

A VIEW OF ELECTROMAGNETIC LIFE ABOVE 100 MHz

An Experimentalist's Intuitive Approach

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BACKGROUND

- **Interest in Electromagnetic life above 100 MHz has increased dramatically in the past decade.**
 - ◆ **Digital Electronics,**
 - ◆ **Telecommunications.**
- **Many simplifying assumptions are no longer true.**
- **Signal Integrity is a significant issue above 100 MHz and EMC engineers must often deal with it.**
- **For some, this frequency range is new territory, but change is part of working in electromagnetics**

PURPOSE/OBJECTIVE

- To present an intuitive approach, based on simple and correct physics, to understanding electromagnetic problems that arise at frequencies above 100 MHz
- This intuitive approach comes from the point of view of an experimentalist rather than from one who specializes in computations
- Experiments determine what are good assumptions
- Objective is to understand how electromagnetic waves interact with the system and determine the tall poles in the electromagnetic “tent”

OVERVIEW (1)

- **Background**
- **Purpose/Objective**
- **“Audio” rectification. Not everything is new and different.**
- **The importance of dimensions. The long and the short of it.**
- **Electrical reactionaries rule. The importance of inductance and capacitance, particularly parasitics.**
- **The importance of being small. If you can't do it correctly, do it quickly.**
- **Life becomes absorbing up here.**
- **The radiating personalities of moving electrons.**

OVERVIEW (2)

- **Dispersion/Absorption.** Some adverse effects can reduce culprit signals.
- **Keep those signals straight.** The importance of skew or timing is everything.
- **The world as a collection of transmission lines.**
- **The Wave Twins: Sound and Light.**
The acoustic/electromagnetic wave analogy.
- **Clock Pulses vs Random Pulses**
- **Measurement Difficulties**
- **Conclusions**

“Audio” Rectification

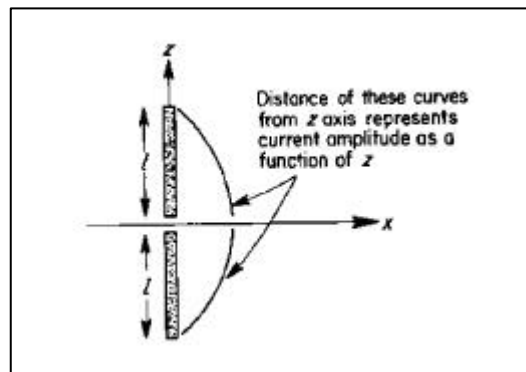
Not Everything is New and Different

- “Audio” Rectification occurs in EMC problems involving high level (>0.7 V) amplitude modulated culprit signals.
- Semiconductors become non-linear and rectify the signal
- New Culprit signal is modulation envelope
 - ◆ generally a low frequency waveform
- EMC analysis can be performed on rectified waveform
- “Audio” rectification can cause EMC problems even if culprit frequency is outside frequency range of system under analysis
 - ◆ Culprit signal gets into and overloads the circuits

The Importance of Dimensions

The long and the short of it

- Above 100 MHz, most systems or portions of them, will become efficient antennae or resonators
 - ◆ Half or Quarter wave antennae
 - ◆ Radiating and Receiving
- Antenna modes are defined by electrical discontinuities
 - ◆ Low or High Impedance Mismatch



Wavelength

- In order to determine if system is electrically large, and requires more sophisticated treatment, look at the system dimensions in terms of wavelength

$$\lambda = v/f$$

where v = propagation velocity ($v = c = 3 \times 10^8$ in air,
 $v = c/(e_r)^{1/2} = 2 \times 10^8$ in plastic)

- Remember to consider the slower propagation velocity when the wave is in a dielectric like cable insulation

Electrical Reactionaries Rule (1)

The Importance of Parasitic Inductance

- Little things mean a lot
 - ◆ particularly if they are parasitics
- Parasitics are capacitances and inductances that are present in the real world but are not on the circuit diagram
- The world is about 1 mH/m or about 25 nH/inch
 - ◆ Corresponds to 300 W transmission line in air
- Impedance of Total Inductance is proportional to frequency
 - ◆ $Z = j\omega L$ or $|Z| = 2\pi f L$
- Total Inductance, $L = L_{\text{pul}} \times \text{length}$, where L_{pul} is the Inductance per unit length

