Making a continuous metal film optically transparent

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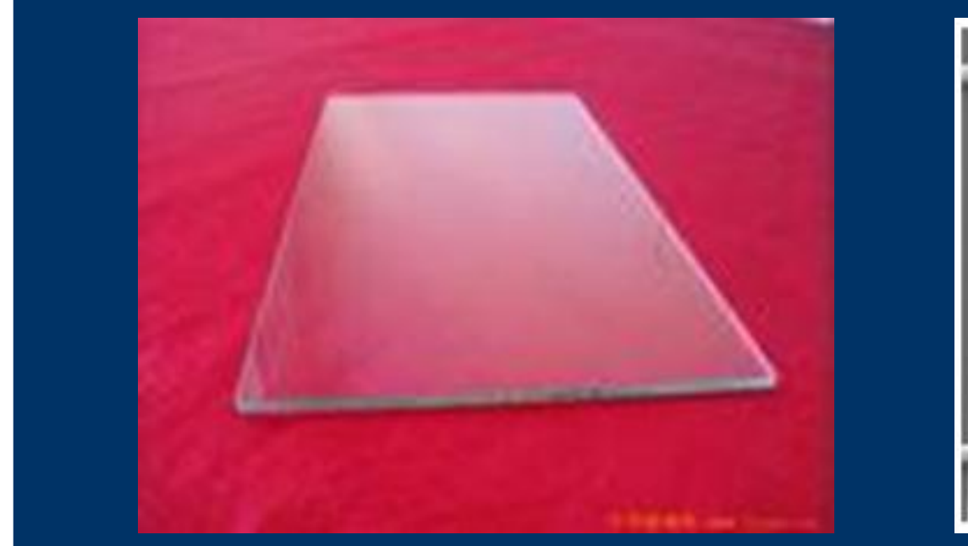
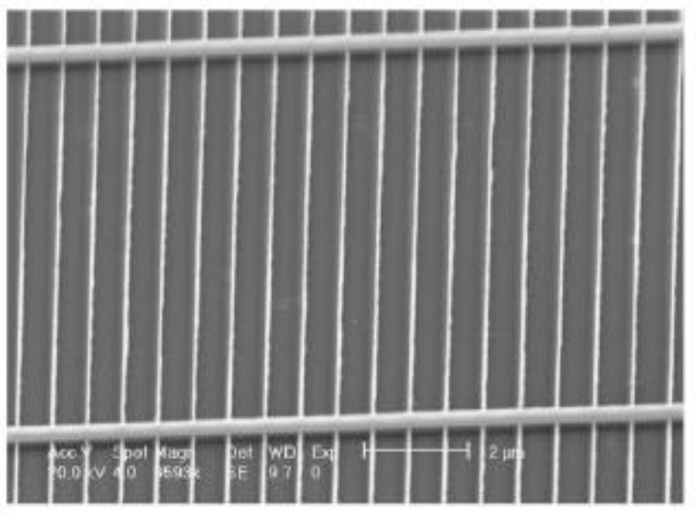
Backgrounds:

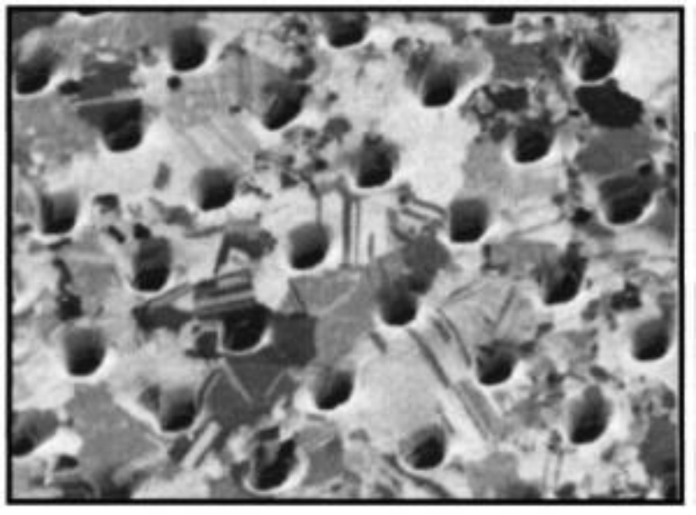
Transparent conducting metals (TCMs) are highly desired due to numerous applications, such as solar cells, displays, and so on.



