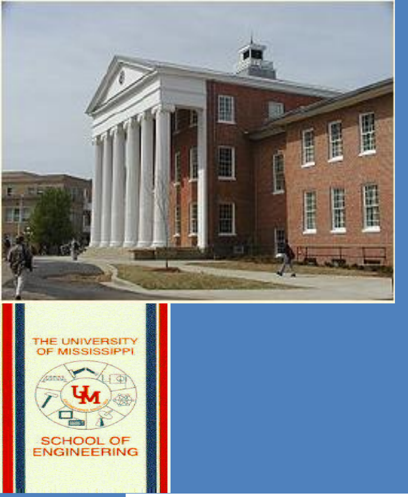

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Near-Field Enhancement Using Uniaxial Wire Medium With Impedance Loadings

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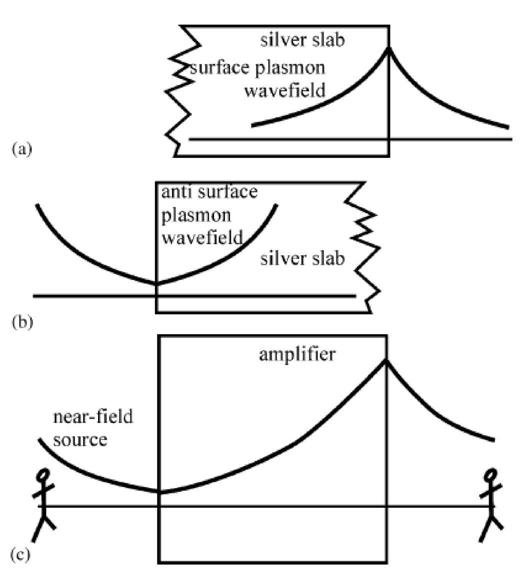
Background and Motivation



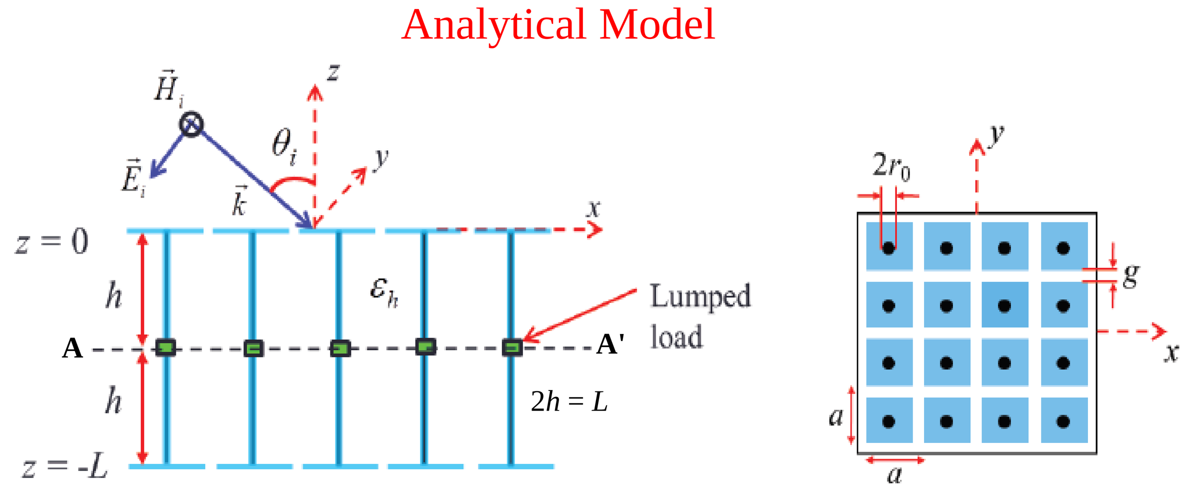
✓ The amplification process is due to the excitation of **surface plasmon resonances** on the surfaces of the slab

✓ "**Spoof plasmons**" as strongly localized surface waves are due to resonant interaction of the electromagnetic field and the charge density oscillations in metals

