華南理工大學
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An Acoustic Metasurface: From Transmitted Waves Manipulation to Surface Modes Excitation

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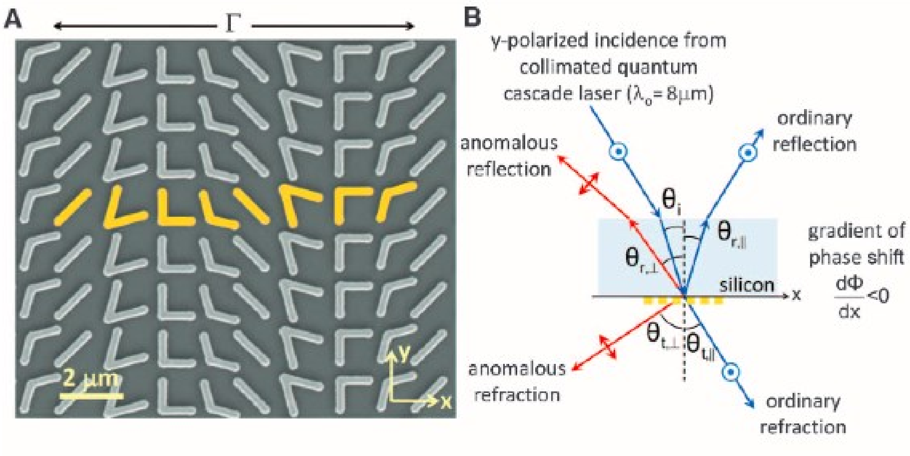
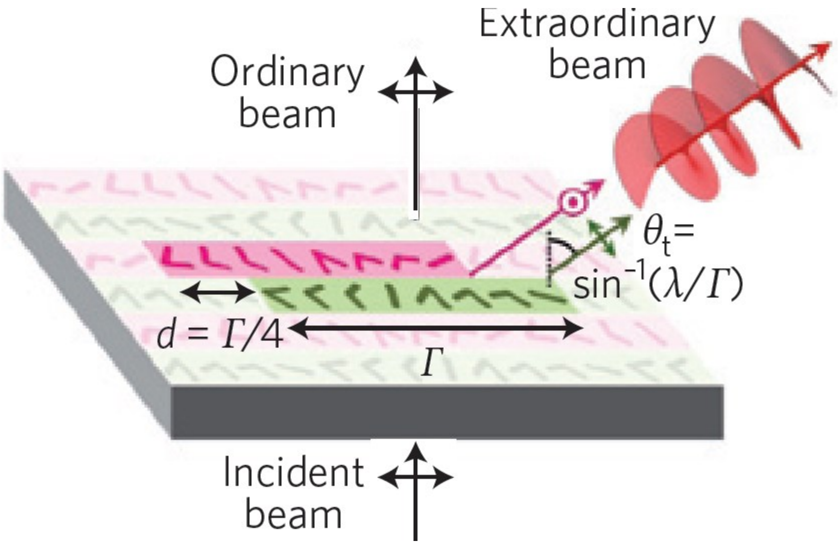
Outline

- ➢ Background and motivation
- ➢ Our acoustic metasurface
    - Design principle
    - Functionalities
    - A unified analytic model
    - A possible realization
- ➢ Summary

