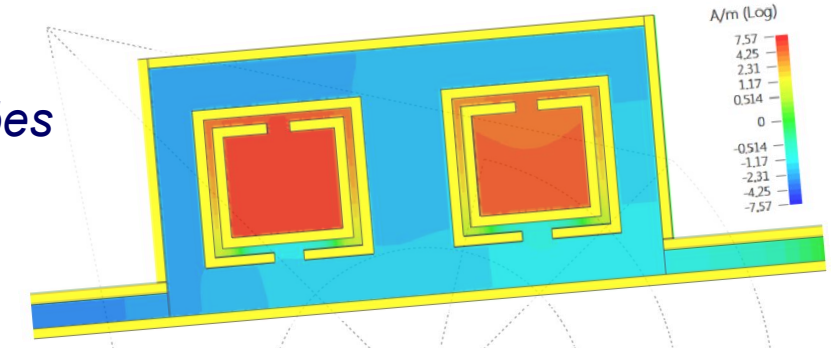
8º Congresso do Comité Português da URSI

Mu-near-zero (MNZ) supercoupling

Instituto de Telecomunicações
Universidade de Coimbra



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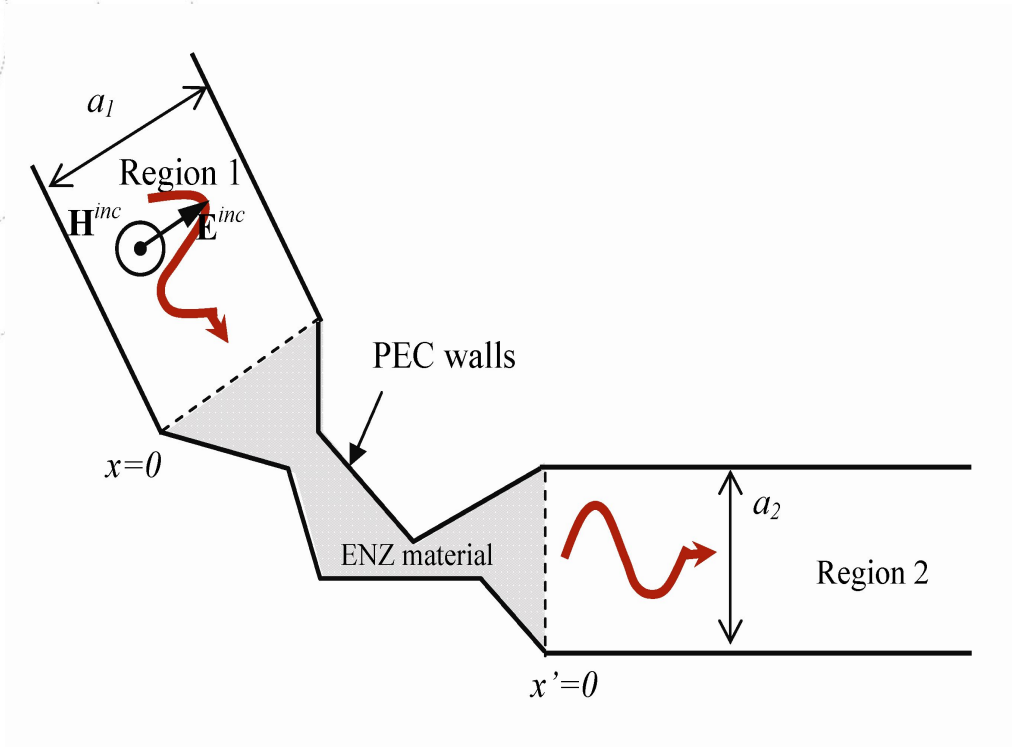
creating and sharing knowledge for telecommunications

Contexto

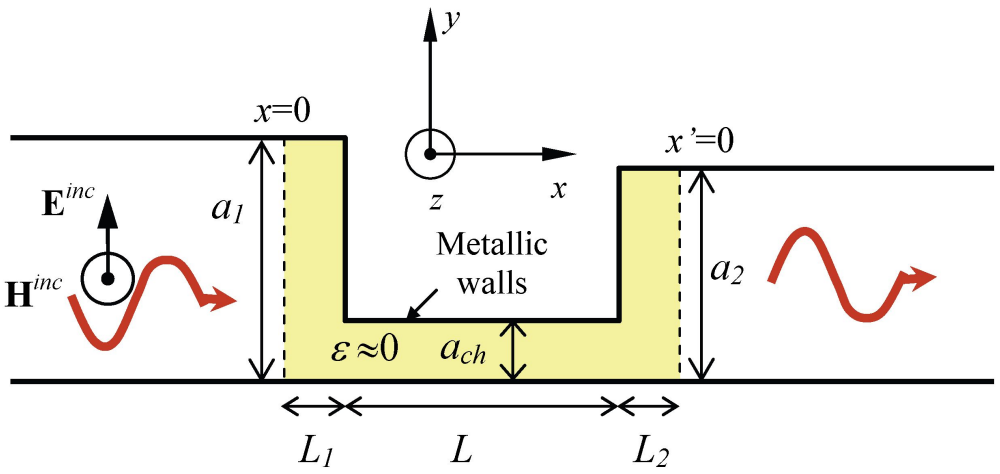
Ligação entre dois guias tendo pelo meio uma secção mais estreita



Tunneling of Electromagnetic Energy through Subwavelength Channels and Bends using ε-Near-Zero Materials,
Mário Silveirinha and Nader Engheta - Physical Review Letters 2006

Transição em forma de "U" e "EM squeezing"

Estudou-se concretamente uma transição em forma de "U"



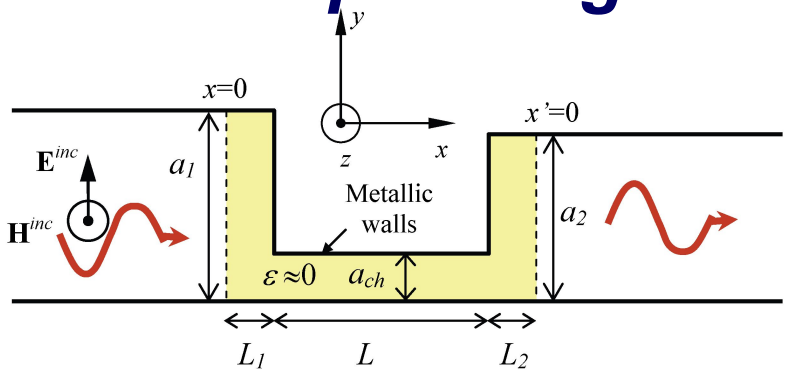
$$\rho = \frac{(a_1 - a_2) + ik_0\mu_r A_D}{(a_1 + a_2) - ik_0\mu_r A_D}$$ **where** $A_D = a_1 L_1 + a_2 L_2 + a_{ch} L$

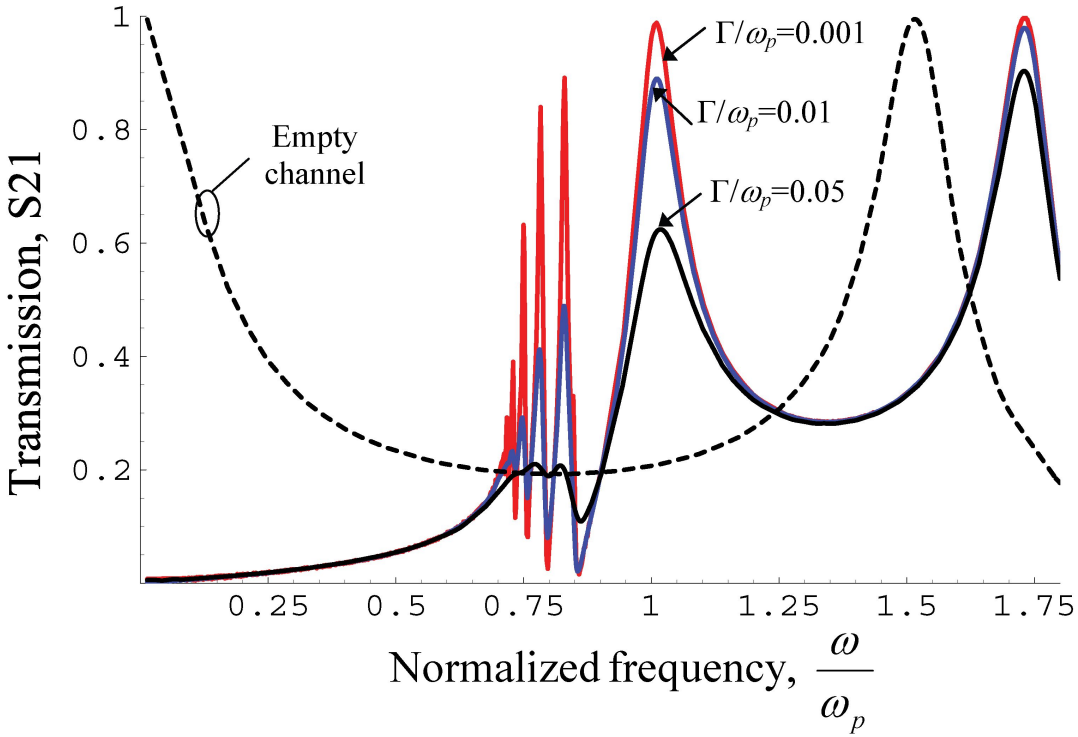
Transição em forma de "U" e "EM squeezing" (cont.)

