

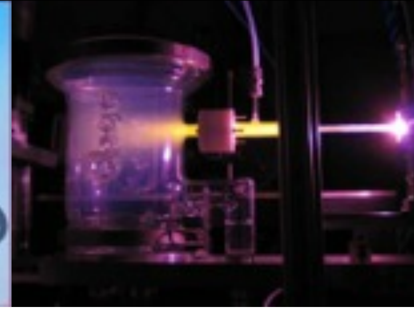


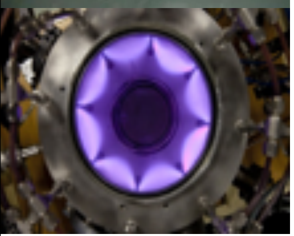
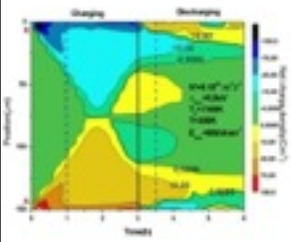


Propagation in waveguides with metamaterial walls

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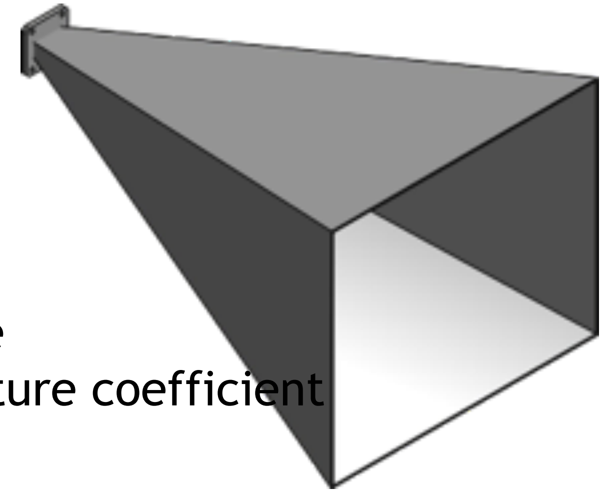
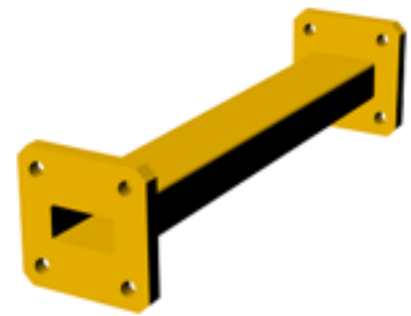
Motivation

$$D = \frac{4\Pi * A_e}{\lambda^2} = \frac{4\Pi * \eta S}{\lambda^2}$$



Ae : effective aperture
S : Physical aperture
D : directivity
η : Effectivity, aperture coefficient
λ: wavelength

$$f_{c,nm} = \frac{c}{2}\sqrt{\left(\frac{n}{a}\right)^2 + \left(\frac{m}{b}\right)^2}$$



a : Width of the rectangular waveguide
b : Heigth of the rectangular waveguide

Smaller and/or lighter antennas and waveguides with the aid of **anisotropic walls**

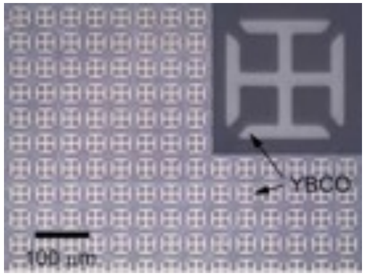
Outline

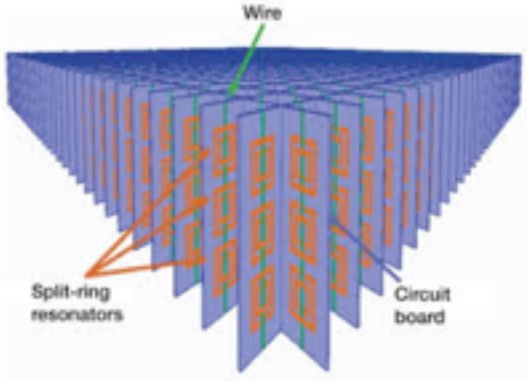
- Introduction
- State of the Art
- New Methodology & Results
- Conclusion & Perspectives

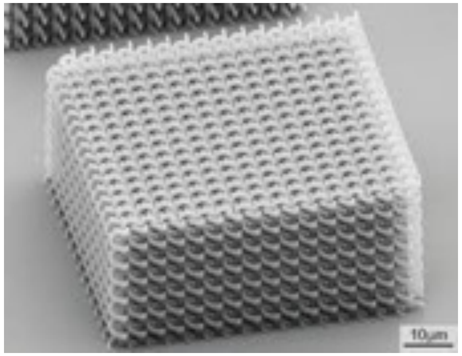
Introduction

Metamaterial

• Materials engineered to have properties that have not yet been found in n
(dielectric and/or metal)
• Arranged in repeating pattern
• With scale smaller than the wavelength of the phenomena they influence





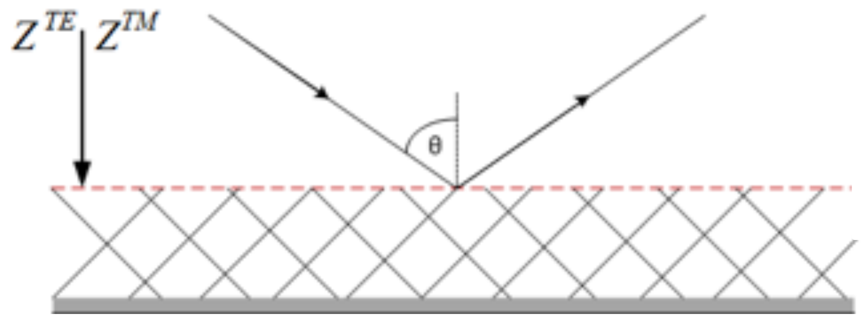


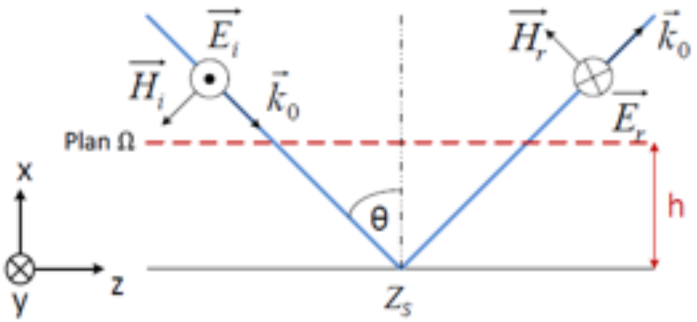
http://spie.org/newsroom/technical-articles/4760-active-terahertz-metamaterials
http://www.iop.org/resources/topic/archive/metamaterials/
http://www.materialsviews.com/wave-propagation-is-under-control-metamaterials-are-going-3d/

