A theoretical study on the conversion efficiencies of gradient meta-surfaces

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Motivations:

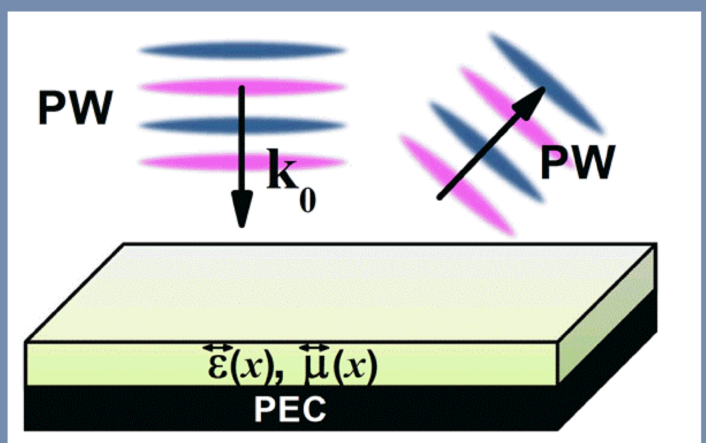
In a recent work (Sun S. et al., Nat. Mater., 11 (2012) 426), nearly 100% efficiency of the conversion of an incident propagating wave (PW) to an obliquely outgoing PW or even a surface wave (SW) is demonstrated in an ideal gradient meta-surface (GM).

However, practical systems might have non-equal and $\varepsilon_{||}(x)$ and $\mu_{||}(x)$ profiles and sometimes use supercells to truncate the profiles to avoid using too large values of ε and μ.

Here, based on non-ideal GM systems, we systematically studied the factors that influence the efficiencies of such conversion processes (both PW-PW and PW-SW).

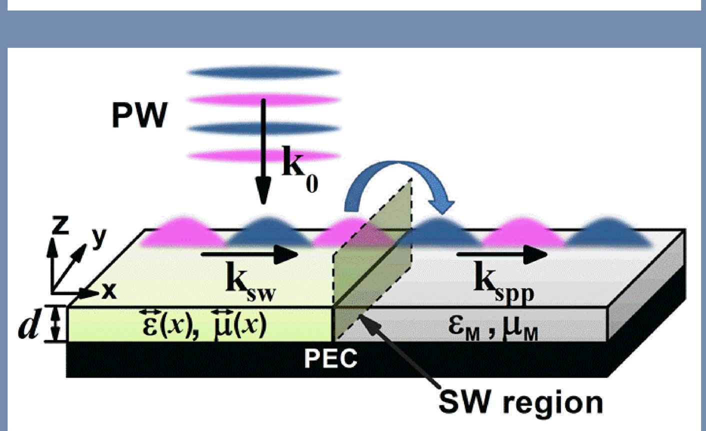
I. Efficiency issues of model GMs

(A) Methods



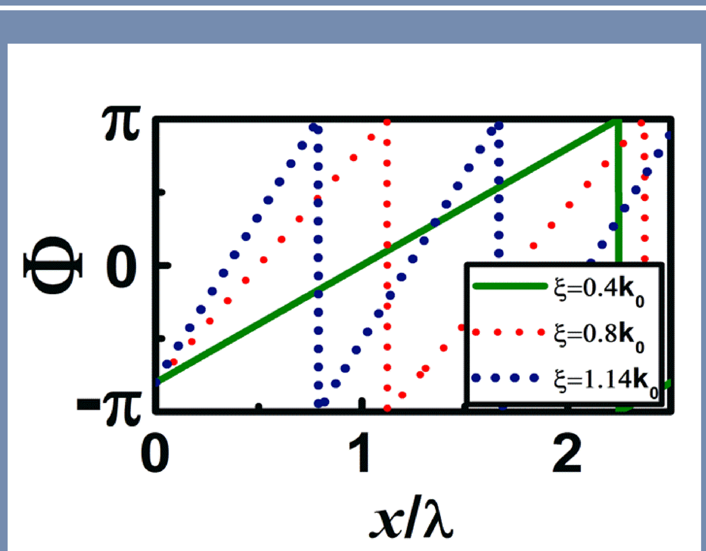
- To study the conversion efficiency for the PW-PW process, we calculate the reflectance:

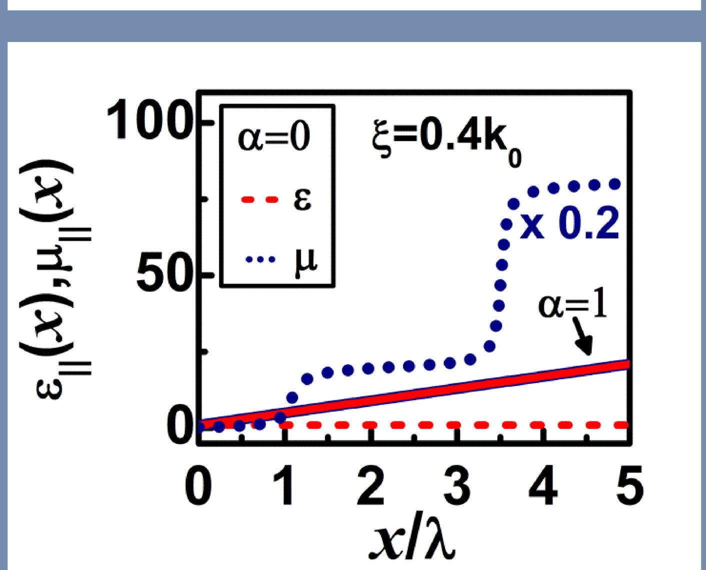
$$R_{PW\text{-}PW} = \left|\rho_{k_x}\right|^2 \cos\theta_r / \cos\theta_i = \left|\rho_{k_x}\right|^2 \sqrt{1-(\xi/k_0)^2}$$



- For the PW-SW process, $k_{SW}=\xi$, $\xi > k_0$.

  Use an eigen-SPP guide material with $k_{SPP} = k_{SW}$, and calculate the power flow ratio as the PW-SW conversion efficiency.





- How to generate the systems we want to study:

We assume

$$\varepsilon_{||}(x) = 1 + \alpha \cdot \xi x / 2k_0 d$$

and then retrieve $\mu_{||}(x)$ by letting the calculated reflection phase

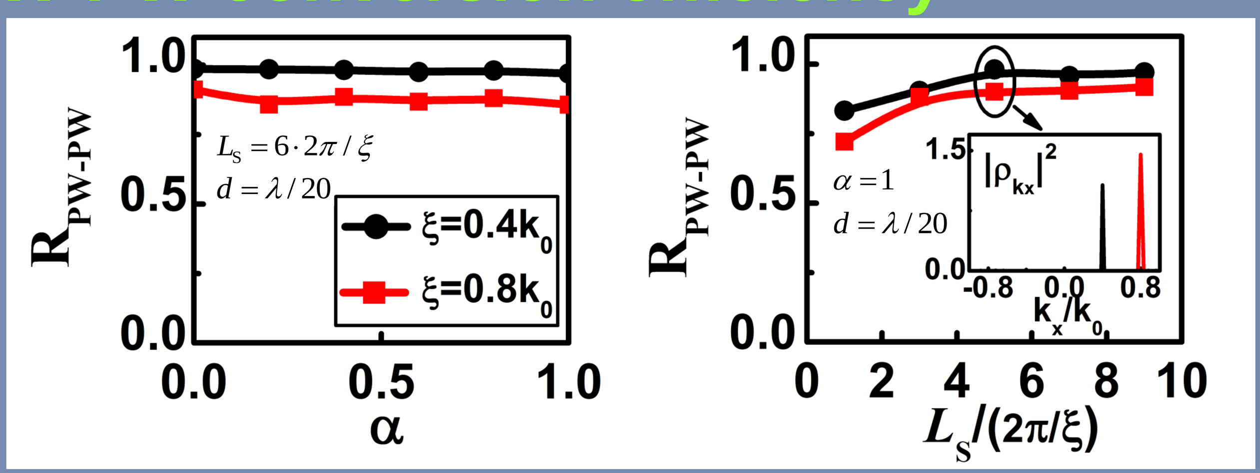
$$\Phi(x) = \cos^{-1}\frac{-\varepsilon_{||} + \mu_{||}\tan^2(\sqrt{\varepsilon_{||}\mu_{||}}k_0 d)}{\varepsilon_{||} + \mu_{||}\tan^2(\sqrt{\varepsilon_{||}\mu_{||}}k_0 d)}$$

