A Hybrid Electromagnetic Bandgap (EBG) Power Plane with Discrete Inductors for Broadband Noise Suppression

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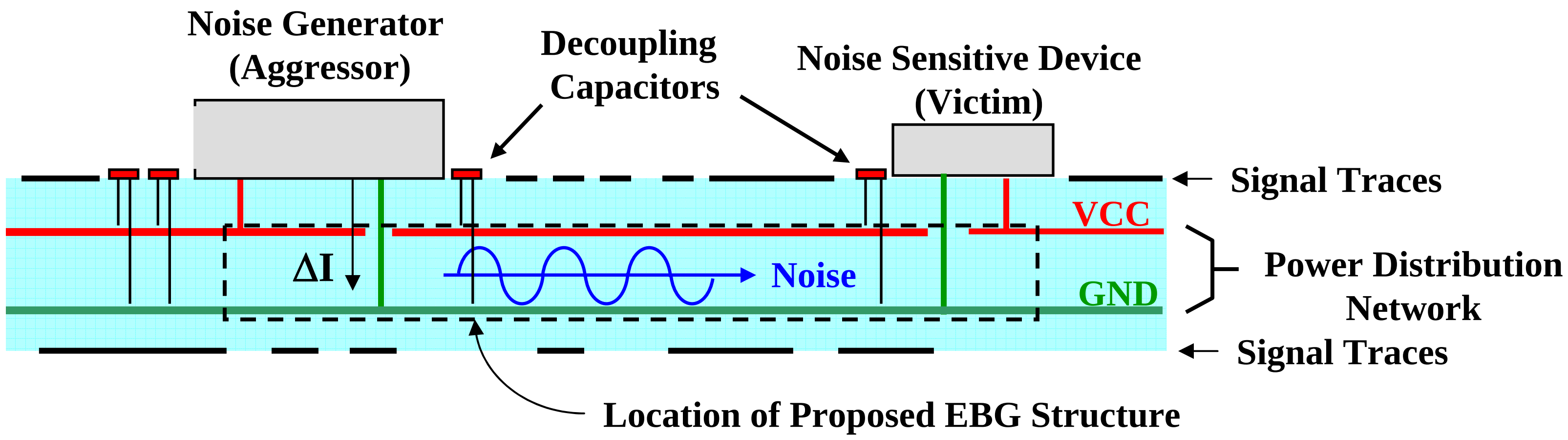
Outline

- Purpose and Applications of Hybrid EBG Structures
- Motivation for an Improved EBG Structure
- Background – What is a Hybrid EBG Structure?
- Hybrid EBG Structure Using Discrete Inductors
  - Prototype Hardware
  - S Parameter Measurements
  - 1D Dispersion Equation
  - Formulas for Cutoff Frequency
  - Impedance Parameter Measurements
- Conclusions

Purpose:
Suppression of Conducted Noise at the Board or Package Level



Applications:

1. To protect RF receivers in mobile systems from de-sensing when sharing power planes with digital processors – must filter to the μV level.

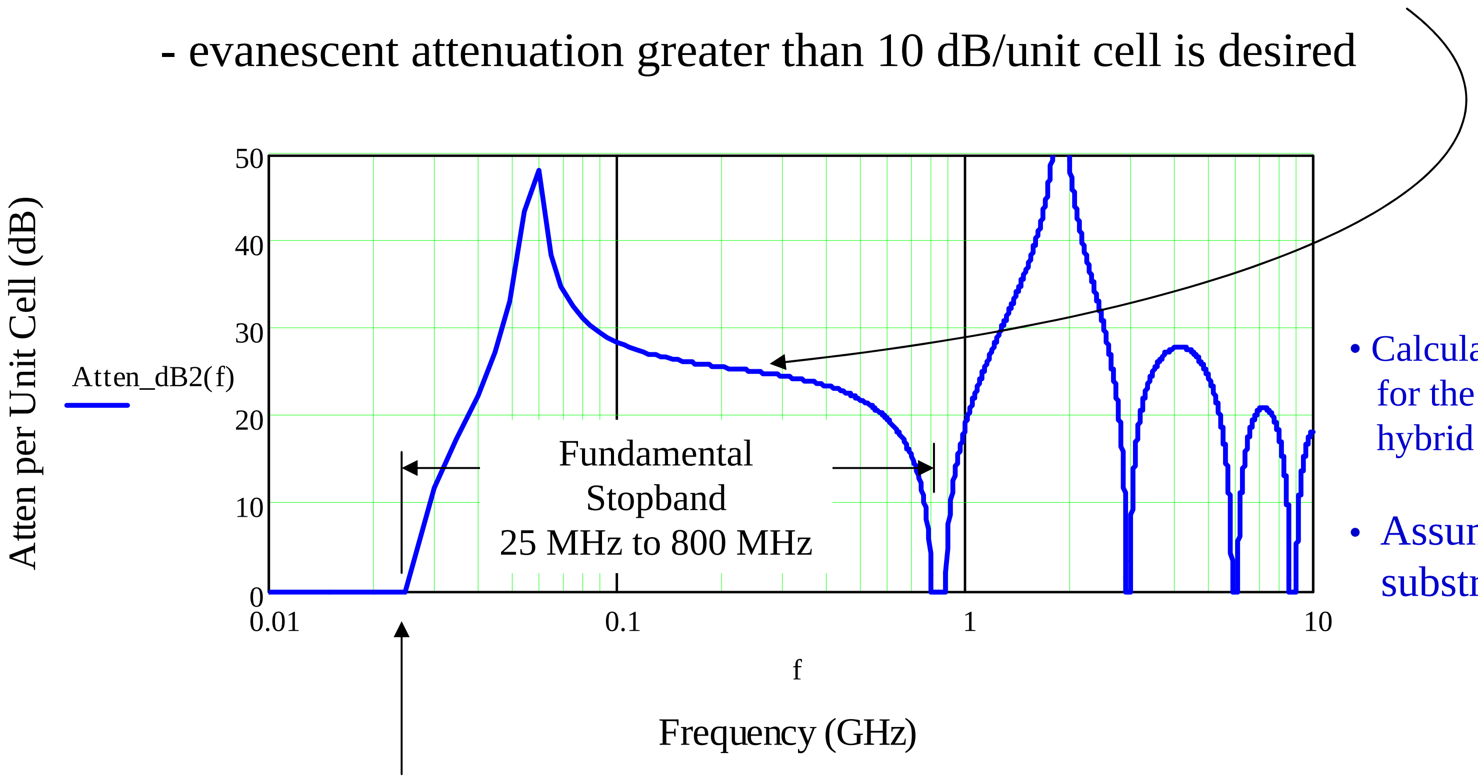
2. To improve noise immunity for analog-to-digital (ADC) converters.