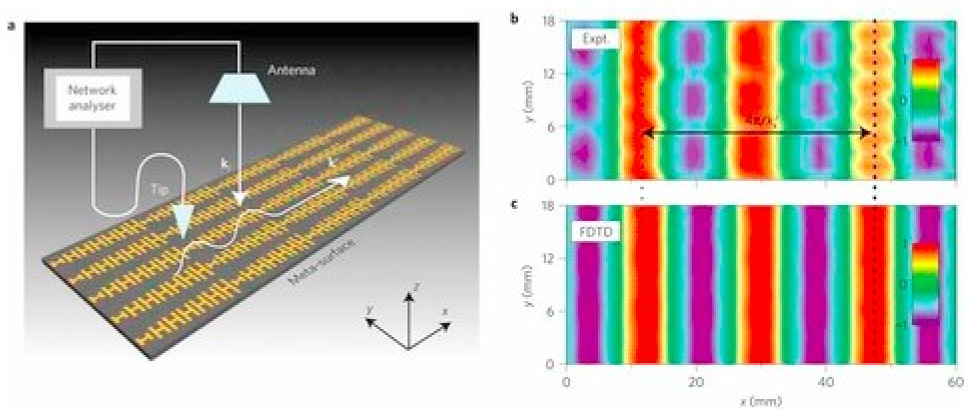
Background: Metasurface for EM waves



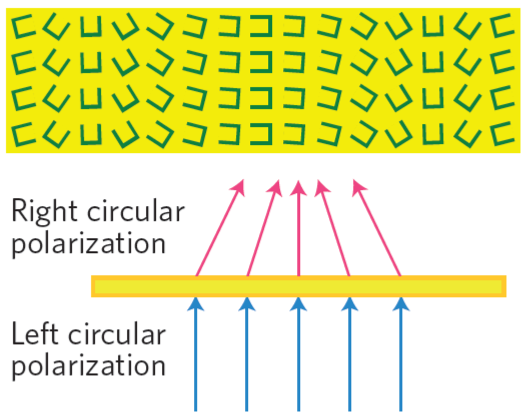
Science 334, 333 (2011)



Nano Lett. 12, 6328 (2012)

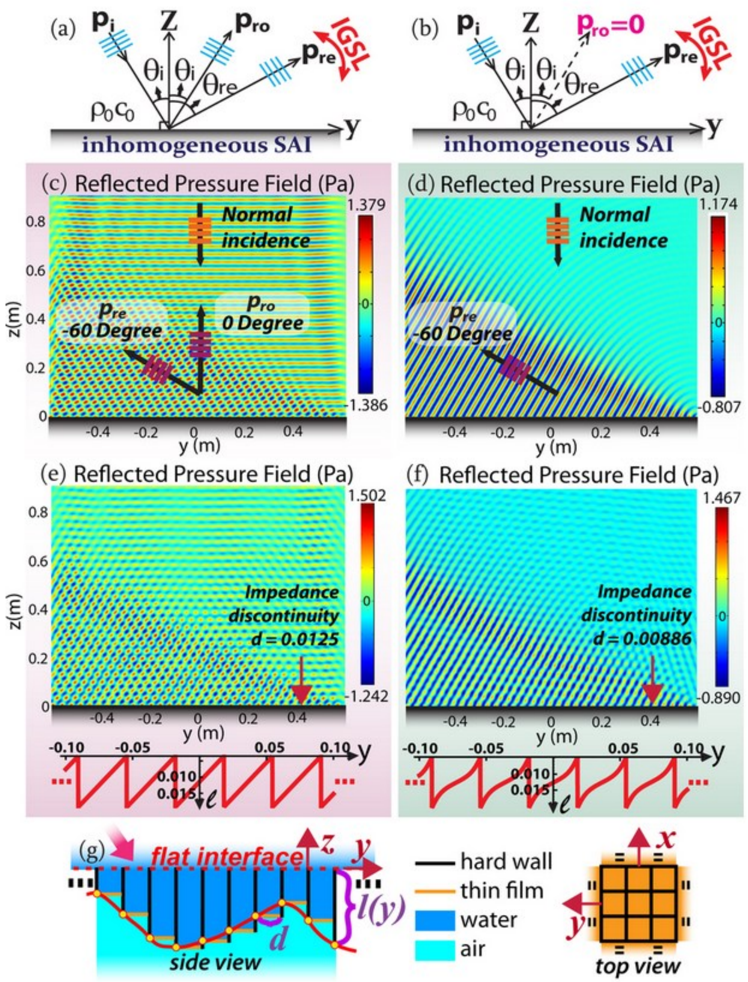


Nat. Mater. 11, 426 (2012)

