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Materials for Capacitor Embedding in PWBs

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Abstract
We have developed a new resin-coated-foil (RCF) material named MCF-HD-45 to be embedded in PWBs to constitute capacitors. The material is composed of a thermosetting resin and a high dielectric constant (Dk) filler. The filler has a multimodal size distribution to attain high loading; a specific surfactant is also essential to preserve the stability of filler dispersion in varnish. These technologies give this material a high Dk of 45 and excellent reliability. In this paper are described the test results for the material applied to a power amplifier module and a low pass filter of cellular phones, as well as the benefit of the database for high frequency circuit simulation.

Introduction
In recent years, wireless equipment such as cellular phones has greatly improved in performance and reduced in size. This trend has pushed forward the technology to miniaturize RF modules. Previously smaller semiconductor and passive devices were adopted for this purpose. However, the technology to embed passive and active devices in PWBs is positively investigated for further size reduction nowadays. There have been many reports on the embedded passives applying low temperature co-fired ceramic (LTCC) or silicon as substrates. Today, organic substrates are positively investigated as the substrates on this purpose,[1-5] because they have a coefficient of thermal expansion (CTE) matching with that of the mother-boards, and also are easy to enlarge size of substrates. If the existing manufacturing process of organic substrates will fit for embedding passives, they have a big advantage of cost effectiveness.

Nowadays, simulation technology is very important for circuit design of RF modules. However, there have been few database for the circuit design applicable to embedded passives in PWBs. The collaboration between circuit designers, PWB manufacturers, and material suppliers will be necessary, to activate the embedded passive technology.

Experimental
A modified epoxy resin was used as the polymer material, Barium Titanium oxide ($BaTiO_{3)}$ of Dk=1500 was chosen as the high-Dk filler, and appropriate solvents were chosen to make the component materials into varnish. Homogenized varnish was prepared by blending then with a sand mill. In this process, some surfactants or dispersion agents were added. The varnish was then coated onto a typical copper foil (3/8 oz.), using standard coating techniques to obtain the new RCF named MCF-HD-45. In this process, the insulation layer thickness was controlled to be around 20 µm. Test specimens for reliability test etc. were fabricated by the conventional lamination process, that is, under 2.5 MPa at 180^{O}C for 60 min. The reliability test was then conducted under the following conditions: 85^{O}C/85%RH/6 V dc.

Circuit simulation was conducted by using the advanced design system (ADS) of Agilent Technologies. High frequency characteristics of the material and its applications were measured by using a vector network analyzer (VNA), of the same maker equipped with a probe station to control stage temperature.

Results and Discussion
The concept of passives embedded in PWBs is shown in Figure 1. A thick film capacitor made of polymer composite material sandwiched between two electrodes such as copper foil, a thin film capacitor made of a thin film and two electrodes, and an inductor made by patterning on the substrates are available as the passives embedded in PWBs.

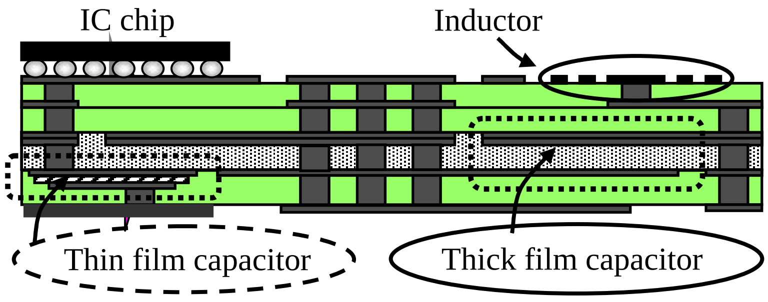


Figure 1 - Concept of Passives Embedded in PWBs

Typical polymer composite materials for embedded capacitors are listed in Tables 1 and 2. For a reference, BC2000 of Sanmina-SCI is a commercially available thin FR-4 prepreg. Interra HK10 of Du Pont, C-Ply of 3M and High-Dk and Condenser Film of Matsushita Electric Works are all copper clad laminate (CCL) type materials; and FaradFlex of Oak-Mitsui Technologies and MCF-HD-45 of Hitachi Chemical are RCF, Resin Coated Foil.[6-18] CFP of Vantico, CX-16 of Asahi Chemical Laboratories, and EP310 of Du Pont are dielectric paste type materials; Nippon Paint has released a new film-type composite material.[19-25] Basically, epoxy resin is used as the polymeric binder component, and $BaTiO_3$ as the high-Dk filler.

