# An Application of Metamaterials to Power Plane Noise Suppression

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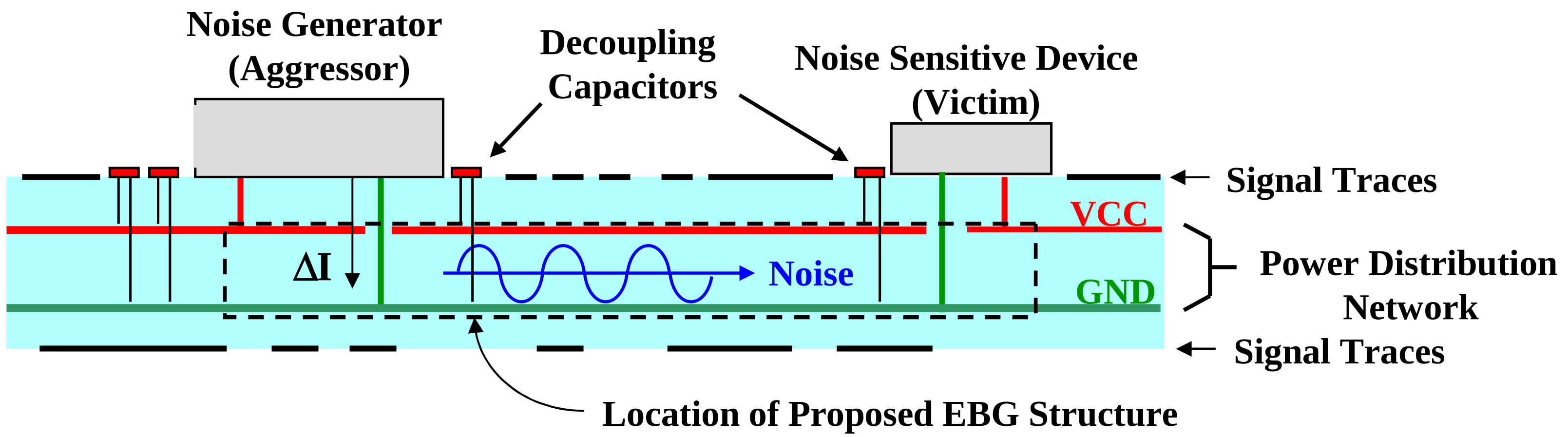
# Outline

- Motivation and Application for Metamaterials
  as EBG Structures
- Metamaterial: Loaded Wire Media
- Equivalence of EBG Structures Using Symmetry Planes
- Dispersion Model for Loaded Wire Media
- Validation with a Full-Wave TLM Simulation
- A Broader View of EBG Structures for Noise Suppression

# Motivation: Suppression of Conducted Noise at the Board or Package Level




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

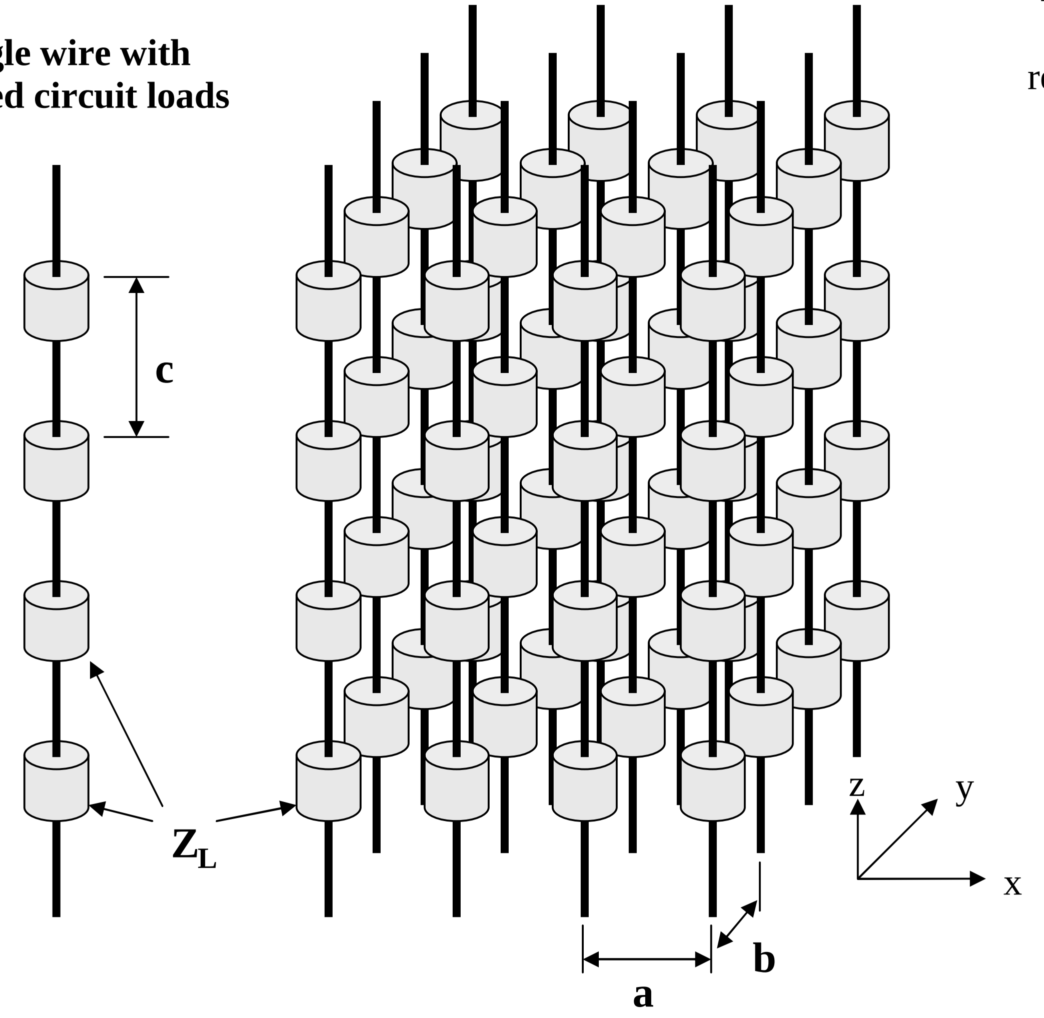
2. To improve noise immunity for analog-to-digital (ADC) converters.