Introduction

$$Z^{TE} = Z_t = \frac{E_t}{H_z}$$

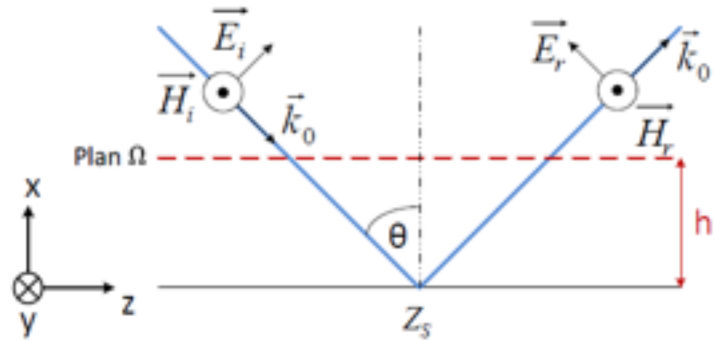
$$Z^{TM} = Z_z = -\frac{E_z}{H_t}$$





TE Case

$$Z^{TE} = -\frac{E_y}{H_z}$$



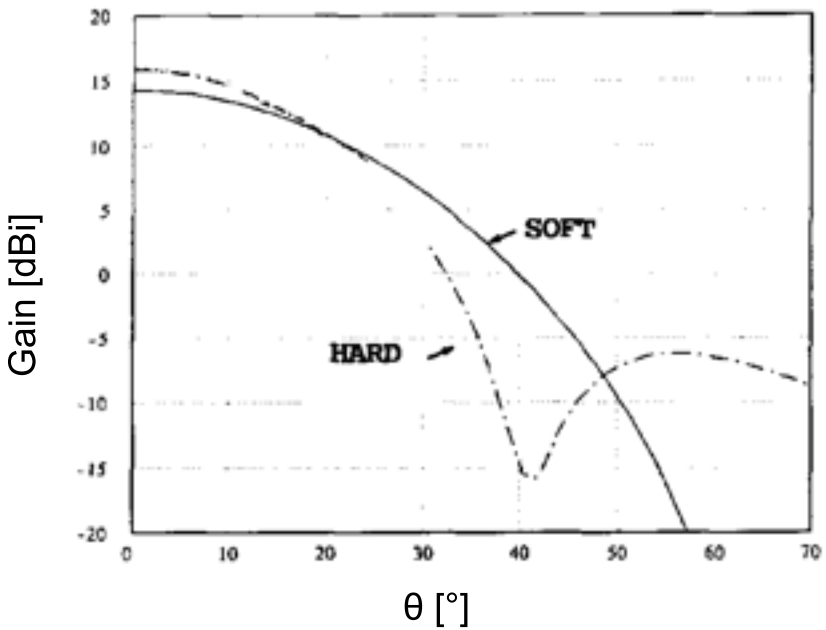
TM Case

$$Z'^{TM} = \frac{E_z}{H_y}$$

Introduction

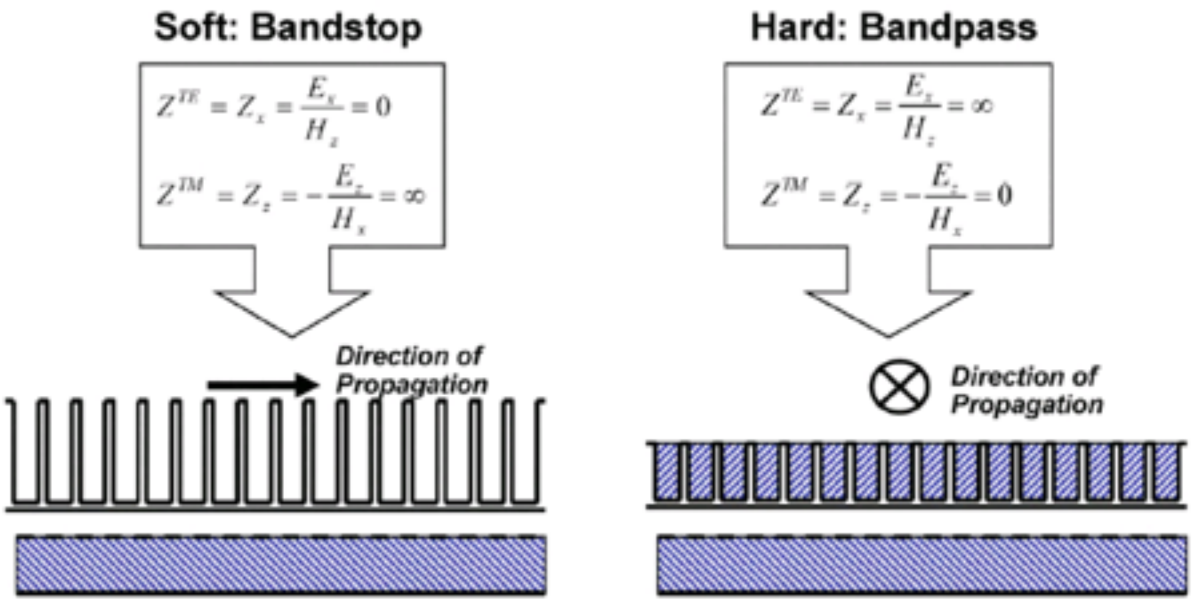
« **Soft** » horn ⟶ Low sidelobes
No fields near the surfaces