Table 1 – CCL Type Composite Materials for Embedded Capacitor

Company	Sanmina-SCI[6-8]	Du Pont[9,10]	3M[11,12]	Matsushita Electric Works[13]	
Product name	BC2000	Interra HK10	C-Ply	High-Dk	Condenser Film
Dielectric material	FR-4	Polyimide $BaTiO_3$	Epoxy $BaTiO_3$	Thermoset $BaTiO_3$	Thermoset $BaTiO_3$
Type	CCL	CCL	CCL	CCL	CCL
Dielectric constant, Dk	ca. 4	3-20	14-18	16	40
Dielectric thickness (μm)	25-50	8-25	4-26	50	10-30
Capacitance density (pF/mm^2)	0.7-1.4	1.4-22	8-48	3	11-40

Table 2 – RCF, Paste and Film Type Composite Materials for Embedded Capacitor

Company	Oak-Mitsui[14-16]	Hitachi Chem.[17,18]	Vantico[19,20]	Asahi Chem. Res., Lab.[21]	Nippon paint[22,23]	Du Pont[24,25]
Product name	FaradFlex	MCF-HD-45	CFP	CX-16	-	Interra EP310
Dielectric material	Epoxy $BaTiO_3$	Epoxy $BaTiO_3$	Photopolymer Ceramics	Epoxy $BaTiO_3$	Thermoset $BaTiO_3$	Sintered $BaTiO_3$
Type	RCF	RCF	Paste	Paste	Film	Paste
Dielectric constant, Dk	30	45	21	15-20	32	>1,000
Dielectric thickness (μm)	16	20-50	11	10-20	50	20-40
Capacitance density (pF/mm^2)	17	8-20	17	24-32	6	160-480

Capacitance density (CD) is calculated from Equation 1 using Dk of the composite dielectric material, its thickness, and the area of electrode overlap. When the composite dielectric material is made of only two components (i.e. matrix resin 'm' and filler 'f'), Dk can be calculated from simple Nielsen's equation[25,26] (Equation 2), where the value n depends on the shape of filler. Table 3 shows the calculated CD values for various t and Dk values, where the shape of filler is assumed spherical.

Capacitance density (pF/mm^2) = $\frac{C}{A} = \frac{\varepsilon_{9x} xDk}{t}$ Eq. 1

$Dk^n = V_m \varepsilon_m^n + V_f \varepsilon_f^n$ (-1 < <1, n $\neq$ 0) Eq. 2

C : Capacitance (pF)
A : Area of electrode overlap (mm^2)
t : Dielectric thickness (μm)
ε_0: Permittivity of vacuum (= 8.85 pF/m)
Dk: Dielectric constant of the composite material
ε_r: Dielectric constant of each component material
V: Volume fraction of each component material

Table 3 – Calculated Value of Capacitance Density

Dielectric constant, Dk	Capacitance density, CD (pF/mm^2)		
	t=50mm	t=20mm	t=5mm
4	0.7	1.8	7.0
10	1.8	4.4	18.0
45	8.0	20.0	80.0
100	18.0	44.0	177.0

We tried to develop a new composite dielectric material having Dk=45 to attain CD of 20 pF/mm^2 with as thin as 20 m film. As we cannot control the shape of filler, our efforts were focused on increasing filler loading ratio.

Figure 2 shows the effect of filler loading ratio on Dk. To attain Dk=45, over 60 vol% of filler loading was necessary, resulting in the adoption of the filler with a multimodal size distribution. A specific surface treatment was also necessary to afford satisfactory process ability with such high loading. Though acidic surfactants are good for dispersing $BaTiO_3$ in matrix polymer, the reliability against copper migration will be degraded. By selecting neutral surfactants, we have developed a new composite material meeting the requirement of Dk=45 and having both good reliability and good dispersivity of $BaTiO_3$, as shown in Figure 3.

General properties of our material are listed in Table 4. Though the material shows relatively great temperature dependence and low dielectric breakdown strength, its Tg of 130°C and solder heat resistance of above 300 s at 260°C are comparable to those of the conventional FR-4.

