Flat-band Optical Transparency: Mechanism in Meta-surface Design

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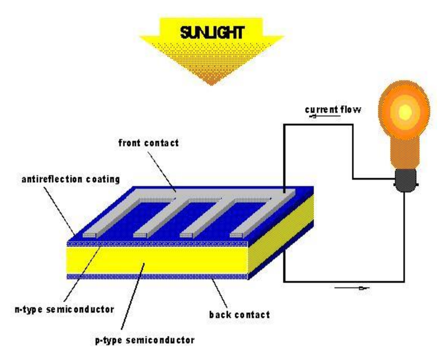
abstract

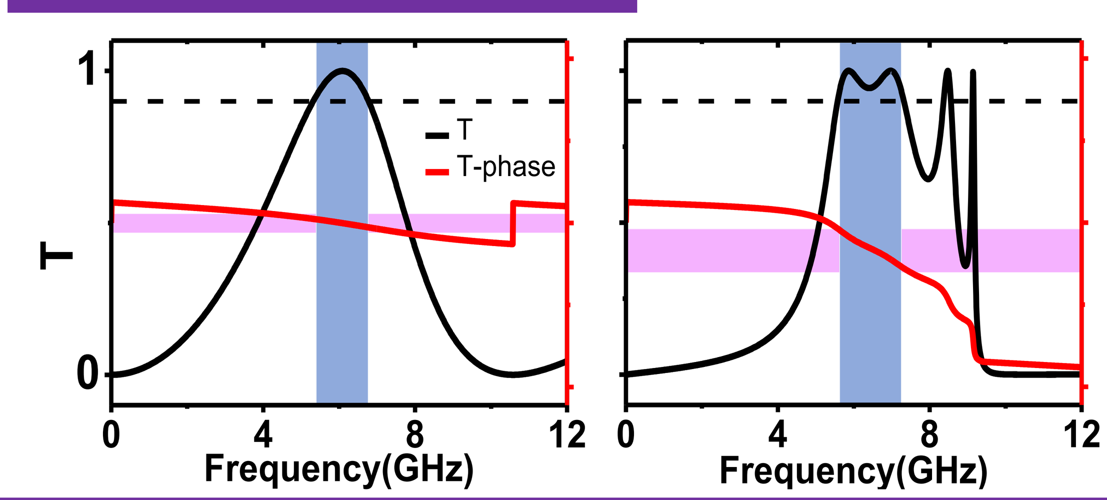
Constructing a structure transparent to light is highly desired in many applications. This transparency has already be achieved through mechanisms like multi-scattering cancellation. While, the transmittance bandwidth of these methods are usually narrow due to their resonant nature. Multi-layer structures have been used to expand the bandwidth, but they are mainly designed by parameter sweeping and the underlying physics is still unknown. In this work, we have built a Couple Mode Theory (CMT) model to re-interpret the transparent mechanism, then we further study the coupling effect between different layers semiquantitatively, providing a clear guideline for designing multi-layer transparent structures.

Background and motivation

Application



Obstacle in flat-band



- Multi-layer indeed expand flat-band bandwidth
- The fluctuation larger with multi-stack layer increase

Multi-mode induced transparency

Basis transformation

$$\frac{d}{dt}a_n = iHa_n + Xa_n + \kappa_n S_j^+ \qquad \frac{d}{dt}\widetilde{a_n} = i\widetilde{H}\widetilde{a_n} + \widetilde{X}\widetilde{a_n} + \widetilde{\kappa_n}S_j^+$$