Indium Tin Oxide



Nano-Meshes



EOT

PROBLEMS: Available approaches sacrifice metal's conductance and are sensitive to structural disorder

Motivation:

- **An apertureless TCM with perfect conductivity**
- **High transmittance**
- **Robust against structural disorder**
- **Wide-angle response**

I. Concept

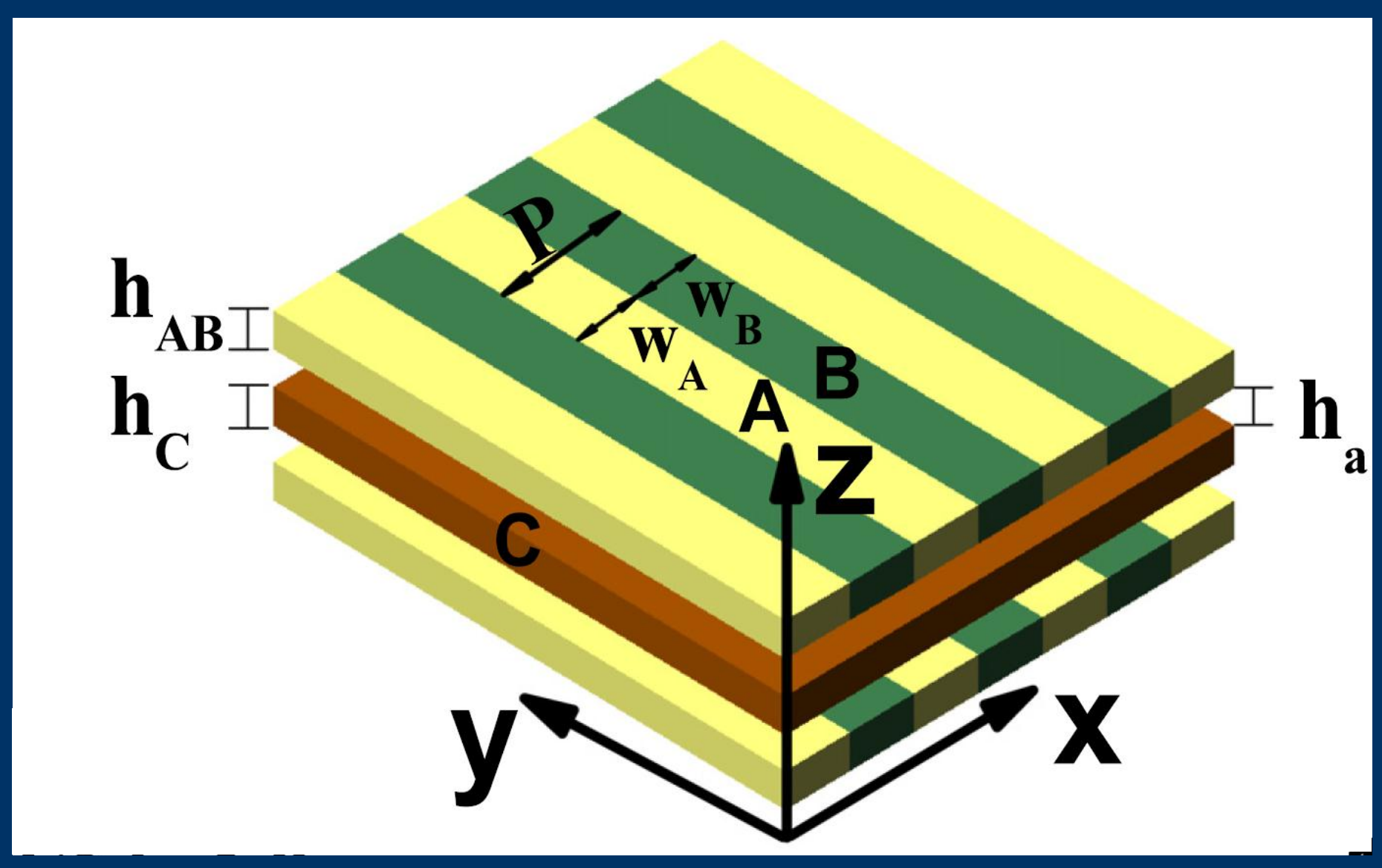


Fig. 1 Geometry of designed TCM structure
Layer C: metal film
Layer AB: dielectric(A) and metallic stripes (B)

