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WHERE THE CHIP MEETS THE BOARD

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A Heuristic Approach to Assess Anisotropic Properties of Glass-reinforced PCB Substrates

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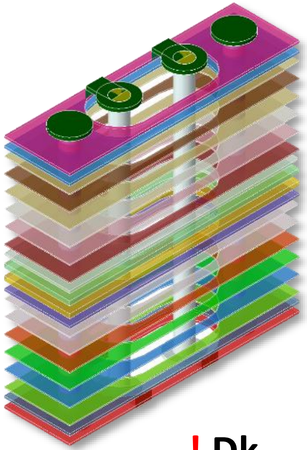
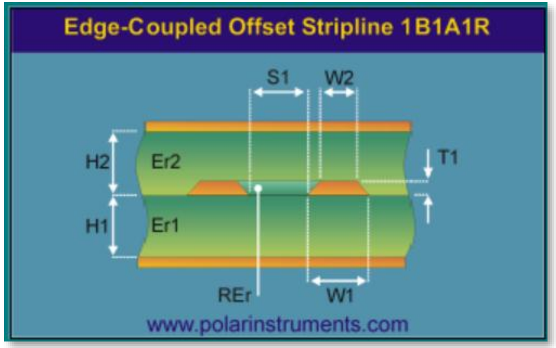
Bio

Lambert (Bert) Simonovich graduated from Mohawk College of Applied Arts and Technology as an Electronic Engineering Technologist. During his 32-year tenure at Bell Northern Research & Nortel in Ottawa Canada, he helped pioneer several advanced technologies into products. He has held a variety of engineering, research and development positions, eventually specializing in high-speed signal integrity and backplane design. In 2009, he founded Lamsim Enterprises Inc., and continues to provide innovative signal integrity and backplane solutions as a consultant. He has authored several publications and holds two US patents. In addition to being a senior member of IEEE, he currently serves as a member of DesignCon's Technical Program Committee and Signal Integrity Journal's Editorial Advisory Board. His current research interests include high-speed signal integrity, modeling and characterization of high-speed serial link architectures. His most notable modeling achievement is the invention of the "Cannonball" conductor roughness model used in conjunction with the Huray model in several electronic design automation (EDA) software tools.

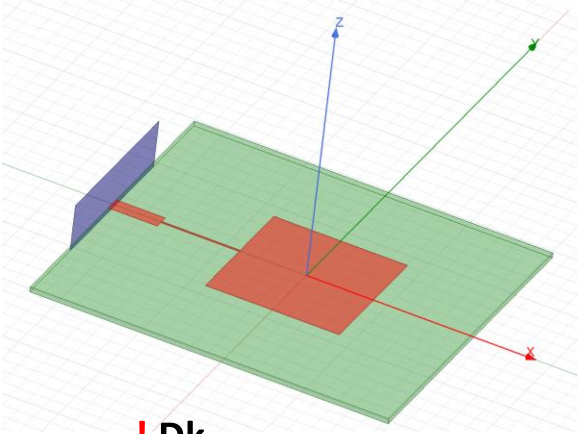
Using Correct Dielectric Material Properties is Crucial For Accurate Modeling



! Dk



! Dk



! Dk

Using incorrect Dk values can affect PCB fabrication yield or reduced performance margins

Stackup Impedance Modeling

Material: Meg-4

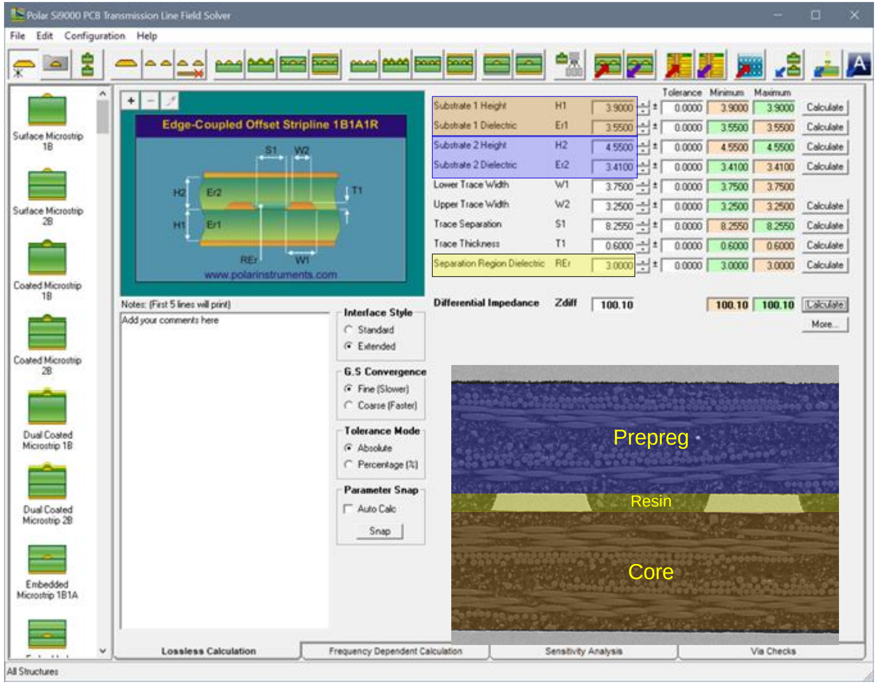
Stackup Construction

Layer #	Prelam Dielectrics Thick.(mil)	Base Cu (oz)	Type		Layup	Glass Type	Resin Content	Dk @10GHz	Df @10GHz	# Plys	Predicted Thick. (mil)
				Pre-lam Information			**Fab Details**				
				S/M							0.50
				Plating							1.60
1		0.25	Foil	**TOP**			Resin Fill	3.00	0.0080		0.30
	7.00		Pre-preg			1078	69%	3.44	0.0080	1	6.32
						1078	69%	3.44	0.0080	1	
2		0.50	RTF	**P**			Resin Fill	3.00	0.0080		0.60
	3.90		Core			1067*2	66%	3.55	0.0080	2	3.90
3		0.50	RTF	**S**			Resin Fill	3.00	0.0080		0.60
	4.64		Pre-preg			1067	70%	3.41	0.0080	2	3.95
						1067	70%	3.41	0.0080		
4		0.50	RTF	**P**			Resin Fill	3.00	0.0080		0.60
	3.90		Core			1067*2	66%	3.55	0.0080	2	3.90
5		0.50	RTF	**S**					0.0080		0.60
	4.64		Pre-preg			1067	70%	3.41	0.0080	2	3.95
						1067	70%	3.41	0.0080		
6		0.50	RTF	**P**			Resin Fill	3.00	0.0080		0.60
	3.90		Core			1067*2	66%	3.55	0.0080	2	3.90
7		0.50	RTF	**S**			Resin Fill	3.00	0.0080		0.60
	4.64		Pre-preg			1067	70%	3.41	0.0080	2	3.95
						1067	70%	3.41	0.0080		
8		2.00	RTF	**P**			Resin Fill	3.00	0.0080		2.40
	3.90		Core			1067*2	66%	3.55	0.0080	2	3.90
9		2.00	RTF	**P**			Resin Fill	3.00	0.0080		2.40
	4.64		Pre-preg			1067	70%	3.41	0.0080	2	3.95
						1067	70%	3.41	0.0080		
10		0.50	RTF	**S**			Resin Fill	3.00	0.0080		0.60
	3.90		Core			1067*2	66%	3.55	0.0080	2	3.90
11		0.50	RTF	**P**			Resin Fill	3.00	0.0080		0.60
	4.64		Pre-preg			1067	70%	3.41	0.0080	2	3.95
						1067	70%	3.41	0.0080		
12		0.50	RTF	**S**			Resin Fill	3.00	0.0080		0.60
	3.90	.	Core			1067*2	66%	3.55	0.0080	2	3.90
13		0.50	RTF	**P**			Resin Fill	3.00	0.0080		0.60
	4.64		Pre-preg			1067	70%	3.41	0.0080	2	3.95
						1067	70%	3.41	0.0080		
14		0.50	RTF	**S**			Resin Fill	3.00	0.0080		0.60
	3.90	.	Core			1067*2	66%	3.55	0.0080	2	3.90
15		0.50	RTF	**P**			Resin Fill	3.00	0.0080		0.60
	7.00		Pre-preg			1078	69%	3.44	0.0080	1	6.32
						1078	69%	3.44	0.0080	1	
16		0.25	Foil	**BOT**			Resin Fill	3.00	0.0080		0.30
				Plating							1.60
				S/M							0.50

H1

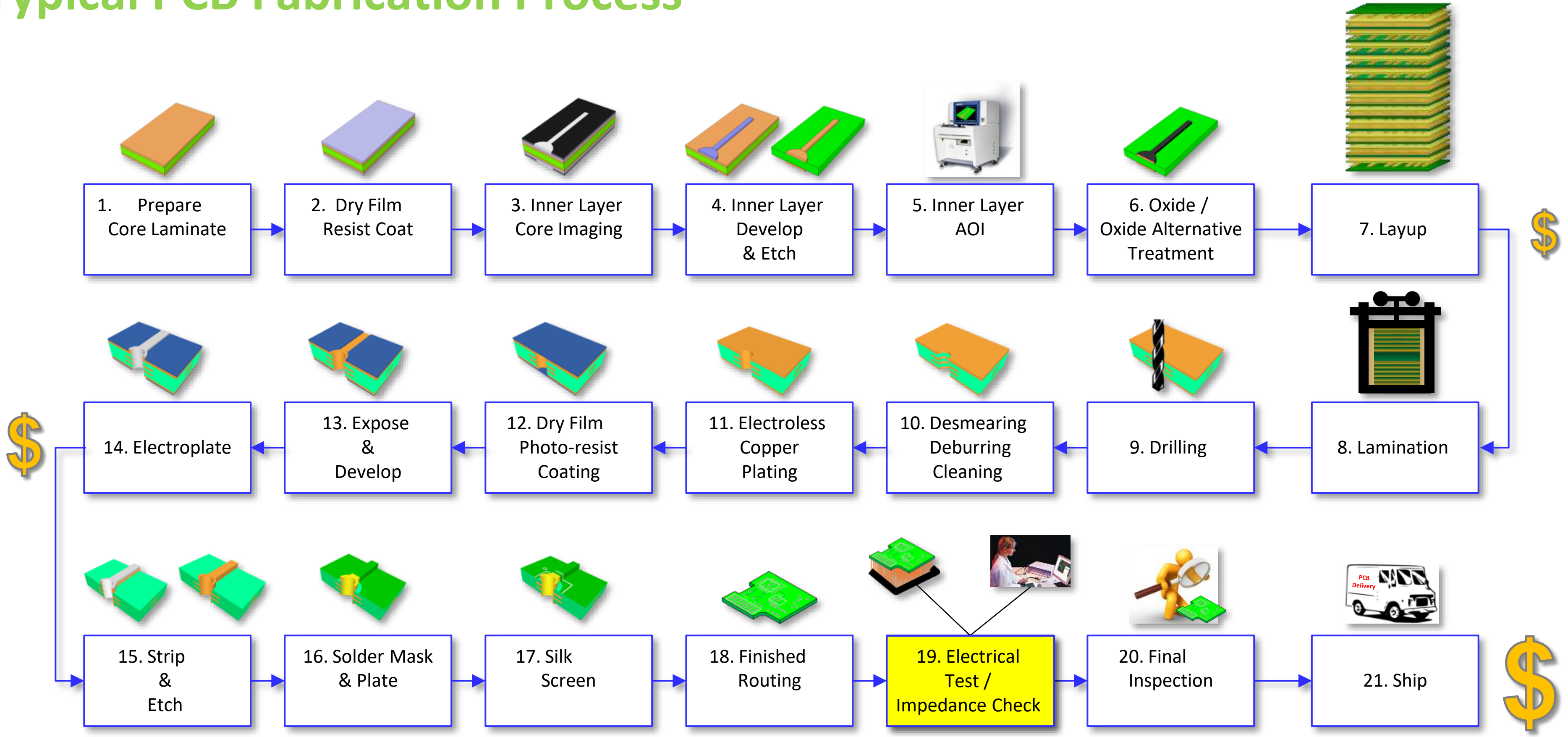
H2

Dwg PCB Thick.	80.0	mil +/-10%
Overall Thick.	79.4	mil Over Plating (Copper to Copper)
Overall Thick.	80.4	mil Over SM
Min Drill	10.0	mil
Aspect Ratio	7.6	Before Plating

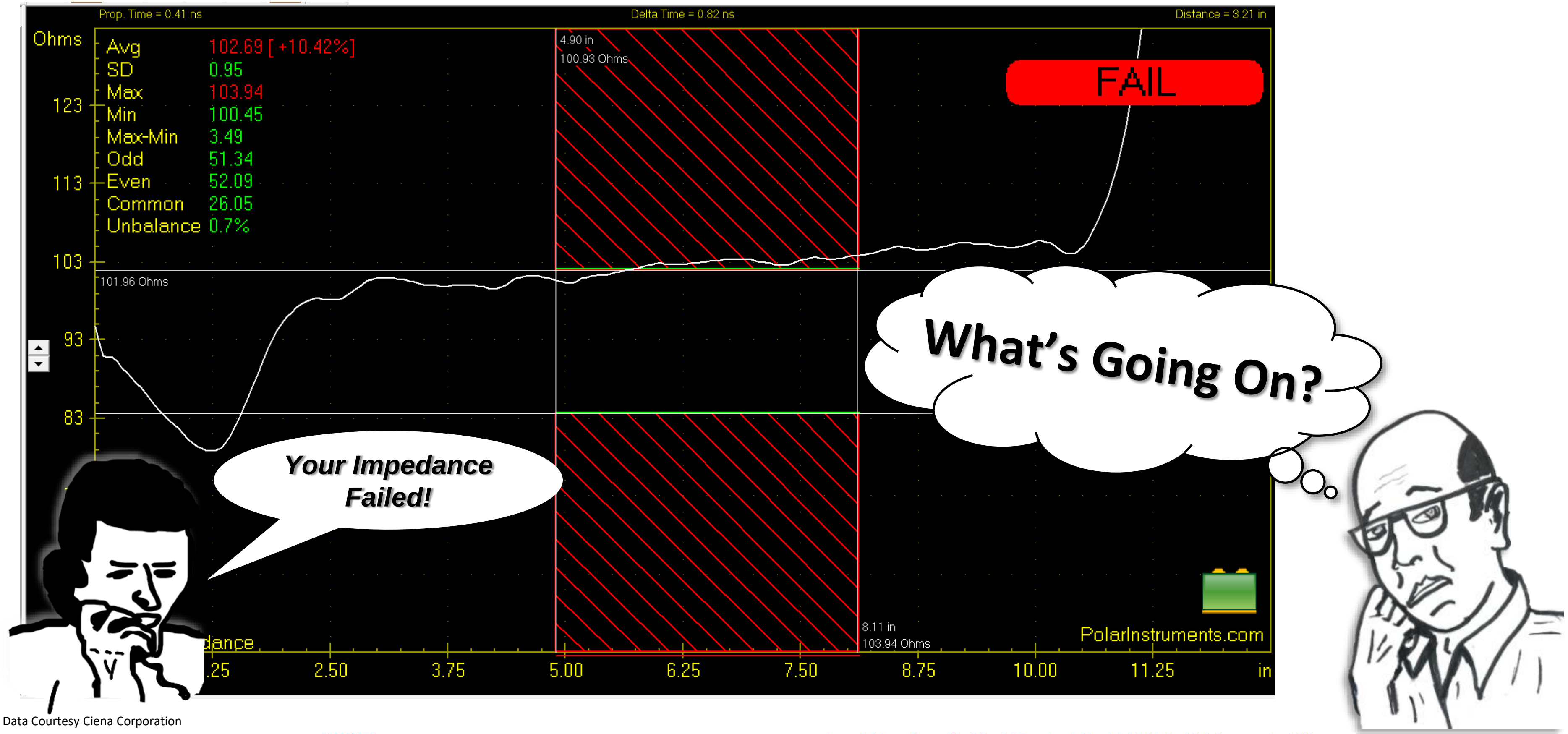


One important parameter for accurate impedance modeling is relative permittivity (ε_r) or dielectric constant (Dk)

