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Reflection Properties of Mushroom-Type Surfaces With Loaded Vias

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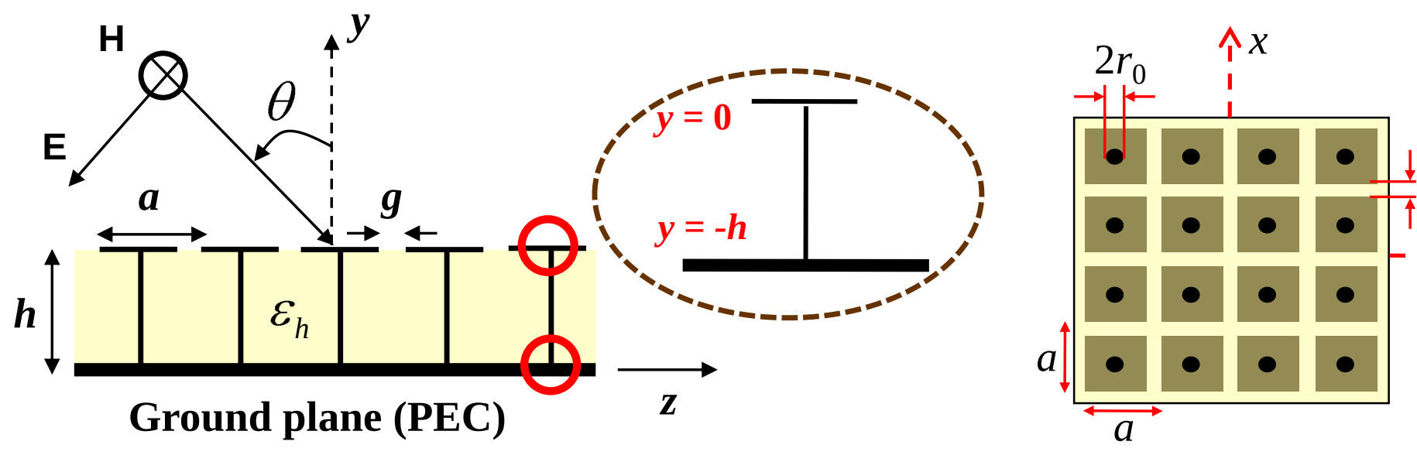
Introduction – Mushroom-Type HIS



