

Metamaterial Waveguides

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Outline

- Introduction to metamaterials and metamaterial waveguides
- New features of closed metamaterial waveguides
- New features of open metamaterial waveguides
- Influence of metamaterial loss and dispersion
- Conclusions

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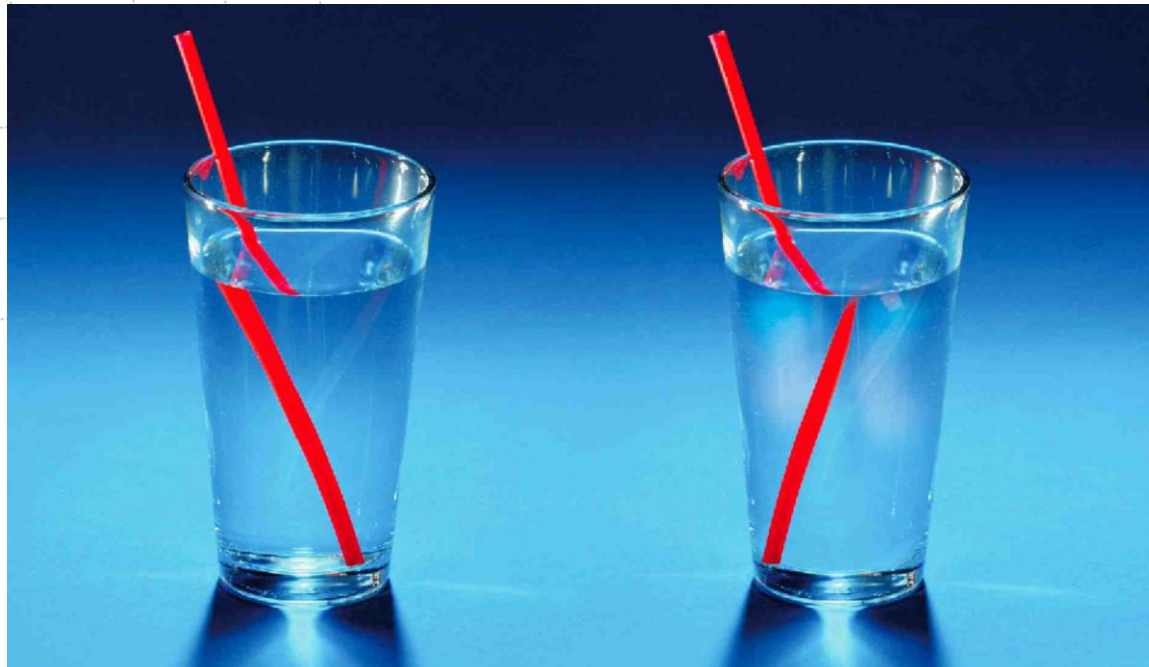
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I. Introduction



Negative refraction

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I. Introduction



Viktor G. Veselago

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Negative index of refraction


$$n^2 = \epsilon\mu$$

$$n = \pm \sqrt{\epsilon\mu}$$

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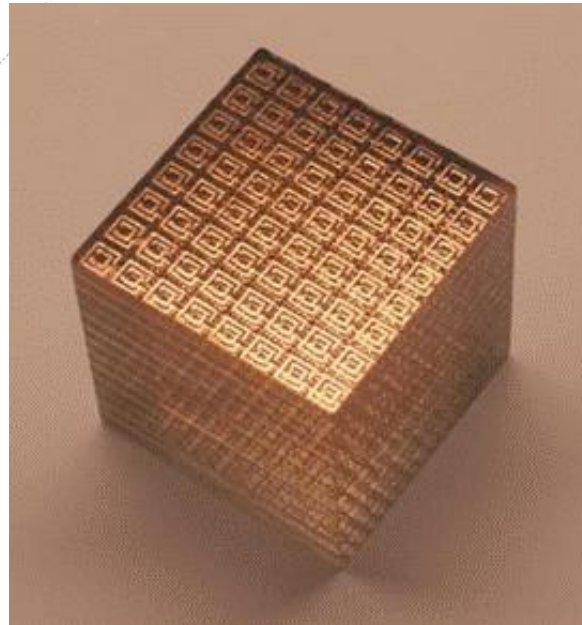
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What are Metamaterials?

Metamaterials are artificial engineered composite structures that can be designed to exhibit specific electromagnetic properties not observed in the constituent materials and not commonly found in nature.



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Types of Metamaterials

- Chiral media
 - Omega media
 - Wire media
-
- Single negative media
 - Double negative media
 - Indefinite media

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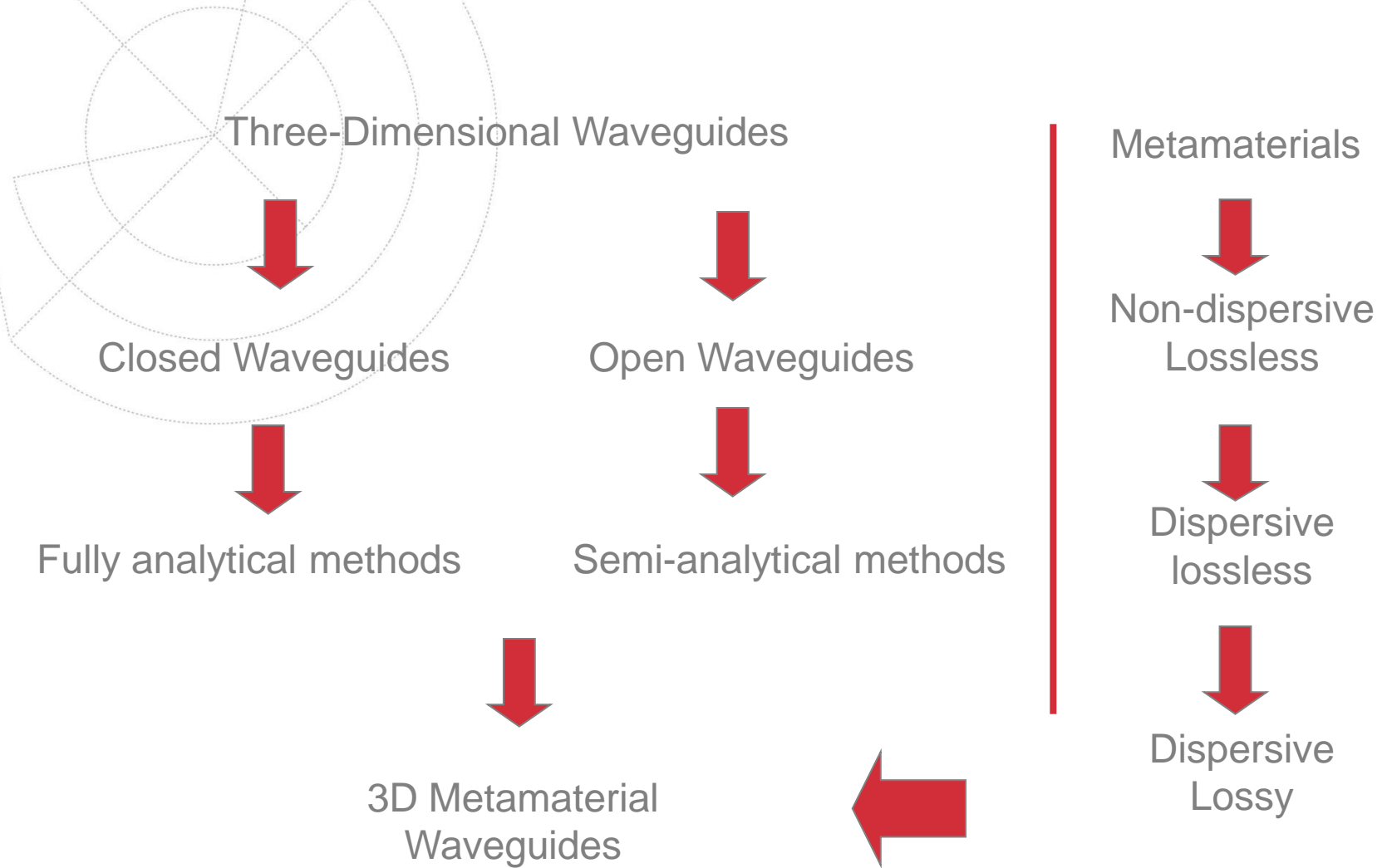
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I. Introduction (DNG Metamaterial Waveguides)



Example of a metamaterial topology

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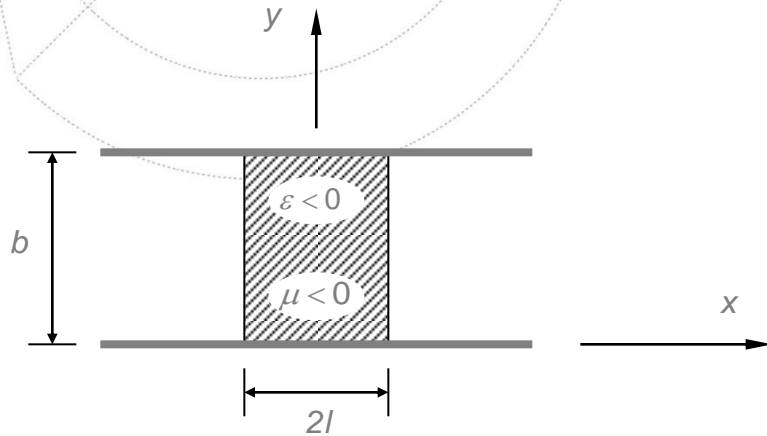
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II. Closed Metamaterial Waveguides

The lossless DNG H-guide



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Other H-guide Geometries



Double-slab H-guide

The diagram shows a cross-section of a double-slab H-guide. It consists of two concentric circular regions. The inner region is divided into several radial segments by lines extending from the center to the inner boundary. The outer region is a larger circle surrounding the inner one. The entire structure is enclosed within a larger, irregular shape that represents the overall waveguide geometry.