$$a_1 = a_2 = L \equiv a$$

$$L_1 = L_2 = a_{ch} = 0.1a$$

$$\mu_r = 1$$





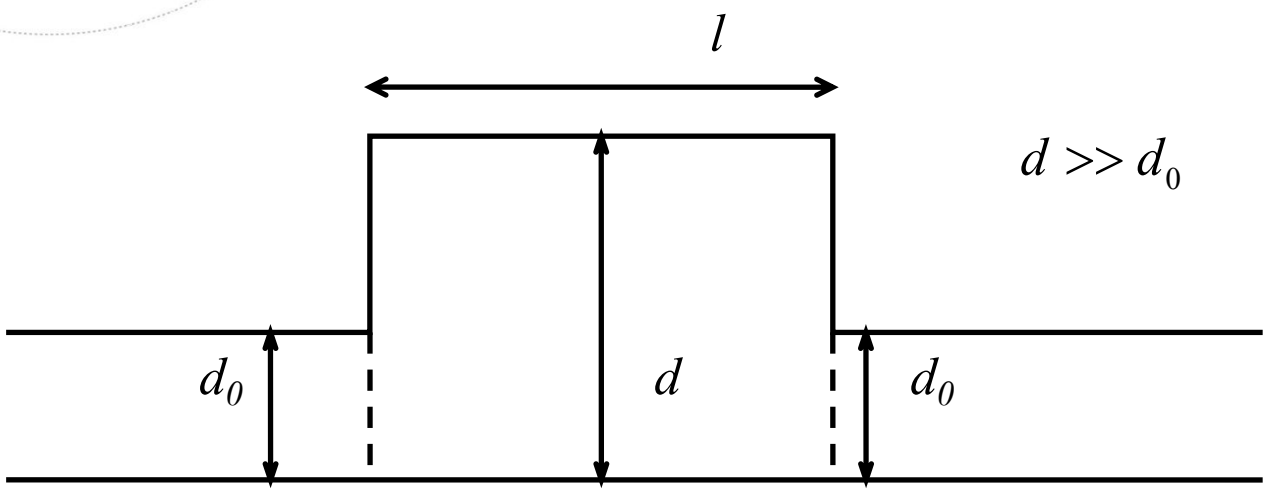
$$\varepsilon = 1 - \frac{\omega_p^2}{\omega(\omega - j\Gamma)}$$

$$\omega_p a / c = \pi / 2$$

Cenário complementar

Conseguir-se-á um efeito de túnel semelhante (sem atraso de fase!) num cenário complementar?

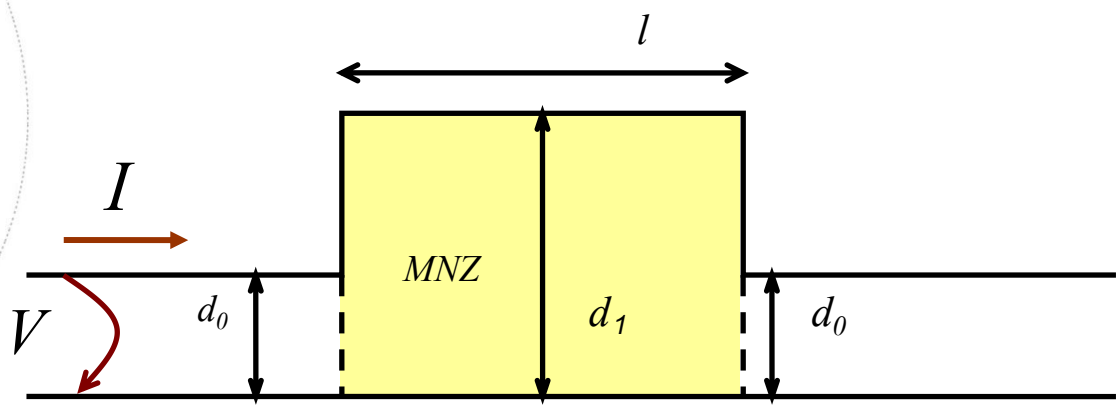
Transmissão através de um canal de transição mais largo



Modelo equivalente de Linhas de Transmissão

$$V = E \times d_1$$

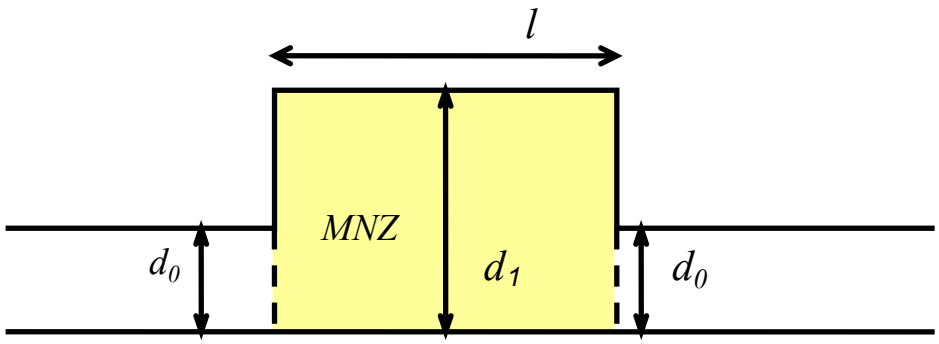
$$I = H \times w$$



$$Z_c = \frac{V}{I} = \eta_{TEM} \frac{d_1}{w} = \sqrt{\frac{\mu}{\varepsilon}} \frac{d_1}{w}$$

Condições de Adaptação

$$Z_{c0} = Z_{c,MNZ}$$



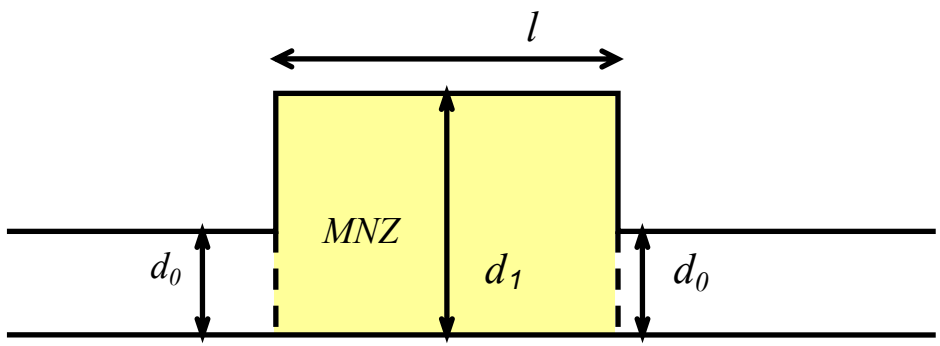
$$\sqrt{\frac{\mu_0}{\varepsilon_0}}\frac{d_0}{w} = \sqrt{\frac{\mu}{\varepsilon}}\frac{d_1}{w}$$

$$\rightarrow \frac{\mu}{\mu_0} = \frac{\varepsilon}{\varepsilon_0}\left(\frac{d_0}{d_1}\right)^2$$

Os materiais MNZ possibilitam uma adaptação virtualmente perfeita entre guias de onda com secções transversais muito diferentes!