$a/h > 1$

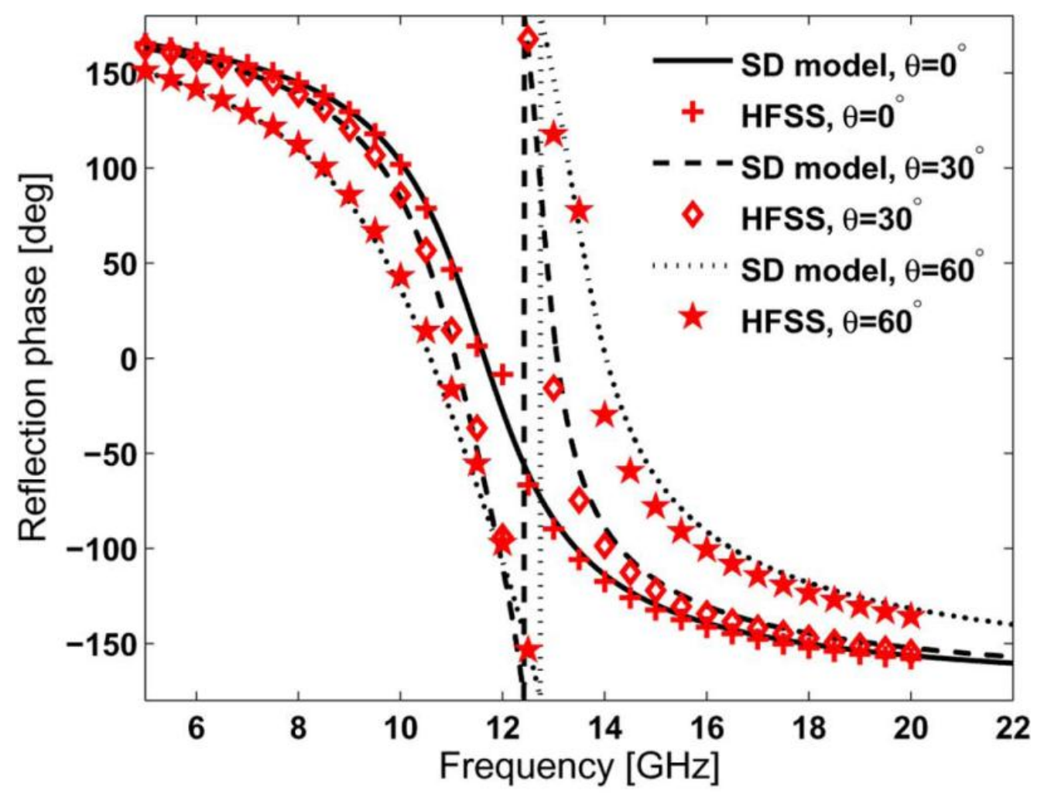
$k_0\sqrt{\varepsilon_r}L << \pi$

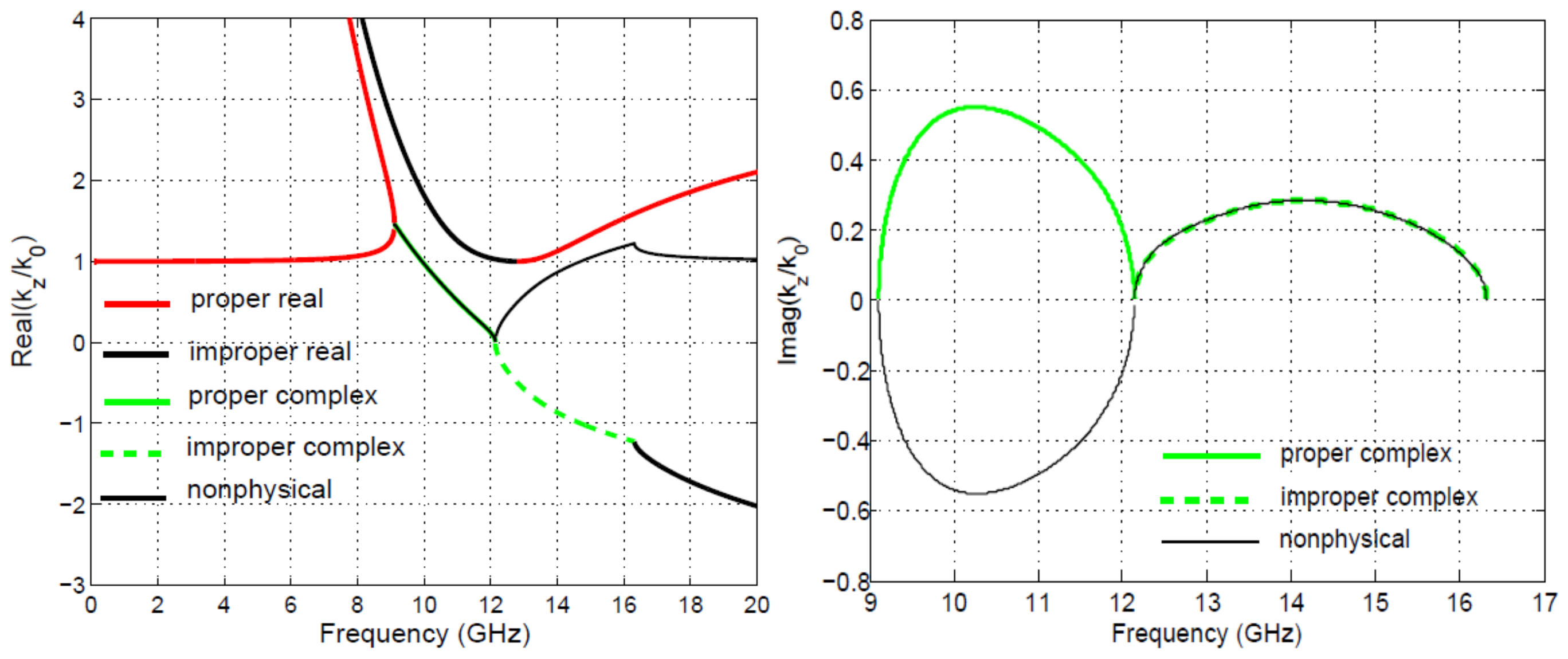
Additional boundary condition for the "**microscopic**" current at the via-ground plane connection ($y=0^-$) and via-patch connection ($y=-h^+$):

