An Overview of Material Options Suitable for Today's Commercial Millimeter Wave Designs

Scott Kennedy, Al Horn, and Greg Bull
With Fuhan Liu, Hunter Chan, Venky Sundaram, and Rao Tummala

Today's commercial microwave design interest in millimeter wave systems is creating strong demand for thin, low-loss, high-performance circuit materials. There is an assortment of both currently available and developmental materials that are suitable to meet these new design demands. Careful selection of products should be made based on the individual design constraints, as well as the process capabilities available.

Introduction

In today's dynamic world of electronic systems, microwave designers are compelled more than ever to consider the material components of the overall system architecture in the earliest design stages. Military microwave designers have been doing this for decades with satellite and radar systems. Recently, commercial interest in millimeter wave frequencies has initiated a large scale, world-wide effort to develop systems requiring thin, high-performance dielectric materials. Examples of this trend include 60GHz wireless high-definition multimedia interface (HDMI) and wireless personal area network (WPAN) systems, ~77GHz automotive radar, and ~94GHz millimeter wave imaging systems. Figure 1 shows the 60GHz design applications in more detail.

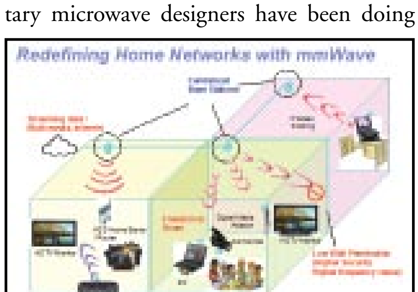

Fig 1 Depiction of Wireless High-Definition Applications in the Home.[1]

Intensive packaging and antenna system design activity is now taking place for all of these millimeter wave categories that require thin, low-loss dielectric materials. There is a portfolio of commercial and developmental materials that address these commercial high-frequency design trends.

Dielectric thickness considerations

Regardless of the particular application, there is a common need to cost effectively incorporate both RF and DC components to the circuit design. Because these designs focus on commercial applications at millimeter wave frequencies, thin materials are desirable to ensure proper signal transmission. As a conservative rule of thumb, dielectric thickness should be maintained at less than 1/8 the wavelength of the signal. This minimizes the possibility of developing transverse modes. As a result, dielectric thicknesses of 125µm or less are commonly discussed for these applications. This places a special emphasis on processing. Material selection should include a processing component to ensure that fabrication concerns related to thin core handling and feature resolution are addressed up front.

Copper considerations

Because the use of thinner dielectric materials requires 125µm or less conductor widths to maintain 50Ω stripline impedance values, copper thickness on laminates used in these applications needs to be typically 12µm or less. This helps to ensure that line width tolerances are maintained throughout the photolithography process.

Copper roughness also plays a critical role in the overall circuit losses. At the thicknesses and millimeter wave frequencies discussed in this article, most of the circuit losses occur through interconnect transitions and conductors. For thin materials having even totally smooth copper foil, the conductor loss still contributes to a very high percentage of the total insertion loss. Figure 2 shows the effects of various roughness values on the insertion loss for 0.004” thick liquid crystal polymer (LCP) microstrip circuit. The RMS roughness values in this chart range from 3.0µm (high profile electrodeposited copper) to 0.42µm (rolled annealed copper).

The conductor loss is minimized for most thin materials through the use of electrodeposited copper foils with ~0.5µm RMS roughness values. This is extremely close to the highly regarded rolled annealed copper foil.