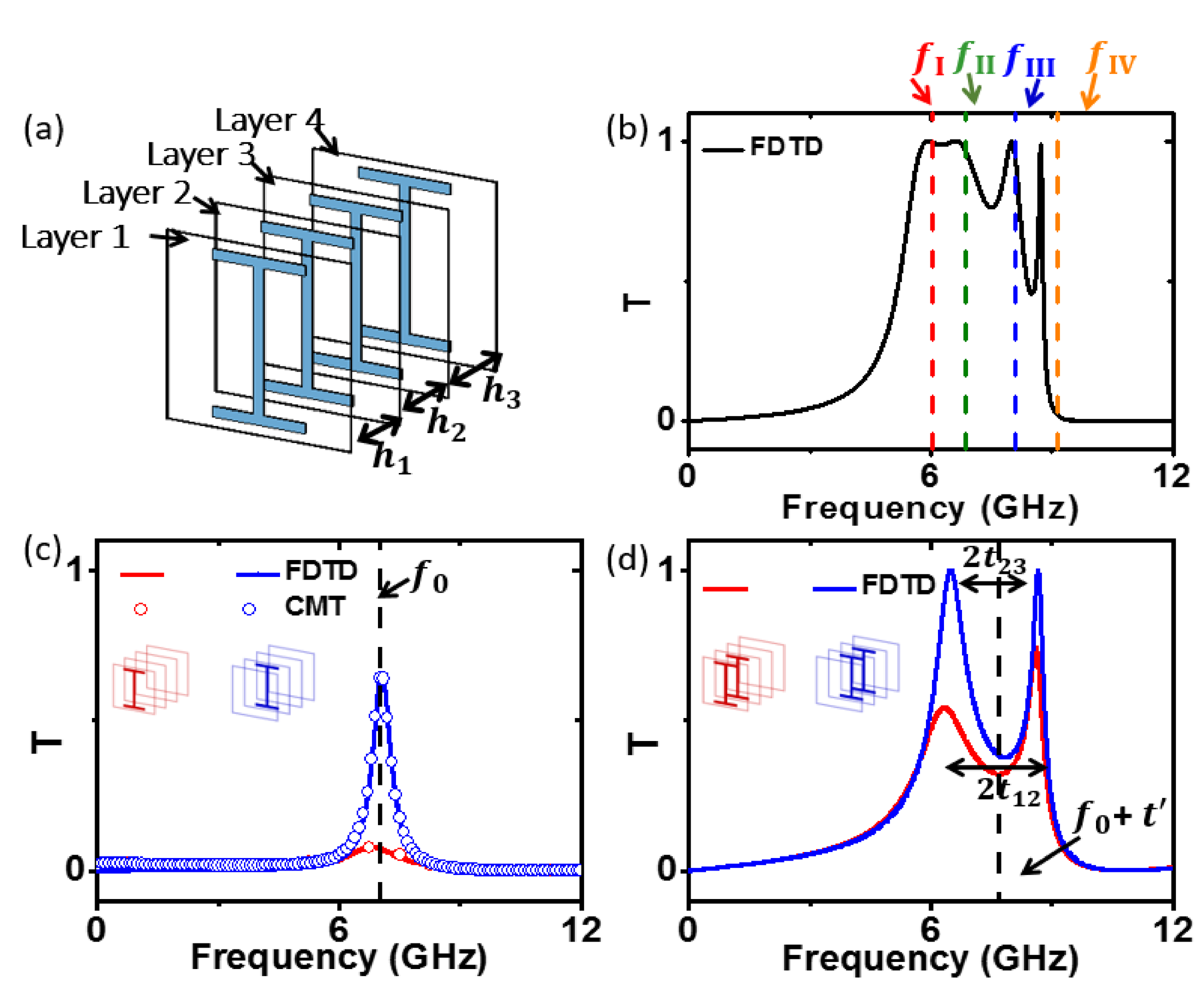
CMT (with near-field coupling) → CMT (with diagonalized H)

$$H = \begin{pmatrix} f_0+t_{11} & t_{12} & 0 & 0 \\ t_{21} & f_0+t_{22} & t_{23} & 0 \\ 0 & t_{32} & f_0+t_{33} & t_{34} \\ 0 & 0 & t_{43} & f_0+t_{44} \end{pmatrix} \qquad \widetilde{H} = MHM^{-1} = \begin{pmatrix} f_I & 0 & 0 & 0 \\ 0 & f_{II} & 0 & 0 \\ 0 & 0 & f_{III} & 0 \\ 0 & 0 & 0 & f_{IV} \end{pmatrix}$$