$$\left.\frac{dI(y)}{dy}\right|_{\substack{y=0^-\\ y=-h^+}} = 0$$

Silveirinha et al., *New J. Phys.*, 10, 2008

Reflection Characteristics and Natural Modes

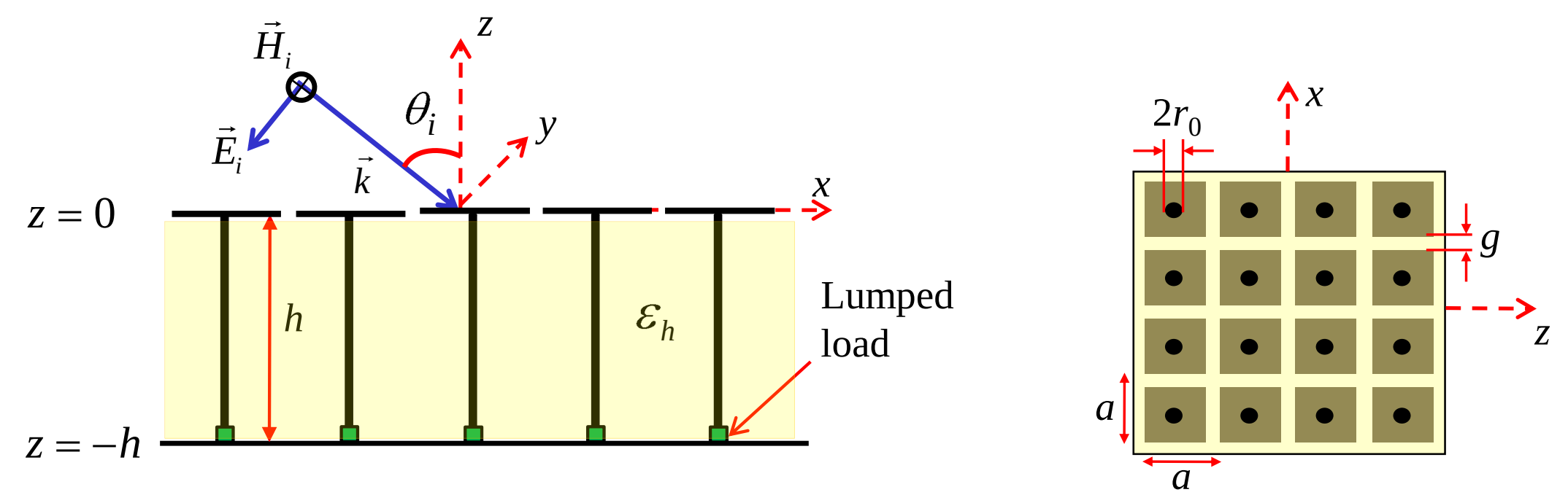




- ✓ Reflection phase characteristics and natural modes (surface waves and leaky waves) are accurately predicted by the homogenization model.
- ✓ The presence of the patch grid significantly reduces the spatial dispersion (SD) effects.

O. Luukkonen et al., *IEEE Trans. Microwave Theory Tech.*, 57, Nov. 2009
A. B. Yakovlev et.al., *IEEE Trans. Microwave Theory Tech.*, 57, Nov. 2009

Mushroom-Type HIS with Loaded Vias



Nonlocal Homogenization model

Wire medium slab is treated as an uniaxial continuous material characterized by **tensor effective permittivity**

$$\frac{\bar{\bar{\varepsilon}}}{\varepsilon_0} = \varepsilon_h\left(\bar{\bar{I}}_t + \left(1 - \frac{k_p^2}{k_h^2 - k_z^2}\right)\hat{z}\hat{z}\right)$$

$$k_p = \sqrt{(2\pi/a^2)/\log\left(a^2/(4r_0(a-r_0))\right)}$$

Plasma wavenumber

TM-polarized plane wave excites **TEM** and **TM** modes in the wire medium slab

$$\eta_0 H_y = A_{TM}^+ e^{\gamma_{TM} z} + A_{TM}^- e^{-\gamma_{TM} z} + B_{TEM}^+ e^{\gamma_{TEM} z} + B_{TEM}^- e^{-\gamma_{TEM} z}$$

$$E_x = \frac{j}{\varepsilon_h k_0}\left[\gamma_{TM}\left(A_{TM}^+ e^{\gamma_{TM} z} - A_{TM}^- e^{-\gamma_{TM} z}\right) + \gamma_{TEM}\left(B_{TEM}^+ e^{\gamma_{TEM} z} - B_{TEM}^- e^{-\gamma_{TEM} z}\right)\right]$$

$$\gamma_{TEM} = jk_0\sqrt{\varepsilon_h} \qquad \gamma_{TM} = \sqrt{k_p^2 + k_x^2 - k_0^2\varepsilon_h}$$

