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)

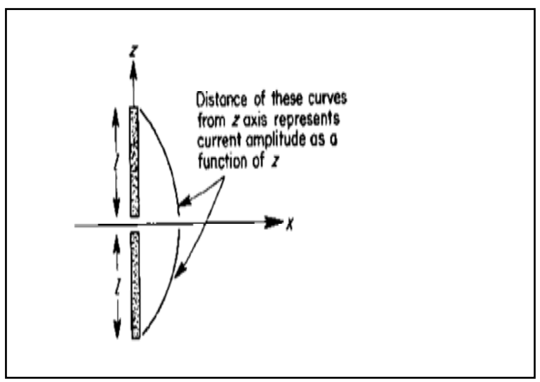
- **Dispersion/Absorption. Some adverse effects can reduce culprit signals.**
- **Keep those signals straight. The importance of skew or timing is everything.**
- **The world as a collection of transmission lines.**
- **The Wave Twins: Sound and Light.**
  The acoustic/electromagnetic wave analogy.
- **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, $v = c/(\varepsilon_r)^{1/2} = 2 \times 10^8$ 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 μH/m or about 25 nH/inch**
  - **Corresponds to 300 Ω transmission line in air**
- **Impedance of Total Inductance is proportional to frequency**
  - $Z = j\,\omega L$ **or** $|Z| = 2\pi f L$
- **Total Inductance,** $L = L_{pul} \times$ **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**
  - **$C = \varepsilon_o \varepsilon_r A/d$**
    - **where ε_o 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/mm^2 (1 mm = 0.040")**

Examples of Parasitic Impedance

Frequency	Impedance of 1 cm Loop, L = 10 nH	Impedance of 2.5 mm^2 pad C = 0.52 pF
0.1 GHz	6.3 Ω	3090 Ω
1 GHz	63 Ω	309 Ω
10 GHz	630 Ω	30.9 Ω

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

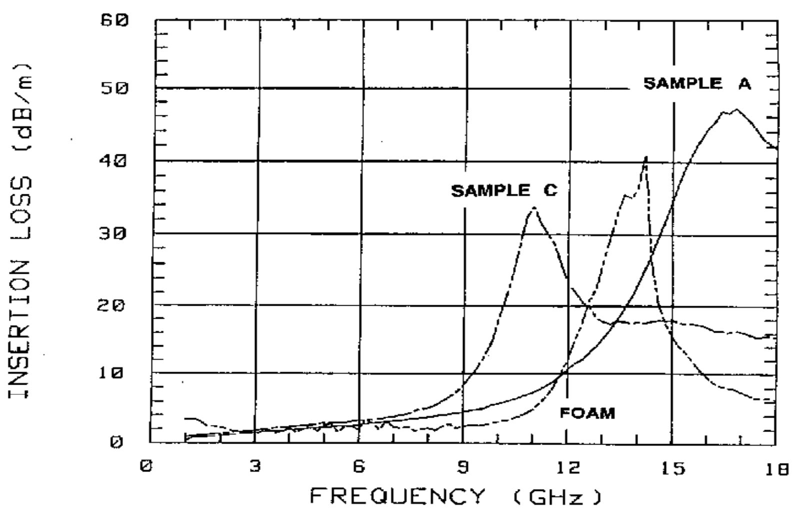
- The smaller something is, the smaller is its effect on impedance (self and radiation) and the less electromagnetic effect it has
- Capacitance and Inductance of transmission lines is distributed and only becomes apparent if line is mismatched
- In practice, gradual transitions, particularly unbalanced 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

