RTT TECHNOLOGY TOPIC
April 2015

Millimetric Materials

Our November 2013 technology topic, The Second Age of the Atom, summarised progress with graphene including IBM research on graphene for high Ft active devices.

http://www.rttonline.com/ttopics/tt2013.html

This included the potential use of graphene to improve the performance of printed circuit boards. In the past 18 months the increasing interest in the use of millimetre frequencies between 30 and 300 GHz for 5G mobile broadband networks has motivated an increase in materials research.

This is in response to the specific challenge of implementing 5G at E band above 70 GHz combined with a range of modulation and coding options which deliver high spectral utilisation but require close control of phase noise and distortion.

The materials research includes optimization of existing integrated circuits based on gallium arsenide and silicon semiconductor processes including silicon CMOS and silicon germanium.

The physical size of a high frequency transmission line is dependent on the dialectic constant of the PCB material. The constant is the ratio of the permittivity of the material compared to free space. A lower ratio means the material concentrates electric flux more efficiently. For 50 ohm impedance, the width of the transmission line reduces as the dialectic constant reduces. The resulting circuit dimensions are more compact but can be hard to fabricate and variations in the dielectric constant across the circuit board can introduce phase distortion. The constant needs to stay constant over temperature and time.

Reinforcement materials used in the circuit board such as glass weave, can additionally disturb signal propagation velocity. These impairments are familiar to engineers requiring phased matched channels in radar systems and are now becoming, or should be becoming, more familiar to 5G design teams.

Millimetre wave circuits also require low dissipation. Any roughness of a copper surface will produce high conductor losses at higher frequencies. Thinner laminates are generally needed to minimize unwanted resonances but this in turn can cause fabrication issues including tolerance and yield. Selecting modulation and coding options purely on the basis of spectral utilisation is therefore ill advised and needs to be tempered with an understanding of the associated component fabrication cost and risk of performance impairment in devices realised at consumer price points that need to be an order of magnitude lower than they are today.

This month's topic draws on a paper written by Tarun Amla of the Isola Group, Chandler, Arizona published in the February 2015 edition of Microwave Journal. Used with permission and with thanks.
http://www.microwavejournal.com/articles/23810-new-thermoset-pcb-material-emerging-for-mmwave-applications
http://www.isola-group.com/
Additional resources are available on the Rogers and Laird web sites
http://www.rogerscorp.com/acm/index.aspx
http://www.lairdtech.com/
Our thanks to Paul Cooper of Quovo for comments and suggestions www.qorvo.com

Printed circuit boards started being used in consumer radio receivers after the Second World War. The thermal plastic polymer, Polytetrafluoroethylene (PTFE) had been discovered in April 1938 at the Dupont Research Labs. Combined with woven glass, these lithographically printed circuit boards were robust enough to be used in ordnance applications including anti-aircraft proximity fuses.

In the 1950's a thermosetting industrial fibreglass composite laminate of filament glass cloth with an epoxy resin known as FR4 was introduced and is still in widespread use today. It is strong, moisture resistant and has excellent electrical properties – at least up to microwave frequencies.

http://www.microwavejournal.com/articles/23790-stem-works-february-2015

The basic principle of a printed circuit board is to produce a sandwich of thin electrically conductive layers and insulating layers of polymer, glass, ceramic or polymer filled with glass or ceramic. Over time the number of layers has increased together with the need to support RF and digital technologies and the mechanical and thermal properties of the dielectrics have become more important as has the requirement to handle more power.

Millimetre wavelengths (10mm to 1 mm) and frequencies (30 to 300 GHz) are particularly challenging for PCB materials. The standardized methods and techniques for measuring dielectric constant become increasingly inaccurate and unreliable. The designer is faced with conflicting performance requirements including dielectric loss, thermal stability, thermal management, layer count, twist and warp resistance, stability with humidity and temperature, thermal cycling tolerance, power handling capability and passive intermodulation.

The skin depth of copper at millimetre frequencies is extremely small. This means that surface roughness translates directly into attenuation loss producing conductor losses which can exceed dielectric loss. This can be reduced by using smooth high purity copper though this increases cost.

Products shipped at consumer price points and or at lower frequencies will generally use a mix of FR-4 and RF optimized substrates but scaling this approach to millimetre frequencies particularly for devices combining high speed digital and RF functions is problematic.

