Microwave and mm-meter wave applications: a new challenge for ceramic thick film technology.

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Abstract

Applications for microwave circuitry are expanding rapidly, particularly in the field of portable communication systems, and the operating speeds of digital integrated circuits (ICs) continue to increase, creating the need for suitable interconnect materials, integrated components and packaging solutions.

Several papers have been written in the last five years to describe the characterisation and the performance of ceramic thick film in high frequency applications and to compare these properties with other interconnect technologies such as thin film and high performance PWBs under the same test conditions.

This paper briefly discusses these issues and reviews the reasons for the choice of thick film in some recent microwave and mm-wave modules for wireless communication and airborne radar applications, where the operating frequencies are in the medium-high GHz range. In particular, different modules are discussed and details given of their design and construction.

The first two examples considered are two converter modules, both mm-wave, one Down-Converter operating in the 7.0-8.5 GHz frequency range and one transmitting Up-Converter, operating at a frequency of 23 GHz. Both modules have been manufactured using thick film materials on alumina substrates.

The other applications described are a highly integrated mm-wave module operating in the frequency range of 27 to 30 GHZ and a high power Ka band amplifier. Both application use LTCC multi-layer substrates.

The paper also reviews in some detail the packaging solutions adopted in each case, including some information about the choice of materials, components and interconnect technologies.

Key words: ceramic substrate, ceramic thick film, converter modules, LTCC, microwave, mm-wave, multilayer materials, wireless communications.

Introduction

Wireless communications continue to grow at a very fast rate, notably enhanced by the rapid expansion of portable communication systems and open an important market opportunity to electronic interconnect technologies, having excellent performance in the high frequency range.

These applications require digital and linear ICs, with increasing functional density and faster signal processing, as well as high performance transmitter and receiver circuits. The first part of the presentation will deal with the development of the characteristics of advanced ceramic materials in the frequency band between 500 MHz and 20 GHz. These ceramic materials include thick film conductors on alumina substrates and circuits using Green Tape™ (LTCC: Low Temperature Cofired Ceramics). Conductor patterning techniques include conventional screen printing, Fodel® photoimaging and etching processes. Thin Film depositions have also been considered, since this has been the most viable technology, and, until mid-nineties probably the only one, to fabricate microwave circuits above 1 GHz. These data have been benchmarked against printed circuit boards (PCB) laminates, including PTFE based PCBs. Although in the range between 1 GHz and 20 GHz, where most of the current portable communications are operating, the differences in attenuation values are not large, some other considerations become important, such as the fact that ceramic MCMs facilitate tuning, reduce passive components and circuit size and simplify thermal management, thus providing an attractive balance between performance and cost. Most portable phones available on the market include, since many years, ceramic power amplifiers manufactured on alumina and, more recently on LTCC. In fact one of the most successful interface example of ceramic thick film/LTCC application for short range wireless connectivity and data transmission has been Ericsson's Bluetooth.

It is important to note that the fabrication of microwave circuits requires a close involvement of the designer, from circuit layout to final production, because of the special geometries required for transmission and receiver lines, for waveguides, to limit reflection and propagation losses, as well as for the construction of specific components, such as couplers, dividers, filters, inductors and frequency multipliers. It's also important to say that thick film elements have been used in microwave circuits for many years.

Since the mid nineties, more opportunities have arisen for the use of ceramic circuitries for high frequency modules, enhanced by more information available on their performance in the GHz range and by new material offering, including LTCC and FODEL® photodefinable conductors, for such applications.

The second part of the presentation will deal with specific microwave and mm-wave applications developed recently to illustrate the advantage of thick film approaches from a technical and performance standpoint.

High Frequency characterisation of materials from 0.5 to 20 GHz

Typically, low frequency data are available based on capacitor measurements obtained with inductance-capacitance-resistance (LCR)meters or impedance analysers, up to 100 MHz frequency. Higher frequency are often based on bulk material measurements in single frequency resonant cavities.

Recognising the need for broader higher frequency data, a test method using a microstrip-resonator test pattern has been developed during mid-nineties at DuPont Electronic Technology, Microcircuit Materials at RTP, North Carolina, to measure the characteristics of materials across the 0.5 and 20 GHz range.

Details of the test method are described in the reference works [1][2][3].

