Physical RF Circuit Techniques and Their Implications on Future Power Module and Power Electronic Design

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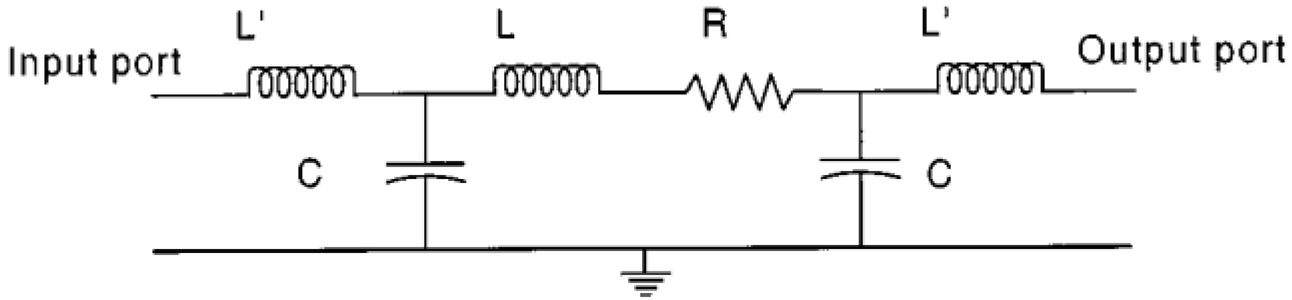
PREES Laboratory

NC STATE UNIVERSITY

Overall Motivation

- Wide Bandgap (WBG) semiconductor devices are able to switch much faster than conventional Silicon semiconductor technology
- Wire and ribbon bonds used with packaged circuits and modules lead to undesirable parasitic effects that impact performance, especially at higher operating frequencies
- Consider reflection loss and insertion loss when using these “flexible welded interconnects” under high power and high frequency



$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

Two-Port Network Analysis

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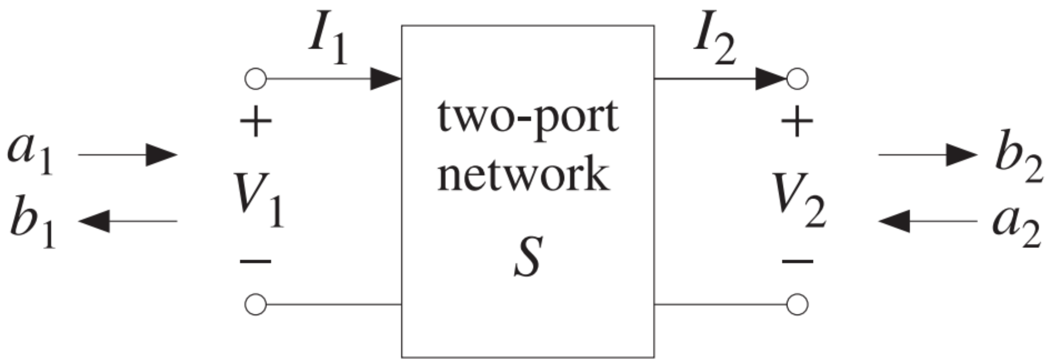
- Scattering Parameters (S-Parameters)
  - Used to characterize a network ("part/all of a power module") and its behavior within an external circuit
  - Important for high frequency design because of its simplicity
  - Power flow into and out of the two-port is expressed very simply in terms of the traveling wave amplitudes.