It is generally assumed that PTFE is stable with temperature however the crystalline structure of the material and the manufacturing process (sintering) produces a range of crystallinity which will produce batch to batch variation. The material can also suffer permanent deformation, also known as creep, at close to room temperature. The impact of this is relatively trivial at lower frequencies but significant at frequencies above 70 GHz and has been a particular design concern for automotive applications with a sub-zero to 85 degree C temperature gradient. The lower expansion coefficient of copper also introduces a risk of fatigue failure from high plastic strains. Hybrid mixes of FR4 and ceramic filled substrates will have a tendency to delaminate due to temperature cycling and higher layer board combinations are likely to oxidize.

These problems can be mitigated by using different filler materials but these are often highly abrasive and result in high drill wear for the inter layer through holes. The drilling costs can be higher than the material cost. Alternatives such as plasma drilling can be used but are equally expensive.

All of the above has led to work being done on finding combinations of materials that deliver a more optimum compromise between electrical and thermal mechanical properties and cost, essentially thermoset materials that behave like standard FR4 but with properties that do not degrade with temperature.

The materials need to have low conductor loss both to minimize power consumption and to limit heat rise on the board. Conductor surface roughness not only increases parasitic capacitance but also results in a phase constant that will change in frequency, affecting phase and group velocity.

These effects can be mitigated by using low profile copper which also reduces insertion loss and heat rise but this in turn requires a thermoset that provides high peel strength even when smooth low profile copper is used. Lower loss also increases power handling capability. The thermoset needs to have good predictable dimensional stability, low drilling cost and similar flow and fill behaviour to FR4. The desired and required outcome will be low cost multi-layer printed circuit boards optimised for mixed RF/digital signal processing at millimetre frequencies across extended temperature gradients.

Summary

Our February technology topic, Automotive Radar, http://www.rttonline.com/ttopics/tt2015.html, highlighted the importance of E band 77 GHz automotive radar market as a development platform for high performance RF for extreme operational conditions (vibration, moisture and heat gradient).

The January technology topic, Defence Spectrum - the new Battleground http://www.rttonline.com/ttopics/tt2015.html, highlighted the importance of the E band mobile broadband defence market as a development platform for higher power RF including RF for long distance telemetry and system control. This includes the development of low Coefficient of Material Expansion (CTE) polymers with good electrical characteristics for E band transceiver printed circuit boards.

Graphene may have a role to play in producing thermally and electrically optimised printed circuit boards though present research is focusing more intently on energy conversion and storage where the combination of high electrical conductivity, physical flexibility and high surface to weight ratio opens up particular opportunities in electric charge storage in batteries and super capacitors and as catalysts in solar and fuel electrodes. By comparison, thermoset PCB material innovation may seem prosaic but is likely to have a more fundamental short term impact on the cost and performance economics of 5G-E band network and user devices.

The cellular market in 1982 was crucially dependent on the availability of stable low cost high quality FR4 capable of working efficiently at 800 and 900 MHz, a key enabler for base stations and user equipment. Thirty five years on the same material, mechanical and manufacturing constraints apply and need to be factored into 5G mobile broad spectrum planning, technology planning and the economic modelling of wide area high data rate delivery cost.

A note about dielectic constants and microstrip lines

The microstrip line is transmission-line geometry with a single conductor trace on one side of a dielectric substrate and a single ground plane on the opposite side. In a microstrip line, the electromagnetic (EM) fields exist partly in the air above the dielectric substrate and partly within the substrate itself.

The effective dielectric constant of the line is therefore expected to be greater than the dielectric constant of air (1) and less than that of the dielectric substrate.

There are three types of losses that occur in microstrip lines: conductor (or ohmic) losses, dielectric losses, and radiation losses. An idealized microstrip line, being open to a semi-infinite air space, acts similarly to an antenna and tends to radiate energy. Substrate materials with low dielectric constants (5 or less) are used when cost reduction is the priority.

Similar materials are also used at millimetre-wave frequencies to avoid excessively tight mechanical tolerances. However, a lower dielectric constant translates into a lower concentration of energy in the substrate region and, hence, higher radiation loss. Radiation loss depends on the dielectric constant, the substrate thickness, and circuit geometry.

The use of high-dielectric-constant substrate materials reduces radiation losses because most of the EM field is concentrated in the dielectric between the conductive strip and the ground plane.

The benefit in having a higher dielectric constant is that the package size decreases by approximately the square root of the dielectric constant. This is an advantage at lower frequencies but may be a problem at higher frequencies due to manufacturing tolerances. In most conventional microstrip designs with high substrate dielectric constant, conductor losses in the strip conductor and the ground plane dominate over dielectric and radiation losses.

Parameters related to the metallic material forming the strip, ground plane and enclosing walls, for example conductivity, surface roughness and skin effects, determine the conductor losses.

When designing antennas at millimetre wavelengths, the same effects need to be taken into consideration though the design aim is of course to maximise rather than minimize radiation loss!

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