Qualified S-parameter

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Outline

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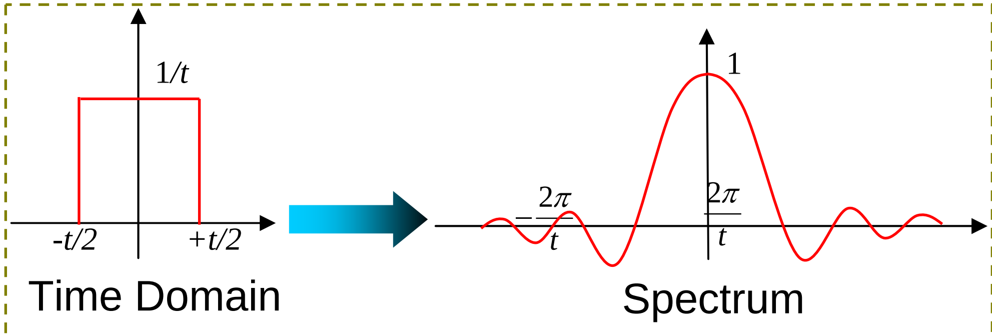
Introduction

- S-parameter is widely used to describe the property of modern electronic and electrical interconnects.
- S-parameter is obtained by either simulation or measurement.
- S-parameter from simulation or measurement may not perfect that would lead to incorrect results.
- How engineers guarantee the goodness of S-parameter of passive interconnects?

Frequency Band

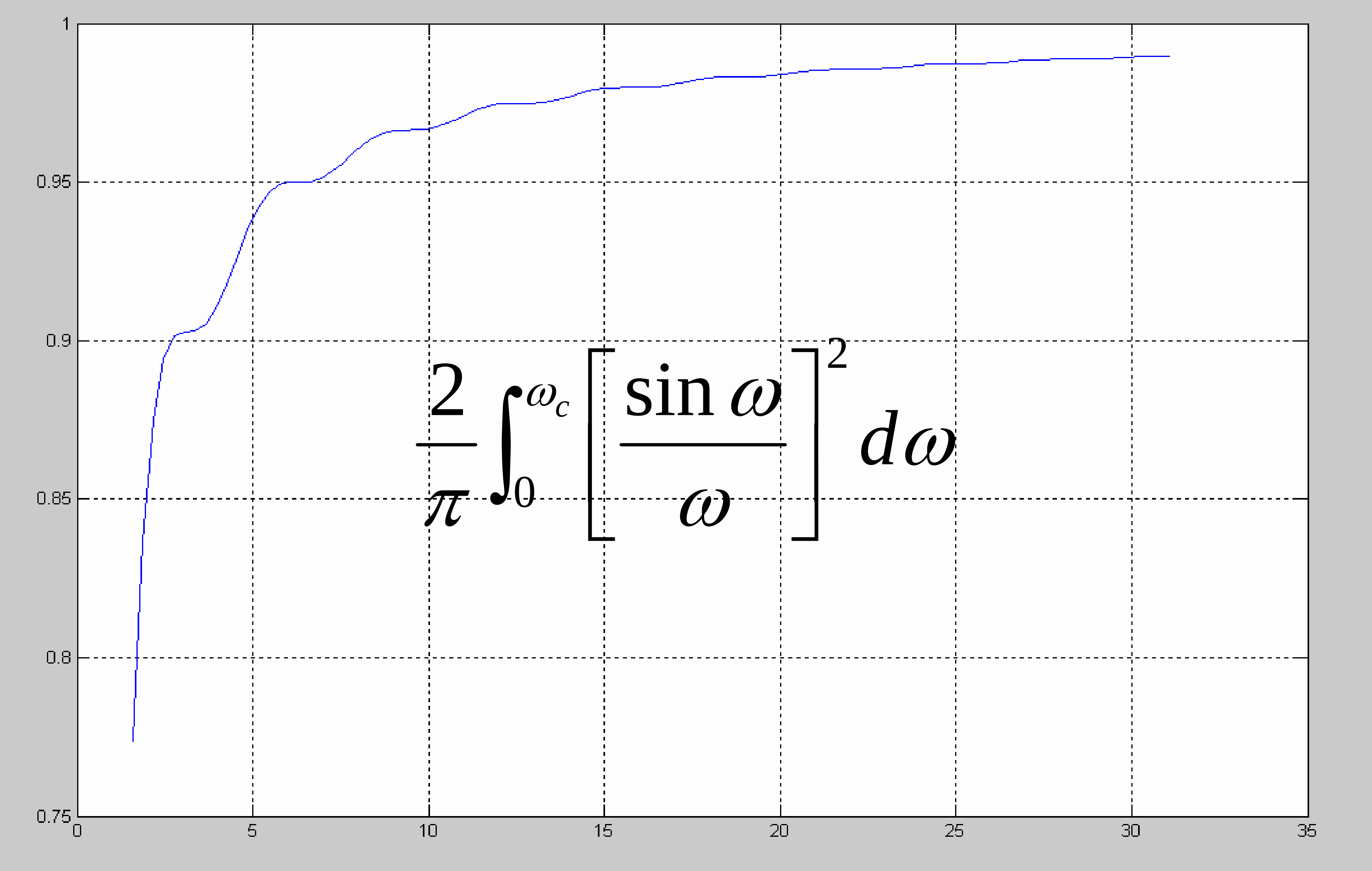
- Look at a window function. Window function can approximate to a single binary bit.
- The spectrum of the window function is SINC function, and can be used to "guess" the frequency band.
- SINC function shows DC or low frequency information cannot be neglected.