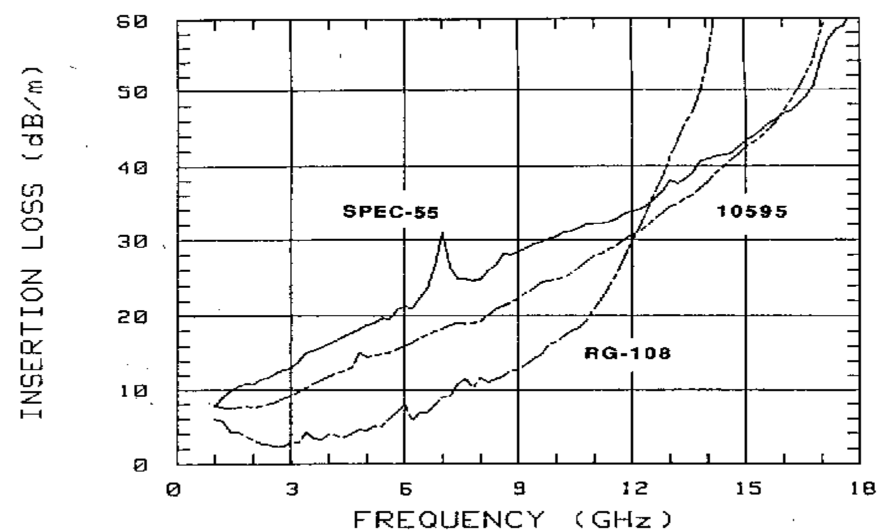
- A major difference between Low Frequency (< 100 MHz) and High Frequency (> 100 MHz) effects is the presence of absorption at high frequencies
- Cable and PCB trace (well shielded) attenuation:
  - $\alpha = (8.686/2)\,(R/Z_o + GZ_o)$ dB/m
- Skin Effect Loss
  - $R = (f\mu_o/\sigma\pi)^{1/2}\,(1/d + 1/D)$
- Dielectric Loss
  - $G = \omega C \tan\phi = \omega C$ (power factor)
- Above a few hundred MHz, dielectric loss is increasingly important
- <u>Typical cable attenuation is 0.3 - 3 dB/GHz*m</u>
- 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
    $R_{radiation} = 789 \, (\text{length} / \lambda)^2 = 789 \, l^2 f^2 / c^2$
- 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**

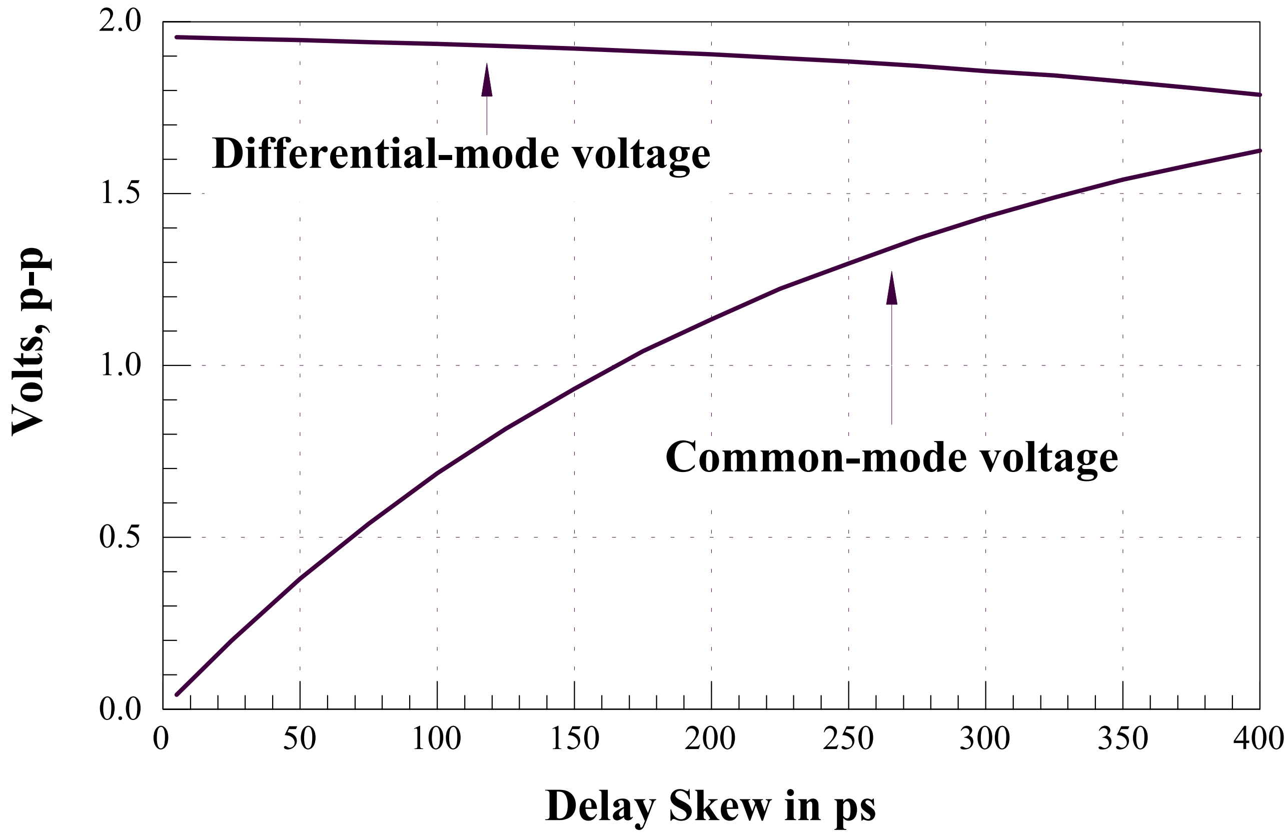
Keep Those Signals Straight
The Importance of Skew, or Timing is Everything