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

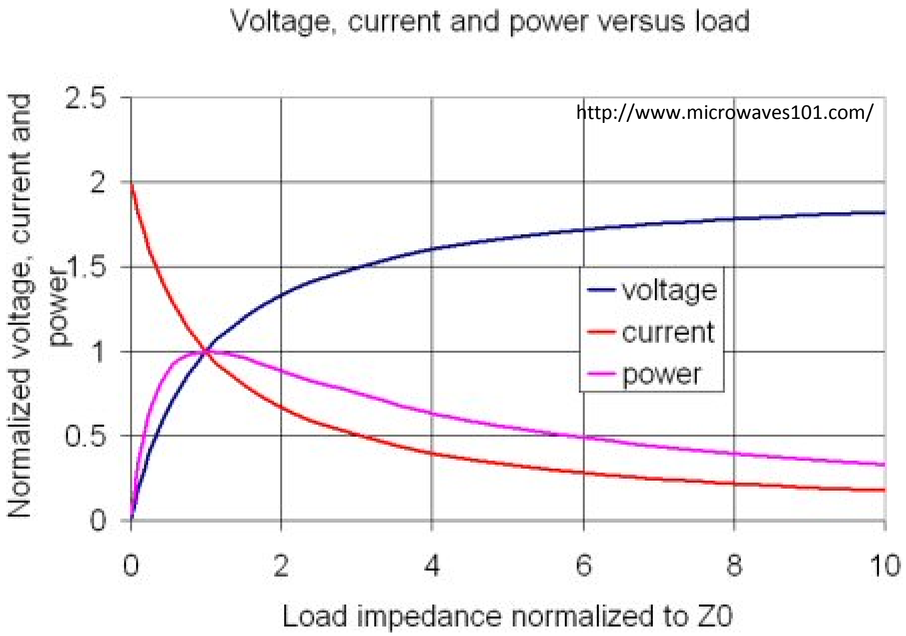


$$\frac{1}{2}\mathrm{Re}[V_1^* I_1] = \frac{1}{2}|a_1|^2 - \frac{1}{2}|b_1|^2$$

$$-\frac{1}{2}\mathrm{Re}[V_2^* I_2] = \frac{1}{2}|a_2|^2 - \frac{1}{2}|b_2|^2$$

RF Parameter Definitions

- Radio frequency (RF) is a rate of oscillation in the range of around 3 kHz to 300 GHz
- Reflection Coefficient (Γ) & Voltage Standing Wave Ratio (VSWR)
- Characteristic Impedance (Z_o)
  - Any media that can support an electromagnetic wave has a characteristic impedance associated with it
- Impedance Matching
  - A measure of how well a network is matched to its intended characteristic impedance
  - Maximum power transfer is obtained from source to load, but maximum power transfer doesn't necessarily mean most efficient



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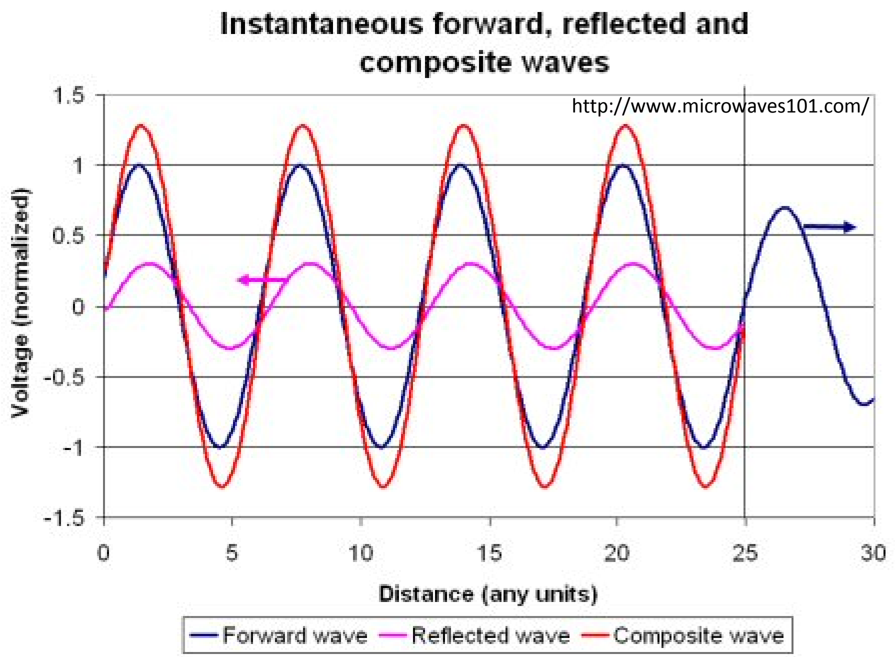
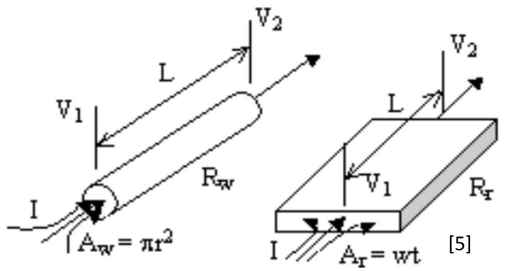