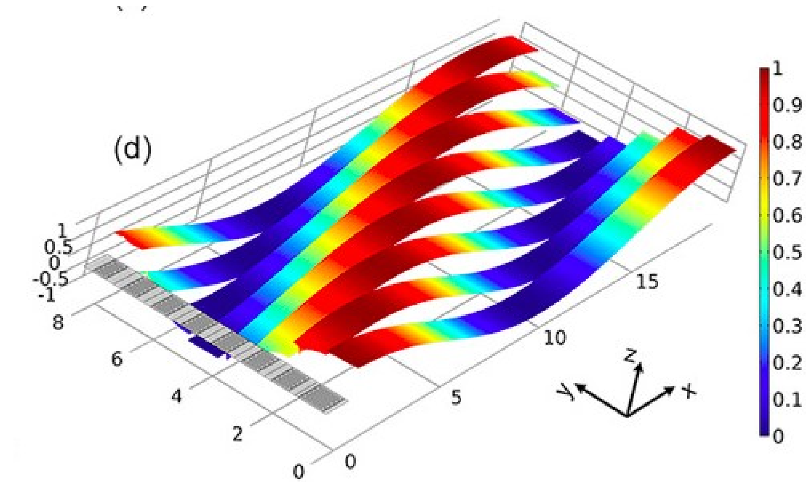


Opt. Express 14, 15882 (2012)

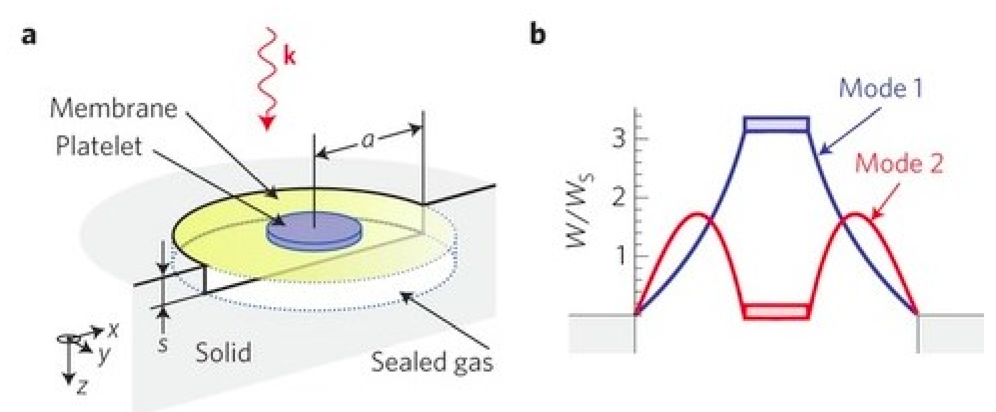
Background: Metasurface for Acousitc Waves



