# Electromagnetic Bandgap Structure Integrated within an LTCC Package For Millimeterwave Parasitic Mode Suppression

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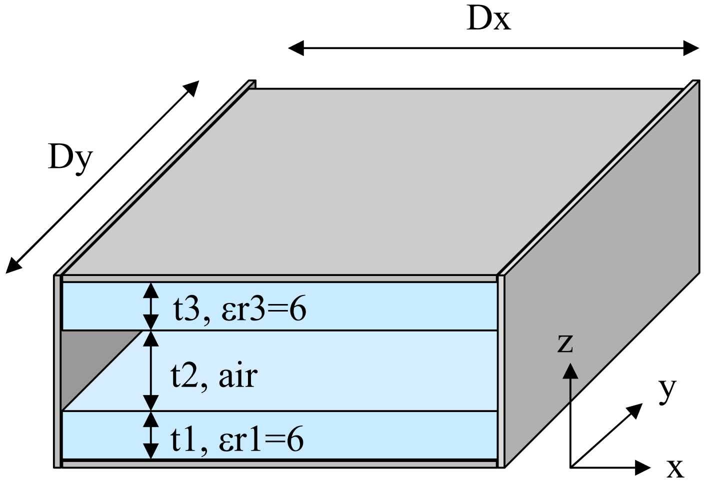
# Outline

1. Motivation: To suppress cavity resonances
2. What is an electromagnetic bandgap (EBG) structure?
3. Why is an EBG structure useful in an RF package?
4. Full-wave two port simulations
5. Analysis using the transverse resonance method (TRM)
6. Summary

# Cavity Modes in a Multi-Layer Rectangular Shielded Package

**Define the physical parameters:**

| | | | |
|---|---|---|---|
| $t1 := 0.25\text{mm}$ | Thickness of dielectric region 1 | $\varepsilon r1 := 6$ | Permittivity of dielectric region 1 |
| $t2 := 0.5\text{mm}$ | Thickness of dielectric region 2 | $\varepsilon r2 := 1$ | Permittivity of dielectric region 2 |
| $t3 := 0.25\text{mm}$ | Thickness of dielectric region 3 | $\varepsilon r3 := 6$ | Permittivity of dielectric region 3 |
| $Dx := 10\text{mm}$ | Cavity x dimension | | |
| $Dy := 10\text{mm}$ | Cavity y dimension | | |



**Calculate the cavtiy resonant frequencies for the quasi-TEM parallel-plate mode. Assume metal shielding on all walls.**

$m := 0,1..6 \qquad n := 0,1..6$

$$\varepsilon\_eff\_z := \frac{t1 + t2 + t3}{\frac{t1}{\varepsilon r1} + \frac{t2}{\varepsilon r2} + \frac{t3}{\varepsilon r3}} \qquad \varepsilon\_eff\_z = 1.714$$

$$F_{m,n} := \frac{c}{2\pi} \cdot \sqrt{\frac{1}{\varepsilon\_eff\_z}\left(\frac{m \cdot \pi}{Dx}\right)^2 + \frac{1}{\varepsilon\_eff\_z}\left(\frac{n \cdot \pi}{Dy}\right)^2}$$

**Resonant frequencies for the cavity are then:**

$$\frac{F}{\text{GHz}} = \begin{pmatrix} 0 & 11.4 & 22.9 & 34.3 & 45.8 & 57.2 & 68.7 \\ 11.4 & 16.2 & 25.6 & 36.2 & 47.2 & 58.4 & 69.6 \\ 22.9 & 25.6 & 32.4 & 41.3 & 51.2 & 61.7 & 72.4 \\ 34.3 & 36.2 & 41.3 & 48.6 & 57.2 & 66.8 & 76.8 \\ 45.8 & 47.2 & 51.2 & 57.2 & 64.8 & 73.3 & 82.6 \\ 57.2 & 58.4 & 61.7 & 66.8 & 73.3 & 81 & 89.4 \\ 68.7 & 69.6 & 72.4 & 76.8 & 82.6 & 89.4 & 97.1 \end{pmatrix}$$

# What is an Electromagnetic Bandgap (EBG) Structure? (1 of 2)

1. In general, an electromagnetic bandgap (EBG) structure is a **2D or 3D metal and/or dielectric structure that will suppress the propagation of electromagnetic waves.**

2. EBG structures are **always periodic**, or repeating, structures. They have a unit cell and a period,

3. EBG structures **always have bandgaps, or stopbands**, where electromagnetic waves are forbidden.

4. They are omni-directional. Waves are **forbidden to propagate in all possible directions** (full bandgap).

5. EBG structures have been designed for widely varying frequency ranges, **from VHF to millimeterwave.**

# What is an Electromagnetic Bandgap (EBG) Structure? (2 of 2)

Dan Sievenpiper's high-impedance surface is the most published EBG structure. It was originally conceived to suppress surface currents (TM surface waves) in open structures.

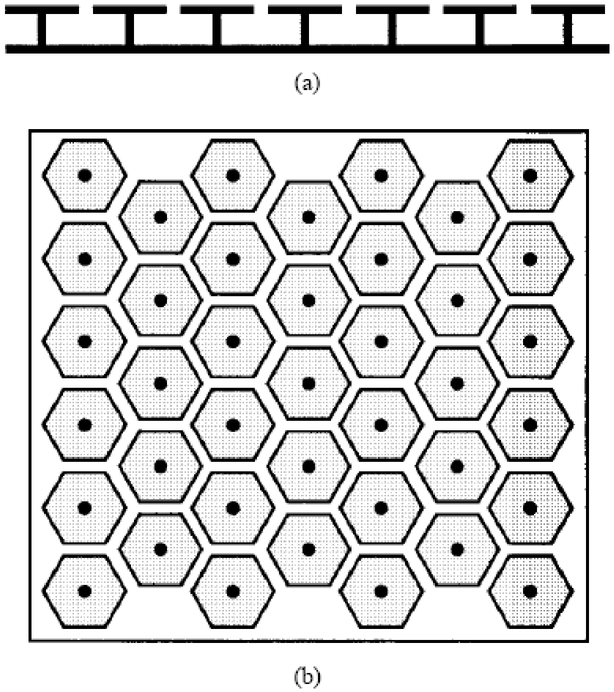
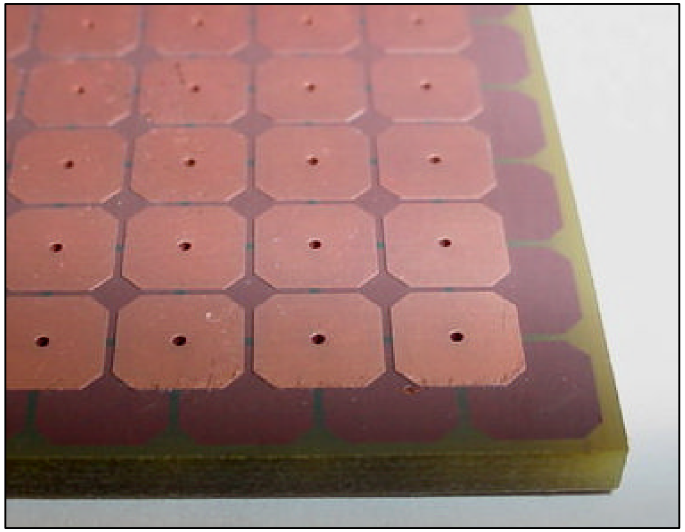


Fig. 1. (a) Cross section of a high-impedance surface, fabricated as a printed circuit board. The structure consists of a lattice of metal plates, connected to a solid metal sheet by vertical conducting vias. (b) Top view of the high-impedance surface, showing a triangular lattice of hexagonal metal plates.

Sievenpiper et. al., IEEE Trans. MTT, Nov 1999, pp. 2059-2074.

Features:

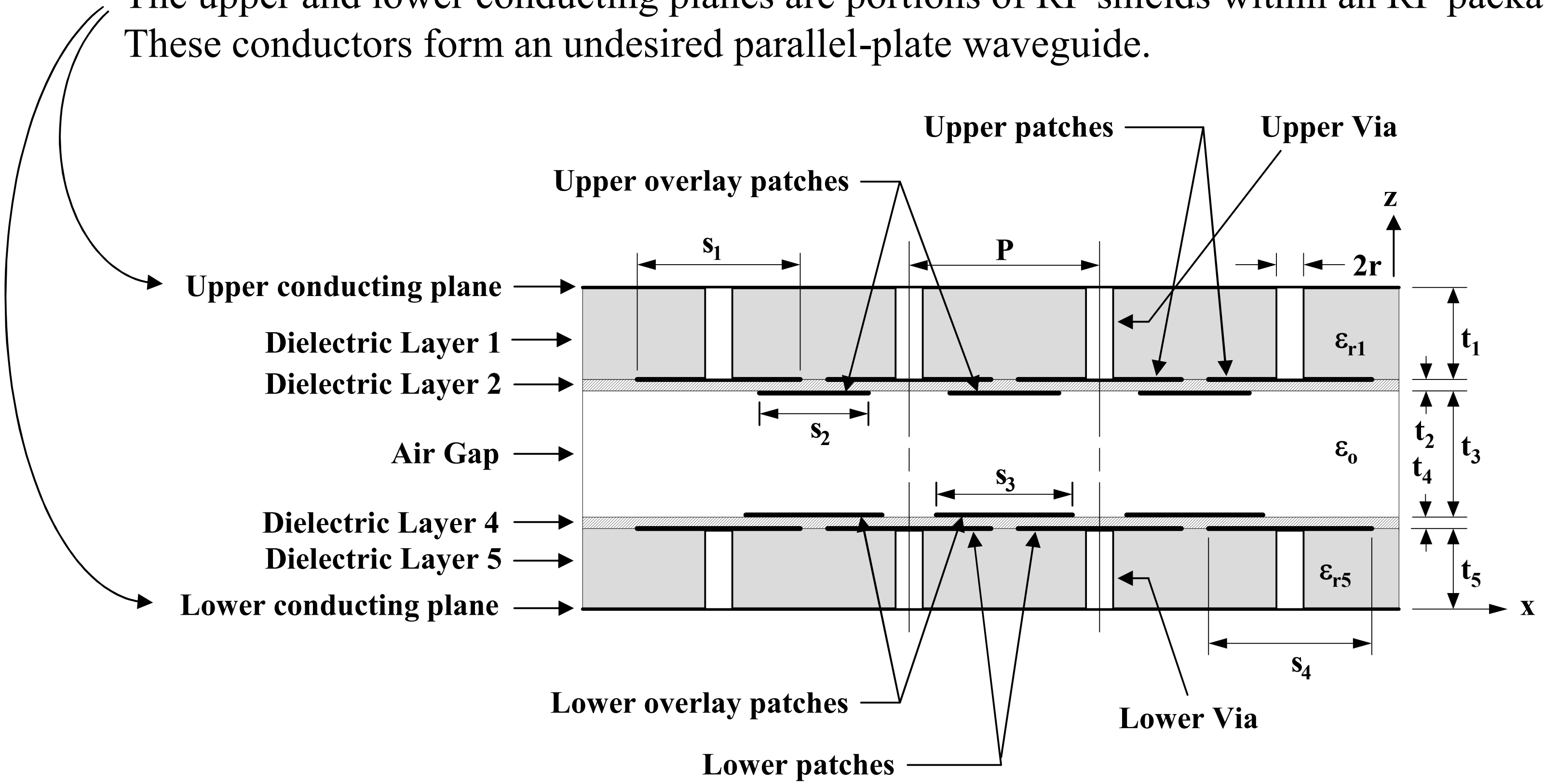
1. 2D array of patches
2. Metal backplane, or ground plane
3. Array of vias between patches and ground plane