$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

Useful, Known Information

- In order to decrease Z_o, it is known:
  - Multiple bond wires in parallel decrease a bond wire's resistance and inductance
  - Ribbon bonds can eliminate capacitive and mutual coupling b/w multiple wires
  - Design for low loops heights close to ground planes, while keeping sufficient distance between bond wire and die to prevent electric breakdown under highly concentrated electric fields, increases capacitance
  - A large ribbon width has lower inductance (width and thickness are not linked to one and other like they are for wire)
- For power electronics, a ribbon bond is more suitable to carry more current at higher frequencies than a round wire bond

$$R_w = \frac{\rho L}{A_w} = \frac{\rho L}{\pi r^2} \qquad R_r = \frac{\rho L}{A_r} = \frac{\rho L}{wt}$$



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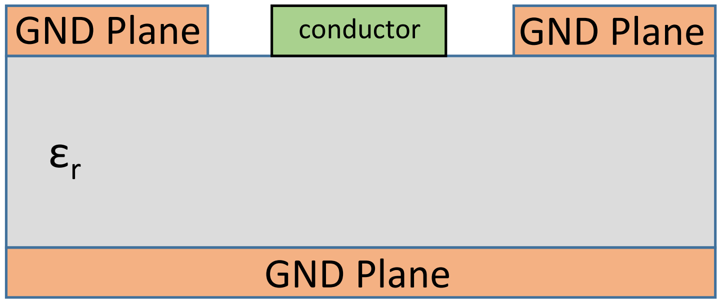
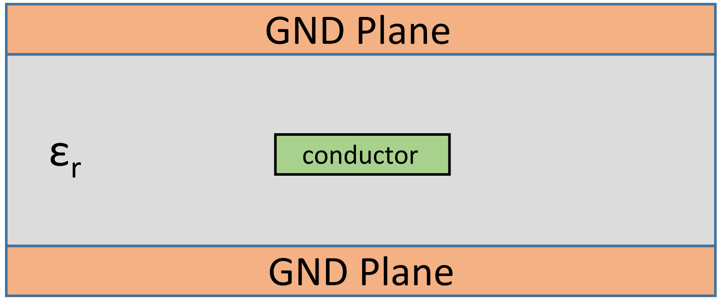
Physical RF Circuit Techniques

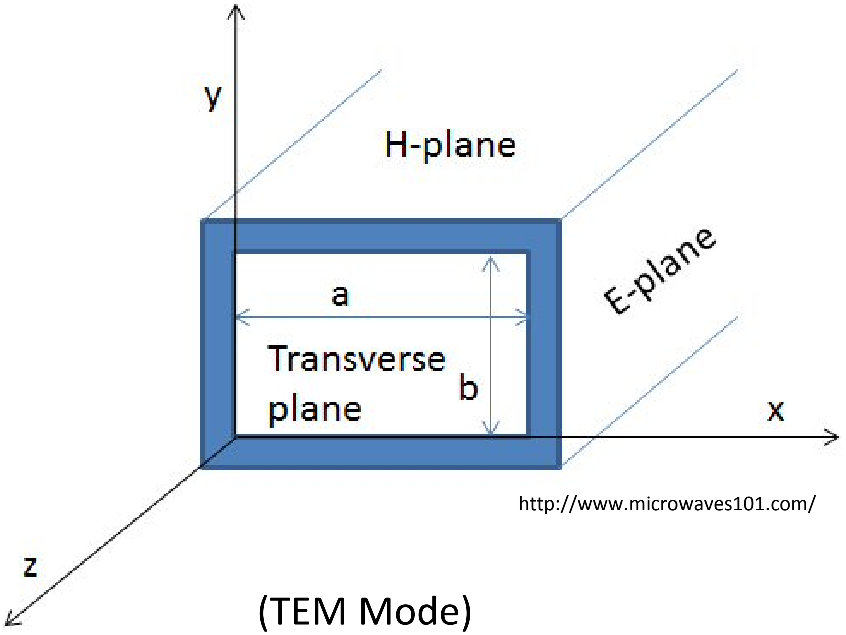
- Circuit Designs to allow for TEM Modes
  - Stripline
  - Grounded Co-planar Waveguide (GCPW)
  - Parallel Conductors
  - Coaxial Cable