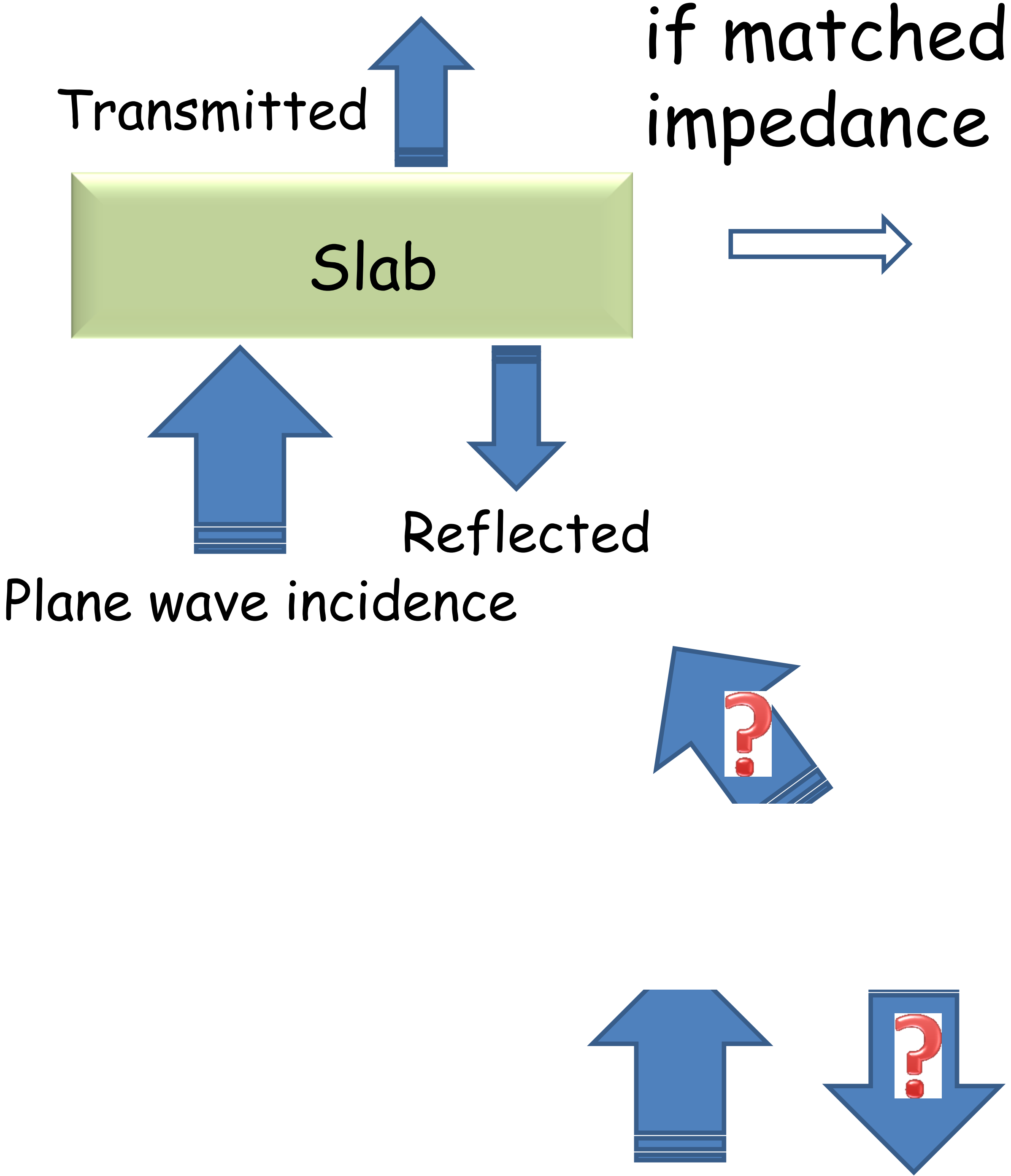
Sci. Rep. 3, 2537 (2013)



