Integration of Thin Film Passive Circuits Using High/Low Dielectric Constant Materials

P. Chahal, A. Haridass, A. Pham, R. R. Tummala, M. G. Allen, M. Swaminathan and J. Laskar
Packaging Research Center
Electrical and Computer Engineering
Gerogia Institute of Technology
813 Ferst Drive
Atlanta, GA-30332-0560
Ph. # (404) 894-9097, Fax # (404) 894-0957, e-mail: pchahal@eecom.gatech.edu

Abstract:

Integration of passives is a continuous challenge towards achieving high performance packages with low profile, improved reliability, maximum packaging efficiency and low cost. This paper discusses the design, fabrication and measurement of integrated passive structures using dielectric constants of 3.3 and 9.1, and thickness in the range of 10 - 21 µm for wireless applications. The use of polymer-ceramic composite material provide the design flexibility to combine both high dielectric constant and low dielectric constant materials within a single module. This allows for the design of matching networks, RF filters and ability to decouple power supplies for mixed signal applications with reduced size.

Key Words: RF, thin film, ceramic-polymer composites, integrated passives.

I. Introduction:

The recent trend in packaging has been towards light weight, low cost, high performance wireless devices. Most wireless applications require a large number of passive components for system implementation. The current state of the art is to use discrete packaged passive components that are surface mounted onto the wireless module. To achieve improvements in performance, cost, reliability and profile embedding of these passive components into the substrate is required. Though this approach eliminates the surface mounted components, the performance of the embedded components are dictated to a large extent by the parasitics associated by the surrounding environment. To achieve improvements in performance and size goals for future packages, one of the requirements is the availability of a range of materials with different properties for design implementation [1]. This paper discusses the use of high and low dielectric constant materials in a single module using thin film process. Examples of passives that can be implemented using a this technology are impedance matched networks, RF filters, delay lines, $\lambda/4$ stubs, inductors, RF capacitors and decoupling capacitors.

The integration of passives in between thin interlayer dielectrics (<3 µm of polyimide, SiO_2, Silicon-Nitride, etc.) with a ground plane has been demonstrated and resulted in the miniaturization of MMICs [2]. One of the barriers in the use of thin films for multilayer integrated passives is the loss associated with the physical dimensions and the material set that degrades performance. These losses are primarily conductor losses that reduce the Q (quality) factor of the fabricated devices. Conductor losses are typically less pronounced as dielectric thickness is increased due to a large separation of the device from the ground plane and this is easily achieved in a package as compared to on chip. Integration of passives within a package is becoming a preferred approach as compared to on-chip.

Ceramic based multilayered packages is currently the most common approach for the miniaturization of RF circuits [3 - 5]. One of the inherent benefits of ceramics is the availability of a wide range of dielectric materials as part of a single module along with low loss. To achieve miniaturization and performance, realization of both high and low dielectric constant material in a single package is therefore essential. As an example, capacitors require a thin film of high dielectric constant material to achieve the capacitance in a small area while high Q inductors require a low dielectric constant as the surrounding medium to reduce the parasitics associated with the device.

Use of lumped elements or distributed elements are the two approaches of passive circuits. The lumped element technique uses a group of discrete elements such as resistors, capacitors, and inductors; while the distributed element technique uses transmission lines with associated electrical lengths for implementing the circuit. Both methods are in use today and have been implemented in ceramic based multilayer packages. However, little information is available for organic based substrates. Organic polymers have gained interest in digital packaging applications due to ease of processability and low dielectric constants [1]. Low dielectric constant polymers are currently available for various applications. Organic polymers on low cost PWB substrate is being pursued at the Packaging Research Center, Georgia Tech as a means of achieving high density interconnections with embedded passive devices at low cost. This package is referred to as SLIM (single level integrated module) which consists of multilayered thin film with passives on an organic board with a resulting projected packaging efficiency of 80 percent. This paper presents the use of polymer-ceramic composite thin film material for embedded passive circuits which can be combined with low dielectric constant interlayer dielectrics in a single multilayered module.