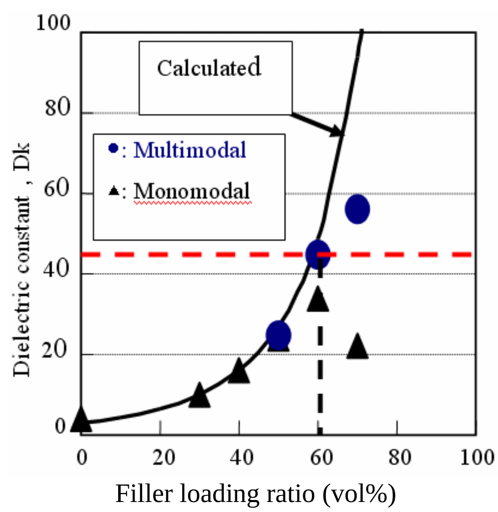
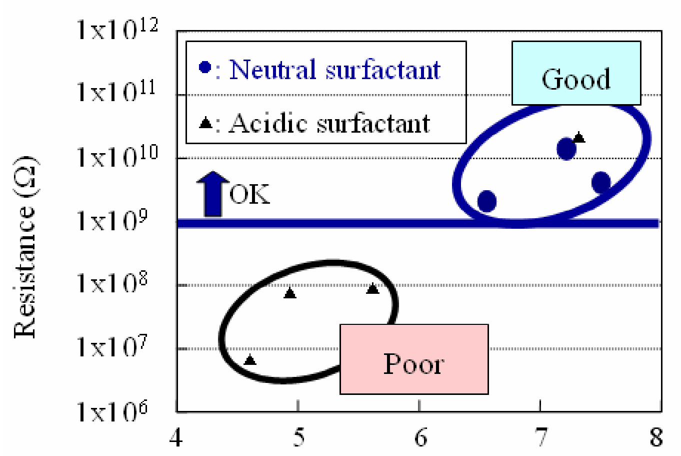


Figure 2 – Effect of Filler Loading Ratio on Dk



pH of extracts
(C-1000 h/85°C/85%RH/6 V dc)

Figure 3 – Insulation Resistance of our Material with Various Surfactants

Table 4 – General Properties of MCF-HD-45

Item	Condition	Unit	MCF-HD-45
Dielectric thickness	-	μm	20 ~ 50
Dielectric constant, Dk	1 MHz, 25°C	-	45
	1 GHz, 25°C	-	42
	Change 25 → 120°C	%	9
	Change 25 → -20°C	%	-4
	After PCT 4 h	%	13
Dissipation factor, Df	1 MHz, 25°C	-	0.021
	1 GHz, 25°C	-	0.031
	Change 25 → 120°C	%	0
	Change 25 → -20°C	%	-14
	After PCT 4 h	%	86
Breakdown strength	As received	kV/mm	20
Volume resistivity	As received	Ω · cm	8.2×10^{13}
Water uptake	After PCT 4 h	%	0.5
Tg	TMA	°C	135
Tensile strength	As received	GPa	4
Solder heat resistanse	260°C float	s	>300
Copper peel strength	GTS-12 μm	kN/m	0.6

Comparison of the embedded capacitor manufacturing processes for both CCL and RCF type materials is shown in Figure 4. The buried capacitance applying BC2000 is in practical use, because the conventional manufacturing process of PWBs can be applied. This process cannot be applied to thin and hard-to-handle dielectric material for high CD capacitor. On the contrary, the build-up process can be applied to embed such thin dielectric material. However, it is necessary to control the thickness of RCF type dielectric material having high-flow property to obtain the designed capacitor embedded in the substrate. Therefore, we will strongly recommend a novel process, in which an extra process for surface flattening is applied before lamination of RCF, as shown in Figure 5.