(GCPW)



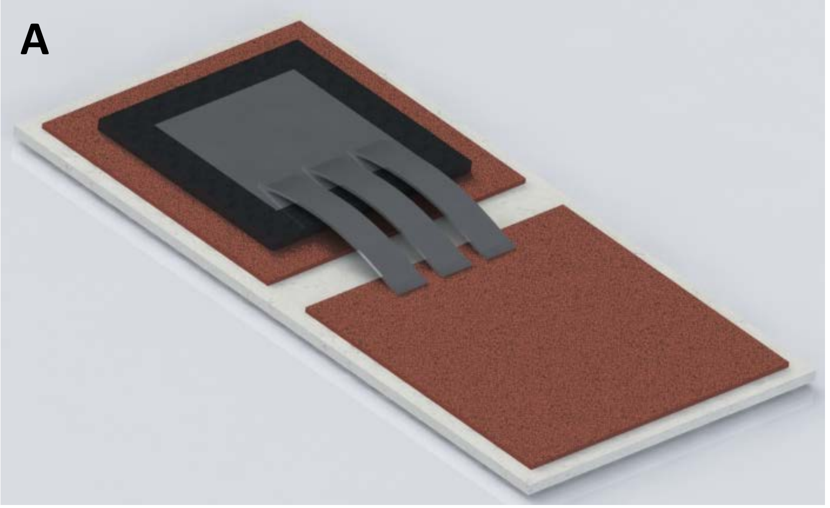
(Stripline)