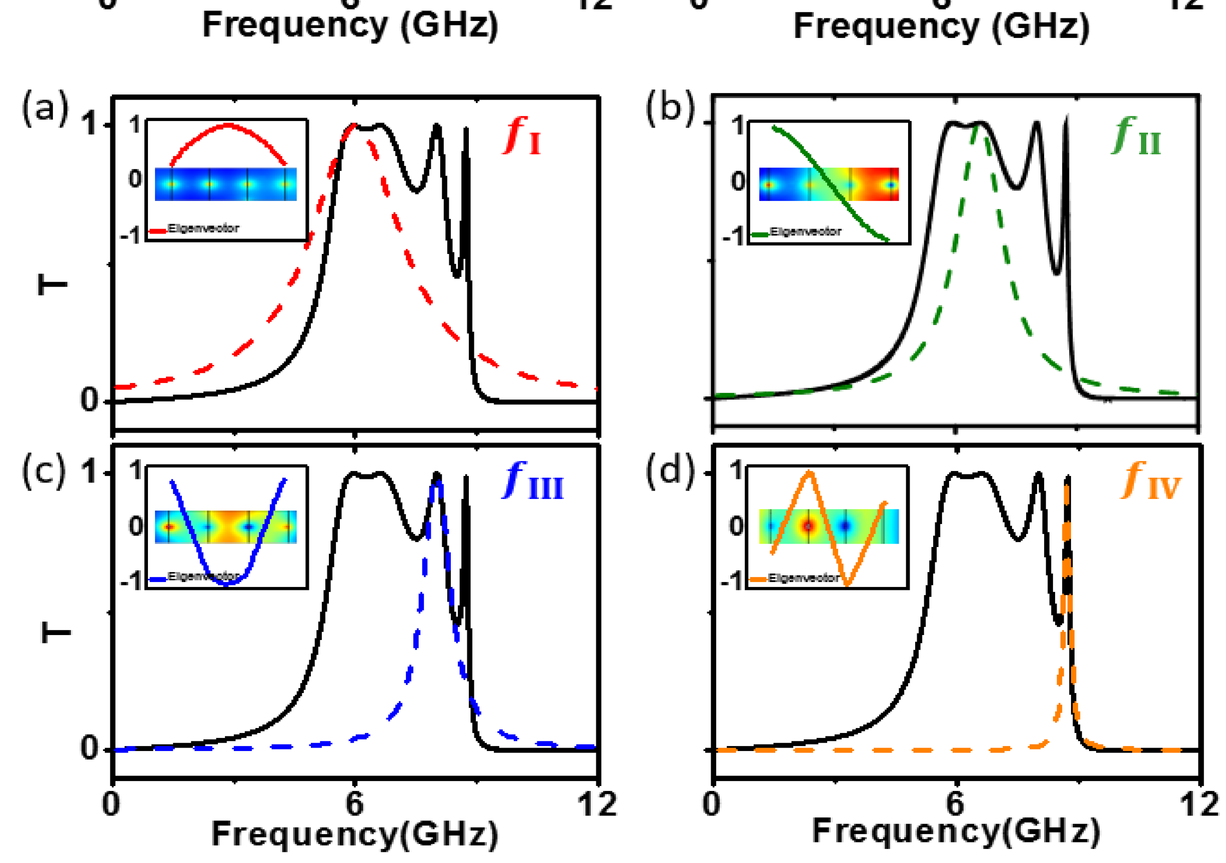
$$\widetilde{\kappa_n} = \widetilde{D_n} = (\widetilde{d_I}, \widetilde{d_{II}}, \widetilde{d_{III}}, \widetilde{d_{IV}})^{-1} = M\cdot(d_1, d_2, d_3, d_4)^{-1}$$

$$\widetilde{\Gamma_n} = |\widetilde{D_n}|^2 \rightarrow (\widetilde{\Gamma_I}, \widetilde{\Gamma_{II}}, \widetilde{\Gamma_{III}}, \widetilde{\Gamma_{IV}}) = (|\widetilde{d_I}|^2, |\widetilde{d_{II}}|^2, |\widetilde{d_{III}}|^2, |\widetilde{d_{IV}}|^2)$$