« **Hard** » horn ⟶ High Directivity
Uniform distribution of the fields at aperture



Lier, E.; Kildal, P.-S., "Soft and hard horn antennas," *Antennas and Propagation, IEEE Transactions on* , vol.36, no.8, pp.1152-1157, Aug. 1988

Introduction



Lier, E.; Shaw, R.K., "Metamaterial hybrid mode horn antennas« , *APSURSI '09. IEEE*, pp.1-4, 1-5 June 2009

Outline

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- New Methodology & Results
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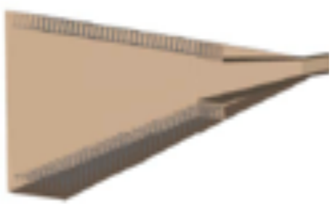
State of the Art

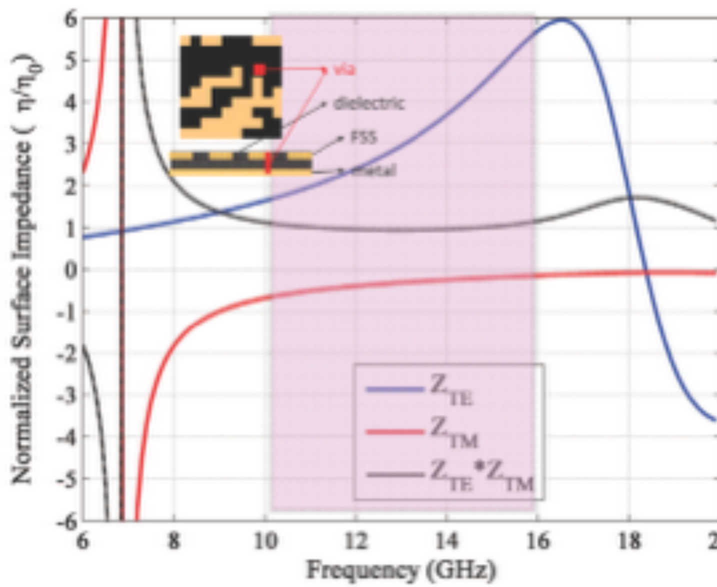
Balanced hybrid condition:

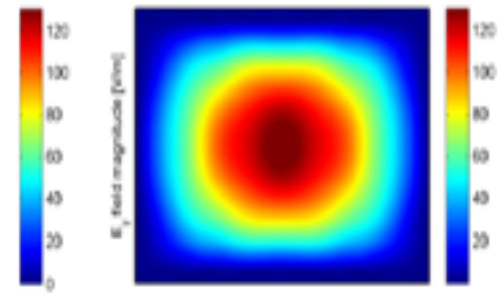
$$Z^{TE} * Z^{TM} = - X^{TE} * X^{TM} = Z_0^{\,2}$$

Classical horn   Metamaterial horn

2010:

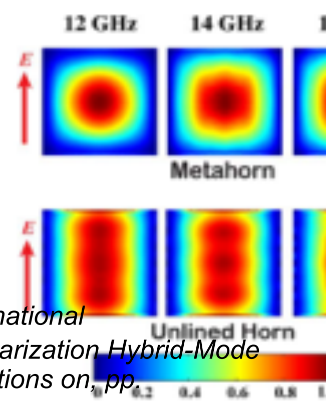






Scarborough, C.P.; Qi Wu; Gre … *material soft-surface horn antennas,"*
Antennas and Propagation Soc … *1-17 July 2010*

2011-2013:



Qi Wu; Scarborough, C.P.; Gregory, M.D.; Werner, D.H.; Shaw, R.K.; Lier, E., "Broadband metamaterial-enabled hybrid-mode horn antennas," *Antennas and Propagation Society International Symposium (APSURSI), 2010 IEEE*, vol., no., pp.1-4, 11-17 July 2010

Qi Wu; Scarborough, C.P.; Martin, B.G.; Shaw, R.K.; Werner, D.H.; Lier, E.; Wang, X., "A Ku-Band Dual Polarization Hybrid-Mode Horn Antenna Enabled by Printed-Circuit-Board Metasurfaces », Antennas and Propagation, IEEE Transactions on, pp. 1089-1098, March 2013

Outline

- Introduction
- State of the Art
- New Methodology & Results
- Conclusion & perspectives

Outline

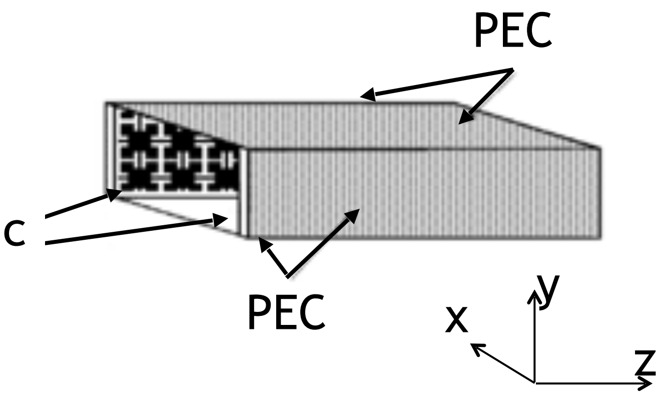
- Introduction
- State of the Art
- New Methodology & Results
  - Exact solutions for fixed anisotropic surface impedances
  - Range of required anisotropic surface impedances
  - Metamaterial optimization (with consideration of dispersion)
- Conclusion & perspectives

New methodology and results

Theoretical study (1/4)