3. To protect low voltage digital devices with small noise margins from false logic states, e.g. memories.

Motivation for a Better EBG Structure

1. To increase the attenuation per unit cell for the fundamental stopband

- evanescent attenuation greater than 10 dB/unit cell is desired



- Calculated attenuation for the prototype hybrid EBG structure
- Assumes no substrate losses

2. To decrease the lower band edge frequency of the fundamental stopband

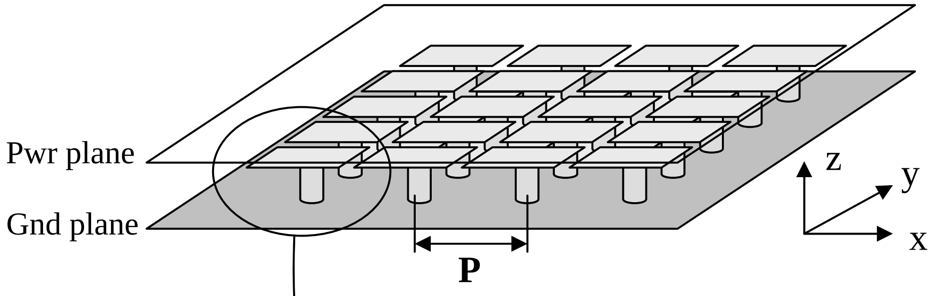
- a cutoff frequency of less than 100 MHz is desired

3. To increase the bandwidth ratio of the fundamental stopband beyond a decade.

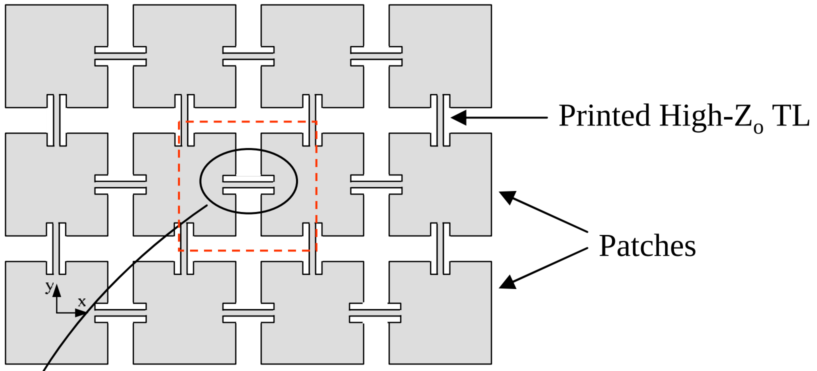
Background: What is a Hybrid EBG Structure?

Ref: Will McKinzie, *2006 IEEE EPEP Conf.*, Oct 23-25, 2006, Scottsdale, AZ, pp. 51-54

Arrays of Resonant Vias: Periodic array of vias exists between the power and ground planes.

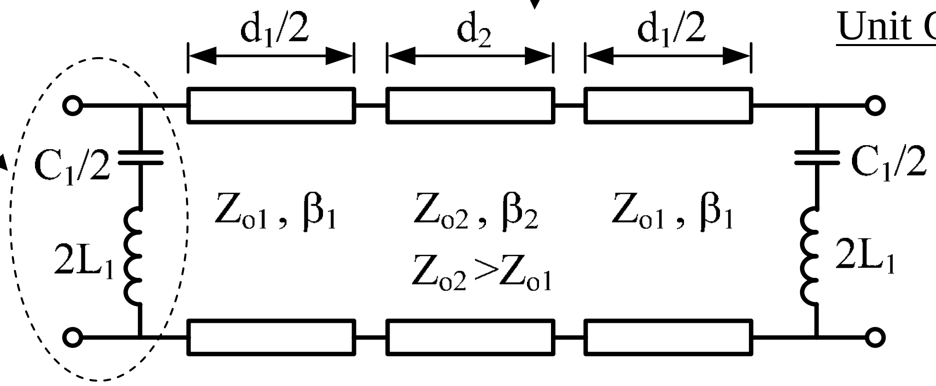


Inductive Grid EBG Structures: Power plane is comprised of a 2D grid of etched TL networks.



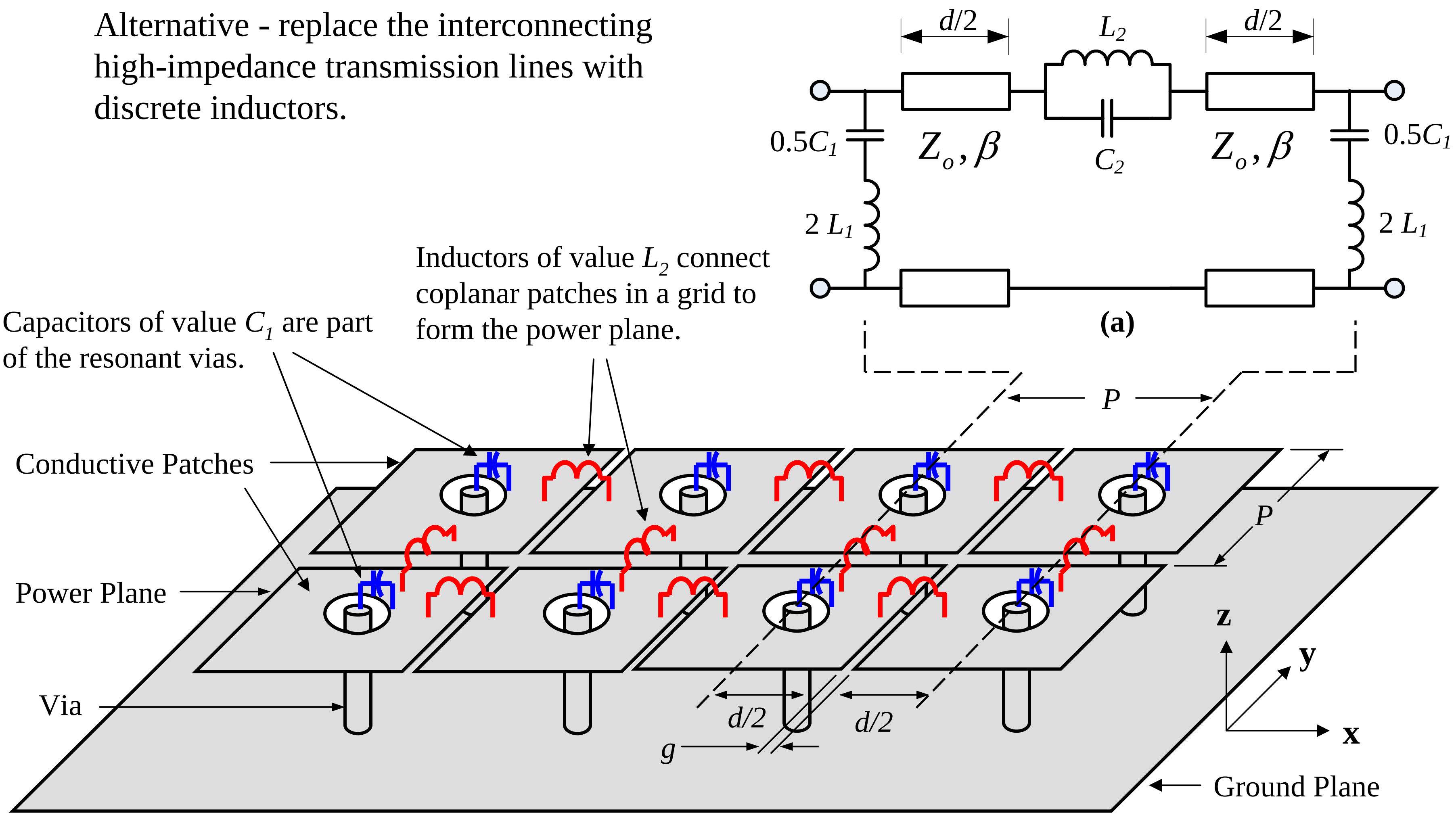
Each Unit Cell Combines a Resonant Via + High-Impedance TL

Hybrid EBG Structure:
Unit Cell Equivalent Circuit



Hybrid EBG Power Plane Using Discrete Series Inductors

Alternative - replace the interconnecting high-impedance transmission lines with discrete inductors.