Thick high dielectric constant printed circuit boards (polymer-ceramic composite based) are commercially available with a range of dielectric constants (typically, 3 - 10) for digital/RF applications [6]. Fabrication of thin film structures using photodefinable polymer-ceramic composites has previously been discussed by the authors in refs. [7, 8]. The authors believe that a combination of both the low and high dielectric constant materials in thin film form can further enhance this technology for mixed signal applications. Advantages in the use of polymer-ceramic composite materials are:

(1) dielectric constant can be tuned to the required values.

(2) processing is compatible with that of the interlayer dielectrics (low ε_r).

(3) The curing of the material is dictated by the polymer matrix material (binder) used and thus curing can be controlled to be substrate compatible.

Previous work by the authors demonstrated the application of this material towards decoupling capacitors for MCM-L technology. Dielectric constants as high as 65 with loss-tangent below 0.04 was demonstrated. This paper will focus towards a dielectric constant close to that of alumina ($\varepsilon_r \cong 9$), a common substrate material for RF applications to allow comparison between these two materials sets.

II. Material Selection/ Process:

Larger the surface roughness higher the losses at high frequency and also processing defects tend to be high for rougher films. The surface roughness of the films is largely dependent on the size and shape of the filler particles. and Thus small spherical particles should be used. Films loaded with 1μm spherical particles produced films with surface roughness of ~0.5 μm and higher. Barium titanate ($BaTiO_3$) powder with average particle size of 0.1 μm (available from Cabot Performance Materials) produced smoother surface (~0.20μm surface roughness). The dielectric constant of this material is nearly 2000 and loss-tangent lies below 0.1. High dielectric constant composites can be achieved using such small particles [8]. Thus, this material was selected as the filler material. The loss-tangent of the composite material typically lie in between the loss-tangent of the polymer and the ceramic fillers. Thus, other ceramic fillers (~0.1μm particles) such a barium strontium titanate can be used (upon availability) to further improve the loss of the material.

Some of the polymer material requirements are: (1) Low molecular weight (for high loadings), (2) High cross-linking density, (3) low moisture absorption, (4) Low curing temperature (PWB compatible), (5) Photodefinable, (6) Low loss-tangent. Several polymer materials are available that satisfy these conditions. However, preliminary study showed that $BaTiO_3$ particles are not compatible (gelling of the material was noted) with most polymer materials (e.g., Photo-BCB, Probimer-4959 epoxy). Polyimides (PI2721- product of DuPont, Ultradel 7505- product of Amoco) were found to be compatible with $BaTiO_3$ particles (no gelling was noted). Thicker films (~15μm) made from Ultradel 7505 (requiring low temperature curing, <230 °C) based composite were found to flake-off during processing. No further study was carried out using this material. Polyimide-2721 based composites (different volume ratios) were found to have good adhesion with PWB and most metal (Cr, Cu, Al and Ti) coated glass substrates. This material has good mechanical properties and is thermally stable to high temperatures. However, the curing temperature requirement is not compatible with PWB substrates. Upon change of ceramic fillers, low temperature curable polymer materials can be used or other photo-polymers should be analyzed for compatibility with $BaTiO_3$.

Uniform dispersion of $BaTiO_3$ particles in the polymer matrix was ensured through viscosity control and mixing over 100hrs (porcelain balls were introduced in the material to help improve mixing). The dielectric thickness was noted to decrease upon curing by approximately 20%. This need to be compensated in order to attain a film with required thickness. Table 1 outlines the electrical characteristics, obtained from measurements and data sheets, of the materials used in making samples for this paper.

Table 1. Characteristics of materials used

Material	ε_r (1KHz)	tan-delta (1KHz)	$V_{breakdown}$ (V/cm)	Vol. Resist. (Ω-cm)
Polyimide	3.3	0.002	$> 2X10^4$	$>10^{16}$
Composite	9.7	0.006	$> 2X10^4$	$>10^{12}$

* From DuPont Electronics data sheet

Fabrication of very small vias (~50 μm) in composite material is required to carry out multilayer integration using composite materials. Processing of small vias have been demonstrated previously by the authors in refs. [7], [8] and thus will not be presented here.

