/R module packages in the production stage (i.e. after the prototype stage); hence, it is one of the most critical factor in package material selection as well. Since the number of modules per system is as high as 100s, 1,000s or even tens of 1,000s, a high T/R module cost can deny the existence of whole system. The cost reduction plan from prototype stage to the production stage can not be neglected. The development and manufacturing of an antenna system is a long term project, often times over a decade. Before even the cost is discussed, the long term availability of the candidate material has to be gauranteed.

In some systems the modules will seek a higher electrical performance with cost increase. In others the modules will compromise any spec other than the mechanical reliability and fair electrical functionality for the cost reduction. The package itself takes a fairly large potion of the module cost. Although extra features in the package, such as RF connectors and imbedded passives add to the package cost, they can reduce the module assembly cost and the antenna integration cost. Therefore, the cost evaluation should be done, in terms of not only the packages themselves, but also resulting assembly benefit the extra package feature could bring in as a result of the selection of the particular material.

4. Material comparison

Four ceramic material groups are compared to identify pros and cons of each group, based on the electrical, mechanical, thermal and cost perspectives. The ceramic materials for T/R module packages can be roughly categorized into:

1) Alumina with thick-film tungsten (inner) and plated gold (surface),
2) Medium-loss LTCC with thick-film gold (inner and surface),
3) Low-loss LTCC with thick-film gold (inner and surface), and
4) Aluminum nitride with thick-film tungsten (inner) and plated gold (surface).

Table I

	ε_r 2 GHz	ε_r 10 GHz	tan δ 2 GHz	tan δ 10 GHz	Sheet resistance [mΩ/sq.]
Al_2O_3	8.5	8.5	0.0010	0.0013	8 - 10
Med LTCC	7.8	7.8	0.0050	0.0060	<5
Low LTCC	5.9	5.9	<0.002	<0.002	2 - 5
AlN	8.6	8.5	0.0170	0.0038	8 - 10

Table I lists typical values of dielectric constants and loss tangents of these ceramics at 2GHz and 10GHz and sheet resistance of the respective conductor materials. [11] [12] [13] Although this table does not indicate the whole picture, it is well known that low-loss LTCC materials outperform the other groups in terms of loss at high frequencies. To obtain a better understanding of losses, attenuation constants were calculated for various widths of 50-ohm microstrip (MS) and 50-ohm stripline (SL).

An on-line loss calculator (TX) was used to obtain figures 6 and 7. The attenuation losses of both microstrips and striplines were calculated at 10 GHz for various line width by keeping impedance at 50 ohm while changing the dielectric thickness. It is seen that the loss-per-inch values can be decreased if a lower-loss material is used or the width of transmission lines is increased. Although the conductor loss of LTCC is lower than that of HTCC due to the conductivity of gold being better than that of tungsten, a higher dielectric loss of medium-loss LTCC than alumina makes the combined loss-per-inch higher than that of alumina as the width of MS and SL increases.

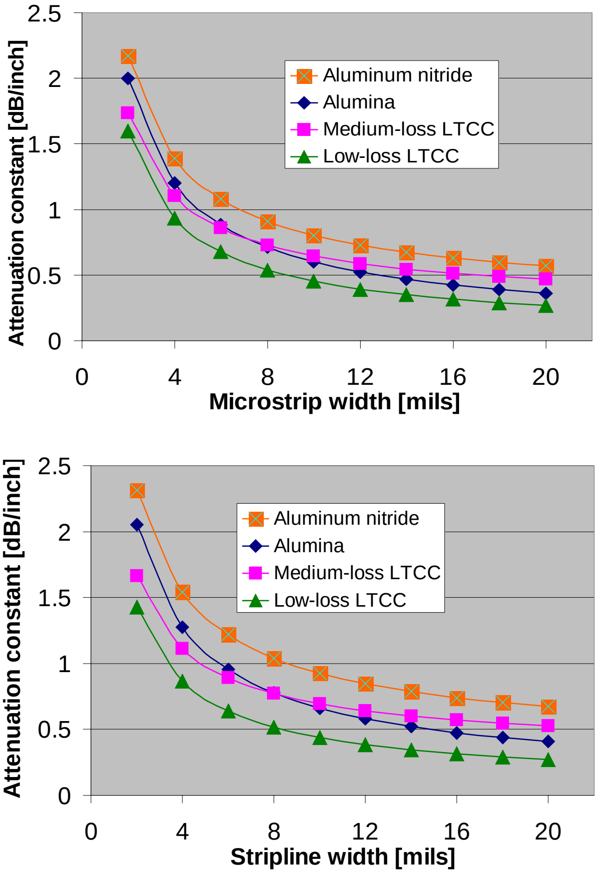


Fig. 6 and 7: Calculated attenuation constants at 10GHz for vaired microstrip width (top Fig. 6) and stripline width (bottom Fig. 7) both at 50 ohm for the 4 materials.