J. B. Pendry and S. A. Ramakrishna, Physica B, 338, 329-332, **2003**

Bi-Layer Mushroom Structure

Analytical Model



Reflection and Transmission Coefficients

Reflection coefficient for the even excitation (PEC symmetry)

$$R_{\text{even}} = \frac{(jk_0 - \eta_0\gamma_0 Y_g)\,K - jk_0\gamma_0 M}{(jk_0 + \eta_0\gamma_0 Y_g)\,K + jk_0\gamma_0 M}$$

where

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

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

C. S. R. Kaipa, et.al., IEEE AWPL, 10, 1503, **2011**

$$\gamma_0 = \sqrt{k_x^2 - k_0^2}\,,\ k_x = k_0\sin\theta_i\,,\ \gamma_{\text{TM}} = \sqrt{k_p^2 + k_x^2 - k_0^2\varepsilon_h}\,,\ \gamma_{\text{TEM}} = jk_{\text{TEM}} = jk_0\sqrt{\varepsilon_h}$$

$$\varepsilon_{zz}^{\text{TM}} = \varepsilon_h k_x^2/\left(k_p^2 + k_x^2\right),\ k_p = \sqrt{(2\pi/a^2)/\log[a^2/4r_0(a - r_0)]}$$

Grid admittance of the patch array $Y_g = j(\varepsilon_h + 1)(k_0 a/\eta_0\pi)\log[\csc(\pi g/2a)]$

Capacitance per unit length of the wire medium $C = 2\pi\varepsilon_h\varepsilon_0/\log\left[a^2/4r_0\,(a - r_0)\right]$

Effective load impedance $Z_{\text{Load,eff}} = j\omega L_{\text{par}} + \dfrac{1}{(j\omega C_{\text{par}} + 1/Z_{\text{Load}})}$

Parasitic capacitance C_{par} Parasitic inductance L_{par}

Z_{Load} Impedance of the lumped load (inductive/capacitive)

Reflection coefficient for the odd excitation (PMC symmetry)

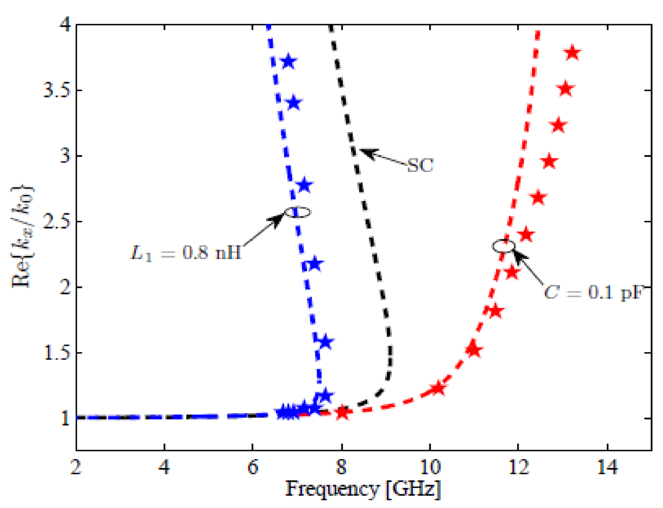
$$R_{\text{odd}} = -\frac{\dfrac{\varepsilon_h k_x^2\tanh(\gamma_{\text{TM}}h)}{\gamma_{\text{TM}}(k_x^2 + k_p^2)} + \dfrac{\varepsilon_h k_p^2\tan(k_{\text{TEM}}h)}{k_{\text{TEM}}(k_x^2 + k_p^2)} - \left(\dfrac{1}{\gamma_0} + j\dfrac{Y_g\eta_0}{k_0}\right)}{\dfrac{\varepsilon_h k_x^2\tanh(\gamma_{\text{TM}}h)}{\gamma_{\text{TM}}(k_x^2 + k_p^2)} + \dfrac{\varepsilon_h k_p^2\tan(k_{\text{TEM}}h)}{k_{\text{TEM}}(k_x^2 + k_p^2)} + \left(\dfrac{1}{\gamma_0} - j\dfrac{Y_g\eta_0}{k_0}\right)}$$

Yakovlev et al., *3rd Int. Congress on Advan. Electromag. Materi. in Microwa. and Optic.*, (2009)

Reflection and Transmission coefficients for the bi-layer mushroom structure

$$R = \frac{1}{2}\left(R_{\text{even}} + R_{\text{odd}}\right)$$
$$T = \frac{1}{2}\left(R_{\text{even}} - R_{\text{odd}}\right)$$