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

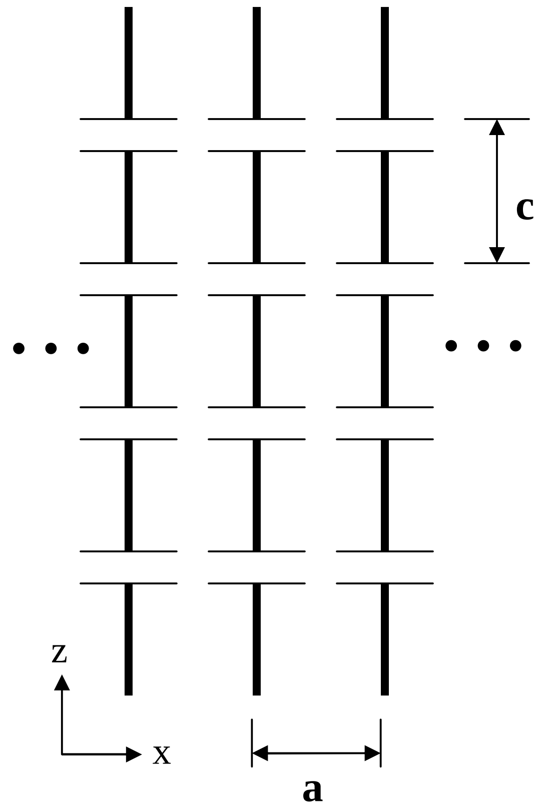
# Metamaterial: A Loaded Wire Media

**Single wire with lumped circuit loads**

**Replicate the loaded wire as a periodic array with a rectangular lattice in x and y:**



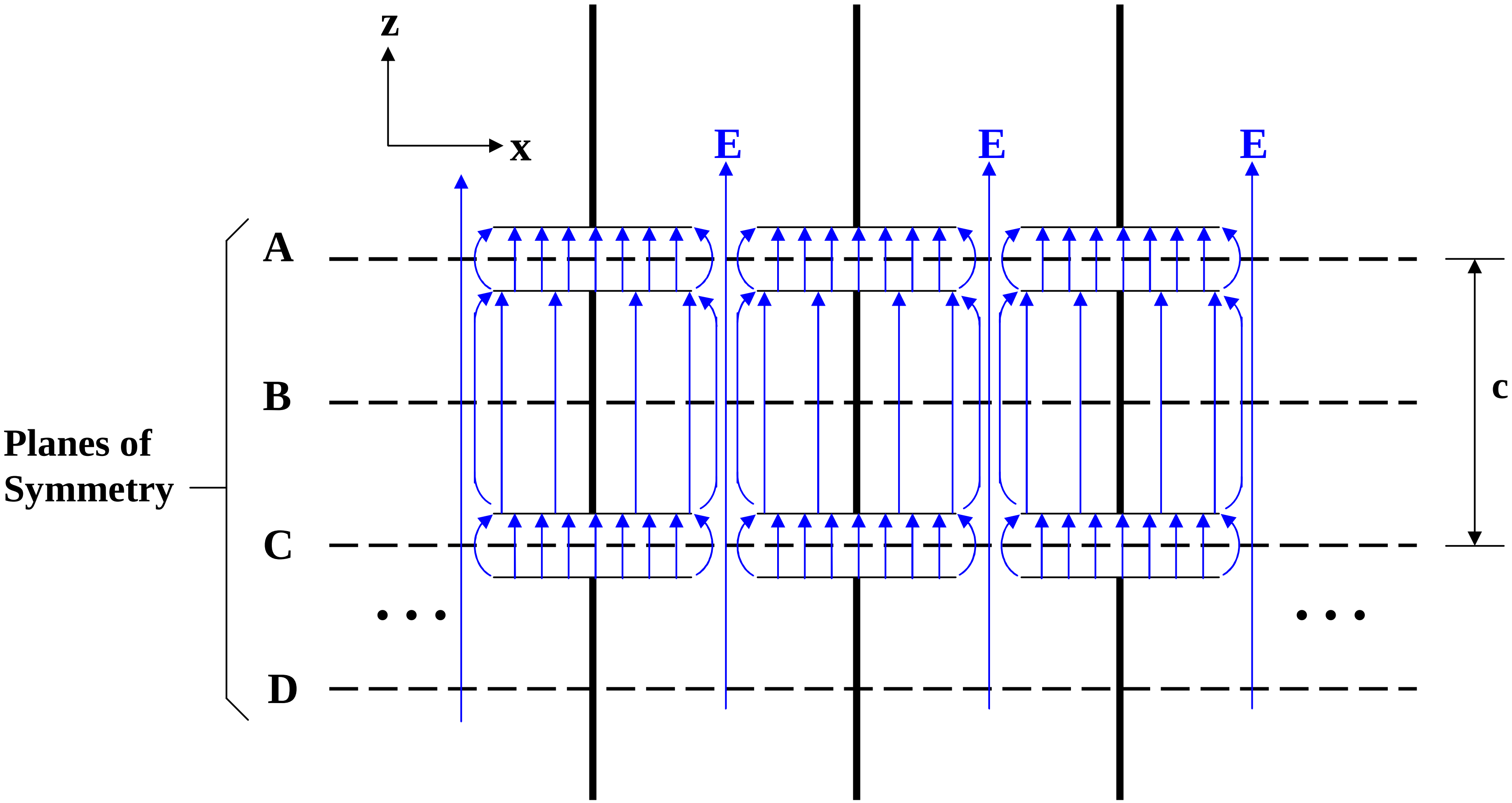

**Assume the loads are now parallel-plate capacitors.** For clarity, dielectric layers required for physical support are not shown.



# Planes of Symmetry

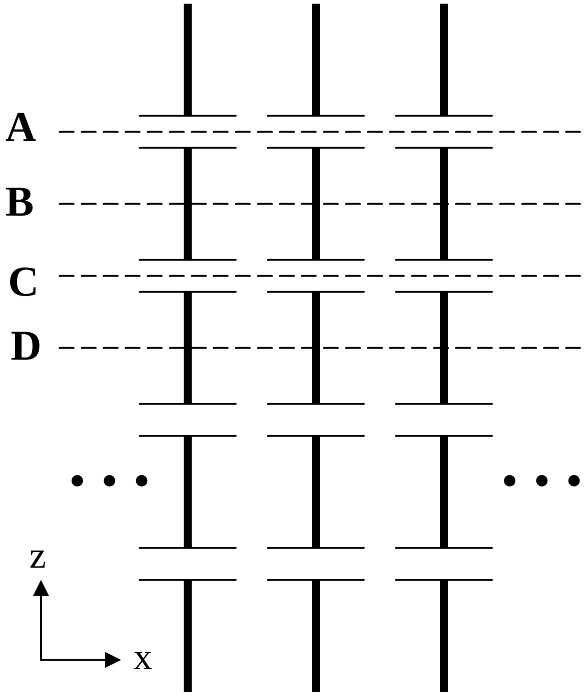
**Assumptions:**

1. **Wave propagation in the x and y directions only:** $k_z = 0$.
2. **TM to z mode so the E field is z directed.**