S. Rogers et. al., IEEE APS Symp, 2003.

# EBG Structure Used in this Work

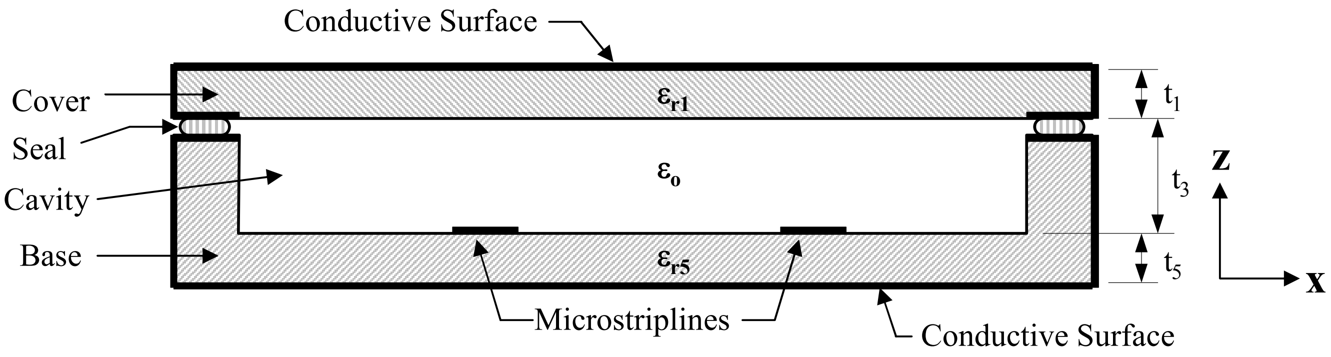
The upper and lower conducting planes are portions of RF shields within an RF package. These conductors form an undesired parallel-plate waveguide.



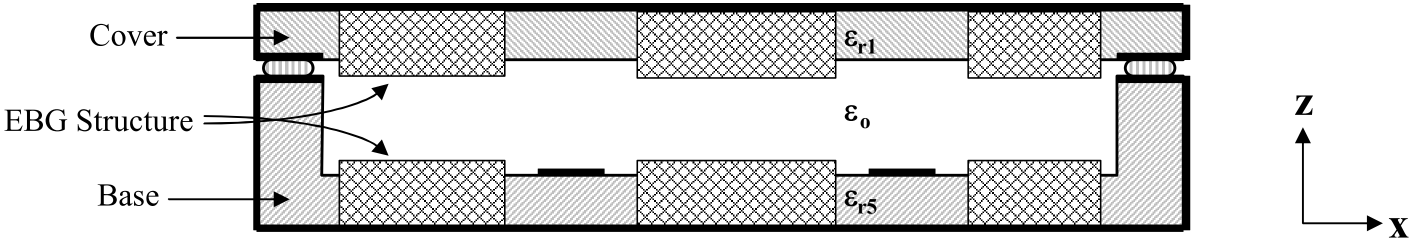
For this application, an EBG structure is a periodic metal and dielectric structure that functions as as bandstop filter for undesired parallel-plate waveguide modes.

# Why is an EBG Structure Useful in an RF Package?

Assume we have a shielded chip carrier or a System in Package (SiP).



Selectively introduce EBG structures into the cover and base:



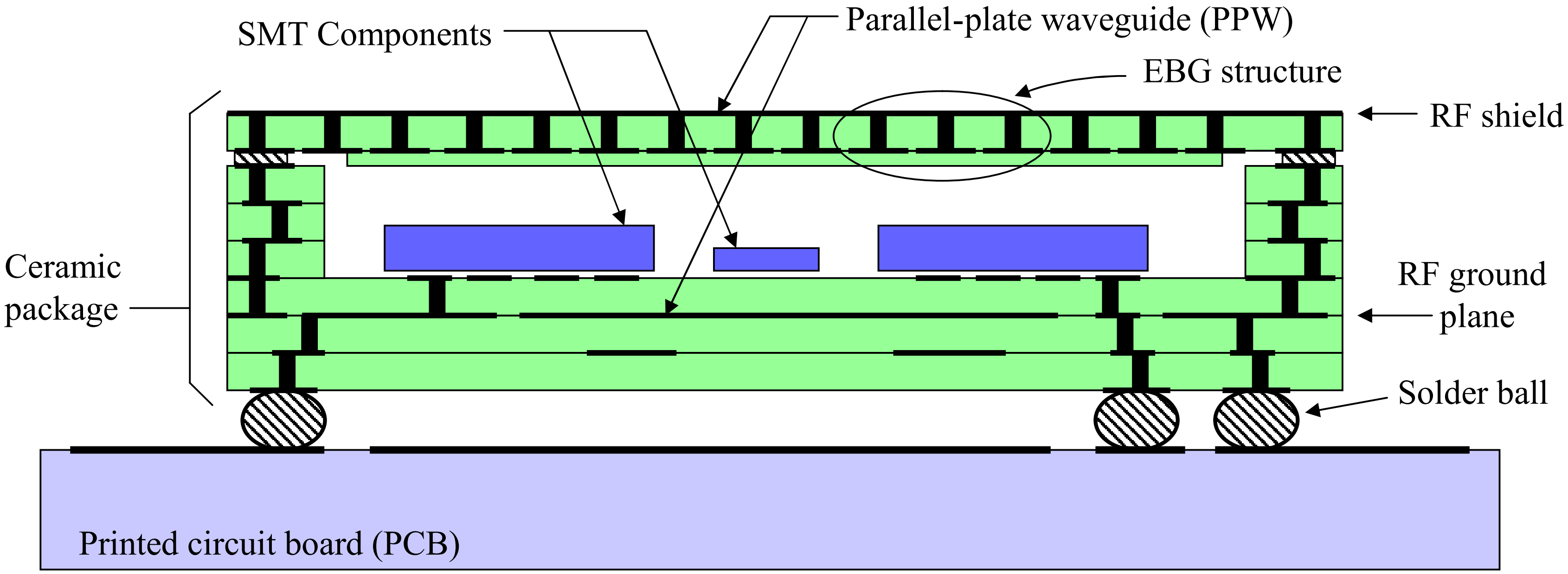
The EBG structure can be used to

1. Mitigate internal coupling or crosstalk between RF transmission lines inside the package.
2. Prevent transmission lines and vertical interconnects from exciting parasitic package modes.

# An EBG Structure is Integrated into the Cover of a Shielded Module to Suppress Coupling and Parasitic Modes

Metal shields are often used for EMI and EMC reasons. A cavity is formed when a metalized cover is designed into a ceramic SiP module. However, any enclosed metal cavity has characteristic resonant modes, which in this package application, can cause undesired system effects.

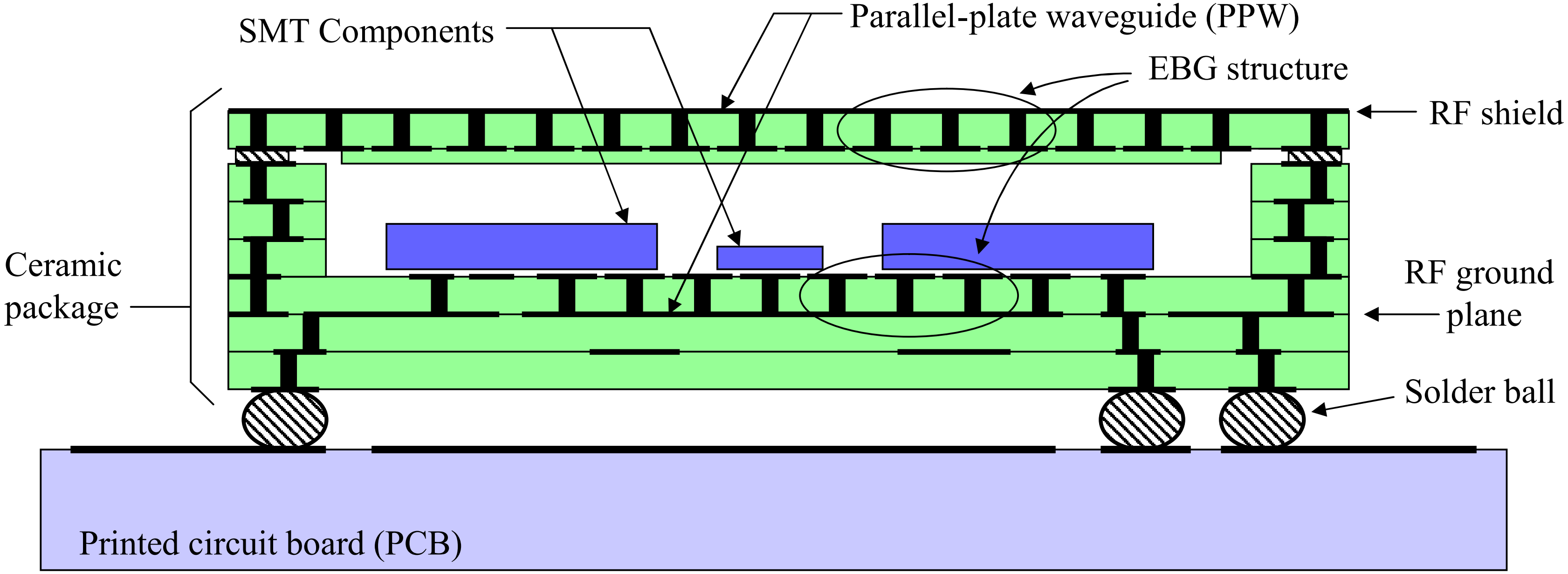
An EBG structure may be fabricated into the cover of the ceramic module to cutoff PPW modes over a limited band of frequencies.