Limite MNZ

$$Z_c = \sqrt{\frac{\mu}{\varepsilon}}\frac{d_1}{w}$$



$$\Gamma = \frac{Z_{in} - Z_{c0}}{Z_{in} + Z_{c0}}$$

$$Z_{in} = Z_{c,MNZ}\frac{Z_{c0} + jZ_{c,MNZ}\tan\left(\beta_{MNZ} l\right)}{Z_{c,MNZ} + jZ_{c0}\tan\left(\beta_{MNZ} l\right)}$$

If $\mu \to 0$

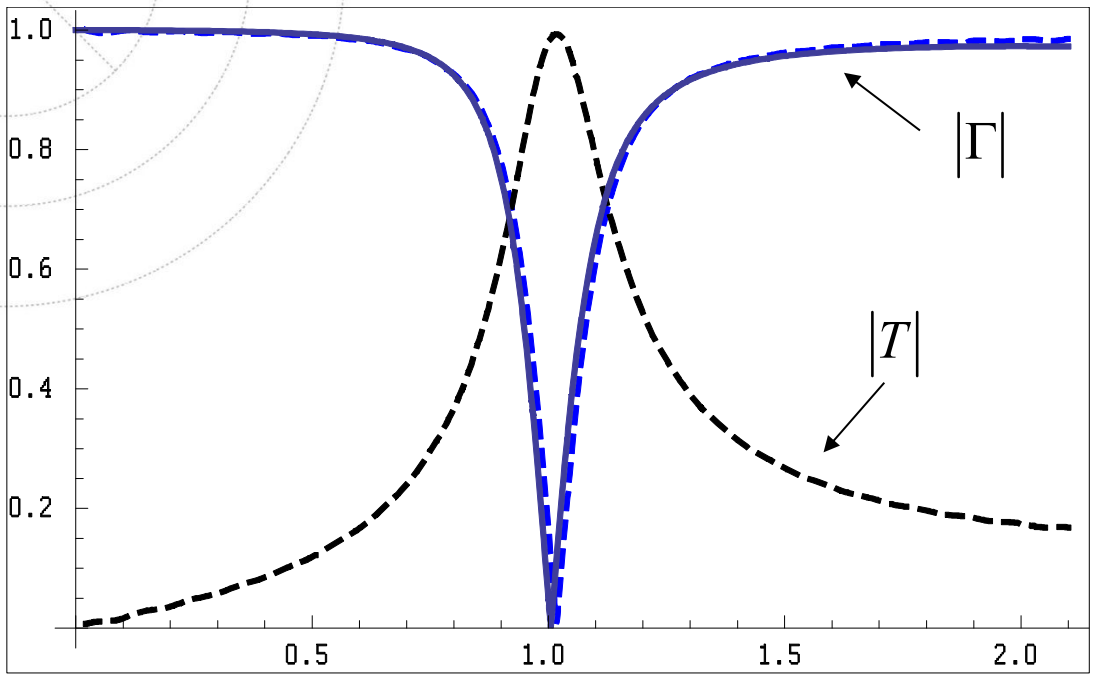
$$\Gamma = \frac{-j\frac{\omega}{c}\varepsilon_r\frac{d_0}{d_1}l}{2 + j\frac{\omega}{c}\varepsilon_r\frac{d_0}{d_1}l}$$

Exemplo numérico

$$d_0 = 0.1 d_1$$

$$l = d_1$$

$$|\Gamma|, |T|$$



$$\omega / \omega_m$$

$$\mu_r = 1 - \frac{\omega_m^2}{\omega^2}$$

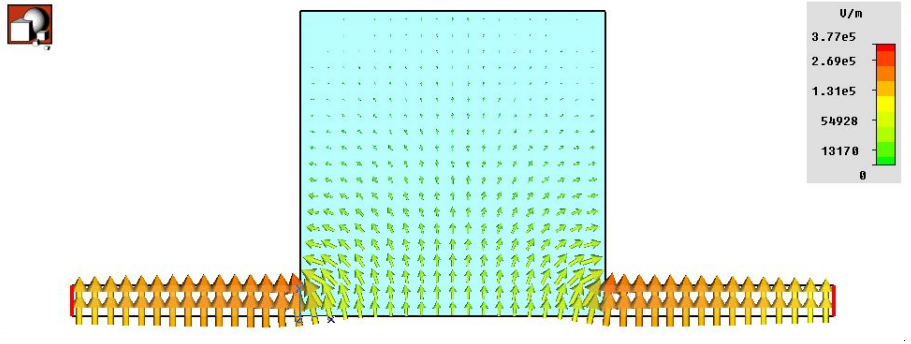
$$\omega_m d_1 / c = 1.0$$

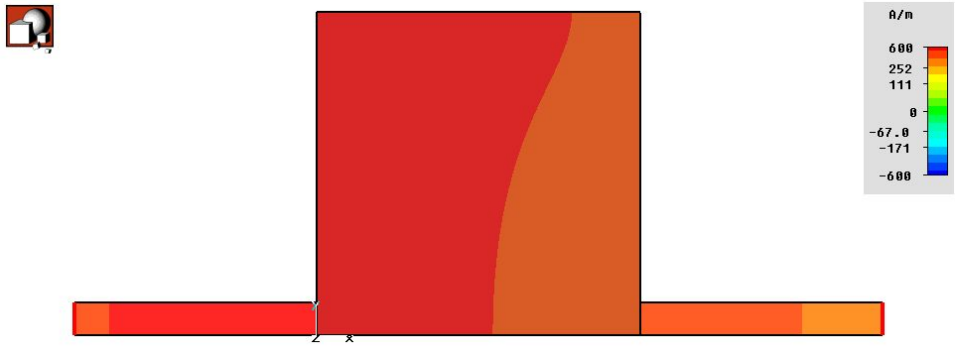
$$\Gamma_m = 0.001 \omega_m$$

Linha a cheio: Modelo analítico LT

Linha Tracejada: CST Microwave Studio

Amplitude dos campos eléctrico e magnético (meio MNZ)





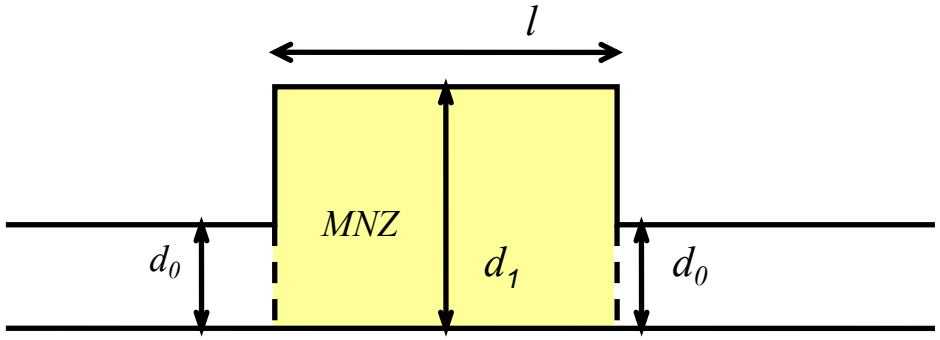
O campo eléctrico é altamente atenuado na transição

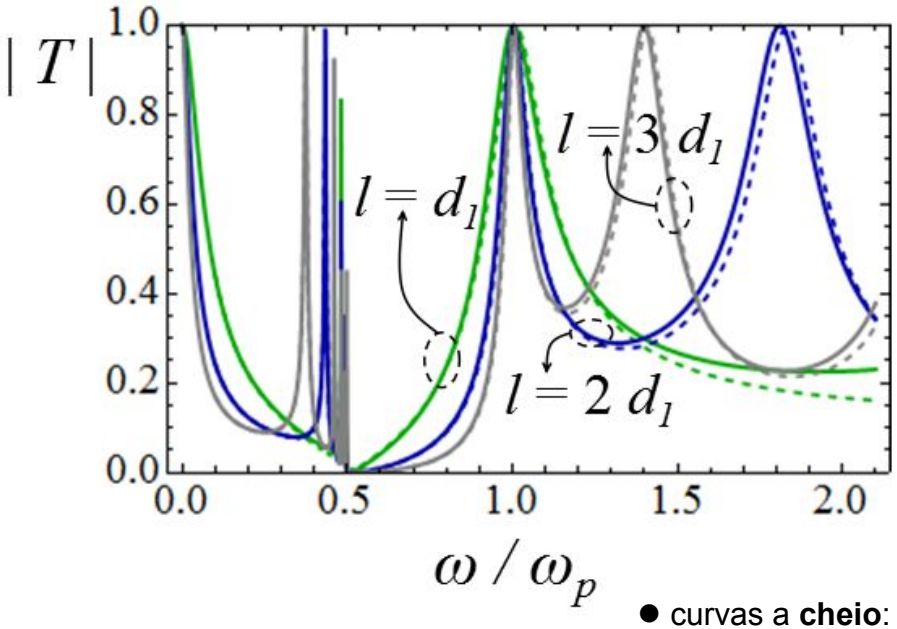
O campo magnético é semelhante em todas as regiões

