LOW DIELECTRIC FABRICS FOR CIRCUIT BOARD APPLICATIONS

Brian Morin, Innegrity LLC, Greer, SC

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 tangent of 0.013 using standard epoxy resins. In another embodiment, the cyclic olefin copolymer fibers were melted to form the resin component, yielding a substrate with dielectric constant of 3.25 and loss tangent of 0.0013. In the last example, a special low dielectric resin was used, giving a substrate with dielectric constant of 2.8 and loss tangent of 0.0009. Substrates made from this fiber have passed Peel Strength, Solder Float, Water Uptake, and have a low coefficient of thermal expansion. Model hybrid fabrics with 75% COC by volume give epoxy substrates with dielectric constant of 2.9 and loss tangent of 0.006.

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 place more severe demands on circuit board substrates. They demand lower dielectric constant and loss as well as light weight.

Innovations in this area include the use 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 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 (see Table 1), 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]

The other driving need for an affordable microwave circuit board substrate is data integrity. Data integrity is lost in transmission and reception inside a board, in which the dielectric loss reduces signal intensity and at the same time increases 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 such as those used in global positioning and satellite communications.

Additionally, as electronics become more and more portable, hanging from our hips and our arms and our necks, sitting on our laps and in all of our overnight bags, the weight of the circuit board substrate also plays a role, and lower density materials become more and more desirable.

	2004	2025
# PCs globally[3]	600 million	2.5 trillion
Processor chip speed[4]	3.2 GHz	35 GHz
Processor power[5]	100 W	1000 W
Motherboard clock speed[6]	800 MHz	3 GHz
Stripline dielectric loss at motherboard clock speed[7]	0.3 dB/cm	1.5 dB/cm

Table 1. Personal computer comparison between 2004 and 2025.

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 loss tangent must both be low, below 3.0 and 0.002 respectively, as they determine the energy loss and frequency range of the substrate.[8] The coefficient of thermal expansion must be low to prevent cracking in via holes and to ensure the integrity of attachments to components. Last, the material must be able to withstand the thermal strain of soldering processes and high use temperatures.

Example high frequency circuit board substrate materials are listed with their electrical and mechanical properties below in Table 2. Their dielectric properties are depicted in Figure 1. 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.

Property	Units	PPE PS film[9]	Polyimide film[10]	Glass PTFE[11]	LCP film[12]	FR-4
Dielectric Constant		2.6	3.3	2.17	2.9	5.2
Loss Tangent		0.0025	0.011	0.0004	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

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

3) High Modulus Fibers: Fibers are known to be the strongest materials on earth.[13], [14] Current high modulus fibers come in five classes: glass fibers, metal fibers, carbon fibers, Aramid fibers, and ultra high molecular weight polyethylene (UHMWPE) fibers.[15] For low dielectric applications metal and carbon fibers are not suitable because of their conductivity. Glass fibers, with a dielectric constant of 6.2,[16] are also unsuitable at high usage rates, though in small amounts they may be used with an appropriate resin such as PTFE.[17] UHMWPE fibers, have a low dielectric constant of 2.25 and also low loss, but melt at 135 C. Aramid fibers have superior thermal resistance and a dielectric constant of 3.85,[18] though their high loss tangent of 0.019 and cost have inhibited widespread use.