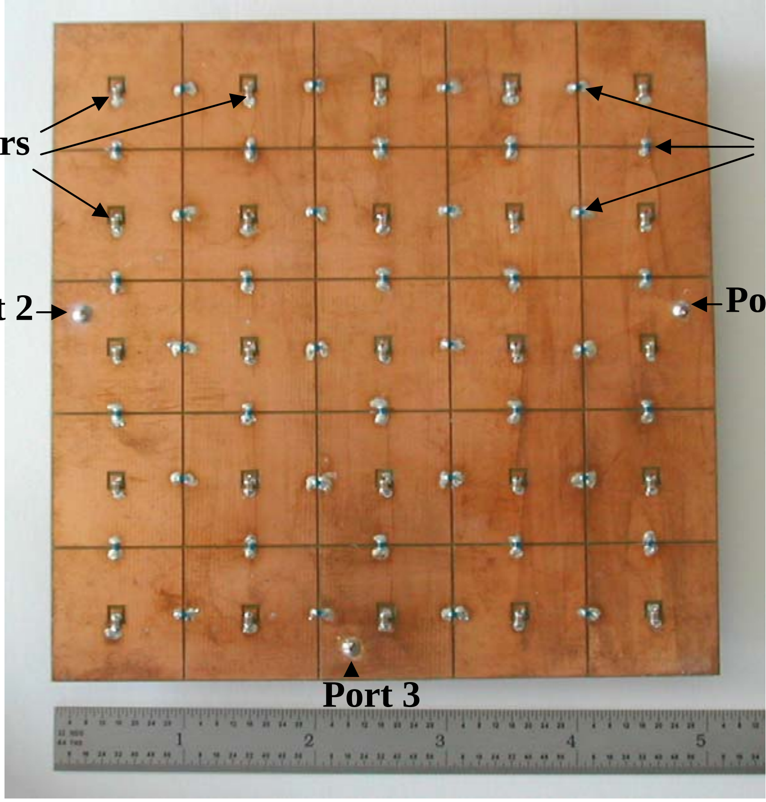


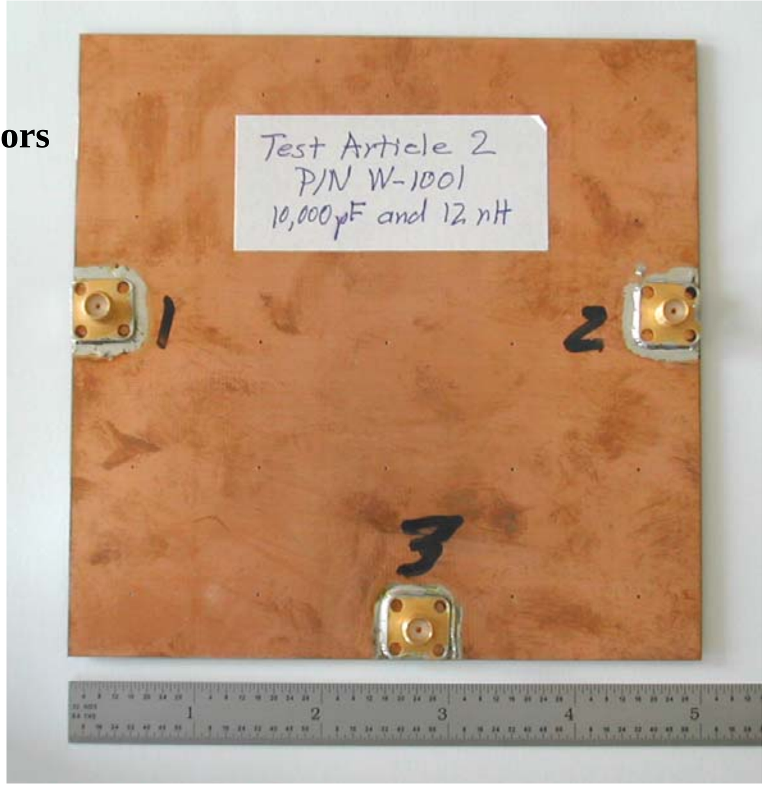
Inductors of value L_2 connect coplanar patches in a grid to form the power plane.

Capacitors of value C_1 are part of the resonant vias.