- **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



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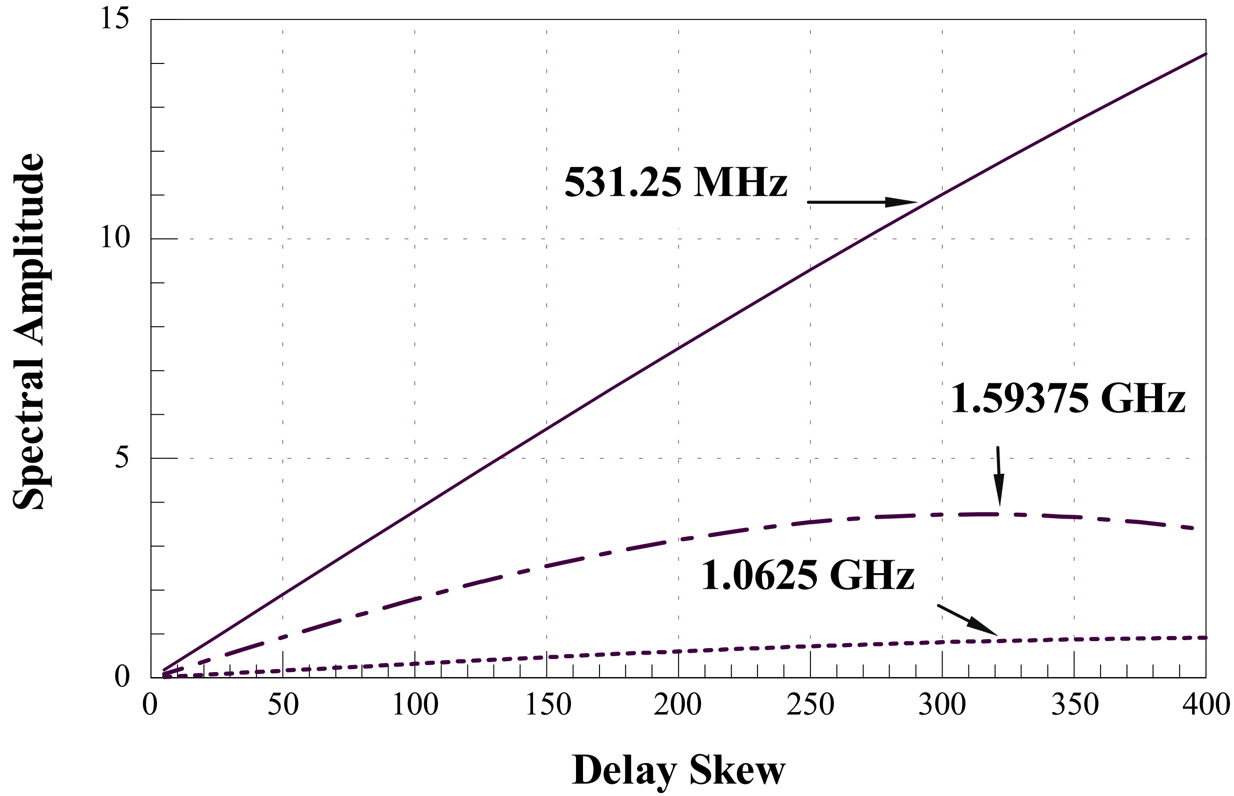
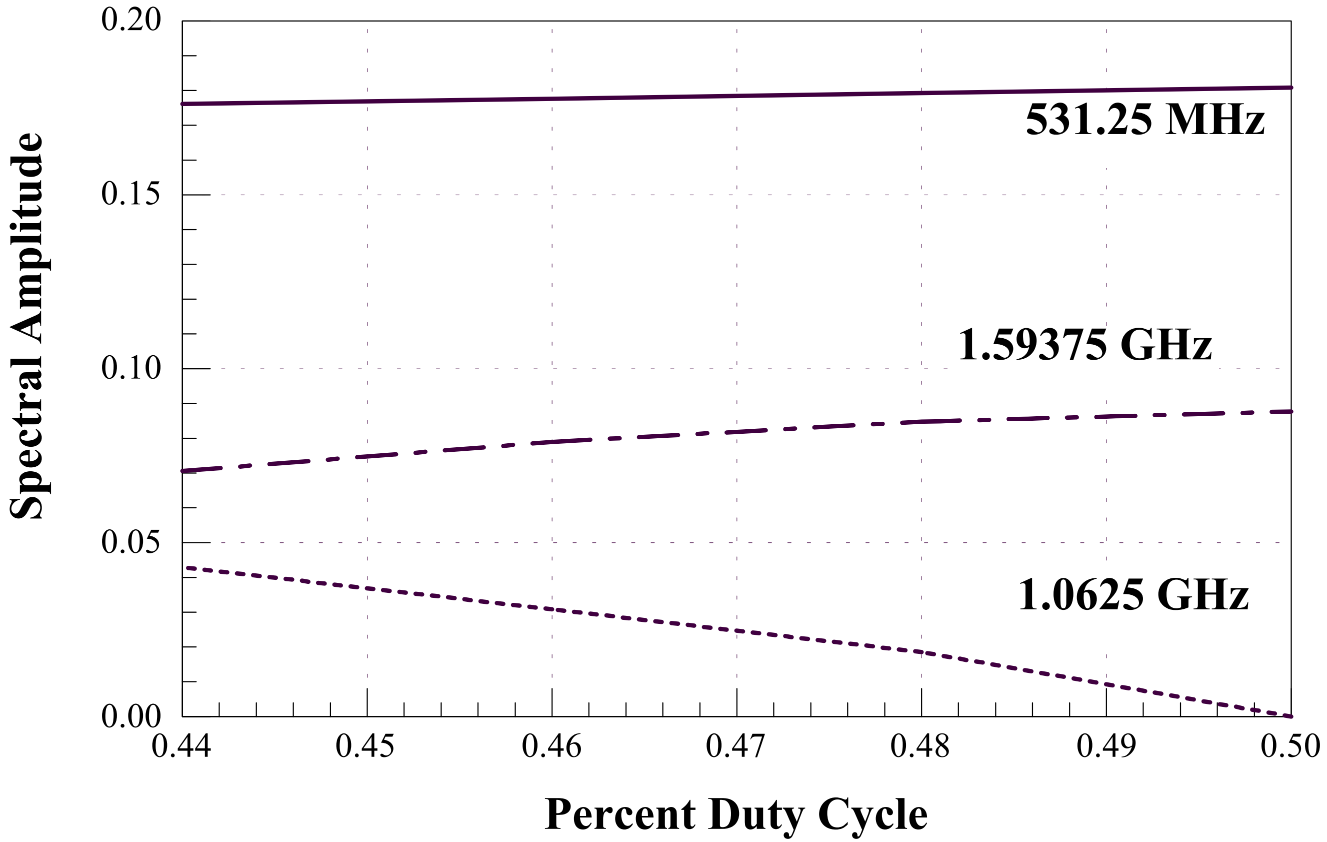