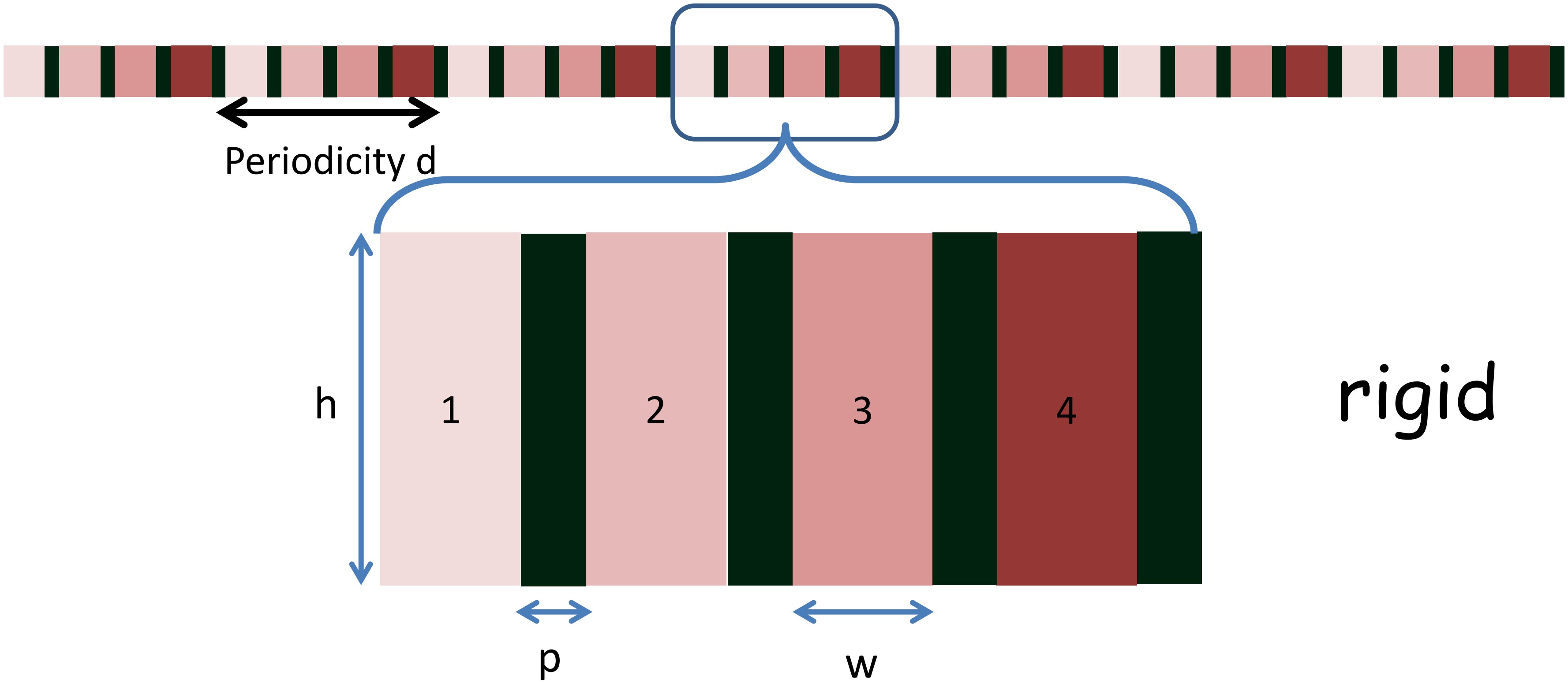
Sci. Rep. 3, 2546 (2013)



Nat. Mater. 13, 873 (2014)