Embodiment of a Hybrid EBG Structure

Prototype Hardware

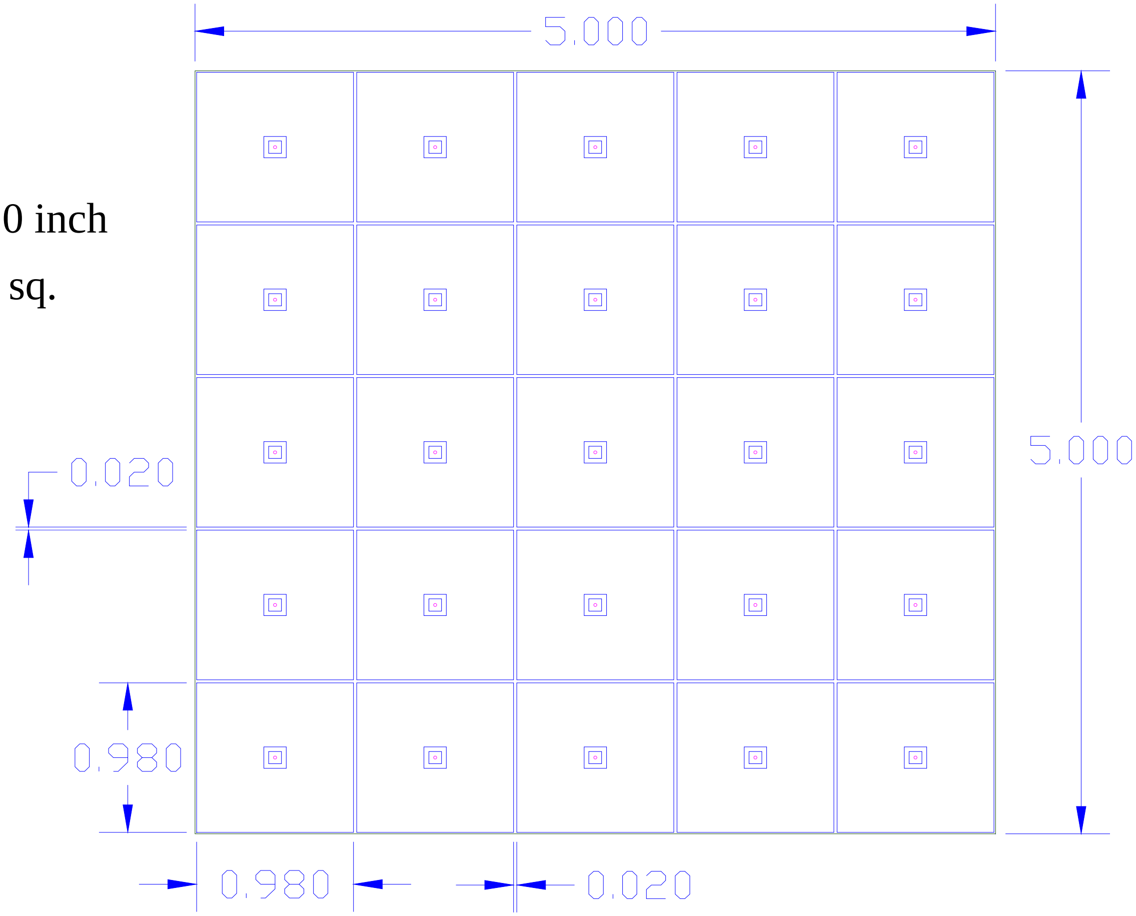




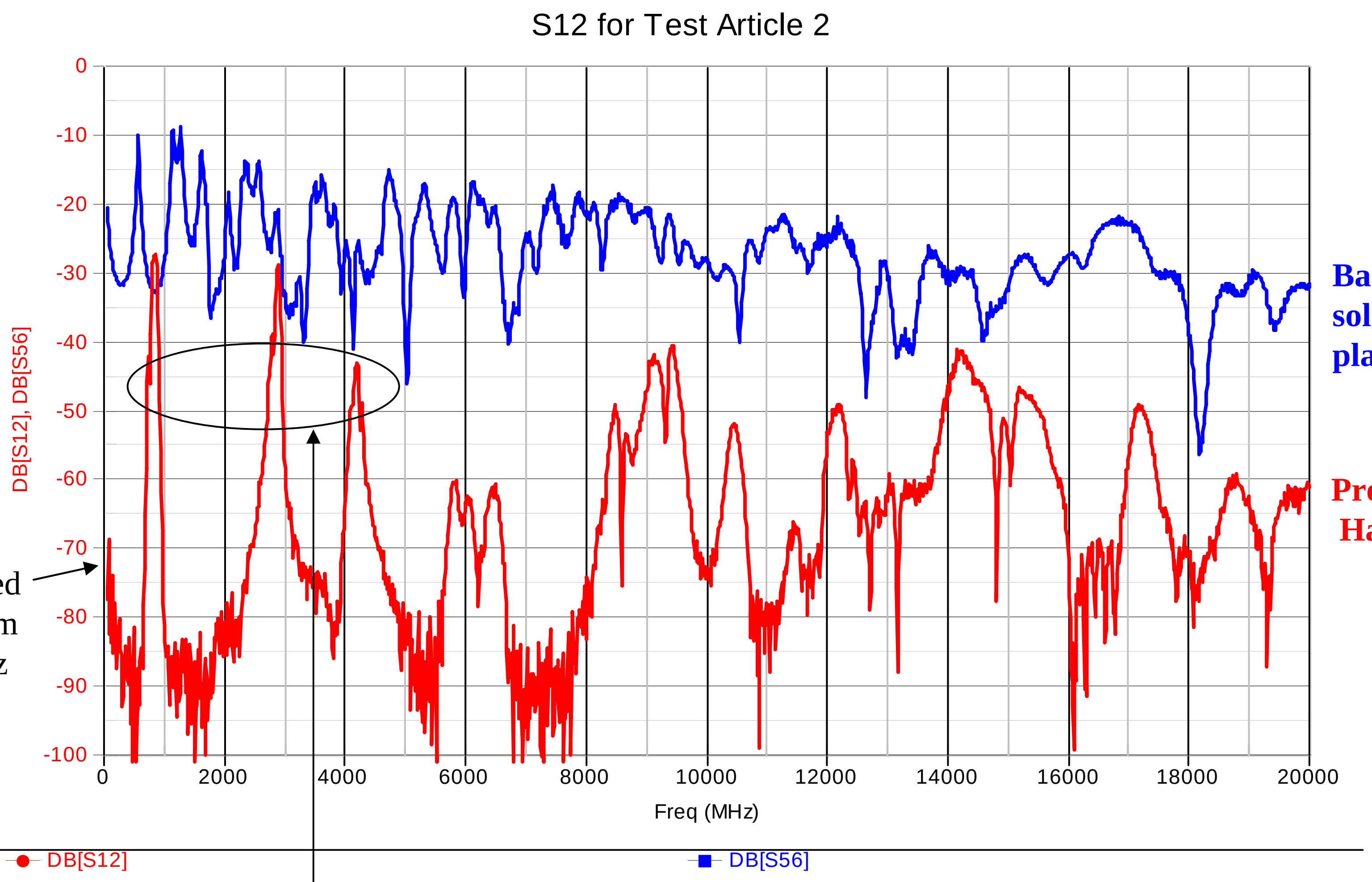
The test article is P/N W-1001; 18 mil FR4 with a 1” period and 20 mil gaps. 12 nH muRata chip inductors (Digikey P/N 490-1170-ND) bridge each gap (40 PL) and 10,000 pF chip caps (Panasonic P/N PCC103BNCT-ND) are used at each via (25 PL).

Printed Circuit Board for the Prototype Hardware

- FR4 board, *h* =.018 inch thick
- 0.5 oz. Cu
- 5x5 patch array
- Period: P = 1 inch
- Gaps between patches: g = .020 inch
- Nominal patch size is .98 inch sq.
- Vias are 20 mil dia.
- Vias are spaced 1 inch apart