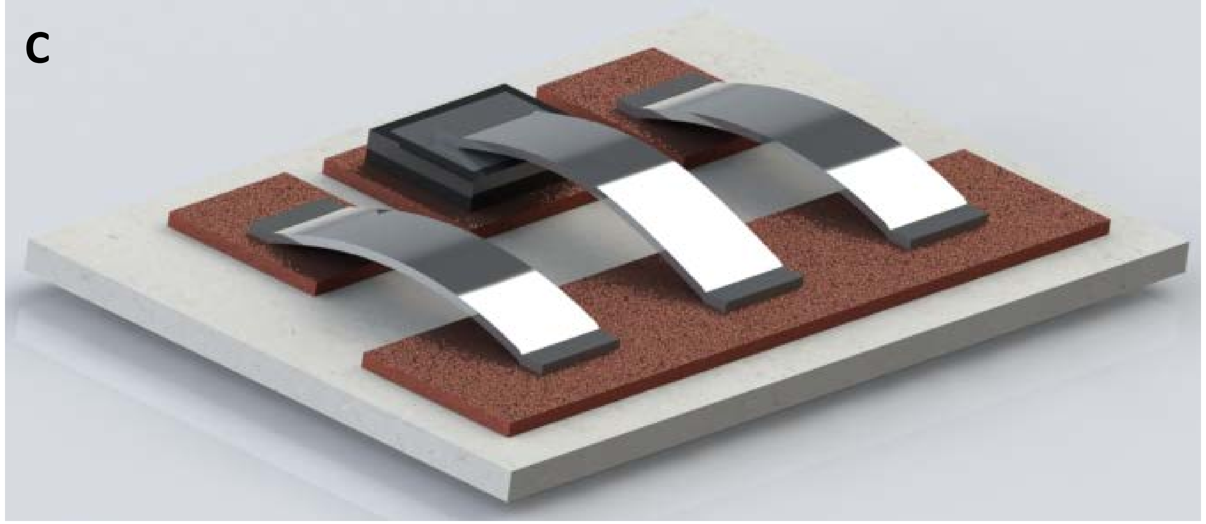


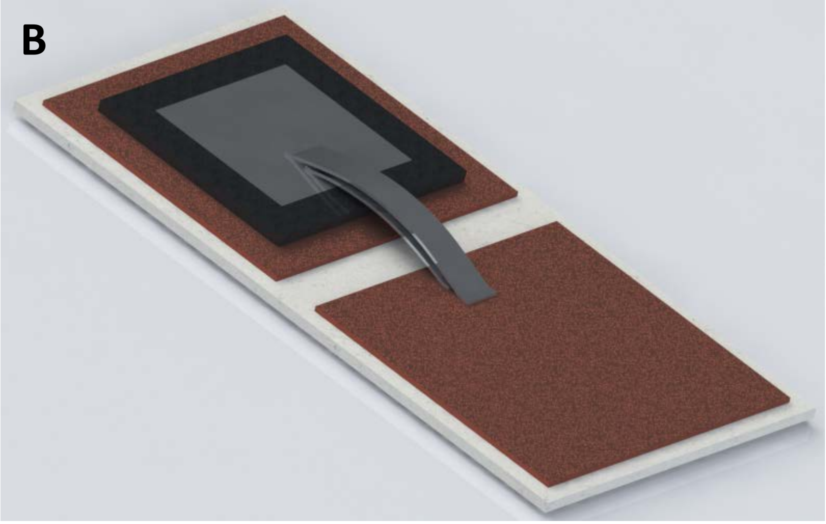
(TEM Mode)

Proposed RF Models for Testing

A. Parallel Ribbon Bond Conductors
B. Stacked Ribbon Bond Conductors
C. GCPW Ribbon Bond Conductor





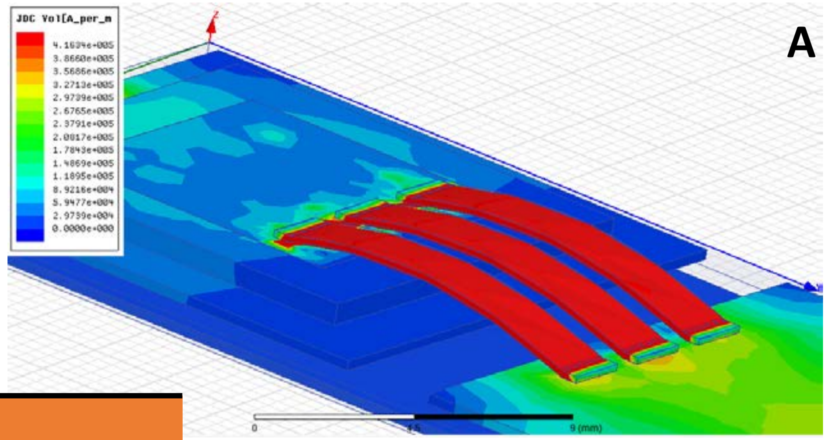


Q3D Model Simulation Results

A. Parallel Ribbon Bond Conductors

B. Stacked Ribbon Bond Conductors

C. GCPW Ribbon Bond Conductor



Frequency (MHz)	Parasitic Resistance (mΩ)	Parasitic Inductance (nH)	Parasitic Capacitance (pF)	Parasitic Conductance (mSie)	Z_o (Ω)
1.0E-9 (DC)	0.307	13.127	88.542	1.0E-9	17470-j772
0.1	0.647	10.927	88.133	0.248E-3	11.62-j3.01
0.5	1.188	10.549	87.636	1.51E-3	11.06-j1.04
1.0	1.596	10.457	87.416	3.08E-3	10.98-j0.64
10.0	4.607	10.306	86.681	31.46E-3	10.91-j0.05

P = 120W
@ 100kHz, 10A excitation

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A. Parallel Ribbon Bond Conductors