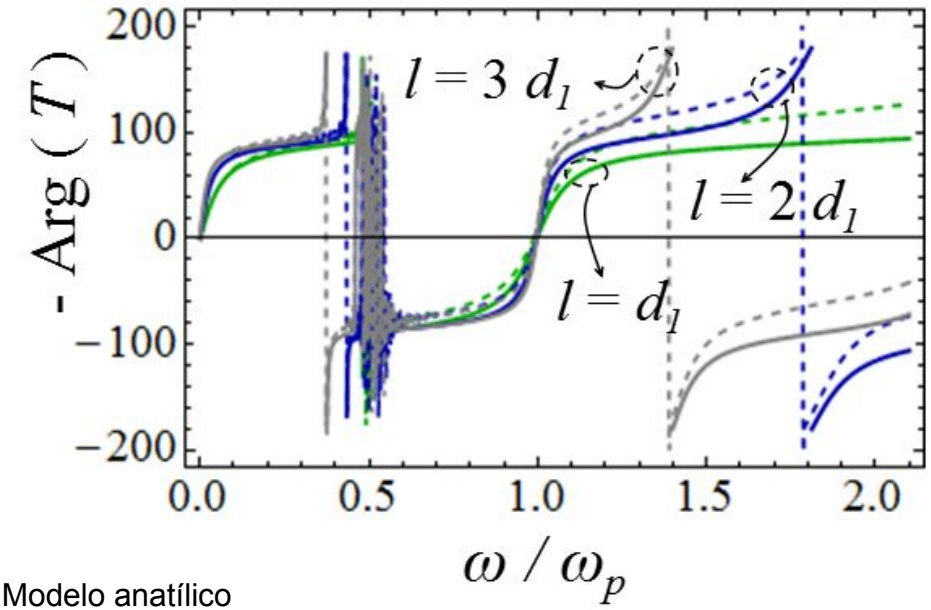
Influência do comprimento do canal mais largo

$$\frac{d_1}{d_0} = 10$$

$$\omega_c / \omega_r = 0.001$$





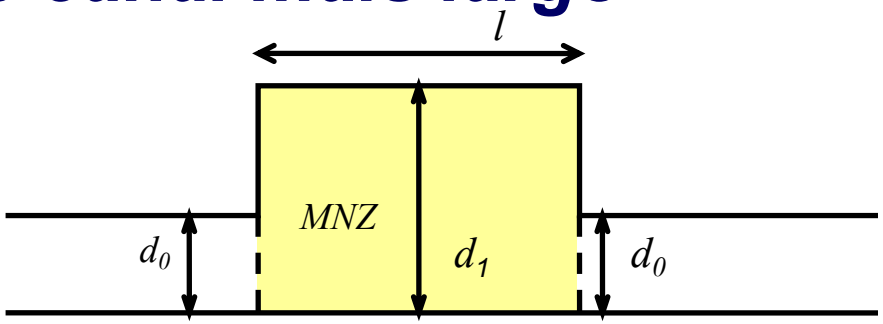


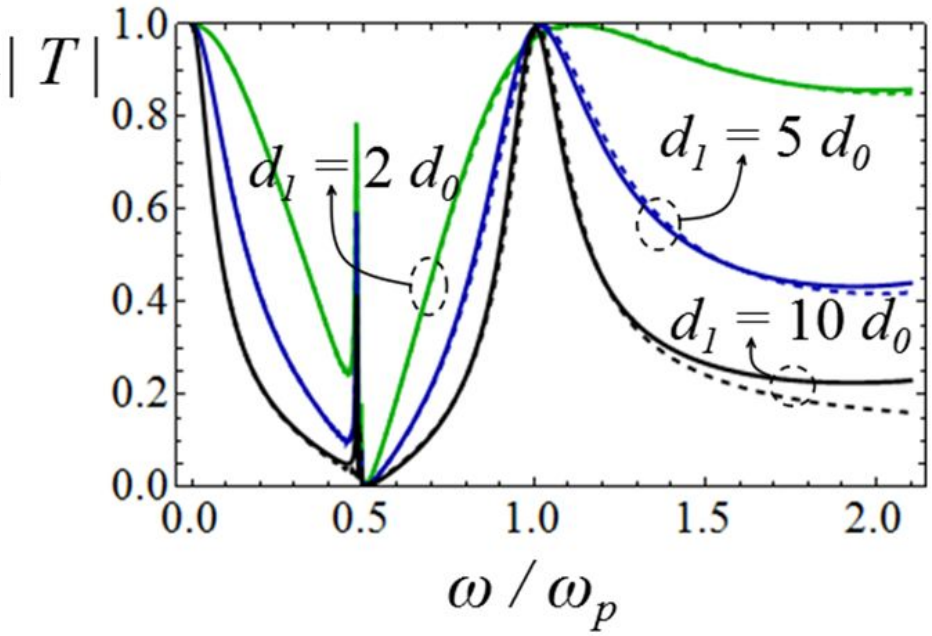
- curvas a **cheio**: Modelo anatílico
- curvas a **tracejado**: Full wave simulations with CST Microwave Studio®

Influência da altura do canal mais largo

$$\frac{l}{d_0} = 10$$

$$\omega_c / \omega_r = 0.001$$



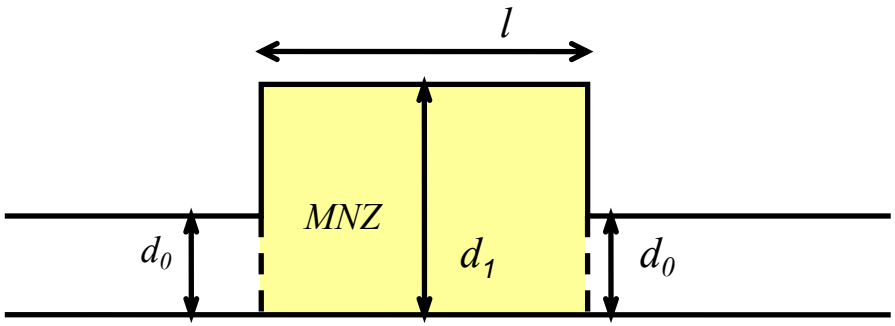


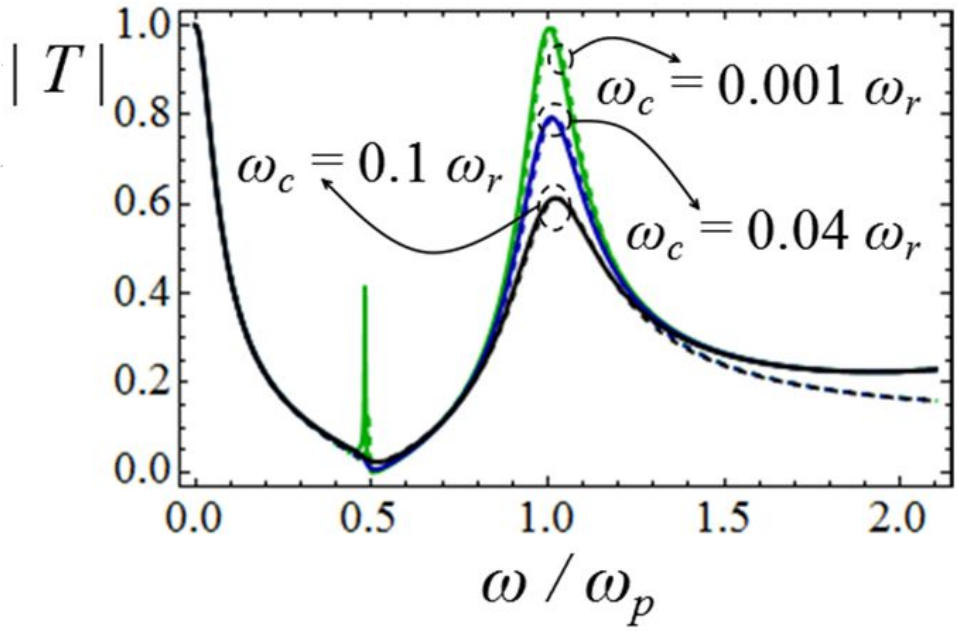
- curvas a **cheio**: Modelo anatílico
- curvas a **tracejado**: Full wave simulations with CST Microwave Studio®

Influência das perdas

$$\frac{l}{d_0} = 10$$

$$\omega_c / \omega_r = 0.001$$

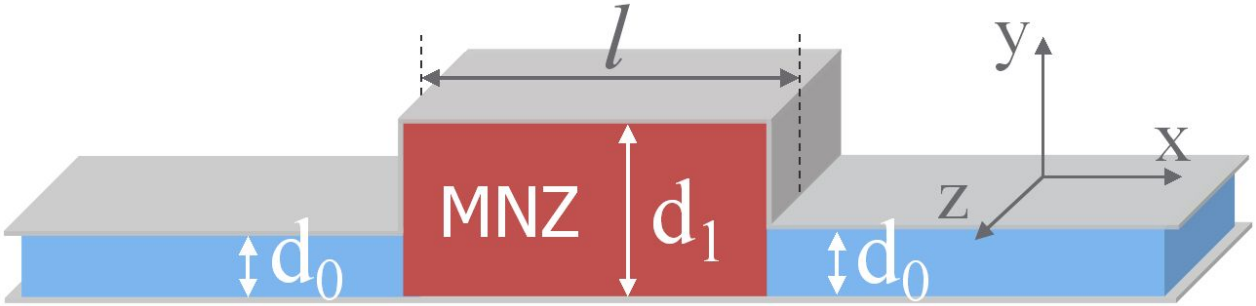


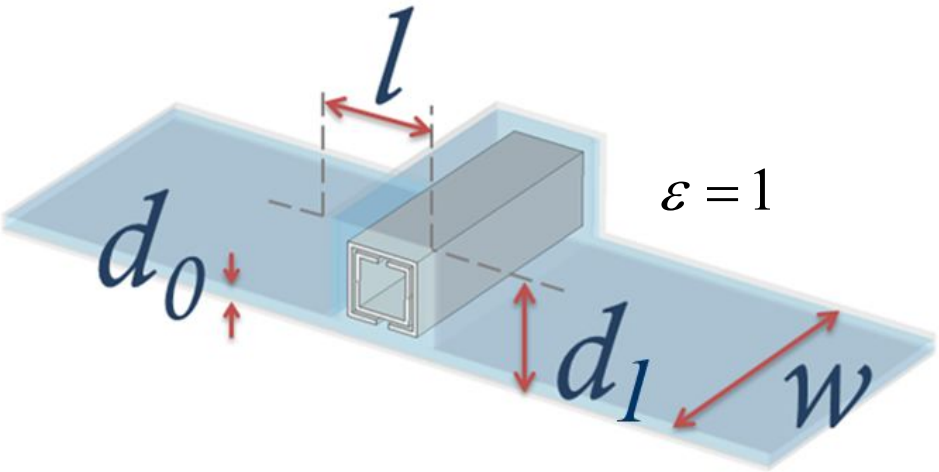


- curvas a **cheio**: Modelo anatílico
- curvas a **tracejado**: Full wave simulations with CST Microwave Studio®

