The Frequency Domain

Beyond Design

by Barry Olney, IN-CIRCUIT DESIGN PTY LTD / AUSTRALIA

As system performance requirements increase, the PCB designer's challenges become more complex. The impact of lower core voltages, higher frequencies, and faster edge rates has forced us into the frequency domain. At first, signal integrity (SI) can look quite daunting, but if we take the time to absorb the key concepts, then it is like visualizing a multilayer PCB from a different perspective. In this month's column, I look at the frequency domain.

Perhaps one of the most fundamental steps in the process of gaining proficiency in high-speed digital, RF, and microwave design is learning to think in the frequency domain. For most of us, the vast majority of our early experience with electrical circuits and signals remains within the context of voltages and currents that are either static or dynamic with respect to time.

Digital design, on the other hand, is a world of frequencies, so we need a different paradigm. The frequency domain can provide valuable insight to understand and master many SI effects, such as impedance, lossy transmission lines, and the power distribution network (PDN).

In the time domain, the system is evaluated according to the progression of its state with time. In the frequency domain, the system is analyzed according to its response for different frequencies. In a linear system, a transformation (usually Fourier transform) can convert the model into the frequency domain from the time domain. The system is changed from time to frequency to make it easy to understand the response of the system because the time domain is more complex for higher orders.

Put simply, a time-domain graph shows how a signal changes over time (Figure 1), whereas a frequency domain graph (Figure 2) shows how much of the signal lies within each given frequency band over a range of frequencies (bandwidth).

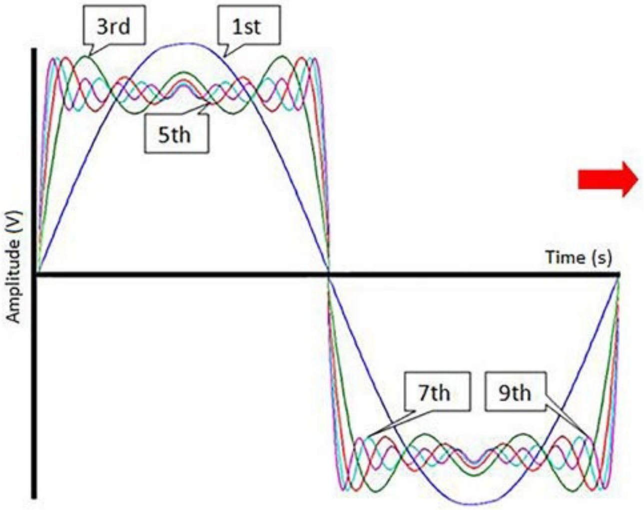

Figure 1: A square wave created by odd harmonics.

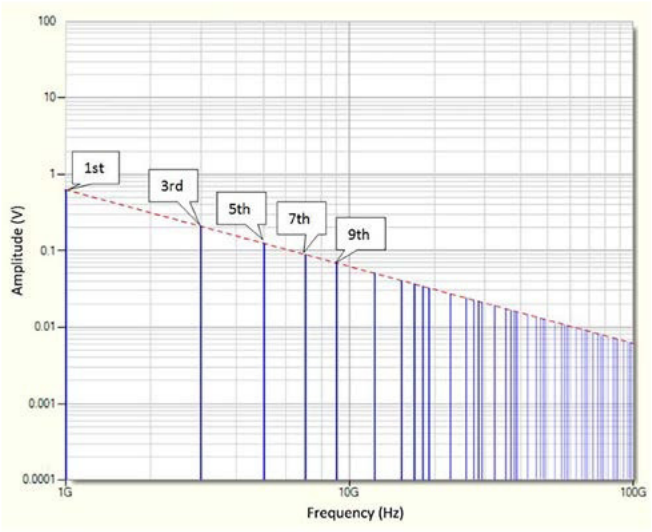

Figure 2: Frequency transform of a square wave.

The Fourier Theorem states that every function can be completely expressed as the sum of sine and cosine waves of various amplitudes and frequencies. The Fourier series expansion of a square wave is made up of a sum of harmonics. If the waveform has an even mark to space ratio, then the even harmonics cancel. Also, as the frequency increases, the amplitude decreases.