# EBG Structures Are Integrated into the Cover and Base of a Shielded Module to Suppress Coupling & Parasitic Modes

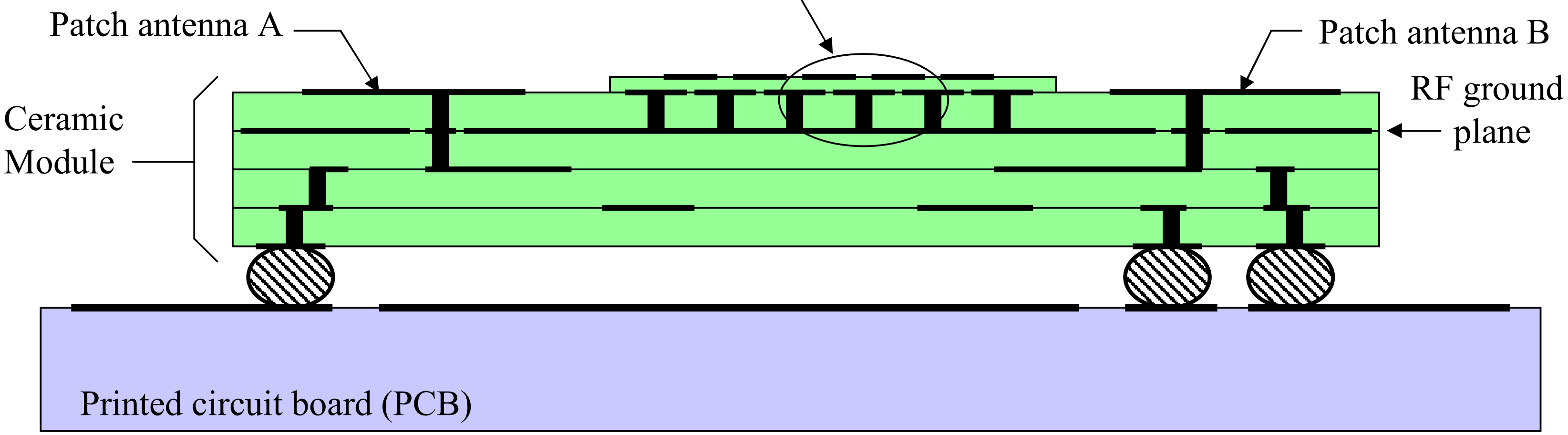
Metal shields are often used for EMI and EMC reasons. A cavity is formed when a metalized cover is designed into a ceramic SiP module. However, any enclosed metal cavity has characteristic resonant modes, which in this package application, can cause undesired system effects.

An EBG structure may be fabricated into the cover and into portions of the base of the ceramic module to cutoff PPW modes over a limited band of frequencies. Stopband bandwidth and attenuation per unit cell is improved with the use of both base and cover EBG structures.

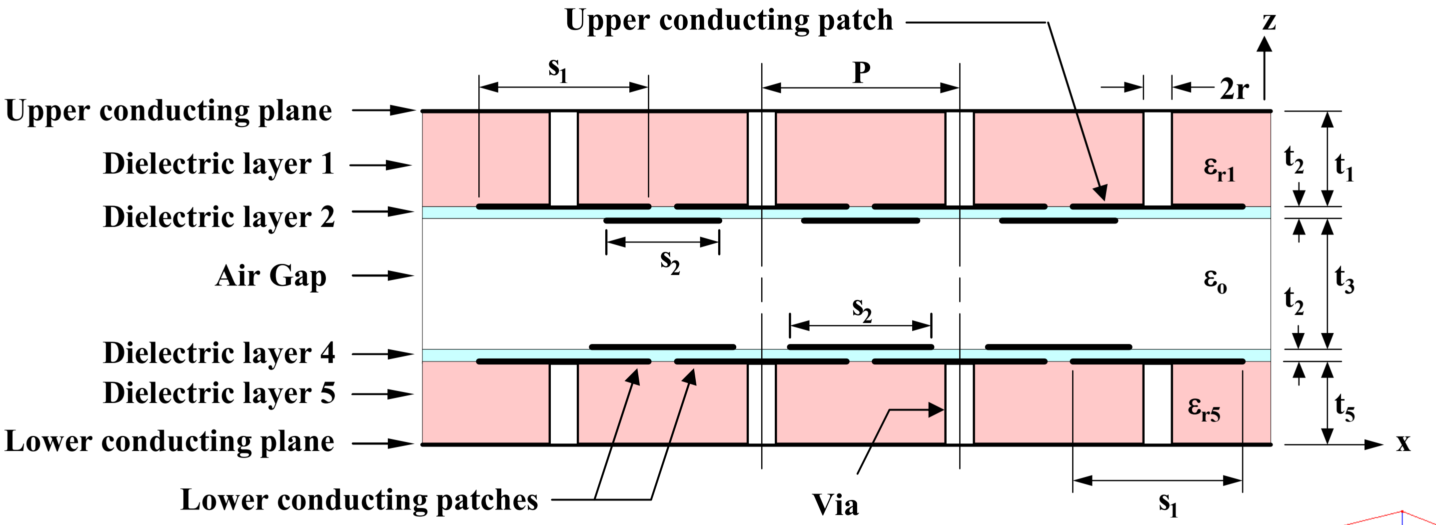


# Other Uses for EBG Structures in an RF Package

1. Mitigation of external coupling or crosstalk between signal pads on the bottom of the package, between the package and board. (A. Ziroff et. al, *33rd European Microwave Conf.*, 2003)
2. Suppression of external surface currents around an antenna element to control pattern shape
3. Mitigation of external mutual coupling between embedded slot or patch antenna elements
    - In diversity or MIMO antenna systems - need to isolate adjacent antennas on the package
    - Dominant coupling mechanism is TM surface waves on the same ground plane
    - An external EBG structure may be fabricated into the top of the package
    - Minor impact on antenna efficiency



# Example 1: Full-Wave Simulation



**Analysis parameters:**

P = 500 um, square lattice

s1 = s2 = 390 um

t1 = t5 = 300 um (12 mils)

t2 = t4 = 25 um (1 mil)

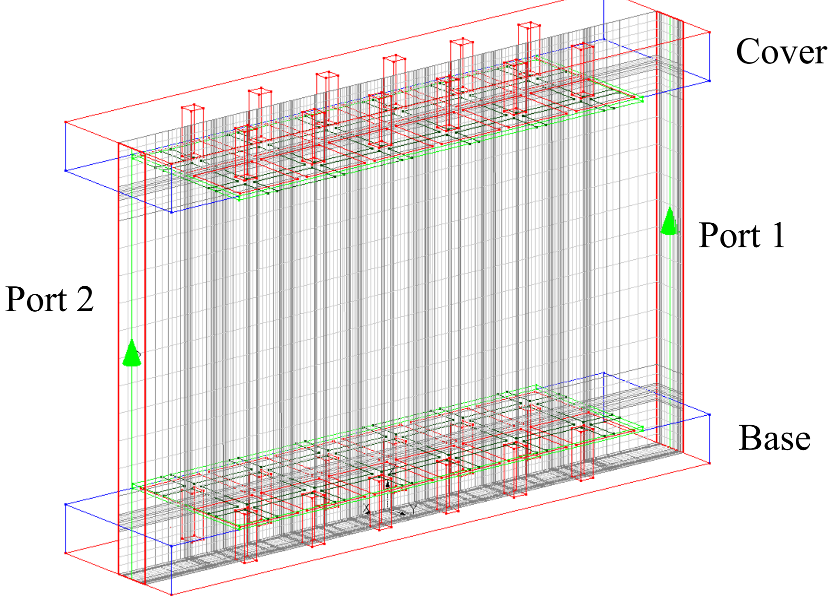
t3 = 2050 um (air gap)

2r = 90 um on a side as a square via (area of a 4 mil via)