Tangential electrical and magnetic fields are related via the sheet impedance at the air patch interface ***z* = 0**

Nonlocal Homogenization Model

- Generalized additional boundary condition at the via-to-patch connection, $z=0^-$:

$$\frac{dI(z)}{dz} + \left(\frac{C}{C_{patch}}\right) I(z) = 0$$

In terms of field components

$$\left(k_0\varepsilon_h \frac{dE_z}{dz} + k_x\eta_0 \frac{dH_y}{dz}\right) + \left(\frac{C}{C_{patch}}\right)\left(k_0\varepsilon_h E_z + k_x\eta_0 H_y\right) = 0$$

- Generalized additional boundary condition for the lumped load at the via-to-ground connection, $z=-h^+$:

$$\frac{dI(z)}{dz} - j\omega C Z_{\text{Load}} I(z) = 0$$

Z_{Load} → Load impedance

In terms of field components

$$\left(k_0\varepsilon_h \frac{dE_z}{dz} + k_x\eta_0 \frac{dH_y}{dz}\right) - \left(j\omega C Z_{\text{Load}}\right)\left(k_0\varepsilon_h E_z + k_x\eta_0 H_y\right) = 0$$

S. I. Maslovski et al., New J. Phys., 12, 113047, **2010**

$$Z_L = j\omega L_{par} + \frac{1}{j\omega C_{par} + (1/Z_{\text{Load}})}$$

L

L_{par} and C_{par} are the correction terms, due to non-uniformity in the charge and current distribution by inserting a load in the wire