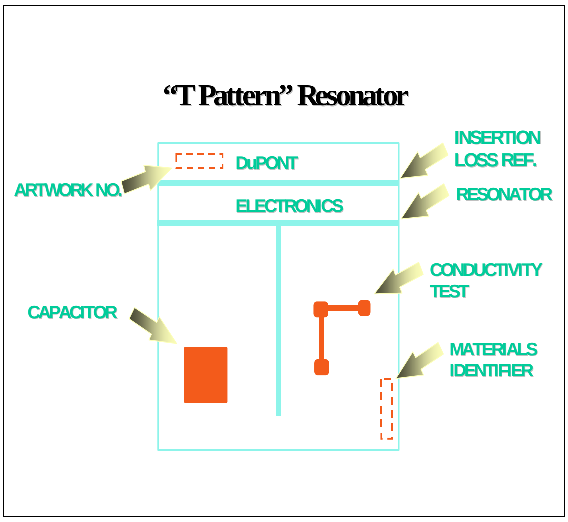

Fig.1 T-pattern resonator to measure material properties over a broad frequency range.properties over a broad frequency range.

Figure 1 shows the typical T-pattern resonator; the circuit,, with overall dimensions 2" x 6", is designed to have a nominal characteristic impedance of 50 Ohm, with a stub length that results in a primary resonance at approximately 0.5 GHz. Line widths and stub lengths vary with the dielectric constant of the material. A microstrip configuration is used with the return plane on the opposite surface of the test circuit.

The transmission response of the T-pattern resonator; the resonant frequency at each null is used to determine the material's dielectric constant. The Quality factor (Q) is determined by dividing the resonant frequency by the 3-dB bandwidth at the null. The measured Q at each resonant frequency is then used to determine the attenuation and the material loss tangent.

In order to determine the material's dielectric constant, the effective dielectric constant at the primary resonance is calculated on the measured stub length, line width and resonant frequency. Corrections for open-end and T-junction effects are calculated from the line dimensions and measured impedance.

This calculation is repeated at each of the higher-resonant frequencies and additional corrections for dispersion are made using the physical impedance and primary resonance data

Dielectric constants, loss tangents and attenuation data were obtained and plotted in graphs not reported in this paper.

Figure 2 is a graphical summary of the 50Ω(ohms) microstrip attenuation versus frequency for the various material systems tested. Tested materials include: conventional FR4 PWBs, advanced PWBs (Polyimide and BT epoxy), Teflon® based laminates conventional LTCC Green Tape™ 951, using various conductors (Au, Ag and

FODEL® Ag) as well as on alumina substrates with thick film and thin film conductors. It can be seen that any of the conductors on 96% alumina, including thick film gold, thin film gold Fodel® gold and silver compositions, promise low attenuation relative to the more expensive PTFE laminates. LTCC exhibits lower attenuation than any of the conventional PWBs materials over the measurement range.

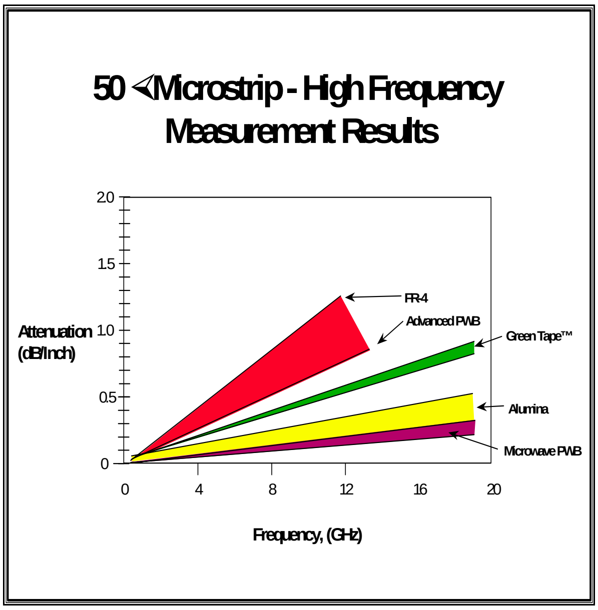

Figure 2. Attenuation measured for 50Ω microstrip lines on a variety of dielectric materials.

New materials have become available such as LTCC Green Tape™ 943 Low Loss material, that was developed in response to the increasing need for component interconnect technologies. The new material provides electrical attenuation equal or lower to the values obtainable using alumina circuits (thick and thin film).