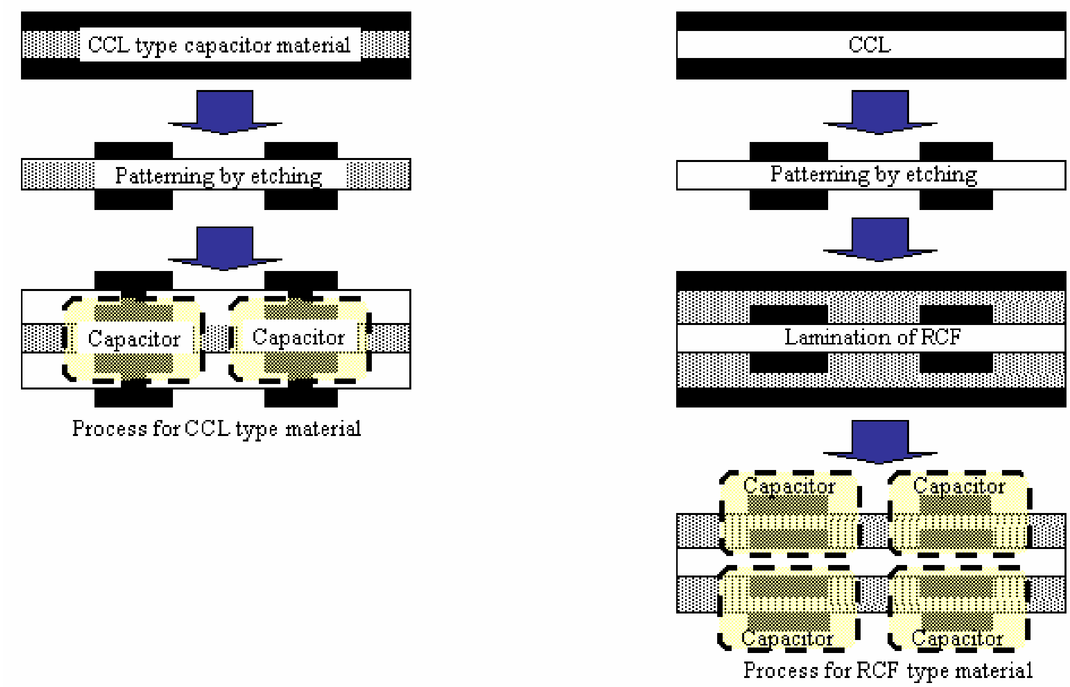


Figure 4 - Comparison of the Embedded Capacitor Manufacturing Processes for Both CCL and RCF Type Materials