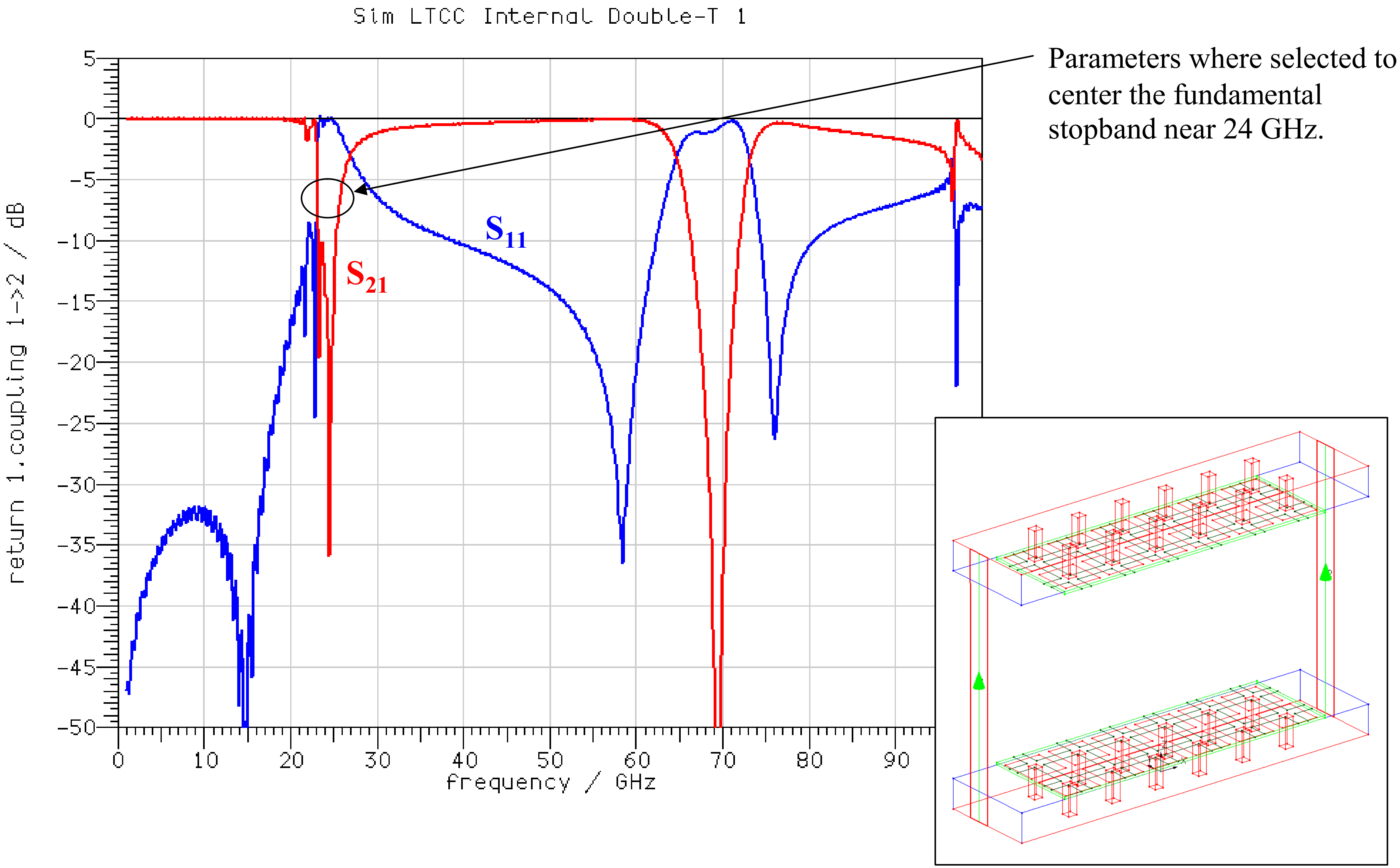
Dielectric layers 1 and 5 are ceramic with $\varepsilon_{r1} = \varepsilon_{r5} = 6$

Dielectric layer 2 and 4 are ceramic with $\varepsilon_{r2} = \varepsilon_{r4} = 10$

All simulations performed using Microstripes™

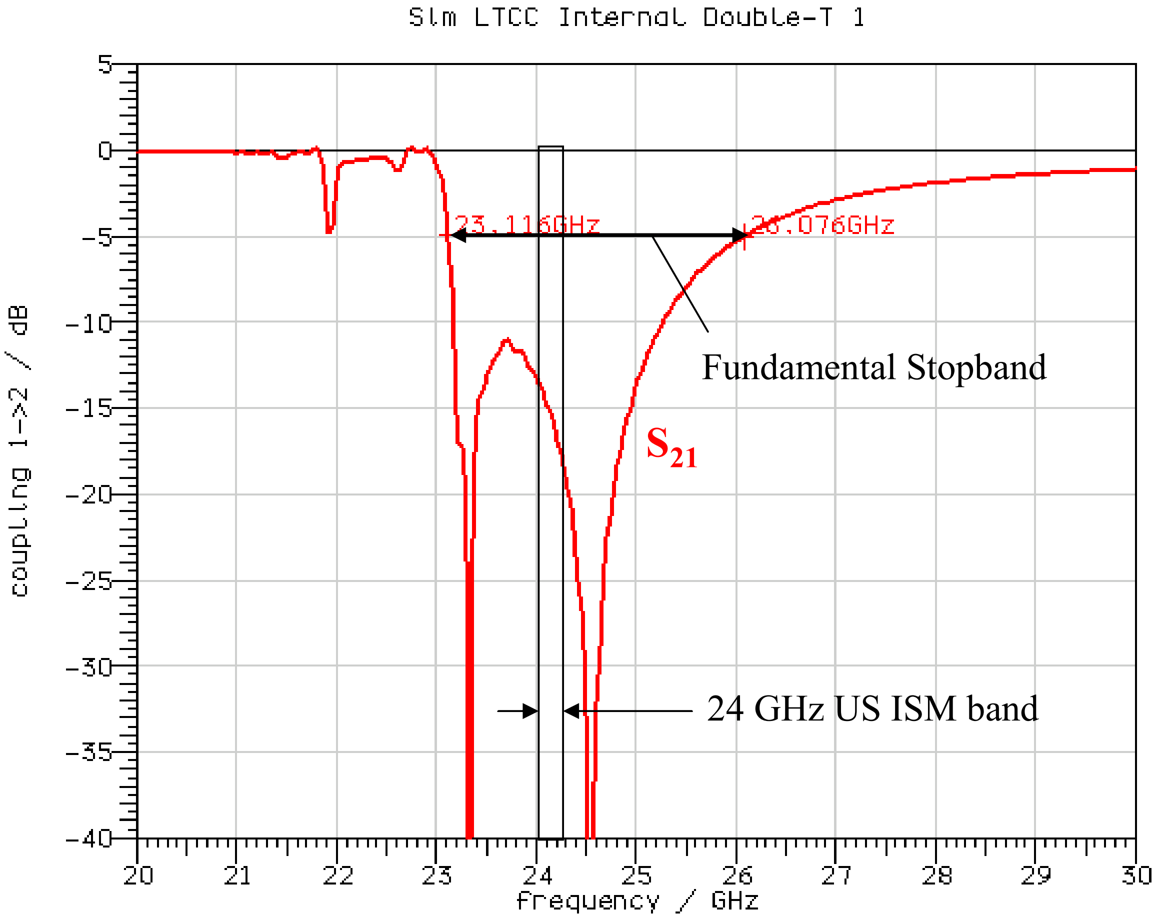


# Transmission and Reflection Response for Example 1



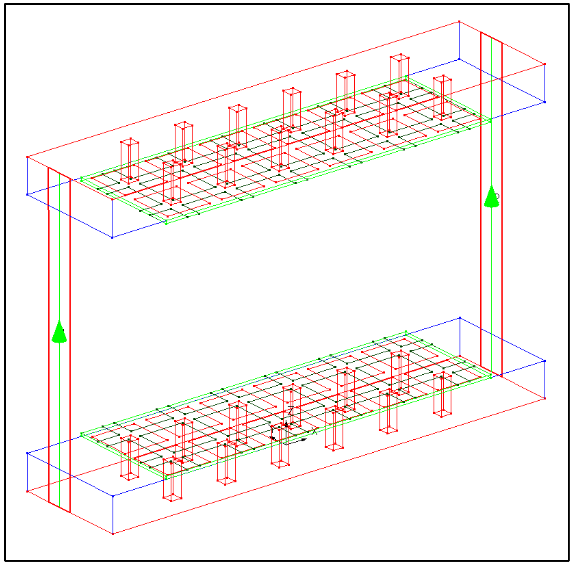
Parameters where selected to center the fundamental stopband near 24 GHz.

# Transmission Response for Example 1



The fundamental stopband encompasses the
24 GHz US ISM band: 24.0 GHz to 24.250 GHz.

Design parameters:
P = 500 um, square lattice
s1 = s2 = 390 um patch sizes
t1 = t5 = 300 um (12 mils)
t2 = t4 = 25 um (1 mil)
t3 = **2050 um air gap**
90 um square via
$\varepsilon_{r1} = \varepsilon_{r5} = 6$
$\varepsilon_{r2} = \varepsilon_{r4} = 10$



# Example 2: Full-Wave Simulation

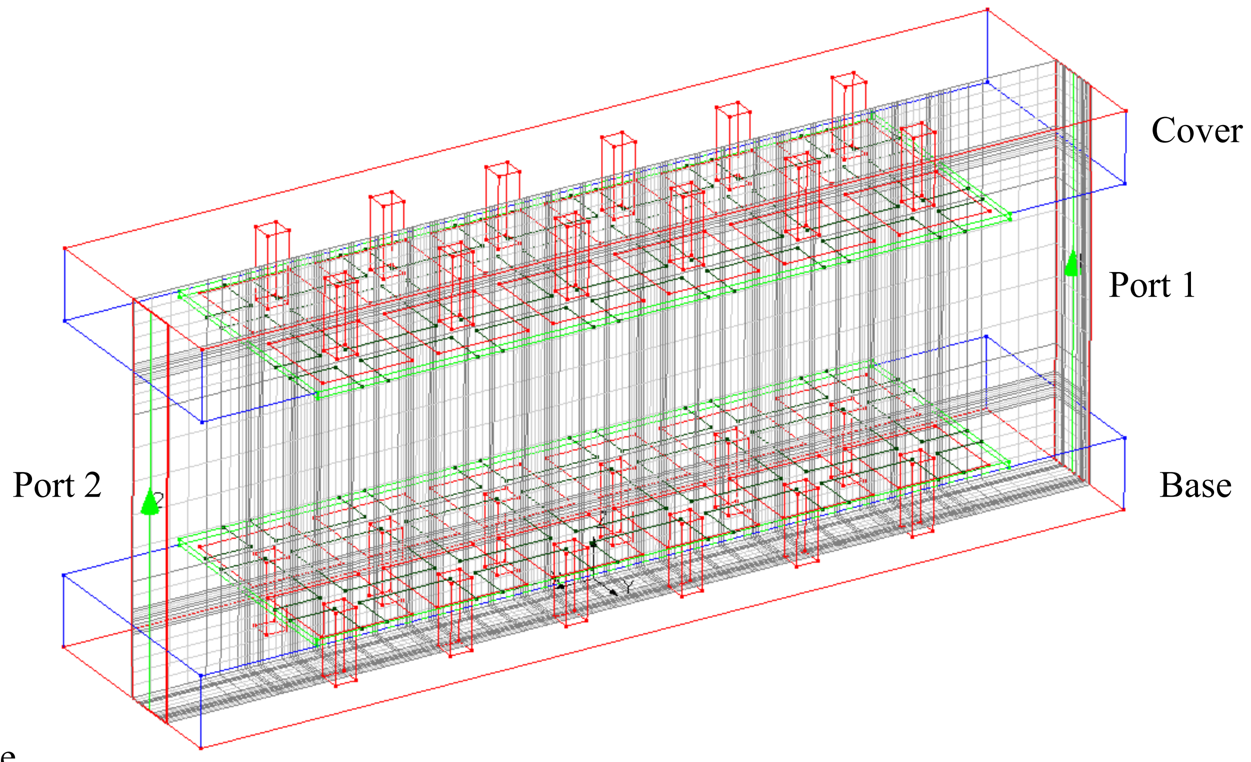
Design parameters:
P = 500 um, square lattice
s1 = s2 = 390 um patch sizes
t1 = t5 = 300 um (12 mils)
t2 = t4 = 25 um (1 mil)
t3 = **1050 um air gap**
90 um square via
$\varepsilon_{r1} = \varepsilon_{r5} = 6$
$\varepsilon_{r2} = \varepsilon_{r4} = 10$