III. Test Vehicle Description/Fabrication:

A test vehicle was designed to evaluate the composite material for high frequency wireless applications using integrated passive devices. Structures incorporated included both lumped devices and distributed elements and some of these are:

(1) T-line resonators to measure the frequency behavior of the dielectric material.

(2) Microstrip lines to measure the transmission line behavior and to characterize dielectric material.

(3) Inductors (serpentine lines and spirals) and capacitors to measure RF performance.

(4) Distributed and quasi-lumped filters to measure frequency shift, bandwidth, and insertion loss.

Several structures of the above types were incorporated into the test vehicle with varying physical dimension. Two samples of thickness 12.5 and 21.2μm were fabricated using high dielectric constant material and one using a 12.5 μm thick low dielectric constant material. The same set of structures were fabricated on all these samples using the same set of masks to allow for detailed analysis on the effect of both dielectric constant and thickness on the performance of the structures. The dielectric layers were deposited using spin coating technique. Curing of the composite was conducted under the conditions suggested by the manufacturer (DuPont Electronics). The fabrication steps are shown in Figure 1. Figure 2 shows a photomicrograph of a section of the test vehicle on a high dielectric constant material which shows coplanar waveguides, microstrip lines and T-line resonators.

Copper metallization was used for its high conductivity and ease of processing. Deposition of the copper metal was carried out using e-beam (seed layer and bottom electrode) and electroplating techniques. The high dielectric constant test structures contained copper layers of 2μm (common ground plane), and 3.5 μm thickness for bottom and top electrodes respectively. The low dielectric constant test substrate contained 2 μm and 2.5 μm metallization of bottom and top electrodes respectively. Electroplating of the ground plane was conducted around the dielectric structures for planarization to achieve uniform photoresist (PR) coating (Figure 1). Thickness difference of approximately 4μm was measured between the plated bottom electrode and the dielectric surface for all three samples.

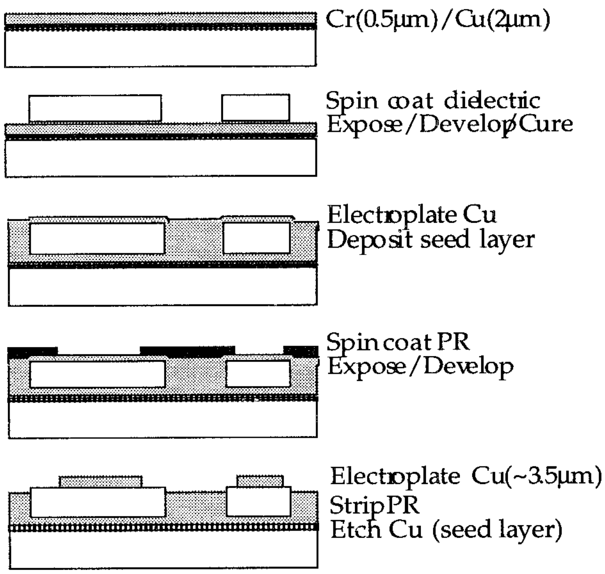

Figure 1. Test vehicle fabrication steps.

IV. Measurement Results:

The fabricated test structures were measured using a HP8510C Vector Network Analyzer and Cascade Microtech™ air coplanar waveguide probes with a Ground-Signal-Ground configuration (150 μm pitch) from 45MHz to 10 GHz (201 data points). On-wafer Line-Reflect-Match (LRM) error correction calibration were carried out using commercially available impedance standard substrate (ISS). For comparison with measured results, some of the structures were simulated using the Microwave Design System (MDS, from Hewlett Packard). The material parameter that were used in the model are: (1) dielectric constant = 9.1, (2) tan-δ=0.008, (3) surface roughness = 0.2 μm, (4) metal thickness (t) = 3.5 μm and (5) conductivity = $2.5X10^{-7}$ Ω-cm.