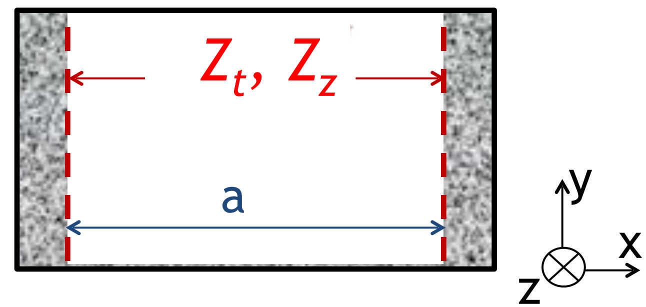
Maxwell equations:

$$\vec{E}_T = \frac{1}{k_c^2}\left(-\gamma \nabla_T E_z - j\omega\mu_0 \nabla_T H_z \times \vec{z}\right),$$
$$\vec{H}_T = \frac{1}{k_c^2}\left(j\omega\varepsilon \nabla_T E_z \times \vec{z} - \gamma \nabla_T H_z\right),$$



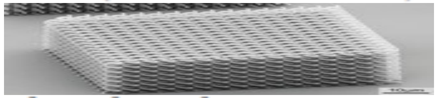
Anisotropic Boundary conditions:

$$Z_t = \left.\frac{E_y}{H_z}\right|_{x=0} = -\left.\frac{E_y}{H_z}\right|_{x=a},$$
$$Z_z = -\left.\frac{E_z}{H_y}\right|_{x=0} = \left.\frac{E_z}{H_y}\right|_{x=a},$$



Longitudinal fields expressions:

$$E_z = A_m\left(e^{jk_x x} + K_E e^{-jk_x x}\right)\sin(k_y y),$$
$$H_z = B_m\left(e^{jk_x x} + K_H e^{-jk_x x}\right)\cos(k_y y),$$



with:

$$k_c^2 = \gamma^2 + k_0^2,$$
$$k_c^2 = k_x^2 + k_y^2.$$

New methodology and results

Theoretical study (2/4)

Dispersion equation developed with the **Modal Expansion Theory (MET)** for a rectangular waveguide:

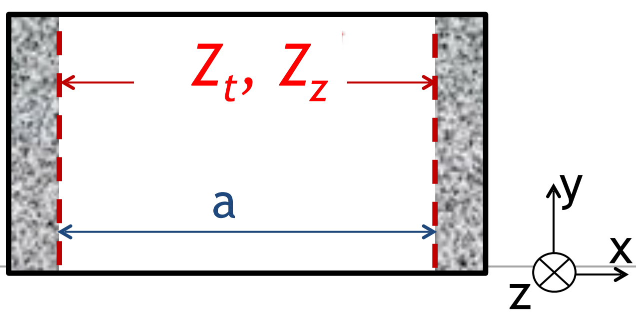
$$2\left(\frac{\gamma k_y}{k_c^2}\right)^2 \frac{Z_z}{Z_0}\left(-\frac{Z_t}{Z_0}+\frac{e^{-j2k_xa}+1}{1-e^{-j2k_xa}}\frac{k_0k_x}{k_c^2}\left(\frac{Z_z}{Z_0}\frac{Z_t}{Z_0}+1\right)-\left(\frac{k_0k_x}{k_c^2}\right)^2\frac{Z_z}{Z_0}\right)$$

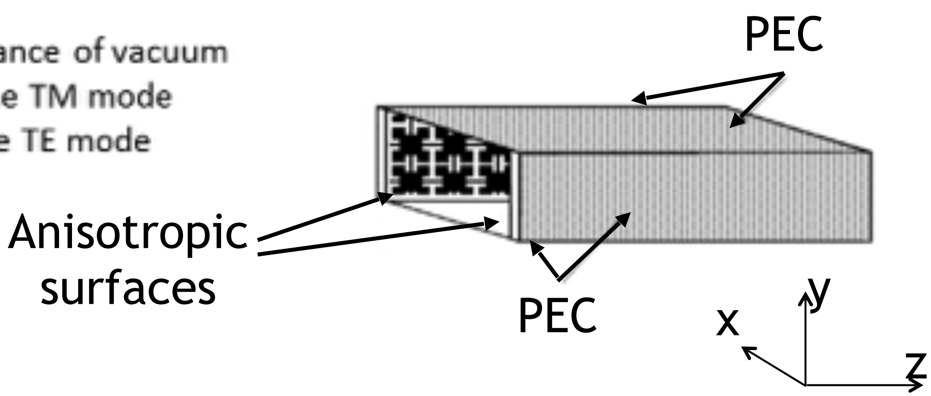
$$+\left(\left(\frac{\gamma k_y}{k_c^2}\right)^4+\left(\frac{k_0k_x}{k_c^2}\right)^4\right)\frac{Z_z^2}{Z_0}-2\left(\frac{k_0k_x}{k_c^2}\right)^3\frac{e^{-j2k_xa}+1}{1-e^{-j2k_xa}}\frac{Z_z}{Z_0}\left(\frac{Z_z}{Z_0}\frac{Z_t}{Z_0}+1\right)+\left(\frac{k_0k_x}{k_c^2}\right)^2\left(1+\left(\frac{Z_z}{Z_0}\frac{Z_t}{Z_0}\right)^2+4\left(\frac{e^{-j2k_xa}+1}{1-e^{-j2k_xa}}\right)^2\frac{Z_z}{Z_0}\frac{Z_t}{Z_0}\right)$$

$$-2\frac{k_0k_x}{k_c^2}\frac{e^{-j2k_xa}+1}{1-e^{-j2k_xa}}\frac{Z_t}{Z_0}\left(\frac{Z_z}{Z_0}\frac{Z_t}{Z_0}+1\right)+\frac{Z_t^2}{Z_0}=0$$

a: waveguides width
γ, k_x, k_y: propagation constants
k_0: propagation constant in vacuum
k_c: cut-off frequency
Z_0: characteristic impedance of vacuum
$Z_z = Z^{TM}$: Z_S seen by the TM mode
$Z_t = Z^{TE}$: Z_S seen by the TE mode