A square wave can be expressed as Equation 1:

Equation 1:

$$F(t) = \cos(\omega t) - \cos(3\omega t)/3 + \cos(5\omega t)/5 - \cos(7\omega t)/7 + \cos(9\omega t)/9$$

Any waveform in the time domain can be completely and uniquely described by a combination of sine waves. If we switch to the frequency domain and use sine wave descriptions, we can solve problems faster than in the time domain.

Impedance is defined in both the time and frequency domains. However, it is far easier to understand and apply the concepts of AC impedance in the frequency domain. Decoupling capacitors are spread throughout the PDN. Thinking in the time domain, you can say that decoupling capacitors store and supply charge on-demand to the loads. However, in the frequency domain, decoupling capacitors also lowers the impedance at different frequencies to help to meet the AC impedance target. So, there are two distinct functions of capacitors that work in unison but in different domains.

Further, when dealing with electromagnetic compatibility (EMC) issues, both FCC/CISPR specifications and methods of measuring the emissions of the product are more readily performed in the frequency domain.

The Fourier series expansion of a square wave is made up of a sum of harmonics. Figure 3 shows the conversion of a square wave from the time to the frequency domain and the resultant amplitudes of the frequency components. If the waveform has an even mark to space ratio, then the even harmonics cancel. The Zeroth harmonic is the DC value, and the fundamental (first harmonic) frequency is the largest in amplitude tapering off as the odd harmonic frequency increases. If the AC waveform is offset (from zero), then the DC voltage component will appear at DC (0 Hz).

The high-frequency content of a square wave is significantly affected by the rise time of the waveform. A fast rise time results in higher frequency components. Also, as the frequency increases, the amplitude decreases. In the real world, one needs to consider the maximum bandwidth of a signal, including harmonics, rather than assume the perfect square wave fundament frequency model. For example, a 200-MHz clock may have harmonics up to the fifth, meaning we need to consider the bandwidth up to 1 GHz.

Technology moves fast, and much has changed over the years since I have been in high-speed multilayer design, particularly advances in lithography that enable IC manufacturers to ship smaller and smaller dies on chips. In 1987 we thought that 0.5-micron technology was the ultimate, but today, 5-nm technology is at the cutting-edge. As of 2019, Samsung and TSMC have begun commercial production of 5-nm nodes.

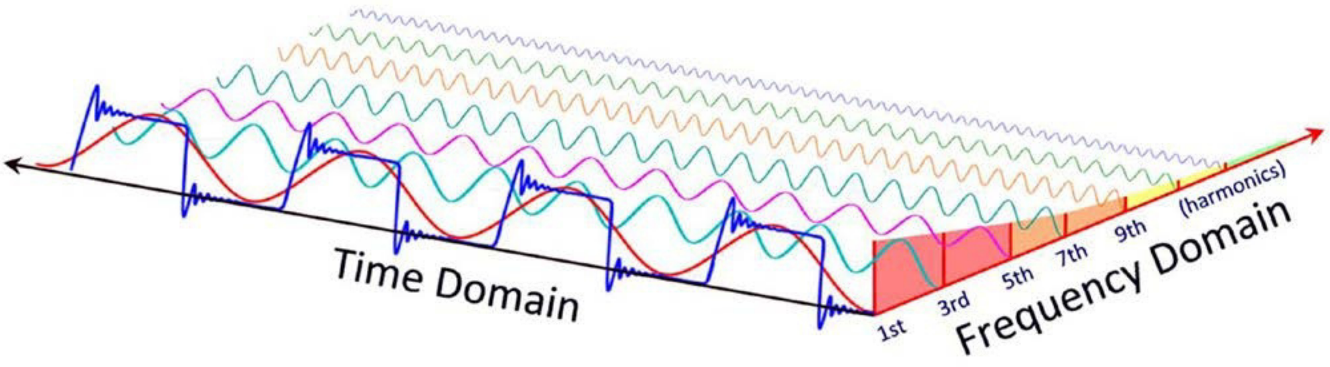

Figure 3: Harmonics of a square wave transformed from the time to the frequency domain.

