Next Generation High Dk, Low Df Organic Laminate for RF Modules and High Frequency Applications

Fuhan Liu*, Vivek Sridharan, Tapobrata Bandyopadhyay, Venky Sundaram, Rao Tummala,
3D Systems Packaging Research Center, Georgia Institute of Technology, 813 Ferst Dr NW, Atlanta, GA 30332, USA
Kiyoshige Kojima, Naomi Shiga, Toshihiko Jimbo[+]
R&D Center, Zeon Corporation, 1-2-1, Yako, Kawasaki-ku, Kawasaki-shi, 210-9507 Japan
[+]Zeon Chemicals L.P. West Coast Office, 5 Centerpointe Drive, Suite 401, Lake Oswego, OR 97035, USA

* Phone: 404-385-6230 / FAX: 404-894-3842 / Email: fliu@ece.gatech.edu

Abstract

In this paper, we present a novel high density high performance ultra-thin organic laminate, X-R-1, with low cost standard PCB fabrication processes for RF and high frequency applications. The X-R-1 substrate, developed at Zeon Corporation is a new generation halogen-free high dielectric constant (Dk) and low loss tangent (Df) dielectric laminate material. Its dielectric constant is 6.5-6.7 in the range of 1-20GHz, similar to typical LTCC substrates but larger than most organic materials such as LCP, PTFE and Epoxy based materials. Its dielectric loss tangent is 0.003, similar to that of LTCC, LCP and PTFE but much lower than epoxy based materials. The thicknesses of the core used in this study are 50um. The clad copper on both sides is a 12um thick profile-free copper foil which provides extremely smooth surface. Microminiaturization of RF devices can be achieved by the combination of high Dk and ultra-thin substrate. The combination of low Df and smooth surface leads to RF and high frequency signals having minimum propagation loss. The material is suitable for mechanical and laser through hole drilling and fully compatible with the low cost standard PCB facilities and processes. Because of the smooth surface, 25um very fine copper lines and spaces were achieved by wet etching process. Copper filled through holes with 40um diameter drilled by CO_2 laser have been demonstrated. Panel size of 6"x6" test vehicles with RF filters and transmission lines was fabricated and measured. Test data on the filters at 2.4GHz and 5GHz has been presented in this paper. This high Dk and low Df laminate with standard PCB processes provides a low cost organic platform for RF and high frequency circuit applications.

Introduction

The current trend in advanced electronic devices, modules and micro-systems is small, light, multi functional, and high speed, while maintaining lower cost. Driven by these needs, the electronic packaging industry has been developing new advanced packaging materials and processes. In the field of RF and high speed/frequency systems the efforts are focused on (1) advanced packaging substrate material solutions for high speed systems, (2) miniaturization of devices and modules, and (3) development of low cost fabrication processes.

In RF and high speed/frequency applications, the dielectric loss dominates the overall signal loss and must be kept low to achieve high quality factors. The conventional PCB materials, such as FR-4 and epoxy based materials are not suitable because they cause excessive losses and distortion. The dielectric loss tangent Df for a typical FR-4 is about 0.02. The advantages of ceramic materials are very low loss of around 0.002-0.007 at high frequencies. Low temperature co-fired ceramic (LTCC) uses a green tape prepared from slurry of ceramic oxide, plasticizer, and solvents. The tape sheets are punched with holes for z-direction interconnects between layers. Then holes are then filled with a conductive paste using screening process. The wiring on the x-y plane are formed by printing conductive paste on each sheet and then stacking them together. The substrate is then fired in a furnace with precisely controlled temperature profile to a peak temperature of 850-900^{0}C. LTCC provides excellent RF performance. The dielectric constant Dk of LTCC is in the range of 6-9 which is twice the dielectric constant of FR-4 (3.5-4.2). A higher Dk leads to miniaturization of RF circuits. However, the key limiting factors of LTCC are the high temperature processes, thickness, weight, low wiring density, and cost.