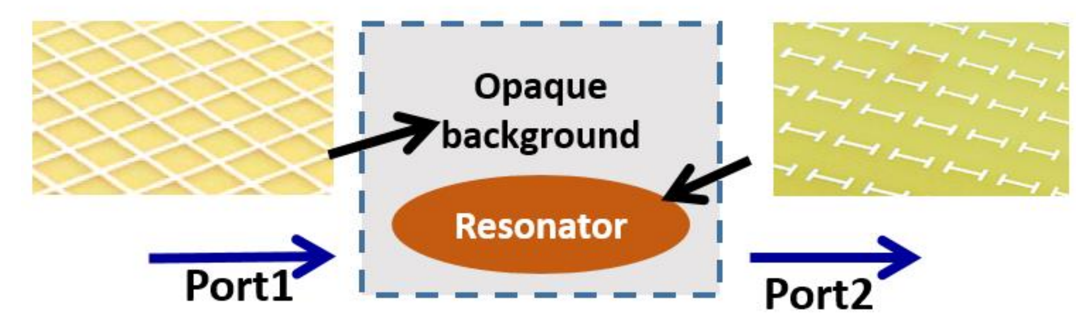
Resonance frequency



Q factor



Single resonance induced transparency

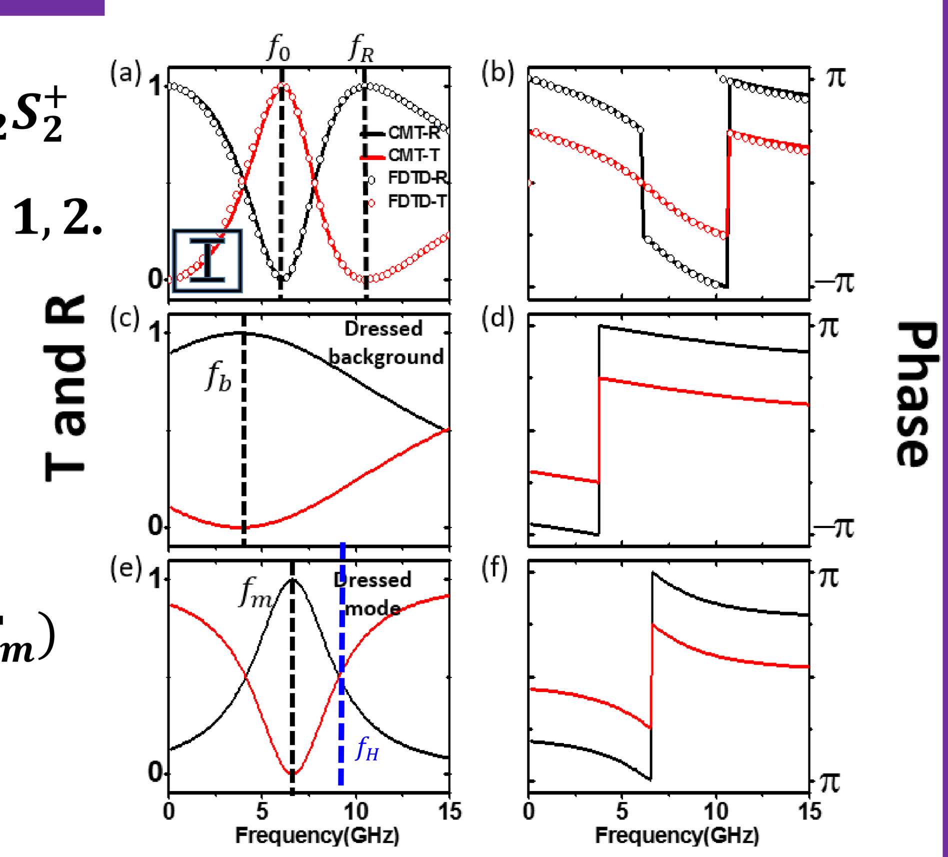


CMT for one mode two ports

$$\frac{d}{dt}a = if_m a + \Gamma a + \kappa_1 S_1^+ + \kappa_2 S_2^+$$

$$S_j^- = C_{jj'}S_{j'}^+ + d_j a, \text{ where } j, j' \in 1, 2.$$

$$t = -b/(ai + b)$$



Discussion

$$f_0 = (\Gamma_b f_m + \Gamma_b f_m)/(\Gamma_b + \Gamma_m)$$

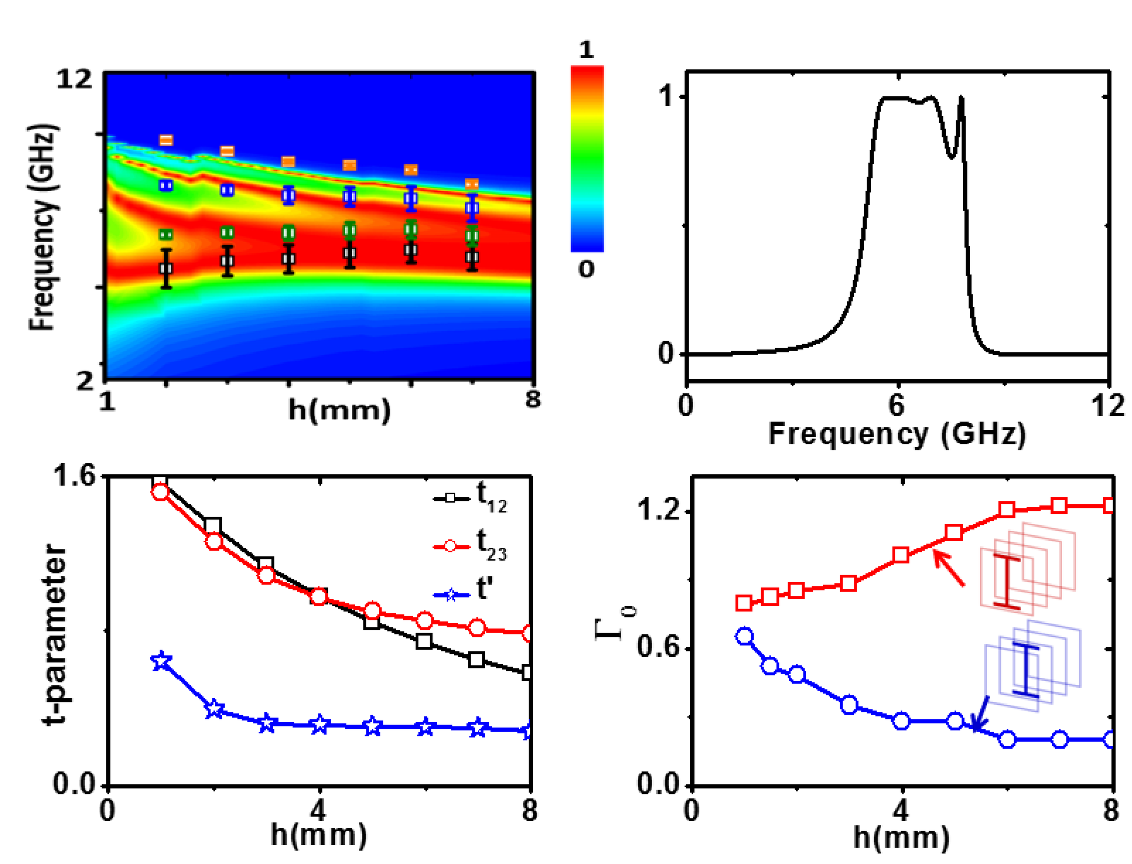
$$f_R = \bar{f} + \sqrt{\Delta f^2 + \Gamma_b \Gamma_m}$$

$$\text{when } \Gamma_b \rightarrow \infty, f_0 = f_m$$

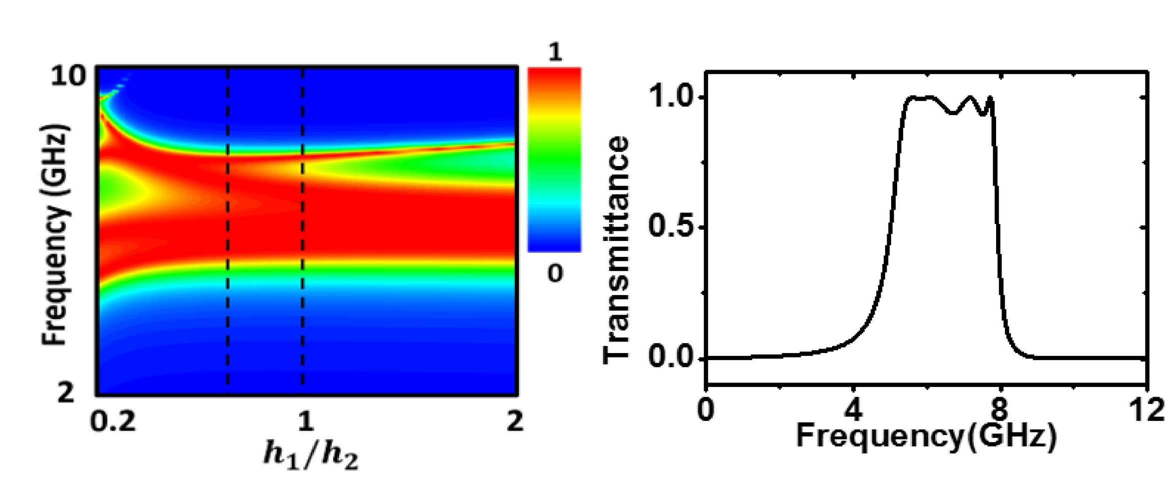
$f_0(f_R)$ is not only depend on frequency of background and resonance mode frequency but also their radiation decay rate.

Phase diagram and optimized strategy

Equally separation



Keep total Thickness unchanged



Conclusion

- Build a cmt model for single resonance induced transparency
- Use basis translation method get the frequency and Q factor of multi-layer system
- Based on our theory, we give a optimized flat-band strategy.

Reference

[1]Zhou L, Wen W, Chan C T, et al. Electromagnetic-wave tunneling through negative-permittivity media with high magnetic fields[J]. Physical review letters, 2005, 94(24): 243905