satisfy the given

$$\Phi(x) = \Phi_0 + \xi x$$

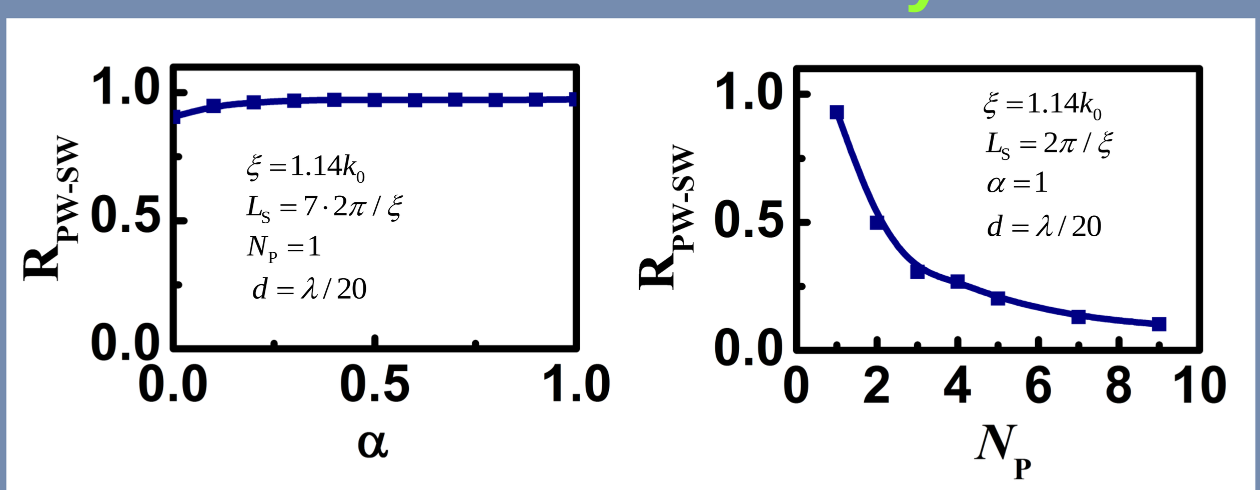
$\alpha \in [0,1]$, a parameter to measure the degree of impedance mismatch: from completely impedance-mismatched to impedance-matched