PTFE (Teflon) is an organic material which has ultra-low dielectric loss over a wide frequency range. It offers excellent electrical performance for RF and microwave applications. PTFE has been used in high frequency circuits due to its extremely low dielectric loss tangent (<0.001). However, there are several PCB fabrication challenges for this advanced material. They are: 1) multilayer lamination, 2) desmearing and metallization, and 3) dimensional stability. In order to make multilayer PTFE, high temperature and high pressure is required [1]. The PTFE laminates are bonded together by using a bonding film or is fusion bonded under a high pressure. The fusion bonding is a high temperature (~370^{0}C) process that is not compatible with the capability of most lamination processes in the PCB industry. Teflon is well known for its non-stick properties that makes it very difficult to let other materials, for example plated copper, adhere to it. PTFE substrates also require special desmear processes using harsh alkaline chemistries or plasma processes that are not compatible with low cost organic substrate infrastructure. In addition, the PTFE is a thermoplastic polymer which becomes soft during the multilayer substrate fabrication processes at high temperature and high pressure. Hence, the dimensional stability of multilayer substrates is a big concern since fine circuit features cannot be kept in their original position without movement.

Liquid crystal polymer (LCP) has excellent high frequency performance, low moisture uptake, and low CTE and has generated a lot of interest in the past few years for RF module applications. However, LCP has also faced FR-4 process compatibility issues similar to PTFE. It needs high temperature, high pressure, and highly precise temperature control for multilayer fabrication [1]. LCP is a thermoplastic material as well and dimensional stability of multilayer substrates remains an area of concern. Both LCP and PTFE require non-standard metallization processes to achieve good copper adhesion.

The primary criteria for selecting a high performance substrate include electrical and mechanical properties, capability for high density wiring, compatibility with standard PCB processes, and cost. From these criteria one can say that the LTCC, PTFE and LCP are excellent high performance and high frequency materials but the fabrication process is a challenge for all of them. Some other weaknesses such as thickness and weight for LTCC, mechanical instability for PTFE and LCP, and as well as high cost limit the applications of these materials. Alternative advanced packaging materials need to be developed. To address these needs, a novel ultra-thin high Dk low Df organic laminate material, X-R-1, has been developed, and will be introduced in this paper.

X-R-1 High Dk Low Df Laminate Material

X-R-1 is a new organic laminate designed for high-density interconnect, multilayer RF substrate applications developed by Zeon Corporation. Its dielectric loss tangent is 0.003 measured at 1 GHz, equivalent to that of typical LTCC and LCP. Its dielectric constant is 6.5-6.7 in the range of 1-20 GHz which is similar to typical LTCC materials. The thickness of X-R-1 laminate used in this study is 50um which is much thinner than typical ceramic substrate and FR-4. Profile-free 12 um thick copper foils are clad on both sides. The profile-free copper provides a smooth surface for fine copper line wet etching and benefits for low RF and high frequency propagation loss. Fine pitch copper traces and fine via holes can be achieved on this material by using standard PCB facilities and processes. Unlike LTCC (ceramic), PTFE and LCP substrates, the fabrication processes of X-R-1 substrate are totally compatible with conventional FR-4 material.

The X-R-1 is a thermo-setting glass fiber reinforced hydrocarbon polymer which is dimensionally stable. Process characterization test vehicles were designed and fabricated for evaluating this new material. Diameter of 40um through holes were drilled by CO_2 laser and 25um copper lines and spaces were fabricated by using wet chemical etching method, primarily due to the smooth copper foil. Furthermore, to demonstrate RF integration, 2 metal layer structure test vehicles were designed, fabricated and tested. The test vehicle included RF characterization structures such as transmission lines, inductors and capacitors and bandpass filters.

Due to the ultra thin X-R-1 substrate with high Dk, low Df, and profile-free copper, about 40% size reduction compared to low Dk materials was seen on the bandpass filters with low insertion loss and good return loss. Due to the high adhesion strength of profile-free copper, the low loss X-R-1 substrate shows lower transmission loss, compared to LTCC. The new X-R-1 laminate provides a thin, light, high performance and low cost RF organic platform with high functionality and flexibility. Table 1 lists selected properties of the X-R-1 laminate. Figure 1 shows the dielectric constant Dk (6.5-6.7) measured in the range of 1-20GHz.

