Experimental realization of three-dimensional hyperbolic cavities in the microwave regime

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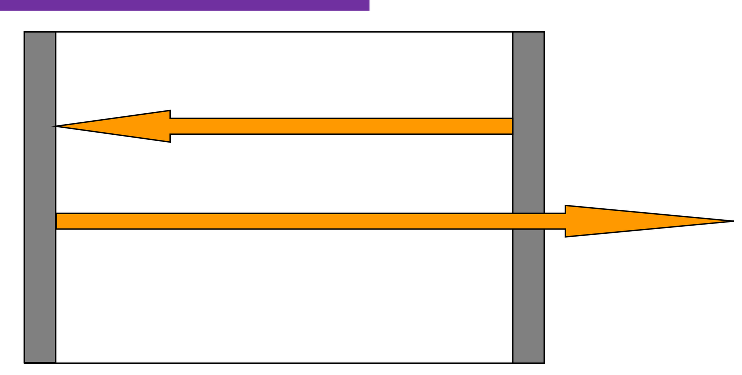
abstract

The local density of states of electromagnetic waves plays a pivotal role in controlling light-matter interactions, and thus devices that can provide both high resonance quality (Q) factors and small mode volumes have found important applications. Conventional diffraction-limited cavities cannot be made too small, and thus their applications are restricted. Here, we fabricate a cavity made by hyperbolic metamaterials in microwave regime, and experimentally demonstrate its unusual properties, employing a near-field scanning technique [1]. Like its optical counterpart [2], the cavity exhibits a very small mode volume (with characteristic length smaller than 1/10 of the wavelength) and an anomalous scaling law for its resonance modes. While the cavity also has a very large Q factor, due to the nearly lossless nature of metals in microwave regime.

Moreover, our work may not only stimulate making high-performance microwave devices with such deep-subwavelength cavities, but also serve as an effective platform to investigate interesting phenomena based on light-matter interactions.

Background and motivation

Conventional cavity

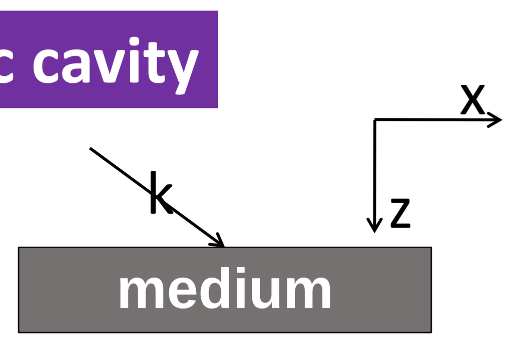


Resonance condition

$$\begin{cases} 2kd + \Delta\phi_1 + \Delta\phi_2 = 2\pi m \\ k = 2\pi/\lambda \end{cases}$$

The volume is big

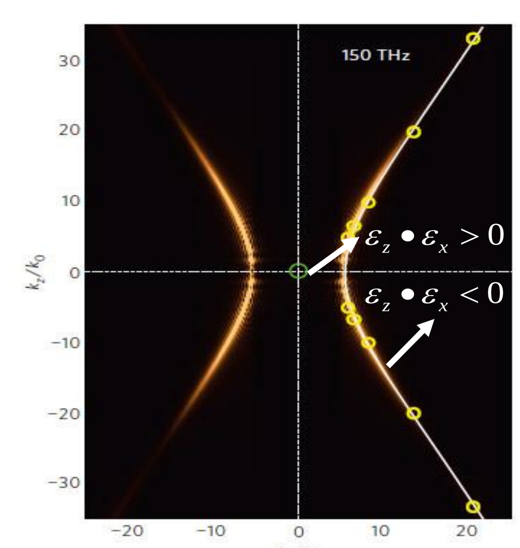
Hyperbolic cavity



$$\vec{\varepsilon} = \begin{pmatrix} \varepsilon_x & & \\ & \varepsilon_x & \\ & & \varepsilon_z \end{pmatrix}$$