Workspace
- $-4P < x < 4P$
- $0 < y < 0.5P$
- $0 < z < t1 + t2 + t3$

Boundary Conditions:
- ABCs at xmin and xmax
- H-wall at ymin and ymax
- ABC at zmin and zmax

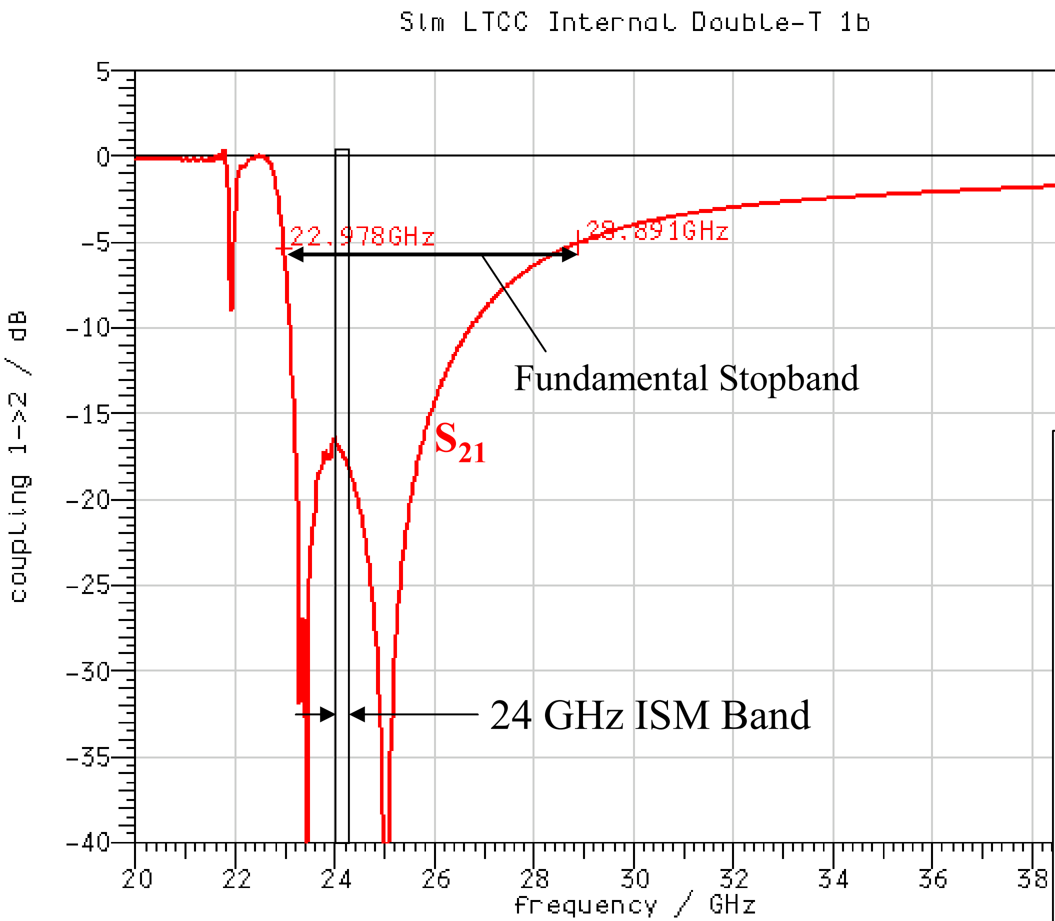
Material Loss:
- All vias, and ground planes are modeled as lossless
- Substrate, superstrate, and FSS dielectrics are modeled as lossless ceramic.

**The air gap height is reduced from example 1 by about 50%.**



Dynamic meshing enabled
Minimum cell size is 10 um
Maximum cell size is 200 um

# Transmission Response for Example 2



Design parameters:
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s1 = s2 = 390 um patch sizes
t1 = t5 = 300 um (12 mils)
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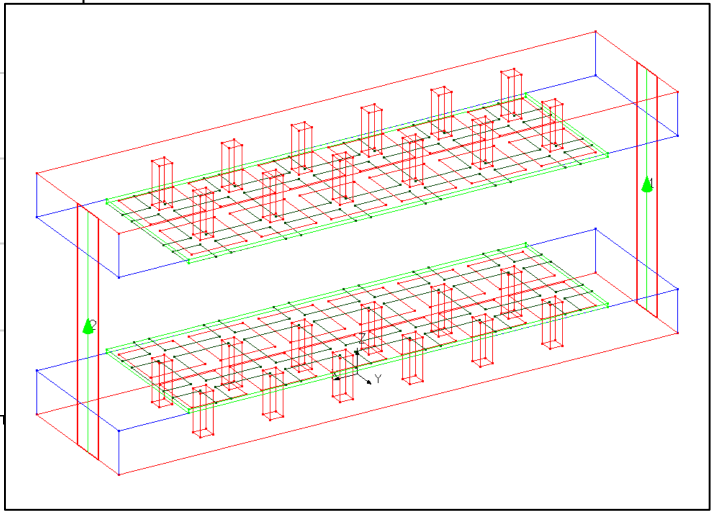
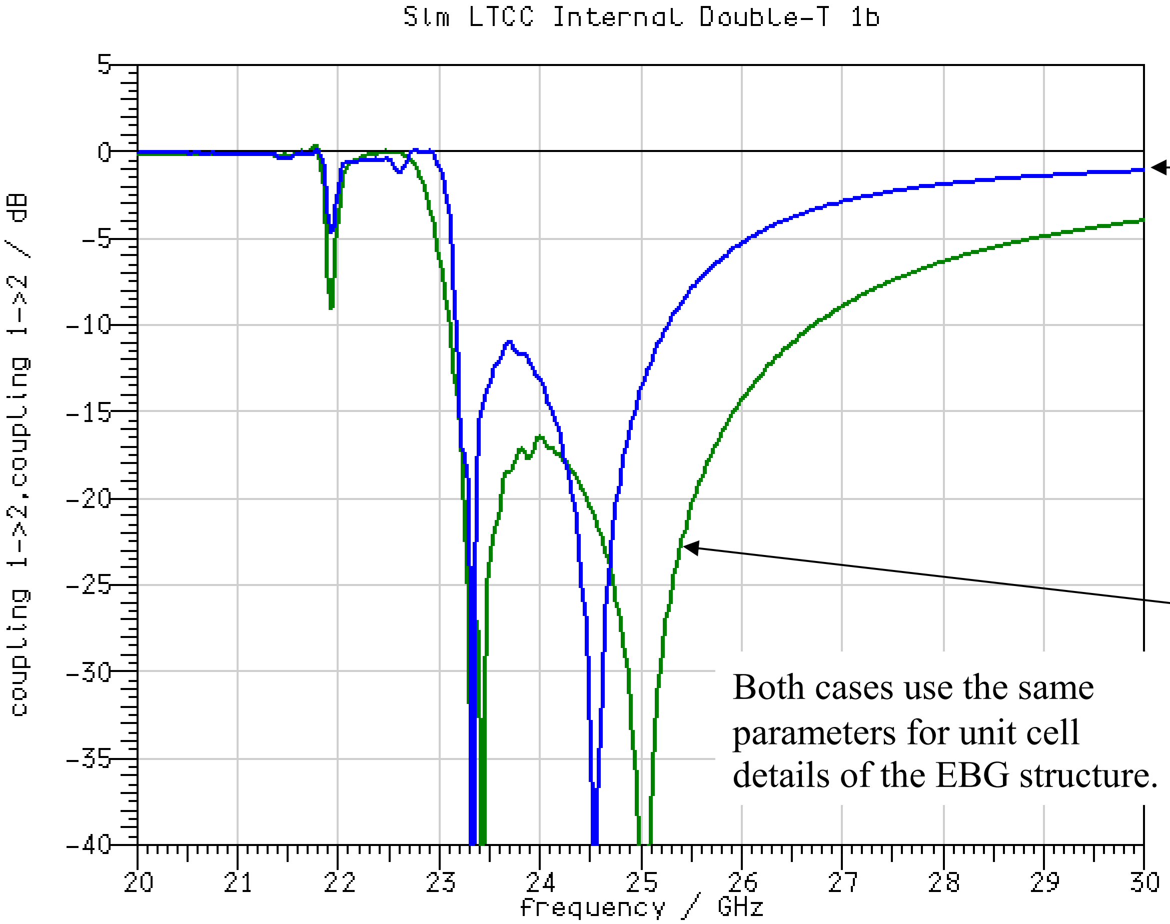
t3 = **1050 um air gap**
90 um square via
$\varepsilon_{r1} = \varepsilon_{r5} = 6$, $\varepsilon_{r2} = \varepsilon_{r4} = 10$

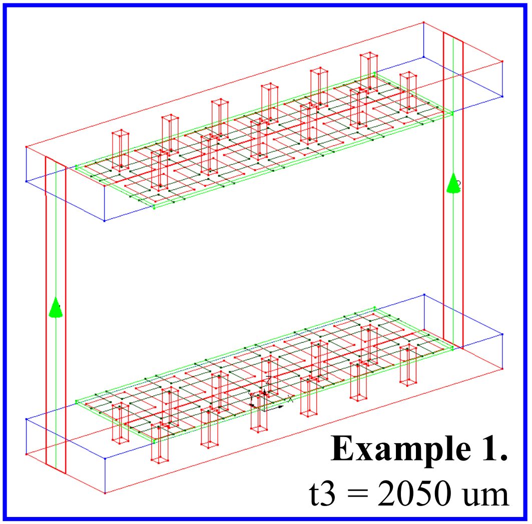


The fundamental stopband encompasses the
24 GHz US ISM band: 24.0 GHz to 24.250 GHz.

