AFFORDABLE MICROWAVE CIRCUIT BOARD SUBSTRATE MATERIAL

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ABSTRACT:
While glass fibers are commonly used to reinforce circuit board substrates, they have a high dielectric constant and loss. Cyclic olefin copolymer fibers have a lower dielectric constant and loss. By combining these fibers with glass fibers in unique hybrid cloths, we have made circuit board substrate materials with a dielectric constant of 3.08 and loss of 0.013 using standard epoxy resins that are common in FR-4 glass reinforced substrates. The comparative glass materials had a dielectric constant of 4.49 and loss of 0.019. Substrates made from this fiber have passed Peel Strength, Solder Float, Water Uptake, and have a low coefficient of thermal expansion.

INTRODUCTION

1) Microwave Circuits: As digital technology permeates every part of our life, more and more high frequency applications are reaching the average consumer. From internet infrastructure, wireless communications and laptop and desktop computers to automotive collision avoidance, cell phones and global positioning, high frequency electronics are reaching into our homes, our cars, and our pockets. As the speed of these electronics increases to higher and higher frequencies, they increasingly place more severe demands on the circuit board substrates they reside on. Among other features, they demand lower dielectric constant and dielectric loss, which control the circuit density and transmission energy loss, as well as better mechanical properties which are becoming increasingly important as electronics become more and more portable.

This is an area of continual innovation, and has seen the introduction of polyimide films, Teflon glass composites and liquid crystalline polymer films as substrate materials. These materials represent the state of the art in electrical and physical properties, but have in the past been too expensive to penetrate deeply into mainstream digital electronic applications. In the coming years, as PC motherboard voltages drop down below 2V and motherboard frequencies are predicted to reach 3 – 5 GHz, the FR4 glass-epoxy substrates will be inadequate. [1]

Two key performance parameters are driving the need for an affordable microwave circuit board substrate. The first is energy savings, which is related to the heat output of the device, the battery life of portable devices, as well as the cost of the energy itself. The US Energy Information Administration predicts that the energy consumption in the "all other" residential category, which includes computers and office equipment, will increase in the US alone by *4 quadrillion* BTUs.[2] This energy savings will also increase battery lifetime and reduce the heat load placed on the device thermal management system.

The other driving need for an affordable microwave circuit board substrate is data integrity. Current boards are constructed of glass fiber, with a dielectric constant of 6.2, and epoxy resin, with a dielectric constant in the range of 3.0 to 3.5. Data integrity is lost in transmission and reception inside a board, in which the dielectric loss dissipates energy and reduces signal intensity, at the same time increasing thermal noise present. It is also lost when a signal is sent or received through wireless communications, where the difference in dielectric constant and loss from air helps to determine the transmission loss at the air – board interface. These problems are magnified significantly at higher frequencies, which are used for such applications as global positioning and satellite communications.

2) Current Low Dielectric Substrates: Given these needs, several parameters are important in microwave circuit board substrates. First, they must meet minimum physical characteristics, in general have a flexural modulus of greater than 2.5 GPa and have a suitable machinability for cutting and drilling small via holes. The dielectric constant and dielectric loss must both be low, below 2.5 and 0.002 respectively, as they determine the energy loss and frequency range of the substrate.[3] The coefficient of thermal expansion must be low to allow consistent performance at various temperatures.

	2004	2025
# PCs globally[4]	600 million	2.5 trillion
Processor chip speed[5]	3.2 GHz	35 GHz
Processor power[6]	100 W	1000 W
Motherboard clock speed[7]	800 MHz	3 GHz

[1] SEMATECH, 2003 International Technology Roadmap for Semiconductors, available at http://public.itrs.net
[2] "EIA Annual Energy Outlook 2004 with Projections to 2025," available at http://www.eia.doe.gov/oiaf/aeo/
[3] *Microwave Materials and Fabrication Techniques*, Thomas Laverghetta, Artech House, New York, 2000, p 12.
[4] Microsoft 2004 Annual Report, available at www.microsoft.com.
[5] Gordon Moore, "No Exponential is Forever…but We Can Delay 'Forever'", presentation at International Solid State Circuits Conference 2003, available at www.intel.com/labs.eml
[6] ibid
[7] ibid