Measured Coupling S_{12} for the Prototype Hardware



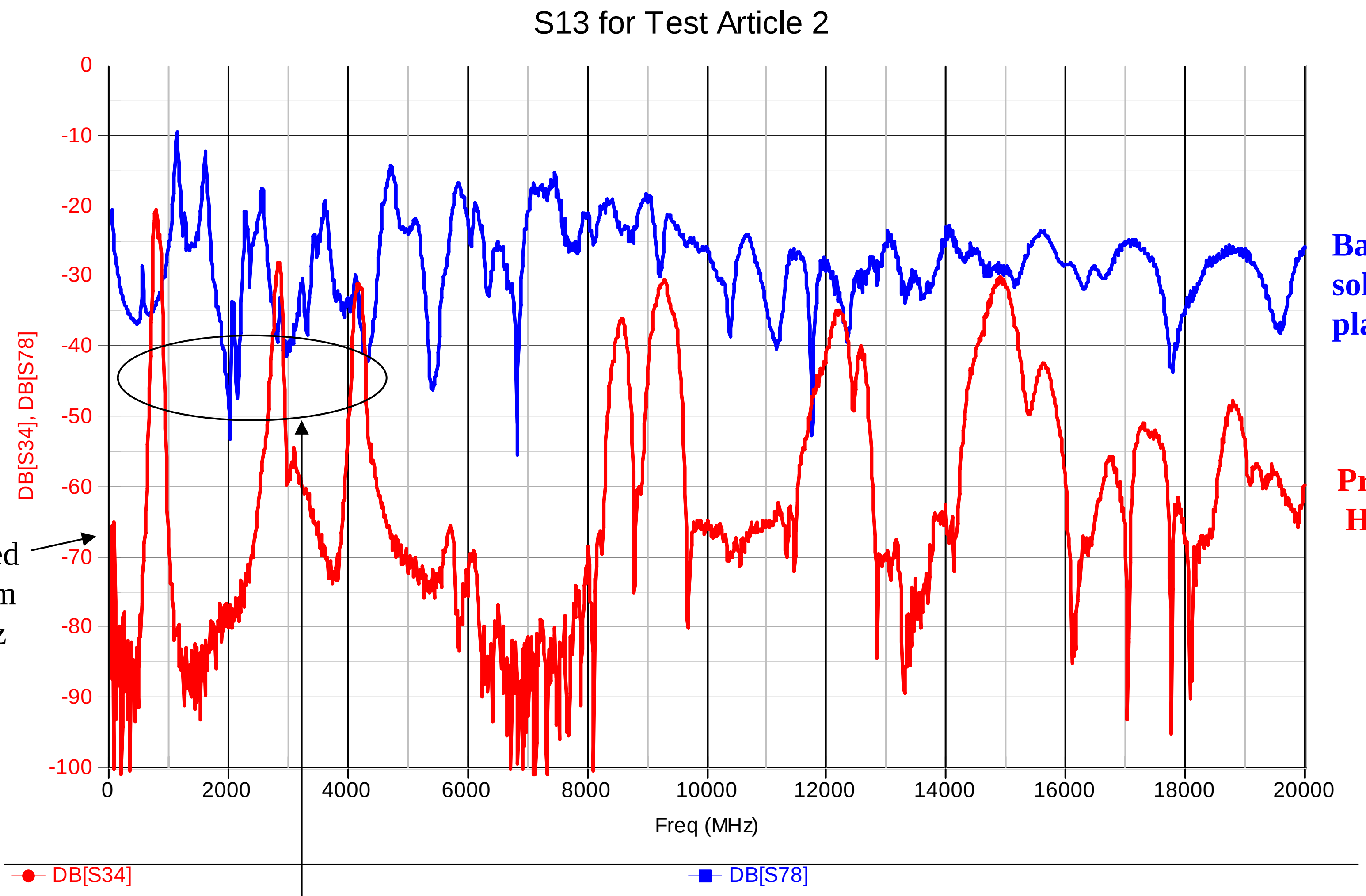
Baseline, solid power plane

Prototype Hardware

Measured data from 50 MHz

These transmission peaks are at least 15 dB below the baseline peaks.

Measured Coupling S_{13} for the Prototype Hardware



Baseline, solid power plane

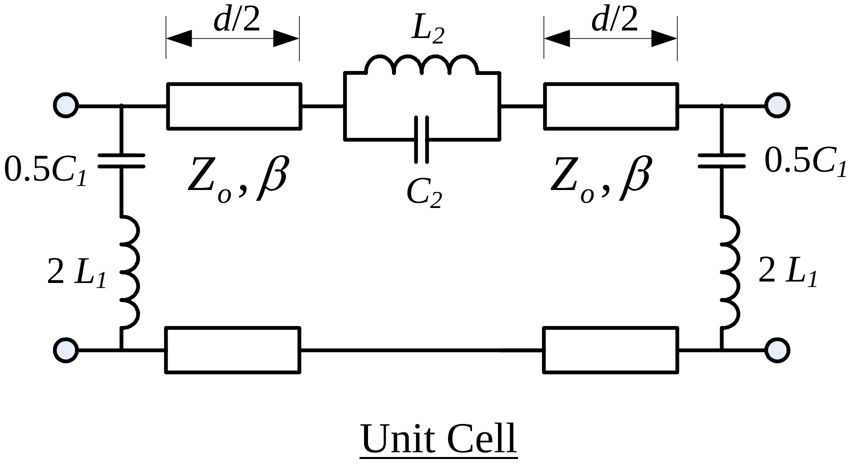
Prototype Hardware

Measured data from 50 MHz

These transmission peaks are about 10 dB (10x) below the baseline peaks.

1D Dispersion Equation (1 of 2)

The filtering properties of the hybrid EBG structure can be understood through a circuit analysis of the unit cell equivalent circuit.



Unit Cell

The quasi-TEM mode on the parallel-plate waveguide of width *d*=*P*-*g* has a characteristic impedance and phase constant of

$$Z_o = \frac{\eta_o}{\sqrt{\varepsilon_r}} \frac{h}{d} \; ; \eta_o \cong 377\Omega$$

$$\beta = \frac{\omega}{c}\sqrt{\varepsilon_r}$$

The admittance of each shunt branch on the ends is $Y_s = \dfrac{j\omega C_1}{1-\omega^2 L_1 C_1}$ where $L_1 = \dfrac{\mu_o h}{2\pi}\ln\left(\dfrac{P}{2\pi r}\right)$ plus a small contribution of parasitic inductance from the chip cap of capacitance C_1.

The impedance of the series branch in the center is $Z_s = \dfrac{j\omega L_2}{1-\omega^2 L_2 C_2}$ where $C_2 = C_g + \dfrac{1}{(2\pi\, f_{SRF})^2 L_2}$ and C_g is the capacitance across the gap between adjacent patches. L_2 is the inductance of the chip inductor and f_{SRF} is its self resonant frequency.

1D Dispersion Equation (2 of 2)

Calculate the ABCD parameters of the unit cell:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ {}^{1}\!/\!_{Y_s} & 1 \end{bmatrix} \begin{bmatrix} \cos(\beta l) & jZ_o \sin(\beta l) \\ jY_o \sin(\beta l) & \cos(\beta l) \end{bmatrix} \begin{bmatrix} 1 & Z_s \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \cos(\beta l) & jZ_o \sin(\beta l) \\ jY_o \sin(\beta l) & \cos(\beta l) \end{bmatrix} \begin{bmatrix} 1 & 0 \\ {}^{1}\!/\!_{Y_s} & 1 \end{bmatrix}$$

where $l = d/2$ and $Y_o = 1/Z_o$.

The propagation constant γ_x for Bloch waves that travel in the x (or y) direction along an infinite cascade of unit cells can be calculated from the ABCD parameters of one unit cell using the relation:

$$\gamma_x = \alpha_x + j\beta_x = \frac{1}{P}\cosh^{-1}\frac{A+D}{2}.$$

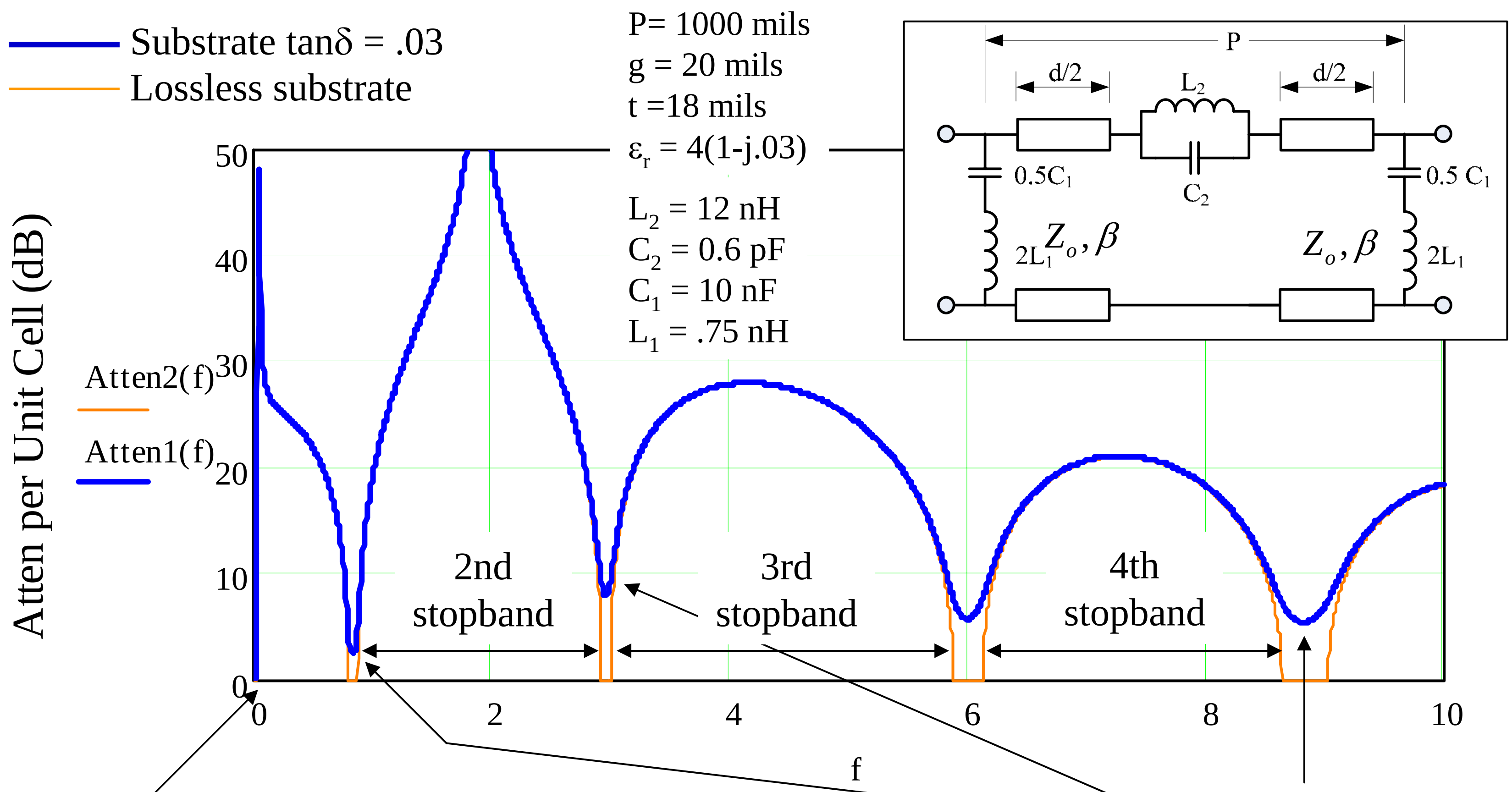
Since the unit cell network is symmetric, then $A=D$. After a few algebraic steps the dispersion equation for the Bloch wave propagation constant, γ_x, becomes