H-guide directional coupler

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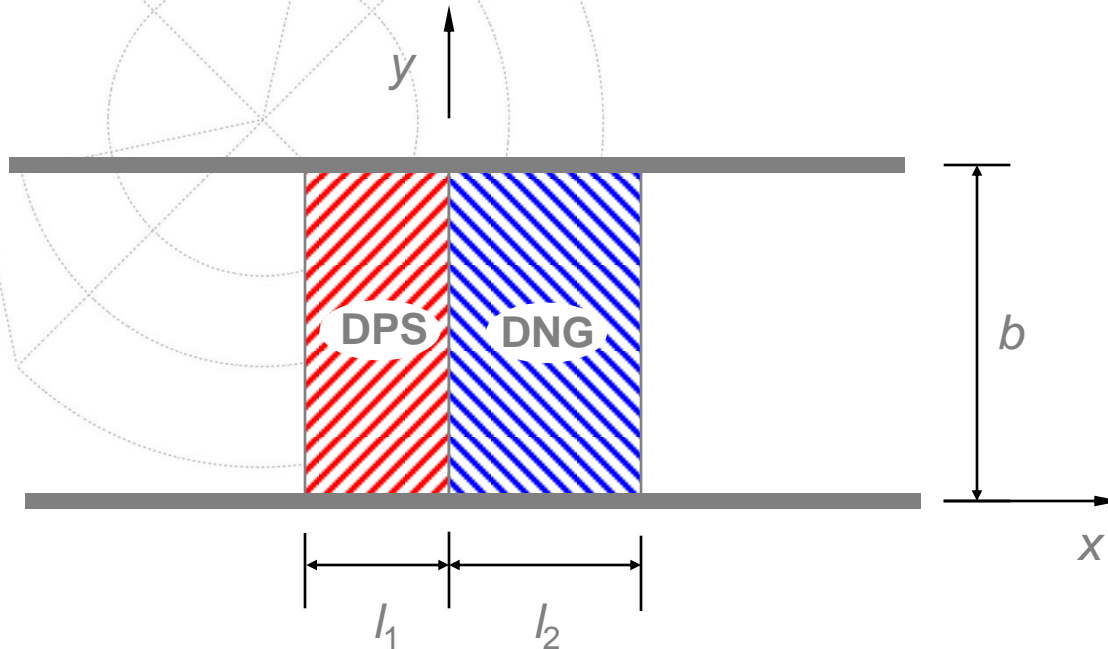
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Double Slab H-guide



Constitutive parameters:

$$\varepsilon_r(x) = \begin{cases} 1 & x < -l_1 \\ \varepsilon_1 & -l_1 < x < 0 \\ \varepsilon_2 & 0 < x < l_2 \\ 1 & x > l_2 \end{cases}$$

$$\mu_r(x) = \begin{cases} 1 & x < -l_1 \\ \mu_1 & -l_1 < x < 0 \\ \mu_2 & 0 < x < l_2 \\ 1 & x > l_2 \end{cases}$$

Geometric parameters:

$$l = l_1 + l_2$$

$$\zeta = b/l$$

$$\xi = l_2/l_1$$

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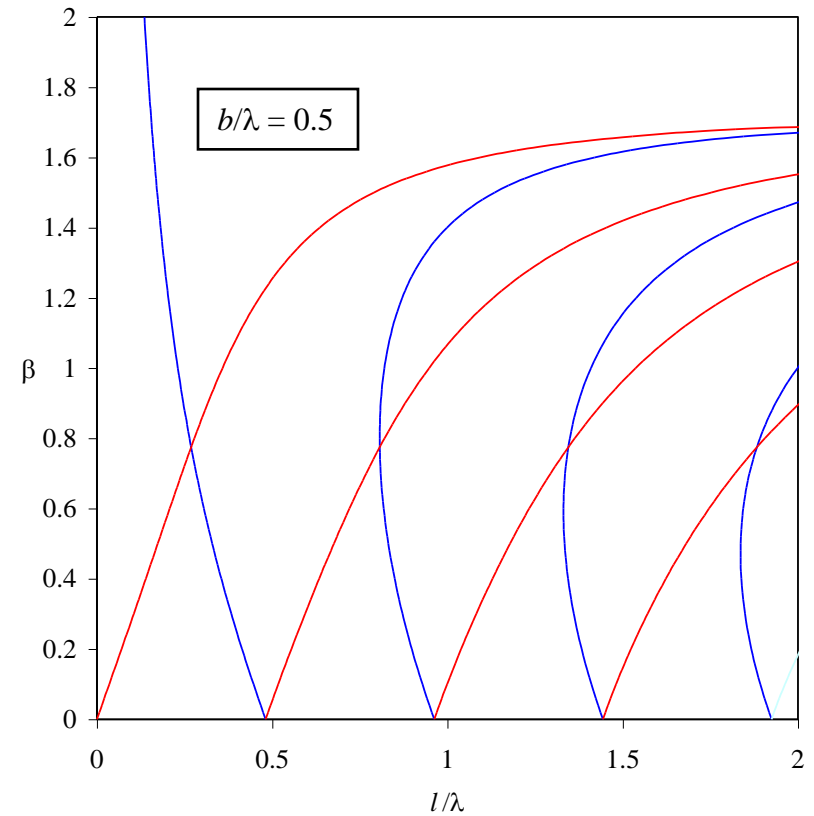
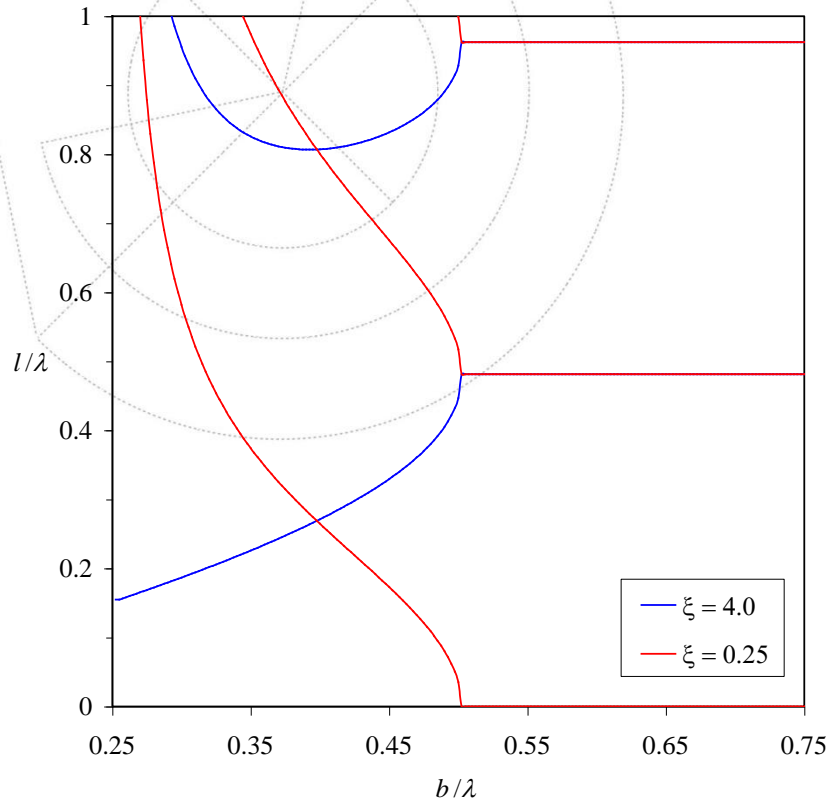


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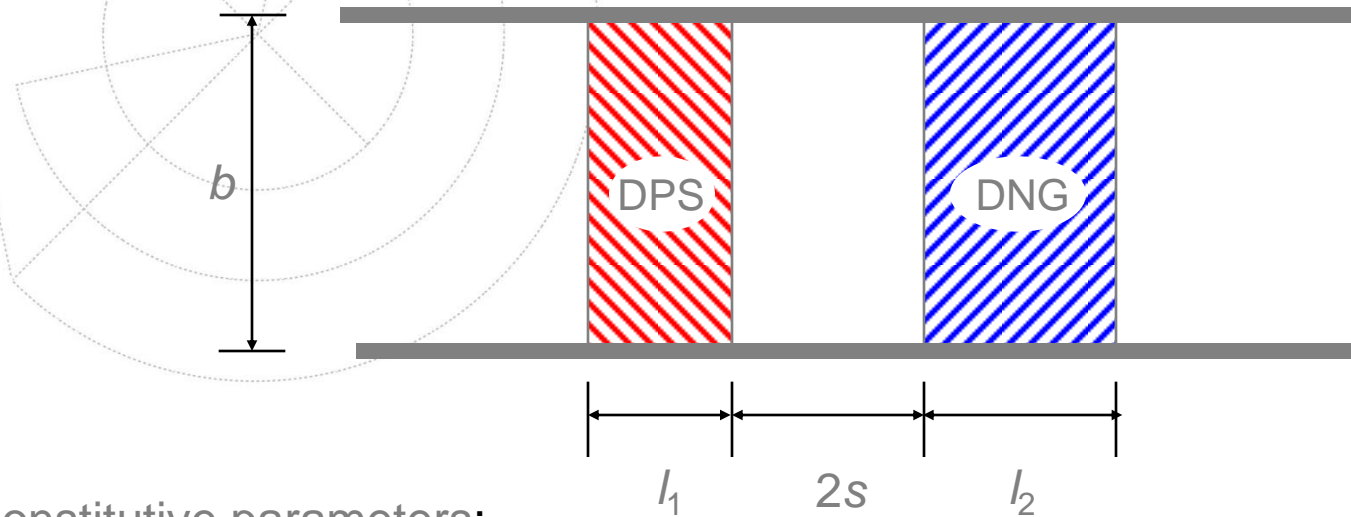
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Operational and Dispersion Diagrams