Stripline dielectric loss at motherboard clock speed[8]	0.3 dB/cm	1.5 dB/cm

Example high frequency circuit board substrate materials are listed with their electrical and mechanical properties below in Table 2. As can be seen, most of the innovative film and reinforced poly tetrafluoroethylene (PTFE) substrate materials have sacrificed mechanical properties in pursuit of superior electrical properties, by comparison with a standard FR-4 glass-epoxy composite. In order to reduce the average dielectric constant of the material, they reduce or eliminate glass fiber and replace the epoxy matrix material with a low dielectric constant matrix such as PTFE.[9] PTFE is very soft, however, so some glass has to be retained, and this glass fiber: PTFE ratio is the key determinant of both physical and electrical properties. PTFE is an expensive material, however, and also difficult to process, further increasing the costs of these boards. The problem, then, is to provide superior dielectric properties which result in improved microwave circuit performance, while controlling cost such that the materials will be affordable for mass consumer electronics applications. This involves more than a simple iterative cost reduction on the current PTFE – glass materials, or iterative performance enhancement of the glass – epoxy materials. Rather, it requires a radical redesign based on new materials and a new structure to ensure that these less expensive materials deliver the electrical and mechanical performance needed for these demanding applications.

Table 2 - Electrical, physical and thermal properties of representative high frequency printed circuit board substrate materials in the market today.

Property	Units	PPE PS film[10]	Polyimide film[11]	Glass PTFE[12]	LCP film[13]	FR-4
Dielectric Constant		2.6	3.3	2.17	2.9	5.2
Loss Tangent		0.0025	0.011	0.0009	0.002	0.025
Flex Modulus	GPa	2.6	3.8	2.1		17
Flex Strength	MPa	114				483
Tensile Strength	MPa	80	241	49	120	345
Density	g/cm^3	1.08		2.23	1.4	1.82

3) High Modulus Fibers: Fibers are known to be the strongest materials on earth.[14], [15] Current high modulus fibers come in five classes: glass fibers, metal fibers, carbon fibers, Aramid fibers, and ultra high molecular weight polyethylene (UHMWPE) fibers.[16] For low dielectric applications metal and carbon fibers are not suitable because of their conductivity. Glass fibers, with a dielectric constant of 6.2,[17] are also unsuitable at high usage rates, though in small amounts they are the fiber of choice when used with an appropriate fluorocarbon resin, such as Teflon PTFE.[18] UHMWPE fibers, have a low dielectric constant of 2.25 and also low loss, but melt at 135 C, and thus do not have the thermal resistance needed for soldering electrical connections onto a microwave circuit board substrate. Aramid fibers, such as Kevlar have superior thermal resistance and a dielectric constant of 3.85,[19] which is lower than glass, though their high dielectric loss of 0.019, as well as their cost, around $30/lb, has inhibited widespread use of the fibers. Carbon fibers are conductive, and thus not useful as dielectric substrate materials.

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[8] Gautam Patel, Katie Rothstein, "Signal Integrity Characterization of Printed Circuit Board Parameters," presentation at DesignCon 1999, available at http://www.teradyne.com/prods/tcs/resource_center/white_papers/designcon_1999.pdf
[9] *Microwave Materials and Fabrication Techniques*, Laverghetta, p 34.
[10] http://www.sheldahl.com/Product/TMComClad.htm
[11] http://www.sheldahl.com/Product/TMNovaClad.htm
[12] http://www.arlon-med.com/Diclad.pdf
[13] http://www.rogerscorporation.com/acm/about_our_products.htm#3000
[14] *Kevlar Aramid Fiber*, H.H. Yang, John Wiley & Sons, Chichester, England, 1993, p 29.
[15] *Structure Formation in Polymeric Fibers*, David R. Salem, Hanser Gardner Publications, Munich, 2000, p 188.
[16] *Handbook of Composites, Second Edition*, S. T. Peters, Chapman & Hall, London, 1998, p 23-28.
[17] Ibid, p 135.
[18] *Microwave Materials and Fabrication Techniques*, Laverghetta, p34.
[19] *Handbook of Composites, Second Edition*, S. T. Peters, p 231.