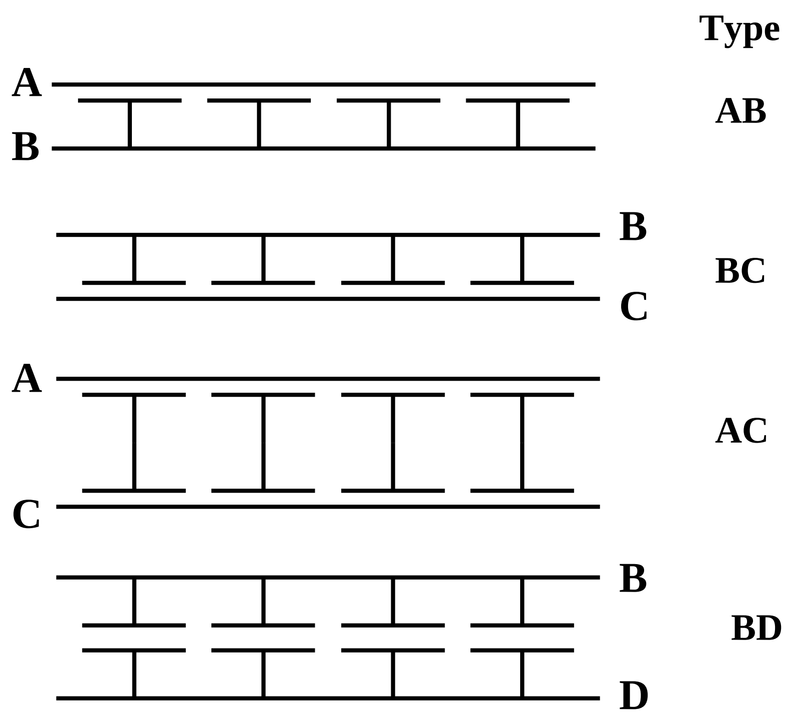
# Employ Planes of Symmetry to Obtain Electromagnetically Equivalent Structures

Recognize that horizontal planes A,B,C, and D are planes of symmetry, which also constitute electric walls for waves traveling in the x or y directions.




Equivalent EBG Structures:

One can create electromagnetically equivalent structures to the infinite loaded wire media by substituting metal walls in place of the planes of symmetry:



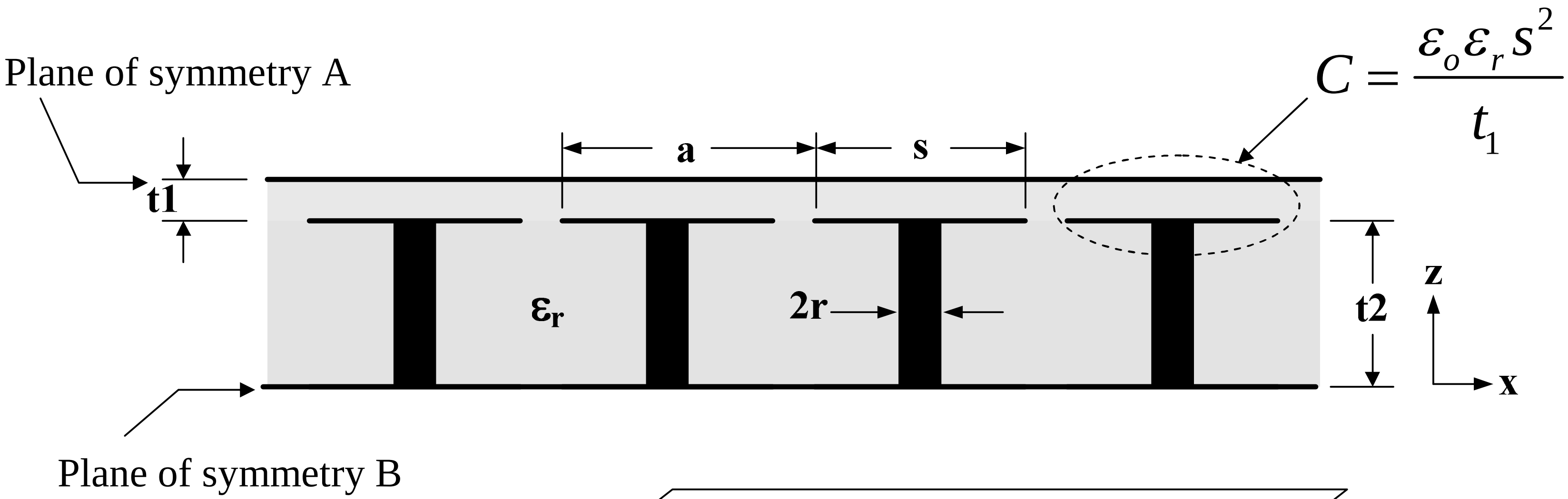

Fields and waves contained between any two horizontal planes of symmetry are exactly the same in both the 3D wire media at left and the parallel-plate waveguides at right.

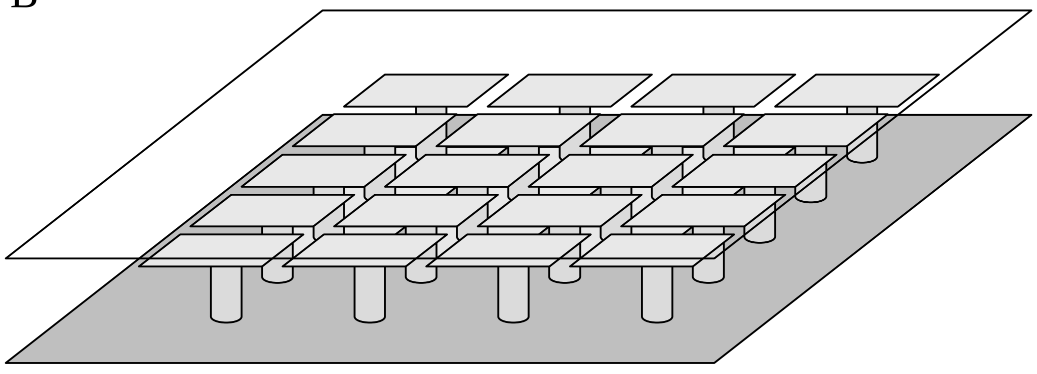
**All four examples on the right have exactly the same filtering properties!**

# Type AB Structure

Consider one of the four equivalent structures: type AB

Define the heights of individual dielectric layers to be $t_1$ and $t_2$ such that $c = 2\left(t_1 + t_2\right)$




Example:
a = b = 0.4 in.
s = 0.34 in.
$t_1$ = .004 in.
$t_2$ = .022 in.
r = .010 in.

# Dispersion Equation for a Loaded Wire Medium

Begin with Tretyakov's analysis of a loaded wire medium, and re-arrange his equation 6.53 into the classic form of a periodically loaded transmission line

$$\cos(q_x a) = \cos(k_x^{(0)} a) + j \frac{\eta_o / \sqrt{\varepsilon_r}}{2\left( Z_s + \frac{k_x^{(o)}}{k} \frac{b}{c} Z_L \right)} \sin(k_x^{(0)} a)$$

where the lattice constants in the *x*, *y*, and *z* directions are *a*, *b*, and *c*.

The eigenwave (Bloch mode) propagation constants for the *x*, *y*, and *z* directions are $q_x$, $q_y$, and $q_z$.

The wavenumber in the host dielectric medium of permittivity $\varepsilon_r$ is $k = \omega\sqrt{\mu_o \varepsilon_o \varepsilon_r}$ and $\eta_o$ is the wave impedance of free space.