if matched
impedance
Transmitted
Slab
Reflected
Plane wave incidence

Sample design



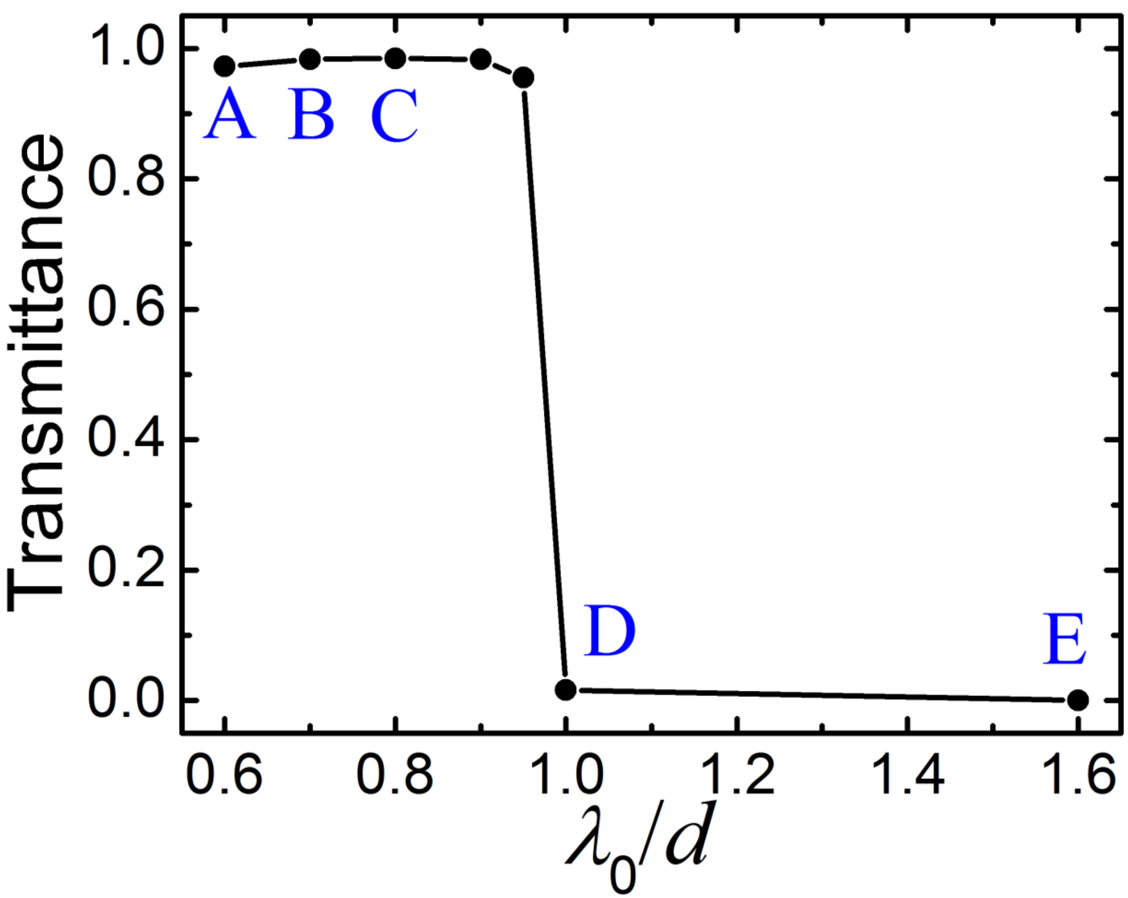
rigid

wave velocity: $c_i = c_0/(1 + (i-1)\,\lambda_0/(mh))$ → Gradient index

mass density: $\rho_i = \rho_0(1 + (i-1)\,\lambda_0/(mh))$

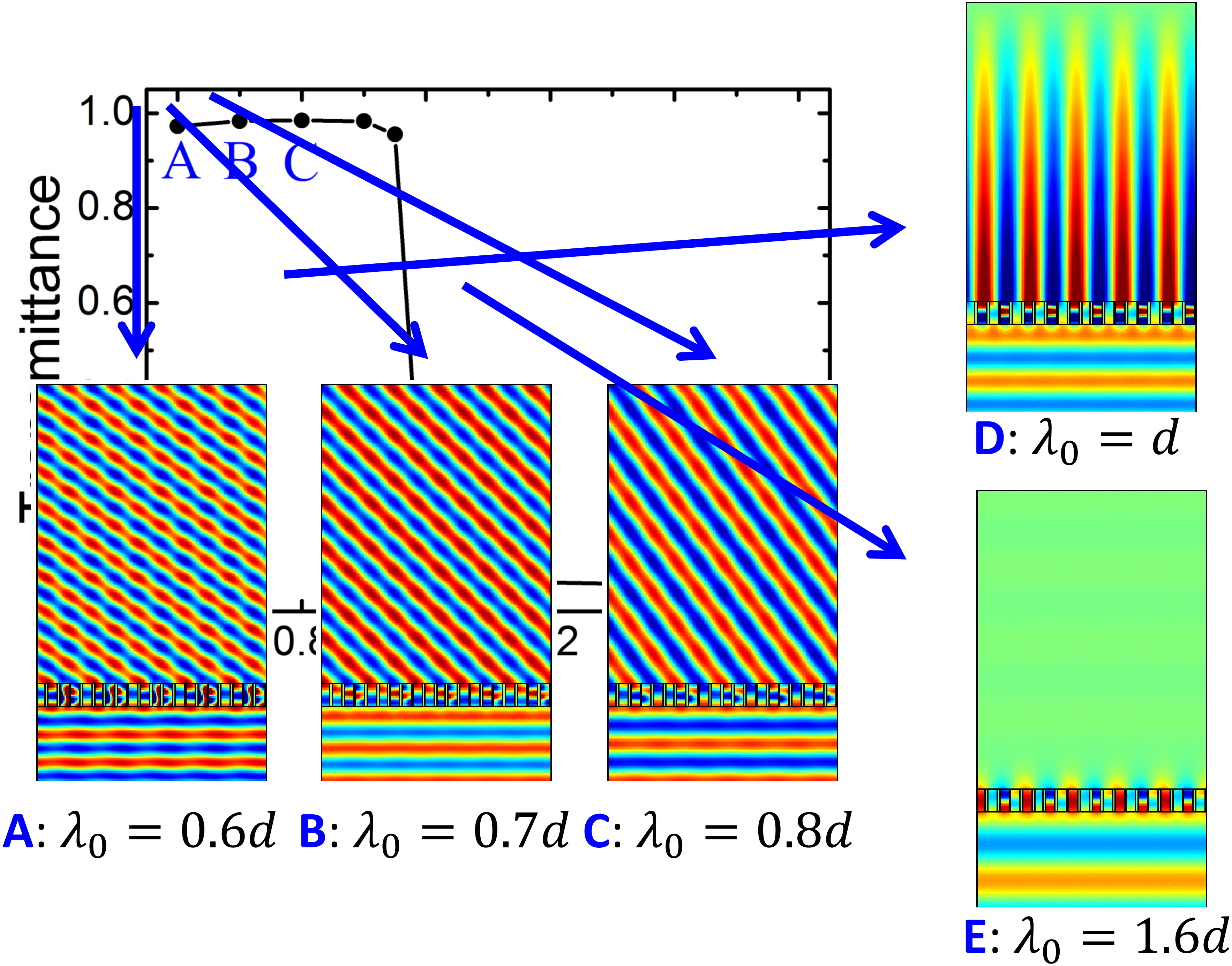
Matched-impedance to the background (c_0, ρ_0).