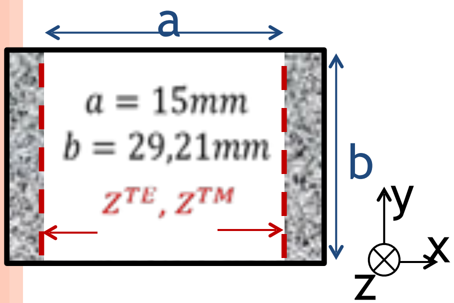
$F(\gamma,f_0)=F(j\beta,f_0)=0$





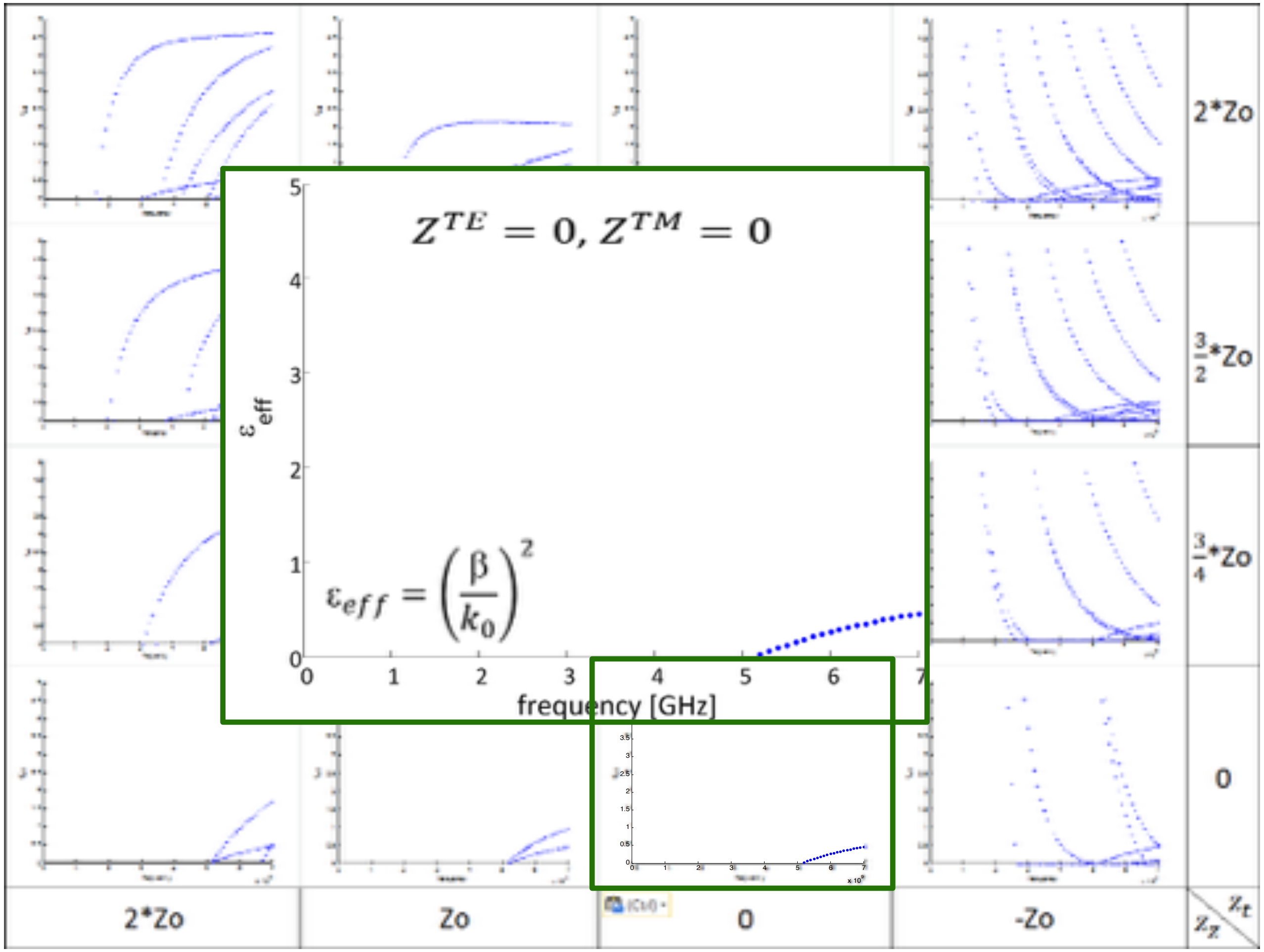
New methodology and results

Theoretical study (3/4)



Required characteristics:

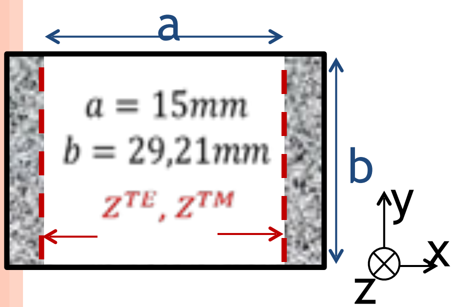
- Lower the f_c of the fundamental mode
- Single-mode bandwidth at least between 3 and 4 GHz