$$\boxed{\cosh(\gamma_x P) = \cos(\beta d) + \frac{Y_s Z_s}{4}\left[1 + \cos(\beta d)\right] + j\left[\frac{Y_o Z_s + Z_o Y_s}{2}\right]\sin(\beta d)}$$

The attenuation constant α_x defines the decay rate across a unit cell in nepers/meter as $e^{-\alpha_x P}$.
The attenuation per unit cell can be calculated in dB using the following relationship:

$$Atten = 20\log\left[\exp(-\alpha_x P)\right] \ \ (dB/unit\,cell)$$

Predicted Stopband Performance for the Prototype Hardware



Predicted cutoff frequency is ~ 25.4 MHz.
Measured data is available down to 50 MHz.

These passband peaks show up prominently in the transmission measurements.

Due to dielectric losses in the FR4, the **stopbands merge and extend beyond 10 GHz** !

Analytic Expression for the Fundamental Cutoff Frequency

It is desirable to derive explicit formulas for the features of the attenuation curve so as to gain insight into the design variables and their tradeoffs. The most useful formula would calculate the lower edge of the fundamental stopband, or the low frequency cutoff for the fundamental stopband. Denote this frequency as $\omega_c = 2\pi f_c$.

At $\omega = \omega_c$, the value of γ_x goes to $j\pi/P$. Furthermore, the frequency of operation is low enough that the patch dimensions are very small with respect to the wavelength of a TEM mode traveling across the patch in the host dielectric. So $\beta d << 1$. Under these conditions small argument approximations may be applied to the trig functions and the dispersion equation reduces to

$$-1 = 1 + \frac{Y_s Z_s}{4}(1+1) + j\left[\frac{Y_o Z_s + Z_o Y_s}{2}\right]\left(\frac{\omega_c}{c}\sqrt{\varepsilon_r}\, d\right).$$

We can simplify some of the terms on the RHS by using the following two relationships:

$$\frac{Y_o\sqrt{\varepsilon_r}\, d}{c} = \frac{\varepsilon_r \varepsilon_o d^2}{h} = C_p$$

Here we have defined the variable C_p to represent the parallel-plate capacitance to ground for the square patches.

$$\frac{Z_o\sqrt{\varepsilon_r}\, d}{c} = \mu_o h = L_p$$

The variable L_p represents the inductance per unit length for a TEM mode in the parallel-plate waveguide under the patches.

Analytic Expression for the Fundamental Cutoff Frequency

With the above parameters of C_p and L_p, the dispersion equation reduces to:

$$-4 = \frac{-\omega_c L_2 C_1}{(1-\omega_c L_1 C_1)(1-\omega_c L_2 C_2)} + j\omega_c\left(\frac{j\omega_c L_2 C_p}{1-\omega_c L_2 C_2} + \frac{j\omega_c L_p C_1}{1-\omega_c L_1 C_1}\right)$$

This dispersion equation can be rearranged into a quadratic form $a\omega_c^4 + b\omega_c^2 + c = 0$

where

$$a = L_2 C_1 \left(4L_1 C_2 + L_1 C_p + L_p C_2\right)$$

$$b = -\left[\left(4L_1 + L_2 + L_p\right)C_1 + L_2\left(4C_2 + C_p\right)\right]$$

$$c = 4$$

Hence an <u>exact expression</u> for the low frequency cutoff is

$$\boxed{\omega_c = \sqrt{\frac{-b-\sqrt{b^2-4ac}}{2a}}} \quad \Longrightarrow \quad f_c = 25.4\ \text{MHz}$$

where the minus sign in the quadratic formula has been selected since the smaller root is needed.

Note that there are six lumped variables that define the cutoff frequency: L_1, L_2, L_p, C_1, C_2, and C_p.

Can we find a simpler expression that will yield insight into the physics of the EBG structure?

Simplified Expression for the Fundamental Cutoff Frequency

For the prototype hardware, L_2 = 12 nH, L_1 = 0.75nH, L_p = .575 nH, C_1 = 10,000 pF, C_2 =.584 pF, and C_p ~ 48 pF.

If we assume the relationships of $L_2 >> L_1,\ L_2 >> L_p,\ C_p >> C_2,\ C_1 >> C_p$, then

$$a = L_2 C_1 L_1 C_p$$
$$b = -L_2 C_1$$

which allows us to write the approximate expression for the cutoff frequency:

$$f_c \cong \frac{1}{2\pi}\sqrt{\frac{1-\sqrt{1-16\dfrac{L_1 C_p}{L_2 C_1}}}{2L_1 C_p}}$$

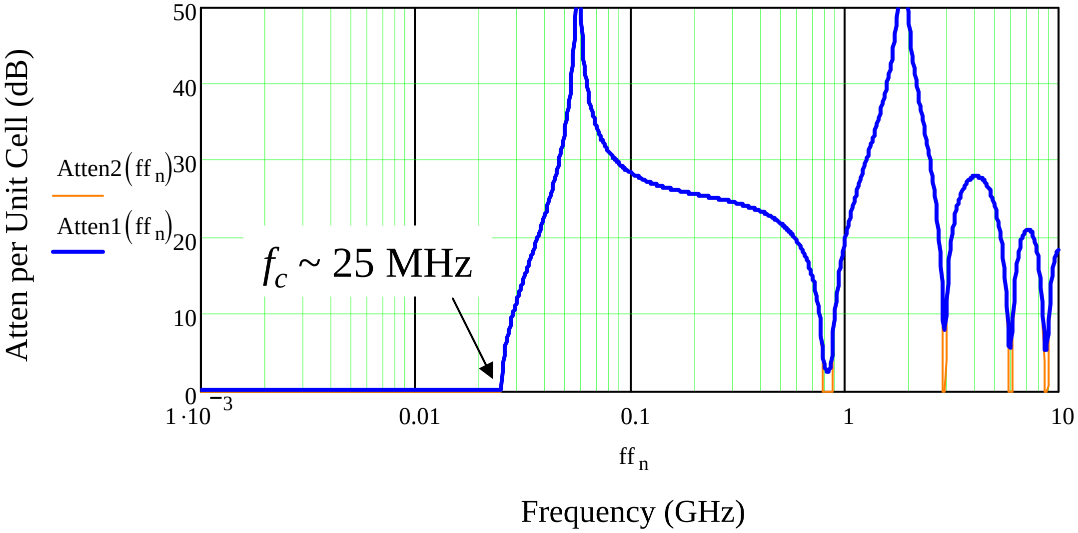
If the inner square root is expanded in a Binomial series then this approximation for cutoff frequency further reduces to

$$\boxed{f_c \cong \frac{1}{\pi\sqrt{L_2 C_1}}} \Rightarrow f_c = 29.1 \text{ MHz}$$

Note that L_2 and C_1 are the discrete inductor and capacitor in each unit cell. They represent the dominant energy storage mechanisms with the EBG structure.