Microstrip lines and quarter-wave resonators (T-line resonator) were used in the characterization of the composite material. Figure 3 shows measured and modeled S-parameters, from 45MHz to 10GHz, of a microstrip line (l = 1800 μm, W= 100 μm, H= 21.2μm) on a high dielectric constant material substrate. A good fit is obtained using the above material parameters.

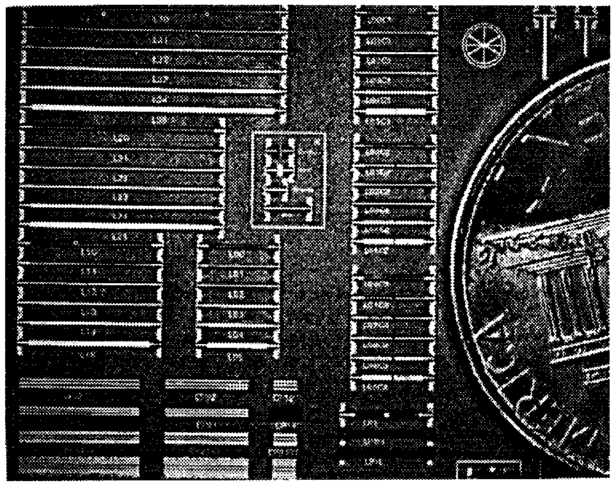

Figure 2. Photomicrograph of a section of the fabricated test vehicle.

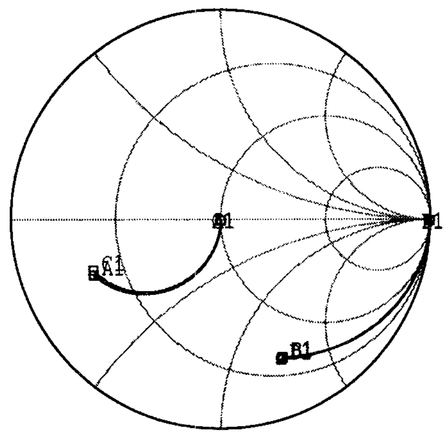

Figure 3 . Measured and modeled S11 and S12 parameter of a microstrip line on high dielectric constant material.

Figure 4 shows the calculated characteristic impedance (real and imaginary parts) using the method in [9] for 100 μm wide lines. Characteristic impedance close to 11.5 and 19.5 were achieved for these two samples. Using a dielectric constant of 9.1 and width of 100 μm, characteristic impedance of 19.3 and 12.0 were calculated which agrees well with measurements. The material has low loss characteristics which is reflected in these impedance plots.

Two lines with similar characteristic impedance (width = 100 μm) and different lengths (length difference = 250 μm) were used in determining the effective dielectric constant as a function of frequency, the details of which are available in ref. [10]. The measured values are plotted in Figure 5. The dielectric constant of the material was calculated to be approximately 9.1 from these data points. These results were also confirmed using T-line resonator measurements over three discrete frequency points, the details of this technique can be found in ref. [11]. Figure 4 shows measurements on a T-line resonator for two different dielectric materials (3.3 and 9.1) with line length and line width of 1.45cm and 100 µm respectively. The dielectric thickness for these samples were 10.2 µm (low dielectric constant) and 12.5 µm (high dielectric constant).

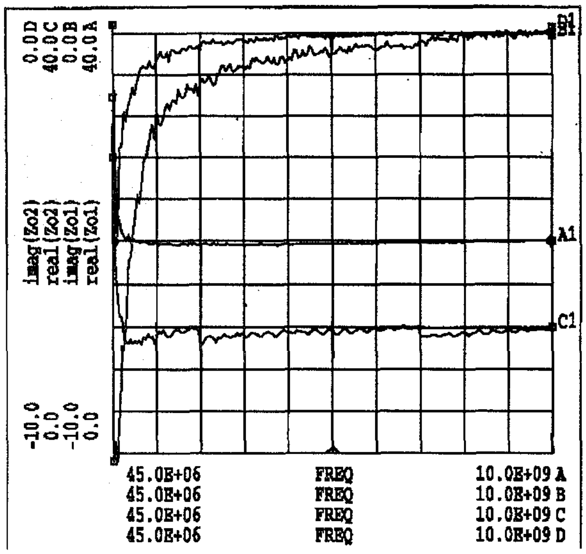

Figure 4 . Characteristic impedance plot of microstrips (W =100µm) for samples with different dielectric thickness (12.5 and 21.2 µm).