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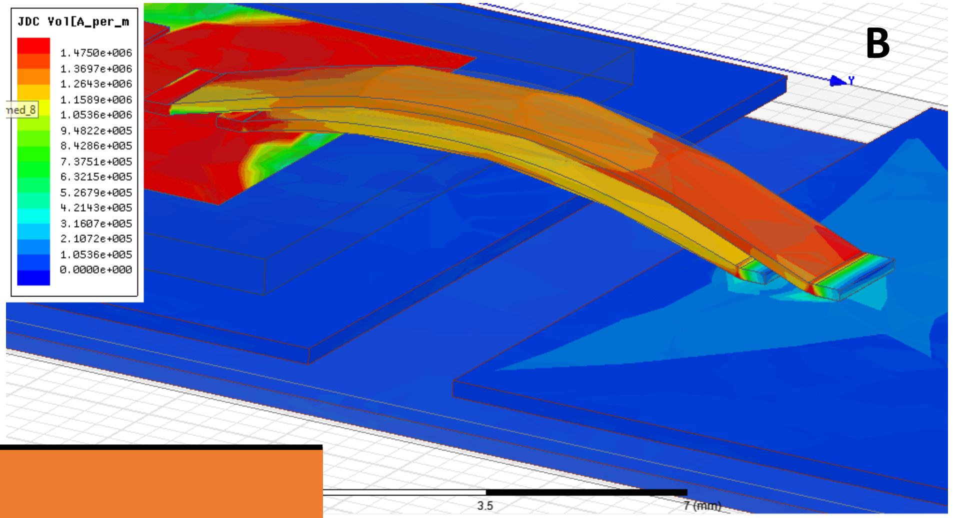


Frequency (MHz)	Parasitic Resistance (mΩ)	Parasitic Inductance (nH)	Parasitic Capacitance (pF)	Parasitic Conductance (mSie)	Z_o (Ω)
1.0E-9 (DC)	0.622	9.038	60.733	5.028E-10	34982-j2105
0.1	1.006	8.003	60.535	0.124E-3	13.19-j6.20
0.5	1.870	7.441	60.286	0.757E-3	11.47-j2.57
1.0	2.534	7.295	60.175	1.55E-3	11.19-j1.74
10.0	7.475	7.049	59.805	1.58E-3	10.87-j0.56

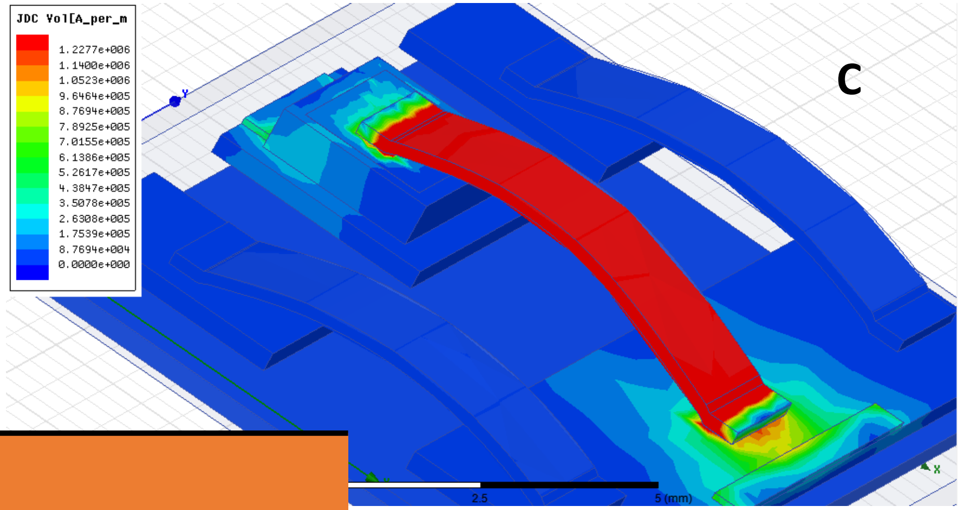
P = 145W
@ 100kHz, 10A excitation

Q3D Model Simulation Results

A. Parallel Ribbon Bond Conductors

B. Stacked Ribbon Bond Conductors

C. GCPW Ribbon Bond Conductor



Frequency (MHz)	Parasitic Resistance (mΩ)	Parasitic Inductance (nH)	Parasitic Capacitance (pF)	Parasitic Conductance (mSie)	Z_o (Ω)
1.0E-9 (DC)	0.486	4.435	14.801	1.58E-10	55280-j2584
0.1	0.723	3.412	14.701	3.93E-5	19.86-j12.22
0.5	1.150	3.121	14.622	0.238E-3	15.55-j4.83
1.0	1.474	3.019	14.588	0.487E-3	14.84-j3.17
10.0	3.872	2.929	14.471	4.97E-3	14.27-j0.69