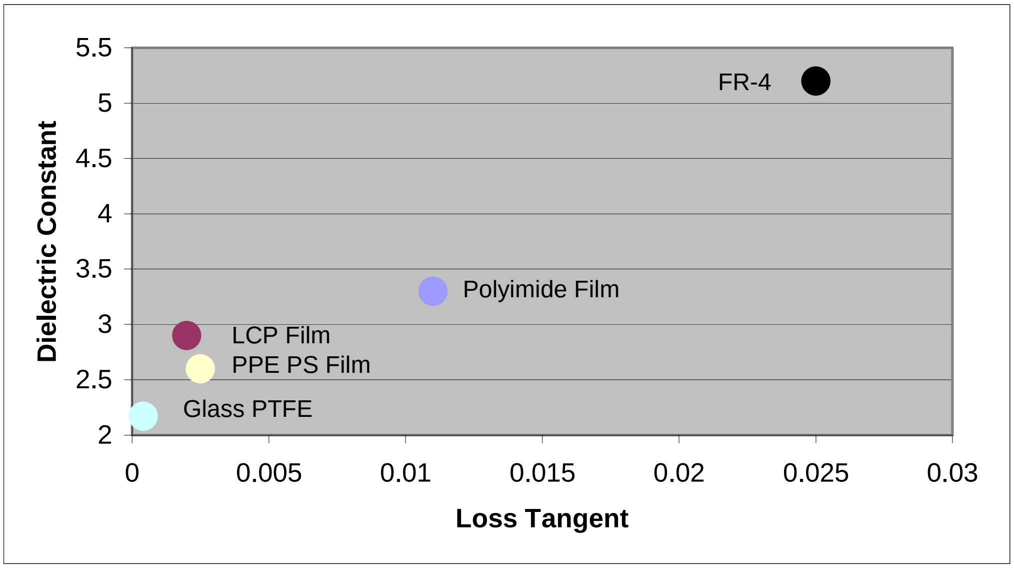

Figure 1. Dielectric constant and loss tangent of various low loss circuit board substrate materials.

Fiber	Tenacity (g/d)	Modulus (g/d)	Dielectric Constant	Loss Tangent	Density (g/cm3)
E Glass	5	250	6.2	0.002	2.5
S Glass	8	300	5.2	0.003	2.5
NE Glass			4.6	0.0007	
D Glass		200	4.0	0.0026	2.14
Quartz	25	370	3.7	0.0001	2.2
HMPP	10	200	2.3	0.0002	0.9
Aramid	23	950	4.5	0.019	1.4
UHMWPE	30	1400	2.3	0.0005	0.96
Carbon	11	3300	***	***	1.8

Table 3. Properties of currently available high modulus fibers.

FIBER AND FABRIC MANUFACTURE AND PROPERTIES

1) Amorphous Hydrocarbons: Amorphous hydrocarbons have dielectric, physical and thermal properties that show promise for high frequency circuit materials. Table 4 shows properties of several.

Property	Units	PP[19]	PPO[20]	COC[21]	Polyether imide[22]

Dielectric Constant		2.3	2.69	2.35	3.15
Loss Tangent		0.0002	0.0007	0.00007	0.0025
Density	g/cm^3	0.9	1.08	1.0	1.27
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
CTE	ppm/C	100	59	60	56
Melting Point	C	165	--	--	--
T_g	C	--	75 – 155	180 – 195	217

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

2) Hybrid Substrates: The basic concept we explore in to first form fibers of cyclic olefin copolymer, and then to form those into fabrics which may also contain glass yarns, which can be used as reinforcements for circuit board substrates. The goal is to make a substrate which requires little or no change from conventional circuit manufacturing techniques.

3) Substrate Manufacture and Testing: For this study, we made four 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. Lurol PP 912 spin finish was added after being diluted 20:1 with water. 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, and is shown on the green and large blue bobbins in Figure 5.

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.

	"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

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.

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 COC sample. The second yarn was prepared by cabling this yarn with 450s glass, and weaving in the same construction. This is the “COC cabled” sample 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.

	COC weft	COC cabled 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

Table 6. Composites made in FR-4 epoxy resin using 1080 style fabric with a 50 denier cyclic olefin copolymer weft (“COC weft”), a 50 denier weft cabled with 450s glass (“COC 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.

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/m^2, compared to 49 g/m^2 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 dielectric constant indicates that there was air remaining in the 18 layer composites. These measurements are shown below in Table 7, along with the predicted values for a sample with 67% COC.

	8 Layer	18 Layer	67% COC Predicted
Dielectric constant	3.53	3.25	3.5
Loss Tangent	0.001	0.0013	0.0007
Density (g/cm^3)	1.5	1.5	1.5
Flexural strength (MPa)	119	120	
Flexural modulus (GPa)	10.6	9.3	
Tensile strength (MPa)	178	228	
Tensile modulus (GPa)	12.4	10.9	

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.

A fourth fabric was woven, this time from yarns prepared by twisting 50 denier COC fiber with 225s glass and weaving the resultant yarns in a style similar to 7626. This fabric was coated with a proprietary low dielectric resin and the results are shown in Table 8, below.