The use of high dielectric constant material allow for low impedance transmission lines that find application as matching networks for low-impedance devices (power FETs and photodiodes). The use of low dielectric constant material for these lines would require very wide lines, which may be impractical for integration. Figure 6 shows the insertion loss and return loss for low impedance microstrip (l = 955 µm, w = 230 µm).

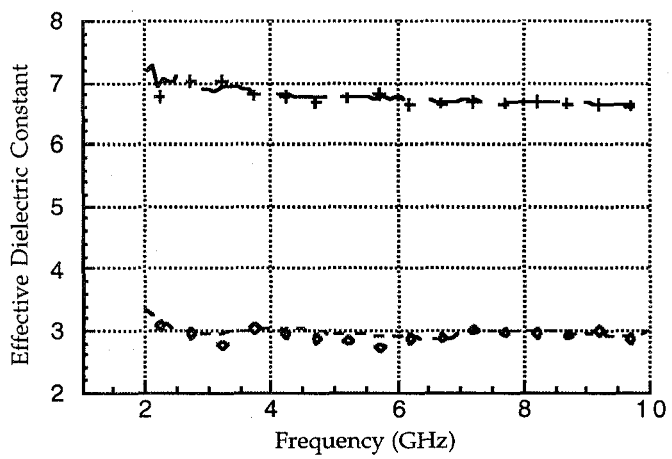

Figure 5. Measured effective dielectric constant.

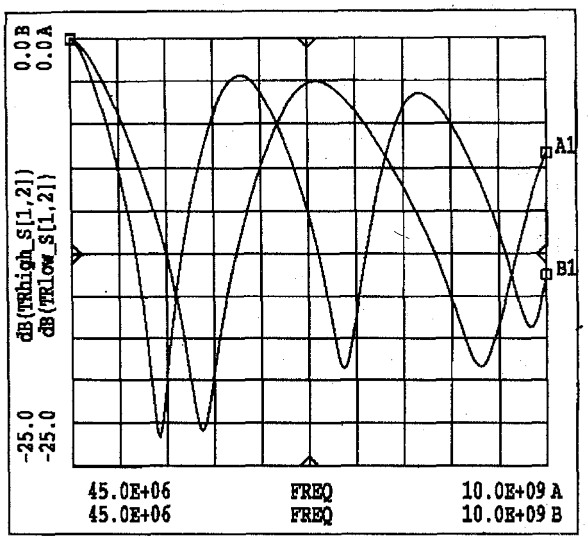

Figure 6. Measured response of a T-line resonator with stub length of 0.145µm and width = 100µm . Min. resonance points: High diel. (f_o = 1.89, 5.77 and 9.65GHz), Low diel. (f_o = 2.78 and 8.61GHz).

Coplanar lines are easier to fabricate (requires no vias) and thus are common in RF circuits. Coplanar lines with spacing (S) of 20µm over a ground plane were fabricated and characterized for the two material sets. Figure 7 shows the measured results of a 0.25cm long line on 12.5 and 21.2 µm thick dielectric layer. The cross-section of the transmission line is sketched in the inset of Figure 7. This also demonstrates that fabrication of passive devices with small features (20 µm) on polymer-ceramic composite is feasible.

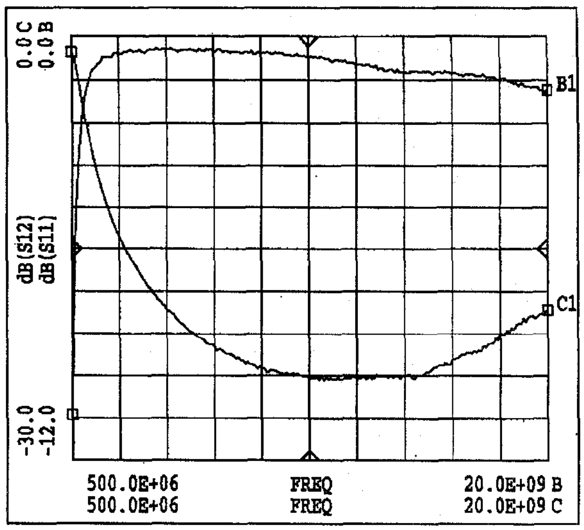

Figure 6. Ultra low impedance microstrip using high dielectric constant material (32, see ref. [7]).