Electrical Reactionaries Rule (2)

The Importance of Parasitic Capacitance

- **Capacitance is proportional to area, inversely proportional to separation**
 - ◆ **$C = \epsilon_0 \epsilon_r A/d$**
 - **where ϵ_0 is permittivity of free space (8.84×10^{-12} F/m), ϵ_r is the relative dielectric constant, area of plate, and d is separation distance.**
- **Plane separation in circuit board is about 0.18 mm (0.007”), ϵ_r of FR4 is about 4.2, therefore capacitance is about 0.21 pF/mm² (1 mm = 0.040”)**

Examples of Parasitic Impedance

<u>Frequency</u>	<u>Impedance of 1 cm Loop,</u> L = 10 nH	<u>Impedance of 2.5 mm² pad</u> C = 0.52 pF
0.1 GHz	6.3 W	3090 W
1 GHz	63 W	309 W
10 GHz	630 W	30.9 W

Components are Not What They Seem

- Discrete capacitors, resistors and inductors may act entirely different than expected because parasitic reactances become more important than rated values above 100 MHz
 - ◆ Many capacitors are inductive and/or resistive above 150 MHz
 - ◆ Feedthrough Configuration tends to be better
 - ◆ Resistors become inductive because of length
 - ◆ End-to-End capacitance of inductors is sometimes a problem
 - ◆ Winding capacitance of transformers significantly changes their characteristics
- Measure critical components to avoid surprises

Calculation of Inductance and Capacitance from Characteristic Impedance

- If Characteristic Impedance is known from measurements, handbook calculations or top-of-the-head estimates, per unit length inductance and capacitance can be derived

- $Z_0 = (L/C)^{1/2}$ $v = (LC)^{-1/2}$

- $L = Z_0/v$ $C = 1/vZ_0$

The Importance of Being Small/Short

- The smaller something is, the smaller is its effect on impedance (self and radiation) and the less electromagnetic effect it has
- Capacitance and Inductance of transmission lines is distributed and only becomes apparent if line is mismatched
- In practice, gradual transitions, particularly unbalanced to balanced or vice versa, seem to be worse than abrupt discontinuities
 - ◆ Probably because they are longer
- ***If You Can't Do it Correctly, Do it Quickly***