Propagation constant $k_x^{(n)}$ is the x component of the $n^{th}$ Flouquet mode wavevector defined as

$$k_x^{(n)} = -j\sqrt{\left( q_y + \frac{2n\pi}{b} \right)^2 + q_z^2 - k^2} \; ; \; q_z \equiv 0$$

Ref: Sergei Tretyakov, *Analytical Modeling in Applied Electromagnetics*, Section 6.3, pp. 209, equation 6.53.

# Dispersion Equation for a Loaded Wire Medium

$$\cos(q_x a) = \cos(k_x^{(0)} a) + j \frac{\eta_o / \sqrt{\varepsilon_r}}{2\left( Z_s + \frac{k_x^{(o)}}{k} \frac{b}{c} Z_L \right)} \sin(k_x^{(0)} a)$$

This denominator contains inductive and capacitive reactance terms.

$$Z_L = \frac{2}{j\omega C}$$

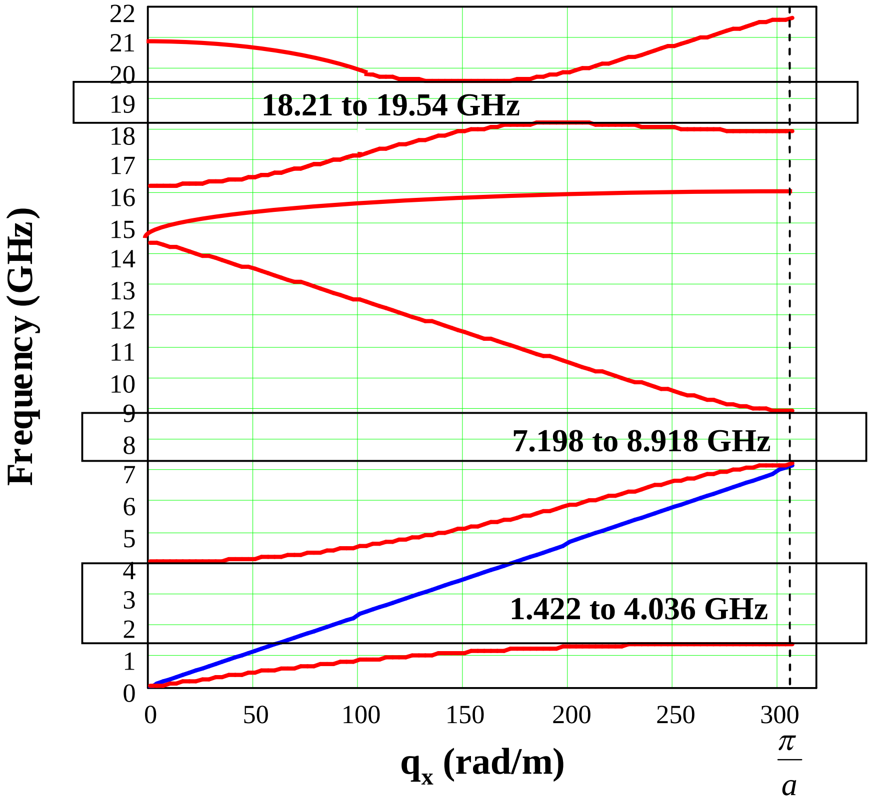
is the series load on the wires, and it is twice the capacitive reactance of C.

The inductive impedance Zs is the shunt (wave) impedance of a wire grid:

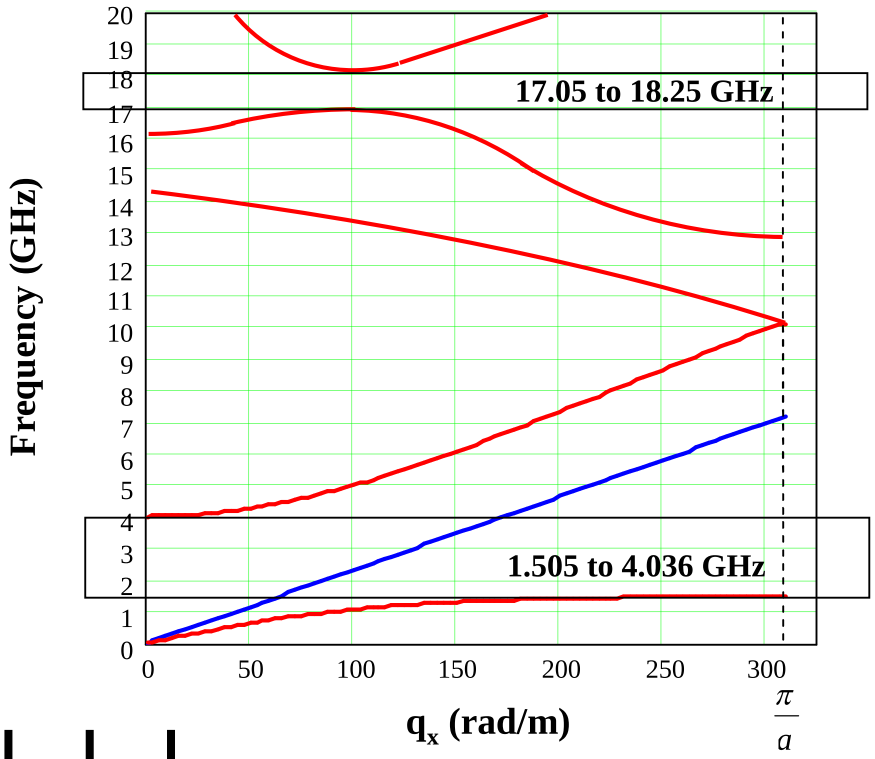
$$Z_s = j \frac{\eta_o}{2\sqrt{\varepsilon_r}} \left[ \frac{b\, k_x^{(0)}}{\pi} \ln\left( \frac{b}{2\pi\, r} \right) + k_x^{(0)} \left\{ \sum_{n \neq 0} \frac{1}{k_x^{(n)}} \frac{\sin(k_x^{(n)} a)}{\cos(k_x^{(n)} a) - \cos(q_x a)} - \frac{b}{2\pi\, |\, n\,|} \right\} \right]$$