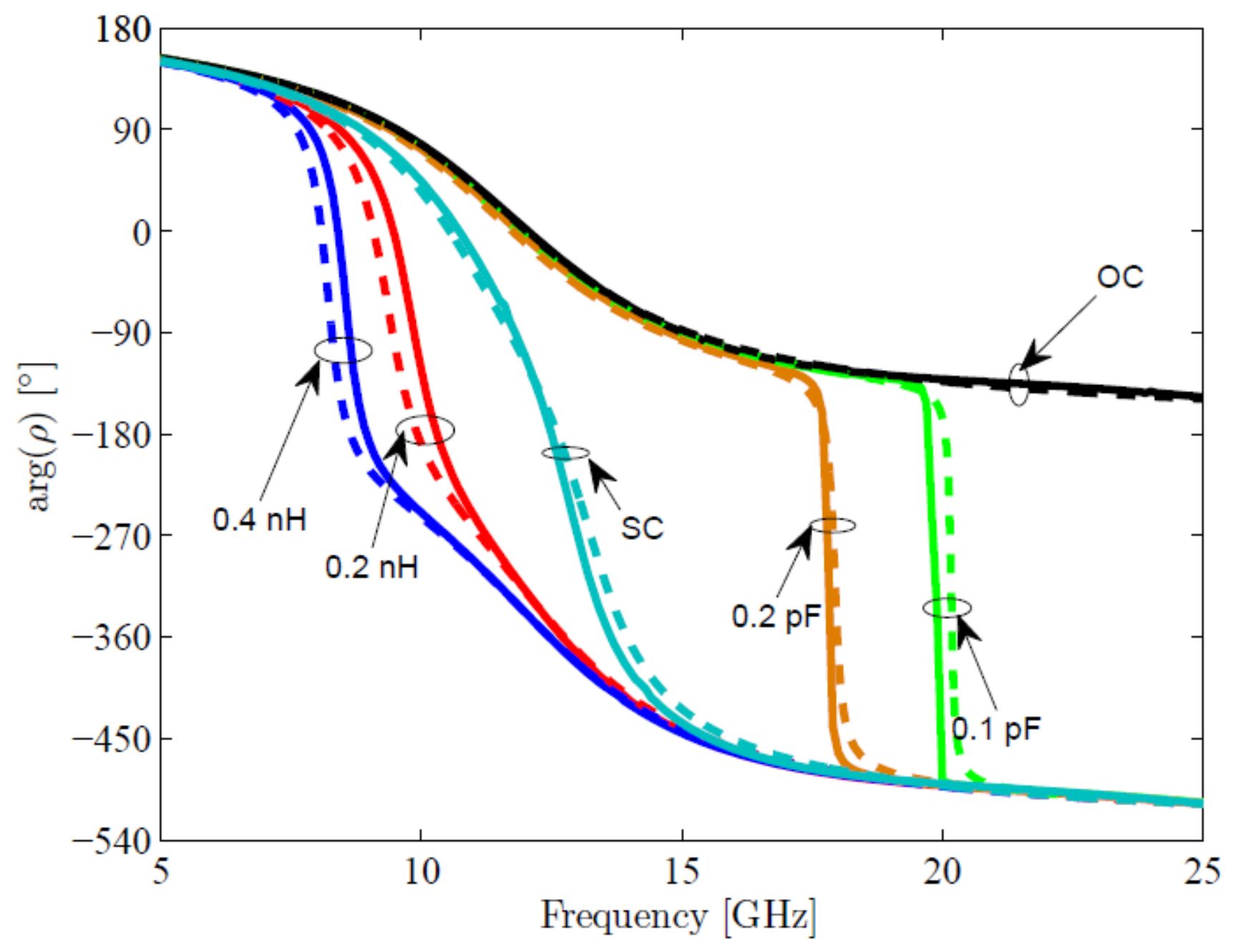
Reflection Coefficient

$$\rho = \frac{(j\omega\varepsilon_0 - \gamma_0 Y_g)K - j\omega\varepsilon_0\gamma_0 M}{(j\omega\varepsilon_0 - \gamma_0 Y_g)K + j\omega\varepsilon_0\gamma_0 M}$$

$$K = \gamma_{\text{TM}}\sinh(\gamma_{\text{TM}}h)\cos(k_{\text{TEM}}h) + j\gamma_{\text{TEM}}\sin(k_{\text{TEM}}h)\left[\left(\frac{\varepsilon_h}{\varepsilon_{zz}^{\text{TM}}} - 1\right)\cosh(\gamma_{\text{TM}}h) + \frac{\varepsilon_h\gamma_{\text{TM}}}{\varepsilon_{zz}^{\text{TM}} j\omega C Z_L}\sinh(\gamma_{\text{TM}}h)\right]$$

$$M = 2(\varepsilon_h - \varepsilon_{zz}^{\text{TM}}) + \cosh(\gamma_{\text{TM}}h)\left(\frac{j\varepsilon_h k_{\text{TEM}}}{\omega C Z_{\text{L}}}\sin(k_{\text{TEM}}L) + \left(\varepsilon_h\left(\frac{\varepsilon_h}{\varepsilon_{zz}^{\text{TM}}} - 2\right) + 2\varepsilon_{zz}^{\text{TM}}\right)\cos(k_{\text{TEM}}h)\right)$$
$$+ (\varepsilon_h - \varepsilon_{zz}^{\text{TM}})\sinh(\gamma_{\text{TM}}h)\left(\left(\frac{\gamma_{\text{TEM}}}{\gamma_{\text{TM}}} + \frac{\gamma_{\text{TM}}}{\gamma_{\text{TEM}}}\right) j\sin(k_{\text{TEM}}h) + \frac{\varepsilon_h\gamma_{\text{TM}}}{j\omega C Z_{\text{L}}\varepsilon_{zz}^{\text{TM}}}\cos(k_{\text{TEM}}h)\right)$$