	COC hybrid / Low D_k Resin
% COC Fiber (vol)	20%
% Low dielectric resin	60%
Dielectric constant	2.8
Loss tangent	0.0009
T288 (minutes)	28
Peel Strength (AR/AS) (lbs/inch)	6.8/5.6
CTE x (50-120 C)	29
CTE y (50-120 C)	28
CTE z (50-120 C)	70

Table 8. Circuit board substrate materials made from low dielectric yarns in hybrid 7626 fabric with glass yarn and proprietary low dielectric resin.

To make model fabrics of the same construction as glass styles 1080 and 2116, COC yarns with the equivalent volume of ECD-450 and ECD 225 yarns are needed. These yarns are shown below.

COC Yarns	Polymer	Denier	Filaments	Filament size (microns)	yds/lb
COC-32/15	CoC	32	15	17	127,688
COC-32/15	CoC	64	30	17	63,844

Table 9. COC yarns with equivalent volume to standard glass yarns, and their basic properties.

Based on these yarns, six fabrics can be compared including glass styles 1080 and 2116, and versions of each which include alternate warp and weft yarns replaced with COC yarns. The basic properties of these fabrics are shown in Table 5, below.

Style	Warp 1	Warp 2	Fill 1	Fill 2	Count e/in	Count p/in	Weight oz/sq yd
1080	ECD 450 1/0	ECD 450 1/0	ECD 450 1/0	ECD 450 1/0	60	47	1.4
1080-I	ECD 450 1/0	COC-35/15	ECD 450 1/0	COC-35/15	60	47	0.95
1080-III	EDC 450/COC-35	COC-35/15	ECD 450/COC-35	COC-35/15	60	47	0.74
2116	ECD 225 1/0	ECD 225 1/0	ECD 225 1/0	ECD 225 1/0	60	58	3.06
2116-I	ECD 225 1/0	COC-70/30	ECD 225 1/0	COC-70/30	60	58	2.09
2116-III	ECD 225/COC-70	COC-70/31	ECD 225/COC-70	COC-70/31	60	58	1.63

Table 10. Basic properties of four fabrics, including glass styles 1080 and 2116, and versions of each which include alternate warp and weft yarns replaced with COC yarns.

Based on these fabric constructions, certain properties can be calculated:

- Wt COC: the weight of COC yarn per square yard of fabric.
- Wt glass: the weight of glass yarn per square yard of fabric.
- % COC (wt): the weight percentage of COC yarn.
- % COC (vol): the volume percentage of Innegra E yarn.
- Thickness: the thickness of the glass styles. The COC style thickness should be similar.
- Dk: The dielectric constant based on the volume ratio of materials. The dielectric constant for glass is taken to be 6.6.
- Loss tangent: The loss tangent based on the volume ratio of materials. The dielectric loss for glass is taken to be 0.006.
- Board Dk: the calculated Dk based on 50% fabric volume and a resin dielectric constant of 3.3.
- Board Loss Tangent: the calculated dielectric loss tangent based on 50% fabric volume and a resin dielectric loss tangent of 0.011.

Style	**Weight**	**Wt COC**	**Wt glass**	**% COC (wt)**	**% COC (vol)**	**Thickness**	**Fabric Dk**	**Fabric Loss Tangent**	**Board Dk**	**Board Loss Tangent**
	oz/sq yd	oz/sq yd	oz/sq yd	%	%	in				
1080	1.4	0	1.4	0%	0%	0.0023	6.6	0.006	5.0	0.009
1080-I	0.95	0.26	0.68	28%	50%		4.5	0.003	3.9	0.007
1080-III	0.74	0.40	0.34	54%	75%		2.9	0.001	3.1	0.006
2116	3.06	0	3.06	0%	0%	0.0037	6.6	0.006	5.0	0.009
2116-I	2.09	0.58	1.51	28%	50%		4.5	0.003	3.9	0.007
2116-III	1.63	0.87	0.76	54%	75%		2.9	0.001	3.1	0.006

Table 11. Properties of glass and Innegra containing electrical fabrics, calculated as described above.

DISCUSSION AND CONCLUSIONS

1) **Existing Substrates:** Substrates that are used for high frequency circuits today range in dielectric constant from 2.17 to 5.2, and loss tangent from 0.0009 to 0.025. For materials with low dielectric, the flexural modulus is low, just above 2 GPa, the density is high, and the cost is very high. In addition, in the case of PTFE and other materials, special processing is required.