Analytical solutions

- **Mode expansion theory**
- **Two approximations: only consider zero-order mode and fundamental Bloch mode in air region and inside AB layers, respectively**
- **$P \ll \lambda$, and h_C, $h_a \ll \lambda$**
- **Material's loss neglected**

Perfect transparency condition

reflection from AB　　reflection from C

$$\left(\frac{Z_0}{Z_{AB}}-\frac{Z_{AB}}{Z_0}\right)2\tan(k_{AB}^z h_{AB})-\left(\frac{a_C}{k_0}-\frac{k_0}{a_C}\right)2\tan(a_C\bar{h}_C)$$
$$-\left(\frac{a_C Z_{AB}^2}{k_0 Z_0^2}-\frac{k_0 Z_0^2}{a_C Z_{AB}^2}\right)\tan^2(k_{AB}^z h_{AB})\tan(a_C\bar{h}_C)=0$$

Multiple scattering effects

Scattering cancellation mechanism (SCM)

- **Tuning Z_{AB} efficiently by adjusting AB structure**
- **Z_{AB} makes reflection from AB layer strong enough to cancel the one from C layer**

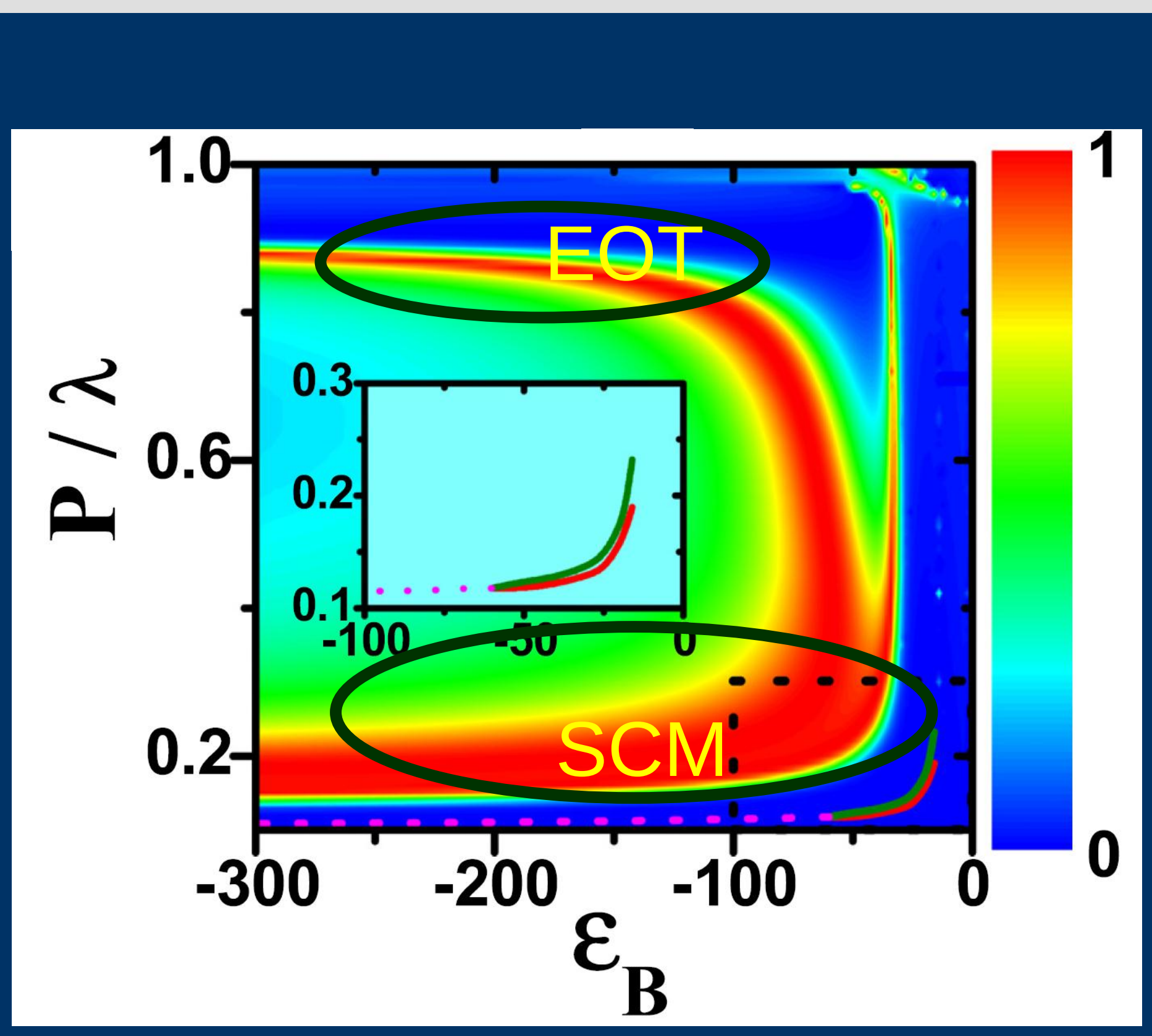


Fig. 2 FEM simulation on transmittance as functions of P/ λ and ε_B, with $\varepsilon_C=-110$, $\varepsilon_a=1$, $\varepsilon_A=12$, $h_{AB}=h_C=2h_a=0.02\lambda$, $w_B=0.1\lambda$

- ***Broad*** SCM transmission band
- ***Independent*** on P in the region of $-90<\varepsilon_B<-30$
- ***Robust*** against structure disorder