The Contra-directional Coupler



$$l = l_1 + l_2$$

$$z = b/l$$

$$x = l_2/l_1$$

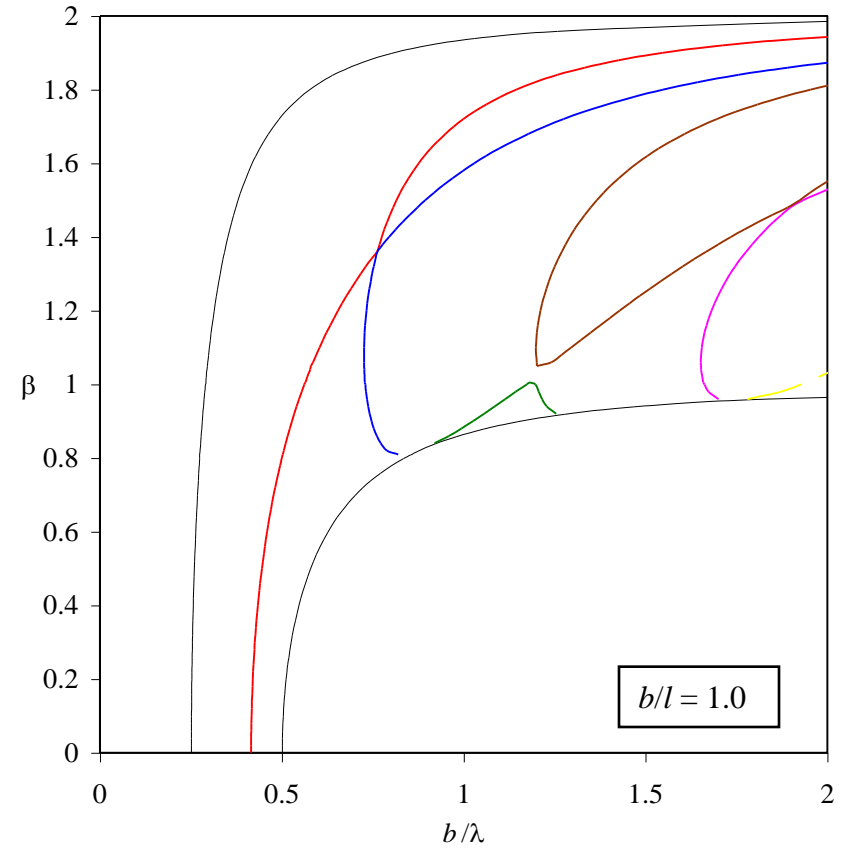
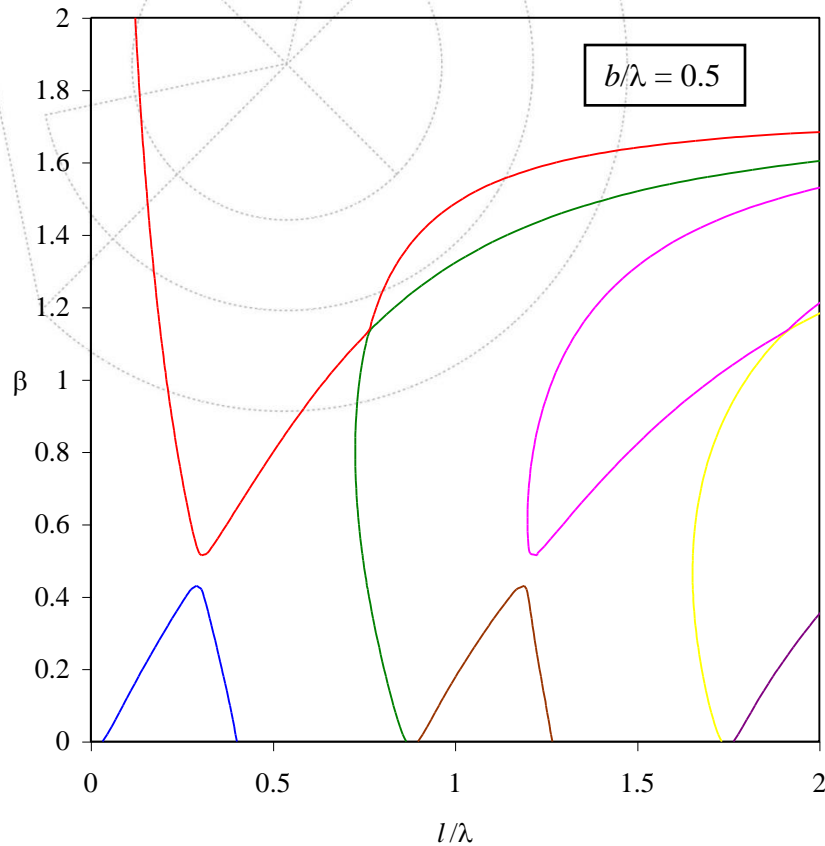
$$h = s/l$$

Constitutive parameters:

$$\mu_r(x) = \begin{cases} 1 & x < -l_1 - s \\ \mu_1 & -l_1 - s < x < -s \\ 1 & -s < x < s \\ \mu_2 & s < x < s + l_2 \\ 1 & x > s + l_2 \end{cases}$$

$$\varepsilon_r(x) = \begin{cases} 1 & x < -l_1 - s \\ \varepsilon_1 & -l_1 - s < x < -s \\ 1 & -s < x < s \\ \varepsilon_2 & s < x < s + l_2 \\ 1 & x > s + l_2 \end{cases}$$

Dispersion Diagrams



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III. Open Metamaterial Waveguides

- The transverse resonance method is used in the characterization of the guided-wave propagation of open DNG waveguides.
- The assessment of the method is done by comparison with the effective index method.
- Proper leaky modes propagate in open three-dimensional double-negative (DNG) metamaterial waveguides.

III. Open Metamaterial Waveguides

Discrete Spectrum

Surface Modes

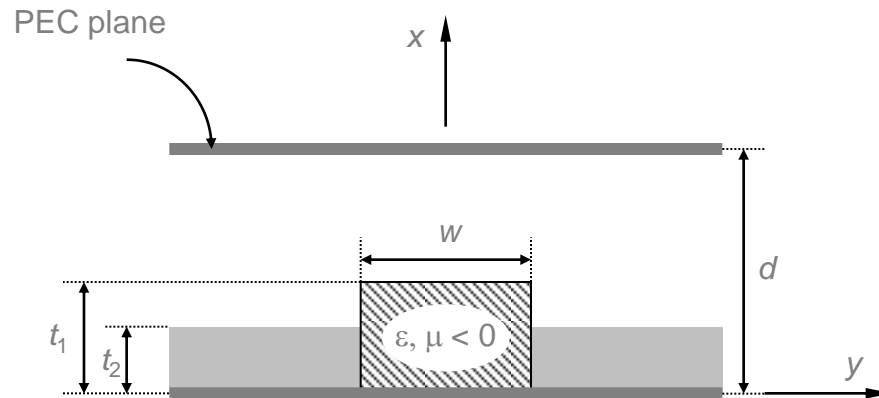
Leaky Modes

Continuous Spectrum

Radiation Modes

Evanescent Modes

Discretization of the Continuous Spectrum:



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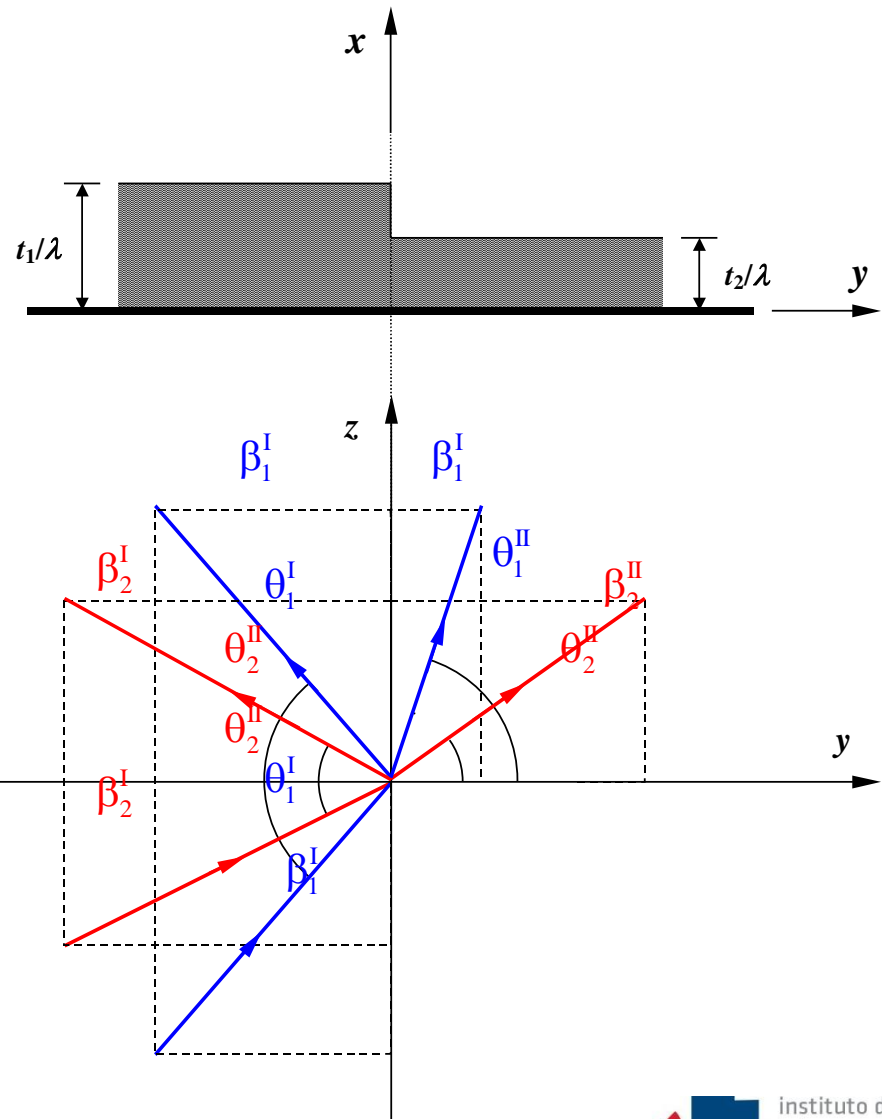
Oblique Incidence

$$\beta = \beta_i^I \sin \theta_i^I$$

$$q_i^I = \beta_i^I \cos \theta_i^I$$

$$q_i^{II} = \beta_i^{II} \cos \theta_i^{II}$$

$$\beta = \beta_i^{II} \sin \theta_i^{II}$$



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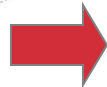
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Mode Matching Technique

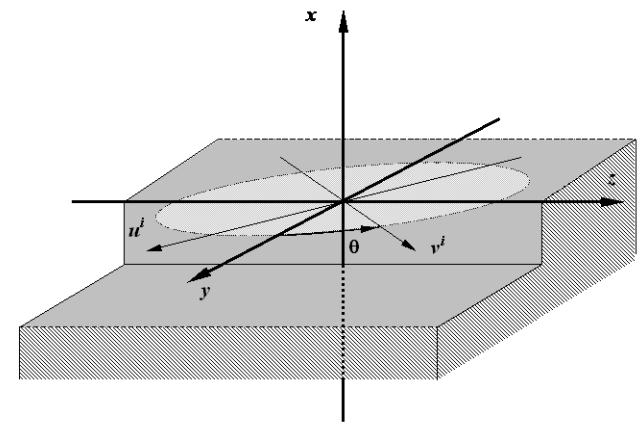
LSE and LSM Modes

Boundary Conditions

$$\left\{ \begin{aligned} E_x^i(d') + E_x^r(d') &= E_x^t(d') \\ H_x^i(d') + H_x^r(d') &= H_x^t(d') \\ E_z^i(d') + E_z^r(d') &= E_z^t(d') \\ H_z^i(d') + H_z^r(d') &= H_z^t(d') \end{aligned} \right.$$



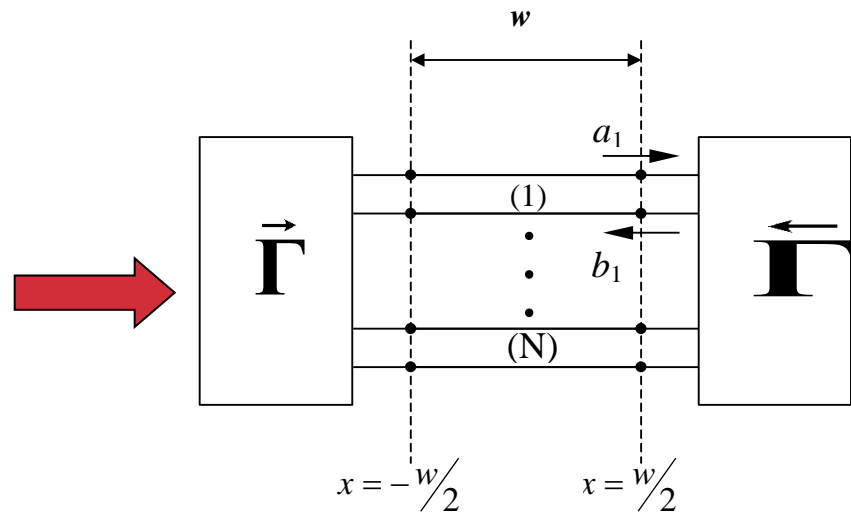
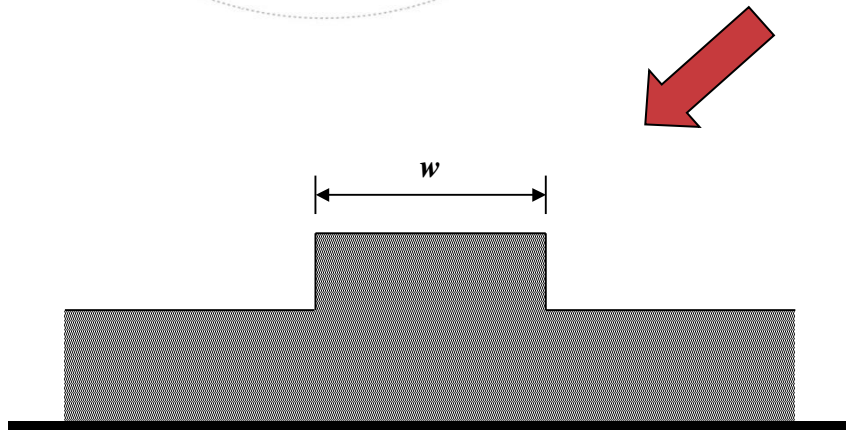
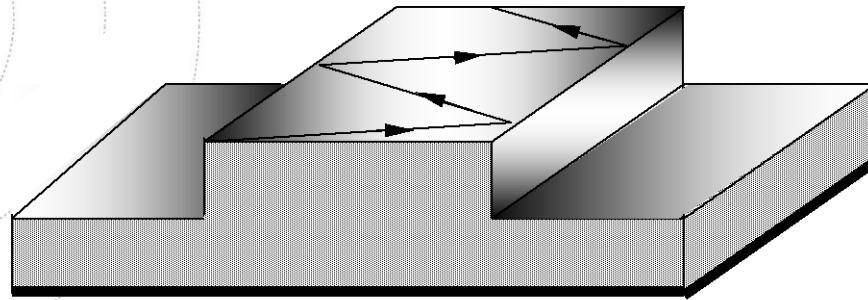
$$\left\{ \begin{aligned} \sum_{n=1}^{\infty} (a_n + b_n) E_{x_n}^i &= \sum_{p=1}^{\infty} c_p E_{x_p}^{II} \\ \sum_{n=1}^{\infty} (a_n + b_n) H_{x_n}^i &= \sum_{p=1}^{\infty} c_p H_{x_p}^{II} \\ -\sum_{n=1}^{\infty} (a_n - b_n) \cos \theta_n^I E_{u_n}^i + \sum_{n=1}^{\infty} (a_n + b_n) \sin \theta_n^I E_{v_n}^i &= \sum_{p=1}^{\infty} c_p \left[-\cos \theta_p^{II} E_{u_p}^{II} + \sin \theta_p^{II} E_{v_p}^{II} \right] \\ -\sum_{n=1}^{\infty} (a_n - b_n) \cos \theta_n^I H_{u_n}^i + \sum_{n=1}^{\infty} (a_n + b_n) \sin \theta_n^I H_{v_n}^i &= \sum_{p=1}^{\infty} c_p \left[-\cos \theta_p^{II} H_{u_p}^{II} + \sin \theta_p^{II} H_{v_p}^{II} \right] \end{aligned} \right.$$