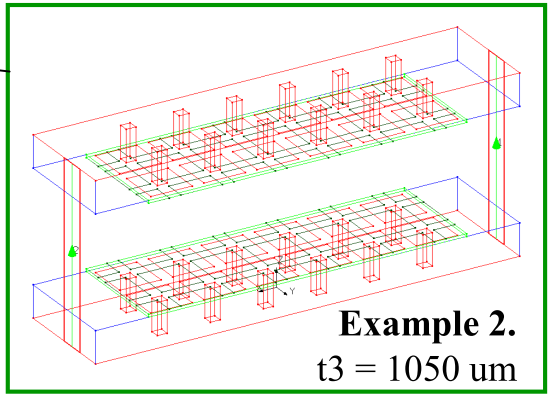
# Comparison of Internal EBG Structures with Different Air Gap Heights



Both cases use the same parameters for unit cell details of the EBG structure.



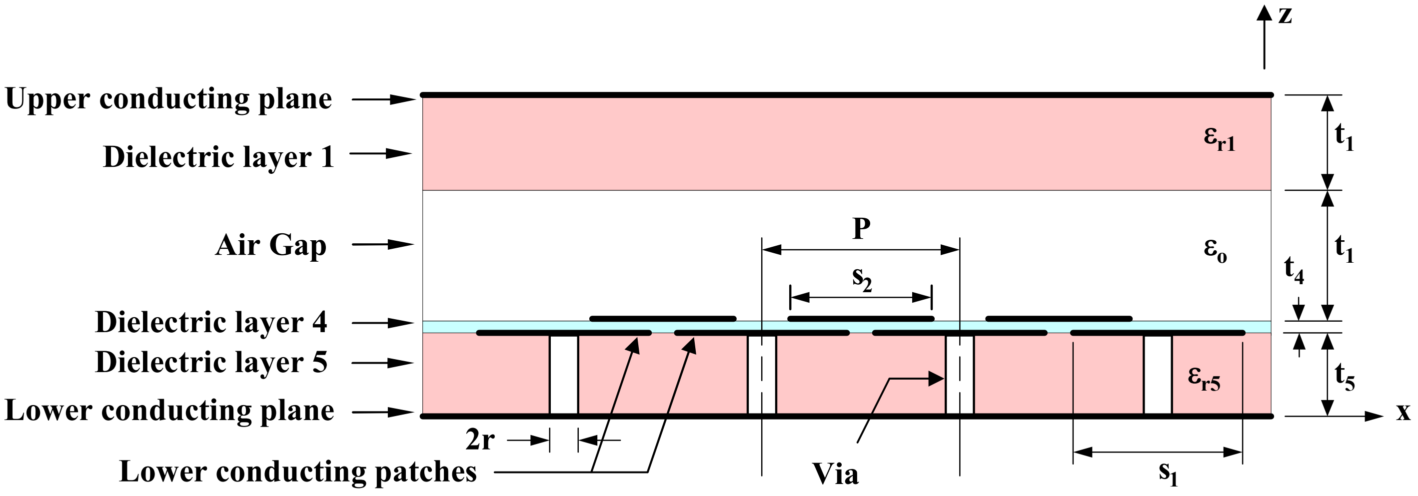
**Example 1.**
t3 = 2050 um



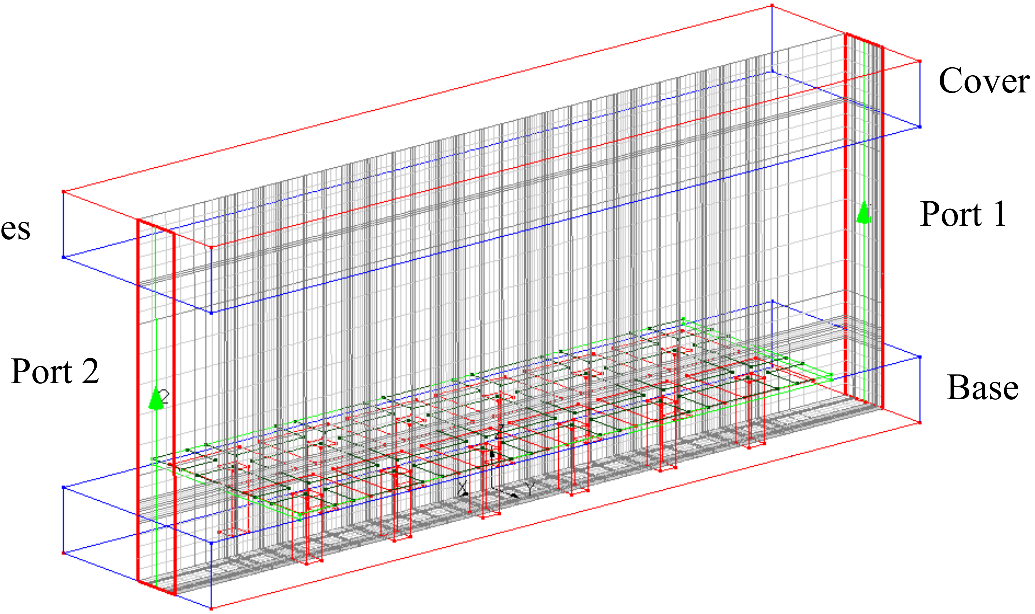
**Example 2.**
t3 = 1050 um

Smaller cover heights yield a broader stopband.

# Example 3: Full-Wave Simulation

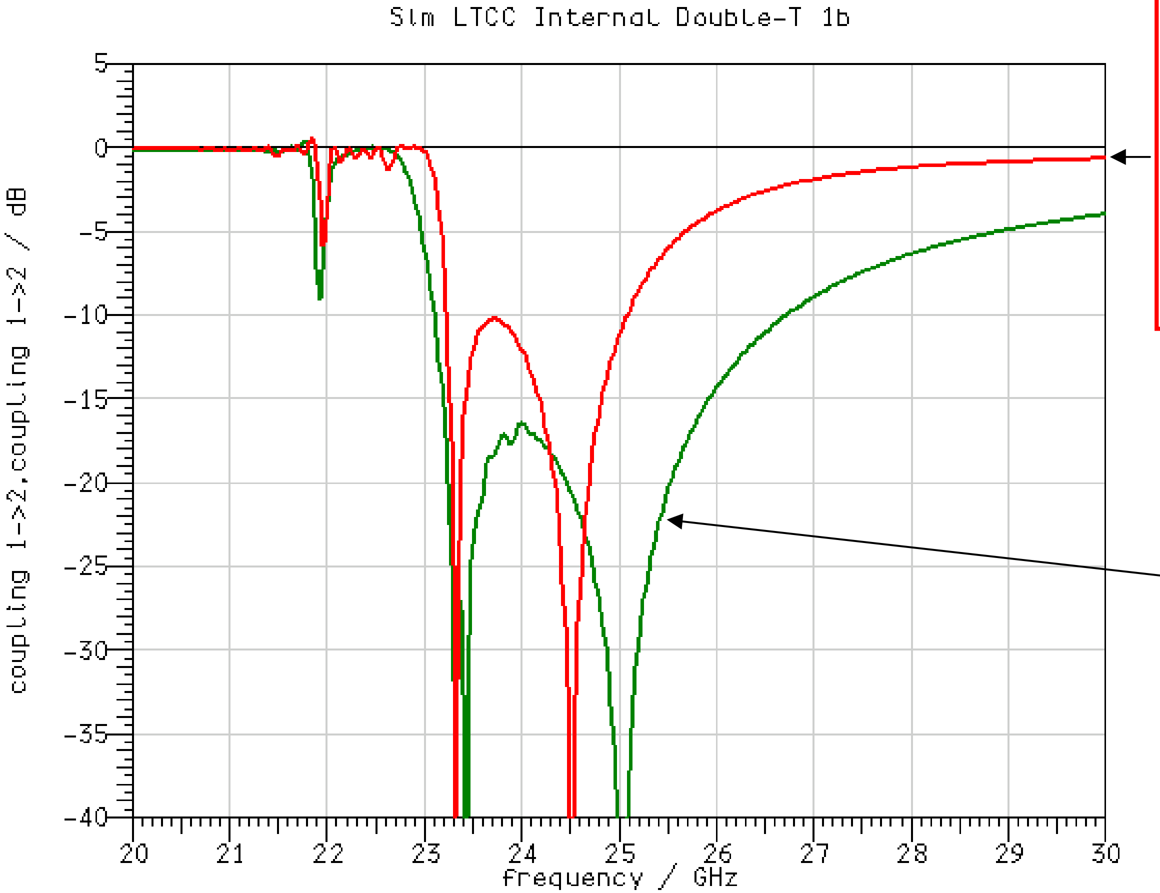


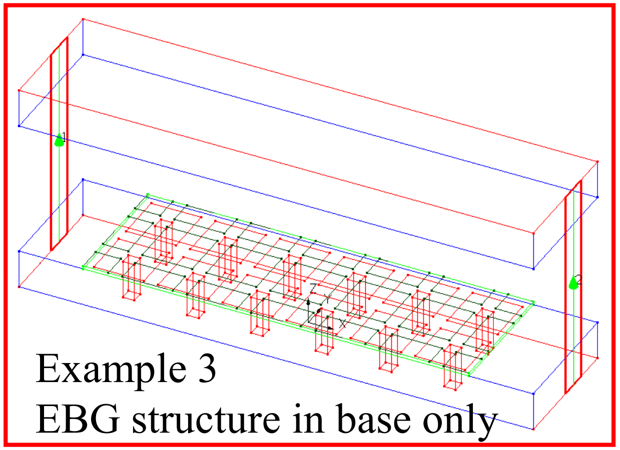
Design parameters:
P = 500 um, square lattice
s1 = s2 = 390 um patch sizes
t1 = t5 = 300 um (12 mils)
t2 = t4 = 25 um (1 mil)
t3 = **1050 um air gap**
90 um square via
$\varepsilon_{r1} = \varepsilon_{r5} = 6$
$\varepsilon_{r2} = \varepsilon_{r4} = 10$