2) **Low Dielectric Yarns:** While several low dielectric glass yarns exist, including both D glass and NE glass (see Table 3), the lowest dielectric constant is still >4.0 and the loss tangent >0.0007. In this paper, we present experiments with a low dielectric polymer fiber made from cyclic olefin copolymer with dielectric constant 2.35 and loss tangent 0.00007. The yarn was combined in this paper with E glass yarns, but could also be combined with D or NE glass, giving even lower dielectric substrates.

3) **Substrates with Low Dielectric Yarns:** Substrates were prepared from several combinations of fabric and resin. Two substrates from hybrid e-glass fabrics and epoxy resin yielded substrates with dielectric constant as low as 3.08, loss tangent as low as 0.012, and density as low as 1.2 g/cm^2. Other substrates were prepared by heat laminating the hybrid fabric to melt the yarn, achieving a dielectric constant of 3.5 and loss tangent of 0.001. Last, substrates were prepared using a proprietary low dielectric resin. These substrates achieved a dielectric constant of 2.8 and loss tangent of 0.0009. These materials are all shown in Figure 2 with the properties of commercial materials ghosted.

4) **Other Advantages:** Electrical properties of the substrates presented here are competitive with the best low dielectric substrates available and also have other advantages. Mechanical properties range from 10 GPa and up for the COC fiber based substrates compared to 2 GPa for most other low dielectric substrates. The density is near 1.2 g/cm^3 for the COC fiber substrates and is much higher for other low dielectric substrates.

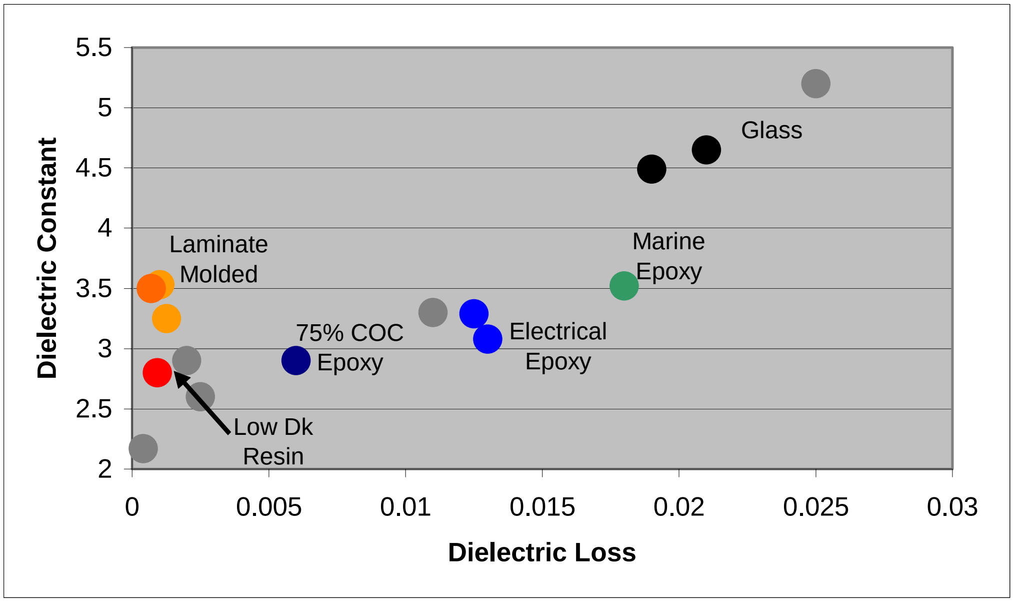

Figure 2. Dielectric constant and loss tangent of the substrates from this study, shown with the commercial substrates from Figure 1 as grey ghosted spots.

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[16] Ibid., p 135.

[17] *Microwave Materials and Fabrication Techniques*, Laverghetta, p34.

[18] *Handbook of Composites, Second Edition*, S. T. Peters, p 231.

[19] Poly propylene homopolymer. Example Atofina HPP 3462, product information available at www.atofina.com .

[20] Poly phenylene ether. Example General Electric Noryl 265, product information available at www.gepolymerland.com .

[21] Cyclic olefin copolymer. Example Ticona Topas 6017, product information available at www.ticona.com.

[22] Example General Electric Ultem 1000, product information available at www.gepolymerland.com .