Scattering Matrix

$$\mathbf{b} = \vec{\Gamma} \cdot \mathbf{a}$$

Transverse Resonance Method



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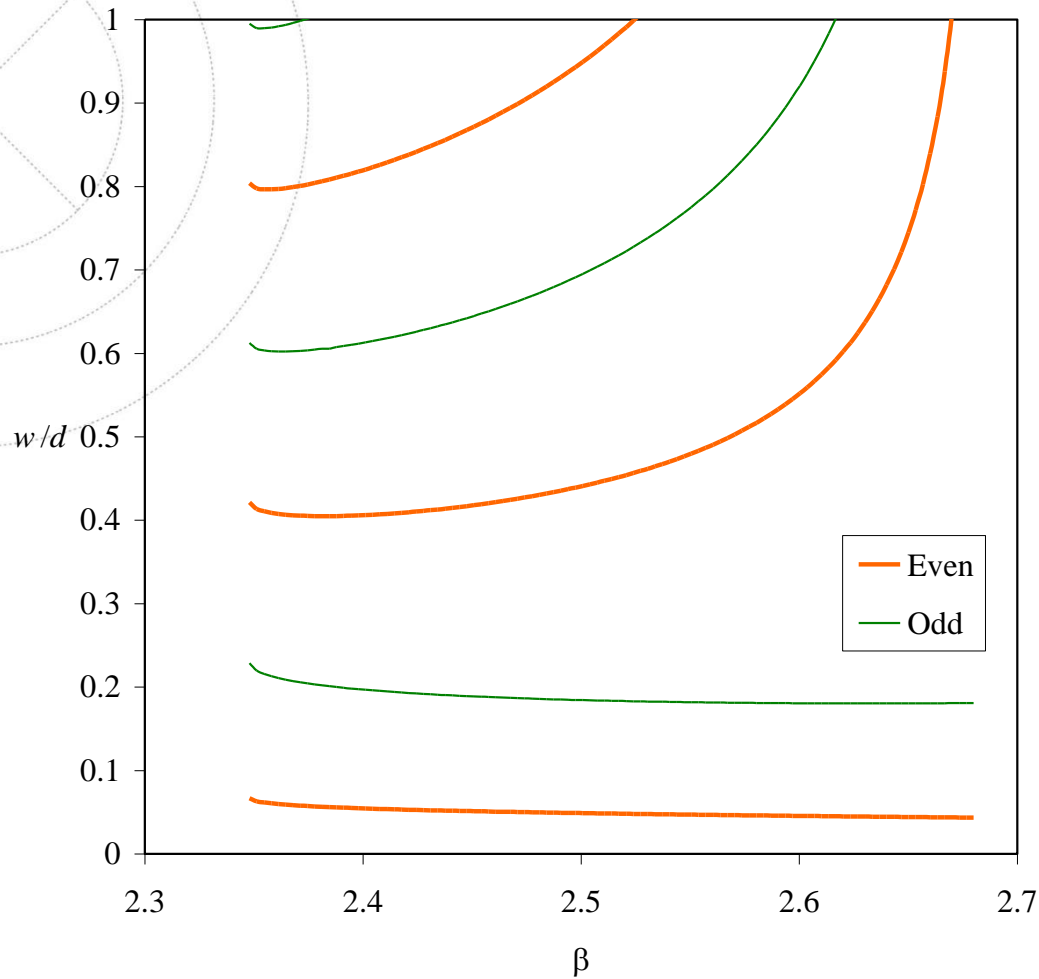


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DNG Ridge Waveguide: Numerical Results



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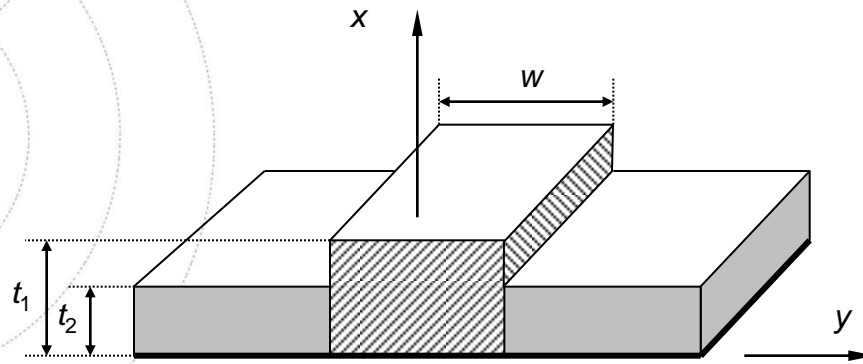


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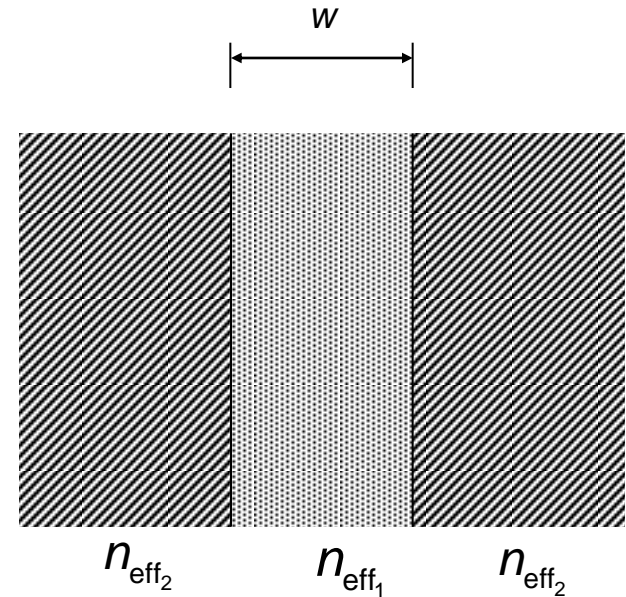
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The Effective Index Method



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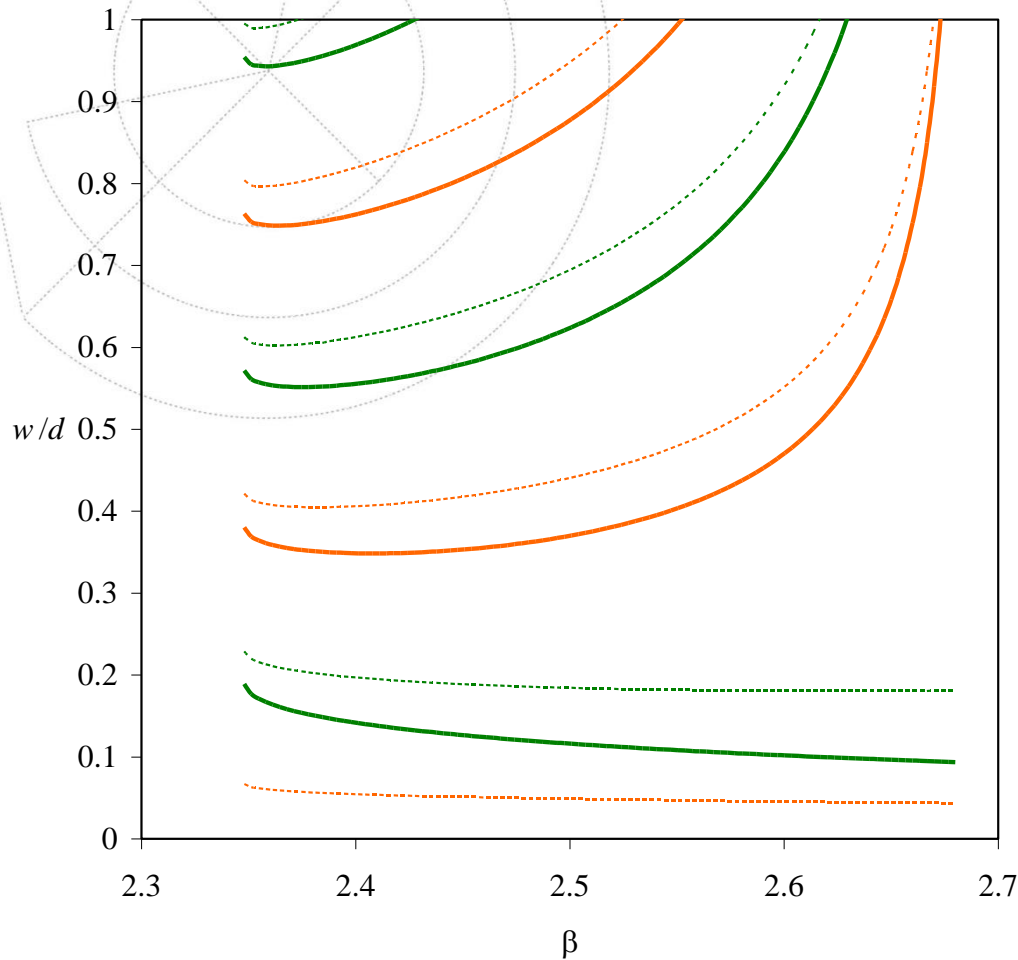
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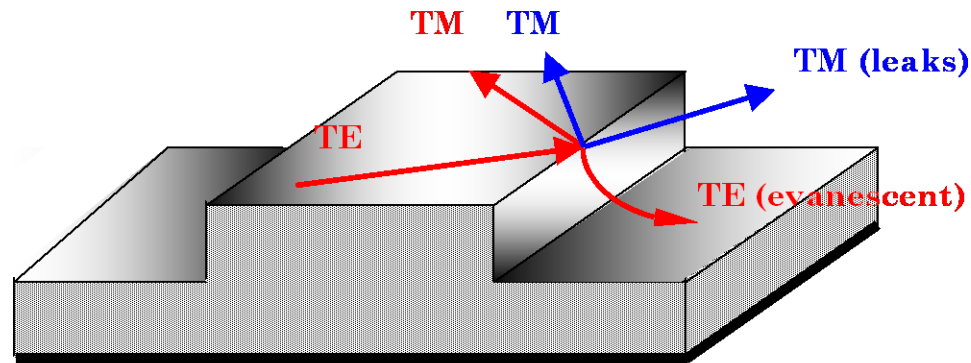
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Numerical Results and Assessment



- There are some limitations to neglect the TE–TM coupling at the sides of the DNG waveguide.
- The EIM is also applicable to DNG waveguides (excluding the super-slow modes and far from the cutoff region), but only when approximate values are desired.

Improper Leaky Modes (DPS waveguide)



S.-T. Peng and A. A. Oliner, "Guidance and leakage properties of a class of open dielectric waveguides: Part I – Mathematical formulations," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 843-855, Sep. 1981.