Typical PCB Fabrication Process



Post Fabrication Impedance Failure

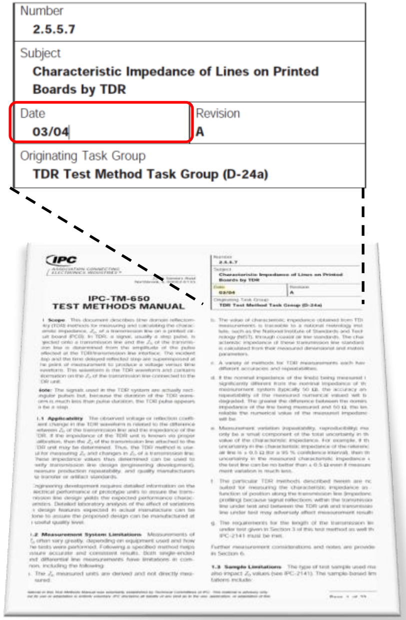


CITS Data Courtesy Ciena Corporation

What You'll Learn

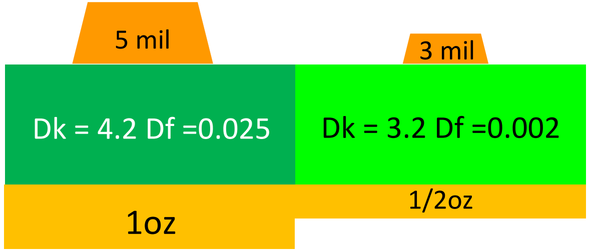
- ✓ TDR impedance test issues
- ✓ Laminate construction & PCB material properties overview
- ✓ Anisotropy explained
- ✓ Popular Dk/Df test methods
- ✓ Transmission line, via impedance and RF antenna implications due to anisotropy
- ✓ Heuristics to assess material anisotropy
- ✓ Dielectric anisotropic validation

Reasons for Today's TDR Test Failures

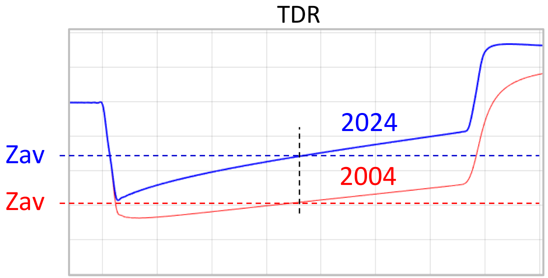


IPC-TM-650 2.5.5.7
Test Method Manual Dated

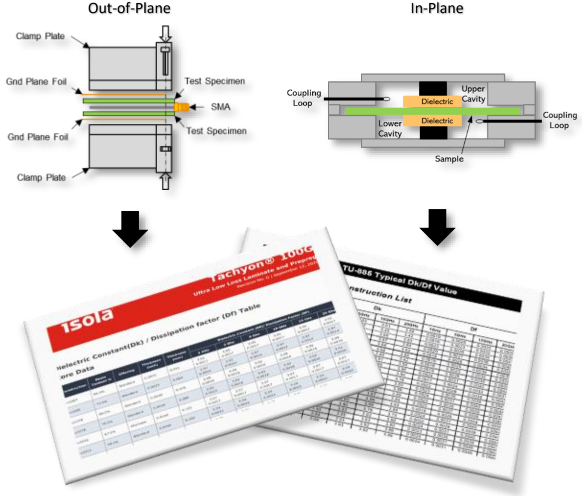
2004 | 2024

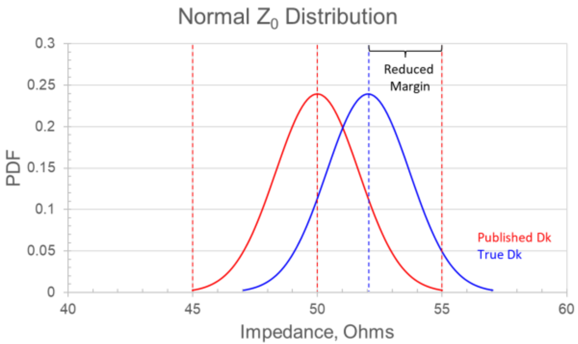


2004	2024
• Wider Traces	• Narrower Traces
• Thicker Copper	• Thinner Copper
• Higher Dk/Df	• Lower Dk/Df
• Looser Tolerance	• Tighter Tolerance



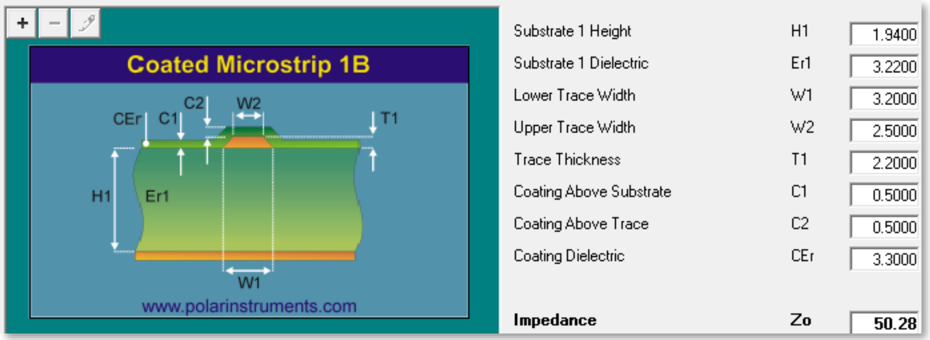
Dk/Df Test Methods

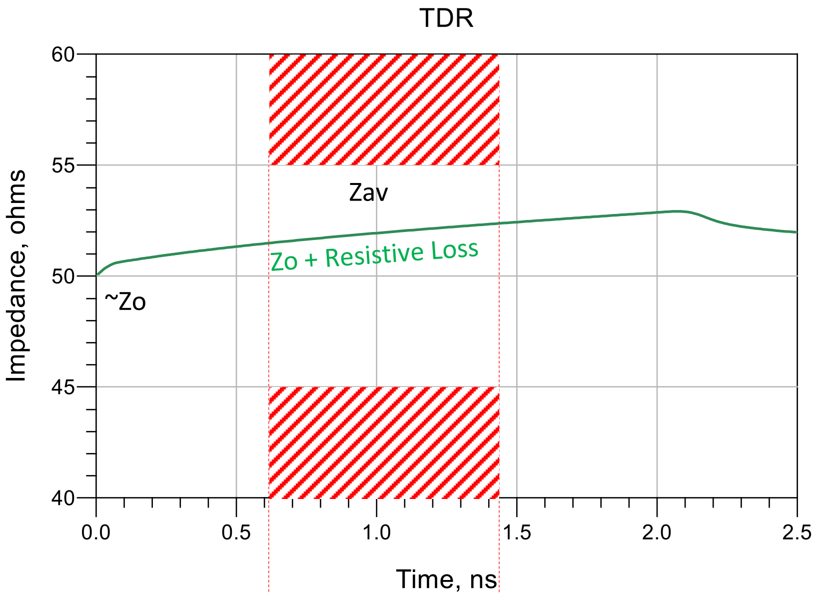


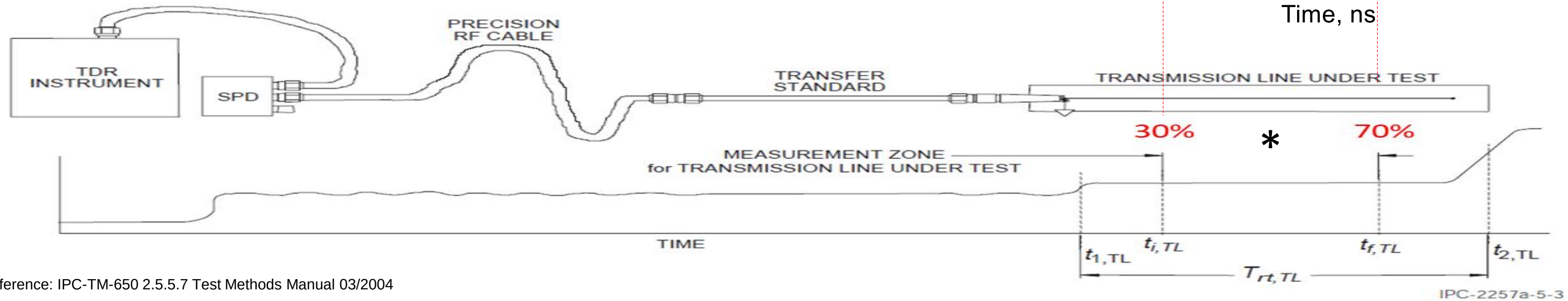


Lossless Model vs Lossy Reality

Lossless Field Solver Prediction



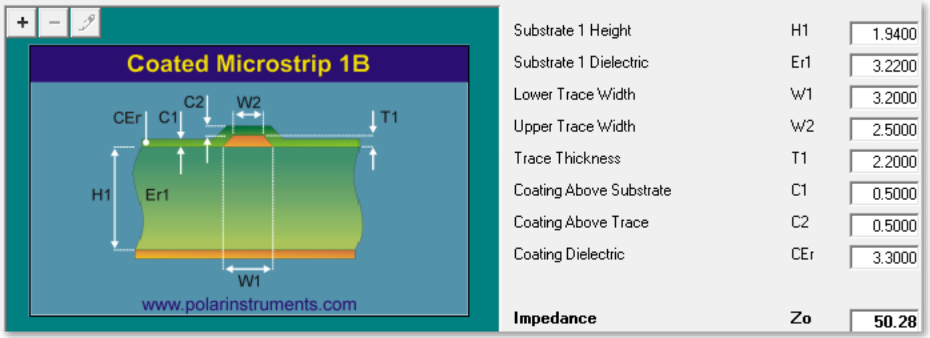


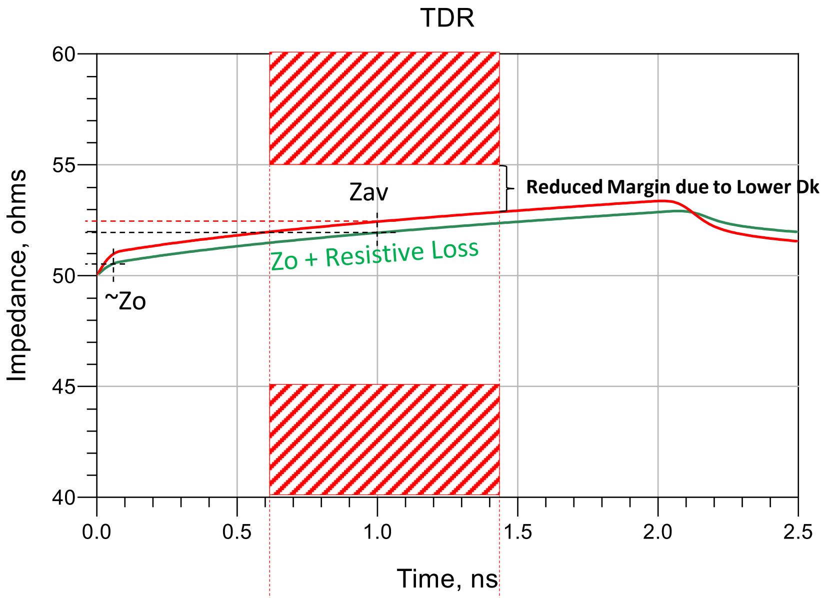


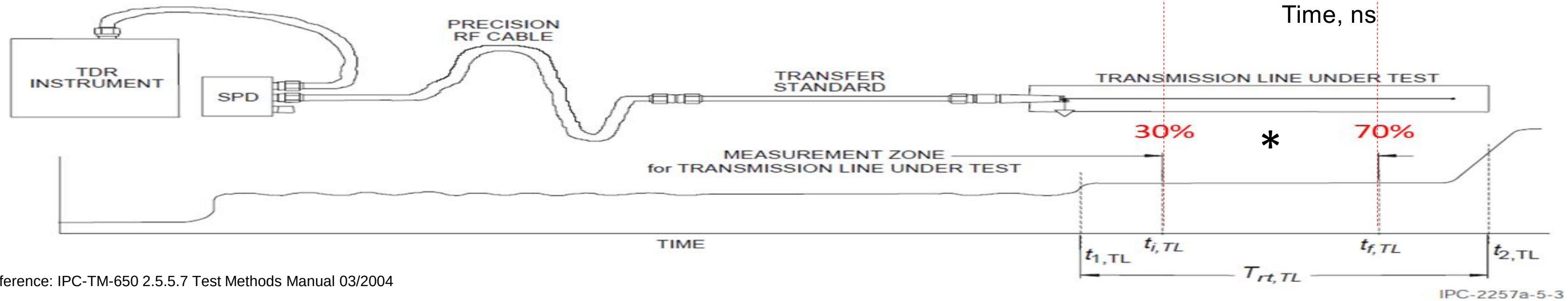
* Reference: IPC-TM-650 2.5.5.7 Test Methods Manual 03/2004

Lossless Model vs Lossy Reality

Lossless Field Solver Prediction

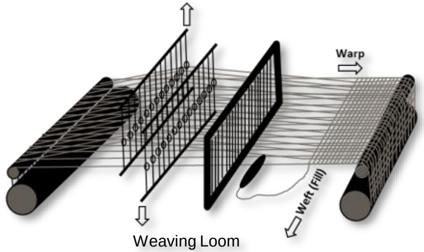


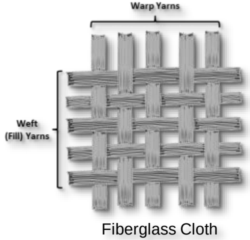


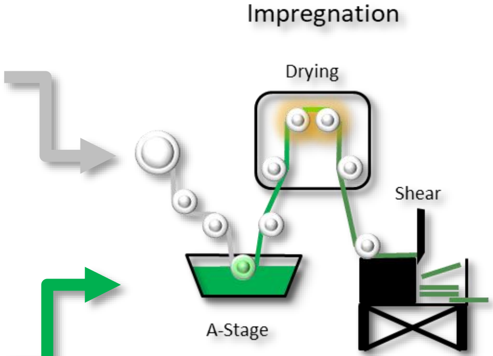


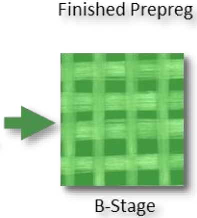
* Reference: IPC-TM-650 2.5.5.7 Test Methods Manual 03/2004