Proof-of-principle demonstration



$w = 0.2d$ and
$h = 0.5d$

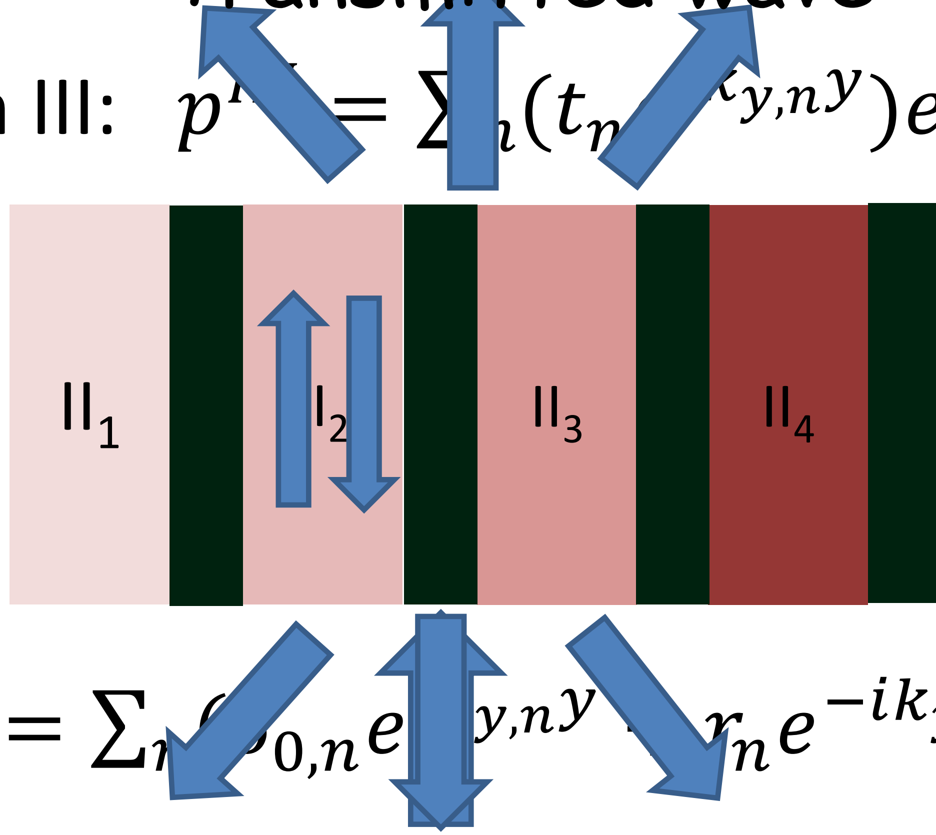
A steep drop of Transmittance from 98% to 1.6% around $\lambda_0 = d$