Dispersion relation

$$\frac{k_x^2}{\varepsilon_z} + \frac{k_y^2}{\varepsilon_z} + \frac{k_z^2}{\varepsilon_x} = \frac{\omega^2}{c^2}$$

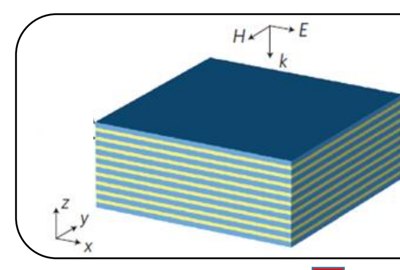


visible regime: low Q factor, high-order mode unchecked directly

micro regime: high Q factor, high-order mode founded experimentally

Theory and design

Effective medium theory



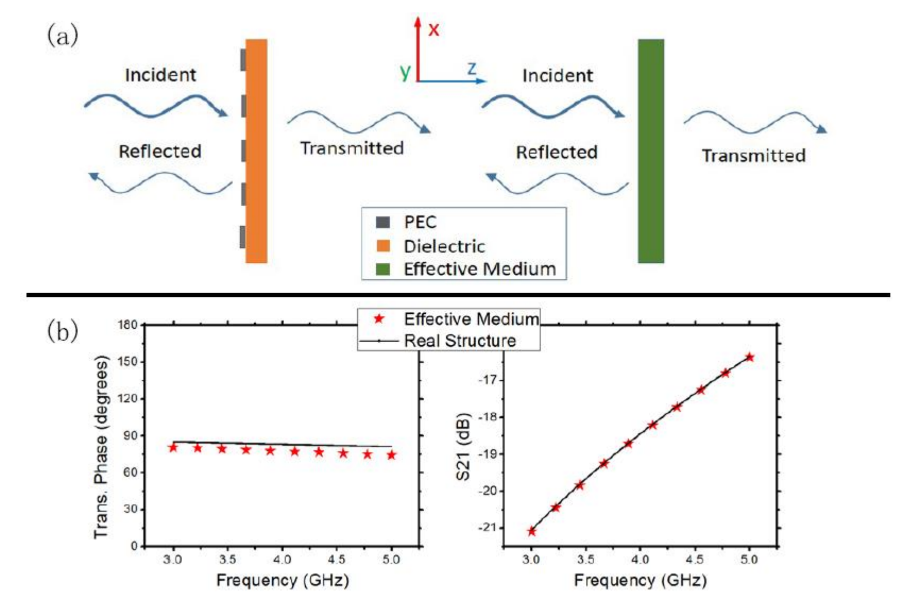
$$\varepsilon_1 = const. > 0$$

$$\varepsilon_2 = \varepsilon_0 - \frac{(\omega_p)^2}{\omega^2 - i\Gamma}$$

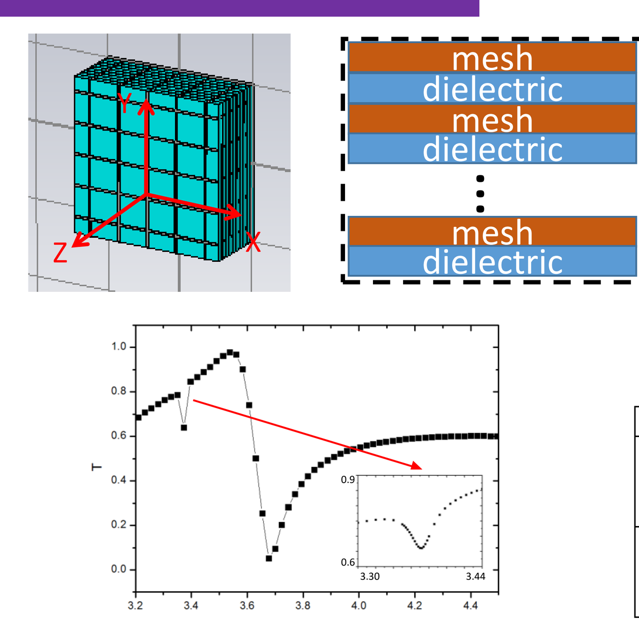
Homogeneous medium

$$\varepsilon_x = \varepsilon_y < 0$$

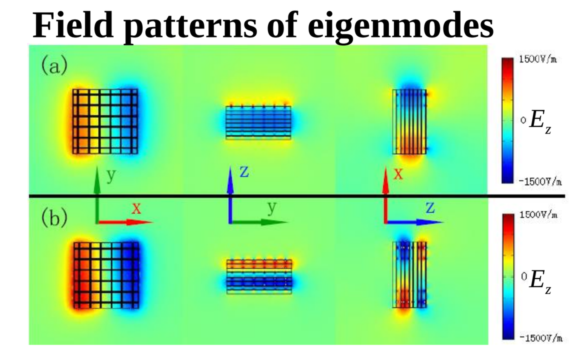
$$\varepsilon_z > 0$$



Simulation results



Field patterns of eigenmodes