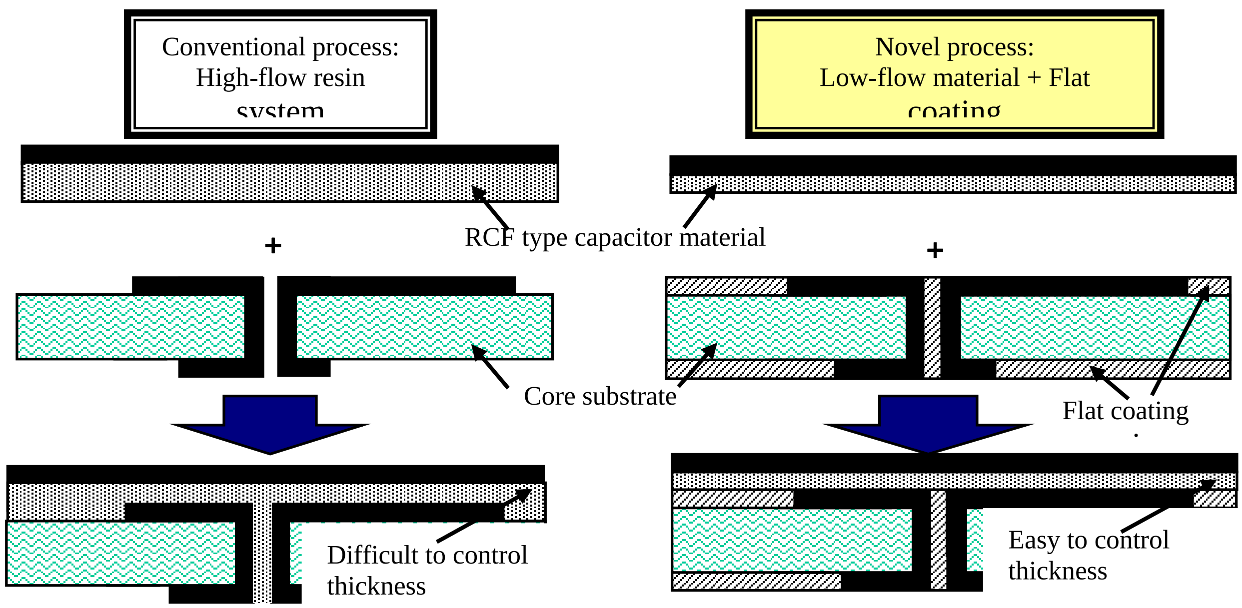


Figure 5 - Novel Process Easy to Control the Thickness

A power amplifier (PA) module of cellular phones was manufactured as a test vehicle of the embedded capacitor applying our new material. The PA module had 7 capacitors and 2 inductors as shown in Figure 6. The 2 capacitors for cutting direct current were embedded in the substrate. The performance of the PA module was measured as listed in Table 5. The PA module using embedded capacitors had the same efficiency as that using SMD. These data suggest that the embedded capacitor will be able to replace the SMD capacitor for cutting DC.

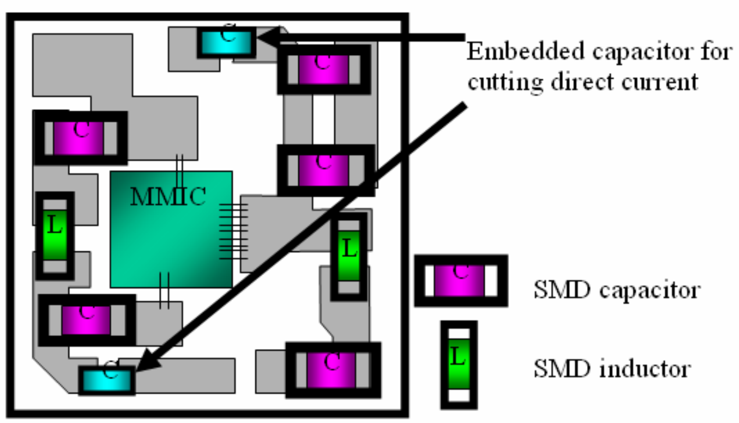


Figure 6 – Image of PA Module having Embedded Capacitors

Table 5 – Performance of PA Module [(a)]

Item	Unit	Conventional SMD	Trial product
SMD capacitor	Piece	7	5
Embedded capacitor	Piece	0	2
Gain	dB	9.5	9.4
Δ efficiency	%	0	-0.2

(a)Frequency:1.95 GHz, Output power:27 dBm

The function of high-frequency filters such as low-pass filters (LPFs), as shown in Figure 7, can be embedded in the substrate. In the first, the equivalent circuit model for the LPF having a certain function was designed by using the circuit simulator ADS as shown in Figure 8, and next a test element group (TEG) for the LPF was manufactured with proper embedded capacitors and inductors, using our material and appropriate patterns, as shown in Figure 9.

In this case, the capacitance value of C31 and C20 were fixed by using the same area of the electrodes, and the pattern length of L25 (spiral inductor) was varied so that various resonant frequencies of around 1.8 GHz could be obtained. In the same manner, the various resonant frequencies around 3.6 GHz could be obtained by controlling the pattern length of L10 (meander inductor).