P = 233W
@ 100kHz, 10A excitation

RF Model Simulation Results

A. Parallel Ribbon Bond Conductors
B. Stacked Ribbon Bond Conductors
C. GCPW Ribbon Bond Conductor

Case	z_L (Ω)	|Γ|	Γ angle (˚)	Γ	VSWR	S11 (dB)
A	0.232-j0.060	0.642	189.5	-0.633-j0.106	2.13	8.82
B	0.264-j0.124	0.597	195.5	-0.575-j0.160	2.34	7.98
C	0.397-j0.244	0.464	213.1	-0.389-j0.253	3.31	5.45

All cases analyzed at 100kHz

Case	z_L (Ω)	|Γ|	Γ angle (˚)	Γ	VSWR	S11 (dB)
A	0.221-j0.021	0.638	182.3	-0.637-j0.026	2.14	8.75
B	0.229-j0.051	0.632	186.1	-0.628-j0.067	2.17	8.60
C	0.311-j0.097	0.525	198.8	-0.497-j0.169	2.81	6.45

All cases analyzed at 500kHz

RF Model Simulation Results

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A. Parallel Ribbon Bond Conductors
B. Stacked Ribbon Bond Conductors
C. GCPW Ribbon Bond Conductor

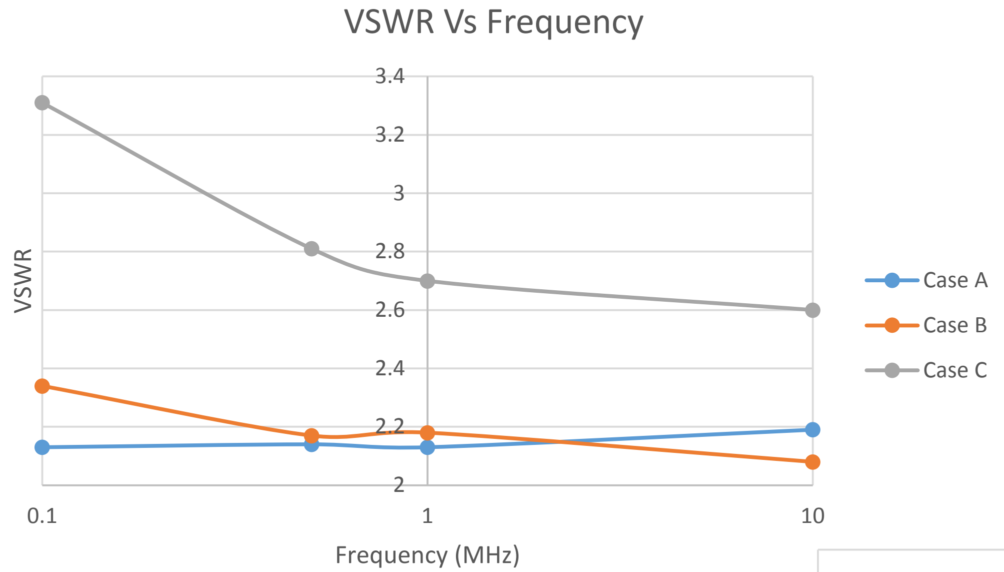
All cases analyzed at 1MHz

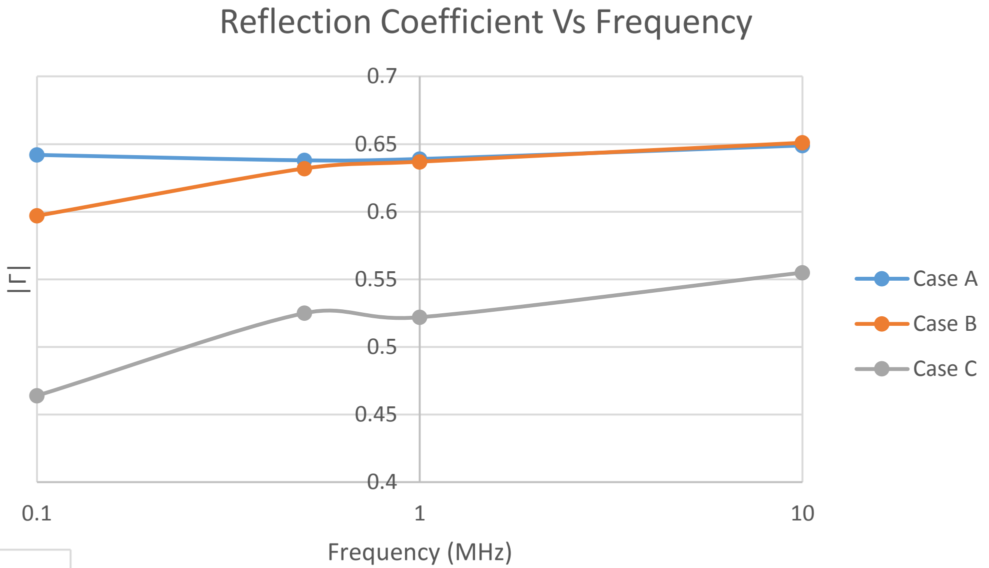
Case	z_L (Ω)	|Γ|	Γ angle (˚)	Γ	VSWR	S11 (dB)
A	0.220-j0.013	0.639	181.8	-0.639-j0.020	2.13	8.80