(B) PW-PW conversion efficiency



L_S: the periodicity of one supercell

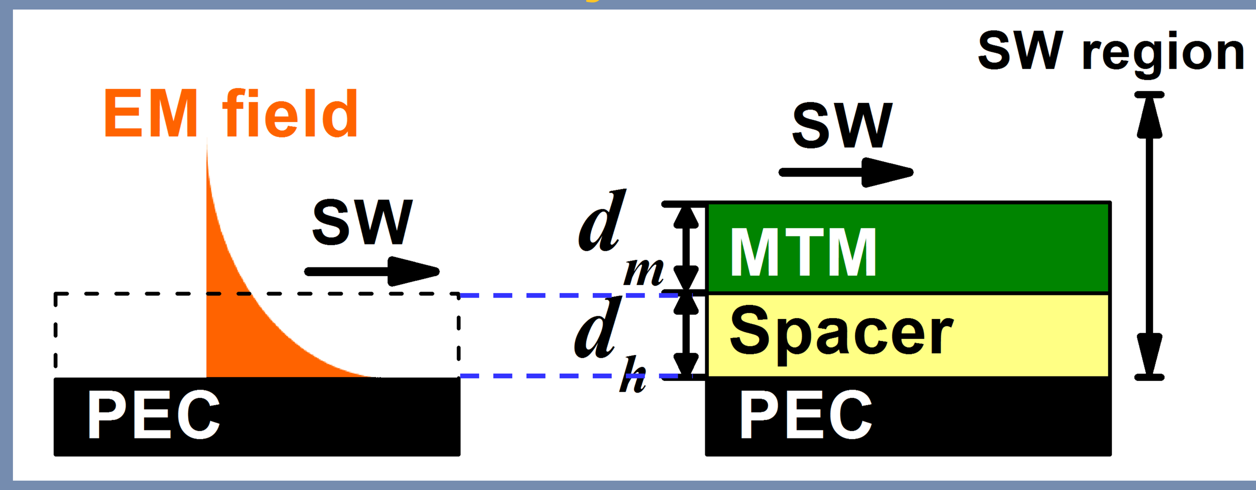
(C) PW-SW conversion efficiency

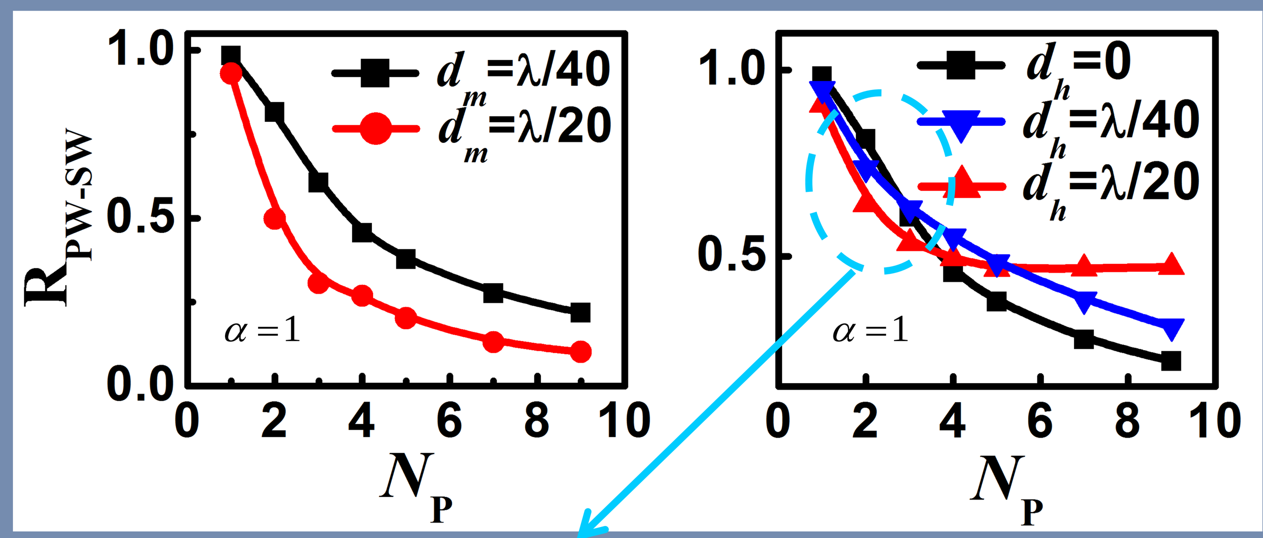


N_P: the total number of supercells inside the device

We found that while intra-supercell impedance-mismatch can hardly affect the conversion efficiencies, the scatterings caused by inter-supercell discontinuities can have non-negligible effects on the PW-SW conversion efficiency.