Dispersion Behavior of the Guided Modes

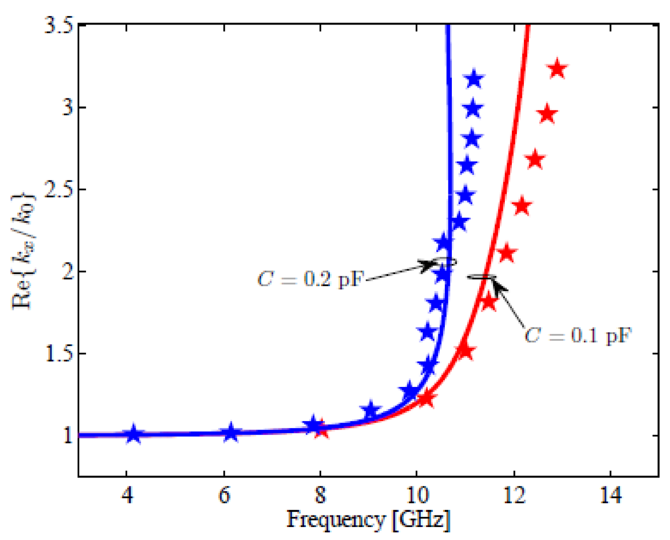


a = 2 mm
g = 0.2 mm
r_0 = 0.05 mm
L = 2 mm
ε_h = 10.2
C_{par} = 0.02 pF
L_{par} = 0.06 nH

Dashed lines: Analytical model
Symbols: HFSS

✓ Reduction of the resonant frequency with **inductive loads** and decrease of the effective plasma frequency

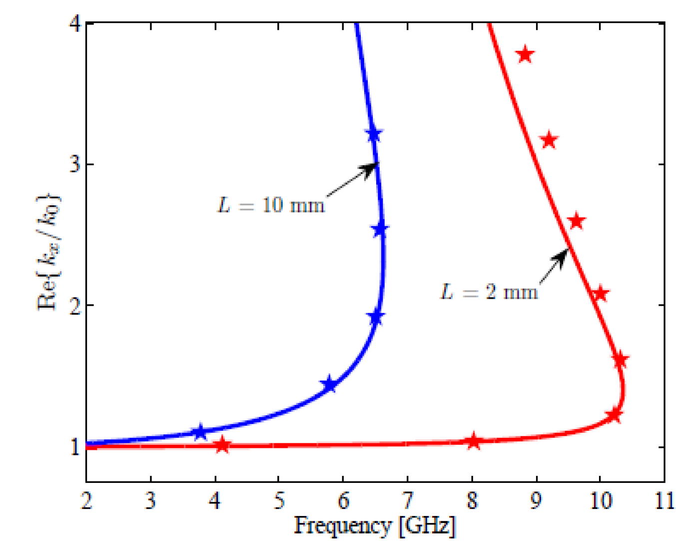
✓ Increase of resonant frequency with **capacitive loads**



a = 2 mm
g = 0.2 mm
r_0 = 0.05 mm
L = 2 mm
ε_h = 10.2
C_{par} = 0.02 pF
L_{par} = 0.06 nH

Solid lines: Analytical model
Symbols: HFSS

✓ Flat dispersion with **capacitive loads**



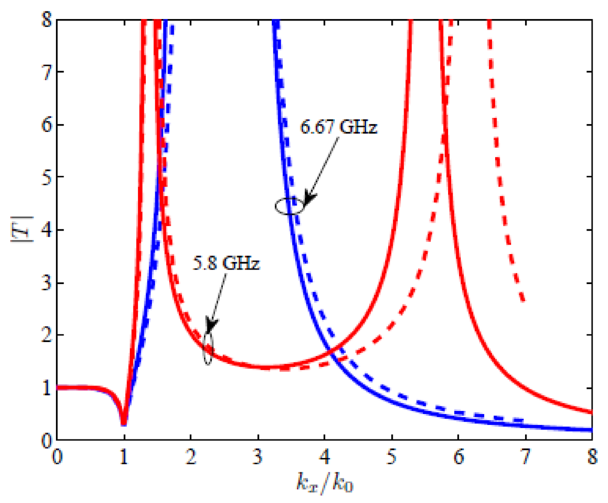
a = 2 mm
g = 0.2 mm
r_0 = 0.05 mm
L_1 = 5 nH
ε_h = 1

Solid lines: Analytical model
Symbols: HFSS

✓ Increasing L/a results in a lower resonant frequency and in an enhancement of the normalized propagation constant $\mathrm{Re}\{k_z/k_0\}$

Imaging with Inductive Loadings

Amplification of evanescent waves



a = 2 mm
g = 0.2 mm
r_0 = 0.05 mm
L_1 = 5 nH
L = 10 mm
ε_h = 1

Solid lines: Analytical model
Dashed lines: CST

✓ Strong amplification of the near field for the wave vector components in the range 1< k_x/k_0 < 4 at the frequency of 6.67 GHz