Also, note that this estimate for cutoff frequency is independent of the period P.

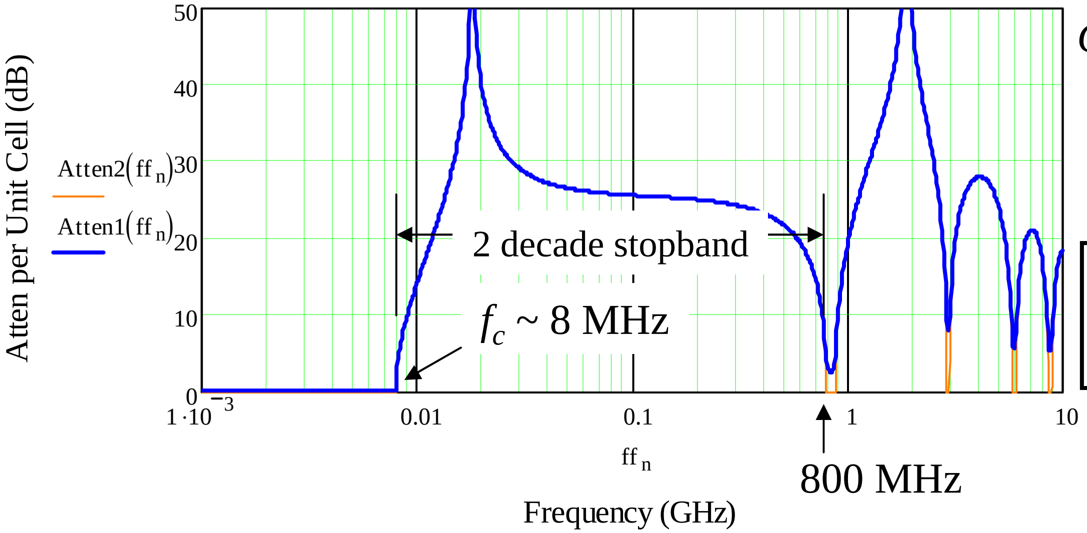
What Happens if the Decoupling Caps Increase?



C_1 = 10 nF

Substrate tanδ = .03

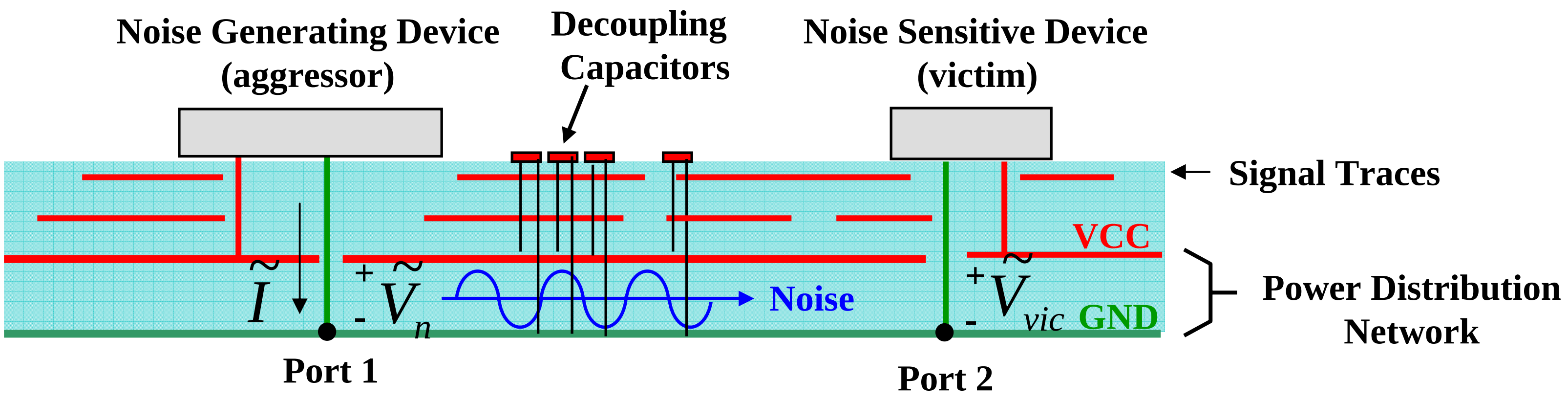
Lossless substrate



C_1 = 100 nF

- The upper stopbands are <u>unchanged</u>.
- The cutoff frequency f_c is lowered by the square root of the increase in C_1.

How Can We Characterize Noise Generation and Propagation?



Let $\tilde{I}$ be the noise current in the frequency domain caused by time-varying switching currents.

Noise voltage generated by the aggressor: $\tilde{V}_n = \tilde{I} Z_{11}$ **Z_{11} is the self-impedance**

Noise power generated by the aggressor: $P_{noise} = \mathrm{Re}\left(\left| \tilde{I}_n \right|^2 Z_{11} \right)$

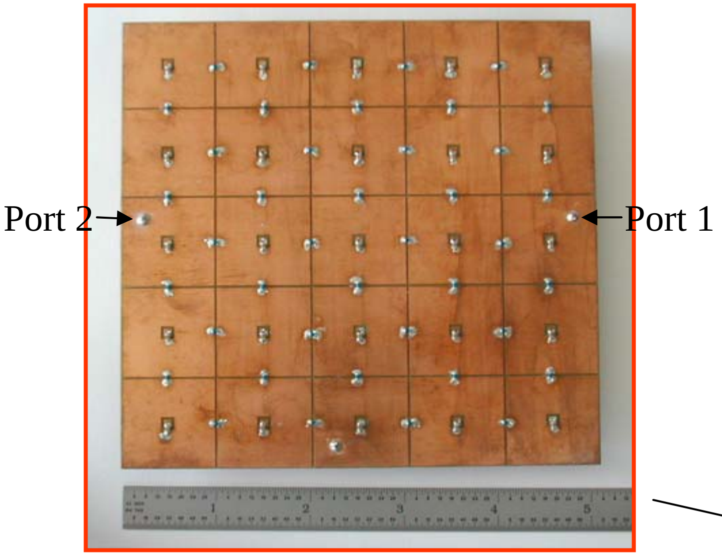
Noise voltage at the victim: $\tilde{V}_{vic} = \tilde{I} Z_{21}$ **Z_{21} is the transfer-impedance**