CCL Laminate Manufacturing Process







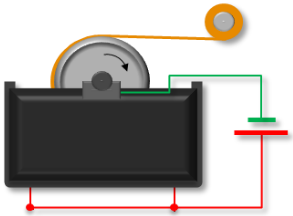


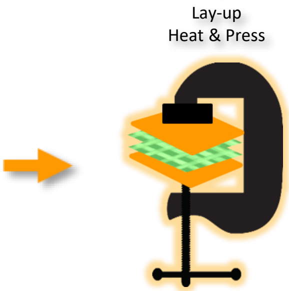
Resin Types	Category
Epoxy	High Loss
HF Epoxy	Standard Loss
Epoxy/Poly Blends	Mid Loss
	Low Loss
Poly	Very Low Loss
Poly w/Hydrocarbon Blends	Ultra Low Loss
PTFE, Fillers and Poly Blends	Extremely Low Loss
Proprietary	PTFE Alternatives

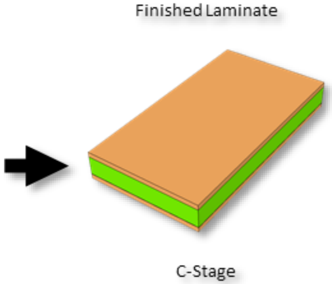
Rolled Copper

OR

ED Copper

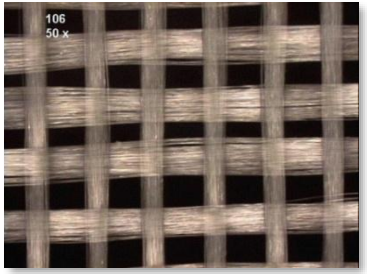




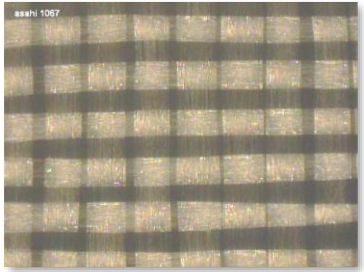


Examples of Common Standard Woven Glass Styles

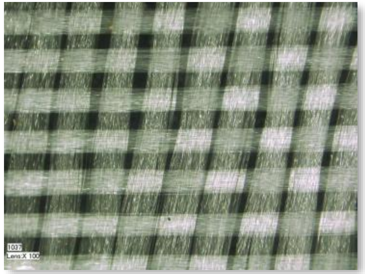
106**



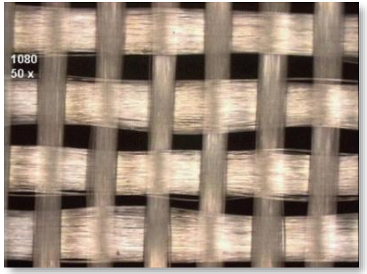
MS 1067**



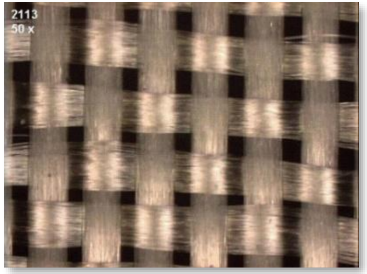
MS 1037**



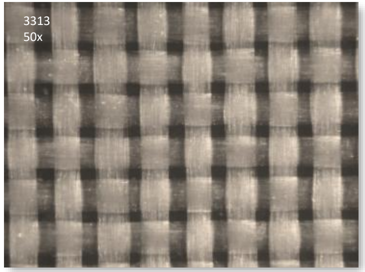
1080**



2113**



3313**



IPC-4412A
Amendment 1

Specification for Finished Fabric Woven from "E" Glass for Printed Boards

IPC-4412A

Finished Fabric Glass Styles

Style	Thread Count (Warp x Fill)	Thickness (mils)
106	56 x 56	1.3
1080	60 x 47	2.1
1037	70 x 73	1.1
1067	70 x 70	1.4
2113	60 x 56	3.1
3313	60 x 62	3.3

Source: **Isola-group; MS = Mechanically Spread

Resin Dk/Df Properties

*Resin Types	Category	Dk Range	Df Range
Epoxy	High Loss		=/>0.02
HF Epoxy	Standard Loss	3.6-5.0	0.015 to < 0.020
Epoxy/Poly Blends	Mid Loss		0.010 to < 0.015
	Low Loss	3.4-4.0	0.007 to < 0.010
Poly	Very Low Loss		0.005 to < 0.007
Poly w/Hydrocarbon Blends	Ultra Low Loss	2.8-3.4	0.002 to < 0.005
PTFE, Fillers and Poly Blends	Extremely Low Loss		0.0015 to < 0.002
Proprietary	PTFE Alternatives	2.0-3.0	< 0.0015

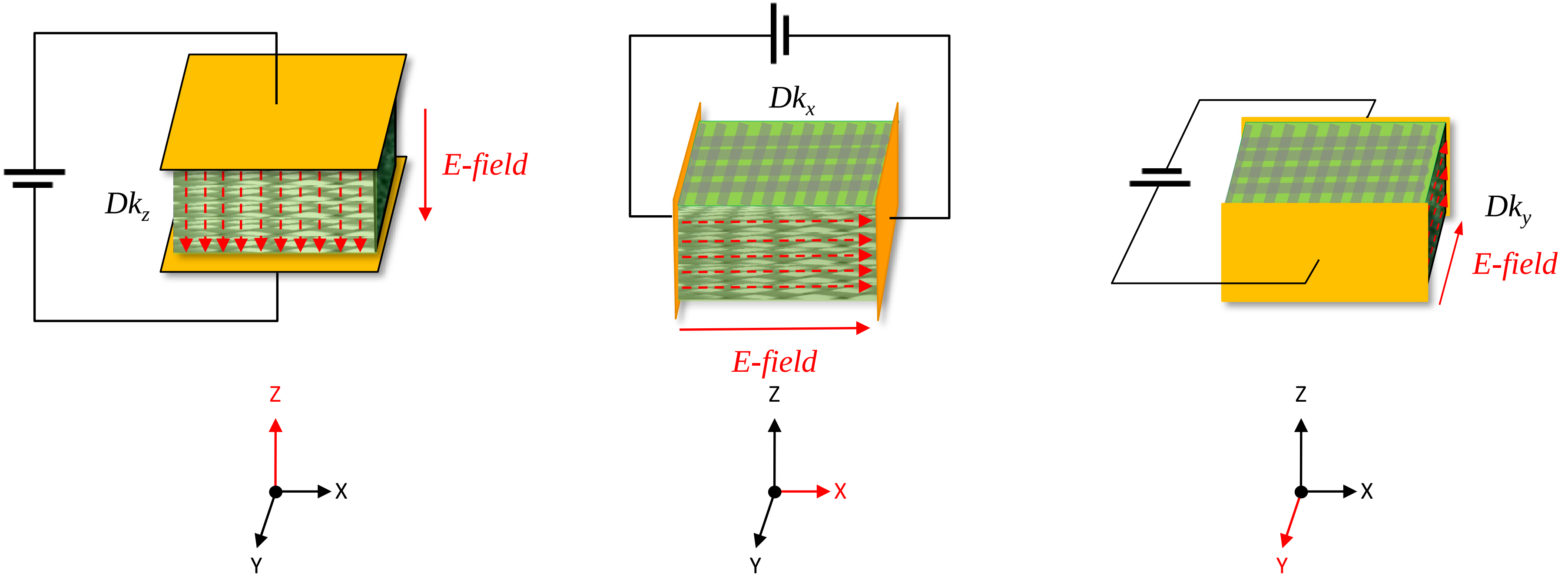
References: *M. Gay, "The Printed Circuit Designer's Guide to…Tm High Performance Materials", 2022, BR Publishing

Glass Dk/Df Properties

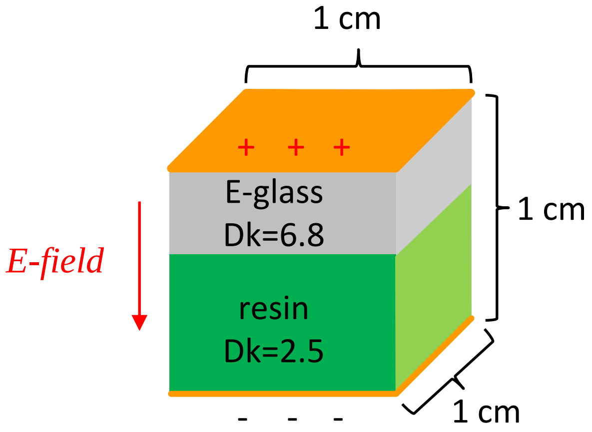
AGY Glass Fiber Properties	Units	L-Glass	E-Glass
Dielectric Constant (Dk)	@1 GHz	4.8	7
Dielectric Constant (Dk)	@10 GHz	4.8	6.8
Dissipation Factor (Df)	@1 GHz	< 0.001	0.005
Dissipation Factor (Df)	@10 GHz	0.003	0.006
Density	g/cm^3	2.3	2.54
Softening Point	°C	850	846
Coefficient of Thermal Expansion	ppm/°C	3.9	5.4
Tensile Load to Failure (D450 fiber)	N	8.5	8.9
Tensile Modulus	Gpa	62	75

Source: AGY Holding Corp

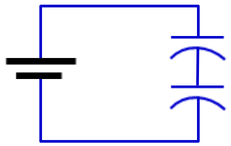
Glass Reinforced Laminates are Anisotropic



Rule of Solid Mixtures



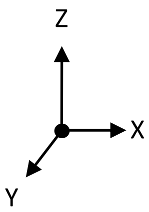
Cmix = CgCr/(Cg+Cr)



Parallel Mixing Rule

$$Dk_z = \left[v_{resin} / Dk_{resin} + v_{glass} / Dk_{glass} \right]^{-1}$$

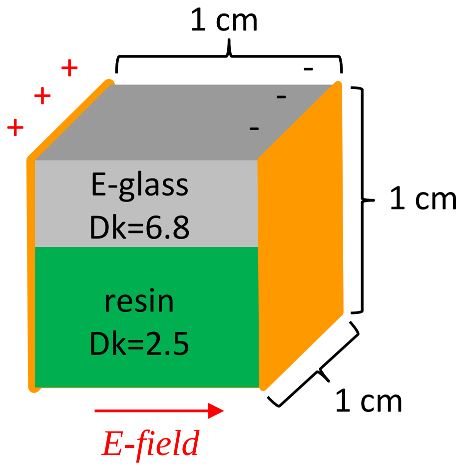
$$= \left[0.7 / 2.5 + 0.3 / 6.8 \right]^{-1} = 3.09$$



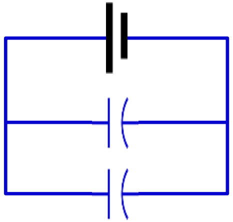
$$v_{resin} = 0.7cm^3$$
$$v_{glass} = 0.3cm^3$$
$$v_{mix} = 1.0cm^3$$

$$\Lambda = \left(\frac{Dk_{xy}}{Dk_z} - 1 \right) \cdot 100$$

$$= \left(\frac{3.79}{3.09} - 1 \right) \cdot 100 \approx 23\%$$



Cmix = Cg+ Cr



Series Mixing Rule

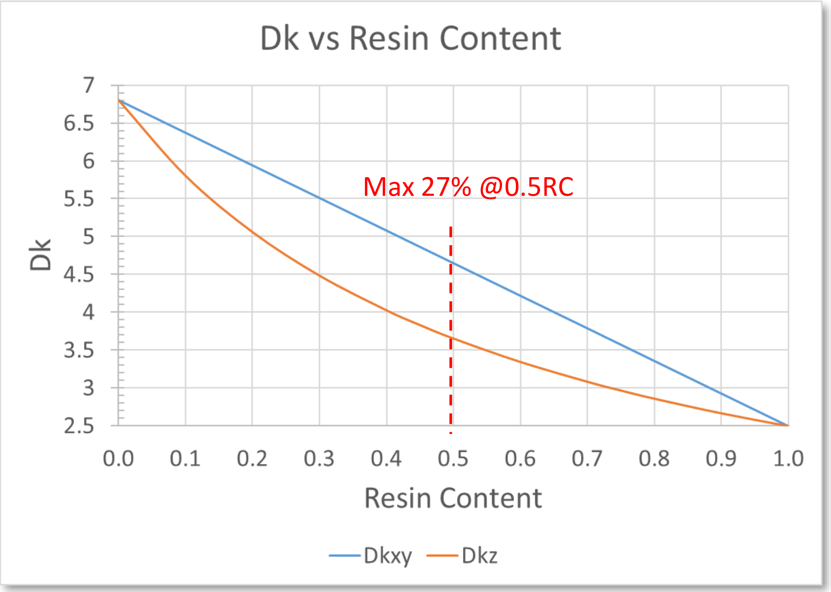
$$Dk_{xy} = v_{resin} \cdot Dk_{resin} + v_{glass} \cdot Dk_{glass}$$

$$= 0.7 \cdot 2.5 + 0.3 \cdot 6.8 = 3.79$$

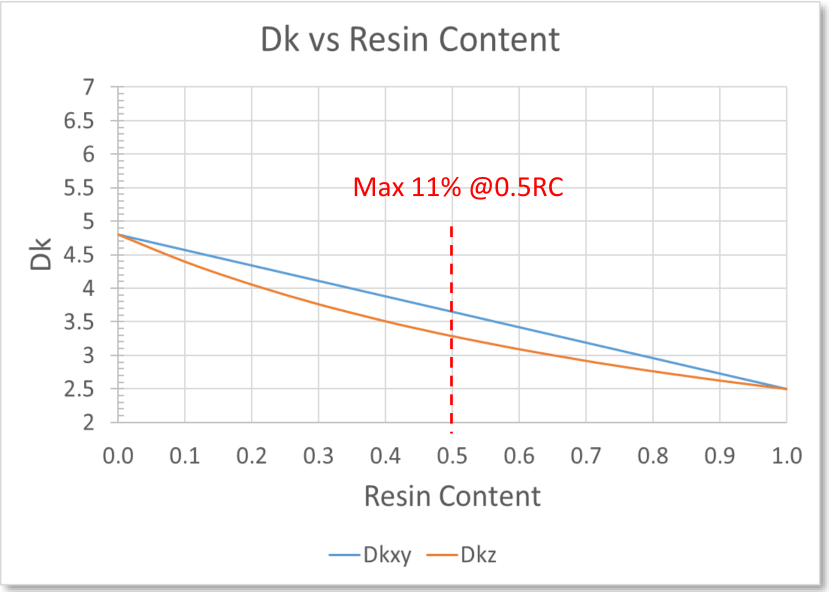
P. S. Neelakanta, "Handbook of Electromagnetic Materials: Monolithic and Composite Versions and Their Applications", CRC Press LLC,1995

Anisotropy vs Glass Resin Mixture

Dkg = 6.8 Dkr = 2.5

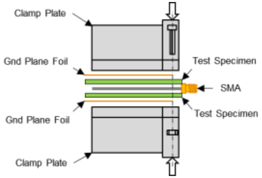
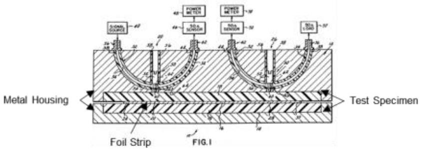
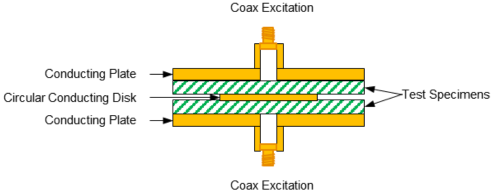
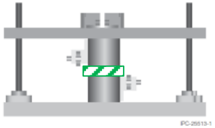
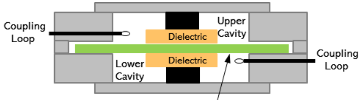