Reflection Characteristics

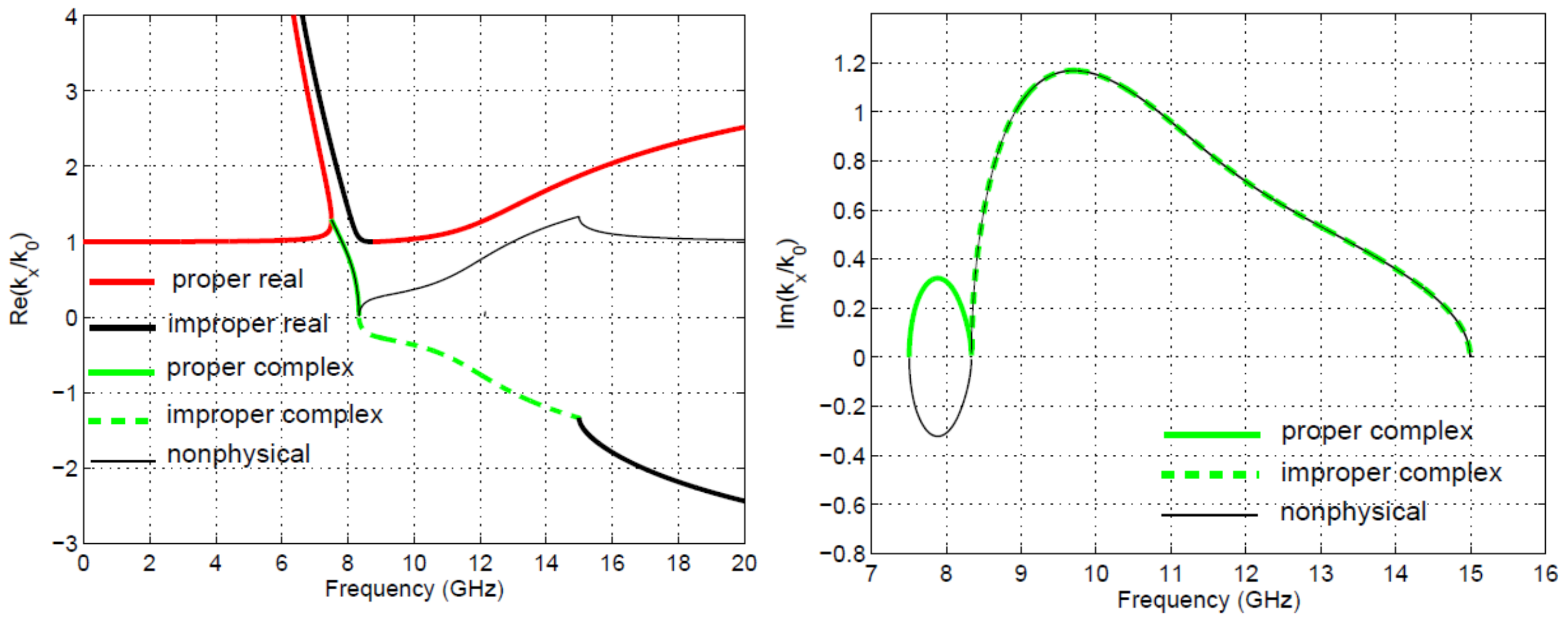


Thickness (*h*) = 1 mm
Period (*a*) = 2 mm
Gap (*g*)= 0.2 mm,
Permittivity ϵ_h = 10.2,

—— Analytical
------ HFSS

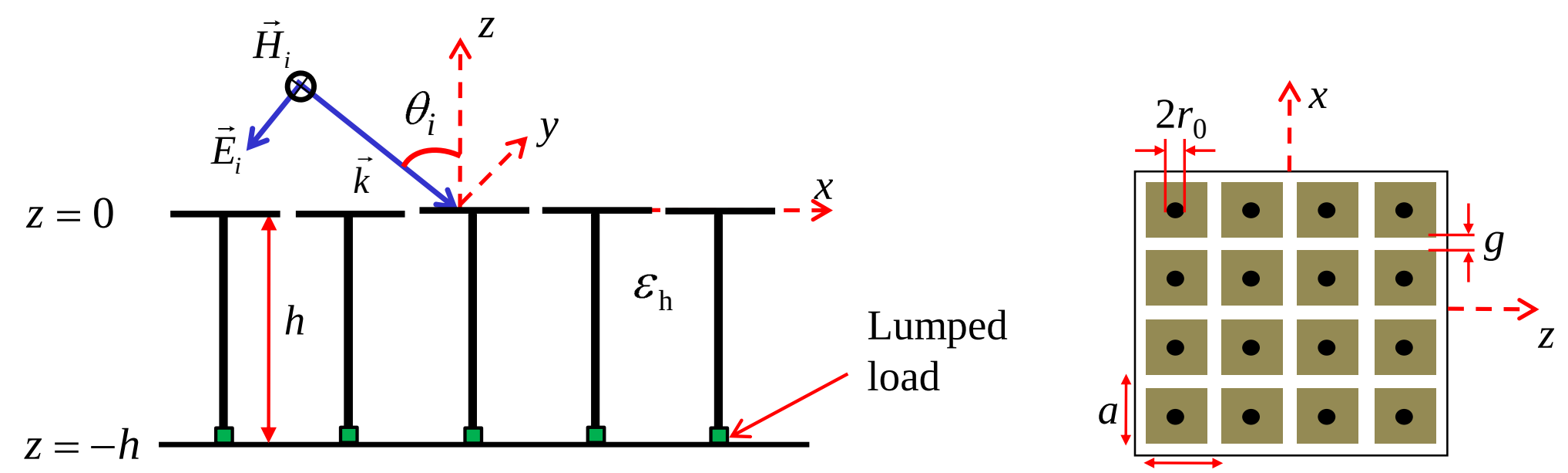
- ✓ The load is connected to the ground plane through a gap of 0.1 mm, by curve fitting, the correction terms are $\boldsymbol{L_{\text{par}}}$ **= 0.02 nH** and $\boldsymbol{C_{\text{par}}}$ **= 0.06 pF.**
- ✓ Reflection phase characteristics depend strongly on the value and the type of load.
- ✓ For an increase in the value of the inductive loads, we have a decrease in the plasma frequency and reduction in SD effects.