Table 1. Properties of X-R-1 laminate

Property	X-R-1
Dk	6.7 (1GHz)
Df	0.003 (1GHz)
CTE, ppm/^{0}C	< 40
Cu Surface Roughness, µm	Rz < 1
Water Absorption, %	< 0.1
Frame Retardant	Halogen Free
Via Hole Formation	Laser drillable
Thickness, µm, minimum	50
Panel Size, mm x mm	340 x 450

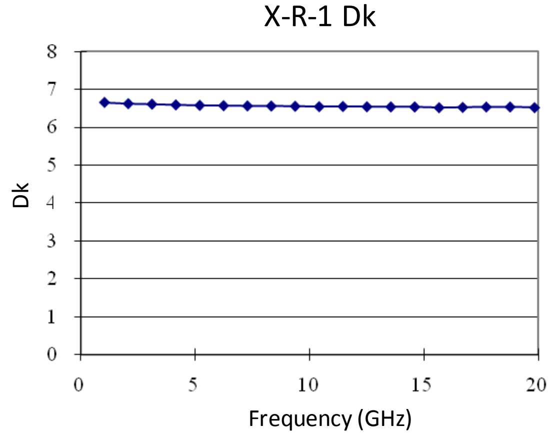


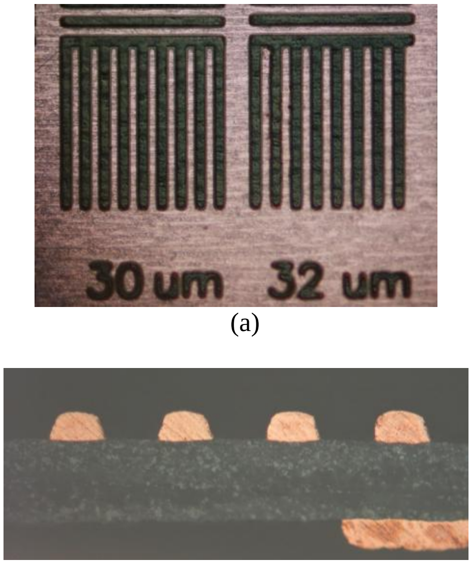
Figure 1. The measured dielectric constant Dk of X-R-1 in the range of 1-20GHz.

High Density Wiring on X-R-1 Laminate with Fine Lines and Small Through Vias

Increasing device complexity drives the printed circuit board (PCB) and packaging industry towards higher wiring density, which allows for fine pitch chip routing, and increases functionality while simultaneously decreasing the on-board interconnect length. The latter has a large influence on system miniaturization and performance improvement because of short interconnection signal propagation delay and attenuation. A process test vehicle (PTV) was designed for fine line and via process development and evaluation of wiring capability of the X-R-1 material.

Subtractive Fine Copper Traces on X-Y plane

Various structures with different line widths and spaces for testing the capability of fine copper trace formation on the X-R-1 laminate were fabricated. In the core fabrication, the common subtractive copper etching method was employed to form the circuitry on X-Y plane. Dry film photo resist MX-5015, provided by DuPont was employed for image transfer from photo-mask to the substrate. The thickness of MX5015 is 15µm which provides a reliable imaging method with high resolution and a simple process for high volume production. A Tamarack exposure system with a 1KW UV source was used for the exposure. This tool provides the benefits of collimation of UV beam and vacuum contact printing for fine line lithography. In addition, a mylar film photo-mask was used for cost reduction. Using the combination of low cost mylar photo mask and dry film MX-5015 for image transfer, minimum resist lines and spaces of 15um were resolved. A spray etcher (Chemcut Corporation) with cupric chloride ($CuCl_2$) etchant was employed for the copper etching. The results showed that lines and spaces of 30um and 25um could be achieved on the X-R-1 laminate. Figure 2(a) shows the top view of etched structures consisting of 30um and 32um fine lines and spaces (100X). Figure 2(b) shows the cross sections of etched 30um lines and spaces (500X). Figure 3(a) shows the top view of etched structures consisting of 25um and 26um very fine lines and spaces (100X). Figure 3(b) shows the cross sections of etched 25um lines and spaces (500X). The thickness of the copper was measured at 13um. All these fine lines and very fine lines have a consistent shape. Due to the profile-free copper foil, very fine copper traces were obtained from the subtractive etching process.



(a)

(b)

Figure 2. Wet etched copper traces on X-R-1; (a) 30um and 32um lines/spaces (Top, 100X) and (b) cross section of 30um lines/spaces (500X).