Table 3 - Properties of currently available high modulus fibers.

Property	Units	Glass	Aramid	UHMWPE	Carbon
Dielectric Constant		**6.2**	3.85	2.3	**conductive**
Dielectric Loss		0.003	**0.019**	0.002	**conductive**
Tensile Strength	GPa	2.6	3.4	3	4
Tensile Modulus	GPa	71	99	170	231
Melt Point	C	1725		**135**	

Using a process that relies on carefully controlling the initial crystallization of a fiber after it has been extruded, we have been able to make polyolefin fibers with very high modulus values, as high as 20 GPa, compared to 3.3 GPa for polypropylene fibers spun conventionally.[20] These fibers have high tenacity, 1.1 GPa, and otherwise retain the dielectric properties of polypropylene, with a dielectric constant of 2.2 and a loss tangent of 0.0002, and are being commercialized under the trade name Innegra™.[21] To date, these fibers have been fabricated into ropes, reinforced sails, composites in vinyl ester resins, as well as used as reinforcement for concrete. However, their melt temperature will not support soldering processes. The fibers also show a high degree of crystallinity, but the lamellar chain folding conformation is absent, and has instead been replaced by two broad, sharp equatorial streaks which represent a highly elongated, dense "shish" crystal conformation surrounded by chain folded "kabobs" and amorphous regions.

FIBER AND FABRIC MANUFACTURE AND PROPERTIES

1) Amorphous Hydrocarbons: There has been significant work on spinning amorphous polymers into optical fibers, though in general, the quality of the fiber in terms of uniformity of shape and material is of primary importance, and the resultant processes are too expensive to consider for this application.[22] However, several polymers in this class have the dielectric, physical and thermal properties that show promise for use as reinforcements for high frequency circuit board materials. Table 4 shows properties of several amorphous hydrocarbon polymers which, in principle, should fit these criteria.

Table 4 - Properties of amorphous hydrocarbon resins which could be made into fibers.

Property	Units	PP[23]	PPO[24]	COC[25]	Polyether imide[26]
Dielectric Constant		2.2	2.69	2.35	3.15
Dielectric Loss		0.0002	0.0007	0.0002	0.0015
Flexural Modulus	GPa	1.38	2.5	3.0	3.5
Tensile Strength	MPa	34.5	63	60	110
Thermal Conductivity	W/m K	0.13			0.22
Thermal Expansion	ppm/C	100	59	60	56
Melting Point	C	165	--	--	--
Glass Transition Temperature	C	--	75 – 155	75 – 170	217

2) Hybrid Substrates: The basic concept we explore in this paper is shown in Figure 1. First, a fiber is made from an amorphous hydrocarbon polymer, such as Topas cyclic olefin copolymer, which is used in this study. The fiber can be woven into a fabric in its neat form using normal textile weaving processes. In addition, a small amount of glass fiber may be needed to achieve the appropriate physical properties (especially the coefficient of thermal expansion) necessary for high speed circuit board substrates. The glass fiber can be combined through yarn processes, such as twisting, air-texturing, air-interlacing, or false twist texturing. It can also be woven into the fabric as intermittent picks. Thus, fabric made of 100% amorphous hydrocarbon resin can be made, and can also be reinforced with 5-50% or more of glass fiber if necessary to achieve the appropriate physical and thermal properties. The relative proportion of glass to our fibers can be controlled by

[20] US Patent Application "Melt-Spun Multifilament Polyolefin Yarn Formation Processes and Yarns Formed There from", USSN: 10/983,153, filed November 5, 2004.
[21] www.innegrity.com .
[22] For example, Toray makes a polymer optical fiber, Raytela. These fibers use materials such as polycarbonate or PMMA, and careful control is exerted over the uniformity in dimensions over the length of the fiber, which is a key determinant in optical fiber performance. More information can be found at http://www.moritexusa.com/products/product_category.php?pcid=25&plid=4
[23] Poly propylene homopolymer. Example Atofina HPP 3462, product information available at www.atofina.com .
[24] Poly phenylene ether. Example General Electric Noryl 265, product information available at www.gepolymerland.com .
[25] Cyclic olefin copolymer. Example Ticona Topas 6017, product information available at www.ticona.com.
[26] Example General Electric Ultem 1000, product information available at www.gepolymerland.com .

the weight of the fabric: to reduce the glass fraction, the glass fabric can be chosen to be ½ to ¼ of the volume of our fibers fabric fabric, or even less if desired.