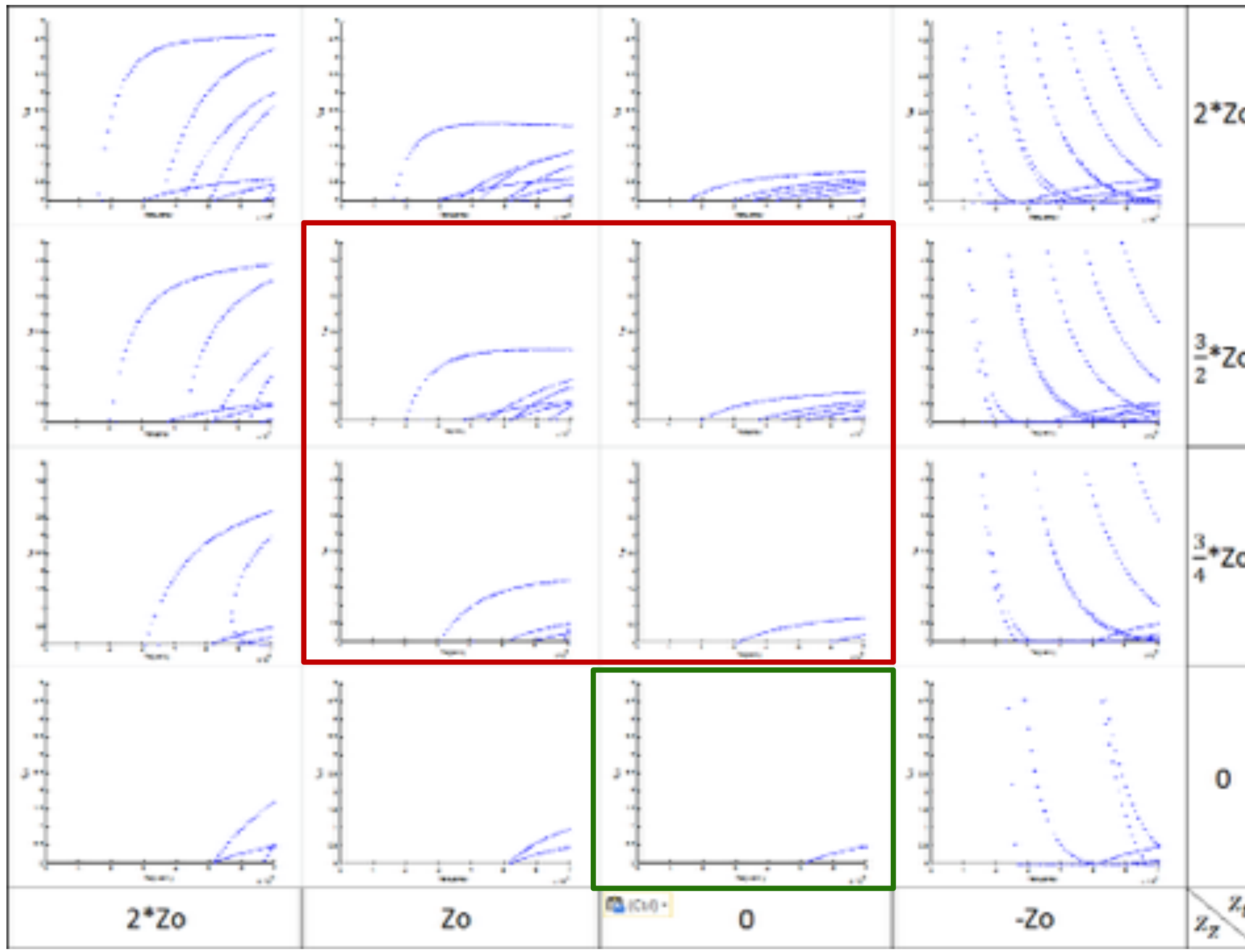


$$Z_t = Z^{TE}, Z_z = Z^{TM}$$

New methodology and results

Theoretical study (3/4)





$$Z_t = Z^{TE}, Z_z = Z^{TM}$$

Required characteristics:

- Lower the f_c of the fundamental mode
- Single-mode bandwidth at least between 3 and 4 GHz

Surface impedance boundaries:

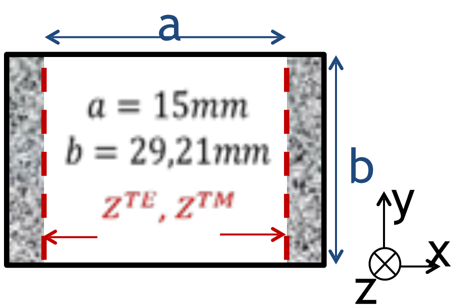
- $j\frac{3}{4}Z_0 < Z^{TE} < j\ Z_0$
- $0 < Z^{TM} < jZ_0$

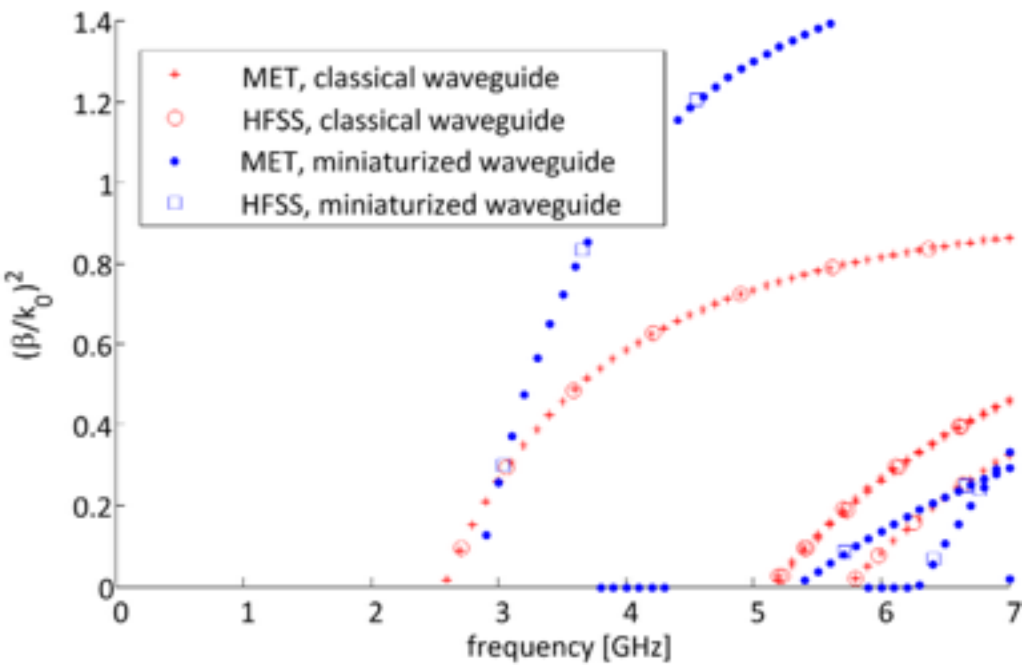
New methodology and results

Theoretical study (4/4)