Dkg = 4.8 Dkr = 2.5

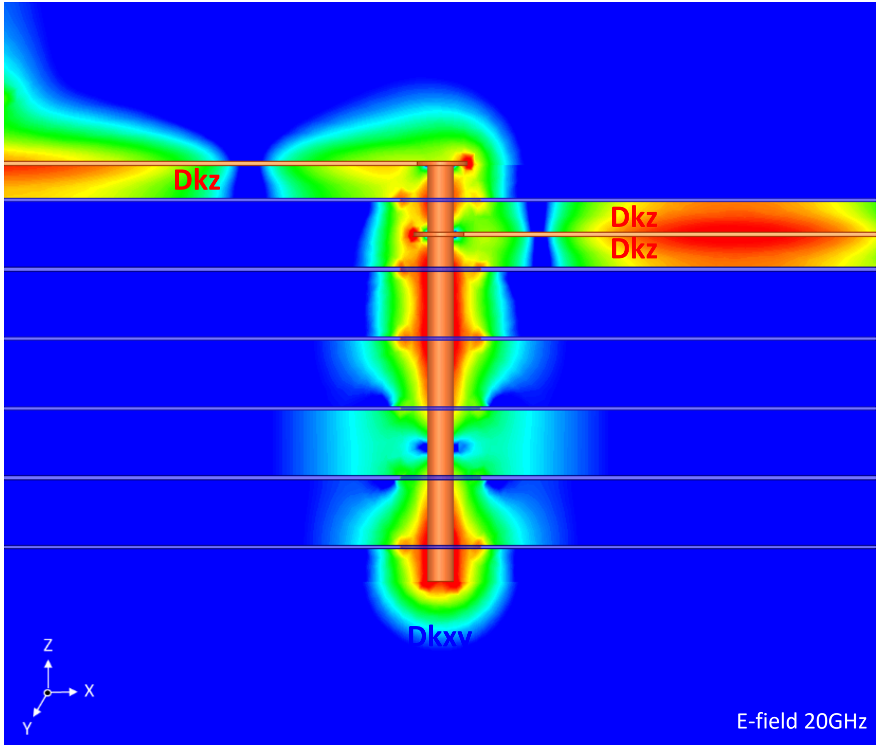


The closer the Dkr/Dkg match the lower the anisotropic effect

Popular Dielectric Constant Test Methods Used

	Test Method	In-plane (Dkxy)	Out-of-plane (Dkz)
	**Clamped Stripline Resonator** **Ref: IPC-TM-650 2.5.5.5 RevC**		✓
	**Bereskin Stripline Resonator** **Ref: Patent US5187,443, Feb. 16, 1993**		✓
	**Balanced-type Circular Disk Resonator** **Ref: IEC 63185:2020**		✓
	**Split-cylinder Resonator** **Ref: IPC-TM-650 2.5.5.13**	✓	
	**Split-post Dielectric Resonator** **(a.k.a. Split-post Cavity)**	✓	

Dk Anisotropy Implications for SI Modeling

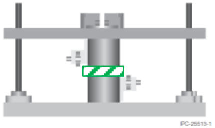


	Dkxy	Dkz
Trace Impedance	χ	✓
Via Impedance	✓	χ
Via Stub Resonance	✓	χ

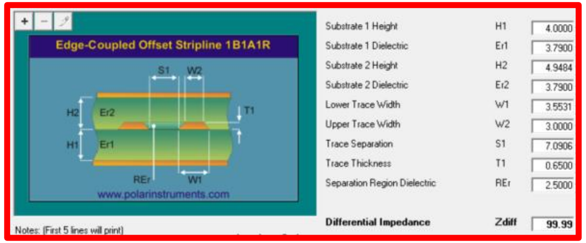
HFSS simulation courtesy of Juliano Mologni, Ansys