Imaging a line source

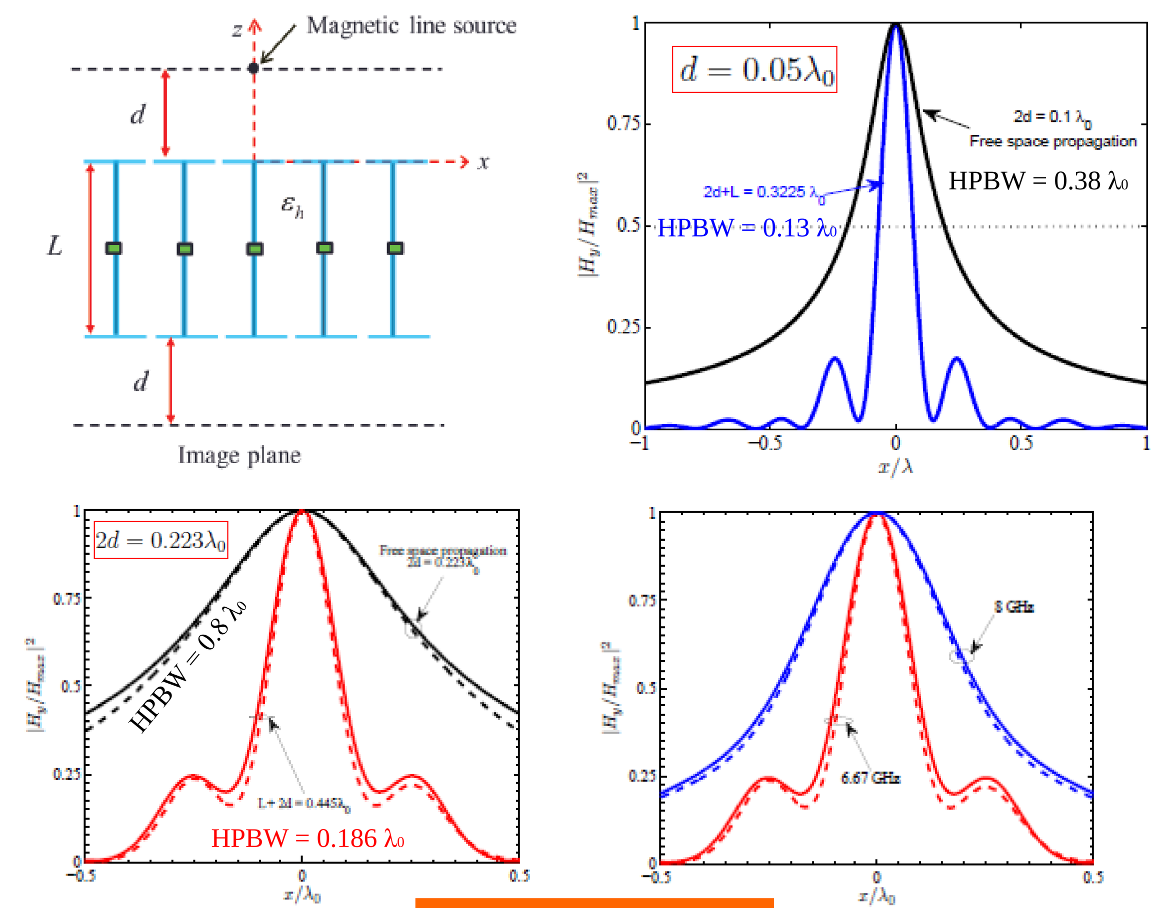
$\mathbf{J}_m = \hat{\mathbf{y}} I_0\delta(z - d)\delta(x)$ Current density of the magnetic line source

$\mathbf{H}(x, z) = \hat{\mathbf{y}}\dfrac{I_0 k_0^2}{j\omega\mu_0}\left[\dfrac{1}{4j}H_0^{(2)}(k_0\rho)\right]$ Incident magnetic field