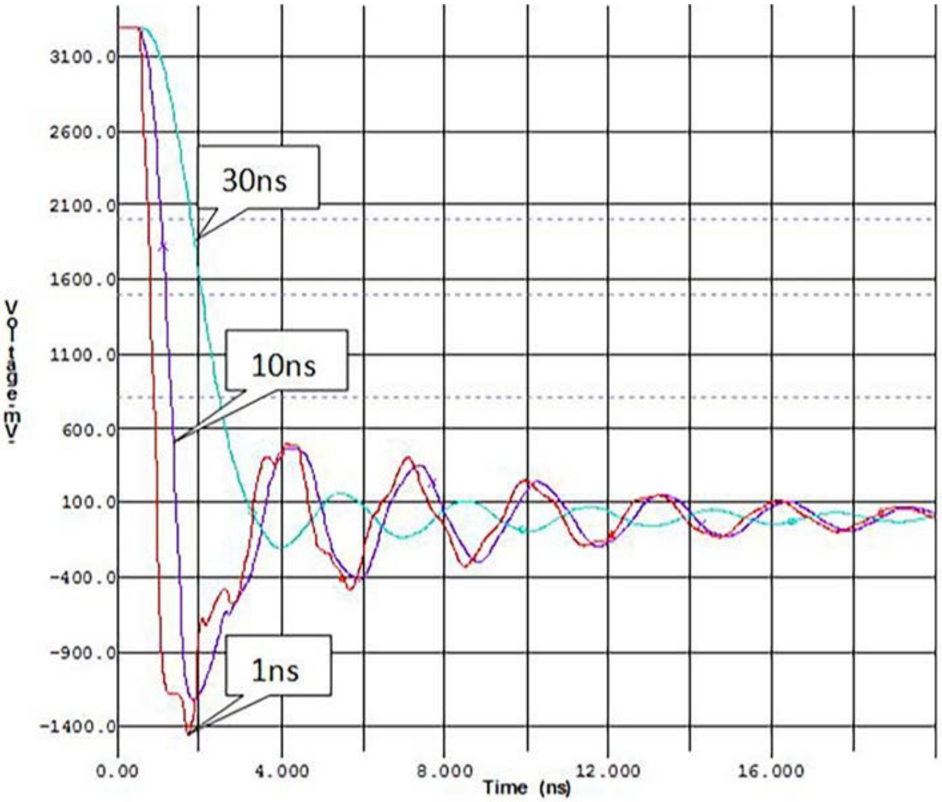

Figure 4: Edge rate changes in the time domain over the years (simulated in HyperLynx).

Power consumption in FPGAs has also become a primary factor for FPGA selection. Whether the concern is absolute power consumption, usable performance, battery life, thermal challenges, or reliability, power consumption is at the center of it all. To reduce power consumption, IC manufacturers have moved to lower core voltages and higher operating frequencies, which means faster edge rates, of course. And faster edge rates mean reflections and signal quality problems. The enhancements in driver edge rates have a significant impact on signal quality, timing, crosstalk, and EMC.

Figure 4 illustrates the change in edge rates over the years from 30 ns back in the early 1980s to less than 1 ns in 2010. Sub-nanosecond rise times are now common. For the same frequency and length trace, the faster edge rate creates ringing in the unterminated transmission line. This also has a direct impact on radiated emissions. Figure 5 shows the massive increase in emissions from the slowest to