Anisotropy Implications for Transmission Line Modeling

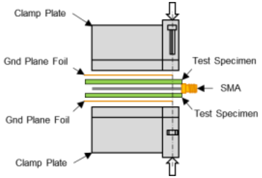
Dkxy



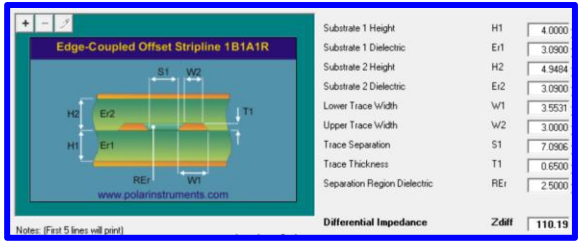
IPC-TM-650 2.5.5.13

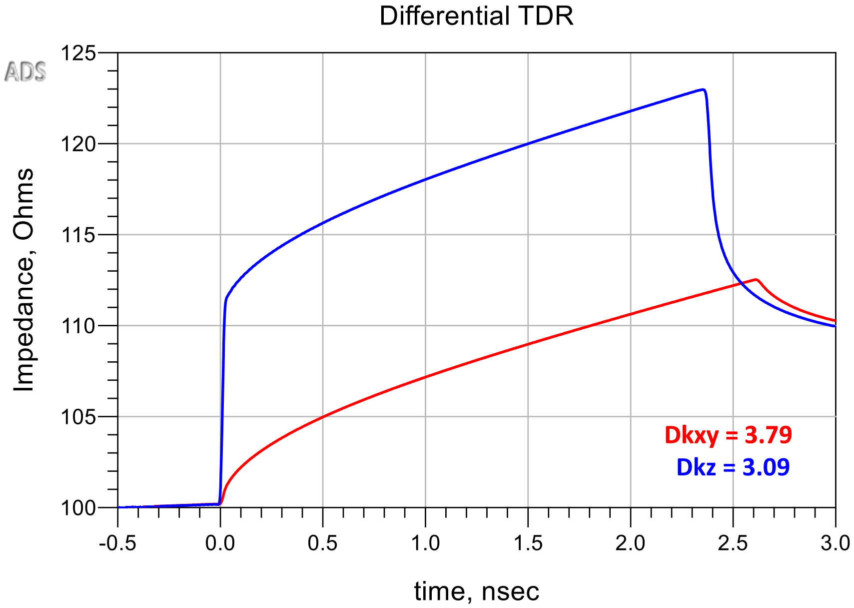


Dkz



IPC-TM-650 2.5.5.5 RevC

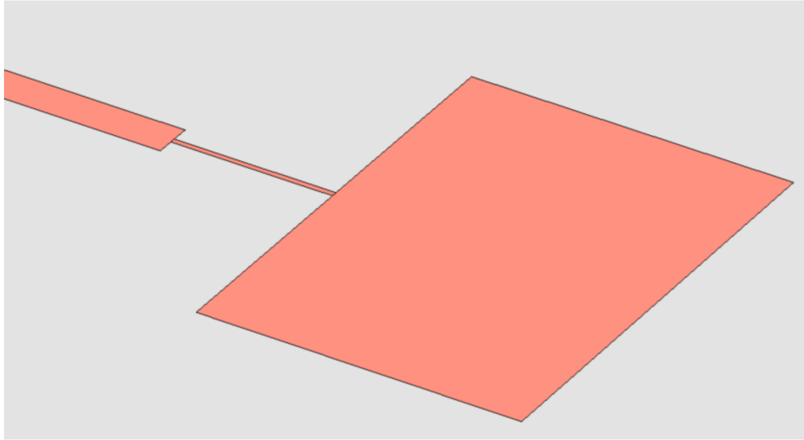


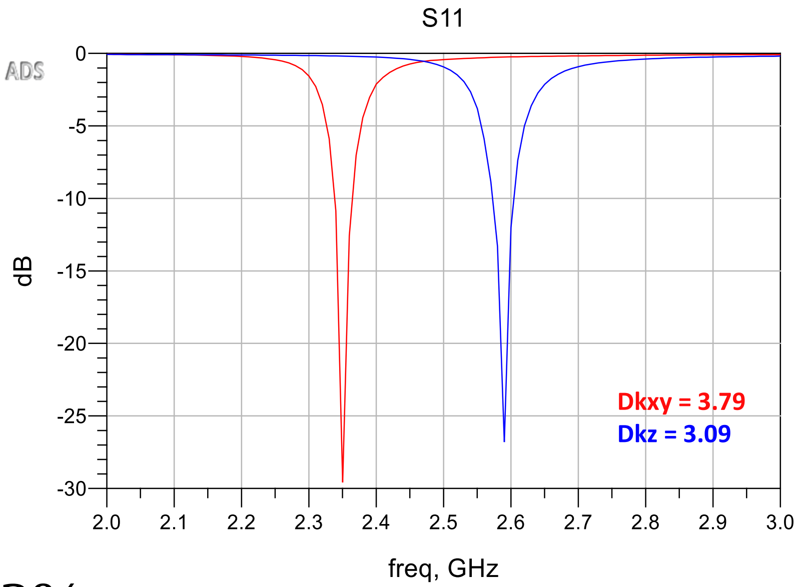


$$\Lambda \approx 23\%$$

Modeled with Polar Si9000 and simulated with Keysight ADS

Anisotropy Implications for Antenna Modeling

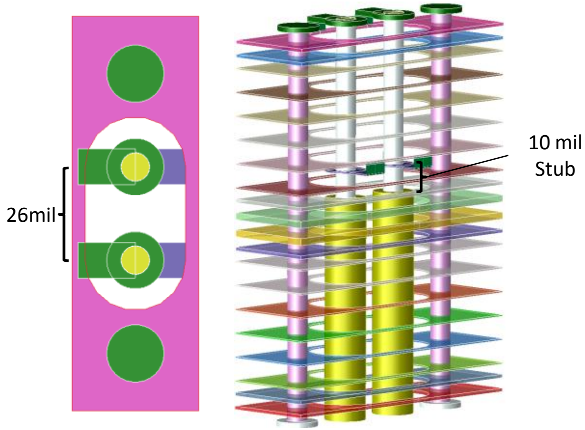


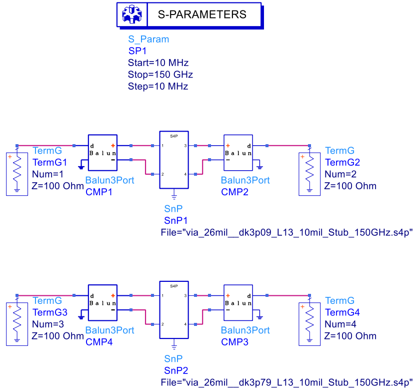


$$\Lambda \approx 23\%$$

Modeled with Sonnet-Lite and simulated with Keysight ADS

Anisotropy Implications for Via Modeling



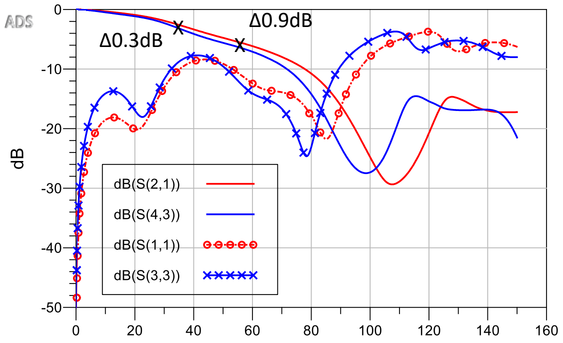


Dkz = 3.09

Dkxy = 3.79

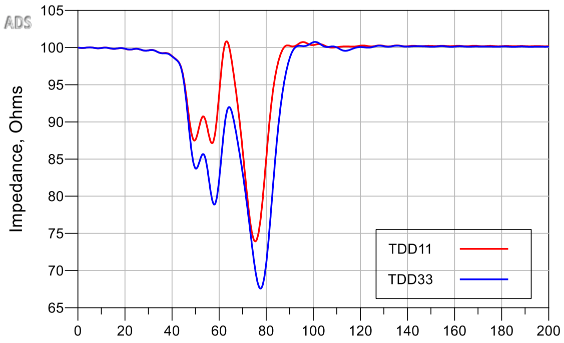
$\Lambda \approx 23\%$

Differential Insertion Loss / Return Loss



freq, GHz

Differential TDR

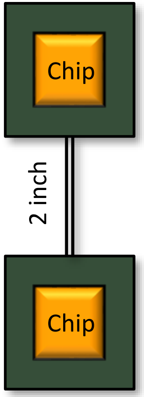


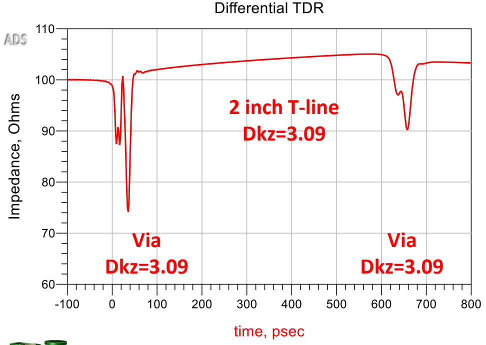
time, psec

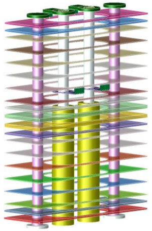
Modeled and simulated with Keysight ADS

Via Impedance Implications on C2C COM Due to Anisotropy

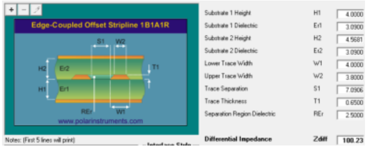
Topology

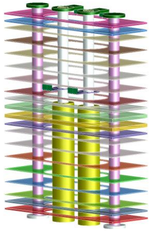


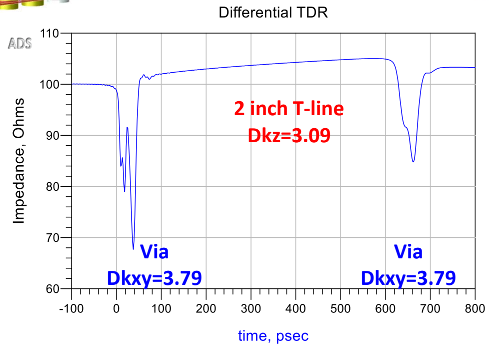


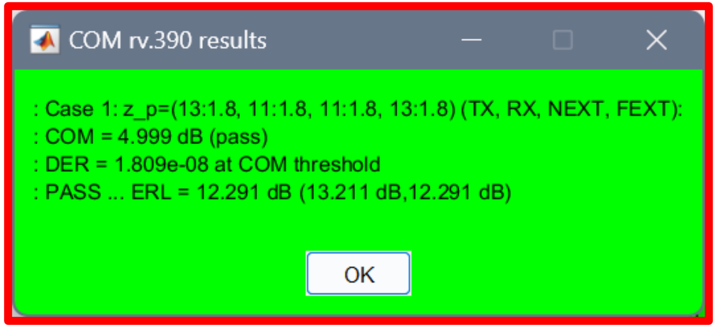


2 inch T-line 100 ohm

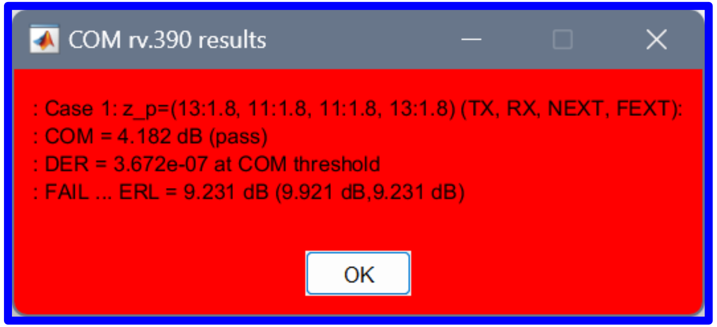




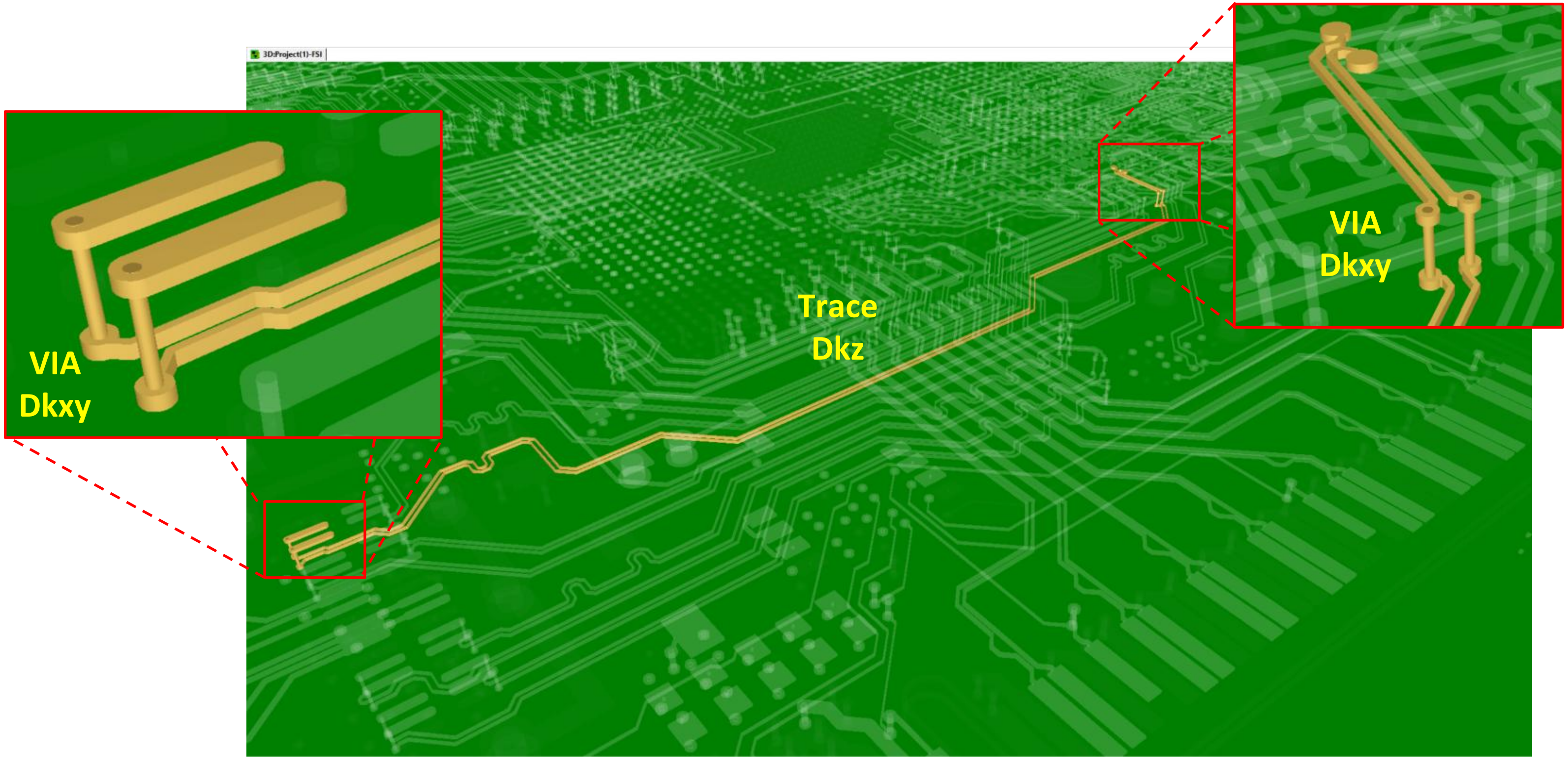




$$\Lambda \approx 23\%$$



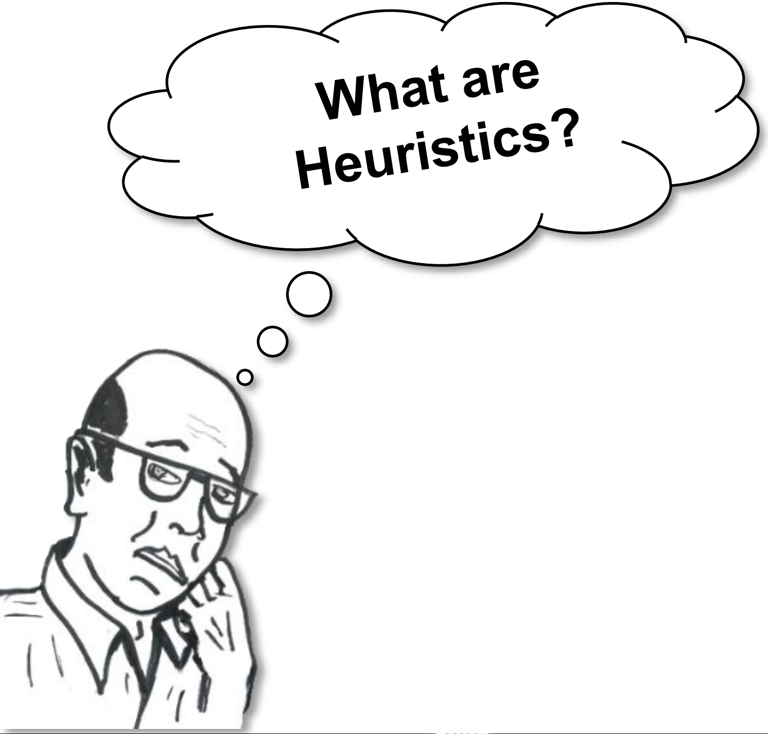
Dk Anisotropic Issue With EDA Tool Net Extraction for SI Analysis



Using the same value for Dk will lead to inaccurate results!

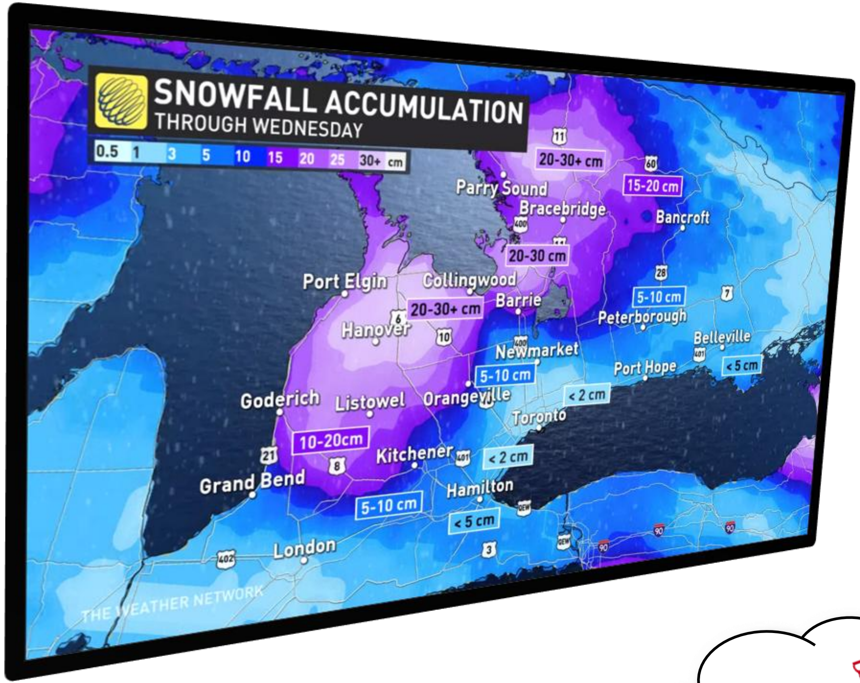
Reference: Intel® Arria® 10 GX FPGA Development Kit viewed with Simbeor Board Analyzer

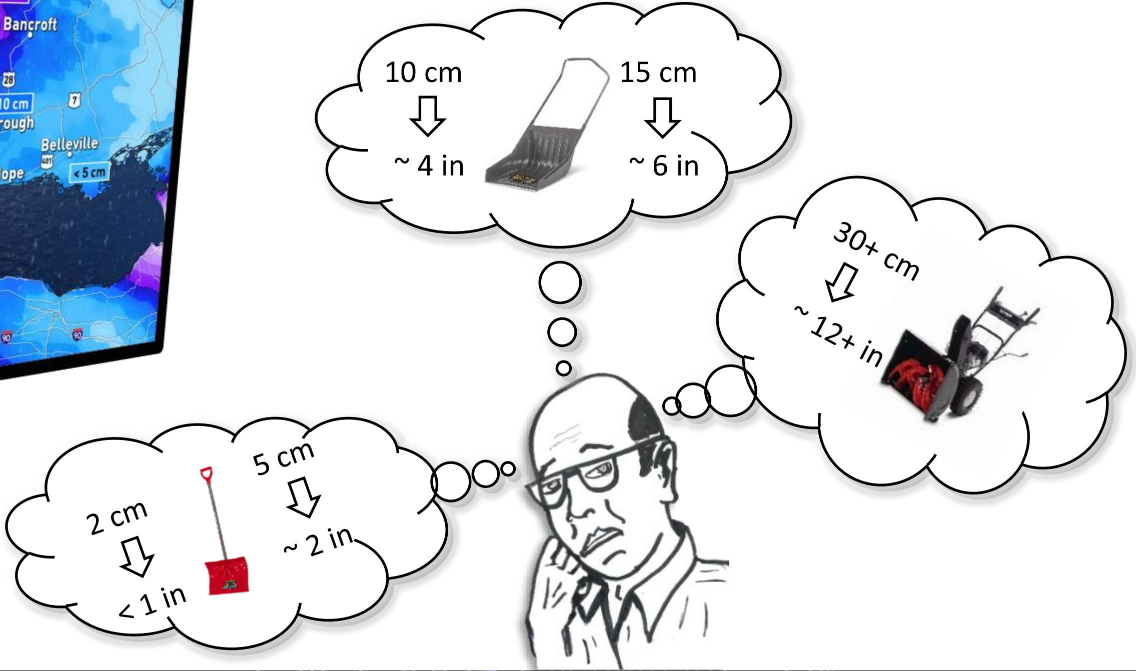
"A Heuristic Approach to Assess Anisotropic Properties of Glass-reinforced PCB Substrates"



- **Mental shortcuts, rules of thumb or problem-solving techniques that help people make decisions and solve problems quickly and efficiently**
- **Does not guarantee absolute accuracy or completeness**
- **Based on past experiences and allows one to use readily obtainable information to come up with solutions when more exact information is not easily available**

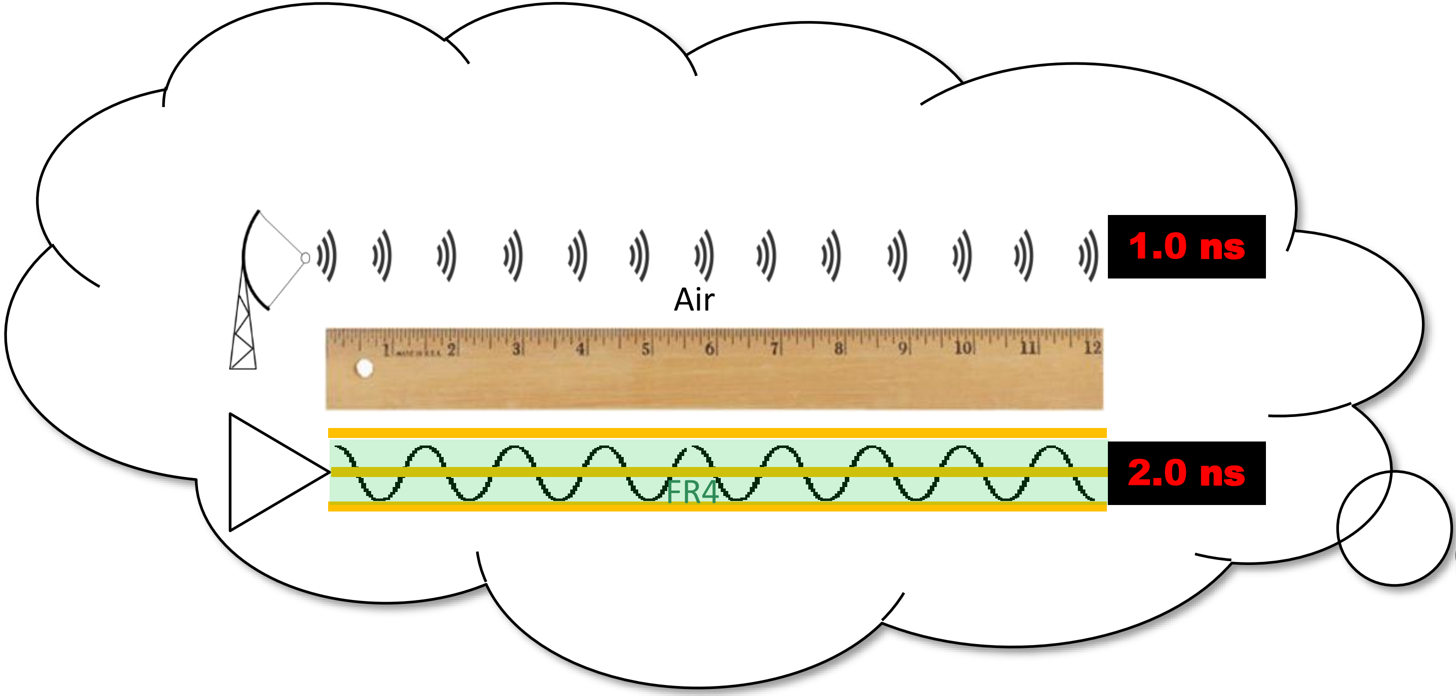
Heuristic Weather Example





Heuristic EM Wave Propagation Example

$$v = \frac{c}{\sqrt{\varepsilon_r}}$$



Heuristically Determine Laminate Anisotropy

Typical Prepreg Construction Table

Glass Style	Resin Content %	Offering	Thickness (inch)	Thickness (mm)	Dielectric Constant (Dk)						Dissipation Factor (Df)					
					1 GHz	2 Ghz	5 Ghz	10 GHz	15 Ghz	20 Ghz	1 GHz	2 Ghz	5 Ghz	10 GHz	15 Ghz	20 Ghz
1035	69.00%	Standard	0.002	0.051	3.06	3.06	3.06	3.06	3.06	3.06	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017
1035	75.00%	Standard	0.0026	0.066	2.97	2.97	2.97	2.97	2.97	2.97	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014
1078	65.00%	Standard	0.0029	0.074	3.14	3.14	3.14	3.14	3.14	3.14	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019
1078	67.50%	Standard	0.0031	0.079	3.09	3.09	3.09	3.09	3.09	3.09	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018
1078	70.50%	Standard	0.0035	0.089	3.04	3.04	3.04	3.04	3.04	3.04	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016
1078	72.00%	Standard	0.0037	0.094	3.02	3.02	3.02	3.02	3.02	3.01	0.0015	0.0016	0.0016	0.0016	0.0016	0.0016
1078	75.00%	Standard	0.0042	0.107	2.97	2.97	2.97	2.97	2.97	2.97	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014
1078	78.00%	Alternate	0.0046	0.117	2.92	2.92	2.92	2.92	2.92	2.92	0.0013	0.0013	0.0014	0.0014	0.0014	0.0014
2116	62.00%	Standard	0.0058	0.147	3.19	3.19	3.19	3.19	3.19	3.19	0.0021	0.0021	0.0021	0.0021	0.0021	0.0021
2116	65.00%	Alternate	0.0064	0.163	3.14	3.14	3.14	3.14	3.14	3.14	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019
1067	70.00%	Standard	0.0022	0.056	3.05	3.05	3.05	3.05	3.05	3.05	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017
1067	71.50%	Standard	0.0024	0.061	3.02	3.02	3.02	3.02	3.02	3.02	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016
1067	74.00%	Standard	0.0026	0.066	2.98	2.98	2.98	2.98	2.98	2.98	0.0014	0.0014	0.0015	0.0015	0.0015	0.0015
1067	76.50%	Standard	0.0029	0.074	2.94	2.94	2.94	2.94	2.94	2.94	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013
106	76.00%	Standard	0.0023	0.058	2.95	2.95	2.95	2.95	2.95	2.95	0.0013	0.0013	0.0014	0.0014	0.0014	0.0014
1080	72.00%	Standard	0.0038	0.097	3.02	3.02	3.02	3.02	3.02	3.01	0.0015	0.0016	0.0016	0.0016	0.0016	0.0016
1080	75.00%	Standard	0.0043	0.109	2.97	2.97	2.97	2.97	2.97	2.97	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014
1080	78.00%	Alternate	0.0046	0.117	2.92	2.92	2.92	2.92	2.92	2.92	0.0013	0.0013	0.0014	0.0014	0.0014	0.0014
3313	63.50%	Standard	0.0046	0.117	3.16	3.16	3.16	3.16	3.16	3.16	0.002	0.002	0.002	0.002	0.002	0.002
3313	66.50%	Standard	0.0051	0.129	3.11	3.11	3.11	3.11	3.11	3.11	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018