Dispersion Behavior for 0.4 nH Load



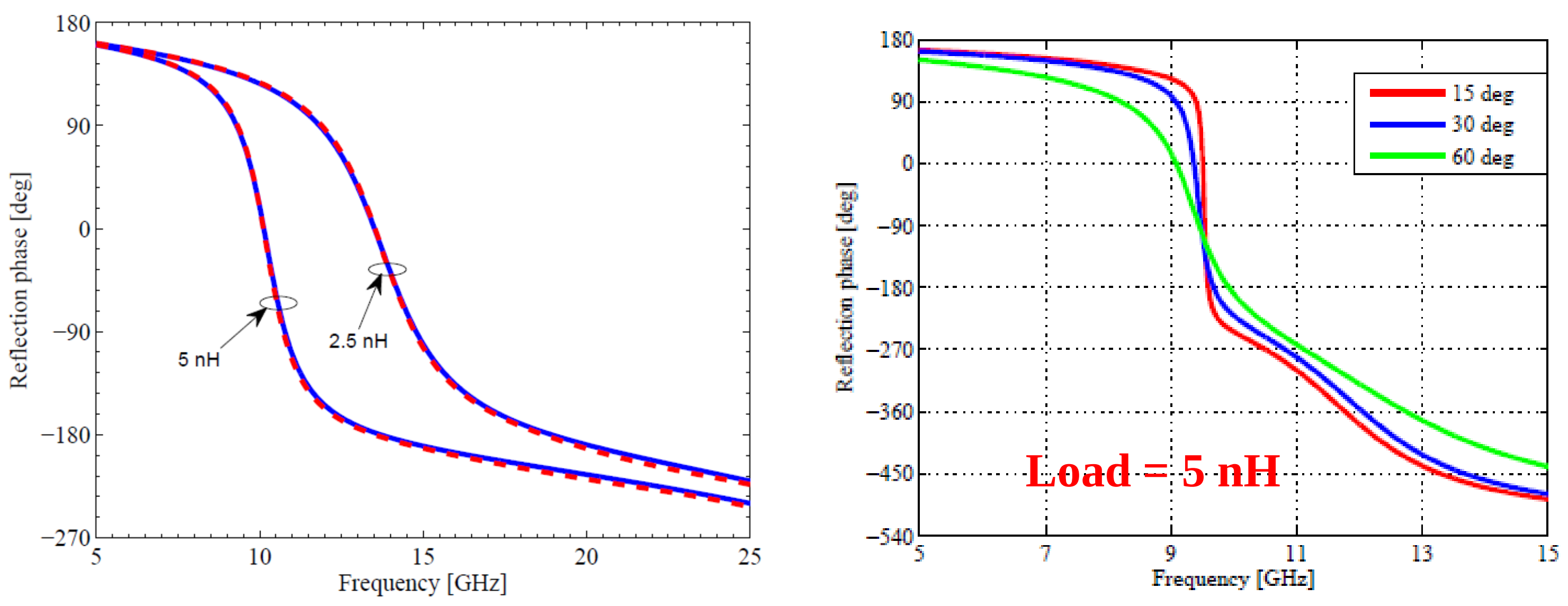
- ✓ The dispersion behavior shifts to lower frequency when compared to the structure without loads.