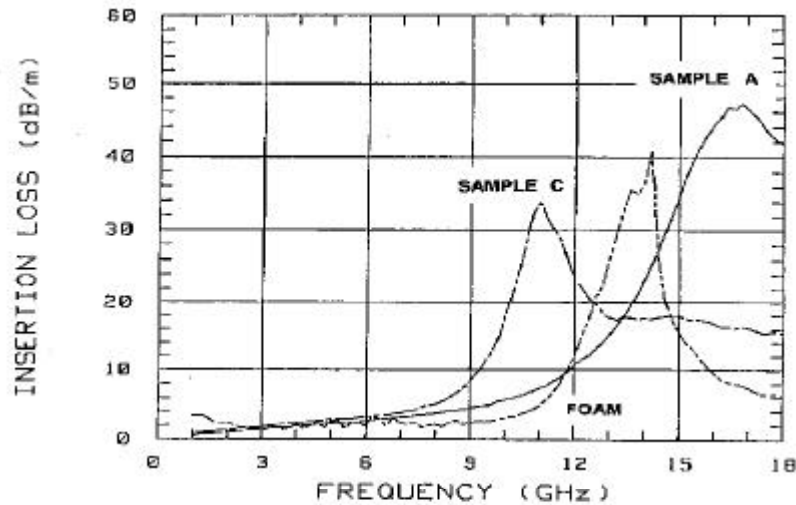
Life Becomes Absorbing Up Here

Fast = Hot

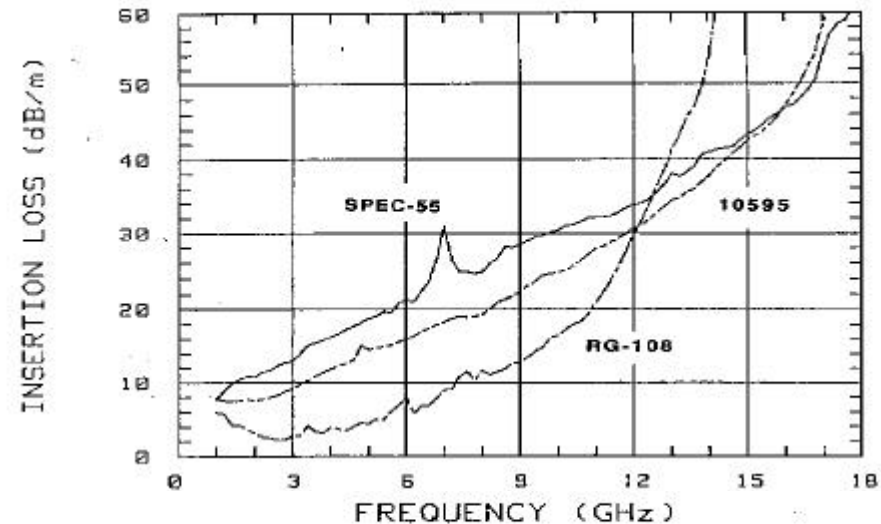
- A major difference between Low Frequency (< 100 MHz) and High Frequency (> 100 MHz) effects is the presence of absorption at high frequencies
- Cable and PCB trace (well shielded) attenuation:
 - $a = (8.686/2) (R/Z_o + GZ_o)$ dB/m
 - **Skin Effect Loss**
 - ◆ $R = (f\mu_o/\sigma)^{1/2} (1/d + 1/D)$
- **Dielectric Loss**
 - ◆ $G = \omega C \tan \delta = \omega C$ (power factor)
- Above a few hundred MHz, dielectric loss is increasingly important
- Typical cable attenuation is 0.3 - 3 dB/GHz*m
- Electrical energy is converted into heat

Attenuation by Radiation

- Leakage through apertures in cable and enclosure shields is also a loss
 - ◆ Looks like a radiation resistance



Insertion Loss of Coaxial Cables with Single Braid Shields



Insertion Loss of Aerospace Cables with Single Braid Shields

Absorption and Shielding Effectiveness

- Absorption increases apparent shielding effectiveness of cables and enclosures
- Shielding effectiveness of enclosure depends on losses inside of enclosure when enclosure is electrically large

The Radiating Personalities of Moving Electrons

- Above 100 MHz, most structures are good antennae
 - ◆ Therefore they scatter and radiate energy
- The greater the rate of change of the voltage/current, the more they radiate
- Radiating energy becomes apparent as a radiation impedance
 - ◆ Increases with frequency, sometimes as frequency squared or faster
 - ◆ For elemental antenna
$$R_{\text{radiation}} = 789 \left(\text{length} / \lambda \right)^2 = 789 \lambda^2 f^2 / c^2$$
- Radiated energy is lost energy
 - ◆ Looks like a resistor