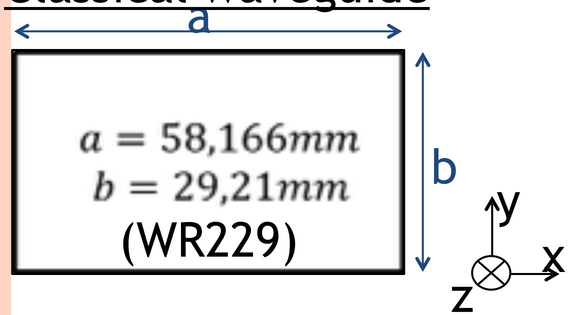
$$Z^{TE} = j\frac{9}{10}Z_0,\ Z^{TM} = \frac{4}{5}jZ_0$$

Miniaturized waveguide





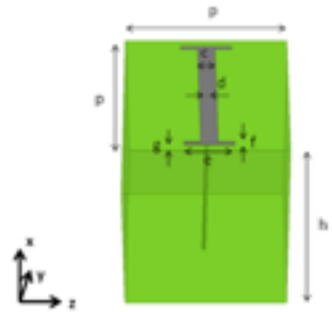
Classical waveguide



Reduction of width of 3/4

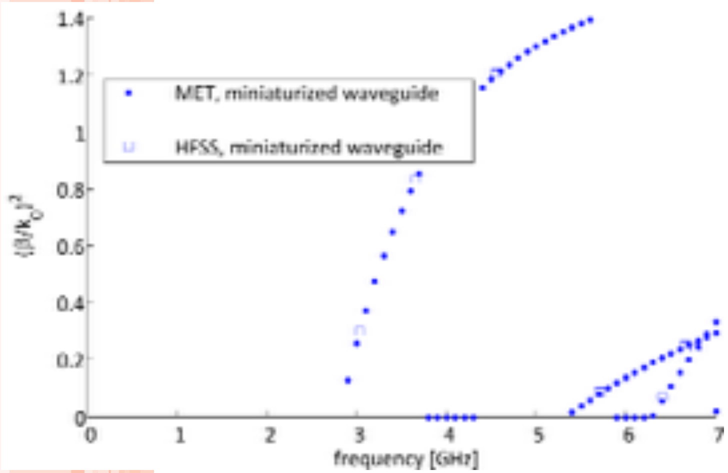
New methodology and results

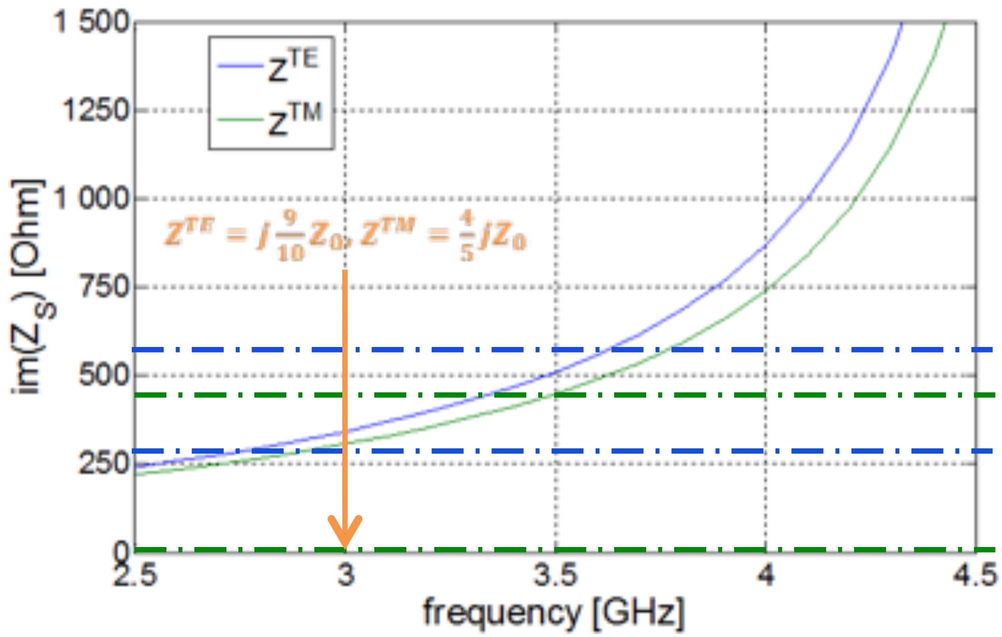
Study of real surface (1/2)



$$p = 7{,}3mm; h = 9{,}3mm; c = 0{,}78mm;$$
$$e = 2{,}3mm; f = 0{,}18mm; g = 0{,}7mm; d = 0{,}18mm;$$
$$\theta = 80°$$