Test Method: TM-650-2.5.5.5C

Source: Isola Tachyon 100G

Determine Glass Properties Used in Laminate

Tachyon 100G

Glass Fiber Properties	Units	L-Glass	E-Glass
Dielectric Constant (Dk)	@1 GHz	4.8	7.0
	@10 GHz	4.8	6.8
Dissipation Factor (Df)	@1 GHz	< 0.001	0.005
	@10 GHz	0.003	0.006
Density	g/cm3	2.3	2.54
Softening Point	°C	850	846
Coefficient of Thermal Expansion	ppm/°C	3.9	5.4
Tensile Load to Failure (D450 fiber)	N	8.5	8.9
Tensile Modulus	Gpa	62	75

Source: AGY Holding Corp

Heuristically Determine Anisotropy from Construction Tables

Glass Style	Resin Content %	Offering	Thickness (inch)	Thickness (mm)	Dielectric Constant						Dissipation Factor					
					1 GHz	2 Ghz	5 Ghz	10 GHz	15 Ghz	20 Ghz	1 GHz	2 Ghz	5 Ghz	10 GHz	15 Ghz	20 Ghz
1035	69.00%	Standard	0.002	0.051	3.06	3.06	3.06	3.06	3.06	3.06	0.002	0.0017	0.0017	0.0017	0.0017	0.002
1035	75.00%	Standard	0.0026	0.066	2.97	2.97	2.97	2.97	2.97	2.97	0.001	0.0014	0.0014	0.0014	0.0014	0.001
1078	65.00%	Standard	0.0029	0.074	3.14	3.14	3.14	3.14	3.14	3.14	0.002	0.0019	0.0019	0.0019	0.0019	0.002
1078	67.50%	Standard	0.0031	0.079	3.09	3.09	3.09	3.09	3.09	3.09	0.002	0.0018	0.0018	0.0018	0.0018	0.002
1078	70.50%	Standard	0.0035	0.089	3.04	3.04	3.04	3.04	3.04	3.04	0.002	0.0016	0.0016	0.0016	0.0016	0.002
1078	72.00%	Standard	0.0037	0.094	3.02	3.02	3.02	3.02	3.02	3.01	0.002	0.0016	0.0016	0.0016	0.0016	0.002
1078	75.00%	Standard	0.0042	0.107	2.97	2.97	2.97	2.97	2.97	2.97	0.001	0.0014	0.0014	0.0014	0.0014	0.001
1078	78.00%	Alternate	0.0046	0.117	2.92	2.92	2.92	2.92	2.92	2.92	0.001	0.0013	0.0014	0.0014	0.0014	0.001
2116	62.00%	Standard	0.0058	0.147	3.19	3.19	3.19	3.19	3.19	3.19	0.002	0.0021	0.0021	0.0021	0.0021	0.002
2116	65.00%	Alternate	0.0064	0.163	3.14	3.14	3.14	3.14	3.14	3.14	0.002	0.0019	0.0019	0.0019	0.0019	0.002
1067	70.00%	Standard	0.0022	0.056	3.05	3.05	3.05	3.05	3.05	3.05	0.002	0.0017	0.0017	0.0017	0.0017	0.002
1067	71.50%	Standard	0.0024	0.061	3.02	3.02	3.02	3.02	3.02	3.02	0.002	0.0016	0.0016	0.0016	0.0016	0.002
1067	74.00%	Standard	0.0026	0.066	2.98	2.98	2.98	2.98	2.98	2.98	0.001	0.0014	0.0015	0.0015	0.0015	0.002
1067	76.50%	Standard	0.0029	0.074	2.94	2.94	2.94	2.94	2.94	2.94	0.001	0.0013	0.0013	0.0013	0.0013	0.001
106	76.00%	Standard	0.0023	0.058	2.95	2.95	2.95	2.95	2.95	2.95	0.001	0.0013	0.0014	0.0014	0.0014	0.001
1080	72.00%	Standard	0.0038	0.097	3.02	3.02	3.02	3.02	3.02	3.01	0.002	0.0016	0.0016	0.0016	0.0016	0.002
1080	75.00%	Standard	0.0043	0.109	2.97	2.97	2.97	2.97	2.97	2.97	0.001	0.0014	0.0014	0.0014	0.0014	0.001
1080	78.00%	Alternate	0.0046	0.117	2.92	2.92	2.92	2.92	2.92	2.92	0.001	0.0013	0.0014	0.0014	0.0014	0.001
3313	63.50%	Standard	0.0046	0.117	3.16	3.16	3.16	3.16	3.16	3.16	0.002	0.002	0.002	0.002	0.002	0.002
3313	66.50%	Standard	0.0051	0.129	3.11	3.11	3.11	3.11	3.11	3.11	0.002	0.0018	0.0018	0.0018	0.0018	0.002

Test Method: TM-650-2.5.5.5C

! RC_w

Dk_z

$$Dk_{xy} = RC_v \cdot Dk_{resin} + GC_v \cdot Dk_{glass}$$

?

Problem: 1. RC% is weight 2. Don't know Dk of resin!

Source: Isola Tachyon 100G

Heuristically Determine Dkxy from Dkz Construction Tables & Glass Properties

Glass Style	Resin Content %	Offering	Thickness (inch)	Thickness (mm)	Dielectric Constant						Dissipation Factor					
					1 GHz	2 Ghz	5 Ghz	10 GHz	15 Ghz	20 Ghz	1 GHz	2 Ghz	5 Ghz	10 GHz	15 Ghz	20 Ghz
1035	69.00%	Standard	0.002	0.051	3.06	3.06	3.06	3.06	3.06	3.06	0.002	0.0017	0.0017	0.0017	0.0017	0.002
1035	75.00%	Standard	0.0026	0.066	2.97	2.97	2.97	2.97	2.97	2.97	0.001	0.0014	0.0014	0.0014	0.0014	0.001
1078	65.00%	Standard	0.0029	0.074	3.14	3.14	3.14	3.14	3.14	3.14	0.002	0.0019	0.0019	0.0019	0.0019	0.002
1078	67.50%	Standard	0.0031	0.079	3.09	3.09	3.09	3.09	3.09	3.09	0.002	0.0018	0.0018	0.0018	0.0018	0.002
1078	70.50%	Standard	0.0035	0.089	3.04	3.04	3.04	3.04	3.04	3.04	0.002	0.0016	0.0016	0.0016	0.0016	0.002
1078	72.00%	Standard	0.0037	0.094	3.02	3.02	3.02	3.02	3.02	3.01	0.002	0.0016	0.0016	0.0016	0.0016	0.002
1078	75.00%	Standard	0.0042	0.107	2.97	2.97	2.97	2.97	2.97	2.97	0.001	0.0014	0.0014	0.0014	0.0014	0.001
1078	78.00%	Alternate	0.0046	0.117	2.92	2.92	2.92	2.92	2.92	2.92	0.001	0.0013	0.0014	0.0014	0.0014	0.001
2116	62.00%	Standard	0.0058	0.147	3.19	3.19	3.19	3.19	3.19	3.19	0.002	0.0021	0.0021	0.0021	0.0021	0.002
2116	65.00%	Alternate	0.0064	0.163	3.14	3.14	3.14	3.14	3.14	3.14	0.002	0.0019	0.0019	0.0019	0.0019	0.002
1067	70.00%	Standard	0.0022	0.056	3.05	3.05	3.05	3.05	3.05	3.05	0.002	0.0017	0.0017	0.0017	0.0017	0.002
1067	71.50%	Standard	0.0024	0.061	3.02	3.02	3.02	3.02	3.02	3.02	0.002	0.0016	0.0016	0.0016	0.0016	0.002
1067	74.00%	Standard	0.0026	0.066	2.98	2.98	2.98	2.98	2.98	2.98	0.001	0.0014	0.0015	0.0015	0.0015	0.002
1067	76.50%	Standard	0.0029	0.074	2.94	2.94	2.94	2.94	2.94	2.94	0.001	0.0013	0.0013	0.0013	0.0013	0.001
106	76.00%	Standard	0.0023	0.058	2.95	2.95	2.95	2.95	2.95	2.95	0.001	0.0013	0.0014	0.0014	0.0014	0.001
1080	72.00%	Standard	0.0038	0.097	3.02	3.02	3.02	3.02	3.02	3.01	0.002	0.0016	0.0016	0.0016	0.0016	0.002
1080	75.00%	Standard	0.0043	0.109	2.97	2.97	2.97	2.97	2.97	2.97	0.001	0.0014	0.0014	0.0014	0.0014	0.001
1080	78.00%	Alternate	0.0046	0.117	2.92	2.92	2.92	2.92	2.92	2.92	0.001	0.0013	0.0014	0.0014	0.0014	0.001
3313	63.50%	Standard	0.0046	0.117	3.16	3.16	3.16	3.16	3.16	3.16	0.002	0.002	0.002	0.002	0.002	0.002
3313	66.50%	Standard	0.0051	0.129	3.11	3.11	3.11	3.11	3.11	3.11	0.002	0.0018	0.0018	0.0018	0.0018	0.002

Source: Isola Tachyon 100G

Test Method: TM-650-2.5.5.5C

Glass Fiber Properties	Units	L-Glass	E-Glass
Dielectric Constant (Dk)	@1 GHz	4.8	7.0
	@10 GHz	4.8	6.8
Dissipation Factor (Df)	@1 GHz	< 0.001	0.005
	@10 GHz	0.003	0.006
Density	g/cm3	2.3	2.54
Softening Point	°C	850	846
Coefficient of Thermal Expansion	ppm/°C	3.9	5.4
Tensile Load to Failure (D450 fiber)	N	8.5	8.9
Tensile Modulus	Gpa	62	75

Source: AGY

IPC-4412A - Amendment 1 Feb-2008

Table II-1 Finished Fabric Glass Styles in SI Units

Style	Warp per cm		Fill per cm	Yarn (SI)	Thickness mm	Nominal weight g/m^2	Min weight g/m^2	Max weight g/m^2
1035	26	x	26.8	5 5.5 1x0 5 5.5 1x0	0.028	30	27.2	32.6
106	22	x	22	5 5.5 1x0 5 5.5 1x0	0.033	24.4	23.4	25.4
1067	27.6	x	27.6	5 5.5 1x0 5 5.5 1x0	0.035	30.7	29.5	31.9
1078	21.3	x	21.3	5 11 1x0 5 11 1x0	0.043	47.8	46.8	49.2
1080	23.6	x	18.5	5 11 1x0 5 11 1x0	0.053	46.8	45.1	48.5
3313	23.6	x	24.4	6 16.5 1x0 6 16.5 1x0	0.084	81.4	79	83.7
2116	23.6	x	22.8	7 22 1x0 7 22 1x0	0.094	103.8	100.7	106.8

Heuristically Determine Glass Content Volume

Glass Style	Resin Content %	Offering	Thickness (inch)	Thickness (mm) *t*	Dielectric Constant						Dissipation Factor					
					1 GHz	2 Ghz	5 Ghz	10 GHz	15 Ghz	20 Ghz	1 GHz	2 Ghz	5 Ghz	10 GHz	15 Ghz	20 Ghz
1035	69.00%	Standard	0.002	0.051	3.06	3.06	3.06	3.06	3.06	3.06	0.002	0.0017	0.0017	0.0017	0.0017	0.002
1035	75.00%	Standard	0.0026	0.066	2.97	2.97	2.97	2.97	2.97	2.97	0.001	0.0014	0.0014	0.0014	0.0014	0.001
1078	65.00%	Standard	0.0029	0.074	3.14	3.14	3.14	3.14	3.14	3.14	0.002	0.0019	0.0019	0.0019	0.0019	0.002
1078	67.50%	Standard	0.0031	0.079	3.09	3.09	3.09	3.09	3.09	3.09	0.002	0.0018	0.0018	0.0018	0.0018	0.002
1078	70.50%	Standard	0.0035	0.089	3.04	3.04	3.04	3.04	3.04	3.04	0.002	0.0016	0.0016	0.0016	0.0016	0.002
1078	72.00%	Standard	0.0037	0.094	3.02	3.02	3.02	3.02	3.02	3.01	0.002	0.0016	0.0016	0.0016	0.0016	0.002
1078	75.00%	Standard	0.0042	0.107	2.97	2.97	2.97	2.97	2.97	2.97	0.001	0.0014	0.0014	0.0014	0.0014	0.001
1078	78.00%	Alternate	0.0046	0.117	2.92	2.92	2.92	2.92	2.92	2.92	0.001	0.0013	0.0014	0.0014	0.0014	0.001
2116	62.00%	Standard	0.0058	0.147	3.19	3.19	3.19	3.19	3.19	3.19	0.002	0.0021	0.0021	0.0021	0.0021	0.002
2116	65.00%	Alternate	0.0064	0.163	3.14	3.14	3.14	3.14	3.14	3.14	0.002	0.0019	0.0019	0.0019	0.0019	0.002
1067	70.00%	Standard	0.0022	0.056	3.05	3.05	3.05	3.05	3.05	3.05	0.002	0.0017	0.0017	0.0017	0.0017	0.002
1067	71.50%	Standard	0.0024	0.061	3.02	3.02	3.02	3.02	3.02	3.02	0.002	0.0016	0.0016	0.0016	0.0016	0.002
1067	74.00%	Standard	0.0026	0.066	2.98	2.98	2.98	2.98	2.98	2.98	0.001	0.0014	0.0015	0.0015	0.0015	0.002
1067	76.50%	Standard	0.0029	0.074	2.94	2.94	2.94	2.94	2.94	2.94	0.001	0.0013	0.0013	0.0013	0.0013	0.001
106	76.00%	Standard	0.0023	0.058	2.95	2.95	2.95	2.95	2.95	2.95	0.001	0.0013	0.0014	0.0014	0.0014	0.001
1080	72.00%	Standard	0.0038	0.097	3.02	3.02	3.02	3.02	3.02	3.01	0.002	0.0016	0.0016	0.0016	0.0016	0.002
1080	75.00%	Standard	0.0043	0.109	2.97	2.97	2.97	2.97	2.97	2.97	0.001	0.0014	0.0014	0.0014	0.0014	0.001
1080	78.00%	Alternate	0.0046	0.117	2.92	2.92	2.92	2.92	2.92	2.92	0.001	0.0013	0.0014	0.0014	0.0014	0.001
3313	63.50%	Standard	0.0046	0.117	3.16	3.16	3.16	3.16	3.16	3.16	0.002	0.002	0.002	0.002	0.002	0.002
3313	66.50%	Standard	0.0051	0.129	3.11	3.11	3.11	3.11	3.11	3.11	0.002	0.0018	0.0018	0.0018	0.0018	0.002