# Dispersion Plots for a Capacitive-Loaded Wire Media

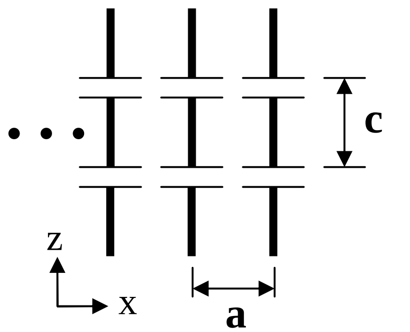
**ΓX Line**

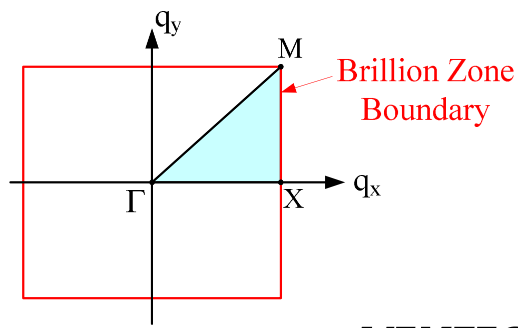



**ΓM Line**



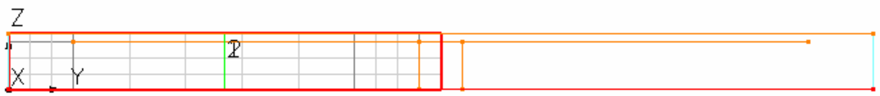

Lateral period, a = b = 400 mils
Z-axis period, c = 52 mils
Patch size, s = 340 mils
Patch separation is 8 mils in z
Via dia. = 20 mils
εr1 = εr2 = 4.2

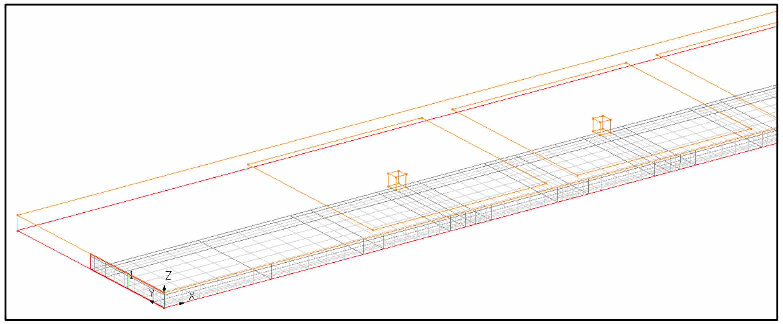


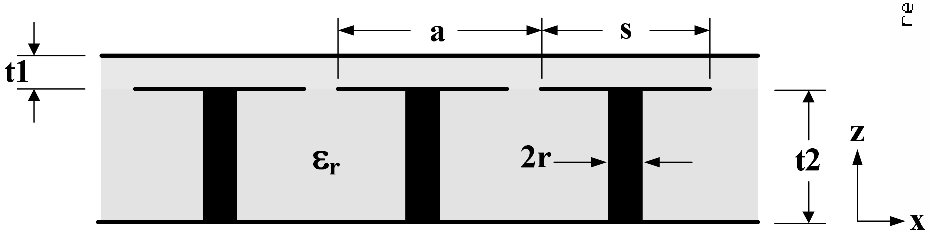



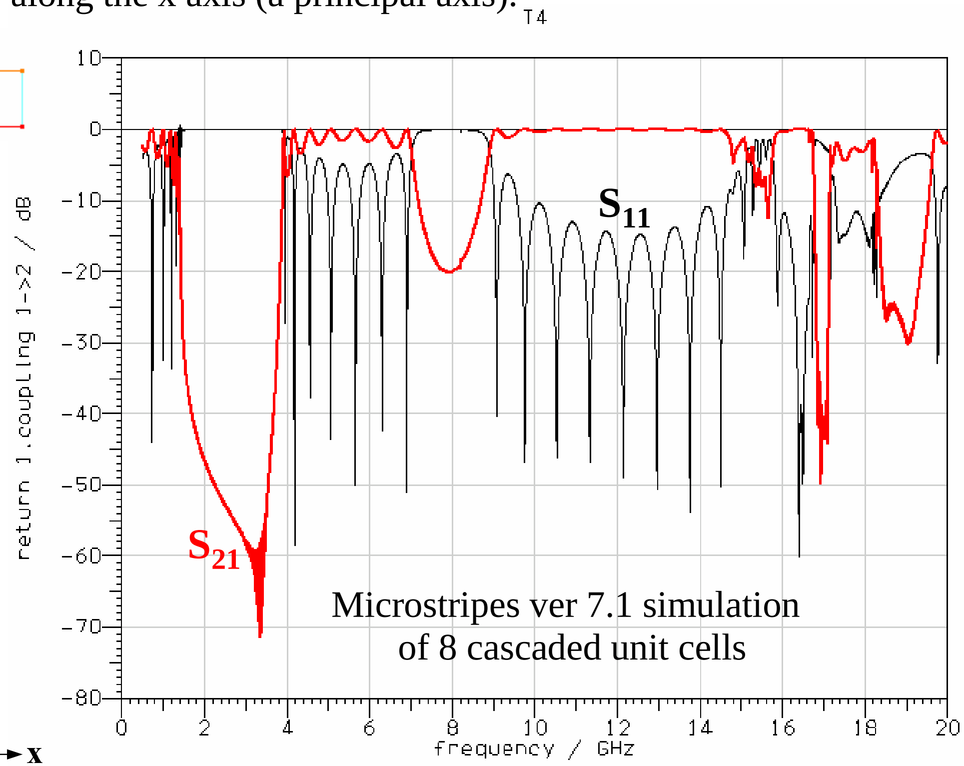
# Comparison of Stopbands:
# Full-Wave TLM Simulation vs. the Analytical Model

Direction of propagation is along the x axis (a principal axis).



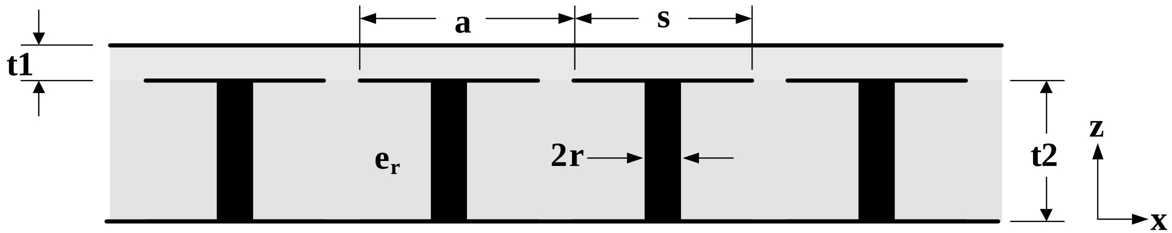



Square lattice of internal Tees
Period, a=b = 400 mils
Patch size, s= 340 mils
Via dia., 2r = 20 mils
t1 = 4 mils
t2 = 22 mils
εr1 = εr2 = 4.2