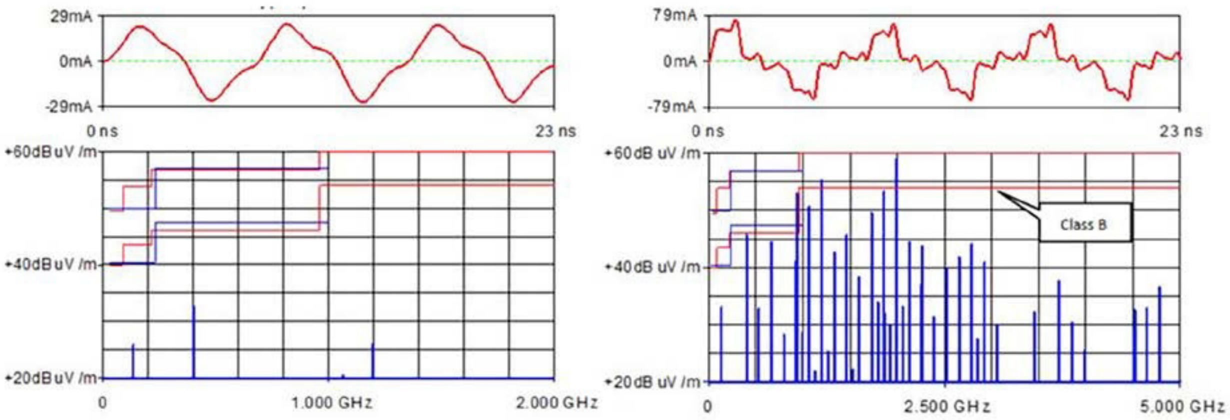

Figure 5: Radiated emissions in the frequency domain from 10 ns edge rate (L) and 1 ns (R).

the fastest rise time. When dealing with 1-ns rise times, the emissions can easily exceed the FCC/CISPR Class B limits for an unterminated transmission line.

At high frequencies, traces on a PCB act as a monopole or loop antennas. Unfortunately, the high-frequency components of the fundamental radiate more readily because their shorter wavelengths are comparable to trace lengths (particularly stubs), which act as antennas. Consequently, although the amplitude of the harmonic frequency components decreases as the frequency increase, the radiated frequency varies depending on the antennas/traces characteristics.

Computer-based products tend to radiate on the odd harmonics. High emissions are generally detected at the third, fifth, and sometimes seventh harmonic of the fundamental clock frequency. If this also occurs where the AC impedance of the PDN is high, then the radiation is projected even farther.

Being able to view a problem in the frequency domain is a powerful tool that provides another perspective that often reveals structure to a problem that isn't obvious in the time domain alone.

Key Points

- The frequency domain can provide valuable insight to understand and master many SI effects
- In the time domain, the system is evaluated according to the progression of its state with time; however, in the frequency domain, the system is analyzed according to its response for different frequencies
- The system is changed from time to frequency to make it easy to understand the response
- The Fourier series expansion of a square wave is made up of a sum of harmonics
- Impedance is defined in both the time and frequency domains; however, it is far easier to understand and apply the concepts of AC impedance in the frequency domain
- If the square wave has an even mark-to-space ratio, then the even harmonics cancel
- The high-frequency content of a square wave is significantly affected by the rise time of the waveform; a fast rise time results in higher-frequency components
- One needs to consider the maximum bandwidth of a signal, including harmonics, rather than assume the perfect square wave fundamental frequency model
- Power consumption in FPGAs has become a primary factor for FPGA selection
- To reduce power consumption, IC manufacturers have moved to lower core voltages and higher operating frequencies, which of course mean faster edge rates
- A faster edge rate creates ringing in the unterminated transmission line; this also has a direct impact on radiated emissions
- The high-frequency components of the fundamental radiate more readily because their shorter wavelengths are comparable to trace lengths (particularly stubs), which act as antennas

Further Reading

- B. Olney, "Beyond Design: When Do Traces Become Transmission Lines," *The PCB Design Magazine,* October 2017.
- B. Olney, "Beyond Design: Signal Integrity, Part 1," *The PCB Design Magazine,* October 2014.
- E. Bogatin, *Signal and Power Integrity: Simplified*, Prentice Hall, 2008. **DESIGN007**

Editor's Note: Figures 1 and 3 drawn by Barry Olney.

Barry Olney is managing director of In-Circuit Design Pty Ltd. (iCD), Australia, a PCB design service bureau that specializes in board-level simulation. The company developed the iCD Design Integrity software incorporating the iCD Stackup, PDN, and CPW Planner. The software can be downloaded www.icd.com.au. To read past columns or contact Olney, click here.

iCD Design Integrity

iCD Stackup Planner

- Precision 2D (BEM) field solver
- Controlled impedance analysis
- Relative signal propagation delay
- iCD Termination Planner
- iCD Materials planner
- Multiple differential technologies
- Heads-up impedance plots
- Dielectric Materials Library >33,000
- Interfaces to Allegro, Altium, Excel, HyperLynx, OrCAD, PADS, Xpedition, Zmetrix TDR, Zuken and IPC-2581B