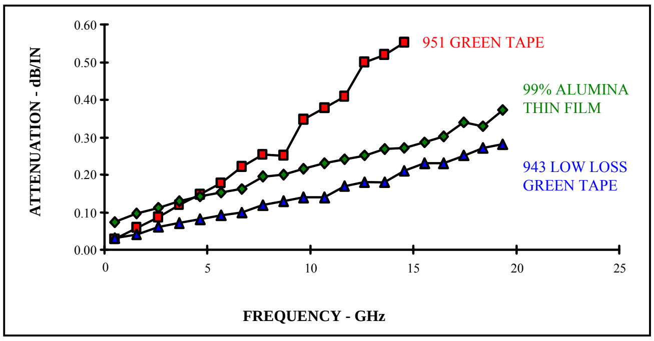

Figure 3. Comparison of 50Ω microstrip lines attenuation measured on Green Tape™: 951 and Low Loss 943, and conventional alumina substrates.

These two graphs illustrate the benefits of using ceramic circuitry in the very high frequency application range. In addition to excellent electrical characteristics shown above, ceramic circuitry provide other advantages such as:

- Low dielectric losses over a wide frequency band;
- Low to medium permittivity, allowing for small structures for RF;
- Good control of dielectric thickness for impedance control;
- Integrating electrical components and functions provides high density and miniaturisation;
- Stable electrical properties under severe environmental conditions;
- Wide range of assembly methods: flip chip, chip & wire, soldering and epoxy attachment;
- High mechanical stability of the circuit structures;
- Good thermal conductivity compared to PCBs;
- High temperature stability of the material (up to 300°C) ;
- Excellent TCE match to semiconductor materials.

Thick film for microwave and mm-wave applications.

As mentioned, thin film started before thick film for microwave applications and allowed to fabricate high performances, repeatable and reliable RF circuits; however at the beginning of the nineties, when the demand for high frequency and microwave circuits began to grow, thin film became less attractive because of its cost and its difficult sourcing.

Thick film elements have became the natural alternative to other available interconnect solutions for several reasons:

- electrical properties: as shown in the previous section of this paper, thick film on alumina exhibit excellent and stable electrical properties, close to the ones exhibited by Teflon® based PWBs;
- cost: lower cost versus thin film and Teflon® based PWBs;
- design and circuit layout: alumina circuits, having a dielectric constant K of about 9-10, allow the design of electrical functions such as filters, mixers, couplers and frequency multipliers using microstrip configuration;
- thermal dissipation: ceramic substrates provide high thermal conductivity;
- conductors: a wide range of different metallurgy, high conductivity, thick film conductors is available;
- resistors: by using different resistive materials small and/or high power resistors are added and laser trimmed to value, with 0.5% accuracy;
- capacitors: single layer, multilayer and feedthrough capacitors can be integrated at +/- 30% tolerance;

● inductors: easy integration of spiral inductors and UHF coils;

● MMICs and PHEMTs: assembly of Monolithic Microwave ICs and Pseudomorphic High Electron Mobility Transistors on thick film substrates is exactly the same as with thin film; soldering (Au eutectic alloy), or conductive epoxy.

Examples of microwave and mm-wave Modules.

The first part of this section describes two different applications of thick film technology on alumina developed by Mi.Tel in Italy, part of Compel Electronic S.p.A. group, a company specialised in the design and production of microwave and mm-wave devices and subsystems.

The first photo shows a 7 to 8.5 GHz Down Converter. On the left, the RF input connector is seen connected to an isolator, printed on a 10 mil garnet substrate, with the terminating resistor printed on the same substrate. Next to it, is a two-stage pre-amplifier printed on a 10 mil (250µm) ceramic substrate. The garnet and alumina substrates are both soldered to the housing.

The two PHEMT's are soldered onto PdAg micro-strips; bias resistors (dark) and by-pass capacitors (blue) are printed onto the same substrate.

The DC supply comes from a miniature SMD connector soldered onto the thick film. After this, there is a 3-resonator image rejection filter. This is made of a gold material in order to obtain the greatest accuracy. The image, of less than 6 GHz, is filtered by more than 15 dB.

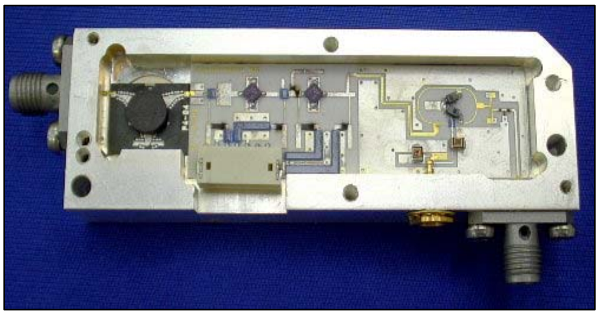

Figure 4. A 7.0 to 8.5 GHz Down Converter, showing thick film capability to obtain an integrated microwave function.