B	0.224-j0.035	0.637	184.0	-0.635-j0.044	2.18	8.65
C	0.297-j0.063	0.522	187.6	-0.517-j0.069	2.70	6.79

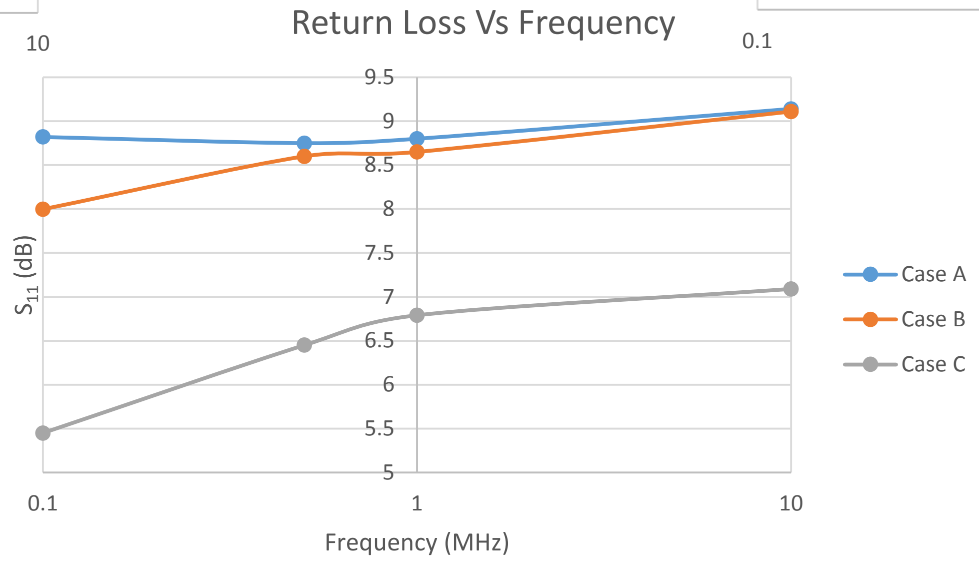
All cases analyzed at 10MHz

Case	z_L (Ω)	|Γ|	Γ angle (˚)	Γ	VSWR	S11 (dB)
A	0.218-j0.001	0.649	180.4	-0.649-j0.005	2.19	9.14
B	0.217-j0.011	0.651	181.9	-0.651-j0.022	2.08	9.11
C	0.285-j0.014	0.555	182.0	-0.555-j0.019	2.60	7.09

RF Model Simulation Results







Summary

- Specific configurations of ribbon bonds have potential of supporting TEM modes within power electronics and behave appropriately under higher operating frequencies
- The ability to understand a power module's characteristic impedance is valuable when attempting to reduce the reflection and insertion loss a module introduces into a power electronics circuit
- Power electronics packaging engineers will soon need to start thinking like RF packaging engineers as improvement in switching losses of WBG devices are reduced allowing for a greater push further into the RF operating range

Thank You