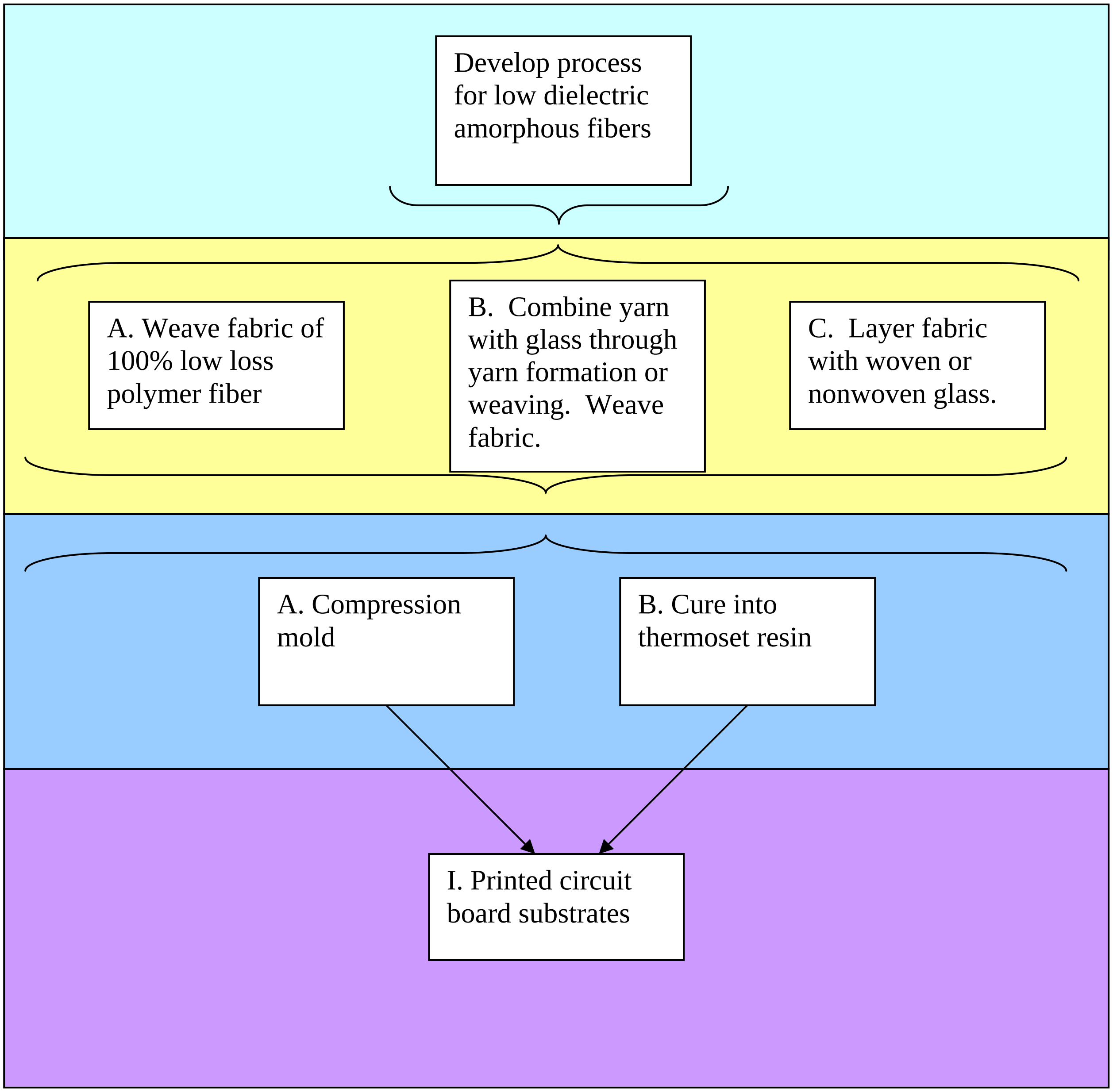

Figure 1 - Ways of combining glass, low dielectric fibers, and resins to form affordable microwave circuit board substrate materials.