Source: Isola Tachyon 100G

Test Method: TM-650-2.5.5.5C

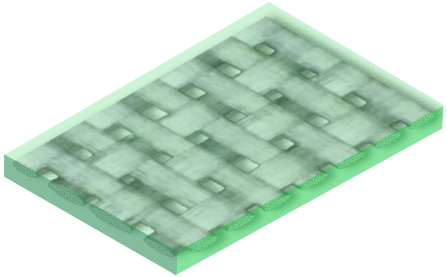
Glass Fiber Properties	Units	L-Glass	E-Glass
Dielectric Constant (Dk)	@1 GHz	4.8	7.0
	@10 GHz	4.8	6.8
Dissipation Factor (Df)	@1 GHz	< 0.001	0.005
	@10 GHz	0.003	0.006
Density *D*	g/cm3	2.3	2.54
Softening Point	°C	850	846
Coefficient of Thermal Expansion	ppm/°C	3.9	5.4
Tensile Load to Failure (D450 fiber)	N	8.5	8.9
Tensile Modulus	Gpa	62	75

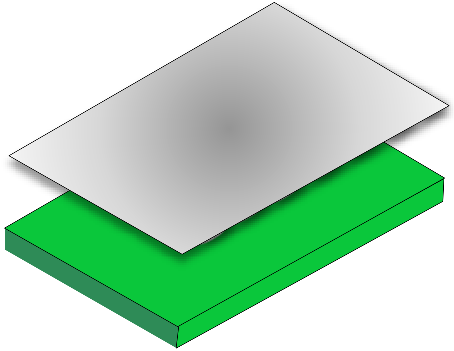
Source: AGY

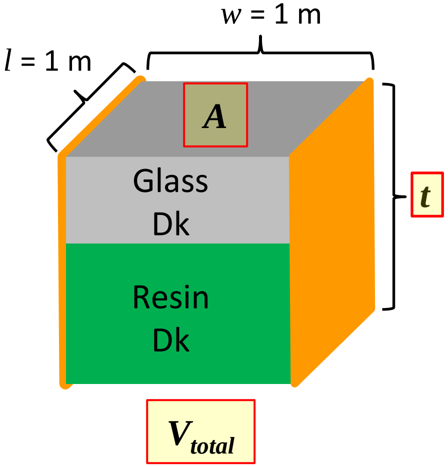
IPC-4412A - Amendment 1 Feb-2008

Table II-1 Finished Fabric Glass Styles in SI Units

Style	Warp per cm		Fill per cm	Yarn (SI)	Thickness mm	Nominal weight g/m² *Wg*	Min weight g/m²	Max weight g/m²
1035	26	x	26.8	5 5.5 1x0 5 5.5 1x0	0.028	30	27.2	32.6
106	22	x	22	5 5.5 1x0 5 5.5 1x0	0.033	24.4	23.4	25.4
1067	27.6	x	27.6	5 5.5 1x0 5 5.5 1x0	0.035	30.7	29.5	31.9
1078	21.3	x	21.3	5 11 1x0 5 11 1x0	0.043	47.8	46.8	49.2
1080	23.6	x	18.5	5 11 1x0 5 11 1x0	0.053	46.8	45.1	48.5
3313	23.6	x	24.4	6 16.5 1x0 6 16.5 1x0	0.084	81.4	79	83.7
2116	23.6	x	22.8	7 22 1x0 7 22 1x0	0.094	103.8	100.7	106.8







$$GCv = \frac{Wg \times A}{(D \times V_{total})}$$

$$= \frac{Wg \times A}{(D \times A \times t)}$$

$$GC_v = \frac{Wg}{(D \times t)}$$

E-Glass to L-Glass Wg Conversion

Glass Fiber Properties	Units	L-Glass	E-Glass
Dielectric Constant (Dk)	@1 GHz	4.8	7.0
	@10 GHz	4.8	6.8
Dissipation Factor (Df)	@1 GHz	< 0.001	0.005
	@10 GHz	0.003	0.006
Density	g/cm3	2.3	2.54
Softening Point	°C	850	846
Coefficient of Thermal Expansion	ppm/°C	3.9	5.4
Tensile Load to Failure (D450 fiber)	N	8.5	8.9
Tensile Modulus	Gpa	62	75

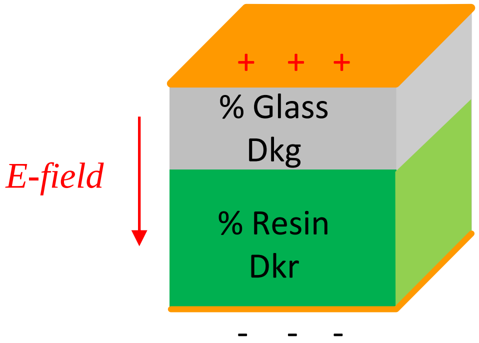
Source: AGY

$$Wg_{L-Glass} = \frac{Density_{L-Glass}}{Density_{E-Glass}}\left(Wg_{E-Glass}\right)$$

$$\approx 0.9Wg_{E-Glass}$$

IPC-4412A - Amendment 1 Feb-2008 (E-Glass) Table II-1 Finished Fabric Glass Styles in SI Units									L-Glass ($0.09Wg_{E-Glass}$)		
Style	Warp per cm		Fill per cm	Yarn (SI)	Thickness mm	Nominal weight g/m2	Min weight g/m3	Min weight g/m4	Nominal weight g/m2	Min weight g/m3	Min weight g/m4
1035	26	x	26.8	5 5.5 1x0 5 5.5 1x0	0.028	30	27.2	32.6	27	24.48	29.34
106	22	x	22	5 5.5 1x0 5 5.5 1x0	0.033	24.4	23.4	25.4	21.96	21.06	22.86
1067	27.6	x	27.6	5 5.5 1x0 5 5.5 1x0	0.035	30.7	29.5	31.9	27.63	26.55	28.71
1078	21.3	x	21.3	5 11 1x0 5 11 1x0	0.043	47.8	46.8	49.2	43.02	42.12	44.28
1080	23.6	x	18.5	5 11 1x0 5 11 1x0	0.053	46.8	45.1	48.5	42.12	40.59	43.65
3313	23.6	x	24.4	6 16.5 1x0 6 16.5 1x0	0.084	81.4	79	83.7	73.26	71.1	75.33
2116	23.6	x	22.8	7 22 1x0 7 22 1x0	0.094	103.8	100.7	106.8	93.42	90.63	96.12

Heuristically Convert Dkz to Dkxy



$$Dk_z = \left[\left(1 - GC_v\right) / Dk_{resin} + GC_v / Dk_{glass} \right]^{-1}$$

Parallel Mixing Rule

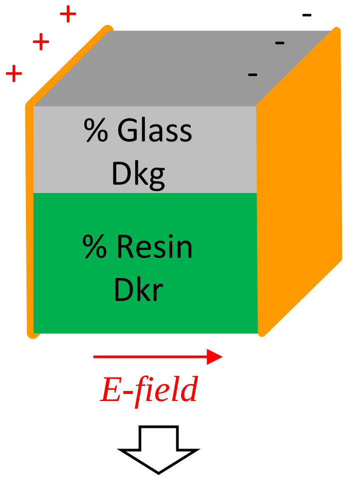
1. Determine Dkresin:

$$Dkr = \frac{Dkz\left(1 - GC_v\right)}{\left(1 - \left(\frac{DkzGC_v}{Dkg}\right)\right)}$$

2. Determine Dkxy:

$$Dkxy = \left(1 - GC_v\right)Dkr + \left(GC_v\right)Dkg$$

Heuristically Convert Dkxy to Dkz



$$Dkxy = (1 - GC_v)Dkr + (GC_v)Dkg$$

Series Mixing Rule

1. Determine Dkresin:

$$Dkr = \frac{Dkxy - GC_v(Dkg)}{(1 - GC_v)}$$

2. Determine Dkz

$$Dk_z = \left[(1 - GC_v) / Dk_{resin} + GC_v / Dk_{glass}\right]^{-1}$$

Practical Tachyon 100G Example

Glass Style	Resin Content %	Offering	Thickness (inch)	Thickness (mm)	Dielectric Constant						Dissipation Factor					
					1 GHz	2 Ghz	5 Ghz	10 GHz	15 Ghz	20 Ghz	1 GHz	2 Ghz	5 Ghz	10 GHz	15 Ghz	20 Ghz
1035	69.00%	Standard	0.002	0.051	3.06	3.06	3.06	3.06	3.06	3.06	0.002	0.0017	0.0017	0.0017	0.0017	0.002
1035	75.00%	Standard	0.0026	0.066	2.97	2.97	2.97	2.97	2.97	2.97	0.001	0.0014	0.0014	0.0014	0.0014	0.001
1078	65.00%	Standard	0.0029	0.074	3.14	3.14	3.14	3.14	3.14	3.14	0.002	0.0019	0.0019	0.0019	0.0019	0.002
1078	67.50%	Standard	0.0031	0.079	3.09	3.09	3.09	3.09	3.09	3.09	0.002	0.0018	0.0018	0.0018	0.0018	0.002
1078	70.50%	Standard	0.0035	0.089	3.04	3.04	3.04	3.04	3.04	3.04	0.002	0.0016	0.0016	0.0016	0.0016	0.002
1078	72.00%	Standard	0.0037	0.094	3.02	3.02	3.02	3.02	3.02	3.01	0.002	0.0016	0.0016	0.0016	0.0016	0.002
1078	75.00%	Standard	0.0042	0.107	2.97	2.97	2.97	2.97	2.97	2.97	0.001	0.0014	0.0014	0.0014	0.0014	0.001
1078	78.00%	Alternate	0.0046	0.117	2.92	2.92	2.92	2.92	2.92	2.92	0.001	0.0013	0.0014	0.0014	0.0014	0.001
2116	62.00%	Standard	0.0058	0.147	3.19	3.19	3.19	3.19	3.19	3.19	0.002	0.0021	0.0021	0.0021	0.0021	0.002
2116	65.00%	Alternate	0.0064	0.163	3.14	3.14	3.14	3.14	3.14	3.14	0.002	0.0019	0.0019	0.0019	0.0019	0.002
1067	70.00%	Standard	0.0022	0.056	3.05	3.05	3.05	3.05	3.05	3.05	0.002	0.0017	0.0017	0.0017	0.0017	0.002
1067	71.50%	Standard	0.0024	0.061	3.02	3.02	3.02	3.02	3.02	3.02	0.002	0.0016	0.0016	0.0016	0.0016	0.002
1067	74.00%	Standard	0.0026	0.066	2.98	2.98	2.98	2.98	2.98	2.98	0.001	0.0014	0.0015	0.0015	0.0015	0.002
1067	76.50%	Standard	0.0029	0.074	2.94	2.94	2.94	2.94	2.94	2.94	0.001	0.0013	0.0013	0.0013	0.0013	0.001
106	76.00%	Standard	0.0023	0.058	2.95	2.95	2.95	2.95	2.95	2.95	0.001	0.0013	0.0014	0.0014	0.0014	0.001
1080	72.00%	Standard	0.0038	0.097	3.02	3.02	3.02	3.02	3.02	3.01	0.002	0.0016	0.0016	0.0016	0.0016	0.002
1080	75.00%	Standard	0.0043	0.109	2.97	2.97	2.97	2.97	2.97	2.97	0.001	0.0014	0.0014	0.0014	0.0014	0.001
1080	78.00%	Alternate	0.0046	0.117	2.92	2.92	2.92	2.92	2.92	2.92	0.001	0.0013	0.0014	0.0014	0.0014	0.001
3313	63.50%	Standard	0.0046	0.117	3.16	3.16	3.16	3.16	3.16	3.16	0.002	0.002	0.002	0.002	0.002	0.002
3313	66.50%	Standard	0.0051	0.129	3.11	3.11	3.11	3.11	3.11	3.11	0.002	0.0018	0.0018	0.0018	0.0018	0.002

Source: Isola Tachyon 100G

Test Method: TM-650-2.5.5.5C

Given T100G 1035 69%RC:

A = 1 m^2

t = 51 um

D = Density of NE-glass (L-glass) = 2.3E6 g/m^3

W_g = Weight of 1035 L-Glass = 0.9(Weight of 1035 E-glass)
= 0.9(30 g/m^2) = 27 g/m^2

Dk = 3.06 (@ 10GHz)

Step 1:
Determine the volume fraction of glass content (GCv):

$$GCv = \frac{Wg}{(D \times t)} = \frac{27}{(2.30E6 \times 5.10E-5)} = 0.23$$

Step 2:
Using a GCv of 0.23 and a Dkg of 4.8 for L-glass at 10GHz and rearranging the parallel mixing rule equation, estimate Dkr value:

$$Dkr_{10GHz} = \frac{Dkz_{10GHz}(1-GC_v)}{\left(1-\left(\frac{Dkz_{10GHz}GC_v}{Dkg_{10GHz}}\right)\right)} = \frac{3.06(1-0.23)}{\left(1-\left(\frac{3.06 \times 0.23}{4.8}\right)\right)} = 2.76$$

Step 3:
Using series mixing rule equation, determine Dkxy:

$$Dkxy = (1-GC_v)Dkr + (GC_v)Dkg = (1-0.23)2.76 + (0.23)4.8 = 3.23$$

Step 4:
Finally 1035/69% RC, 2 mil prepreg @10GHz has a Dk anisotropy of:

$$\Lambda_{10GHz} = \left(\frac{Dkxy}{Dkz} - 1\right)100 = \left(\frac{3.23}{3.06} - 1\right)100 = 5.56\%$$

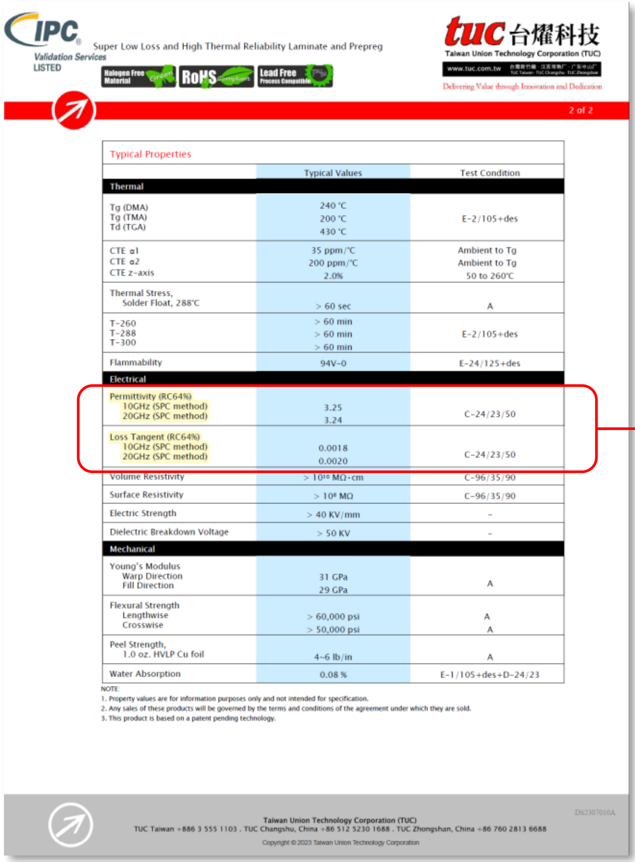
Tachyon 100G Construction Table Dk Anisotropy