Key points: A properly designed EBG power distribution network (PDN) can

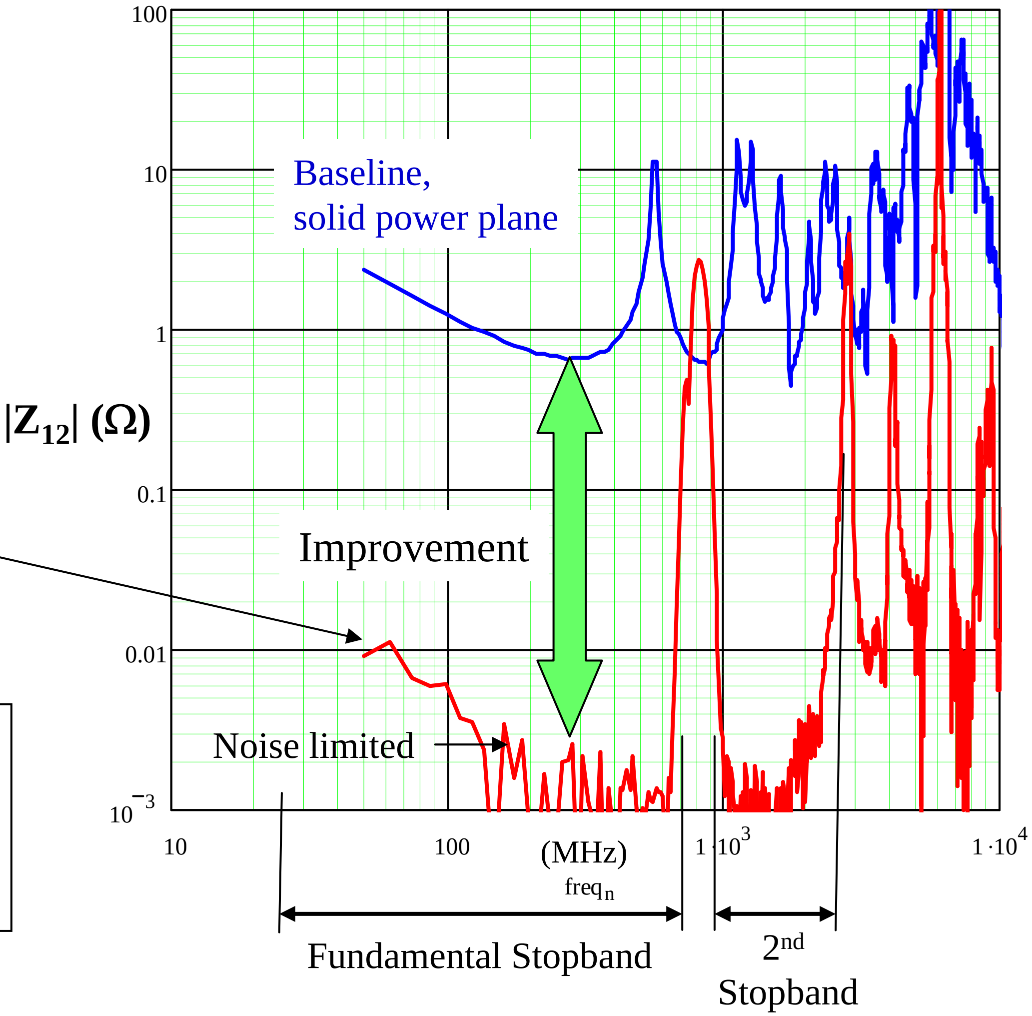
1. **suppress the generation of noise power by lowering Z_{11}**
2. **suppress the propagation of noise power by lowering Z_{21}**

Measured Transfer Impedance Z_{12}

Prototype EBG Power Plane



Measured data covers 50 MHz to 10 GHz



Dramatic improvements in transfer impedance are demonstrated for frequencies in the stopbands of the EBG power plane.

Note: $Z_{12} = \frac{2S_{12}}{\Delta} Z_o$ where $\Delta = (1-S_{11})(1-S_{22}) - S_{12}S_{21}$ and $Z_o = 50\,\Omega$

Conclusions

- A new type of EBG structure is introduced for power distribution networks (PDNs)

- It combines the features of a periodic array of patches with
  - discrete (SMT) inductors as series elements, plus
  - discrete (SMT) decoupling capacitors within the patches.

- This EBG structure may be realized in microstrip or stripline construction.

- Stopband performance of the PDN up to at least several GHz may easily be predicted using a simple dispersion equation.

- The fundamental stopband has been demonstrated to start as low as 50 MHz with a prediction of 25 MHz.

- A fundamental stopband bandwidth ratio of greater than 30:1 is demonstrated. Ratios of 100:1 may be realized by increasing C_1.

- The cutoff frequency f_c for the fundamental stopband may be tailored through component selection for different areas of the PDN.

To Learn More

References on hybrid EBG structures:

[1] Will McKinzie, “A Low Frequency Hybrid EBG Structure for Power Plane Noise Suppression,” *IEEE 15th Topical Meeting on Electrical Performance of Electronic Packaging*, Oct 23-25, 2006, Scottsdale, AZ, pp. 51-54.

[2] William E. McKinzie III, “Systems and Methods for Electromagnetic Noise Suppression Using Hybrid Electromagnetic Bandgap Structures,” *US Patent Publication 2007/0090398*, published April 26, 2007.

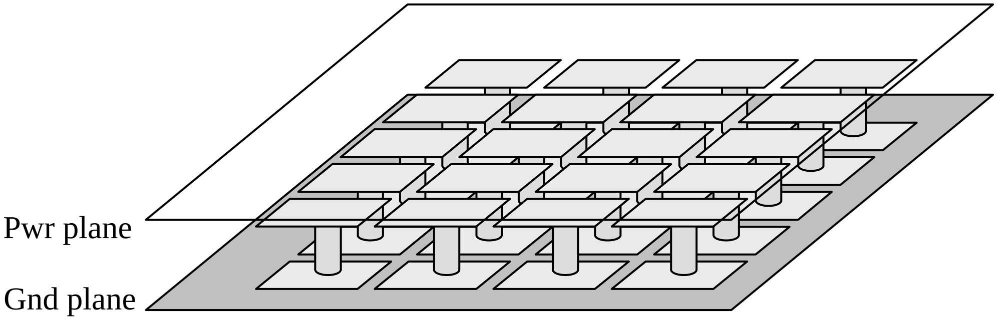
References on inductive grid EBG structures using discrete inductors:

[3] Ki Hyuk Kim et. al., “Design of EBG Power Distribution Networks with VHF-Band Cutoff Frequency and Small Unit Cell Size for Mixed-Signal Systems,” *IEEE Microwave and Wireless Components Letters*, Vol. 17, No. 7, July 2007, pp.489-491.

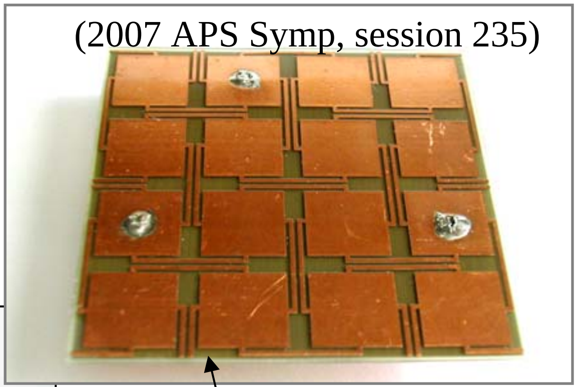
The Bigger Picture:

There exists a suite of tools for noise suppression in power distribution networks:

1. **Parallel-plate EBG structures** for high current, low Z_o, applications:



2. **Coplanar EBG structures** for lower current, low cost applications at microwave frequencies**:**


(2007 APS Symp, session 235)

3. **Hybrid EBG structures** for lower frequency applications (30 MHz to 1.6 GHz) :


(2006 EPEP, pp. 51-54)

2 inches square