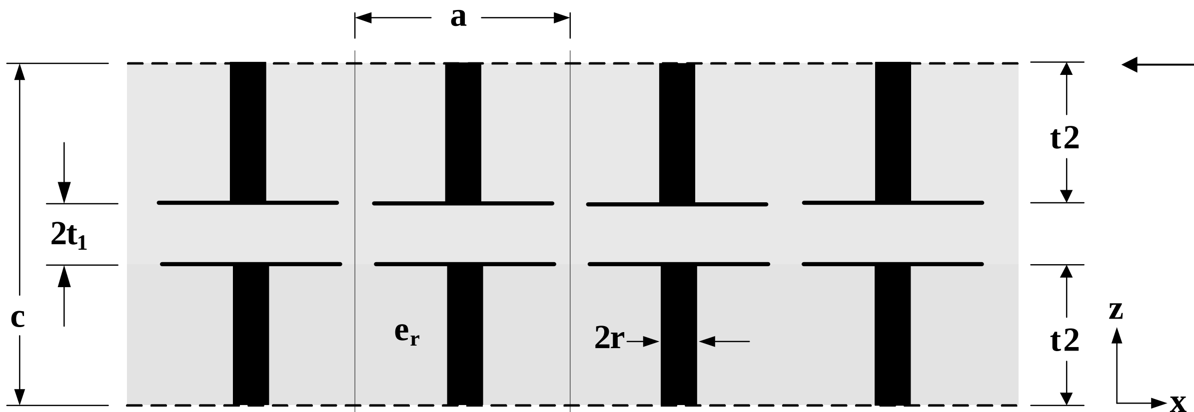
| Stopband | Microstripes | | Eigenvalue Solution | |
|---|---|---|---|---|
| | Lower Band Edge (GHz) | Upper Band Edge (GHz) | Lower Band Edge (GHz) | Upper Band Edge (GHz) |
| Fundamental | 1.401 | 3.906 | 1.422 | 4.036 |
| Secondary | 7.07 | 8.85 | 7.198 | 8.918 |
| Fourth ? | 18.28 | 19.62 | 18.21 | 19.54 |

# Equivalent Transmission Line Circuit for Wave Propagation Along the X Axis




a = Period in the x direction
b = Period in the y direction

**(a) PPW Filter**



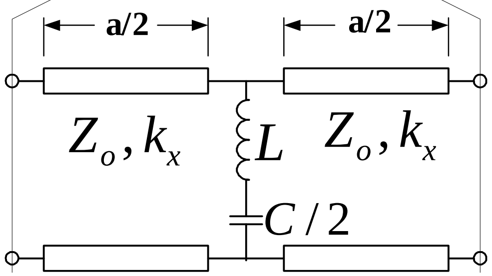

Plane of Symmetry

Using image theory, the PPW can be converted into an infinite wire media.

**(b) Loaded Wire Media**

$$Z_o = \sqrt{\frac{\mu_o}{\varepsilon_o \varepsilon_r}} \left(\frac{c}{b}\right)$$

$$k_x = \omega \sqrt{\mu_o \varepsilon_o \varepsilon_r}$$




$$L = \frac{\mu_o c}{2\pi} \ln\left(\frac{b}{2\pi\, r}\right)$$

$$C = s^2 \varepsilon_r \varepsilon_o / t_1$$

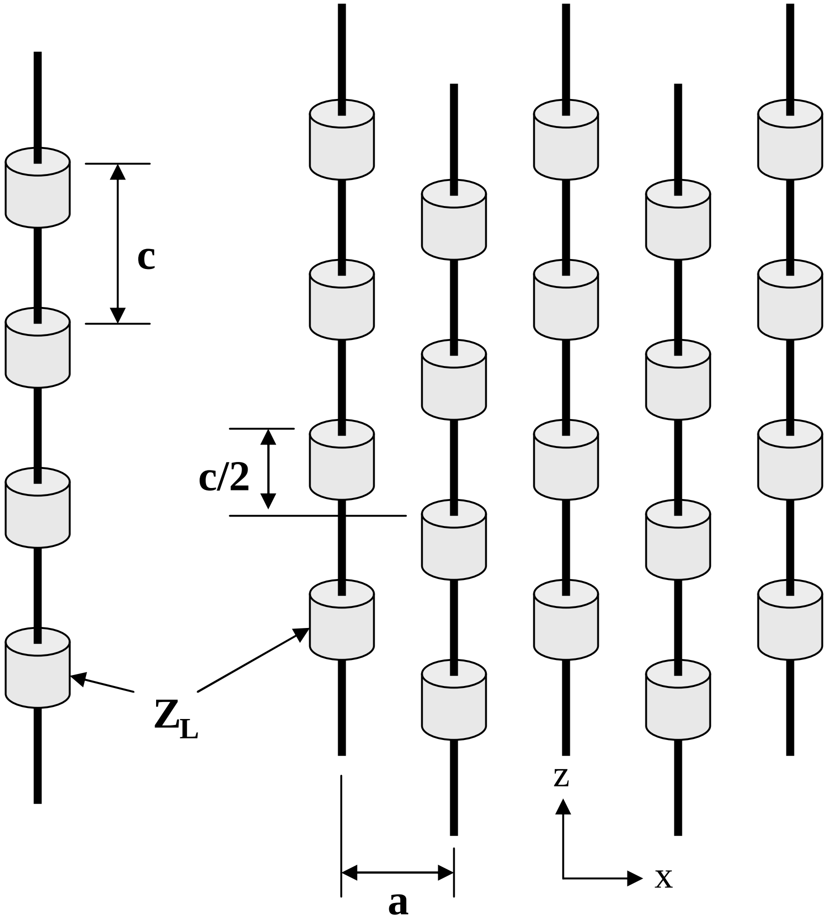
This inductance formula is a low frequency approximation, but it is sufficiently accurate for engineering calculations of the fundamental stopband.

**(c) Equivalent Transmission Line Circuit for the Unit Cell**

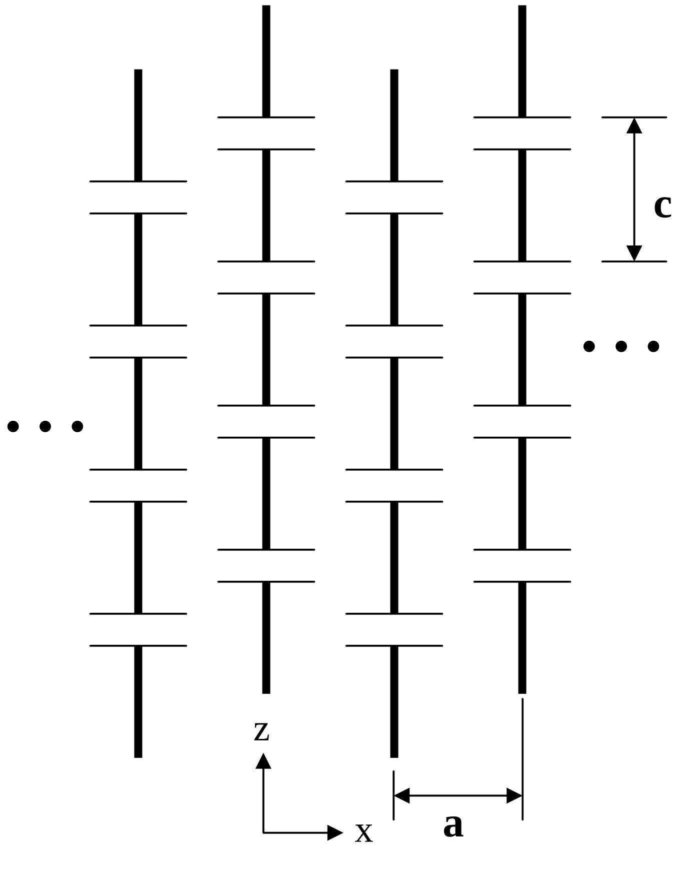
# A Loaded Wire Media with Vertically Offset Loads

Single wire with lumped circuit loads

Now consider the case where alternating grids of loaded wires are offset by ½ of a vertical period c.