A more practical loss comparison was made with examples of T/R module designs. The RF path length from the HPA (the last amplifier in the transmit chain) to the radiator interface and the radiator interface to the LNA (the first amplifier in the receiver chain) was measured and summed up for each line type, MS, SL, and via (coax-mode). The attenuation constant of MS was multiplied with the sum of MS length and the attenuation constant of SL was multiplied with the sum of SL length, and so on. These values were added to obtain the loss value, which is no longer loss-per-inch. Assuming that the same line width and length are used for the 4 materials while varying the dielectric thickness to keep 50-ohm, the loss values were obtained and compared among the materials. It is an imaginative comparison only concerning the effect of dielectric constant, loss tangent, and conductivity on the losses by MS, SL, and vias without considering losses in transitions. The resulting loss values should be looked at only in a relative scale between materials, but not as an estimate of absolute number.

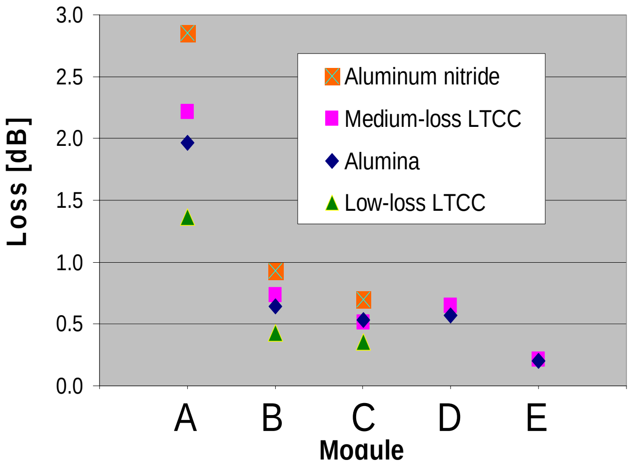


Fig. 8: Loss comparison of 4 material groups on 5 different T/R module geometries. Modules A, B, and C are X-band (10GHz), Module D is S-band (3GHz), and Module E is L-band (1-2 GHz). Note: Modules D and E have only alumina and medium-loss LTCC data.

The results with 5 T/R modules are shown in Figure 8. Modules A, B, and C are in X-band. Module D is in S-band and Module E in L-band. Module A has long transmission lines that make the loss higher than two other X-band modules that have shorter lines. Modules D and E have long transmission lines, but due to lower frequencies, they have smaller loss values. The effect of material difference based on the dielectric constant, loss tangent, and sheet resistance (or conductivity) is put in perspective with the module geometry factor or the frequency factor as a rough estimate. Alumina HTCC has similar losses to those medium-loss LTCC has up to 10 GHz.

Table II

	Flexural strength [Mpa]	Modulus of elasticity [Gpa]	CTE (25-400°C) [x10^{-6}/K]	Themal conductivity [W/mK]
Al_2O_3	314	265	7.0	19
Med LTCC	320	152	5.8	3
Low LTCC	210	92	7.0	2
AlN	400	320	4.7	170

Table II lists typical values of flexural strength, the modulus of elasticity, CTE, and thermal conductivity data from these ceramics. The low-loss LTCC materials contain a higher content of glass phases, which is reflected to lower flexural strength and modulus of elasticity. The brittleness increases as the glass content increases.

Despite slight differences in the strength values, the ultimate reliability factor depends on the package geometry. The co-fire ceramic technology has its limit in creating complex shapes and bearing structural stresses; such as deep cavity, wide cavity, sharp cavity corner radii, thin long wide ledges, tall narrow walls, CTE mismatch with metals, etc. The material strength is only a factor, along with reliability specification, to determine how much more complex geometry the design can take. Even though alumina HTCC has gained the highest trust in structural reliability after being tested in many designs of T/R module packages, the feasibility and the reliability heavily depend on the geometrical details. The use of medium-loss LTCC requires slightly more conservative designs than those for alumina. The use of low-loss LTCC requires quite protective approach.

5. Conclusion

As of today, low-loss LTCC materials have not been used in complex monolithic T/R module packages which would be brazed with seal rings and heat sinks while the medium-loss LTCC and the aluminum nitride materials are only starting to be tested for ”beyond-prototype” stages of monolithic packages. The low-loss LTCC can be used in the metal packages (or ”containers”) as discrete substrates. The cost and weight of the metal package and the cost of extra assembly need be compensated by superior performances and possible benefit of passive integration. In applications where the heat sink brazing is not possible, use of aluminum nitride is desired despite a higher electrical loss at around 10 GHz and higher manufacturing difficulty than other materials, which translates to a higher cost. Medium-loss LTCC material can realize electrical performance and workable mechanical reliability as a T/R module package material while the cost is inevitably higher than alumina, due to the use of gold or silver as its conductor**.** The use of this material may be justified by passive integration and/or broader band capability with slightly lower dielectric constant. Alumina is the current standard up to X-band, due to better reliability and cost than other materials. Its electrical performance is comparative to medium-loss LTCC.

Regardless of what material to choose, the shortcomings of the material should be compensated by the package design and its physical geometry, as well as the strong points of the material should be fully utilized by the same. Continuous development of materials is needed for performance improvement and cost reduction.

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