Dispersion/Absorption

Some Adverse Effects Can Reduce Culprit Signals

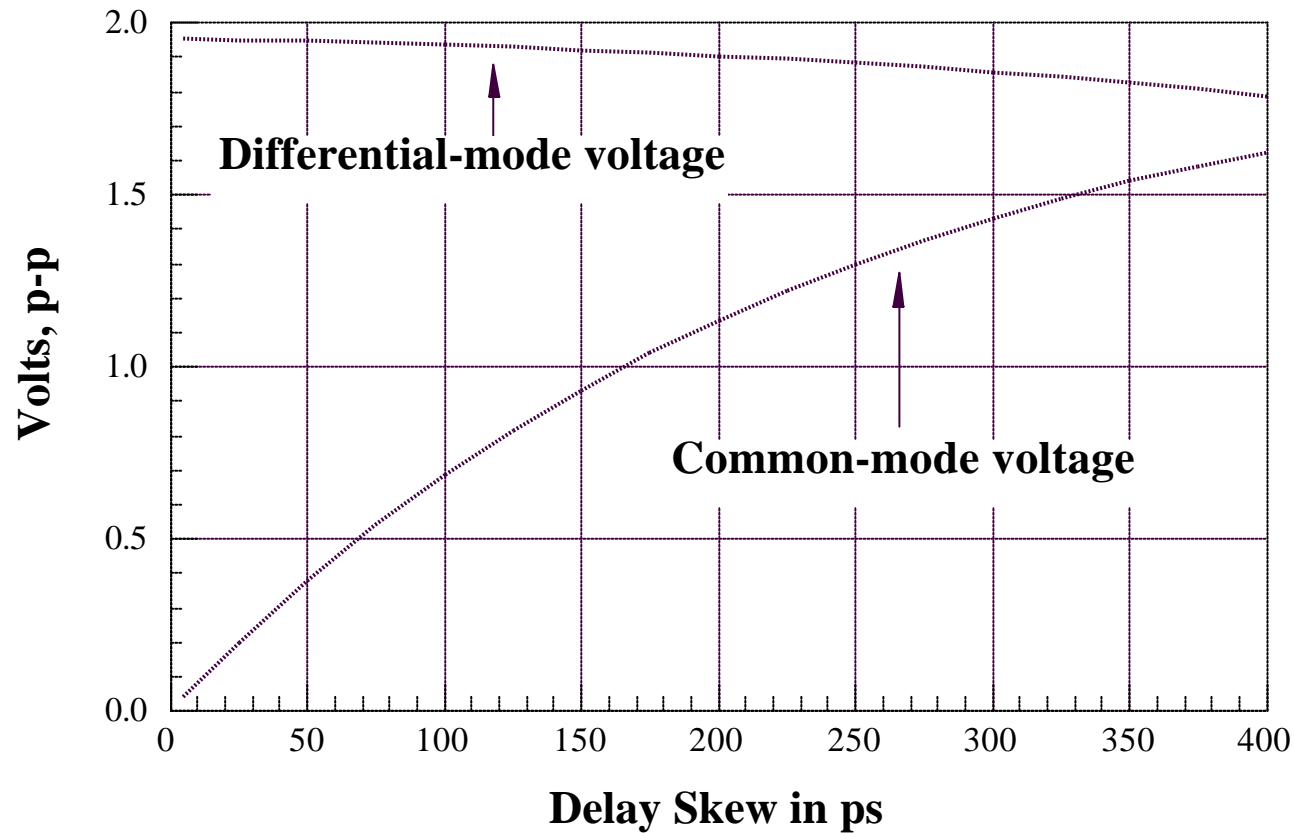
- Dispersion is the change of propagation velocity with frequency
- If high frequencies are faster than low frequencies, pulse is sharpened--Rare
- If high frequencies are slower than low frequencies, pulse is spread out
 - ◆ Total charge or energy may remain the same
 - ◆ Peak amplitude is reduced