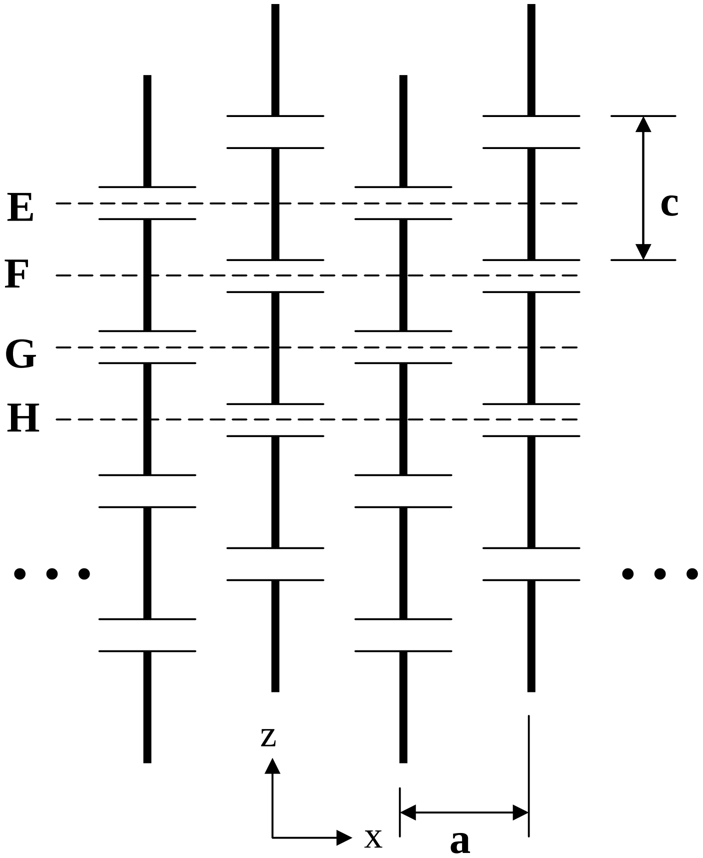



Assume the loads are parallel-plate capacitors. Dielectric layers are omitted for clarity.



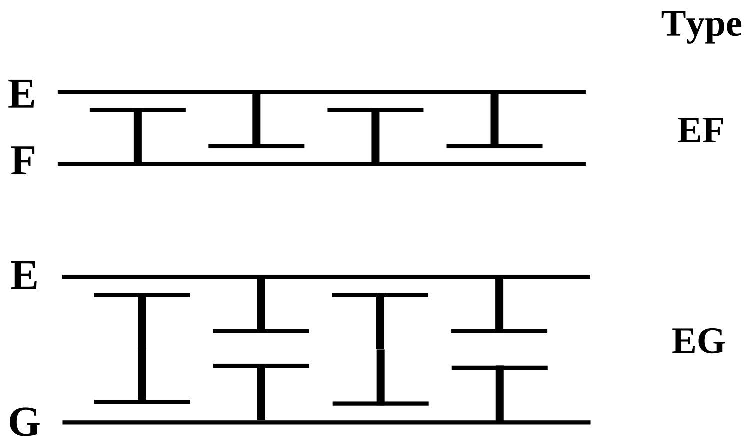
# Again, Employ Planes of Symmetry to Obtain Electromagnetically Equivalent Structures

Horizontal planes E, F, G, and H are planes of symmetry, which also constitute electric walls for waves traveling in the x or y directions.




Equivalent EBG Structures:

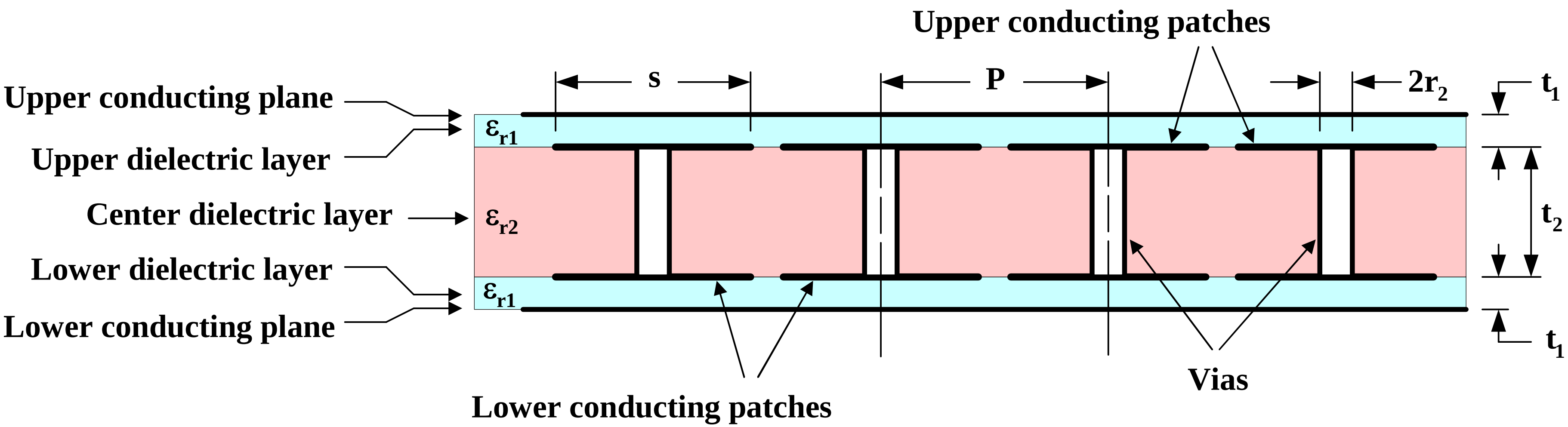
Create an electromagnetically equivalent structure to the infinite capacitively loaded wire media by substituting metal walls in place of the planes of symmetry:



# Structure AC for High Reliability Applications

• Improve reliability since two (blue) dielectric cores separate the power and ground planes.