$$Z^{TE} = j\frac{9}{10}Z_0,\ Z^{TM} = \frac{4}{5}jZ_0$$





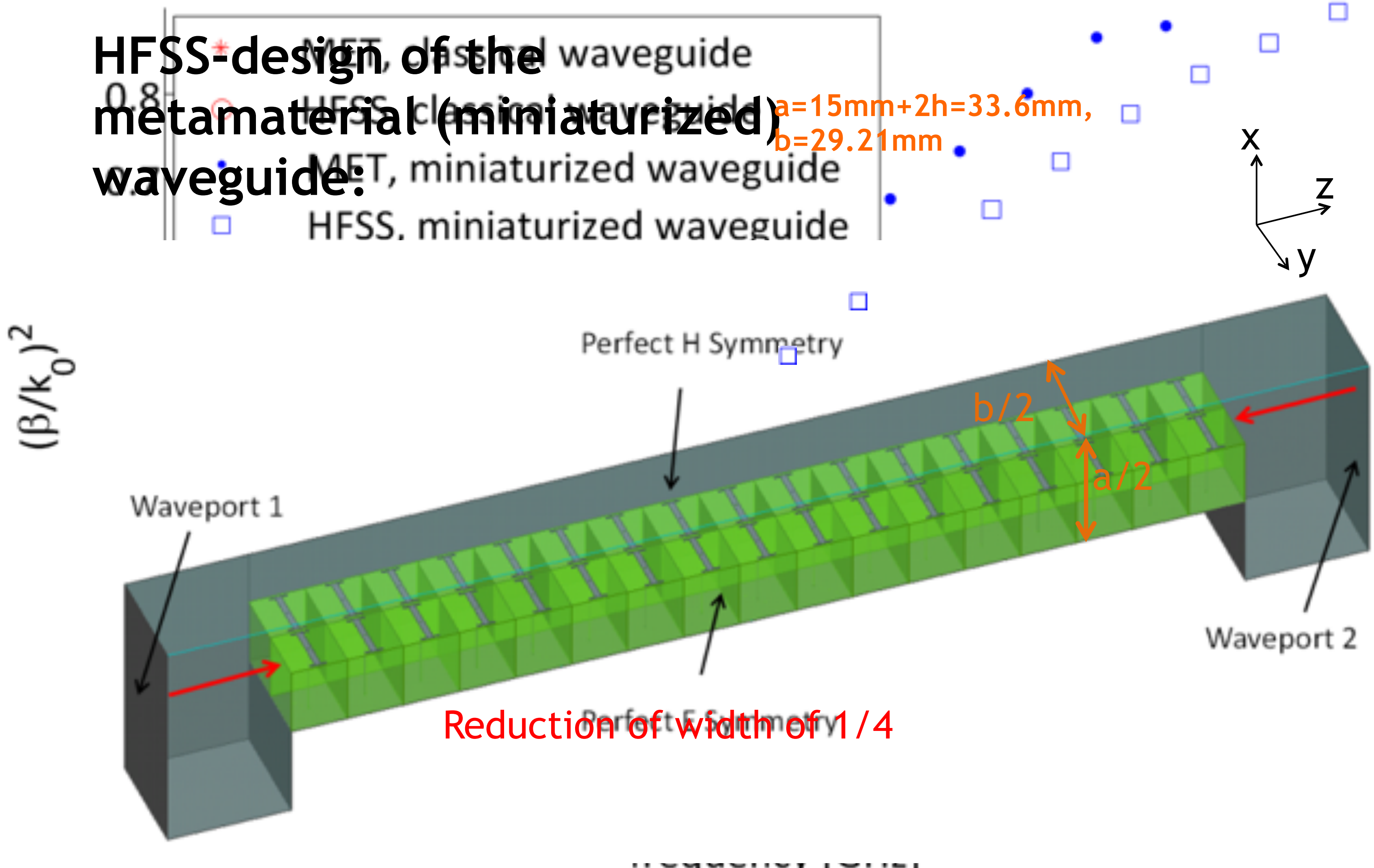
Surface impedance boundaries:

- $j\frac{3}{4}Z_0 < Z^{TE} < j\ Z_0$
- $0 < Z^{TM} < jZ_0$

New methodology and results

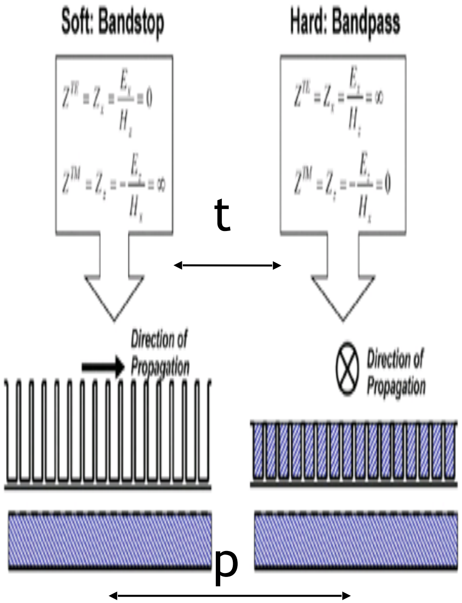
Study of real surface (2/2)

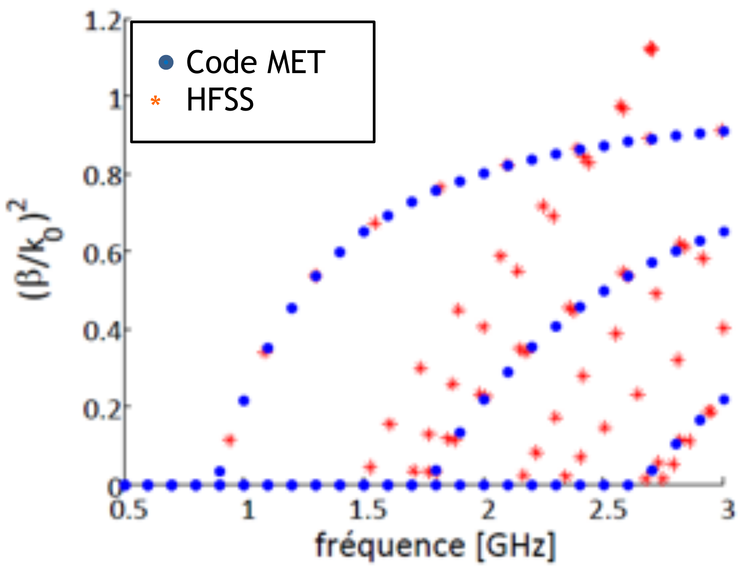
HFSS-design of the metamaterial (miniaturized) waveguide:



New methodology and results

Study of real surface hybrid solution (3/3)





a=32.27mm, b=16.135mm,
p=4mm, t=1.6mm
h=4.55mm

3D FEM Code, incidence on the two axes

Outline

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Conclusions

- Presentation of a new methodology with the aim of:
  - ✓ Identifying properties of new meta-surfaces
  - ✓ Other conditions than the balanced hybrid condition?
- Demonstration of a new meta-surface:
  - ✓ Realizable unit-cell with interesting properties
  - ✓ Reduction of the waveguide's cut-off frequency by 1/4

Perspectives

- Realisation and measurement of a metamaterial waveguide
- Surface impedance calculation in 3D for integration in MET code
- Optimization of the meta-surface during the MET simulation
- Use the methodology for metamaterial horn antennas desig

Thank you for your attention.