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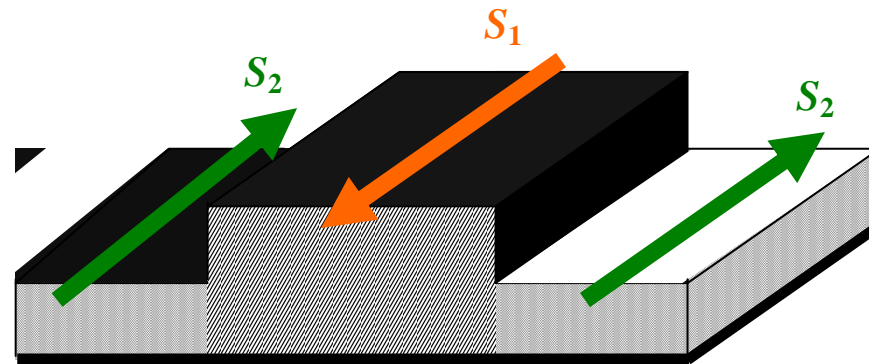
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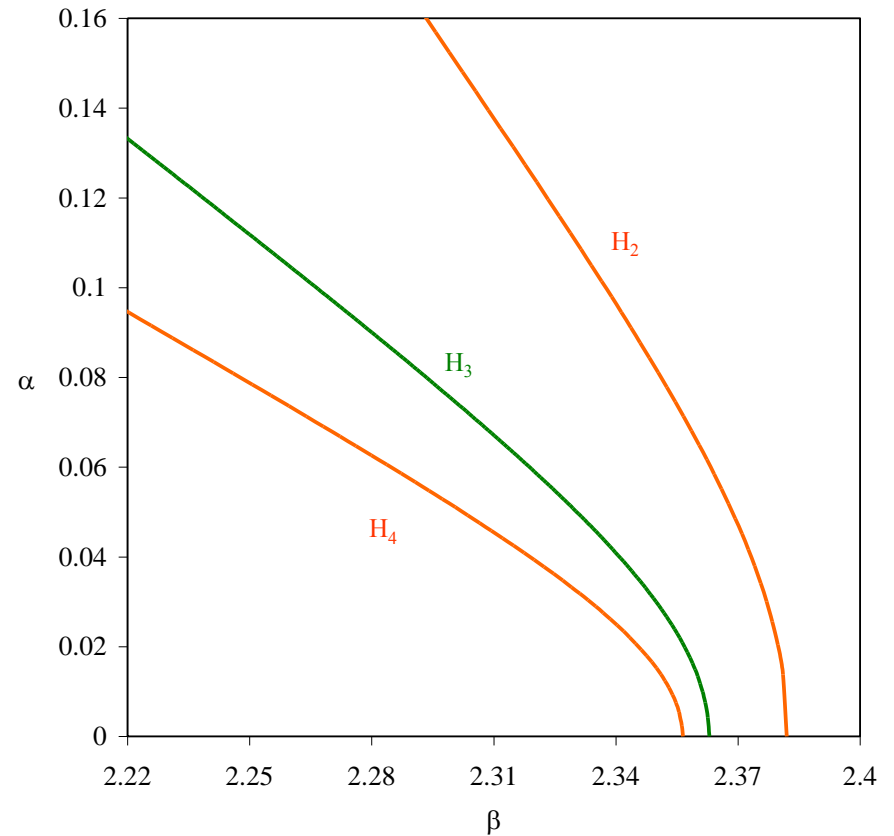
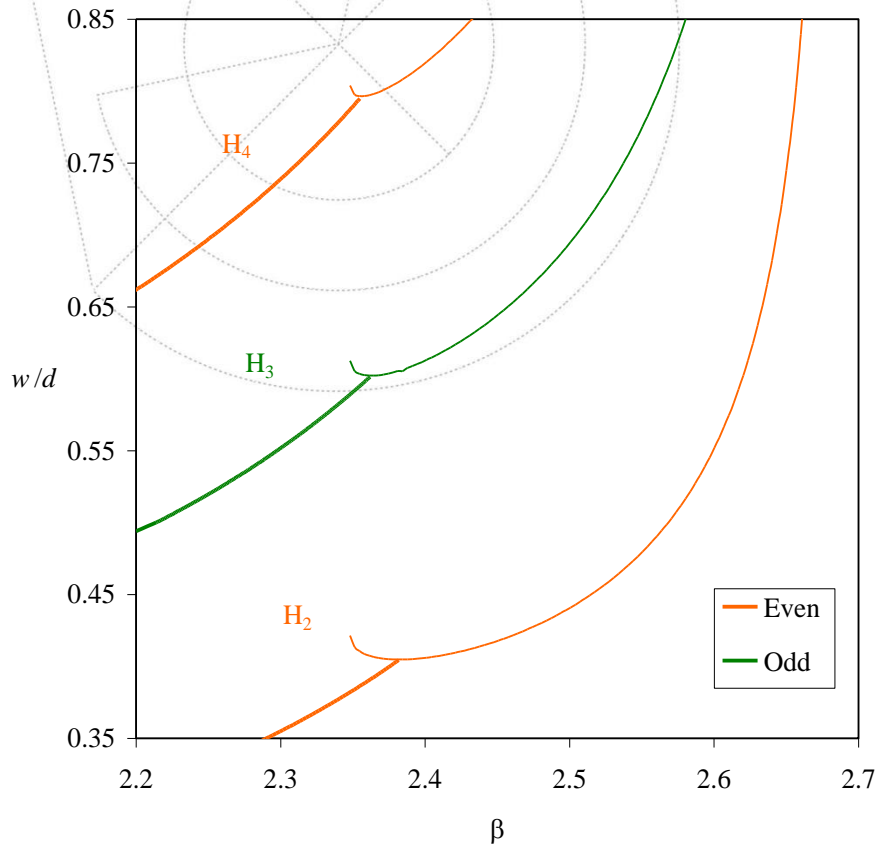
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Proper Leaky Modes (DNG waveguide)



At a certain point of operation, the modes propagating in the inner region of the waveguide become backward modes, exhibiting a power flux which is opposite to that of the modes propagating in the outer region, therefore generating proper leaky modes.

Leaky Modes



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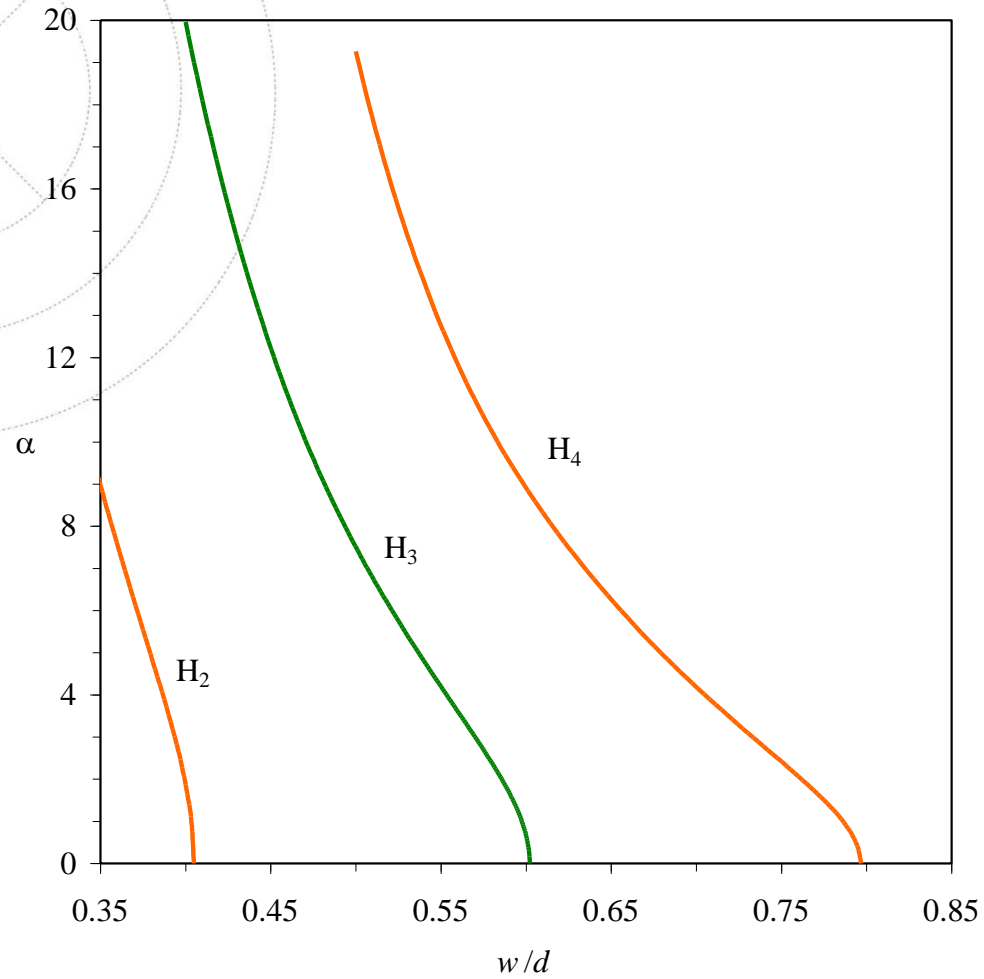
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Leakage Constant



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IV. Metamaterial Loss and Dispersion

- Most work on waveguiding structures ignores metamaterial loss and dispersion.
- Can losses be seen as just a small perturbation of the lossless case?
- How does the presence of dispersion and losses affect the performance of the waveguides involving metamaterials?
- Are there any physical effects arising from metamaterial loss and dispersion that can be used in the design of new devices?