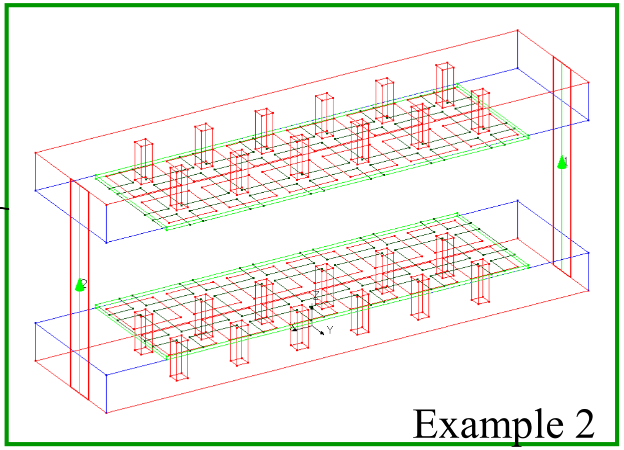
# Comparison of Transmission for EBG Structures in the Base Only vs. Base and Cover

Both cases use the same parameters for dielectric layers, air gaps, and unit cell details.





Example 3
EBG structure in base only



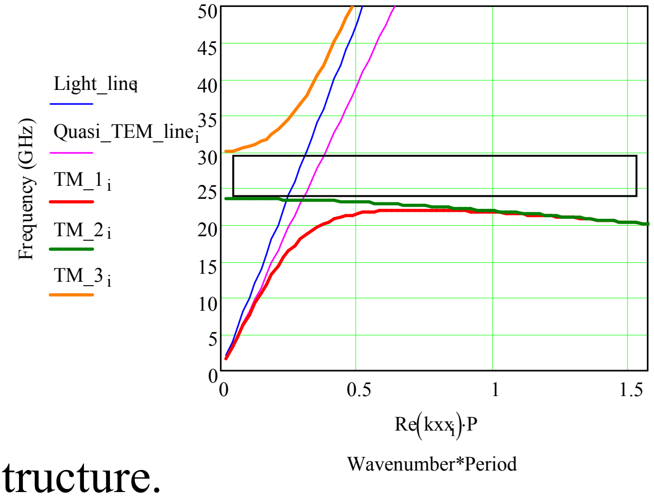
Example 2
EBG structure in cover and base

Use of an EBG structure in the base and cover yield a broader stopband.

# Transverse Resonance Method: Overview

- Mathematical technique to calculate the complex propagation constant in the *x* direction, $k_x$, as a function of frequency

- Plots of $k_x$ versus frequency are dispersion diagrams which reveal stopbands



Stopband

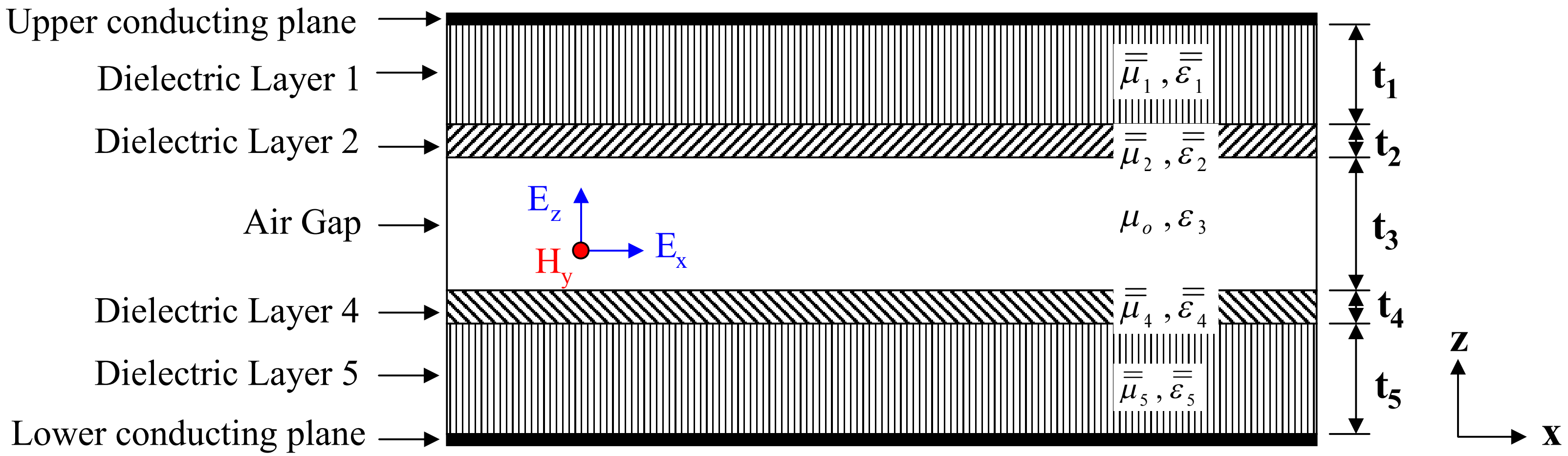
- Method assumes an infinite periodic structure.

- Will be used to find TM modes, whose dominant mode is the quasi-TEM mode of the inhomogeneous parallel-plate waveguide.

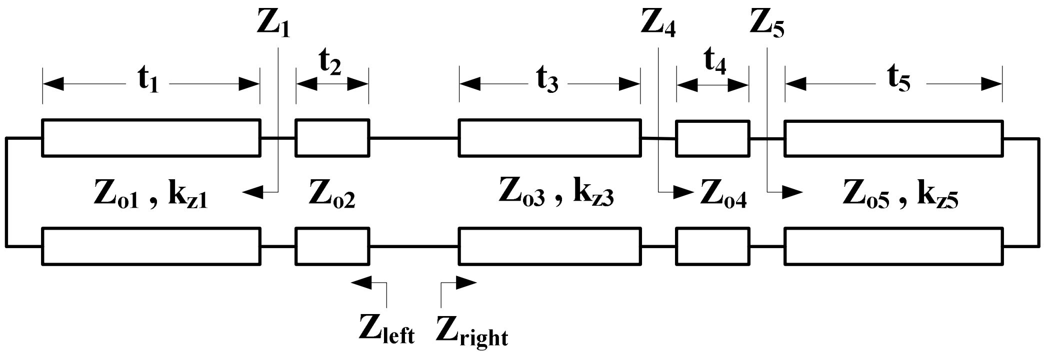
- Fast numerical algorithm that runs on Mathcad or similar math tools.

# Transverse Resonance Method: Transmission Line Model

Transform each layer of the EBG structure into an effective homogeneous media with tensor permittivity and permeability:



Model each layer as an **equivalent transmission line** with a unique propagation constant, $k_{zi}$, in the normal direction.



The TM-to-z mode has a characteristic impedance of $Z_{oi} = \dfrac{k_{zi}}{\omega \varepsilon_o \varepsilon_{xi}}$ for layers $i = 1, 2, 3, 4$ and 5.

# Transverse Resonance Method: Transmission Line Equations

The continuity of $E_x$ and $H_y$ at any reference plane lead directly to the transverse resonance equation:

$$\boxed{Z_{left}(\omega)+Z_{right}(\omega)=0}$$

Where conventional transmission line equations allow us to write

$$Z_{left}(\omega)=Z_{o2}\frac{Z_1\cos(k_{z2}t_2)+jZ_{o2}\sin(k_{z2}t_2)}{Z_{o2}\cos(k_{z2}t_2)+jZ_1\sin(k_{z2}t_2)}$$

where

$$Z_1(\omega)=jZ_{o1}\tan(k_{z1}t_1)$$

and

$$Z_{right}(\omega)=Z_{o3}\frac{Z_4\cos(k_{z3}t_3)+jZ_{o3}\sin(k_{z3}t_3)}{Z_{o3}\cos(k_{z3}t_3)+jZ_4\sin(k_{z3}t_3)}$$

where

$$Z_4(\omega)=Z_{o4}\frac{Z_5\cos(k_{z4}t_4)+jZ_{o4}\sin(k_{z4}t_4)}{Z_{o4}\cos(k_{z4}t_4)+jZ_5\sin(k_{z4}t_4)}$$

$$Z_5(\omega)=jZ_{o5}\tan(k_{z5}t_5)$$

# Transverse Resonance Method: TM Mode Propagation Constants

- ***$k_x$* is only a function of frequency** since the TM mode travels at the same speed in the x direction in all five layers of the multi-layered package.

- ***$k_z$* is a function of frequency and layer** because it depends on permittivity and permeability tensors that depend on layer host medium properties and unit cell geometry.

- For TM modes, the propagation constant in the *z* direction is

$$k_{zi}(\omega,k_x)=\sqrt{\left(\frac{\omega}{c}\right)^2\varepsilon_{xi}\mu_{yi}-k_x^2\frac{\varepsilon_{xi}}{\varepsilon_{zi}}}$$ , for $i = 1,2,4$ and 5.

$$k_{z3}(\omega,k_x)=\sqrt{\left(\frac{\omega}{c}\right)^2\varepsilon_{x3}-k_x^2}$$ for the air region

- Constituent material parameters $\varepsilon_{xi}$ and $\mu_{yi}$ and $\varepsilon_{zi}$ are tensor elements of an effective homogeneous media for each layer except the air region.