Keep Those Signals Straight

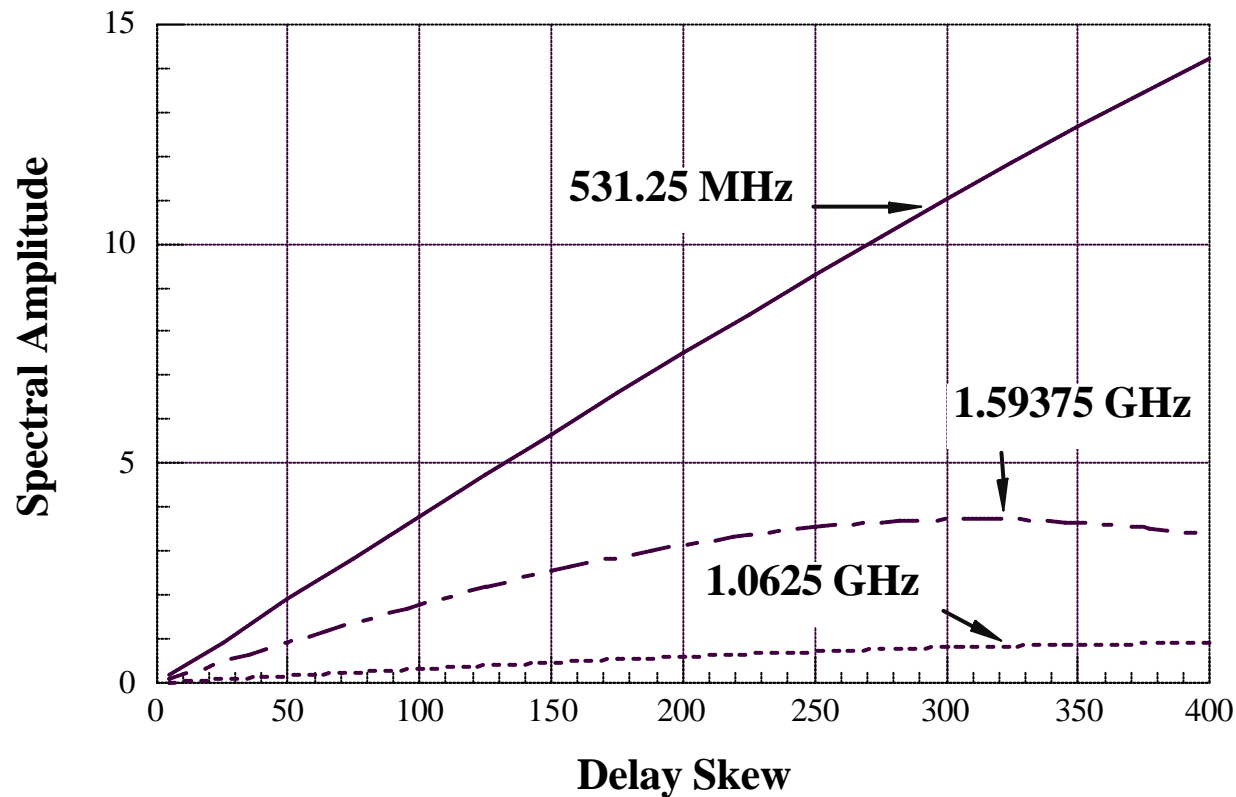
The Importance of Skew, or Timing is Everything

- **Differential Signaling is often used above 100 MHz**
 - ◆ **Decreases EMI problems if balance is good and skew is minimal**
 - ◆ **Improved S/N because signal can be 2x supply voltage**
- **Perfect Differential signals should not radiate**
- **If signals are skewed, a common mode current results which can radiate and cause EMI problems**