II. Optical TCM design

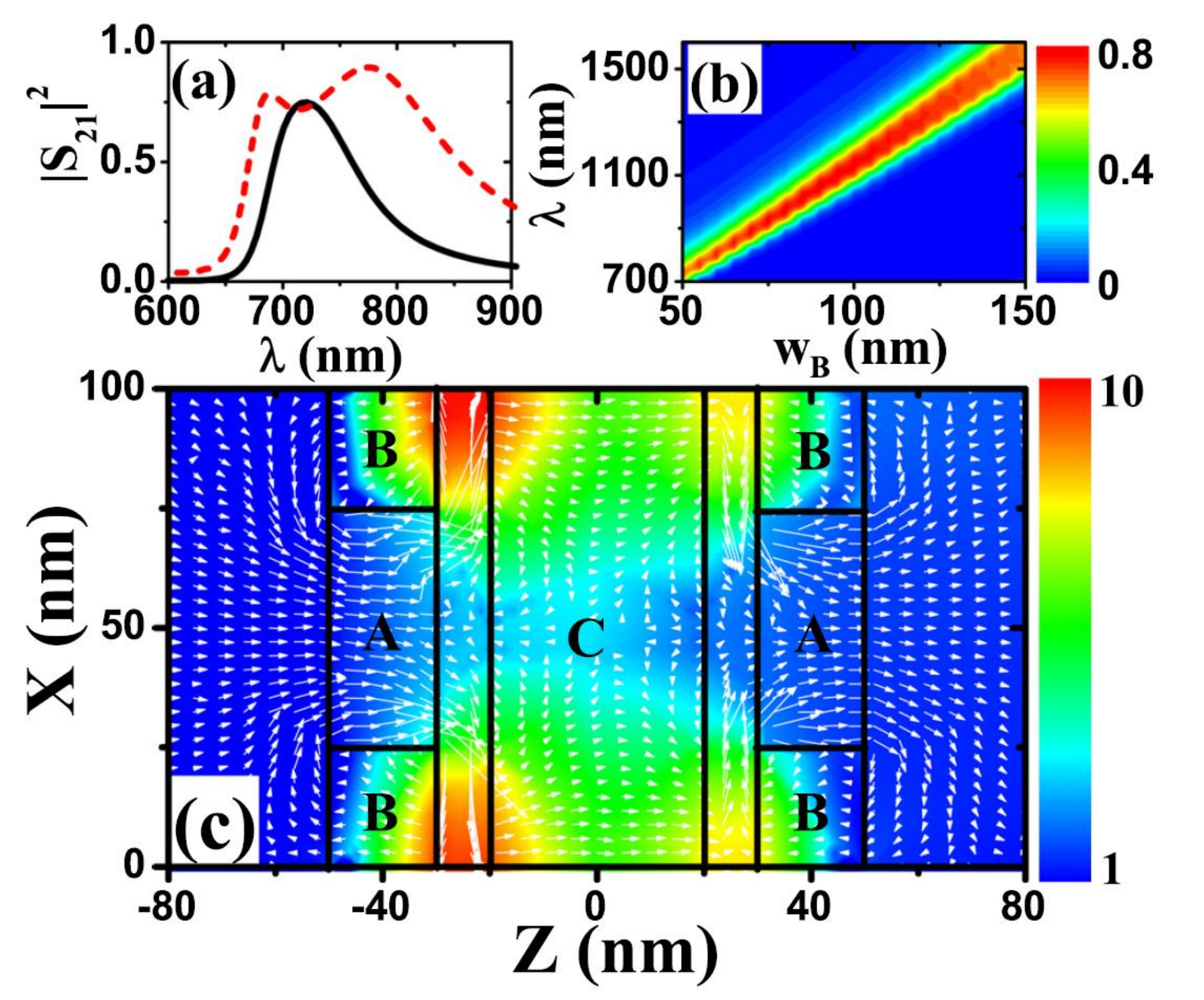


Fig.3 FEM simulation of realistic designs based on Ag films

- ***75% and 90%*** transmittance for ***Ag*** films (h_C=40 and 25nm) at 700 and 776nm, respectively
- **Tunability** of transmission peaks via changing w_B