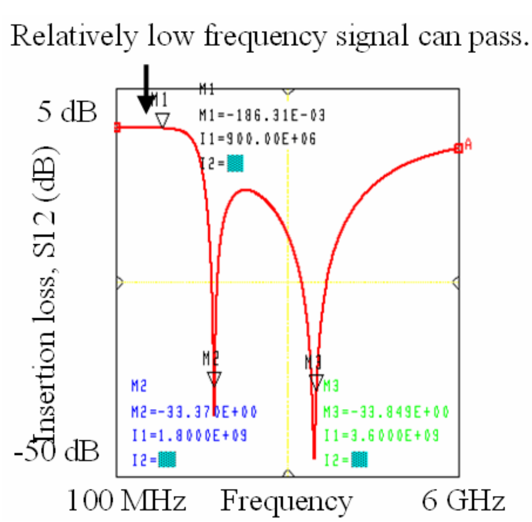


Figure 7 – Example of the Function of LPF

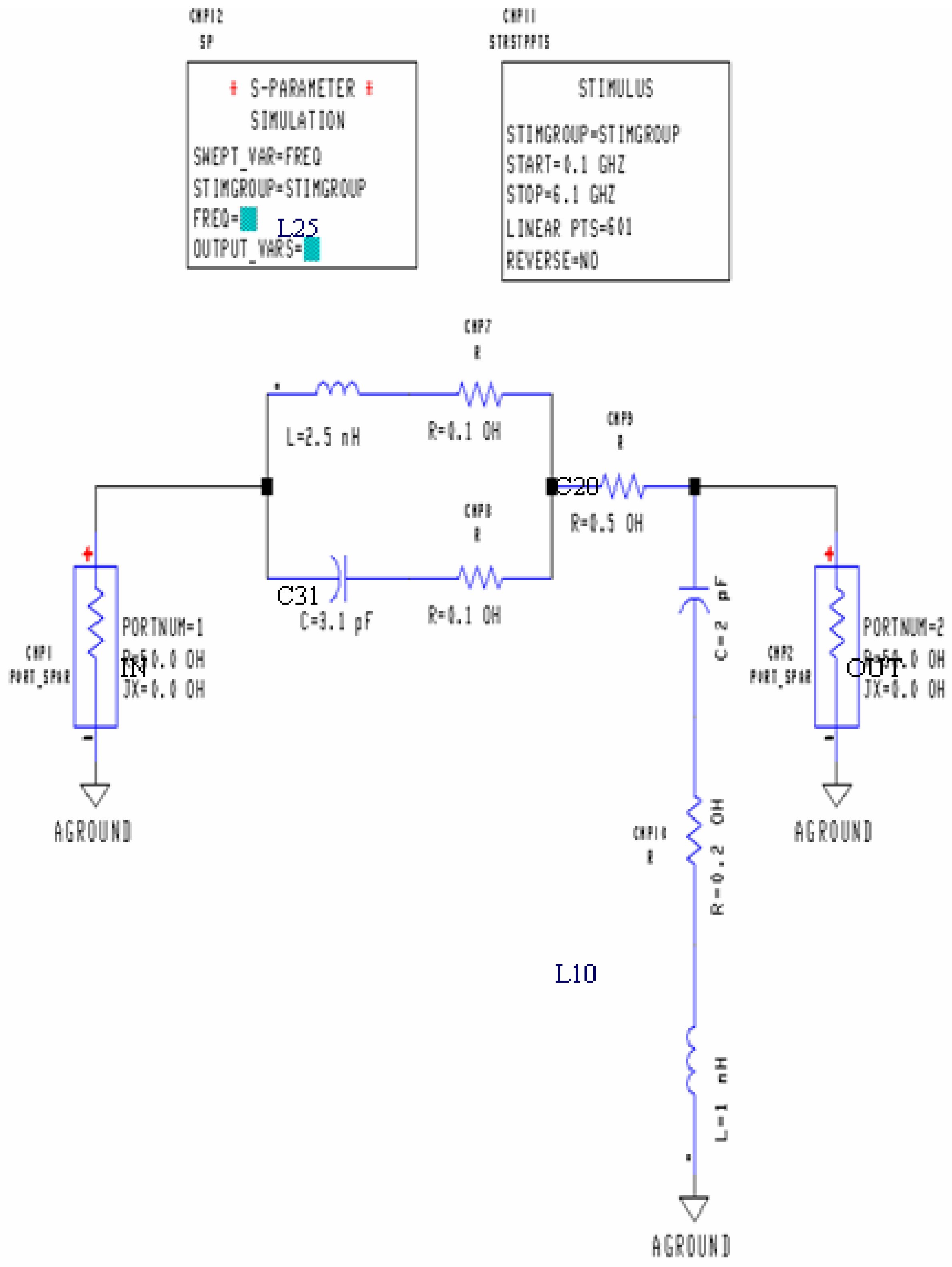
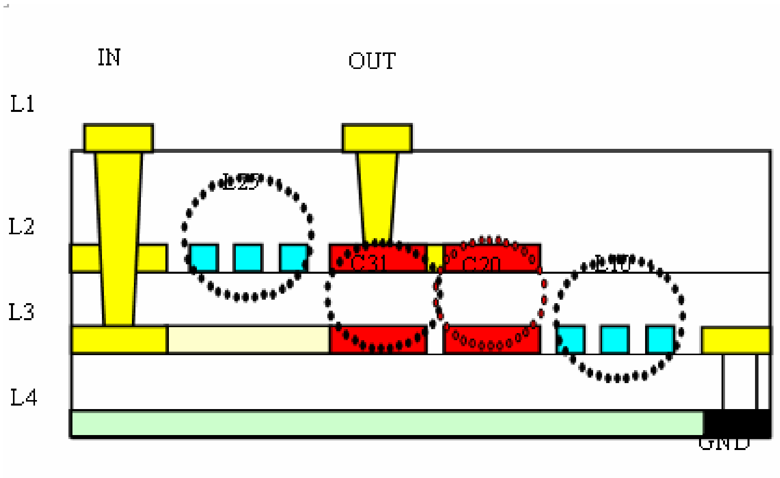