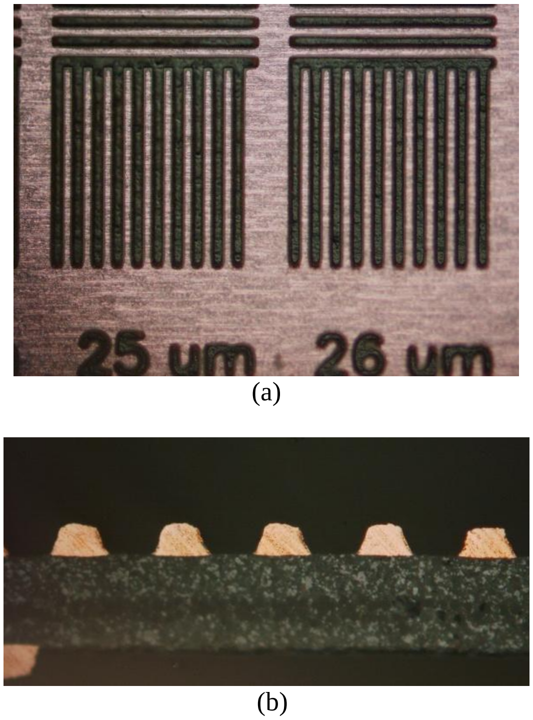


Figure 3. Wet etched copper traces on X-R-1 with (a) lines/spaces of 25um and 26um (100X) and (b) cross section of 25um lines/spaces (500X).

Figure 4 shows the comparison of profile-free copper on X-R-1 laminate and high Tg epoxy laminate. It was observed that the X-R-1 has a much smoother copper interface.

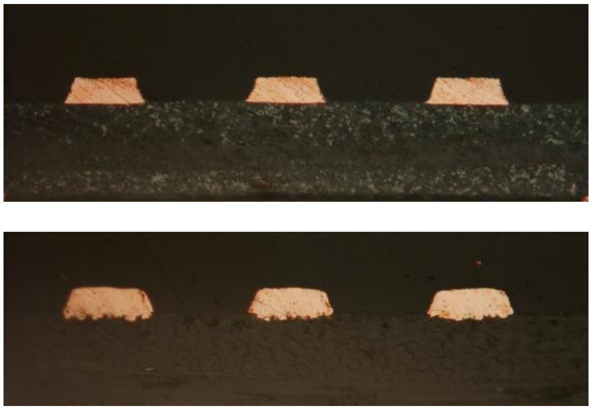


Figure 4. Comparison of Profile-Free Copper on X-R-1 Laminate (Upper) And High Tg Epoxy Laminate (Lower).

Laser Ablation and Small Through Hole Interconnect

The high density wiring core laminate should allow for fine pitch copper line formation on X-Y plane and small through hole formation in the Z-direction as well. The X-R-1 laminate can be easily drilled by mechanical drilling, CO_2 and UV laser drilling. Through holes with a diameter of 40um have been demonstrated by both CO_2 laser and UV laser drilling. Figure 5 shows optical micrographs of top view (upper) and cross section (lower) of a copper plated through hole with 40um diameter drilled by CO_2 laser. Table 2 summaries the processability of the X-R-1 laminate.

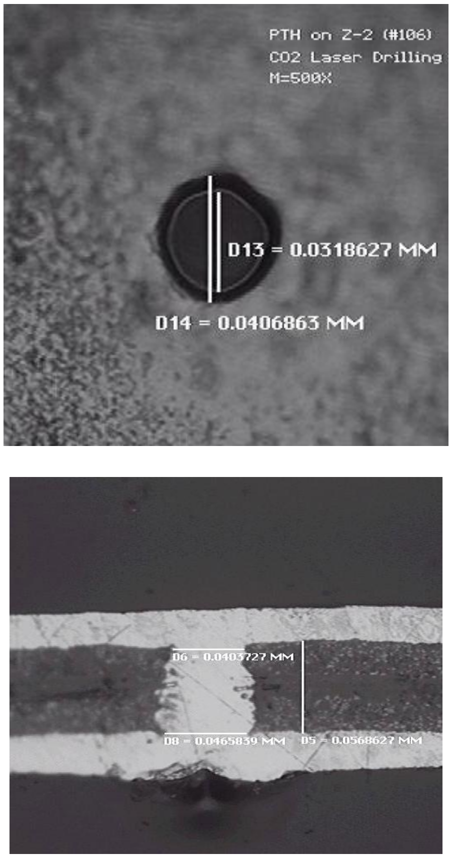


Figure 5. Through holes (40um diameter) in 50um Thick X-R-1 drilled by CO_2 laser