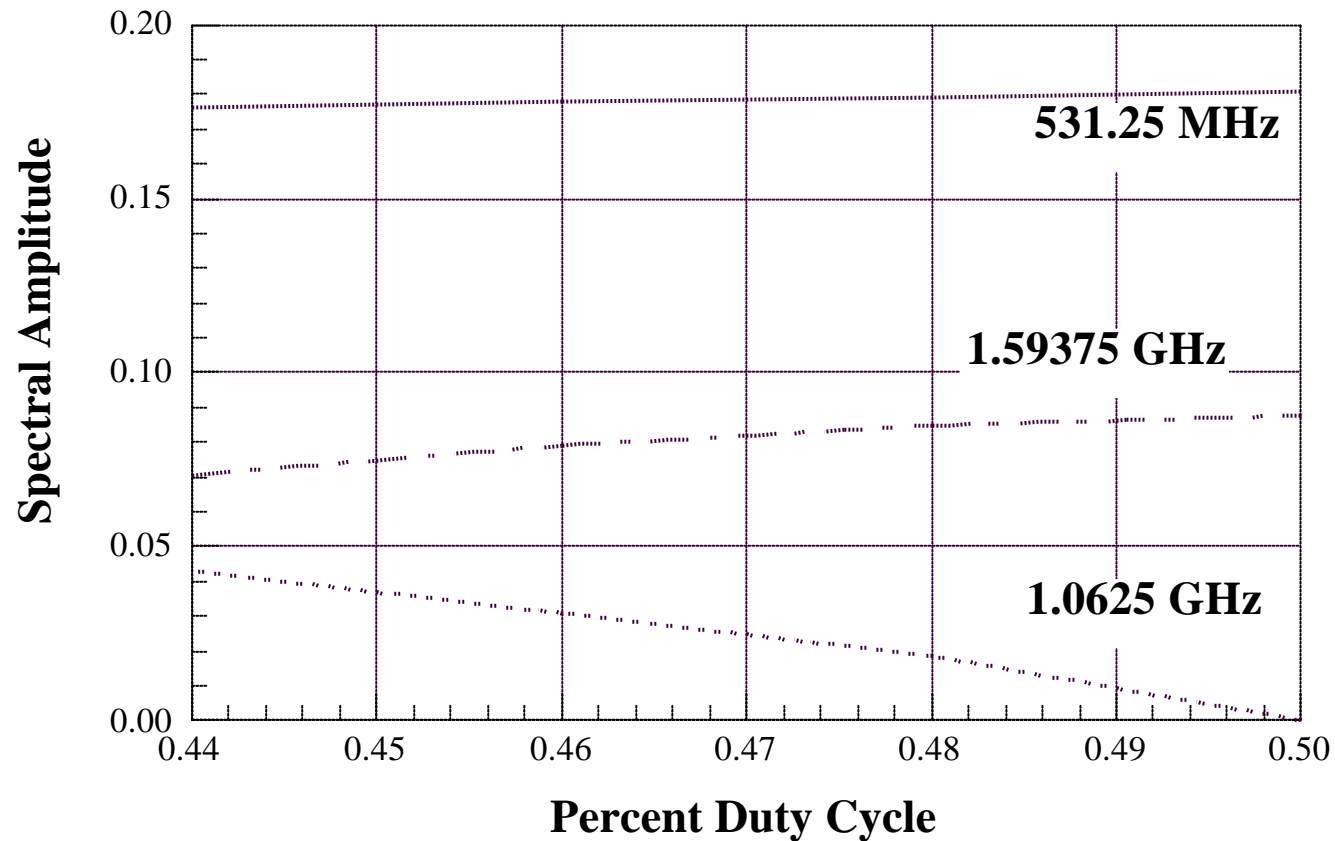
Effect of Skew on Common Mode Signal, 1.064 Gb/s Differential Signal



Effect of Skew on Common Mode Signal, 1.064 Gb/s Differential Signal



Effect of Skew on Common Mode Signal, 1.064 Gb/s Differential Signal



The World as a Collection of Transmission Lines

- Low Frequency analysis uses lumped parameter models
 - ◆ Usually inappropriate when wavelength approaches dimensions of structure
- Transmission Line representation valid at both low and high frequencies
- If lossless transmission line is matched at both ends:
 - ◆ Broad Band--Theoretically no frequency dependence
 - ◆ Signal is 1/2 source voltage
- If $Z_L < Z_0$, Input is inductive after 2 transit times
 - ◆ If $Z_L = 0$, $Z_{in} = j \tan \beta d$, $\beta = 2\pi f/v$
- If $Z_L > Z_0$, Input is capacitive after 2 transit times
 - ◆ If $Z_L = \text{Open}$, $Z_{in} = j / \tan \beta d$