II. An improved model GM with enhanced efficiency



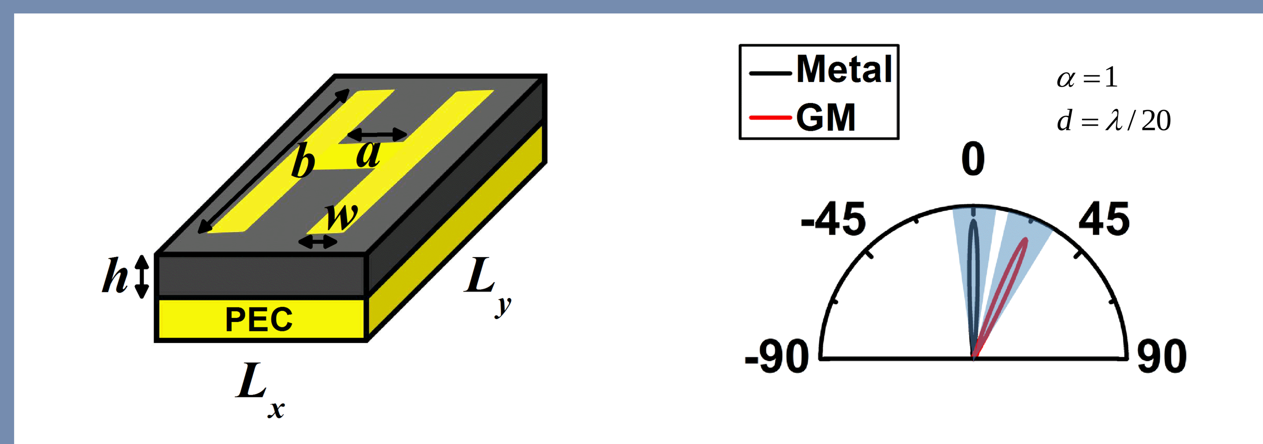


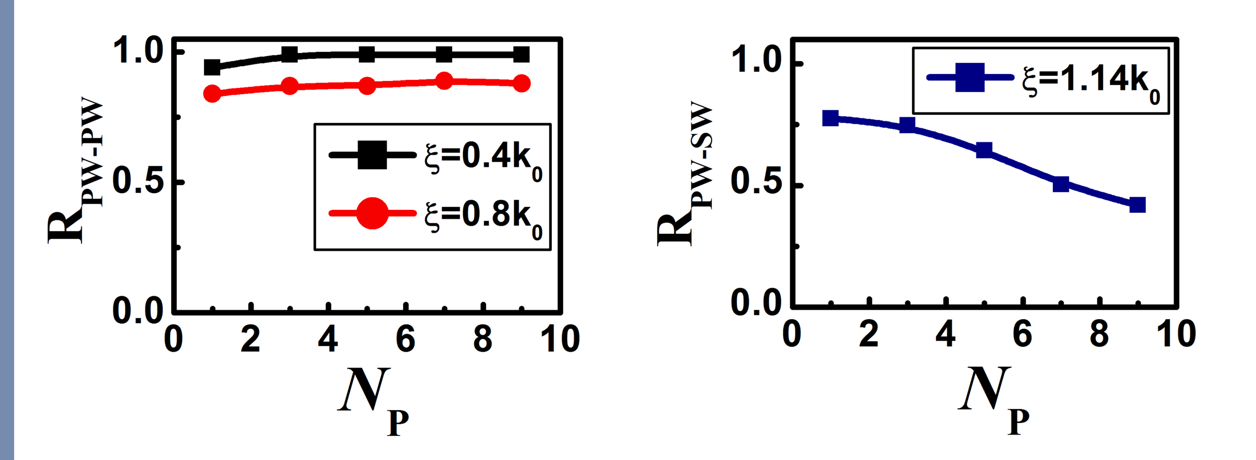
Less subwavelength GM region. There is a subtle balance betweem two mechanisms.