$$\frac{2}{\pi}\int_0^{n\pi}\mathrm{sinc}^2(x)\,dx = \begin{cases}90.28\% & n=1\\ 94.99\% & n=2\\ 96.64\% & n=3\end{cases}$$

- **Start from DC**
  - Sometimes engineers intentionally or accidentally missed the DC and/or low frequency information.
  - S-parameter down to DC has no direct definition by classical wave theory, but can be defined with nodal voltage and current by circuit theory. Some SPICE solvers would extrapolate or "guess" the S-parameter to DC with built-in methods.
  - The extrapolation may change the useable frequency band, consequently leading to possible incorrect outputs such as
    - Incorrect DC IR Drop value or
    - Incorrect Timing Results

SINC function



Frequency Band (con't)

- **The stop frequency should be high enough to cover the relevant frequency content of signal after passing through the channel.**
- **The knee frequency is used intensively in digital systems and described by**

$$f_{knee} = K/T_r$$

  - ***K* = 0.35** Corresponding to the 10%~90% rising edge time
  - ***K* = 0.50** is also used in literatures, corresponding to slightly wider frequency band
  - ***K*** can be greater than 0.5 and will be more accurate, but not necessary.

Frequency Resolution

- **Choice of frequency resolution should consider the following problems**
  - Time domain resolution
  - Enough to reflect and locate each "pole" and "zero" of S-parameters
  - Enough to reflect the exact slope of S-parameters
- **Recall the transmission of typical copper-based microstrip line (low loss):**
  - Phase of S-parameter: $\arg S = \theta = \beta l \approx 2\pi f \sqrt{LC} l$
  - Magnitude of S-parameter: $\mathrm{mag} S = e^{-\alpha l} \approx -\alpha l$
  - Obviously, it is reasonable to choose a constant frequency step.
- **Then with which the exact step will prefer to be used?**
  - 50MHz can be a good empirical constant for most cases.
  - This value as resolution not only makes a fine resolution in time domain, but captures the exact "poles" and "zeros" and the slope of S-parameters.
  - Some finer (less than 50MHz) or coarser (greater than 50MHz) values may be possibly reasonable, but engineers must make a reasonable tradeoff.

Passivity

- Passive devices can only dissipate or temporarily store energy, but never generate it. This relationship is expressed by S-parameter as follows

$$[a_i]^{t*}[a_i]-[b_i]^{t*}[b_i]\geq 0$$

- Rewritten as

$$[a_i]^{t*}[a_i]-[a_i]^{t*}[S]^{t*}[S][a_i]$$
$$=[a_i]^{t*}\left(U-[S]^{t*}[S]\right)[a_i]\geq 0$$