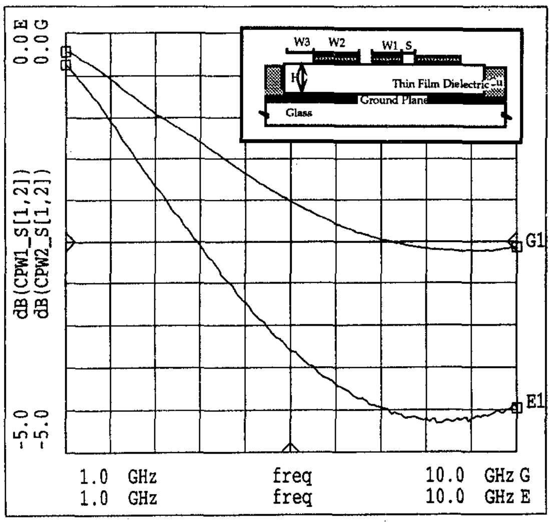

Figure 7. Measured S11 and S12 parameter of a coplanar-waveguide on high dielectric constant materials. W3 = 75µm, W2 = 190µm, W1 = 100µm, S = 20µm.

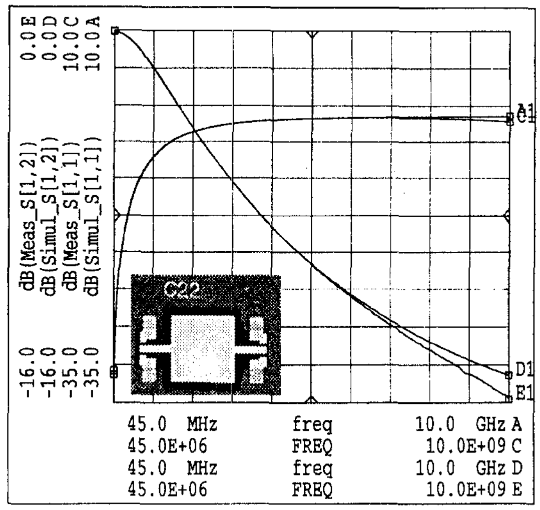

Figure 8. Measured (Meas.) and modeled (Model, ε_r = 9.1 and tan-δ=0.008) S-parameter of a capacitor structure (inset).

The resonant frequency of integrated capacitor occurs at higher frequency as compared to surface mount devices due to reduced parasitics (inductance) and also small dimension are achieved through the use of thin layers dielectric layer. Using low loss-dielectric and highly conductive electrodes, capacitor with high Q-factors can be achieved as required for RF applications. This is possible through the use of polymer-ceramic composites since they allow for thin film capacitors with Cu-electrodes. Several capacitor structures were fabricated with varying dimensions of the top electrode on a patterned dielectric layer to demonstrate low loss RF capacitors. The top electrode was probed at the end points (inset of Figure 8). Figure 8 also shows the measured and modeled S-parameters of a capacitor structure with dimensions of 920µm (square). The effect of the probe pads have not been dembedded from these plots. Modeled plots were retrieved using built-in microstrip models (including step in width) on MDS. The measured S-parameters correlate well up to 7GHz. Based on the simulated results and the low frequency measured capacitance values, the Q-factor of the capacitor structures was determined and are highlighted in Table 2 for different samples.

Table 2. Capacitance and Q-factor of capacitor structures.