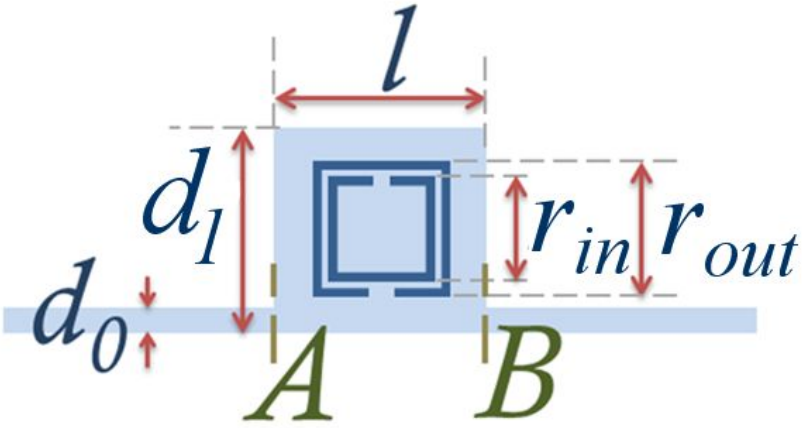
Uso de Metamateriais para conseguir o fenómeno do efeito de túnel

Para conseguir uma resposta MNZ usou-se ***Split Ring Resonators***

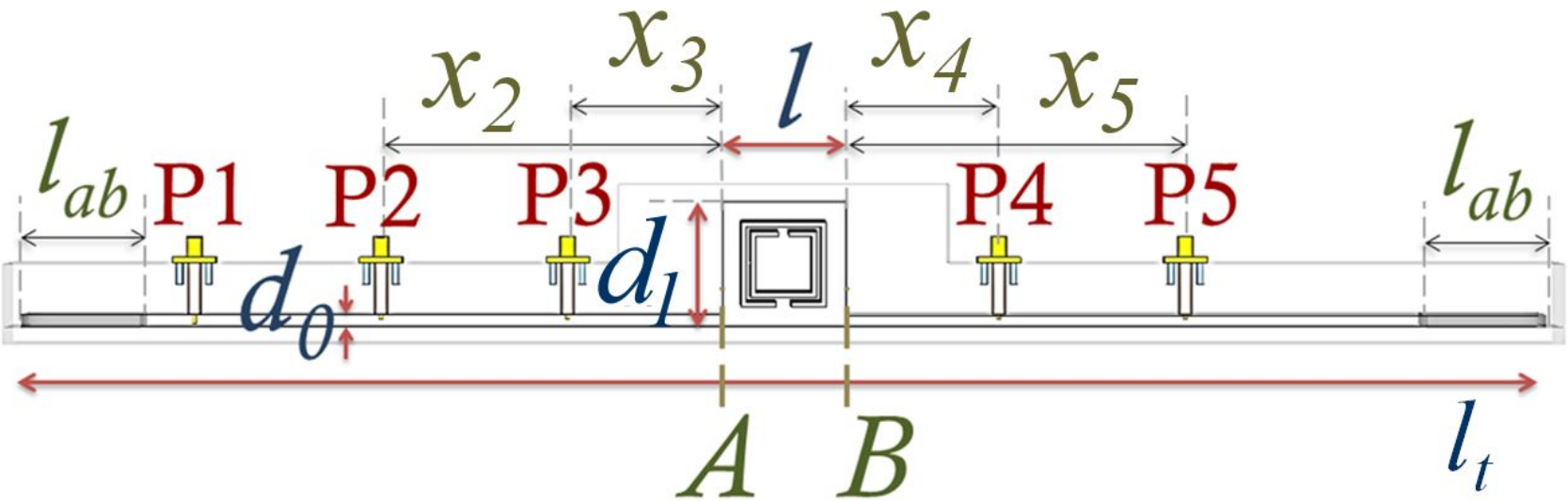


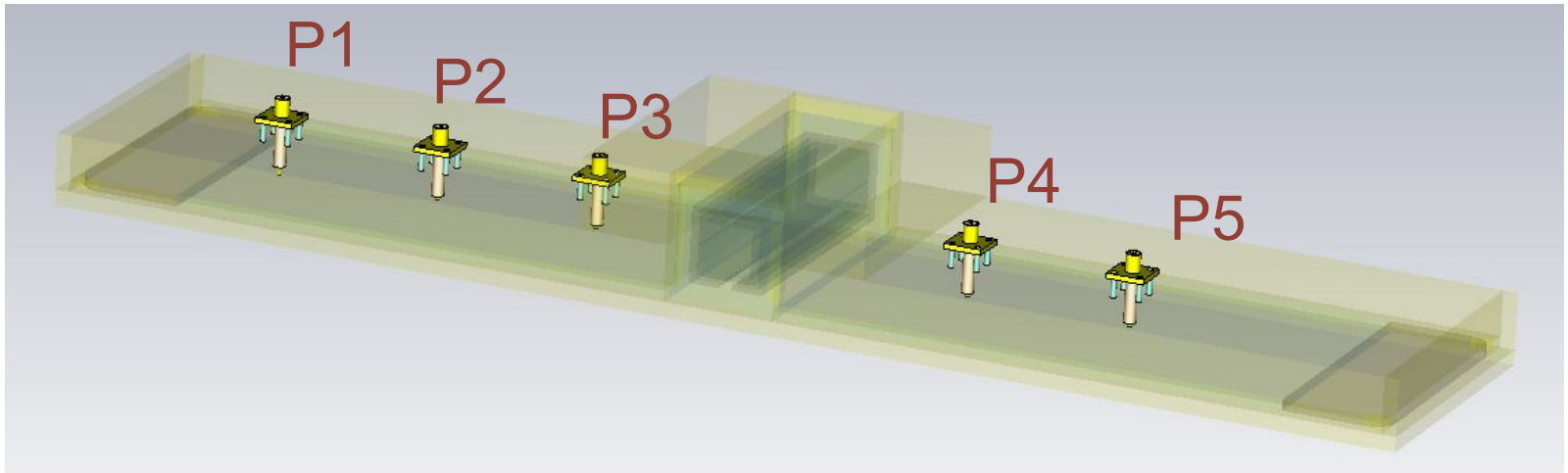


$\varepsilon = 1$

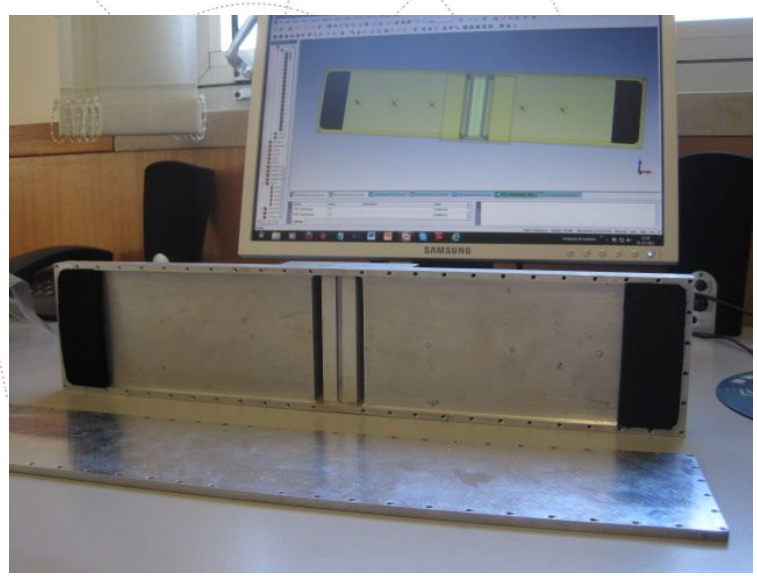


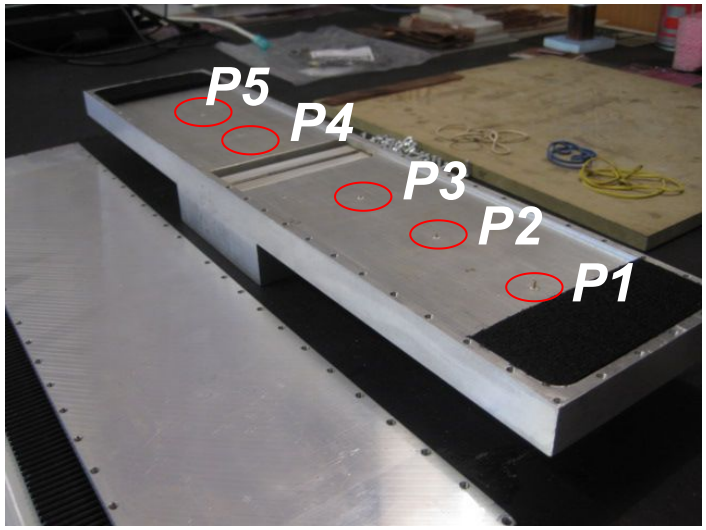
Projecto do Guia com 1 SRR e as sondas

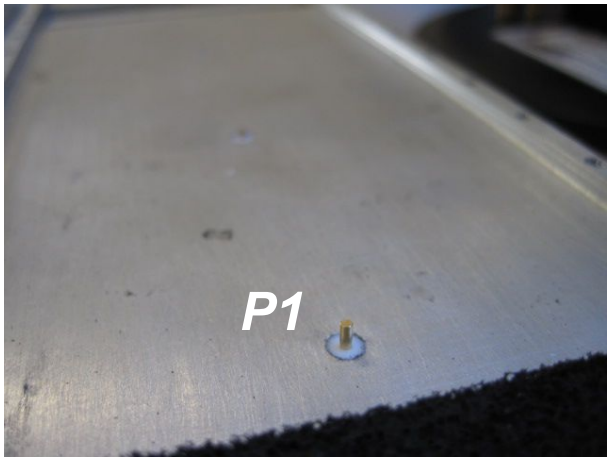


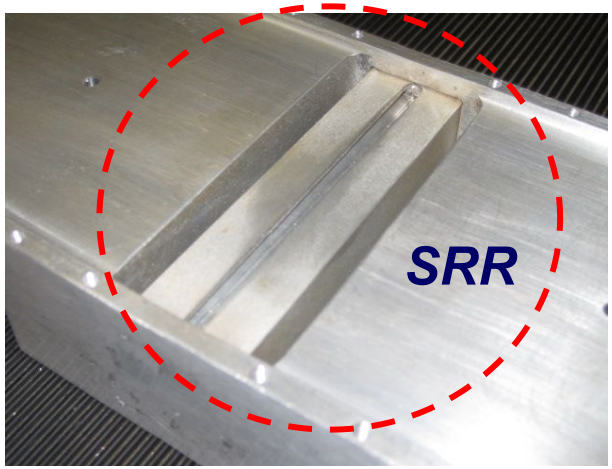