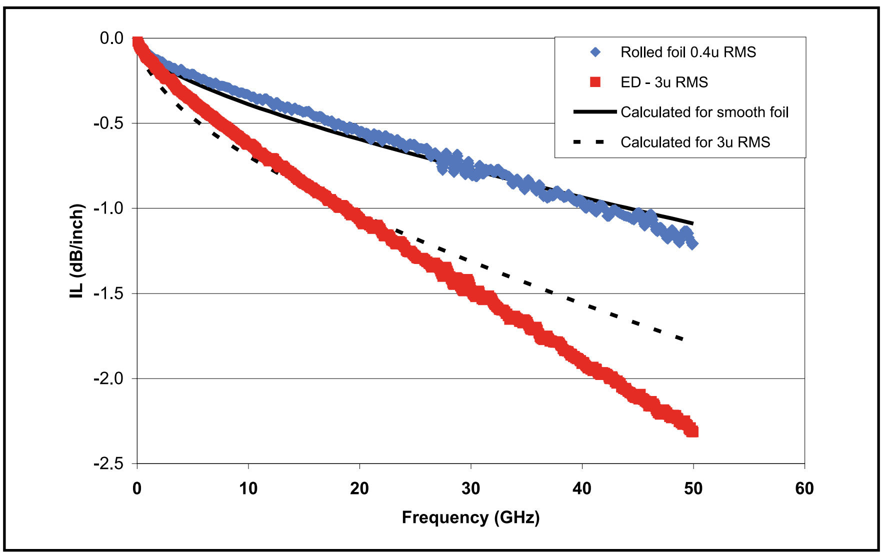

Fig 2 Insertion Loss of 0.004” Unfilled LCP Laminate With Both Very Rough (3µm RMS) ED Copper Foil and Very Smooth (0.4µm RMS) Rolled Copper Foil

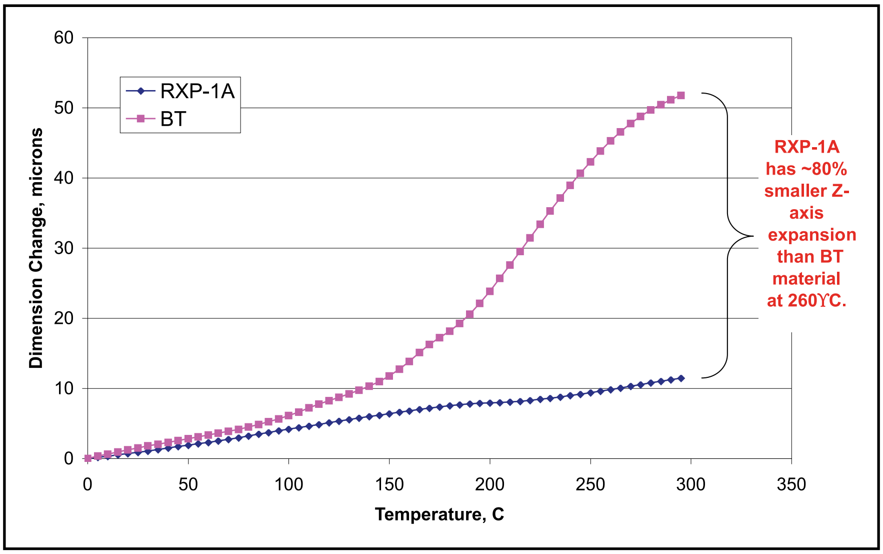

Fig 3 Z-Axis CTE Results Comparing RXP-1A to BT Material

Dielectric stability and uniformity

It is also critically important that the dielectric materials chosen are stable, as temperature fluctuates with operation of the final circuits. Certain components such as filters require a very tightly controlled dielectric constant in order to operate effectively. This material property, known as temperature coefficient of dielectric constant

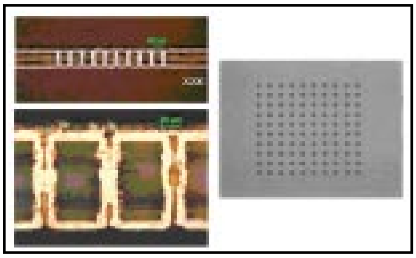

Fig 4 30µm Via at 75µm Pitch Demonstrated in a Thin Core Material. Cross-Section Shown on Left, X-ray Image Shown on Right

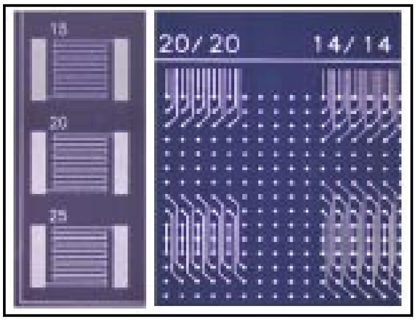

Fig 5 Very Fine Circuitry on Build-Up Material Created Using SAP Process. Pad Size Shown on Right is 40µm.[2]

(TCDK), is inherently negative for most high-performance polymer systems. Additives are typically used to alter the TCDK to create a material with as small a value as possible. Some materials are inherently low without the use of any modification. One such material type is liquid crystal polymer.

Most dielectric materials are composites made of resins, fillers, and sometimes woven glass reinforcement. The uniformity of this composite depends on the uniformity of its constituents. The presence of woven glass in laminates with composite dielectric constants different than about 6.0 can induce variation in circuit performance due to the locally high dielectric constant of the glass relative to the surrounding materials. When possible, it is best to avoid the use of woven glass materials. Alternative flat-weaved glass is being offered in some materials to minimize the impact of these glass bundles. This is especially important in digital designs, but can also be a factor at millimeter wave frequencies.