Capacitor	Area (cmXcm)	C (pF), 100KHz	Q (1GHz)
C1	0.1 X 0.2	8	–
C2	0.4 X 0.2	33	115
C1'	0.1 X 0.2	14	–
C2'	0.4 X 0.2	54	102
C2''	0.4 X 0.2	23	125

C1, C2 : High dielectric material (H = 21.2 µm; ε_r = 9.1)
C1', C2' : High dielectric material (H ≈ 12.5 µm; ε_r= 9.1)
C2'' : Low dielectric material (H = 10.2 µm; ε_r = 3.3)

Some of the applications of meander lines are in resistors, inductors and in delay lines. For resistor and inductor applications such a structure has to be fabricated on a low dielectric material with large H and S in order to have minimum capacitive and inductive couplings. Meander lines with spacing of two to three times the dielectric thickness above the ground plane can be used as a quarter wave (λ/4) stub [2]. Meander lines were fabricated on both high and low dielectric constant materials. A photomicrograph of a fabricated meander-line structure (15-fingers) is shown in Figure 9. Figure 10 shows the S-parameters plot of structures on the two different dielectric materials (5-fingers, effective length = $W_{30\mu m}$ + $W_{100\mu m}$ = 7800µm + 900µm). As can be seen from the S-parameters that high ε_r material introduces more delay which allows for miniature lines. For inductor application the low dielectric material structure will be preferable for its associated resonance at higher frequencies and high characteristic impedance values.

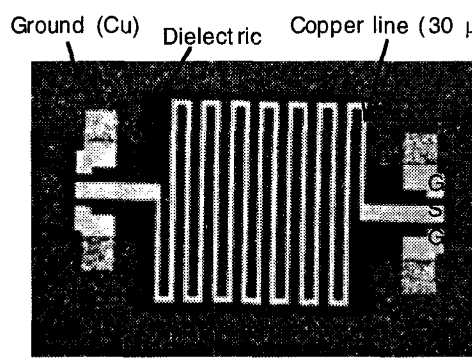

Figure 9. Photo of a meander line structure on composite material (W=30µm, Spacing (S) = 60µm; 15-fingers).

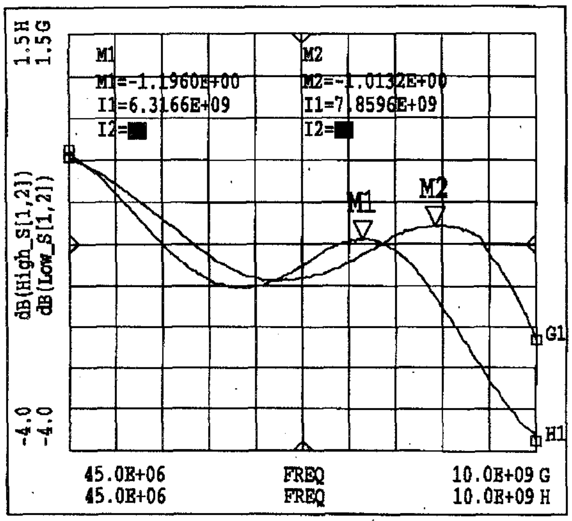

Figure 10. S12 and S11 of meander-like structure on thin films of low and high dielectric constant materials.

V. Structures:

The use of high dielectric photo-composites allow for miniaturization of passives embedded in MCMs. Figure 11 shows example of possible combinations of dielectric material on the same substrate. Combinations of these materials can be used in making miniaturized impedance matching, filters, and other RF circuits.

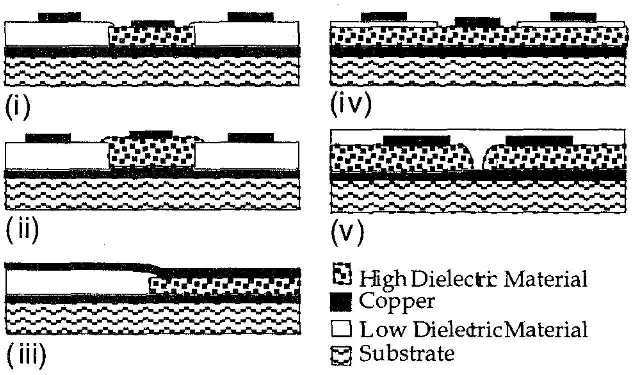

Figure 11. Examples of high/low dielectric combinations.