Magnetic field at the image plane (distance d from the lower interface of the structure) as a Sommerfeld-type integral

$$H_y(x) = \frac{I_0 k_0^2}{j\omega\mu_0\pi}\int_0^{\infty}\frac{1}{2\gamma_0}e^{-\gamma_0(2d)}T(\omega, k_x)\cos(k_x x)\,dk_x$$

f = 6.67 GHz

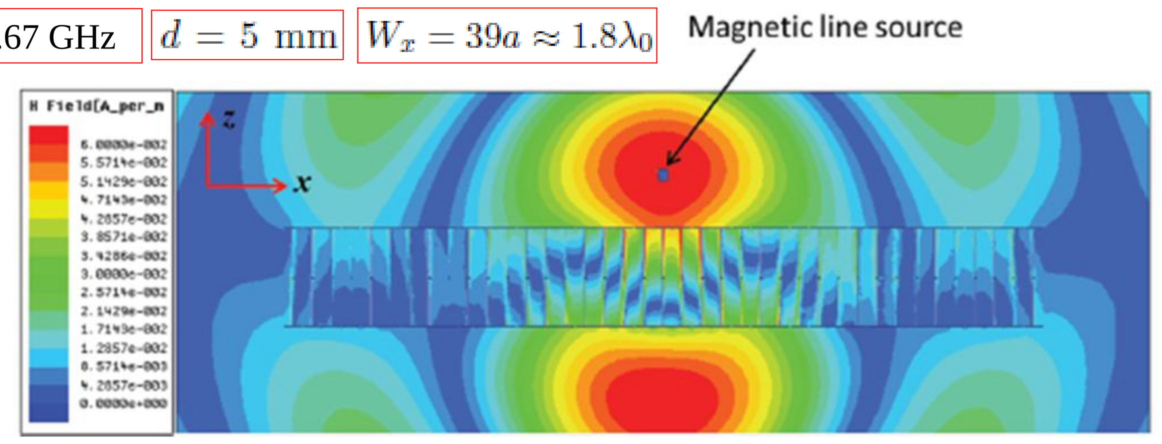


Solid lines: Analytical model
Dashed lines: HFSS

✓ Resolution of the bi-layer mushroom lens is $\lambda_0/6$

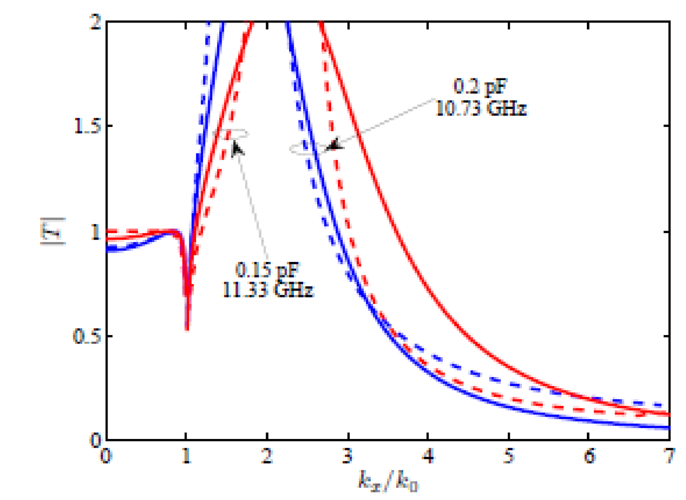
Magnetic field distribution of the inductively loaded bi-layer mushroom structure: HFSS simulation results

f = 6.67 GHz d = 5 mm $W_x = 39a \approx 1.8\lambda_0$



Imaging with Capacitive Loadings

Amplification of evanescent waves

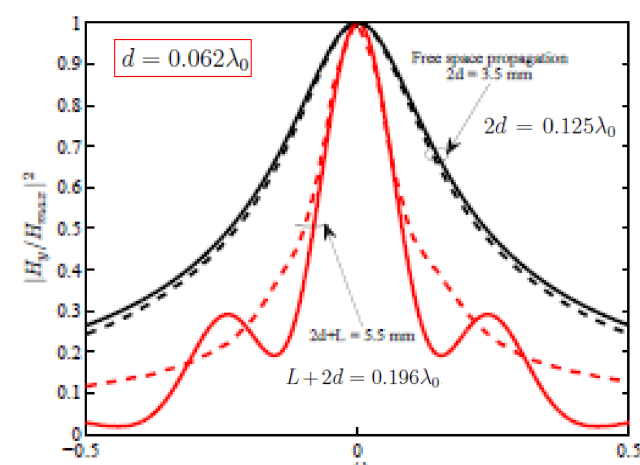


a = 2 mm
g = 0.2 mm
r_0 = 0.05 mm
L = 2 mm
ε_h = 10.2
C_{par} = 0.02 pF
L_{par} = 0.06 nH