# Transverse Resonance Method: Effective Media Model

In the long wavelength limit, the **complexity of the unit cell geometry is replaced by homogeneous layers** whose effective constituent parameters are approximated by:

For $i$ = 1 and 5 (via layers)

$$\bar{\bar{\varepsilon}}_i = \begin{bmatrix} \varepsilon_{xi} & 0 & 0 \\ 0 & \varepsilon_{yi} & 0 \\ 0 & 0 & \varepsilon_{zi} \end{bmatrix} = \begin{bmatrix} \cong \varepsilon_{ri} & 0 & 0 \\ 0 & \cong \varepsilon_{ri} & 0 \\ 0 & 0 & \varepsilon_{ri}\left[1-\left(\dfrac{\omega_p}{\omega}\right)^2\right] \end{bmatrix}$$

$$\bar{\bar{\mu}}_i = \begin{bmatrix} \mu_{xi} & 0 & 0 \\ 0 & \mu_{yi} & 0 \\ 0 & 0 & \mu_{zi} \end{bmatrix} = \begin{bmatrix} \cong \mu_{ri} & 0 & 0 \\ 0 & \cong \mu_{ri} & 0 \\ 0 & 0 & \cong \mu_{ri} \end{bmatrix}$$

For $i$ = 2 and 4 (capacitive FSS layers)

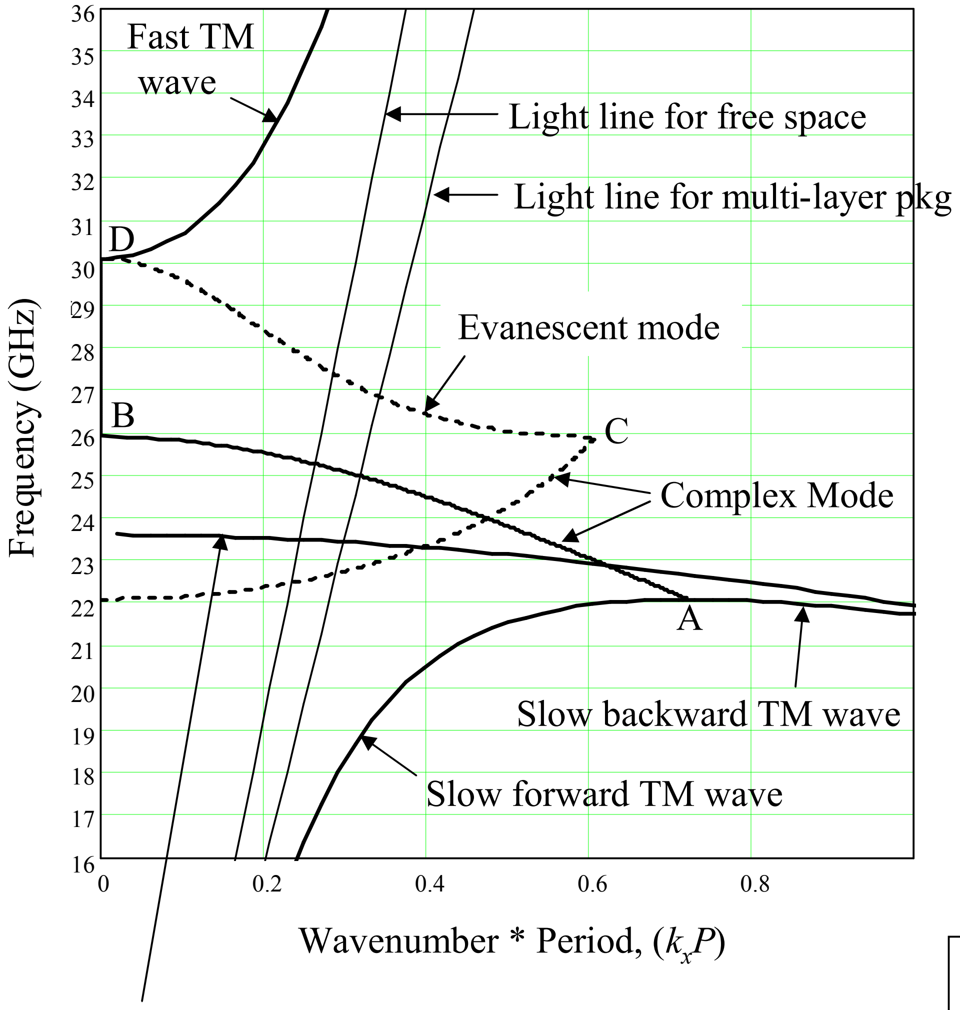
$$\bar{\bar{\varepsilon}}_i = \begin{bmatrix} \varepsilon_{xi} & 0 & 0 \\ 0 & \varepsilon_{yi} & 0 \\ 0 & 0 & \varepsilon_{zi} \end{bmatrix} = \begin{bmatrix} \dfrac{C_i}{\varepsilon_o t_i} & 0 & 0 \\ 0 & \dfrac{C_i}{\varepsilon_o t_i} & 0 \\ 0 & 0 & \cong \varepsilon_{ri} \end{bmatrix}$$

$$\bar{\bar{\mu}}_i = \begin{bmatrix} \mu_{xi} & 0 & 0 \\ 0 & \mu_{yi} & 0 \\ 0 & 0 & \mu_{zi} \end{bmatrix} = \begin{bmatrix} \cong \mu_{ri} & 0 & 0 \\ 0 & \cong \mu_{ri} & 0 \\ 0 & 0 & \dfrac{2\varepsilon_{avg}}{\varepsilon_{trans,i}} \end{bmatrix}$$

Details for the effective media model of the EBG structure is given in the following reference:

S. Clavijo, R. E. Diaz, and W. E. McKinzie. "Design Methodology for Sievenpiper High-Impedance Surfaces: An Artificial Magnetic Conductor for Positive Gain Electrically-Small Antennas," IEEE Trans. Microwave Theory and Techniques, Vol. 51, No. 10, Oct 2003, pp. 2678-2690.

# Transverse Resonance Method: TM Mode Dispersion Plot for Example 2



This backward TM wave is difficult to excite.

Design parameters:
P = 500 um, square lattice
s1 = s2 = 390 um patch sizes
t1 = t5 = 300 um (12 mils)
t2 = t4 = 25 um (1 mil)
t3 = **1050 um air gap**
90 mils square via
$\varepsilon_{r1} = \varepsilon_{r5} = 6$
$\varepsilon_{r2} = \varepsilon_{r4} = 10$

Solid lines are real solutions for $k_x$ indicating propagation.
Dashed lines are imaginary solutions for $k_x$, indicating attenuation.

- A complex backward wave mode exists from 22 GHz to near 26 GHz. It attenuates as it travels.

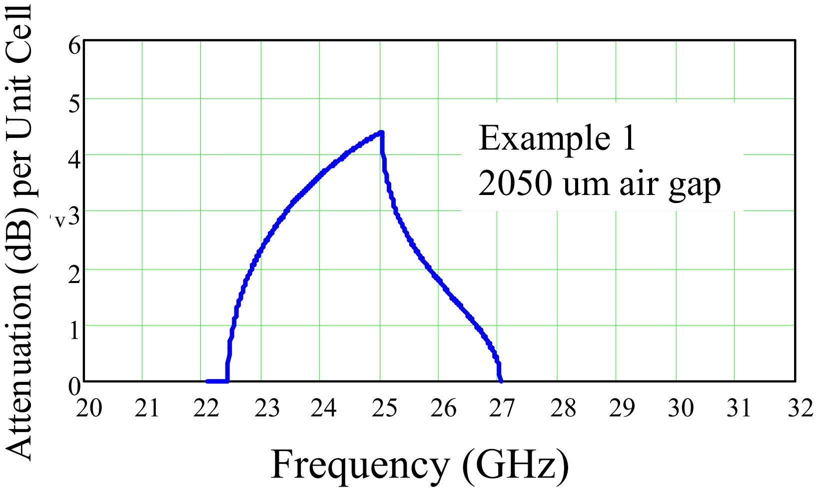
- A purely evanescent mode exists from 26 to 30 GHz, where fields decay exponentially.

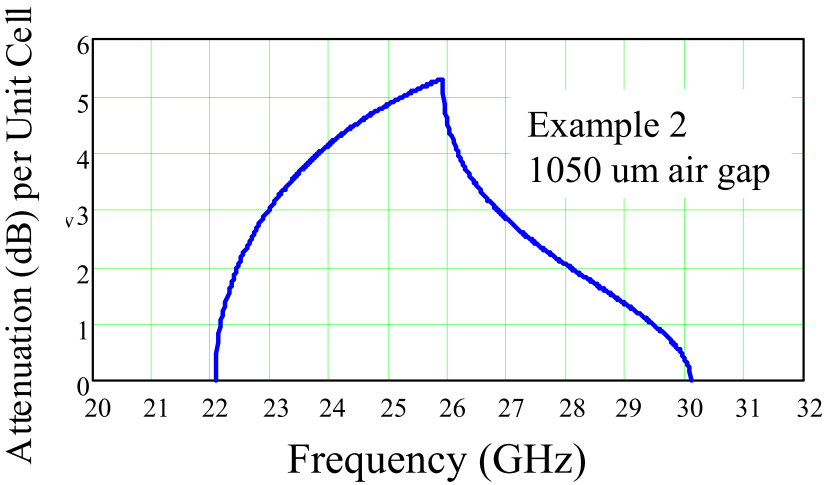
- An apparent stopband for forward waves exists from 22 GHz to near 30 GHz.

# Predicted Attenuation Per Unit Cell

Fields vary as $e^{-jk_xP} = e^{-|\mathrm{Im}\{k_x\}|P} e^{-j\mathrm{Re}\{k_x\}P}$

Use the $\mathrm{Im}\{k_x\}$ data from the transverse resonance analysis to calculate attenuation per unit cell: $Atten(dB) = 20\log_{10}\left[\exp\left(-\left|\mathrm{Im}\{k_x\}\right|P\right)\right]$





Design parameters:
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90 um square via
$\varepsilon_{r1} = \varepsilon_{r5} = 6$, $\varepsilon_{r2} = \varepsilon_{r4} = 10$

The fundamental stopband is predicted to be wider and deeper for smaller air gaps, consistent with full-wave simulations.

# Summary

1. EBG structures may be embedded into multilayer ceramic packages to mitigate internal coupling and parasitic resonances.
2. The fundamental stopband may be predicted using transverse resonance techniques, or by using full-wave two port simulations.
3. The bandwidth of the fundamental stopband is broader
   (a) when EBG structures are used in both the base and cover of the package, and
   (b) when the cover height is reduced.