Summary:

In summary, few of the simple microwave structures presented here indicate that composite materials can be used in making integrated microwave passives with reduced size. These materials offers design flexibility from point of view of dielectric thickness, dielectric constant, use of copper metal, and ease of processing (via formation).

With the capability of incorporating thin high dielectric constant films in MCMs along with low dielectric constant layers gives flexibility in making mixed signal modules (e.g., SLIM) with increased performance and high packaging efficiency. Photodefinable composite material was achieved through the use photodefinable polyimide material as the matrix material with $BaTiO_3$ fillers. Processing of the composite material (high dielectric material) is compatible with that of interlayer dielectrics (low dielectric polymers). The effective dielectric constant of the photodefinable composite material (PI-$BaTiO_3$) was measured to 10GHz and was found to be stable. Further measured results on the test vehicle of this paper will be presented at the conference.

Acknowledgment:

The authors like to acknowledge the NSF (Project # EEC-9402723), DARPA and PRC industrial members for the financial support. DuPont Electronics, Dow Chemicals, TAM Ceramics, Amoco, and Cabot Performance Materials for supplying the materials. Special thanks to MSMA group, Weiping Li, Swapan Bhattacharya for helpful discussions, and Earl Feb and Daniela Staiculescu for help with the network analyzer measurements.

References:

[1] Microelectronics Packaging Handbook, ed. R. R. Tummala, E. J. Rymaszewski, A. Klopfenstein, Chapman & Hall, NY, 1996.

[2] T. Tokumitsu, T. Hiraoka, H. Nakamoto and M. Aikawa, "Multilayer MMIC using a 3μmXN Layer Dielectric Film Structure", IEICE Trans. Electron., Vol. E75-C; No. 6, 1992, pp. 698-706.

[3] J. L. Foure, A. Dravet, J. Cazenave and R. Funk, "Mixed Technologies For Microwave Multichip Module (MMCM) Applications-A Rewiev", IEEE Microwave Systems Conference, 1995, pp. 73 - 81.

[4] M. S. Adler, E. J. Wildi, W. Daum, C. A. Becker, "Multi-Chip Modules for Analog and Microwave: DC to 18GHz", IEEE International Solid-State Circuits Conf., 1993, pp. 170-171.

[5] C. Makihara, K. Ikeda, H. Wada, Y. Sawa, S. Tanahashi, "Multifunction Ceramic Substrataes and Packages for Telecommunication Applications", Proceedings of the International Symp. on Microelect.", 1994, pp. 243 - 247.

[6] B. Daigle, "Printed Circuit Board Material and Design Considerations for Wireless Applications", 46th Electronic and Tech. Conference, 1996, pp. 354 - 357.

[7] P. Chahal, R. R. Tummala, M. G. Allen and M. Swaminathan, "A Novel Integrated Decoupling Capacitor for MCM-L Tech.", 46th Elect. and Tech. Conf., 1996, pp. 125 - 133.

[8] P. Chahal, R. R. Tummala, M. G. Allen, "Integrated Capacitors using Polymer-Ceramic Comp. for MCM-L", Proceed. Int. Symp. on Microelect., 1996, pp. 126-131.

[9] Y. Eo, W. R. Eisendat, "High-Speed VLSI Interconnect Modeling Based on S-Parameter Measurements", IEEE Trans. on Components, Hybrids, and Manufacturing Technology, Vol. 16, No. 5, 1993, pp. 555-562.

[10] M. Lee, S. Nam, "An accurate Broadband Measurement of Substrate Dielectric Constant", IEEE Microwave and Guided Wave Letters, Vol. 6, No. 4, 1996, pp. 168 - 170.

[11] J. Carrol, M. Li, and K. Chang, "New Technique to Measure Transmission Line Attenuation", IEEE Transactions on Microwave Theory and Techniques, Vol. 43, No. 1, 1995, pp. 219 - 221.