Effect of Skew on Common Mode Signal, 1.064 Gb/s Differential Signal



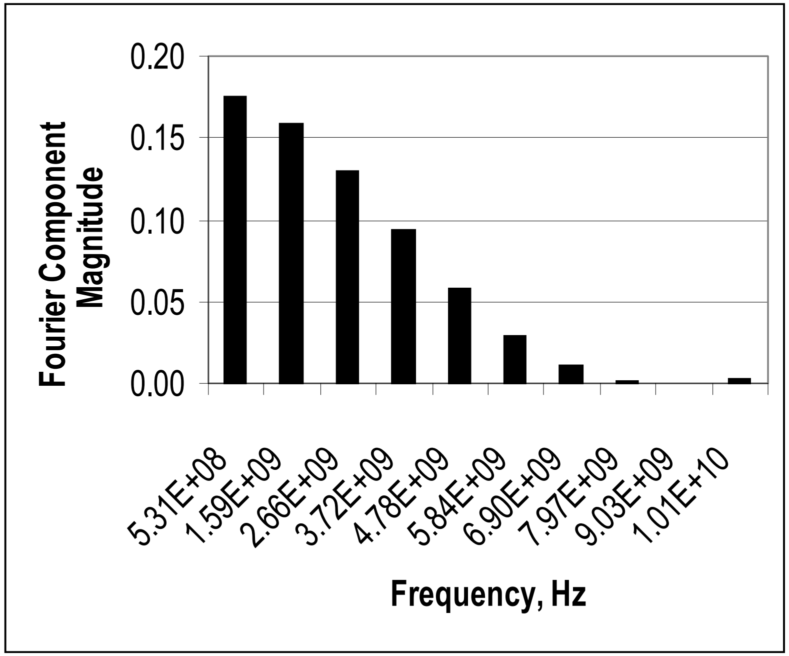
The World as a Collection of Transmission Lines

- **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 = Open, $Z_{in} = j / \tan \beta d$**

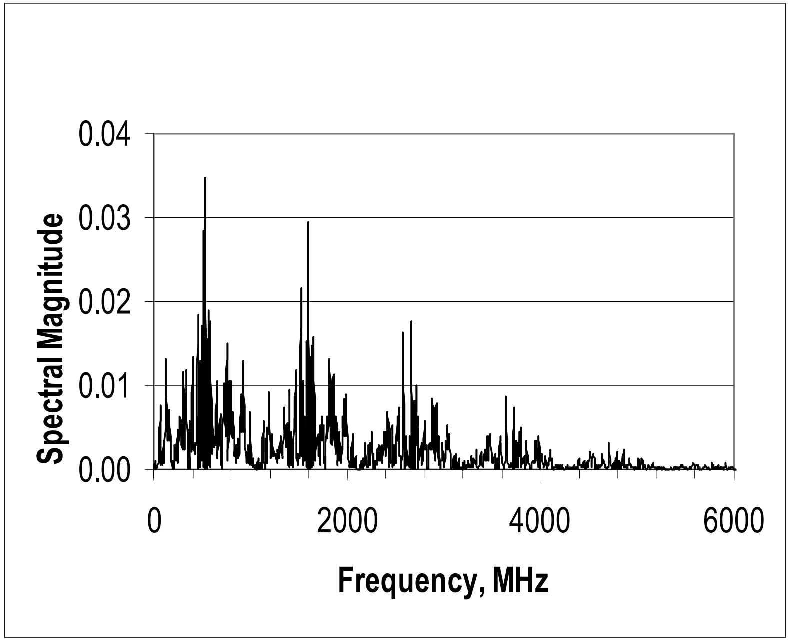
The Wave Twins: Sound and Light
The Acoustic/Electromagnetic Wave Analogy

- **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 ⟷ 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 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