The ring-type mixer makes use of two plastic-packaged diodes. The IF output crosses the ring and reaches the MCX connector through a matching filter. The noise value of the entire module is less than 2 dB and the gain is more than 13 dB.

The DuPont thick film materials used are PtAg QS 264 and QM 17 conductors, Series 2000 resistors, 5744 gold conductor and, for the by-pass capacitors, K5505 high-k dielectric, and 5520 and 9615 encapsulants.

The circuit illustrates the capability of thick film to obtain an integrated microwave function, with only the active SMD components added.

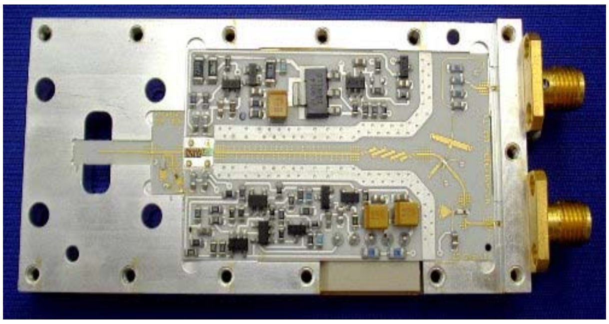

Figure 5. A 23.0 GHz transmitting Up Converter with SMT and 'chip & wire' technologies integrated in the same module.

The second photo shows a 23 GHz transmitting Up-Converter where SMT and 'chip and wire' technologies are integrated on the same module.
Seen, from left to right, are:

- the output wave-guide and the micro-strip adapter
- the detector stage, which is a flip chip, attached with conductive epoxy
- the amplifier, consisting of two MMICs. Both the conductive epoxy attach and the wedge bonding processes are performed using fully automatic machines.
- In front of the amplifier is the bandpass filter and a sub-harmonically pumped mixer, in the form of a flip chip diode.

Here again, the materials used are DuPont QS 264 Pt-Ag and QM 17 conductors, 5744 gold conductor and QM 42 dielectric. The alumina substrates, MMIC chips and chip capacitors are attached to the carrier by means of a suitable conductive epoxy adhesive.

This module is used on p-p FSK/CPM modulated radio links. The output power is adjustable from –30 dBm to +20 dBm and spurious outputs are below –30 dBm.

LTCC substrates for mm-wave applications

Similarly to alumina, thick film on LTCC present several additional advantages for microwave applications:

● Low to medium permittivity, which allows small RF structures to be buried and provide integrated electrical functions;

● Integration of passives (R,L,C) possible;

● Free availability of signal layers;

● High wiring density by using fine line conductors and micro-vias;

● Flexibility of structuring by laser or mechanical tools in the green stage and possibility of integrating channels and cavities.

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Highly integrated mm-wave modules using LTCC and metallised plastic covers.

Realizing subsystems and modules for Broadband Wireless Access (BWA) systems and multi–media services, such as LMDS (Local (Microwave Video Distribution System) are one of the activities of EADS Deutschland GmbH. EADS (European Aeronautic Defence and Space Company) in a joint development with Micro-System Engineering, MSE, have evolved and optimized a new approach for integrating MMIC, individual passive and semiconductor devices as well as microstrip components (couplers, dividers and filters) into a multifunctional package.