III. Proof-of-concept experiments

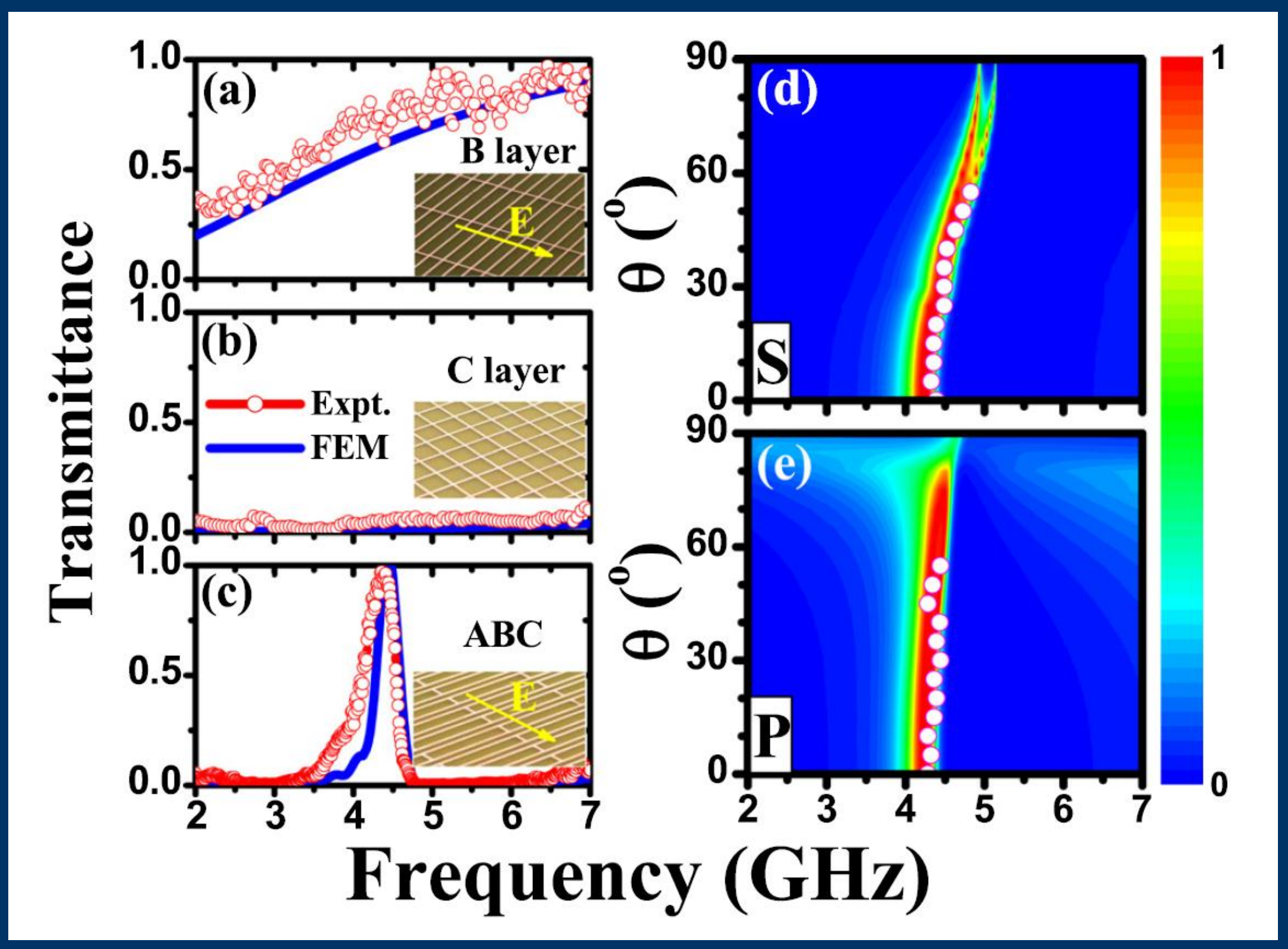


Fig. 4 Measured and simulated transmittance of designed sample at microwave region

- **Metallic meshes mimic plasmonic metal in GHz**
- **Experiments agree well with simulations**
- **Insensitive to incidence angles**