These fabrics can then be used to form traditional epoxy prepreg materials, which can be used in a traditional way, albeit with improved dielectric properties. Additionally, the fabric could be compression molded at a temperature such that the amorphous hydrocarbon, or other low dielectric resin, can flow to create a solid laminate with glass fiber reinforcement and low dielectric thermoplastic matrix resin.

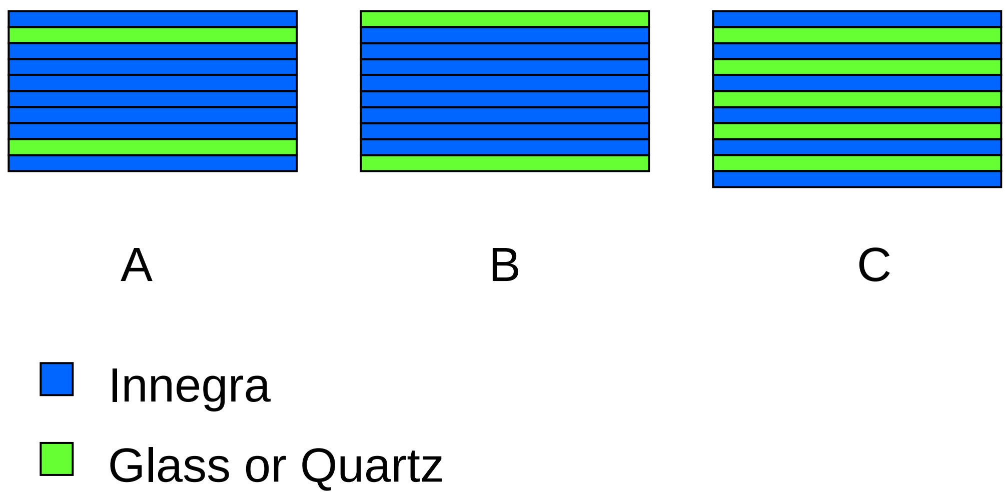

Figure 2 - These schematics represent the possible configurations of our material and glass or quartz fabrics in hybrid composites. Advantages for each are: A: Places low dielectric fiber near the surface to minimize reflection coefficient, while retaining glass fiber just under the surface to maximize physical properties. B. Places glass farthest apart to maximize physical properties. C. Evenly spaced composite materials, for the most uniform dielectric to be experienced by the traveling wave.

3) Substrate Manufacture and Testing: For this study, we made three sets of composites. Topas® 6017 cyclic olefin copolymer was obtained from Ticona. Pellets were fed into a 3/4" extruder with extruder temperature set to 190°C, 230°C and 270°C in extruder zones 1-3, and the melt pump and spin head heated to 290°C. The polymer was extruded through a spinneret with 15 orifices of 0.020" diameter, and passed through ~3 meters of room temperature air, then taken up on a first godet running at 1000 m/min and set at a temperature of 150°C. The yarn thus formed was then passed to a second godet, which was running at 1320 m/min and also set at 150°C, the yarn being drawn between the first and second godets. This first yarn was then passed over a third godet, running at 1320 m/min and at room temperature, and then wound on a bobbin. The drawn yarn was 60 denier in size. This first yarn was then woven as a weft yarn across a warp made of 450s glass yarns with 60 warp yarns/inch. The weft yarn was woven in at 47 picks/inch. This fabric was then dipped in marine grade epoxy resin, and layered in a mold, a total of 8 layers, pressed to force out excess resin, and allowed to cure. The composite thus formed was taken from the mold and measured for electrical and mechanical properties, shown in Table 5 below.

For comparison purposes a glass fabric, style 1080, with 450s glass yarns at 60 ends/inch in the warp and 47 ends/inch in the fill, was molded similarly to the composite described above. The composite was also tested, with the results shown in Table 5.