III. Conversion efficiencies of realistic GM systems

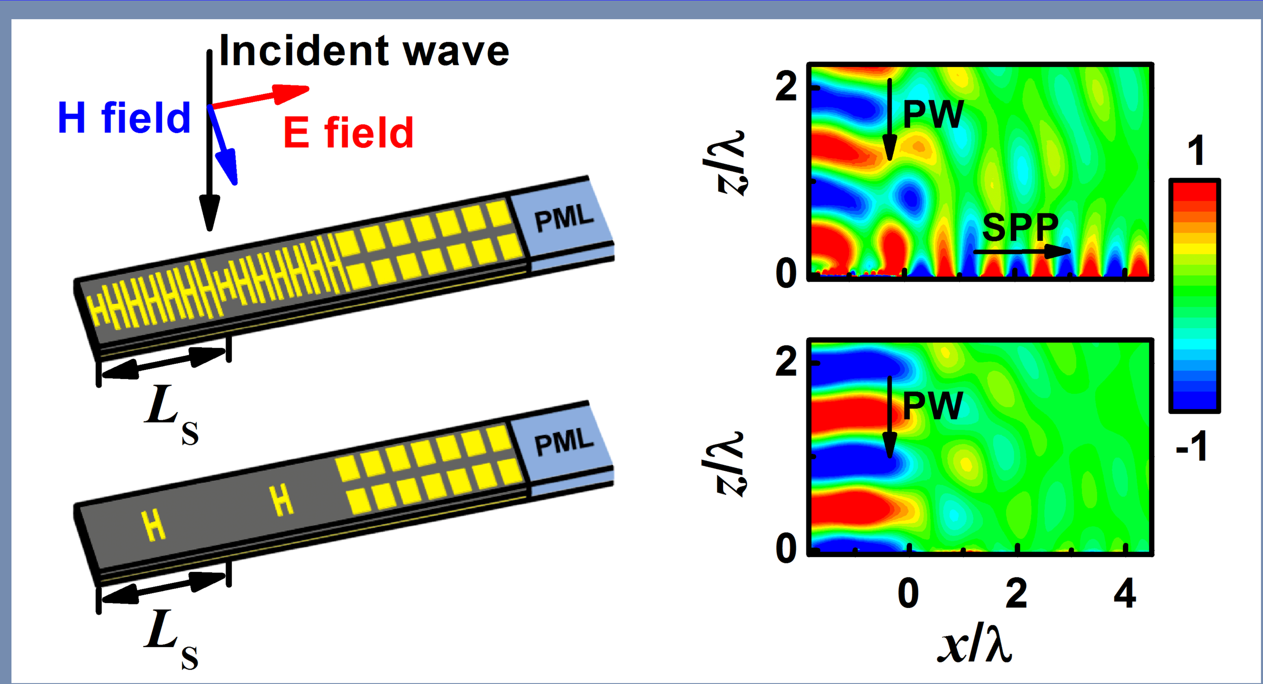
The PW-PW conversion efficiency for a realistic GM

$$R_{PW\text{-}PW} = \frac{\int_{GM} P(\theta_r)\,d\Omega_r}{\int_{Metal} P(\theta_r)\,d\Omega_r}$$





The GM system working as a PW-SW converter can work even with a very small total length.



In contrast, a conventional grating coupler fails to work when its length is too short. The results show a 78% vs. 5.2% efficiency comparison. Because for the GM, every element contributes.

Conclusions:

- We know the key factor affecting the conversion efficiency is the super periodicity scattering through the study of model GM.
- Our improved model GM can describe the realistic GM better.
- Probable application in miniaturized situations where a grating coupler is not suitable.

[1] Che Qu *et al.* Europhys. Lett. 101, 54002 (2013).

[2] Shulin Sun *et al.* Nat. Mater. 11, 426 (2012).