Glass Style	Resin Content %	Offering	Thickness (inch)	Thickness (mm)	Dielectric Constant (Dkz)						Dkxy						Anisotropy
					1 GHz	2 Ghz	5 Ghz	10 GHz	15 Ghz	20 Ghz	1 GHz	2 Ghz	5 Ghz	10 GHz	15 Ghz	20 Ghz	xy:z
1035	69.00%	Standard	0.002	0.051	3.06	3.06	3.06	3.06	3.06	3.06	3.23	3.23	3.23	3.23	3.23	3.23	5.6%
1035	75.00%	Standard	0.0026	0.066	2.97	2.97	2.97	2.97	2.97	2.97	3.11	3.11	3.11	3.11	3.11	3.11	4.7%
1078	65.00%	Standard	0.0029	0.074	3.14	3.14	3.14	3.14	3.14	3.14	3.31	3.31	3.31	3.31	3.31	3.31	5.5%
1078	67.50%	Standard	0.0031	0.079	3.09	3.09	3.09	3.09	3.09	3.09	3.26	3.26	3.26	3.26	3.26	3.26	5.5%
1078	70.50%	Standard	0.0035	0.089	3.04	3.04	3.04	3.04	3.04	3.04	3.20	3.20	3.20	3.20	3.20	3.20	5.1%
1078	72.00%	Standard	0.0037	0.094	3.02	3.02	3.02	3.02	3.02	3.01	3.17	3.17	3.17	3.17	3.17	3.16	5.0%
1078	75.00%	Standard	0.0042	0.107	2.97	2.97	2.97	2.97	2.97	2.97	3.11	3.11	3.11	3.11	3.11	3.11	4.6%
1078	78.00%	Alternate	0.0046	0.117	2.92	2.92	2.92	2.92	2.92	2.92	3.05	3.05	3.05	3.05	3.05	3.05	4.5%
2116	62.00%	Standard	0.0058	0.147	3.19	3.19	3.19	3.19	3.19	3.19	3.37	3.37	3.37	3.37	3.37	3.37	5.7%
2116	65.00%	Alternate	0.0064	0.163	3.14	3.14	3.14	3.14	3.14	3.14	3.31	3.31	3.31	3.31	3.31	3.31	5.4%
1067	70.00%	Standard	0.0022	0.056	3.05	3.05	3.05	3.05	3.05	3.05	3.21	3.21	3.21	3.21	3.21	3.21	5.2%
1067	71.50%	Standard	0.0024	0.061	3.02	3.02	3.02	3.02	3.02	3.02	3.17	3.17	3.17	3.17	3.17	3.17	4.9%
1067	74.00%	Standard	0.0026	0.066	2.98	2.98	2.98	2.98	2.98	2.98	3.12	3.12	3.12	3.12	3.12	3.12	4.8%
1067	76.50%	Standard	0.0029	0.074	2.94	2.94	2.94	2.94	2.94	2.94	3.07	3.07	3.07	3.07	3.07	3.07	4.4%
106	76.00%	Standard	0.0023	0.058	2.95	2.95	2.95	2.95	2.95	2.95	3.08	3.08	3.08	3.08	3.08	3.08	4.4%
1080	72.00%	Standard	0.0038	0.097	3.02	3.02	3.02	3.02	3.02	3.01	3.16	3.16	3.16	3.16	3.16	3.15	4.7%
1080	75.00%	Standard	0.0043	0.109	2.97	2.97	2.97	2.97	2.97	2.97	3.10	3.10	3.10	3.10	3.10	3.10	4.4%
1080	78.00%	Alternate	0.0046	0.117	2.92	2.92	2.92	2.92	2.92	2.92	3.05	3.05	3.05	3.05	3.05	3.05	4.4%
3313	63.50%	Standard	0.0046	0.117	3.16	3.16	3.16	3.16	3.16	3.16	3.35	3.35	3.35	3.35	3.35	3.35	5.9%
3313	66.50%	Standard	0.0051	0.129	3.11	3.11	3.11	3.11	3.11	3.11	3.28	3.28	3.28	3.28	3.28	3.28	5.6%

Dk anisotropy varies depending on glass style and resin content

Dielectric Anisotropic Validation

TUC Thunderclad 400G Laminate



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Halogen Free Material · RoHS Compliant · Lead Free Process Compatible

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2 of 2

Typical Properties

	Typical Values	Test Condition
Thermal		
Tg (DMA) Tg (TMA) Td (TGA)	240 ℃ 200 ℃ 430 ℃	E-2/105+des
CTE α1 CTE α2 CTE z-axis	35 ppm/℃ 200 ppm/℃ 2.0%	Ambient to Tg Ambient to Tg 50 to 260℃
Thermal Stress, Solder Float, 288℃	> 60 sec	A
T-260 T-288 T-300	> 60 min > 60 min > 60 min	E-2/105+des
Flammability	94V-0	E-24/125+des
Electrical		
Permittivity (RC64%) 10GHz (SPC method) 20GHz (SPC method)	3.25 3.24	C-24/23/50
Loss Tangent (RC64%) 10GHz (SPC method) 20GHz (SPC method)	0.0018 0.0020	C-24/23/50
Volume Resistivity	> 10^{10} MΩ·cm	C-96/35/90
Surface Resistivity	> 10^{8} MΩ	C-96/35/90
Electric Strength	> 40 KV/mm	-
Dielectric Breakdown Voltage	> 50 KV	-
Mechanical		
Young's Modulus Warp Direction Fill Direction	31 GPa 29 GPa	A
Flexural Strength Lengthwise Crosswise	> 60,000 psi > 50,000 psi	A A
Peel Strength, 1.0 oz. HVLP Cu foil	4~6 lb/in	A
Water Absorption	0.08 %	E-1/105+des+D-24/23

NOTE:
1. Property values are for information purposes only and not intended for specification.
2. Any sales of these products will be governed by the terms and conditions of the agreement under which they are sold.
3. This product is based on a patent pending technology.

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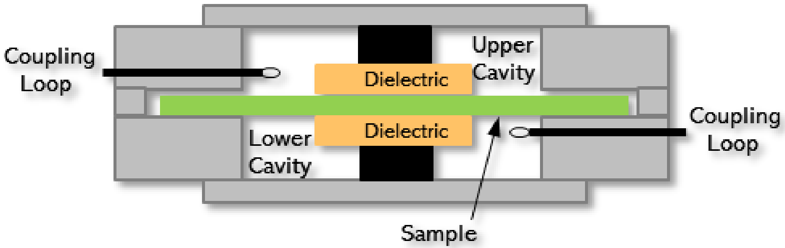
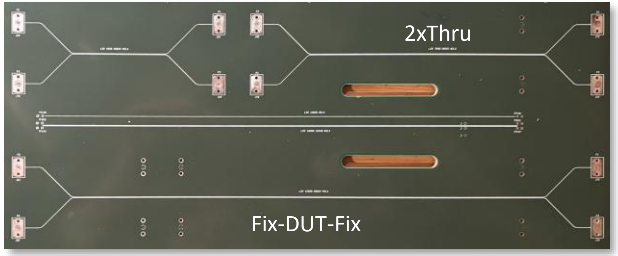
Split-post Dielectric Resonator



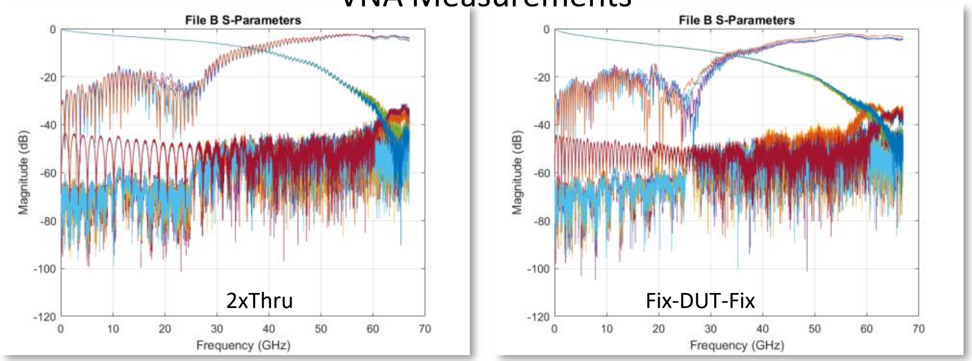
In-Plane Dkxy

Anisotropic Model Validation

SI Test Coupon

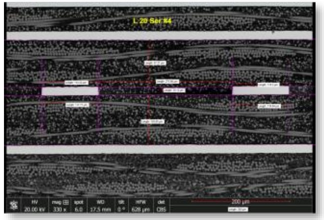


VNA Measurements



De-embed DUT

X-section Parameters



LW; Space; t; H1; H2; Rz; Dkxy_eff

Dkxy_eff

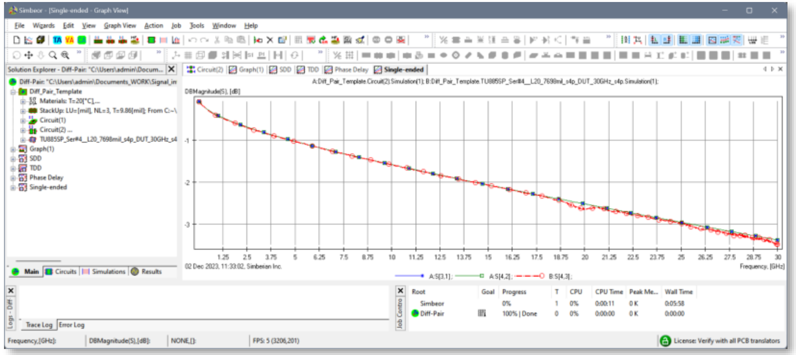
1. Determine Dkresin:

$$Dkr = \frac{Dkxy - GC_v(Dkg)}{(1-GC_v)}$$

2. Determine Dkz:

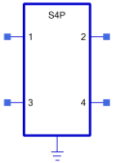
$$Dk_z = \left[(1-GC_v)/Dk_{resin} + GC_v/Dk_{glass}\right]^{-1}$$

Dkz_eff



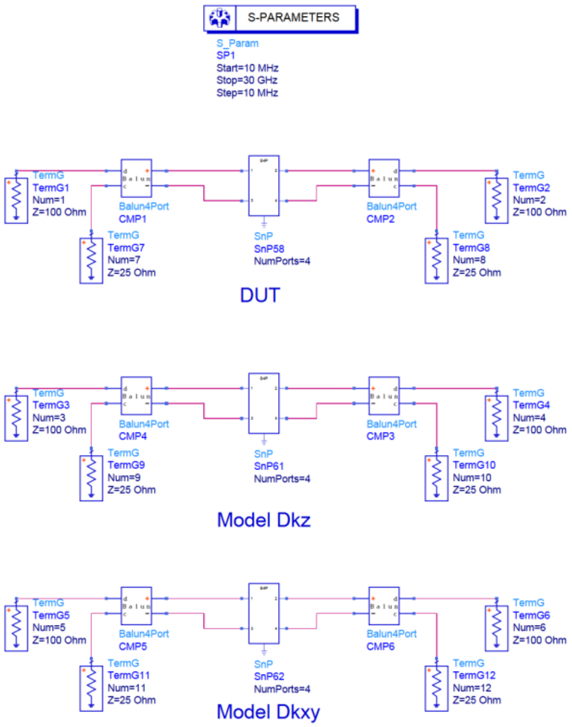
Model

Touchstone Files

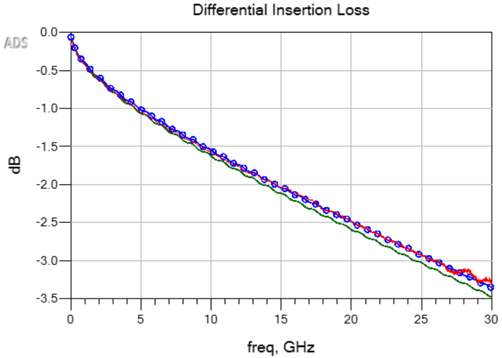


Data Courtesy Ciena Corporation; Modeled by Simbeor

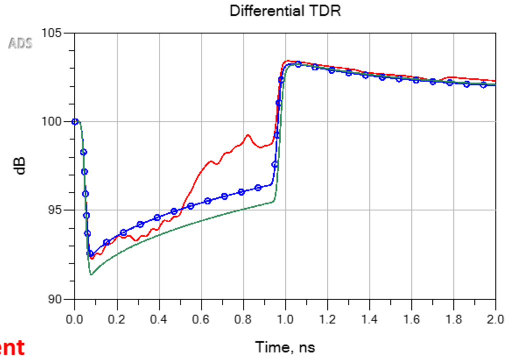
Anisotropic Model Validation



Excellent Correlation!

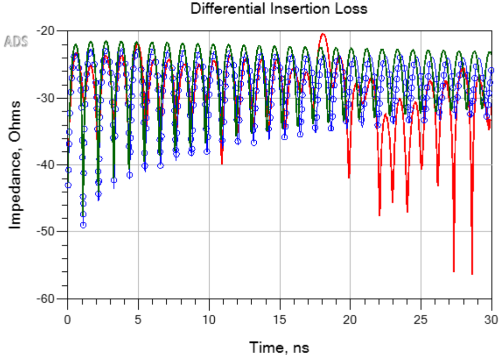


(A)

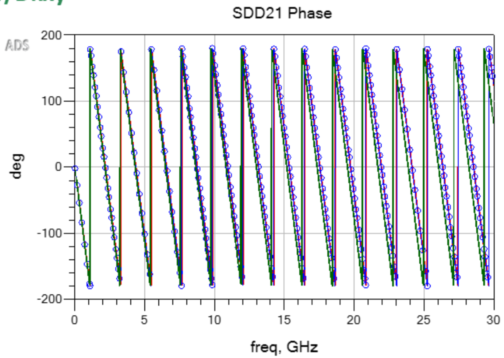


(B)

Measurement
Simulated w/Dkz
Simulated w/Dkxy



(C)



(D)

Data Courtesy Ciena Corporation; Simulated with Keysight Pathwave ADS

Summary

- ✓ **All glass reinforced laminates are anisotropic**
- ✓ **Closer Dk glass/resin mix => better anisotropy**
- ✓ **Important to understand material properties for accurate modeling and simulations**
- ✓ **Using the same Dk value for transmission line and via models leads to inaccurate results**
- ✓ **CCL suppliers should provide both in-plane and out-of-plane Dk/Df in construction tables**
- ✓ **PCB fabricators need to become aware of material anisotropy for better stackup predictions**
- ✓ **Using wrong value for stackup design can lead to poor yield due to reduced margin for process variation**

Acknowledgements

Michael Gay & Alexander Ippich – Isola Corporation

Dr. Alexandre Guterman

Ciena Corporation

Thank You

Lamsim Enterprises inc.

Innovative Signal Integrity & Backplane Solutions

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