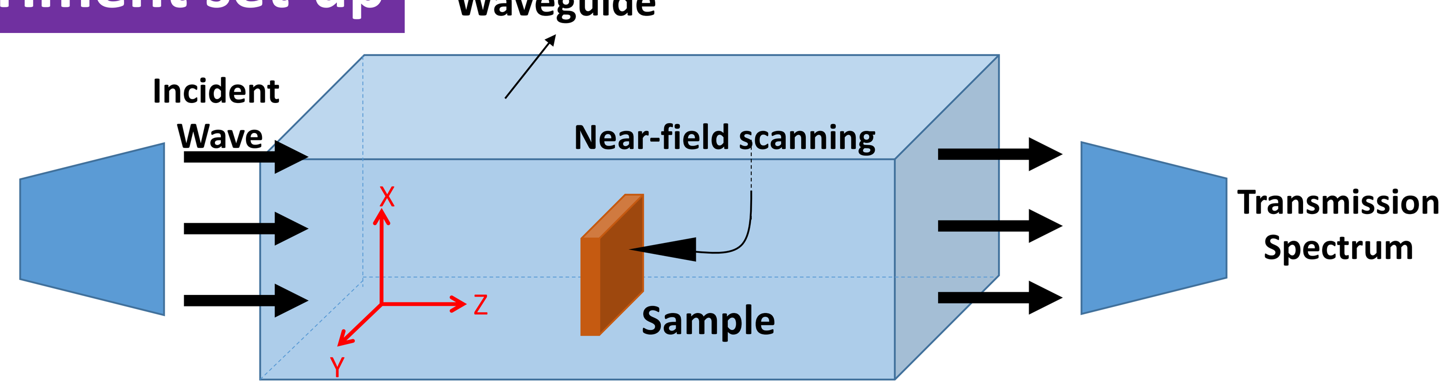


Eigenmodes of a Real-structured Cavity

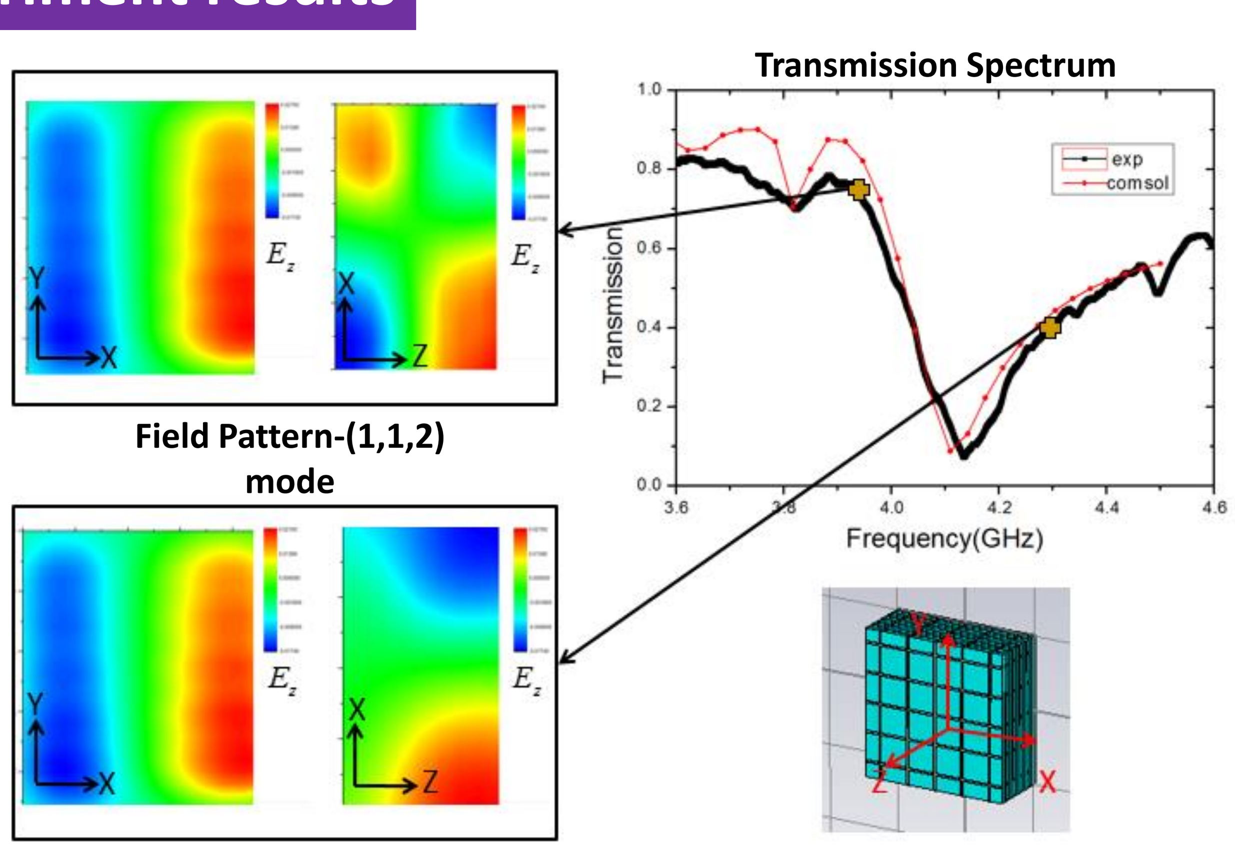
	Cavity Size	No. of Layers	Mesh Period	Modes (1-3)
Cavity 1	18mm*18mm*9.4mm	8	3mm*3mm	4.03 GHz (Q=19) 3.82 GHz (Q=127) 3.63 GHz (Q=200)
Cavity 2	20mm*20mm*8.3mm	10	4mm*4mm	3.62 GHz (Q=27.3) 3.38 GHz (Q=180) 3.18 GHz (Q=250)