Table 2. Processability of X-R-1 Laminate

Item	**X-R-1**
Process Category	PCB Standard
Drill Bit Appearance after 3,000 hits	Good
Smallest Via Diameter, µm	<50 (CO_2 Laser)
	<40 (UV Laser)
Chemical Desmear	Good
Electroless copper plating	Good
Smallest Line/Space, µm	20/20

High Frequency Characterization and Embedded RF Passives Demonstration

Material characterization before design is highly critical and there are several methods to obtain the dielectric constant [2-5]. Transmission line based methods are popular and can extract the dielectric constant at all the measured frequency points. However, it is to be noted that the closed-form expressions used in those methods are only valid for a limited range of the ratios between the strip width and the substrate thickness, and also limited by frequency [3]. Therefore a resonator based method was used.

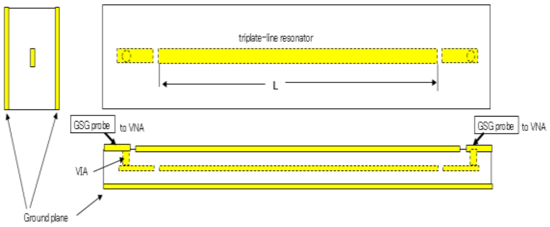


Figure 6. Measurement using Triplate-Line Resonator

$$\varepsilon_r = \frac{C^2 m^2}{4L^2 f_0^2} \quad (1)$$

The dielectric constant was estimated using triplate-line resonator technique and the setup is shown above in Figure 6. The dielectric constant is calculated from equation 1, where m is the resonance mode or number, L is the length of the line. The response of the resonator is shown in Figure 7. The dielectric constant obtained using this technique was 6.5665 ± 0.0366 and detailed data is summarized earlier in Figure 1.

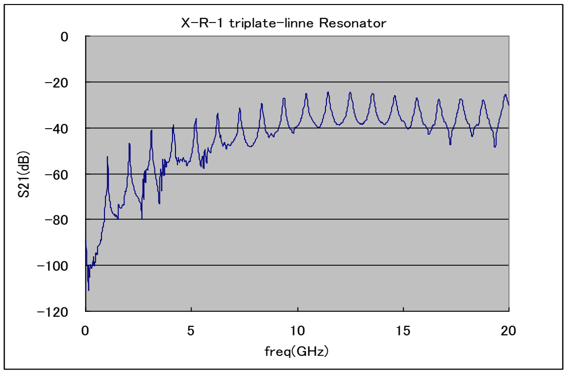


Figure 7. Triplate-Line Resonator Response

Filter Design and Characterization

The two metal layer X-R-1 laminate test vehicle with filters, passives and other structures is shown in Figure 8. Two-metal layer band pass filters were designed for 2.4 GHz, and 5 GHz bands. Filters with insertion losses as low as 0.54dB were designed according to the schematic in Figure 9. This topology was chosen since it is capacitor dominated, which can be used effectively on a high-k material. In the two-metal layer designs, for ease of design and measurement using GSG probes, ground structures were added peripherally on both layers and interconnected using vias.