Figure 8 – Equivalent Circuit Model for the LPF having a Function shown in Figure 7



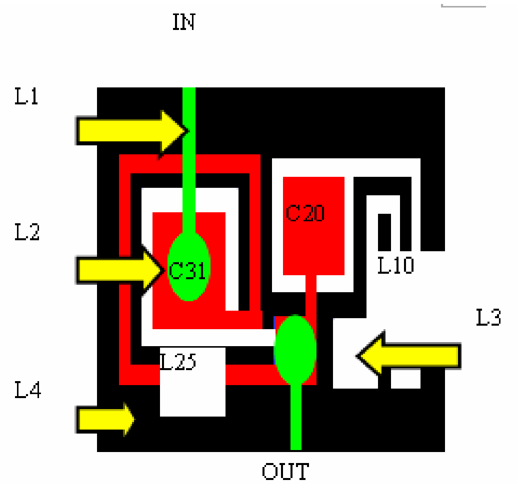


Figure 9 – Image of a LPF Embedded in the Substrate

There were 8 TEGs with various pattern lengths of L25(spiral inductor) and 5 TEGs with various those of L10(meander inductor). The resonant frequency around 1.8 GHz was shifted to lower frequency with increasing length of L25 from 4.9 mm to 7.9 mm; however, the resonant frequency around 3.6 GHz was not shifted significantly as shown in Figure 10. The latter resonant frequency was shifted to lower frequency with increasing length of L10 from 2.4 mm to 3.6mm, the former being nearly constant as shown in Figure 11. These results will suggest that the proper LPF can be obtained by properly selecting the area of the electrodes for component capacitors and the length of the patterning for component inductors.

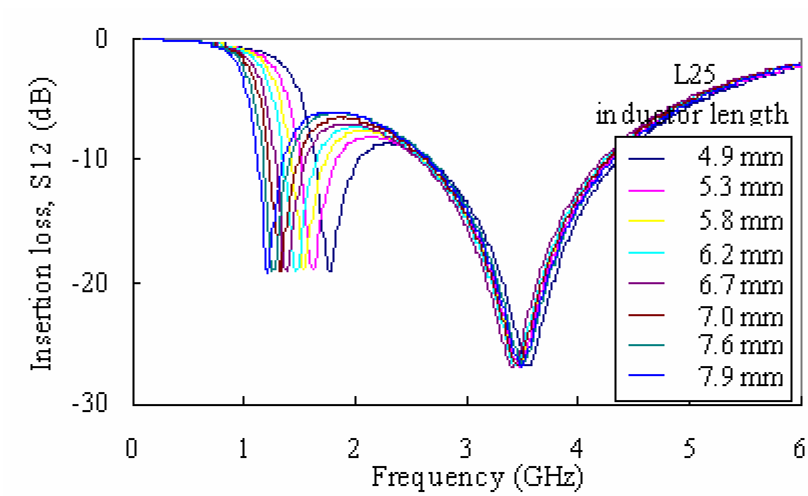


Figure 10 – Relationship Between L25 Inductor Length and the Resonant Frequencies