Solid lines: Analytical model
Dashed lines: CST

✓ Strong amplification of the near field

Imaging a line source



Capacitive loading of 0.2 pF

Distance
Free space propagation 3.5 mm
With structure 5.5 mm

Homogenization results
f = 10.73 GHz

HPBW
Free space propagation 0.47λ_0
With structure 0.16λ_0

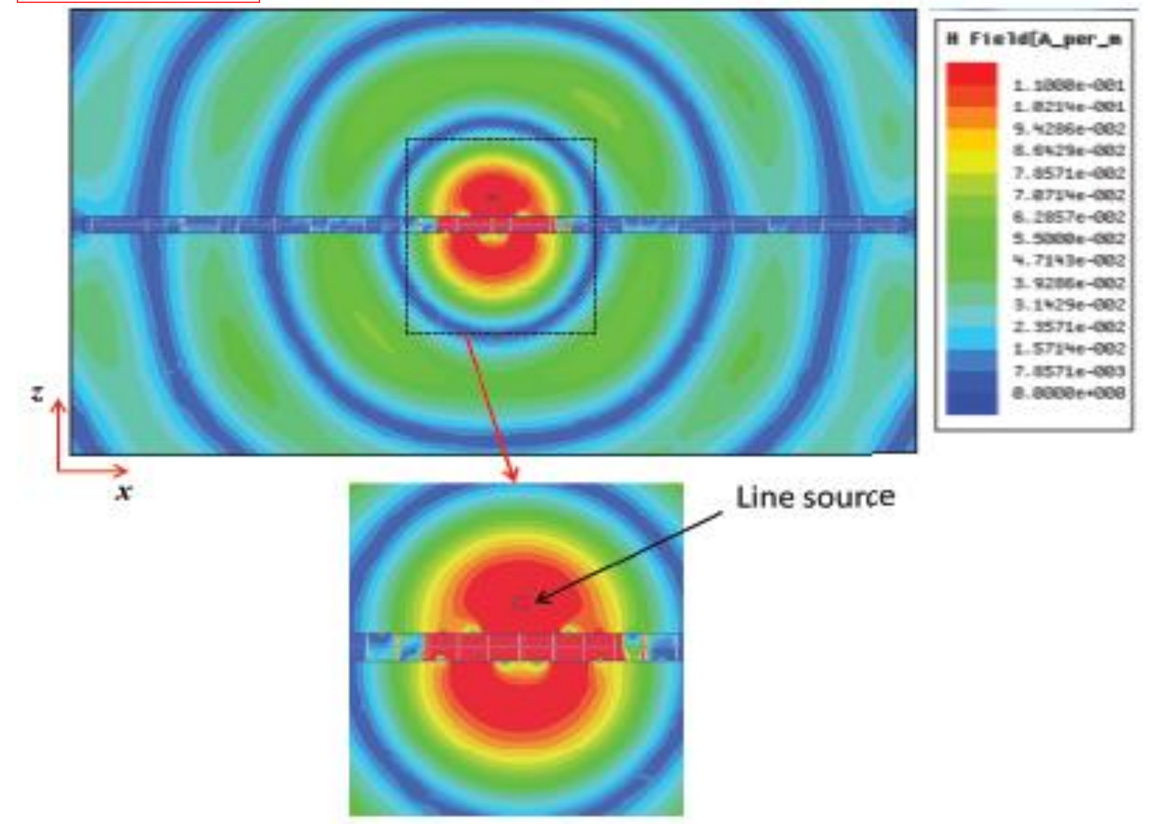
Simulation results
f = 11.27 GHz

HPBW
Free space propagation 0.47λ_0
With structure 0.19λ_0

✓ Resolution of the bi-layer mushroom lens is $\lambda_0/6$

Magnetic field distribution of the capacitively loaded bi-layer mushroom structure: HFSS simulation results

f = 11.27 GHz d = 1.75 mm $W_x = 35a \approx 2.65\lambda_0$



Conclusions

- We demonstrate the possibility of achieving **evanescent-wave enhancement** and **near-field imaging** by using a bi-layer mushroom structure with capacitively/inductively loaded metallic wires
- **Strong interaction of two metallic grids**, coupled by an array of metallic wires
- In the case of capacitive loadings, a **flat dispersion** for the guided modes can be obtained with a sub-wavelength design based on a high-dielectric constant
- Long vias loaded with lumped inductors are used for a sub-wavelength design with a low-dielectric constant