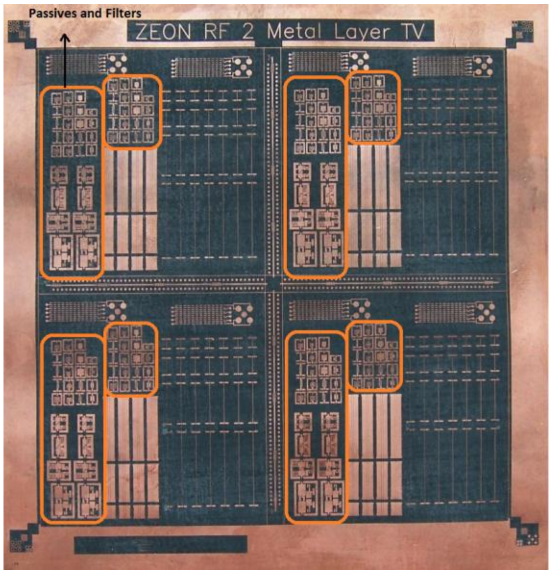


Figure 8. Fabricated RF Test Vehicle on X-R-1 Laminate

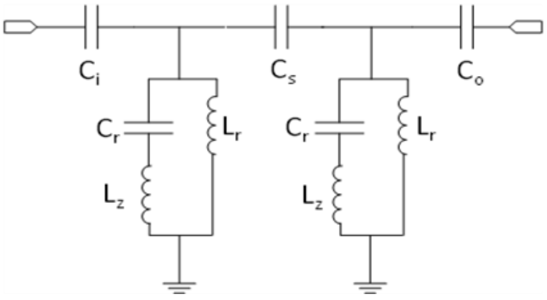


Figure 9. Band Pass Filter (BPF) Schematic

The measurements were carried out using short-open-load-thru (SOLT) calibration by Agilent PNA 8363B with Cascade GSG 500um coplanar probes. For the two-metal layer measurements, the test sample was placed on an FR4 board in order to prevent shorting of all the structures at the bottom layer.

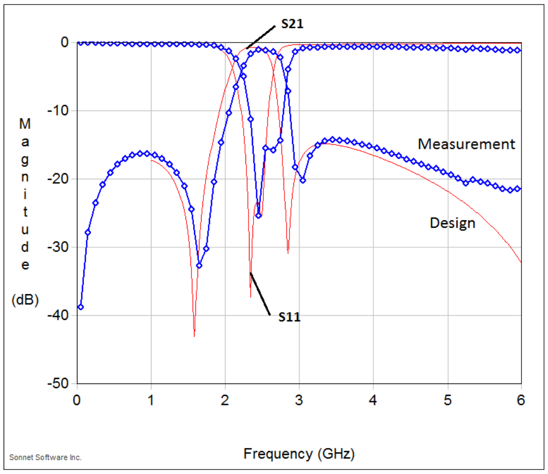


Figure 10. 2.4GHz Filter Response

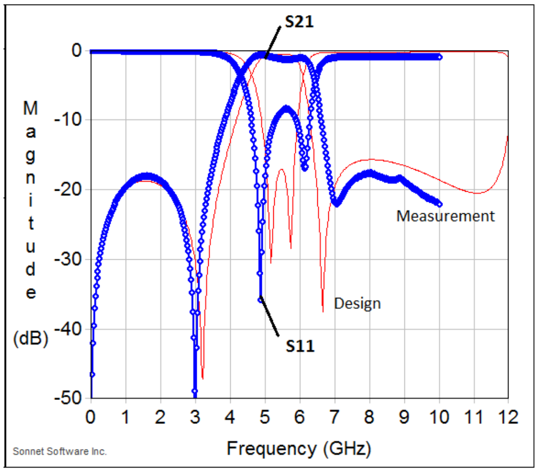


Figure 11. 5GHz Band Pass Filter Response

Figure 10 and Figure 11 show the correlation between simulated and measured frequency responses (S11 and S21) of the two-metal layer 2.4GHz and 5GHz band pass filters respectively. The comparison between designed and measured insertion loss is shown in Table 3.

Table 3. Summary of BPF Measurements

Filter	Insertion loss (dB)		Area (mm^2)	Volume (mm^3)
	Design	Measured		
2.4 GHz	0.76	1.08	3.7x4.6	0.851
5 GHz	0.54	1.12	3.3x3.1	0.511

The discrepancy (loss and frequency shift) between design and measurement, as seen in Table 3, Figure 10 and Figure 11, is due to process variations.

Summary

A novel high Dk and low Df ultra-thin organic laminate X-R-1 which allows for very high density wiring formation by using standard PCB facilities and processes has been demonstrated. Its dielectric constant Dk was measured to be 6.5-6.7 in the range of 1-20GHz and the dielectric loss tangent of X-R-1 is 0.003 at 1GHz. X-R-1 has been designed for excellent adhesion to profile-free copper foil and 25um very fine lines and spaces were achieved by wet etch process. Through vias of 40um diameter were demonstrated in 50um thick X-R-1 glass reinforced laminate using a CO_2 laser. Miniaturized embedded band pass filters at 2.4 GHz and 5 GHz were designed, fabricated and measured with insertion loss comparable to LTCC substrates with much lower thickness. The new X-R-1 laminate provides a low cost high performance organic platform for RF and high frequency applications.

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