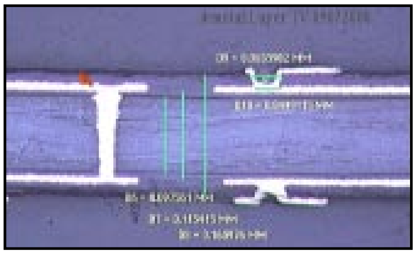

Fig 6 50µm (top) and 25µm (bottom) Blind Via Demonstrated in the Build-Up Material[2]

Currently available material options

Table 1 lists the circuit material options at 0.005" or less thickness values currently available.

It can be seen that there are many material options available. Depending on the particular circuit needs, one or more of these material types may be used. For example, those designs that can tolerate woven glass reinforcement and a RoHS compliant brominated flame retardant may choose the ceramic filled hydro-carbon thermoset materials. They are more rigid and have the easiest and lowest cost fabrication procedures. Other designs will require a halogen-free material without glass reinforcement. These designs can select from the ceramic filled PTFE, ceramic

Table 1. Commercially Available Thin Core Materials

Composite Decription	DK, 10 GHz	DF, 10 GHz	Thickness Options, Microns	X/Y CTE, ppm/C	Br/Cl Free?	V-0/ VTM-0?	Woven Glass Reinforcement?	Processing Issues
Ceramic Filled PTFE	3.00	0.0013	125, 250	17/17	Yes	Yes	No	Plasma for PTH's, handling
Ceramic filled Hydro-carbon Thermoset	3.48	0.0037	75, 101, 168, 254, 338	14/16	No	Yes	Yes	Standard High Volume
Ceramic filled engineered thermoplastic	3.3 - 3.6	0.003	25 - 125	17/17	Yes	Yes	Yes/No	Plasma for PTH's
Unfilled LCP	2.90	0.002	25, 50, 100	17/17	Yes	Yes	No	Plasma for PTH's

Table 2. Commercially Available Thin Adhesive Materials

Composite Description	DK, 10 GHz	DF, 10 GHz	Thickness Options, Microns	X/Y CTE, ppm/C	Cr/Cl Free?	V-0/ VTM-0?	Woven Glass Reinforcement	Process Temp, ° C	Processing Issues
Ceramic Filled PTFE	2.6	0.003	20 - 56	23	Yes	Yes	No	371	Plasma for PTH's
Ceramic Filled Hydro-Carbon Thermoset	3.52	0.004	102	19/17	No	Yes	Yes	177	Standard High Volume
Unfilled LCP	2.9	0.002	25, 50	17/17	Yes	Yes	No	280-285	Good Temp Control Needed, Plasma for PTH's
Modified Epoxy	3.0	0.022	12.5, 25	150/150	Yes	Yes	No	177-200	Standard High Volume
Unfilled CTFE	2.3	0.003	38	>100	Yes	Yes	No	218	Plasma for PTH's, High Flow
Unfilled FEP	2.1	0.001	25, 50	>100	Yes	Yes	No	296	Plasma for PTH's, High Flow
BT/Epoxy/PTFE	2.6	0.004	38, 51, 57,86	60/60	No	No	No	182	Plasma for PTH's, High Flow

→ 20

filled engineered thermoplastic, or unfilled LCP materials.

As far as bonding these thin materials, there are several material options that the circuit designer can select from. Table 2 describes these options in detail.

The exact choice of adhesive will depend on both the electrical demands of the circuit as well as the capability of the circuit fabricator. Some systems, such as RO4450F™ prepreg, process at standard press temperatures and do not require exotic desmear and plating preparation techniques. This material does, however, contain woven glass reinforcement and may not be desirable for applications requiring very high density via pitch (i.e. for flip chip substrate applications). Other applications require non-brominated materials. These types of bonding materials are typically thermoplastic films that require higher process temperatures and special plating techniques such as plasma or chemical treatments to strip fluorine atoms from the polymer surface. A major disadvantage of the thermoplastic systems is that only one lamination step is typically performed in order to bond the multiple circuit cores together. A sequential lamination approach where multiple bond cycles are used is difficult due to the re-melting of the adhesive system in the previously bonded sections. While it is possible to use two or more material types with different melting temperatures, this can be costly and technically challenging. Chip packaging, in particular, is a developing area at millimeter wave frequencies, which requires both a combination of a thermosetting system as well as a halogen free solution.

