Resonance-induced extraordinary transparencies of waveguides at cutoff: a tight binding study

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Previous work

polarizations	TE		TM	
Hollow waveguide	Electric plasma $\varepsilon_{\text{eff}}^{\text{WG}}(\omega)=1-(\omega_c/\omega)^2$		Magnetic plasma $\mu_{\text{eff}}^{\text{WG}}(\omega)=1-(\omega_c/\omega)^2$	
Inclusion	E-resonance	M-resonance	E-resonance	M-resonance
Transparency conditions	Case 1: $\varepsilon_{\parallel}^{\text{in}}>(\omega_c/\omega)^2$ $\bar{\varepsilon}>0,\bar{\mu}=1$	Case 2: $\mu_{\parallel}^{\text{in}}<0$ $\bar{\varepsilon}<0,\bar{\mu}<0$	Case 3: $\varepsilon_{\parallel}^{\text{in}}<0$ $\bar{\varepsilon}<0,\bar{\mu}<0$	Case 4: $\mu_{\parallel}^{\text{in}}>(\omega_c/\omega)^2$ $\bar{\varepsilon}=1,\bar{\mu}>0$
Refraction index	Positive	Negative	Negative	Positive

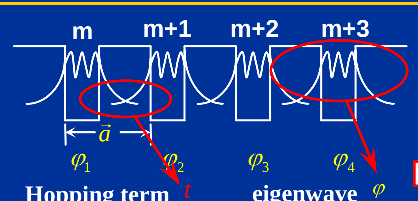
motivations

Effective medium theory (EMT) could explain

1. Extraordinary transparencies √
2. Band width √
3. Parity of modes ×
4. Number of transmittance peaks ×
5. Position of peaks ×
5. etc. ?

Establish a theory to explain those features

1. Extraordinary transparencies √
2. Band width √
3. Parity of modes √
4. Number of transmittance peaks √
5. Position of peaks √
5. etc. …



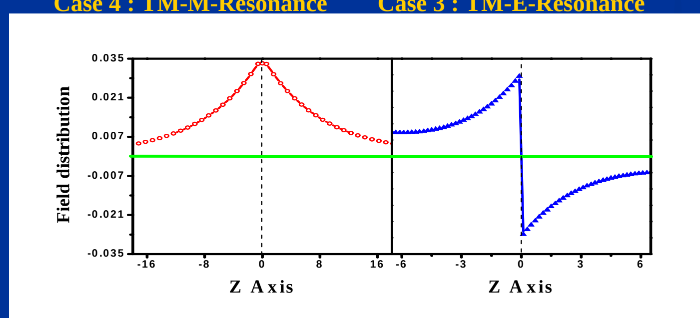
$$t=\langle\varphi_m|\sum_{i\neq n}V_i|\varphi_n\rangle\Big/\langle\varphi_1|\varphi_1\rangle$$

$$\hat{V}_i=\begin{pmatrix}0 & i\Delta\dfrac{1}{\varepsilon(\vec{r})}\nabla\times\\ -i\Delta\dfrac{1}{\mu(\vec{r})}\nabla\times & 0\end{pmatrix}$$

Two typical eigenwave functions

Case 1 : TE-E-Resonance — Case 2 : TE-M-Resonance

Case 4 : TM-M-Resonance — Case 3 : TM-E-Resonance



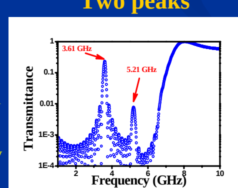
Case1: t<0 normal dispersion
Case2: t>0 abnormal dispersion
Case3: t>0 abnormal dispersion
Case4: t<0 normal dispersion

Agree with EMT and experiment

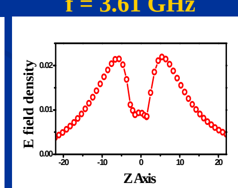
For case 1: only consider 2 layers

$$\omega=\begin{cases}\omega+t, & \varphi=\begin{pmatrix}1\\1\end{pmatrix} \text{ low frequency}\\ \omega-t, & \varphi=\begin{pmatrix}1\\-1\end{pmatrix} \text{ high frequency}\end{cases}$$

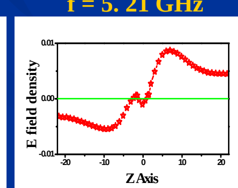
Two peaks



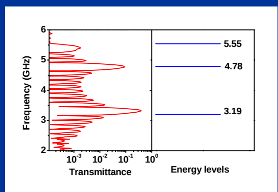
f = 3.61 GHz

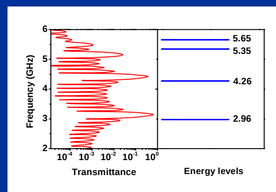


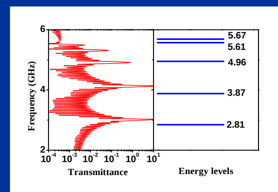
f = 5. 21 GHz



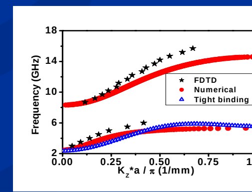
Peaks' positions: FDTD VS. TBM (3 , 4 , 5 layers' cases)







Dispersion



We employ a tight binding method (TBM) to explore the underlying physics behind the unusual transparency in metamaterial-loaded waveguides. Adopting appropriate hopping parameters, we find that the TBM quantitatively explained many interesting phenomena discovered previously by brute-force numerical simulations and experiments, including the number and positions of the transmission peaks， the parities of wave functions， the band width and the group velocities of the transmission bands， and the defect modes, ect.

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