Experiment results

Experiment set-up



Experiment results

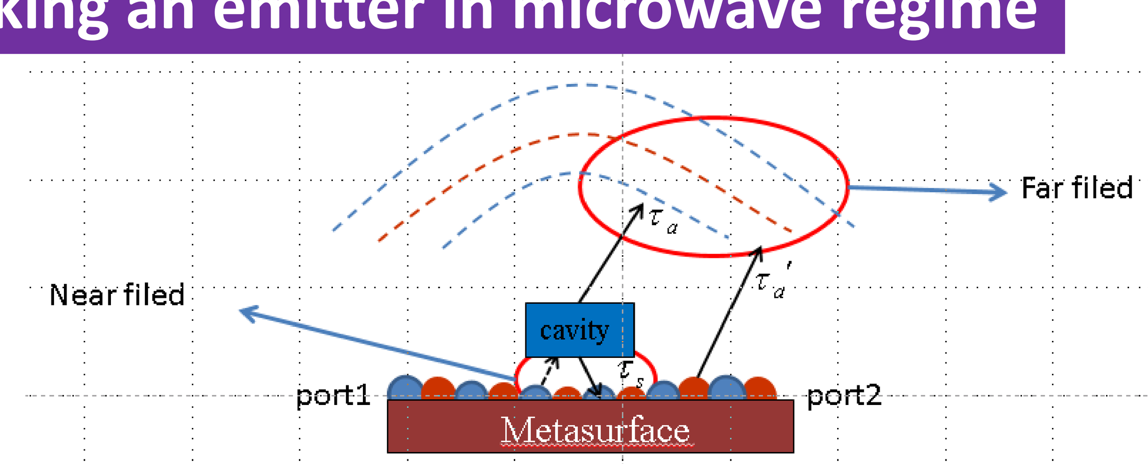


Field Pattern-(1,1,2) mode

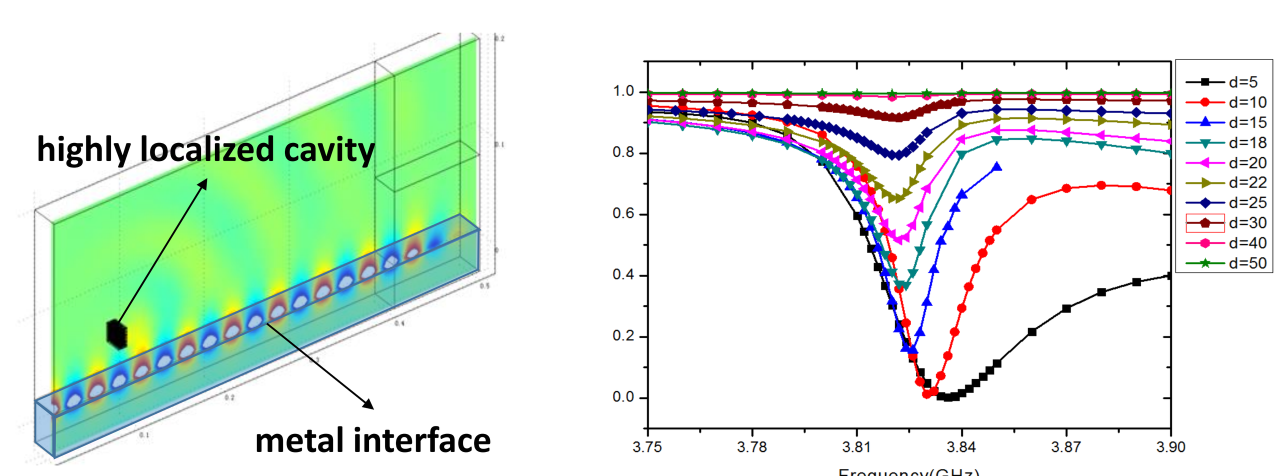
Field Pattern-(1,1,1) mode

A platform for light-matter interaction study

Mimicking an emitter in microwave regime



Currently research progress



Couple mode theory: $t_{spp} = 1 - \frac{\tau_{spp}}{i(\omega - \omega_0 + \tau_{spp} + \tau_a')}$

competition between two energy channels

Conclusion

- A cavity with small mode volume and high Q factor has successfully made in microwave regime
- Near field characterizations give insight of cavity's mode properties
- Mimicking an highly local emitter by this cavity provide a good platform to study light-matter interactions

References

[1] Yang, Xiaodong, et al. "Experimental realization of three-dimensional indefinite cavities at the nanoscale with anomalous scaling laws." Nature Photonics 2012; 6: 450-454.

[2] Sun S, He Q, Xiao S, Xu Q, Li X, Zhou L. "Gradient-index meta-surfaces as a bridge linking propagating waves and surface waves." Nature Materrials 2012; 11: 426–431.