The Lorentz model (I)

$$\varepsilon(\omega) = 1 + \frac{\omega_{pe}^2}{\omega_{0e}^2 - \omega^2 + j\Gamma_e \omega}$$

$$\mu(\omega) = 1 + \frac{\omega_{pm}^2}{\omega_{0m}^2 - \omega^2 + j\Gamma_m \omega}$$

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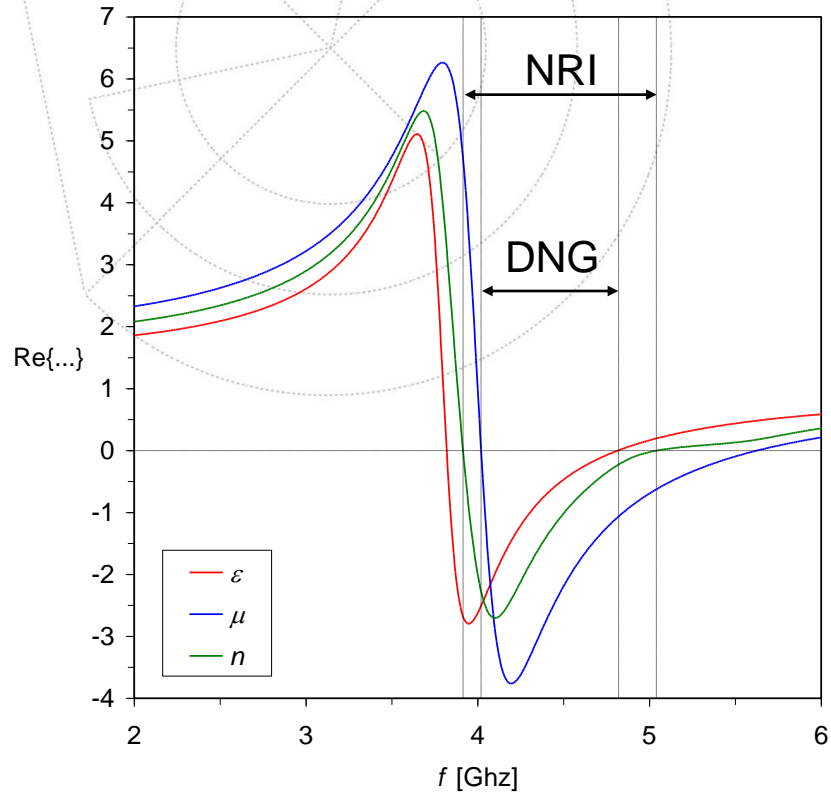
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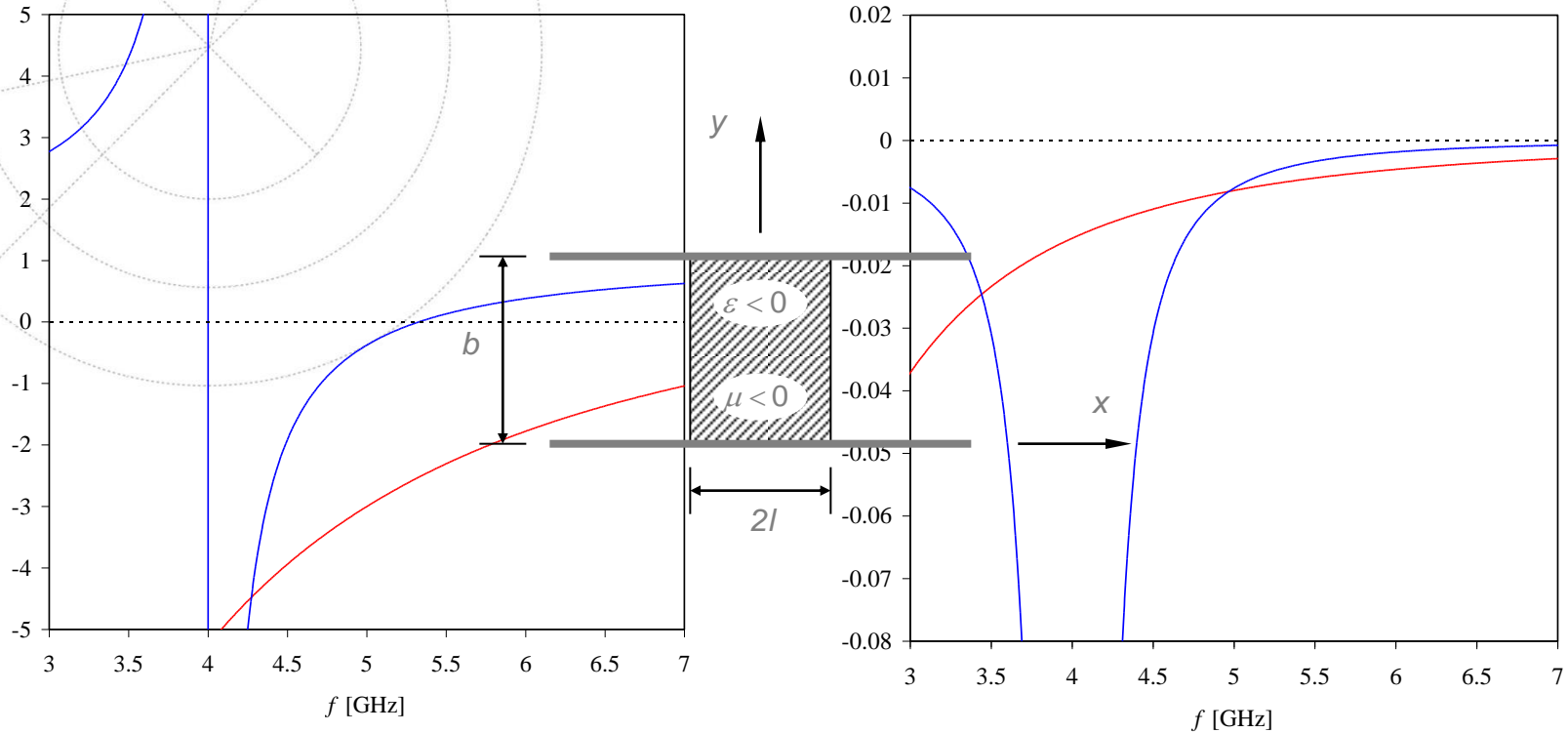
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The Lorentz model (II)



The DNG range is not identically to the NRI range.

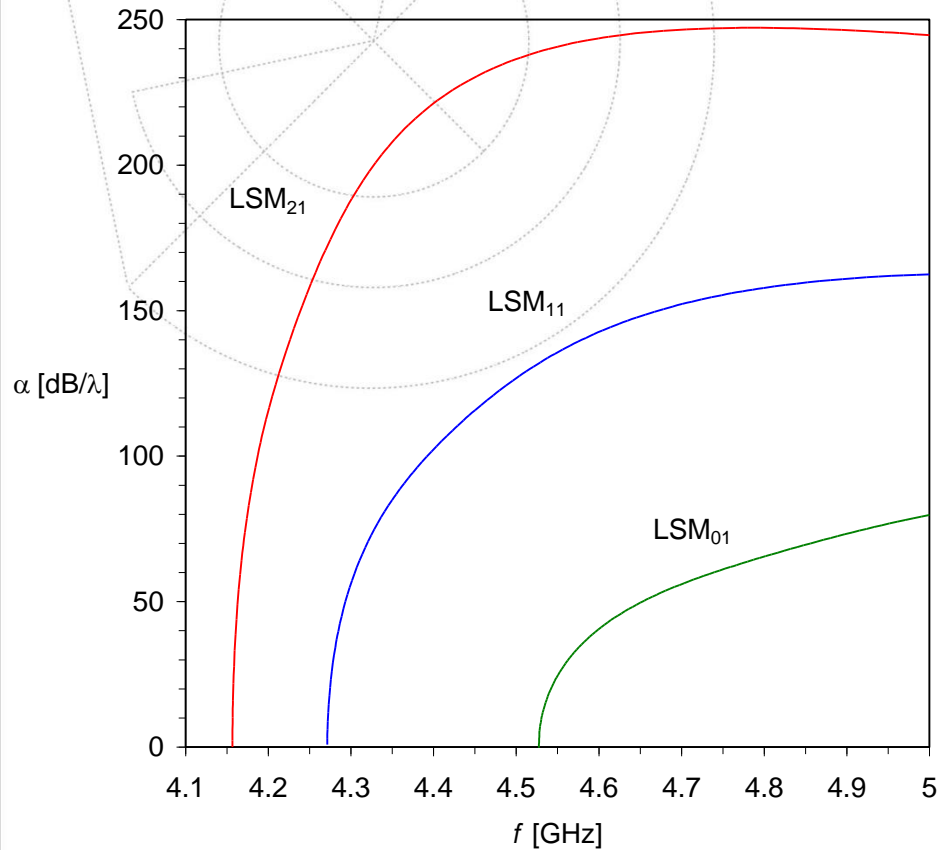
The lossy DNG H-guide



All the modal solutions in the DNG H-guide become complex.