Ultra Thin HIS



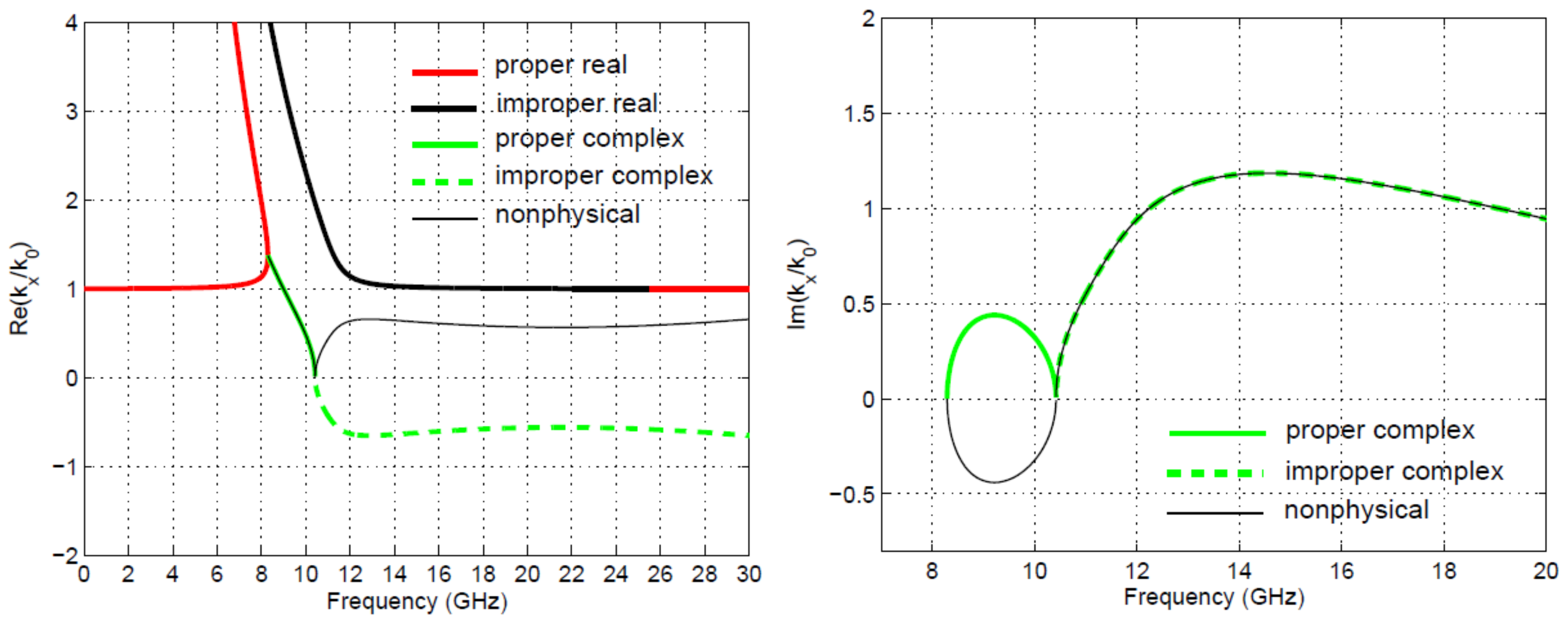
Thickness (*h*) = 1 mm
Period (*a*) = 2 mm
Gap (*g*)= 0.2 mm,
Permittivity ϵ_h = 1,

Reflection Characteristics



- ✓ The resonance frequency is shifted to a much lower value, when compared to the structure without loads.
- ✓ The effects of the parasitic capacitance and parasitic inductance in the air filled structure are negligible.
- ✓ Electrical thickness of the structure at the operating frequencies for 5 nH load is $\approx \lambda_0/30$

Dispersion Behavior for 5 nH Load



- ✓ Exhibits a wide stop-band for surface waves, 8.29 GHz – 25.51 GHz.
- ✓ 73% reduction in the plasma frequency when compared to the structure without loads.

Conclusion

- The reflection characteristics of the mushroom-type surface with loaded vias can be accurately predicted by the homogenization model.
- The reflection phase depends strongly on the value and the type of load. With an increase in the value of the inductive load, we have a decrease in the plasma frequency with a reduction in SD effects.
- Ultra thin structure exhibits wide stop-band for surface waves.
- The proposed concept of lumped loads can be used as EBG substrates in ridge waveguides and in the design of ultra-thin absorbers.