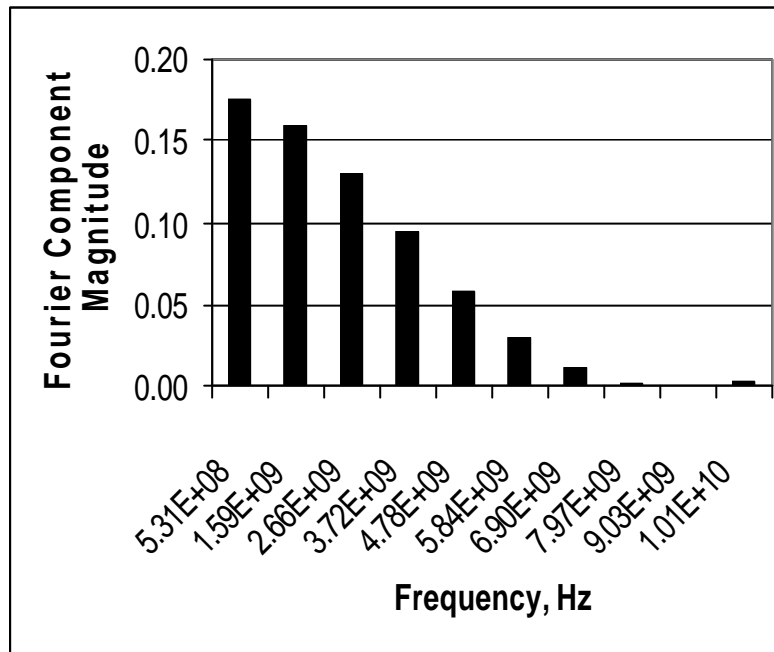
The Wave Twins: Sound and Light

The Acoustic/Electromagnetic Wave Analogy

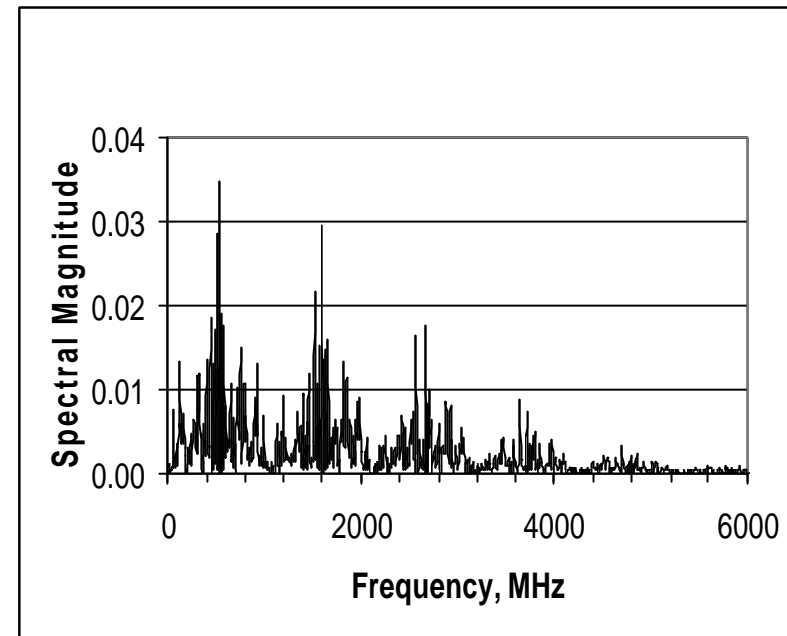
- **Acoustical and Electromagnetic waves are obviously different:**
 - ◆ Acoustical is longitudinal--pressure and particle velocity
 - ◆ Electromagnetic is transverse--voltage and current
 - ◆ Propagation velocities are different by factor of 3×10^5
- **Both have wave properties**
 - ◆ Scattering, diffusion and propagation are similar except corresponding frequency ranges are different :
1 kHz \longleftrightarrow 300 MHz
- **Both use Reverberant/Anechoic Chambers, Transmission Lines and similar mathematical treatments**
- **The analogy sometimes helps the engineer to visualize the microwave problem**

Clock Pulses vs Random Pulses

1 Gb/s



Spectrum of Ideal Clock Pulses



Spectrum of Quasi-Random Pulses

Measurement Difficulties

- **Bandwidth Limitations of Instruments--\$\$\$\$**
- **Probe/Test Fixture Limitations**
 - ◆ **Parasitic Capacitance and Inductance**
 - ◆ **Loading of Circuit Under Test**
 - ◆ **Impedance discontinuities**
 - ◆ **Standing waves in test fixture and instrumentation**
 - ◆ **Series resistance sometimes helps**
- **Measuring current is sometimes desirable**
- **Keep things as small as possible**
- **Care, Care, Care**
- **Patience, Patience, Patience**
- **Try to perform sanity check**

Conclusions

- **The intuitive approach to electromagnetic life above 100 MHz allows the engineer to visualize the system as a collection of components whose characteristics can be estimated, or if necessary, measured**
- **Effects, such as parasitic effects, absorption, radiation losses and wavelength effects become more significant above 100 MHz, but are reasonably well understood**