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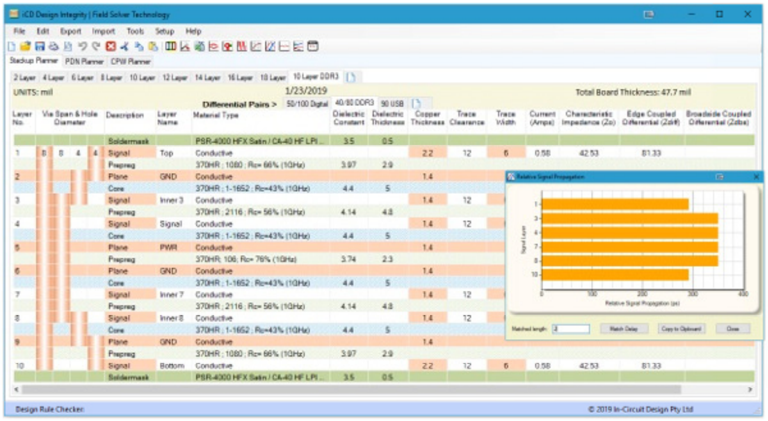

UNITS: mil

1/23/2019

Total Board Thickness: 47.7 mil

Layer No.	Via Span & Hole Diameter	Description	Layer Name	Material Type	Dielectric Constant	Dielectric Thickness	Copper Thickness	Trace Clearance	Trace Width	Current (Amps)	Characteristic Impedance (Zo)	Edge Coupled Differential (Zdiff)	Broadside Coupled Differential (Zdbs)
		Soldermask		PSR-4000 HFX Satin / CA-40 HF LPI ...	3.5	0.5							
1	8 8 4 4	Signal	Top	Conductive			2.2	12	6	0.58	42.53	81.33	
		Prepreg		370HR ; 1080 ; Rc= 66% (1GHz)	3.97	2.9							
2		Plane	GND	Conductive			1.4						
		Core		370HR ; 1-1652 ; Rc=43% (1GHz)	4.4	5							
3		Signal	Inner 3	Conductive			1.4	12					
		Prepreg		370HR ; 2116 ; Rc= 56% (1GHz)	4.14	4.8							
4		Signal	Signal	Conductive			1.4	12					
		Core		370HR ; 1-1652 ; Rc=43% (1GHz)	4.4	5							
5		Plane	PWR	Conductive			1.4						
		Prepreg		370HR; 106; Rc= 76% (1GHz)	3.74	2.3							
6		Plane	GND	Conductive			1.4						
		Core		370HR ; 1-1652 ; Rc=43% (1GHz)	4.4	5							
7		Signal	Inner 7	Conductive			1.4	12					
		Prepreg		370HR ; 2116 ; Rc= 56% (1GHz)	4.14	4.8							
8		Signal	Inner 8	Conductive			1.4	12					
		Core		370HR ; 1-1652 ; Rc=43% (1GHz)	4.4	5							
9		Plane	GND	Conductive			1.4						
		Prepreg		370HR ; 1080 ; Rc= 66% (1GHz)	3.97	2.9							
10		Signal	Bottom	Conductive			2.2	12	6	0.58	42.53	81.33	
		Soldermask		PSR-4000 HFX Satin / CA-40 HF LPI ...	3.5	0.5							

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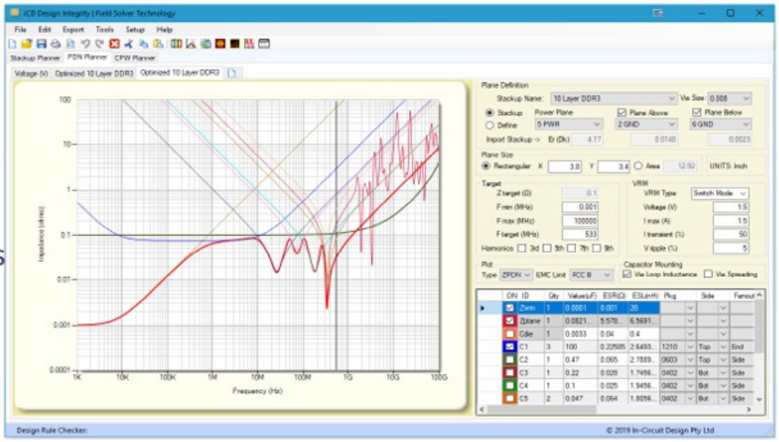
iCD PDN Planner