Attenuation constant

Lossless case



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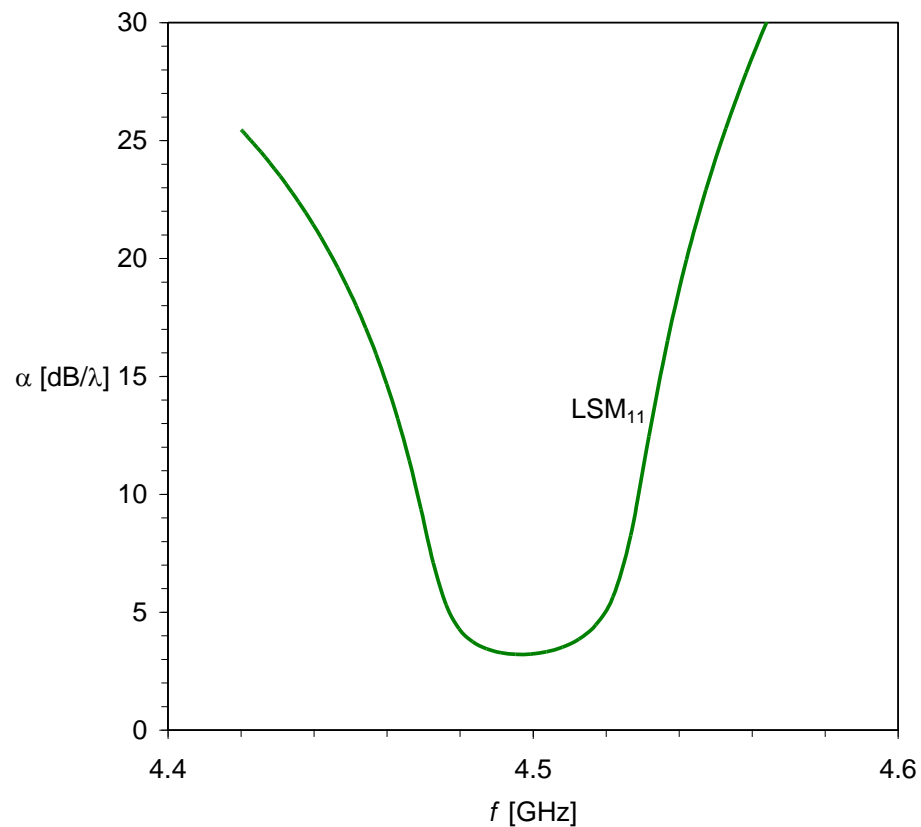
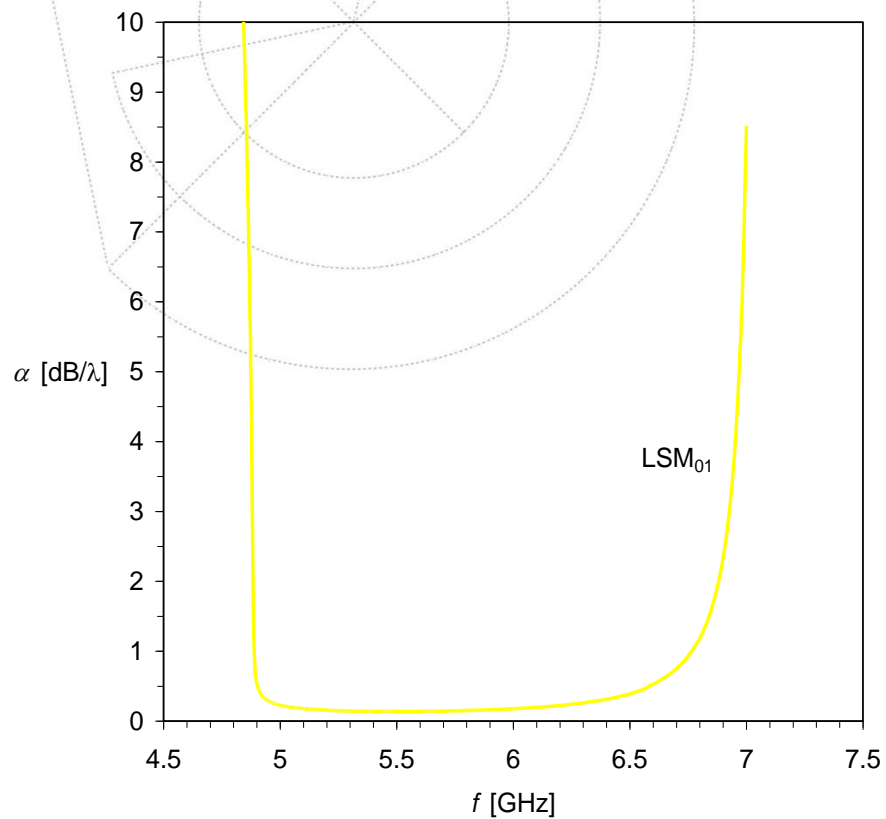
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The DNG H-guide filter (I)



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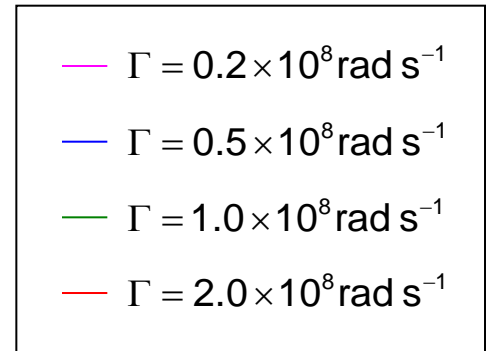
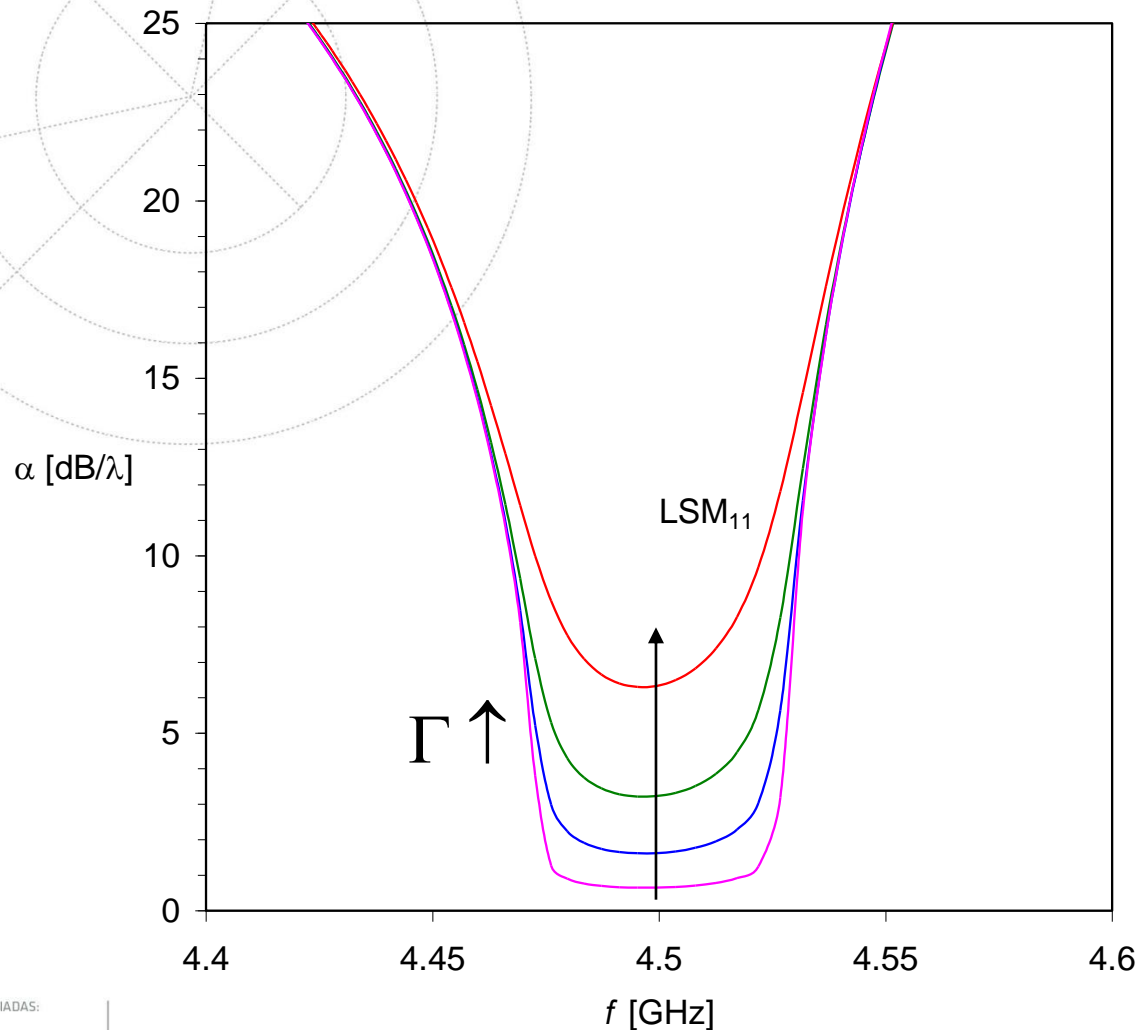
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The DNG H-guide filter (II)



V. Conclusions

- Methods commonly used for conventional three-dimensional waveguides, can be easily generalized to DNG metamaterial waveguides.
- Full-wave analyses (analytical or semi-analytical) provide a physical interpretation for all the modal solutions of DNG three-dimensional waveguides.
- In addition to strongly dispersive media, DNG metamaterials must be also considered as lossy, since both dispersion and losses avoid unphysical meaningless solutions.
- A comparative study between the lossy and lossless cases proves that losses are more than a perturbation strongly affecting the performance of the waveguide.