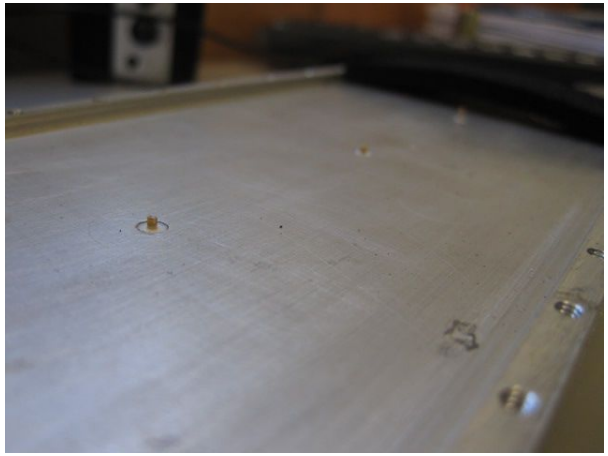
Protótipo do Guia com 1 SRR



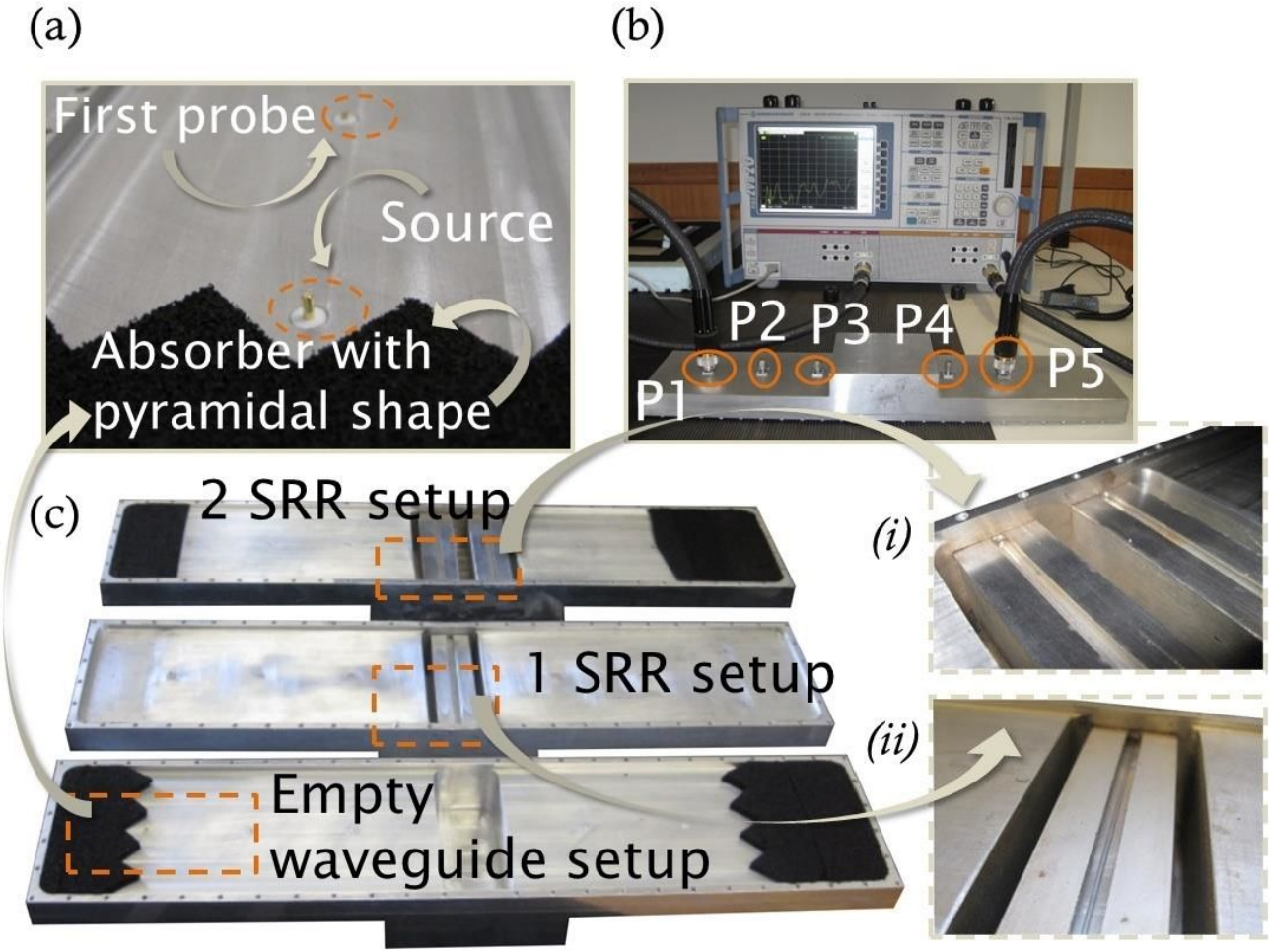




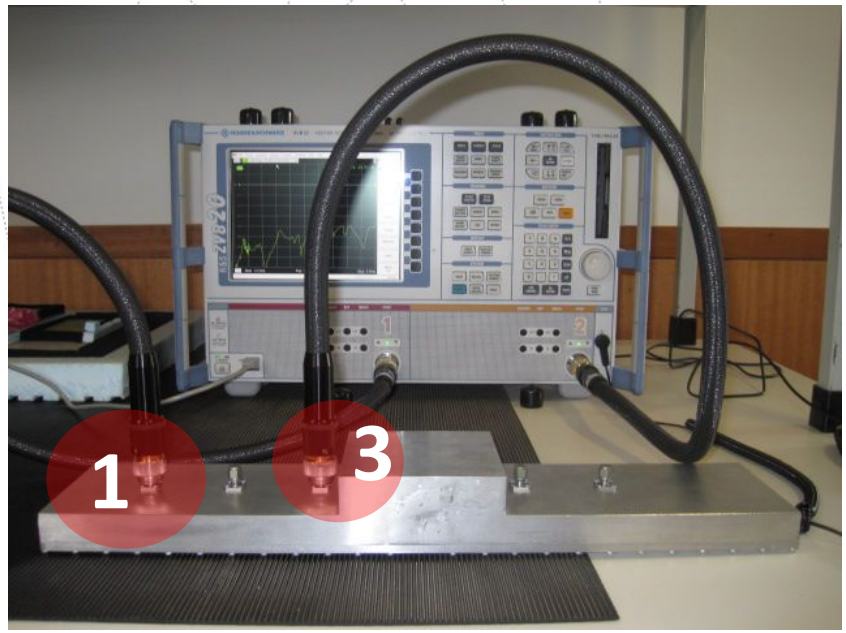




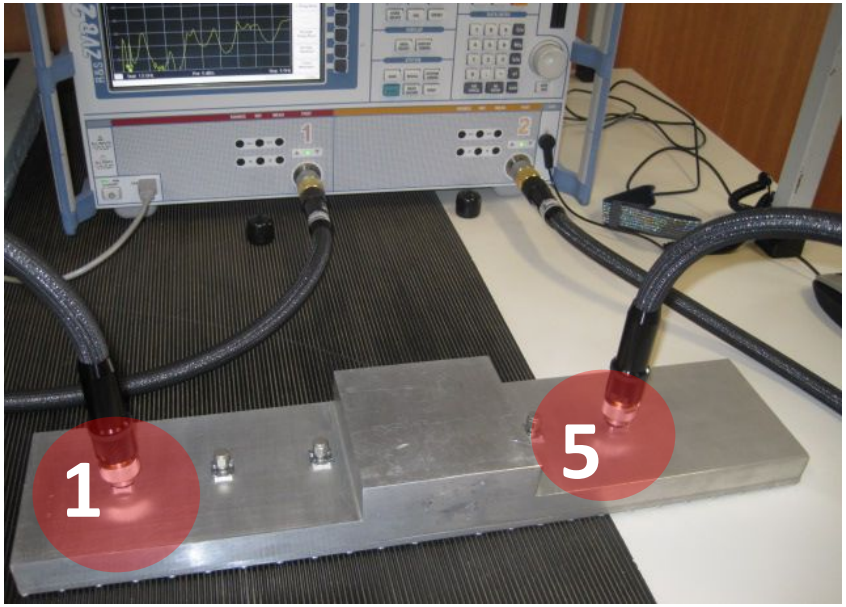
Três Protótipos fabricados



Captura do sinal ao longo do guia através de sondas



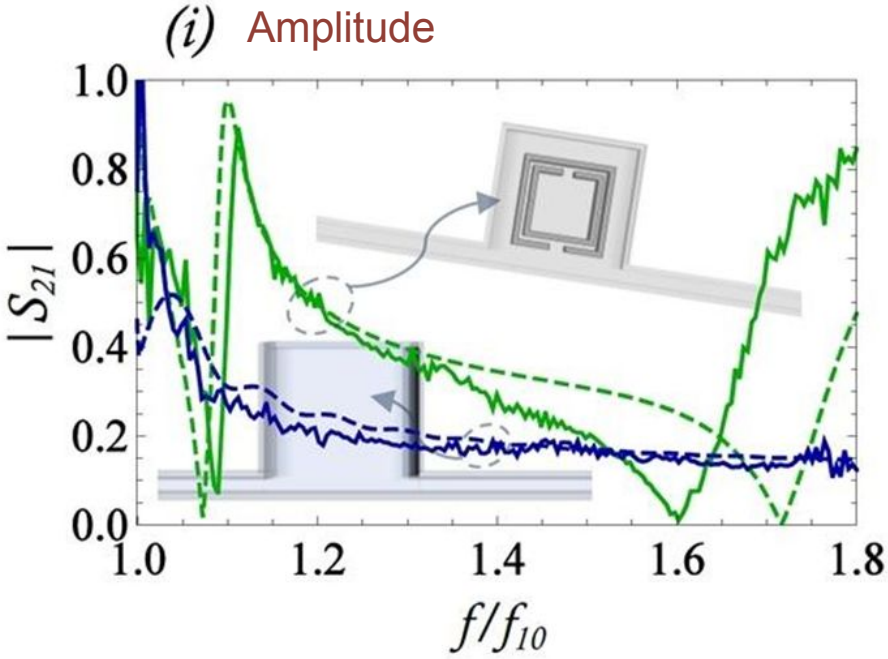
Ex. medição da Tx do porto 1 para o 3 (**S31**)

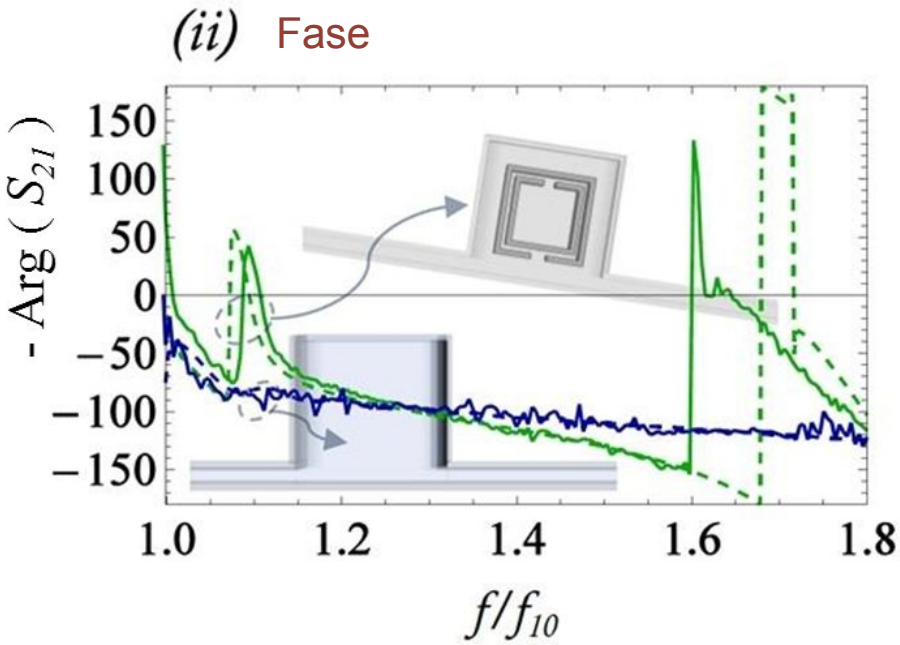


Ex. medição da Tx do porto 1 para o 5 (**S51**)