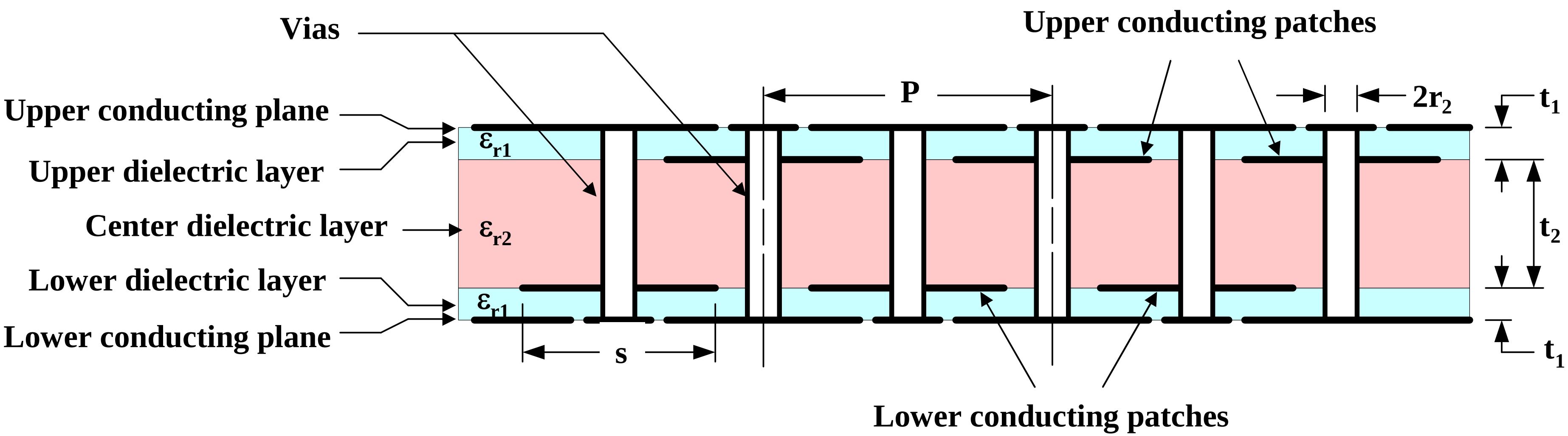
• Mechanically balanced structure to eliminate warping
  - upper and lower cores are matched.



# Structure EF for Lower Frequency Operation

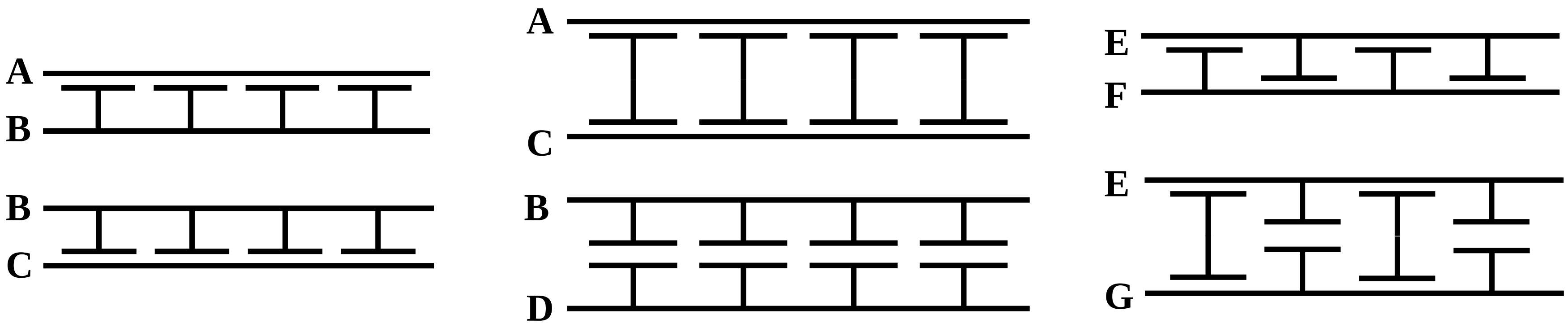
- Mechanically balanced structure to eliminate warping

•The second dielectric layer allows a 2nd coplanar array of patches and vias to be integrated into each unit cell of the array. Hence the density of capacitors is doubled while the unit cell inductance is only reduced by a factor of ln(2). This embodiment results in a net decrease in the cutoff frequency for the fundamental stopband compared to a similar height EBG structure with only one capacitive dielectric layer, such as BD.



# Summary: Metamaterials for Power Plane Noise Suppression

- Beginning with a 3D loaded wire media, at least 6 different parallel-plate EBG structures may be derived having identical stopband performance :




- Stopbands may be calculated from the dispersion equation for 3D wire media:

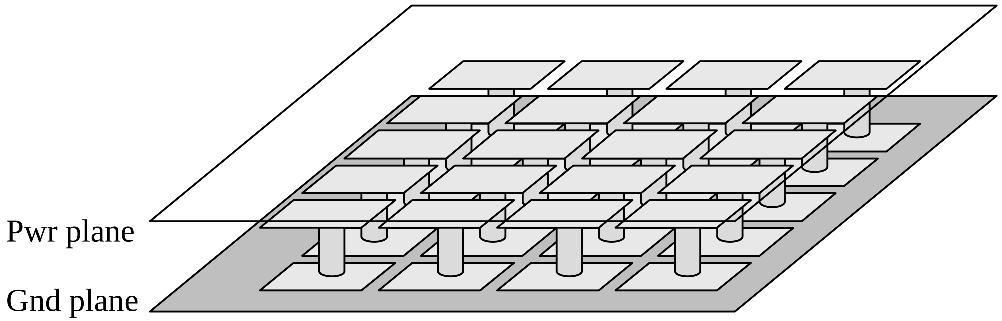
$$\cos(q_x a) = \cos(k_x^{(0)} a) + j \frac{\eta_o / \sqrt{\varepsilon_r}}{2\left( Z_s + \frac{k_x^{(o)}}{k} \frac{b}{c} Z_L \right)} \sin(k_x^{(0)} a)$$

- Applications include omni-directional filters in the power distribution networks at the board and package level.

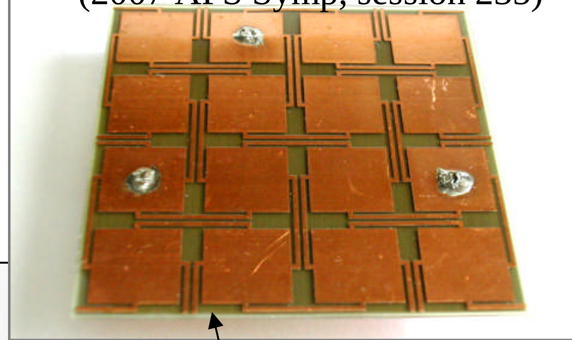
# The Bigger Picture:

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

# To Learn More

References:

1. US Patent 7,215,007 "Circuit and method for suppression of electromagnetic coupling and switching noise in multilayer printed circuit boards."

2. US Patent 7,157,992 "Systems and methods for blocking microwave propagation in parallel plate structures."

3. US Patent 7,123,118 "Systems and methods for blocking microwave propagation in parallel plate structures utilizing cluster vias."

4. Shawn D. Rogers, "Electromagnetic-Bandgap Layers for Broadband Suppression of TEM Modes in Power Planes," *IEEE Trans. on Microwave Theory and Techniques*, Vol. 53, No. 8, August 2005, pp. 2495-2505.