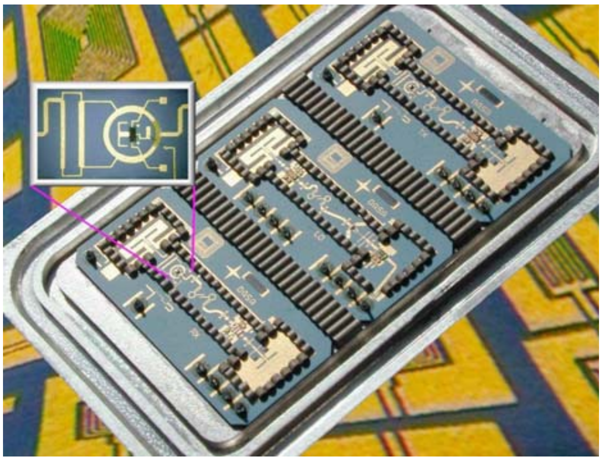

Figure 6. 27-30 GHz communications module

Modules based on this technology are being used in both communication and airborne radar applications. Initially, the following prerequisites were identified: multilayer connectivity, a sufficiently low millimeter-wave loss, good thermal management capabilities, high line resolution (down to 50 micron lines and spaces), high module reliability, and compatibility with soldering, conductive epoxy and wire bonding – all this while maintaining low overall weight and cost. This wide range of apparently contradictory conditions was finally fulfilled using DuPont Green Tape™ DP 951 with a number of screen-printed co-fire and post-fire process steps and soldering the obtained substrate to a conveniently mounted to the resulting flat carrier. A complex yet light weight and (in volume) low-cost metalised plastic cover provides external and internal shielding. It may be used for hermetical sealing, too.

Figure 6 shows a 27 to 30 GHz communications module. The circuit comprises three individual chains (bottom left to top right); Receive (RX), Local Oscillator (LO) multiplier and Transmit-Channel (TX). Integrated hermetical waveguide-to-microstrip transitions provide mm-wave input and output terminals. Flip Chip Schottky diode pairs are being used for up- and down-conversion employing a broadband rat-race mixer, which is part of the LTCC substrate (see insert top left). The narrow lines are 50 micron and are obtained by screen-printing. Special tooling and tight control of the screen printing process are necessary to meet these objectives. MMIC amplifiers are epoxy-mounted to die-bond areas that have thermal vias to provide a good thermal path to the iron-based powder-injection (PIM) base-plate.

All features on this base-plate including precise waveguide windows are obtained form a sintering process without further machining. The cover is metalized plastic providing waveguide backshorts, cut-off channels and additional shielding walls that guaranty more than 80 dB of isolation between neighbour chains. Low-resistance contact to ground is obtained by conductive silicon. The module can be sealed hermetically by a localized soldering process at the outer boundary of the base plate.

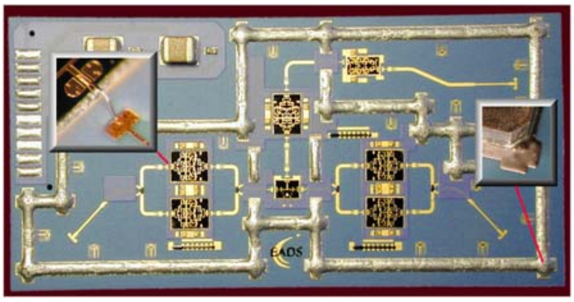

Fig. 7. LTCC substrate manufactured by MSE.

Further optimization was required to fulfill the more stringent weight-, volume and heat dissipation requirements of the second example shown below in Figure 7.

It was designed by EADS / LFK in Ulm, Germany and contains five Ka-band MMIC power amplifiers in CW operating condition. The LTCC substrate was manufactured and assembled at Micro Systems Engineering (MSE) in Berg. Due to the cooling requirements, a sophisticated step-soldering process was required. This included brazing to a molybdenum carrier, and the soldering and epoxy-attach of GaAs-dice and passive components. Connections from the dice to the substrate were made using Au-wedge-wedge ultra-low profile wire bonding (see insert at left of photo). Finally, the module had to be sealed hermetically. For this purpose, a novel sealing process was devised which involves a printed solder reservoir and heating resistors embedded within the LTCC substrate. Along the cover walls, a unique layer arrangement allows direct, localised heating to reflow the solder without thermal stressing of the integrated circuits. Excellent RF shielding is obtained in addition to hermetic sealing. The insert at the right of the photo shows the metallised plastic cover in place. Further developments will include additional LTCC functionality such as embedded high-C-capacitors that are already qualified at MSE.

Conclusion

In this presentation we have reviewed the features and the advantages of thick film on alumina and on LTCC for High Frequency applications.

A few examples of microwave and millimetre wave modules in different architectures and assembly technologies have been reviewed.

Ceramic thick film technologies appear to be the most promising to fulfil the incoming challenge of high volume, low cost transmit-/receivemicrowave modules production, for the reasons explained above.

Many suppliers of RF modules have been able to improve their capabilities by using LTCC technology; high density, miniaturisation and integration of high frequency electrical functions, as well as large advantages in thermal management appear to be the driving force for this choice.

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