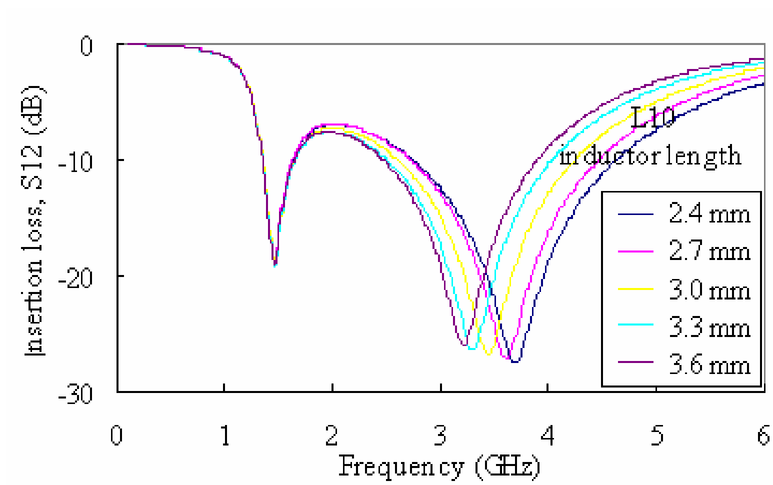


Figure 11 – Relationship between L10 Inductor Length and the Resonant Frequencies

Circuit design technology is very important for embedding functional blocks such as LPF. Next, the optimization of the inductor length was investigated by measuring the resonant frequency of TEGs designed by circuit simulation technique. As the simulation technology is dominant in circuit design, material suppliers are expected to present the database for circuit simulation, such as dielectric properties including deviation, results of 3-D electro-magnetic simulation, LCR values of the equivalent circuit model, measured data of TEG, etc. It will be necessary to promote close collaboration between material suppliers, PWB makers, design tool makers, and set makers to develop the simulation technology for circuit design intensively.

As our material showed relatively high temperature dependence of dielectric properties, the working temperature, as shown in Figure 12, influences the resonant frequency of TEG. The TEG with embedded capacitors using the new material showed large insertion loss compared to that with SMD capacitors, as shown in Figure 13. This is due to the larger dissipation factor (ca. 0.02) of the material.

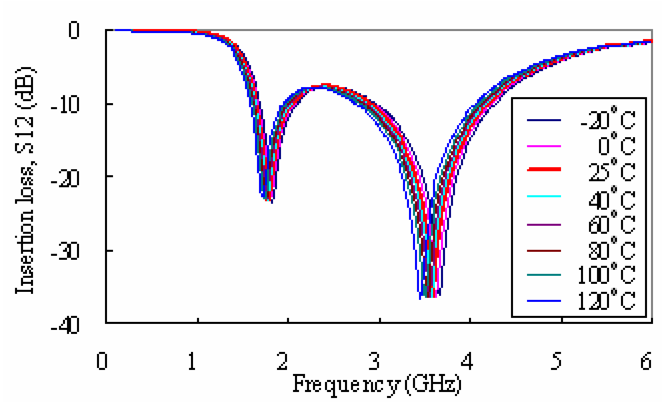


Figure 12 – Temperature Dependence of the Resonant Frequencies of the TEG with Embedded Capacitors ysing MCF-HD-45

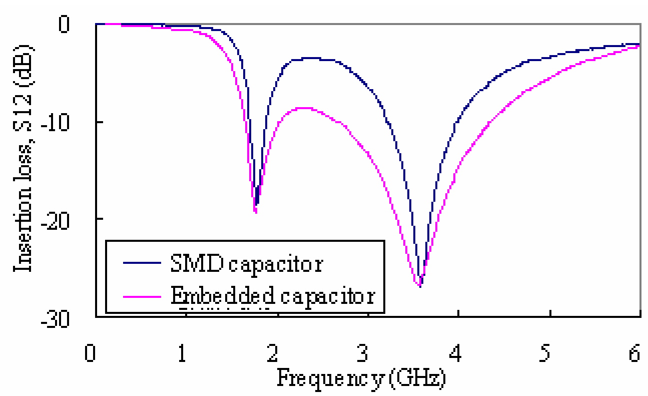


Figure 13 – Comparison of LPF Performance of the TEGs with SMD Capacitors and Embedded Capacitors using MCF-HD-45

Conclusion

We have developed a new composite material named to constitute capacitors in organic substrates with a capacitance density of 20 pF/mm^2. The test results of a trial PA module and TEG for LPF, both with embedded capacitors using the new material were presented. According to the higher frequency trend of digital equipment, the demand for embedded capacitors is growing for their effectiveness in signal integrity. The development of an extremely high-Dk polymer composite material (i.e. Dk over 200) in thin film shape will be strongly desired. And also close collaboration between material suppliers; PWB makers and the circuit designers of set makers will become more and more important.

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