IV. TCM on substrate

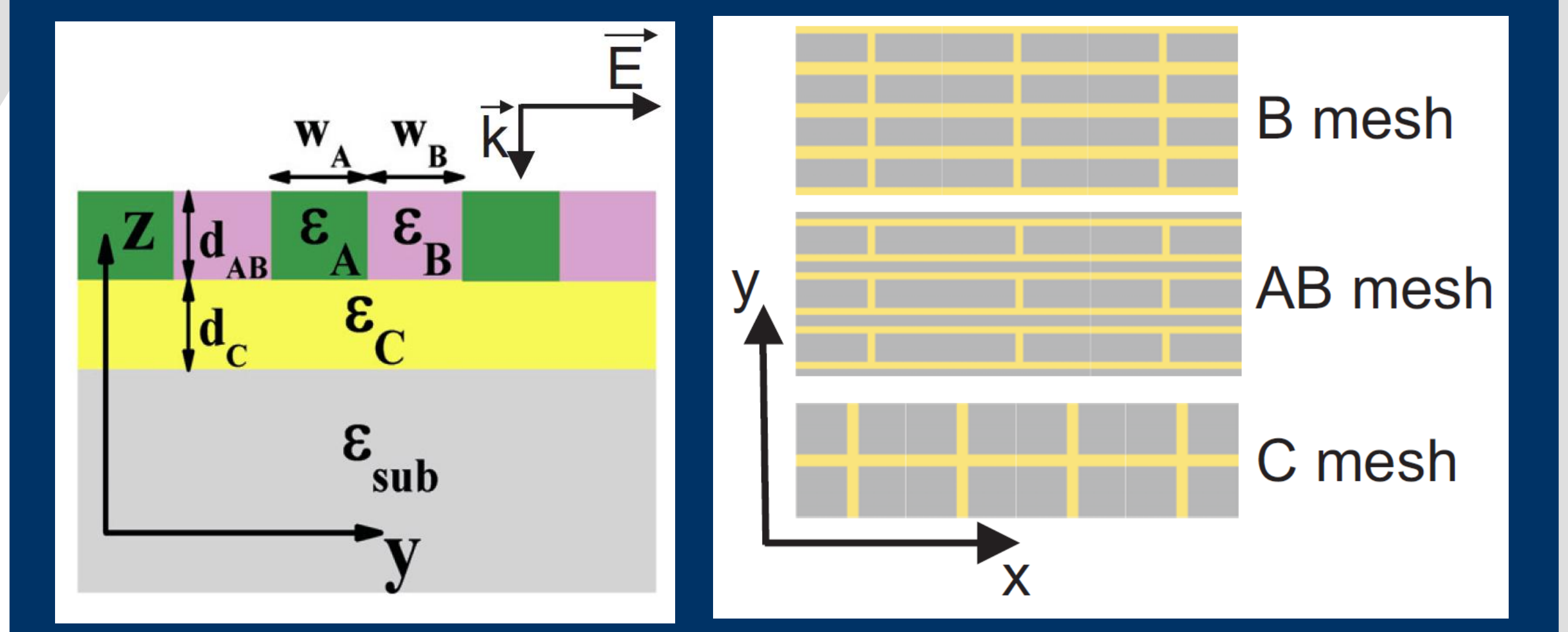


FIG. 5 TCM design on semi-infinite substrate and sample fabricated in Terahertz

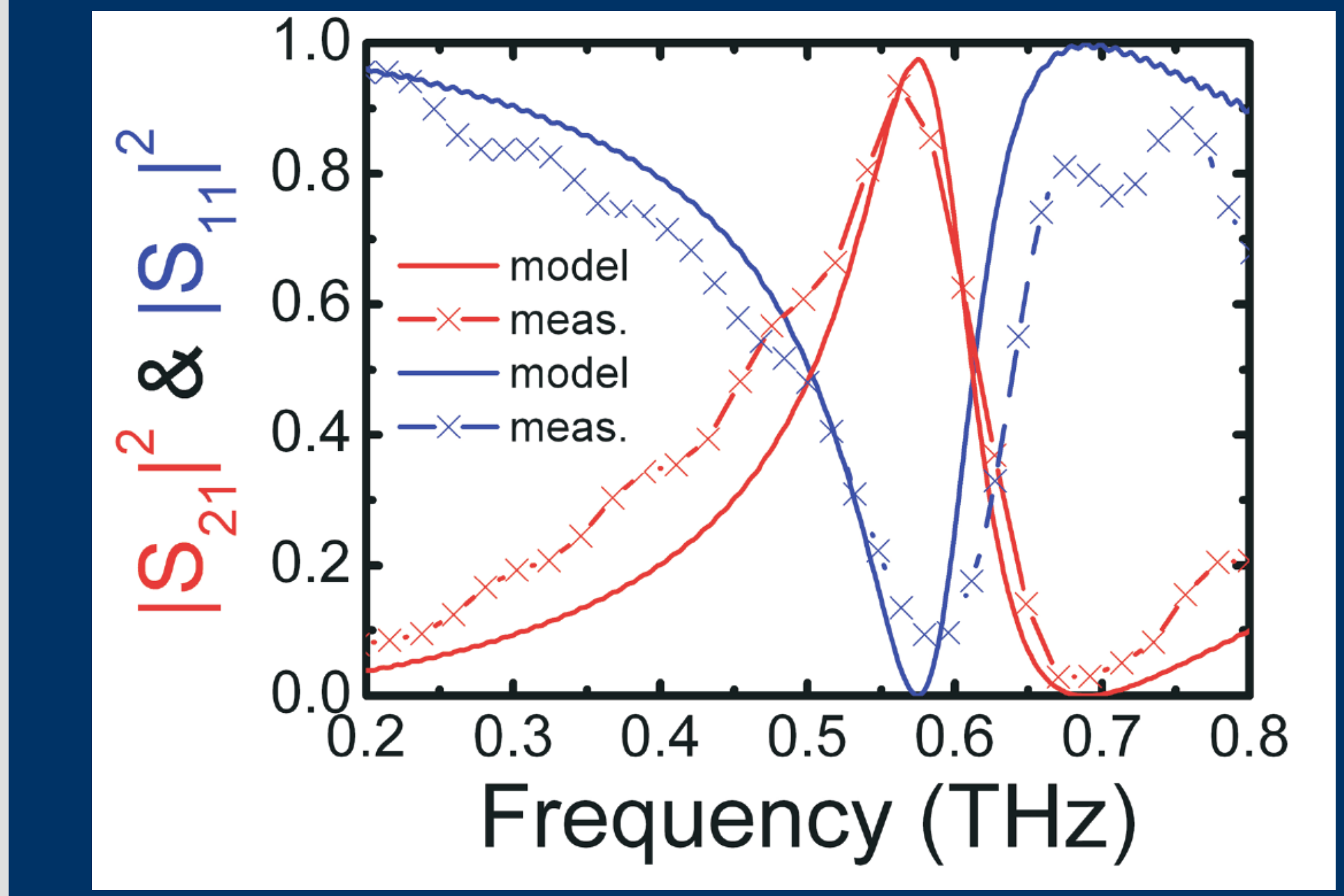


FIG. 6 Measured and simulated transmission and reflection spectrums on THz TCM

- **Great agreement between experiments and simulations**

Conclusions:

- **SCM make a continuous metal film transparent at optical frequency**
- **Experimental demonstrations at GHz and THz regions**
- **Robustness against incident angle and structue disorder**

References:
[1] Zhengyong Song*, et al.,* Appl. Phys. Lett. **101**, 181110 (2012).
[2] Radu Malureanu, *et al.,* Opt. Express **20**, 22770 (2012).