Comparação dos resultados experimentais com as simulações computacionais

Comparação para canal de transição com **1 SRR** e **sem nenhum SRR**.

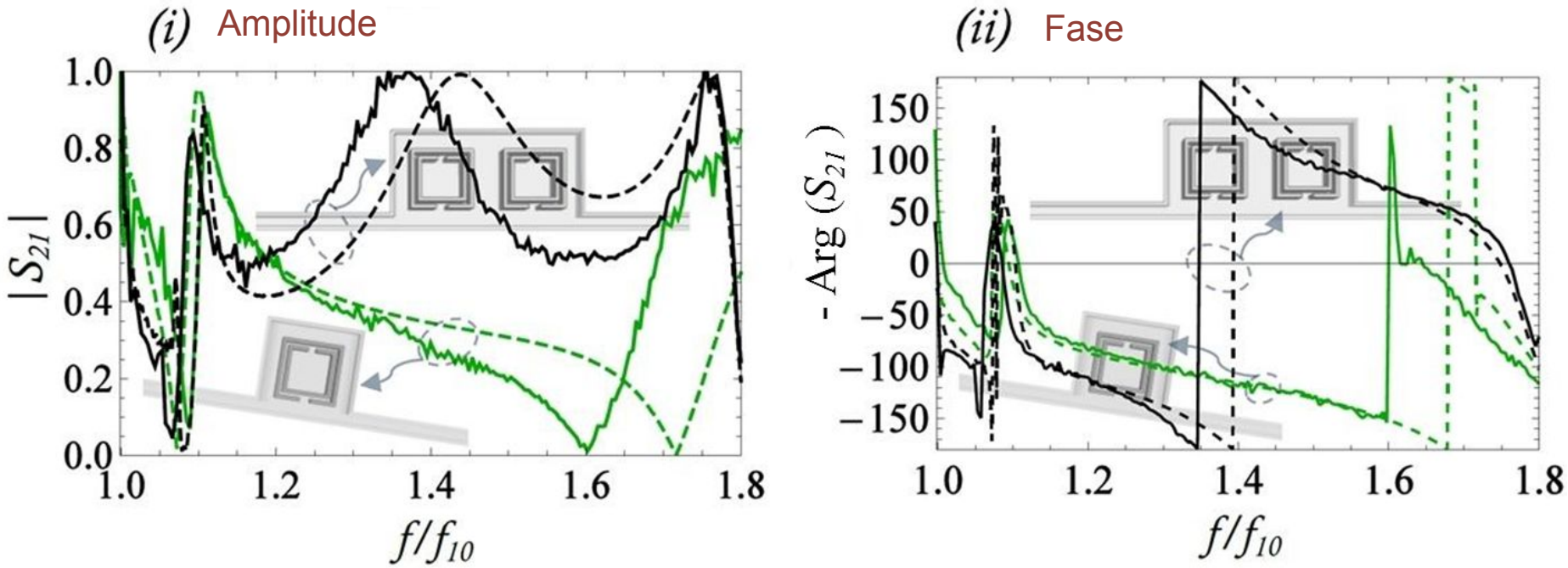




- curvas a **cheio**: Resultados Experimentais
- curvas a **tracejado**: Numerical simulations with CST Microwave Studio®

Comparação dos resultados experimentais com as simulações computacionais

Comparação para canal de transição com **1 SRR** e **2 SRR**.