- So the passivity is expressed as

$$U-[S]^{t*}[S]\geq 0$$

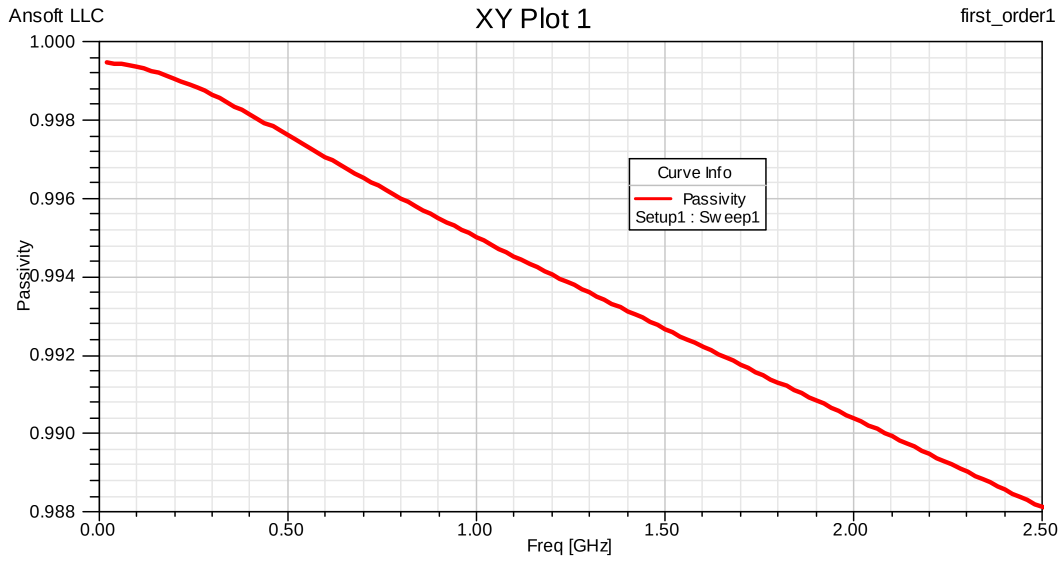
Where *S* is the S-parameter matrix and *U* an identity matrix

- The formula above drops a hint that the eigenvalues λ of $[S]^{t*}[S]$ should be between 0 and 1.

$$0\leq \lambda_i \leq 1$$

Passivity

- **When export S-parameter from HFSS or SIwave, it is recommended to check out the enforcing-passivity function.**
- **With HFSS, passivity can be directly plotted in report window.**



- In SPICE simulators, passivity can be set by options

Causality

- A causal system is defined by its impulse response

$$h(t-\tau)=0 \qquad t<\tau$$

- That is a linear time-invariant system cannot precede its excitation.

- Causality can be tested by performing the Hilbert transform of real part and ensuring that it is identical to the imaginary part (also known as the Kramers-Kroning relation)

$$\mathrm{Re}\left[S_{ij}(f)\right]\otimes\frac{1}{\pi f}=\mathrm{Im}\left[S_{ij}(f)\right]$$

Causality (con't)

- Because of this relation, knowledge of the real part is sufficient to completely specify the system, and the imaginary part is "redundant" information. Thus, a possible check for system causality is to compare the imaginary part of the frequency response with the Hilbert transform of the real part.
  - In order to recover or reconstruct the imaginary part from the real part requires the knowledge of the real part of the transfer function over all frequencies.
  - The real part can also similarly be recovered from the imaginary part due to Hilbert consistency between real and imaginary parts.

Causality (con't)

- **When the S-parameter data has a low top frequency compared to the frequency content of the input signal, different simulators would extrapolate additional data into the raw S-parameter with their built-in methods**

  - Some macro-models (such as rational-function based vector-fitting method) give a natural extrapolation function, which is also causal.

  - Convolution-based simulators generally provide simple constant, linear, or windowing extrapolation functions. Such simple extrapolation functions are not causal, and therefore can give erroneous transient results.

Causality (con't)

- **Three criteria needs to be satisfied to avoid causality violation**
  - The phase delay has to be larger than the minimum signal delay
  - The group delay has to be larger than minimum signal delay and
  - The time-domain impulse response has to be zero before any stimulus
- **Some measures to possibly avoid causality risk**
  - Be careful of dielectric materials with constant ε_r and $\tan\delta$
    - Actually do not use the constant materials.
    - It is recommended use of practical frequency-dependent model:
      1. Djordjevic-Sarkar model (preferred)
      2. Debye model
  - Make enough frequency bandwidth and enough frequency points
  - Be ware of simulation tools used

Reciprocity

- For passive channels without non-reciprocal element (like ferrite) the S-parameters show reciprocity

$$S_{ij} = S_{ji} \quad i \neq j$$

- In practical simulation and measurement, the discrepancy of phase and magnitude between reciprocal elements should be kept within acceptable threshold value.

- In most cases, lower frequency means small discrepancy and higher frequency less accuracy. [2] reports 0.05dB in magnitude and 0.1 degree in phase for frequency lower than 5GHz.

Others

- Reality

$$S(-f) = S^*(f)$$

- Noise
  - Simulation: Inescapable numerical error.
  - Measurement: Introduced by VNA dynamic range

Reference

1. *Advanced Signal Integrity for High-Speed Digital Designs*, Stephen H. Hall, Howard L. Heck

2. *Using S-parameters Successfully in Time-Domain Link Simulation*, Dierk Kaller, Christian Schuster, Young Kwark, Dulce Altabella, Bao Truong, Zhaoqing Chen, Anand Haridass, Erich Klink, IEEE 2005

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if any problem☺