Table 4. Build-Up Material Properties

Property	
CTE (25-150 C), ppm/C	43
T_g (DMA), C	185
Tensile Modulus, MPa	2100
Tensile Strength, MPa	28
Elongation at Break, %	3.4
DK (10GHz)	2.85
DF (10GHz)	0.0030
Water Absorption, % (24 Hrs, 23 C)	0.17
UL 94	V-0
Solder Float (30sec @ 260 C)	5x / 30 sec
Lamination Temperature, C	232
Dielectric Breakdown, V/mil	3308
Laser Processable	Yes

Table 3. Thin Core Material Properties

Property	
CTE-X/Y (0-260 C), ppm/C	13-14
CTE-Z (0-260 C), ppm/C	41-43
T_g (DMA), C	>300
Tensile Modulus, GPa	6-10
Tensile Strength, MPa	70-160
Elongation at Break, %	2-3
DK (10GHz)	3.2-3.4
DF (10GHz)	0.004
Water Absorption, % (24 Hrs, 23 C)	<0.1
UL 94	V-0
Halagen Free?	No
Solder Float (288 C/10 Sec)	Pass
Cu Adhesion, pli	3.5-4.0
Dielectric Breakdown, V/mil	2000-2500
Prepreg Lam Temp, C	177

New developments in materials for chip packaging applications

As a result of the needs for thin, low-loss, thermosetting materials for chip packaging applications, a build-up material and thin core solution has been developed. These materials provide a much needed low-loss offering to the predominantly epoxy or bismaleimide-triazine (BT) based, higher-loss packaging materials available in the market today.

Thin core material

Suitable, high Tg core materials in the thickness range of 50µm to 100µm have also been developed. This type of material is useful to create very thin, low-warp substrates for IC packaging. These core materials utilize a thermosetting, hydrocarbon-based resin system, smooth ED copper foil for improved loss performance, and flat glass reinforcement to minimize the effect of the glass weave on signal propagation. A basic summary of the material properties is found in Table 3.

The range of values obtained represent measurements from both 50µm- and 100-µm thick laminate materials. Aside from the outstanding electrical properties, one main feature of this thin core material is that the Tg is above the lead-free solder reflow temperatures (up to 260°C). This prevents any change in expansion rate of the core material during this reflow process. As a result, substrate warpage is minimized. This is shown in Figure 3 for an experimental version called RXP-1A.

These core materials can be processed using standard conditions and wet chemical desmear techniques. A halogen-free version of this core material is currently being developed. Very high density vias have been demonstrated using this core material. These results are shown in Figure 4.

Build-up materials

In order to address the needs for thin, low-loss build-up materials, a system that is capable of being used in very high-performance substrates with minimal changes to standard processes has been developed. This material has been manufactured in thicknesses from 9µm to 60µm. It can be offered on smooth ED copper or a Mylar® release film. A summary of the properties of this material is shown in Table 4.

This material requires a slightly higher lamination temperature (232°C vs. <200°C) than what is required for standard epoxy based materials. It also has shown to provide acceptable adhesion to additive plating techniques following CF_4/O_2 plasma. Figure 5 shows very fine line circuitry deposited onto our build-up material using a semi-additive process (SAP).

The build-up material is laser processable in order to create very fine via structures for high density interconnect structures. Figure 6 shows a 50µm blind via structure made using the thin core and build-up material in a 1-2-1 substrate combination.

The results from reliability testing indicate that the combination of the thin core and build-up material creates a very high reliability combination. Testing on through-via and blind-via test structures indicate MSL-3 or better capability with >99% PTH survival through 1,400 thermal cycles from -55°C to 125°C.[2]

Conclusion

Today's commercial microwave design interest in millimeter wave systems is creating strong demands for thin, high-performance circuit materials. Both currently available and developmental materials are well-suited to meet these new design demands. Careful selection of products should be made based on the individual design constraints, as well as the process capabilities available. ☐

References

1. http://domino.watson.ibm.com/comm/research_projects.nsf/pages/mmwave.apps.html, 2/24/09.

2. F. Liu, V. Sundaram, H. Chan, G. Krishnan, J. Shang, J. Dobrick, J. Neill, D. Baars, S. Kennedy, R. Tummala, Ultra-High Density, Thin Core and Low Loss Organic System-on-Package (SOP) Substrate Technology for Mobile Applications, ECTC 2009.

> **Today's commercial microwave design interest in millimeter wave systems is creating strong demands for thin, high-performance circuit materials.**