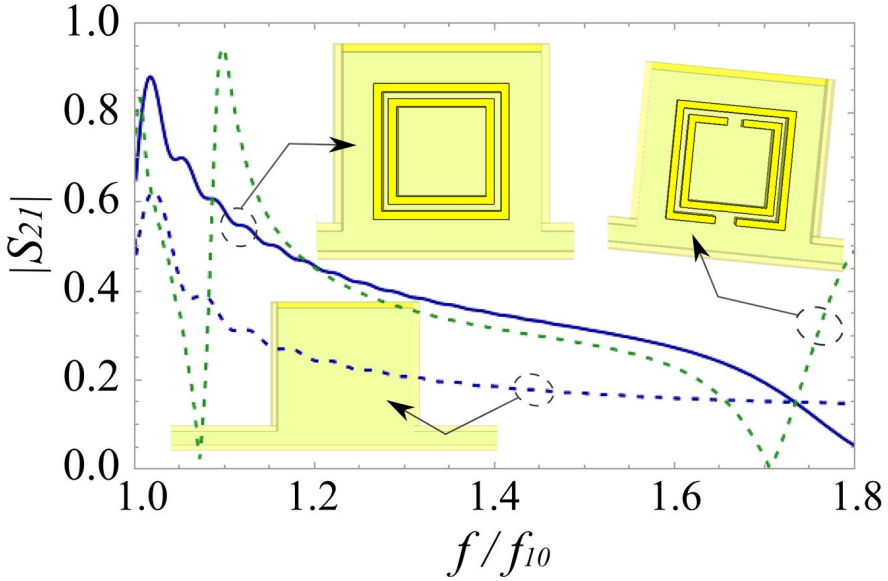


- curvas a **cheio**: Resultados Experimentais
- curvas a **tracejado**: Numerical simulations with CST Microwave Studio®

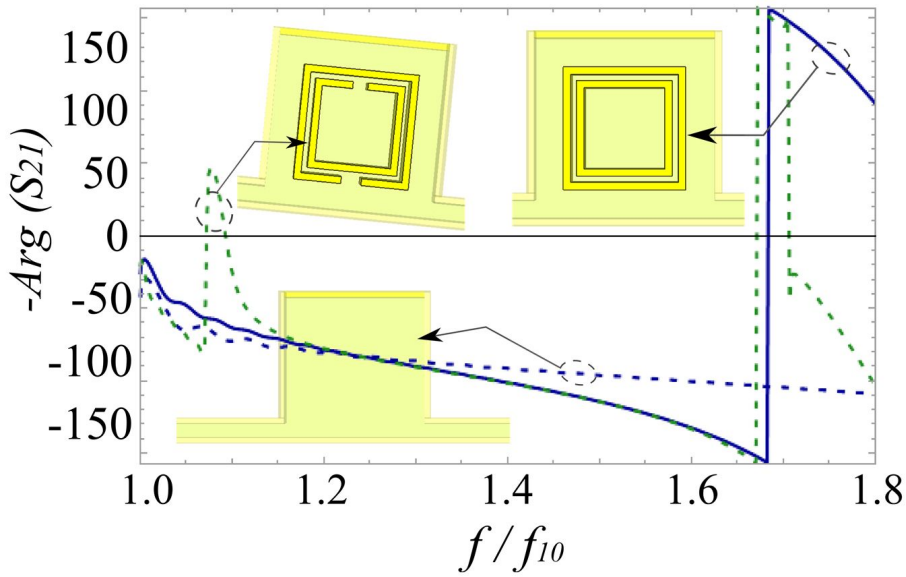
Simulações numéricas de controlo (1ª)

Simulação com as aberturas do SRR fechadas

Amplitude



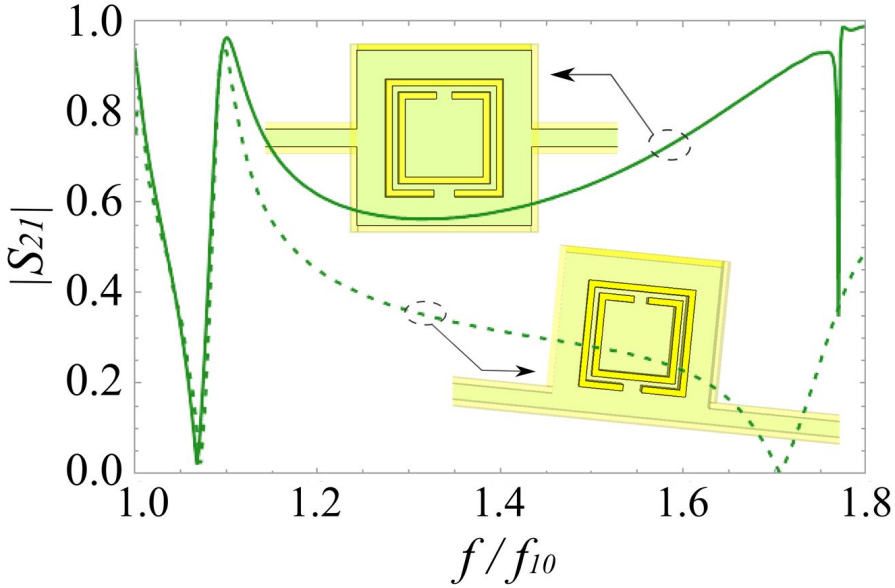
Fase



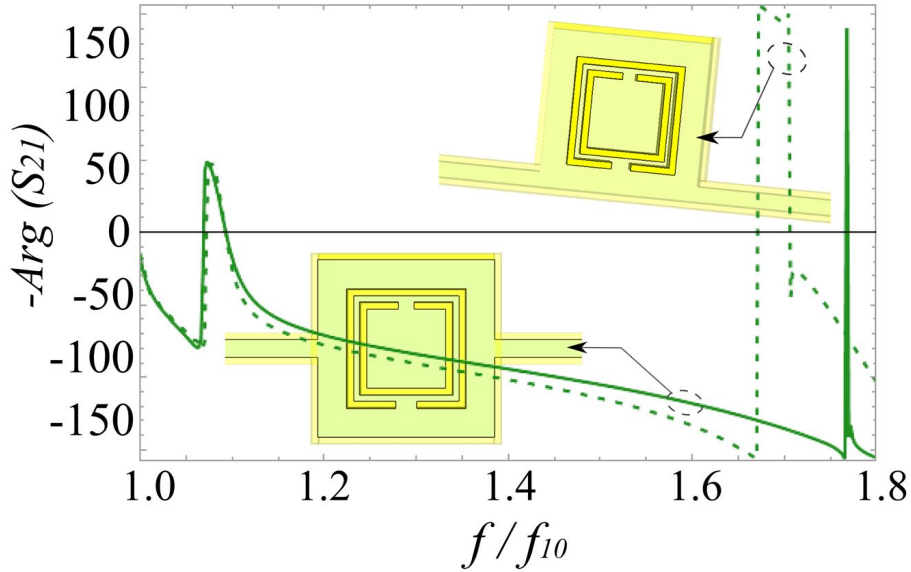
Simulações numéricas de controlo (2ª)

Canal de transição centrado no eixo dos canais de entrada e saída.

Amplitude



Fase



Conclusões

- Os meios MNZ têm um potencial interessante na passagem ("tunneling") de ondas EM sem atraso de fase através de canais largos.

- Foi proposta uma implementação do canal com características MNZ baseada em metamateriais (SSR) e usando guias de onda metálicos.

- Independentemente do comprimento do canal de transição, verificou-se a ausência de atraso de fase (entre a entrada e saída do canal) e o "efeito de túnel" à ressonância MNZ.