Table 5 - Dielectric and physical properties of epoxy substrates reinforced with 1080 glass fabric, and a similar fabric made by replacing the weft yarns with 60 denier cyclic olefin copolymer yarns.

	"1080" with low dielectric polymer weft yarn	1080 glass fabric
Dielectric Constant	3.52	4.65
Loss Tangent	0.018	0.021
Flexural Modulus	2764 ksi	3125 ksi
Flexural Strength	42.4 ksi	43.3 ksi
Density	1.2 g/cm^3	1.6 g/cm^3

A second sample was made by preparing a 50 denier yarn similar to the yarn above. This was made into two fabric samples. The first is similar to above; with a style 1080 glass warp and cyclic olefin copolymer fill at 47 picks per inch. Composites made with this fiber in an FR-4 epoxy resin are shown in Table 6 below as the "Our Material" sample. The second yarn was prepared by cabling this yarn with 450s glass, and weaving in the same construction. This is the "Our cabled weft" below. These were prepared in epoxy laminates along with a 1080 glass fabric, and the dielectric and physical properties for all three laminates are shown in Table 6 below.

Table 6 - Composites made in FR-4 epoxy resin using 1080 style fabric with a 50 denier cyclic olefin copolymer weft ("our proprietary weft"), a 50 denier weft cabled with 450s glass ("our proprietary cabled weft") and 100% glass. All fabrics had a 450s glass warp. The inclusion of cyclic olefin copolymer yarn greatly reduces the dielectric constant and loss.

	Our Material	Ourcabled weft	1080
Dielectric constant	3.08	3.29	4.49
Dielectric loss	0.0131	0.0125	0.0190
Flex Strength	25 kpsi	25 kpsi	29 kpsi
Tensile Strength	48 kpsi	47 kpsi	60 kpsi

Last, another set of samples was prepared using 125 denier cyclic olefin copolymer yarn, prepared similarly to the yarns above. This yarn was twisted with a 450s glass yarn, and woven as a weft yarn across a style 1080 warp at 47 picks per inch. The weight of the resultant fabric was 70 g/m2, compared to 49 g/m2 for 1080 glass. This fabric was cut into 4" x 6" pieces and placed into a mold at 200 C, then compressed at 500 psi for 2 hrs. Two composites were made in this way, one with 8 layers and the other with 18 layers. The dielectric properties and density of these composites was measured. Note that the density indicates that there was air remaining in the resultant composites. A composite with equal volume proportions of glass and cyclic olefin copolymer would have a density of 1.75 g/cm^3. These measurements are shown below in Table 7, along with the predicted values if the samples had been fully compressed. To optimize dielectric properties, larger cyclic olefin copolymer yarns could be used to reduce the glass content to 25% or less.

Table 7 - Dielectric constant, dielectric loss and density of composites made by melting the cyclic olefin copolymer fibers in a hybrid fabric. While the dielectric constant is higher than the substrates made with FR-4 epoxy resin, the dielectric loss is lower.

	8 Layer	18 Layer	50% Our material (Predicted)	75% Our Material (Predicted)
Dielectric constant	3.53	3.25	3.9	3.05
Dielectric loss	0.0036	0.0041	0.002	0.0015
Density (g/cm^3)	1.5	1.5	1.75	1.4
Flexural strength (MPa)	119	120		
Flexural modulus (GPa)	10.6	9.3		
Tensile strength (MPa)	178	228		
Tensile modulus (GPa)	12.4	10.9		

CONCLUSIONS

1) Comparison to Existing Substrates: Substrates that are used for high frequency circuits today range in dielectric constant from 2.17 to 5.2, and in dielectric loss from 0.0009 to 0.025. This broad range gives a broad range of performance. In general, the flexural modulus is low, just above 2 GPa, which is barely sufficient to support copper circuits, and the cost is very high. In addition, in the case of PTFE and other materials, special processing is required. In this paper, we describe a new substrate fabric which has the following characteristics:

- Low dielectric constant: 3.0 to 3.5.
- Low dielectric loss: 0.0036 to 0.013.
- Low density: 1.2 to 1.5 g/cm^3
- High flexural stiffness: up to 18 GPa
- Processing similar to FR-4 epoxy substrates
- Cost effective