- AC impedance analysis with resonance
- Integration of stackup plane data
- Definition of voltage regulator, bypass/ decaps and mounting loop inductance
- PDN EMI Plot with FCC and CISPR Limits
- Extensive Capacitor Library >5,650
- Capacitor S-Parameter model import

Analyze multiple power supplies to maintain low impedance over entire frequency range dramatically improving product performance



Plane Definition

Stackup Name: 10 Layer DDR3

Via Size: 0.008

● Stackup ○ Define

Power Plane: 5 PWR

☑ Plane Above: 2 GND

☑ Plane Below: 6 GND

Import Stackup -> Er (Dk) 4.17 0.0148 0.0023

Plane Size

● Rectangular X 3.8 Y 3.4 ○ Area 12.92

UNITS: Inch

Target

Z target (Ω) 0.1

F min (MHz) 0.001

F max (MHz) 100000

F target (MHz) 533

Harmonics ☐ 3rd ☐ 5th ☐ 7th ☐ 9th

VRM

VRM Type: Switch Mode

Voltage (V) 1.5

I max (A) 1.5

I transient (%) 50

V ripple (%) 5

Plot

Type ZPDN

EMC Limit FCC B

Capacitor Mounting

☑ Via Loop Inductance ☐ Via Spreading

ON	ID	Qty	Value(uF)	ESR(Ω)	ESL(nH)	Pkg	Side	Fanout
☑	Zvrm	1	0.0001	0.001	20			
☑	Zplane	1	0.0821...	5.578...	6.5691...			
☐	Cdie	1	0.0033	0.04	0.4			
☑	C1	3	100	0.22505	2.6493...	1210	Top	End
☐	C2	1	0.47	0.065	2.7889...	0603	Top	Side
☐	C3	1	0.22	0.028	1.7456...	0402	Bot	Side
☐	C4	1	0.1	0.025	1.9456...	0402	Bot	Side
☐	C5	2	0.047	0.064	1.8056...	0402	Bot	Side

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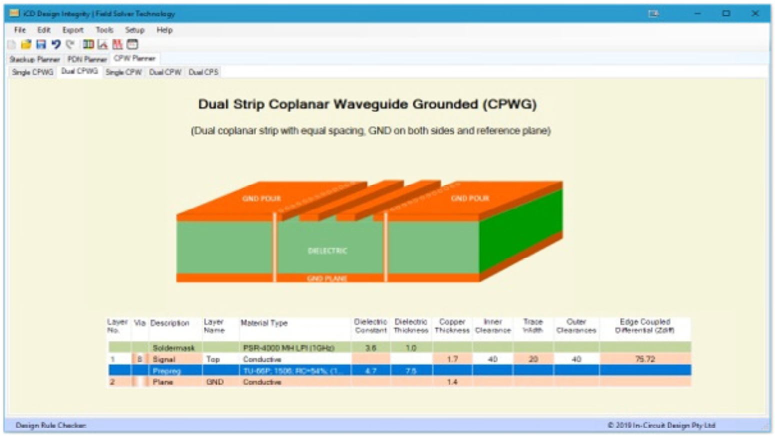
iCD CPW Planner

- Reduces radiation loss
- Fast Coplanar Waveguide analysis
- Model single and dual (differential) CPWs plus a dual Coplanar Strip (CPS)
- Characteristic impedance and edge-coupled differential impedance
- Optional Dielectric Materials Library

Model microstrip Coplanar Waveguides to reduce radiation loss, of high-speed serial links, significantly improving product performance



Dual Strip Coplanar Waveguide Grounded (CPWG)

(Dual coplanar strip with equal spacing, GND on both sides and reference plane)

Layer No.	Via	Description	Layer Name	Material Type	Dielectric Constant	Dielectric Thickness	Copper Thickness	Inner Clearance	Trace Width	Outer Clearances	Edge Coupled Differential (Zdiff)
		Soldermask		PSR-4000 MH LPI (1GHz)	3.6	1.0					
1	8	Signal	Top	Conductive			1.7	40	20	40	75.72
		Prepreg		TU-66P: 1506: RC=54% (1...	4.7	7.5					
2		Plane	GND	Conductive			1.4				

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