1.0
0.8
0.6
mittance
A
B
C
0.8
2
D: λ0 = d
E: λ0 = 1.6d
A: λ0 = 0.6d
B: λ0 = 0.7d
C: λ0 = 0.8d

A unified analytic model based on coupled-mode analysis

Transmitted wave

Region III: $p^{III} = \sum_n (t_n e^{ik_{y,n}y}) e^{iG_n x}$



$k_{y,n} = \sqrt{{k_0}^2 - {G_n}^2}$

$G_n = 2n\pi/d$

Region I: $p^I = \sum_n (\delta_{0,n} e^{ik_{y,n}y} + r_n e^{-ik_{y,n}y}) e^{iG_n x}$

Incident wave

Reflected wave

Region II: $p^{II} = a_i e^{ik_0 y} + b_i e^{-ik_0 y}$ (in the *i*-th slit)

Matching the boundary conditions

$$1+r_0+\left(r_1 e^{iG_1\alpha_i}+r_{-1}e^{iG_{-1}\alpha_i}\right)\mathrm{sinc}\left[\frac{G_1 w}{2}\right]=a_i+b_i \qquad (i=1,2,3,4),$$

$$t_0+\left(t_1 e^{iG_1\alpha_i}+t_{-1}e^{iG_{-1}\alpha_i}\right)\mathrm{sinc}\left[\frac{G_1 w}{2}\right]=a_i e^{ik_i h}+b_i e^{-ik_i h} \qquad (i=1,2,3,4),$$

$$\left(1-r_0\right)\frac{k_0 d}{\rho_0}=\sum_{i=1}^{4}\frac{k_i w\left(a_i-b_i\right)}{\rho_i},$$

$$t_0\,\frac{k_0 d}{\rho_0}=\sum_{i=1}^{4}\frac{k_i w\left(a_i e^{ik_i h}-b_i e^{-ik_i h}\right)}{\rho_i},$$

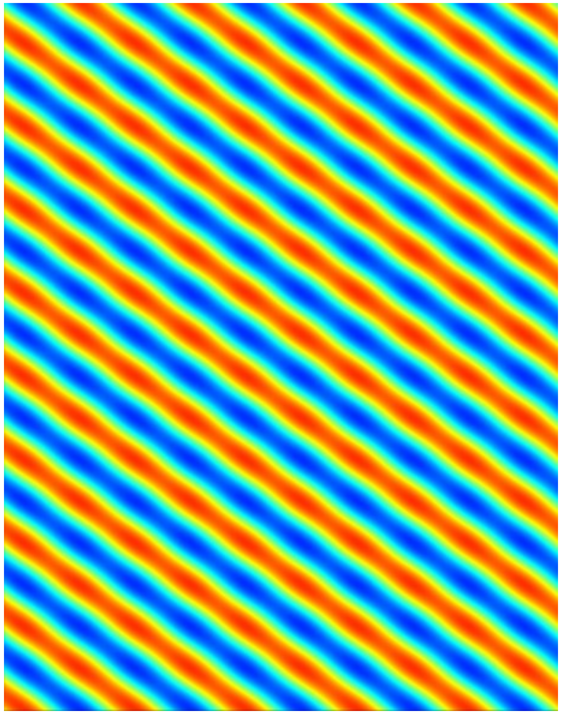
$$-r_{\pm1}\,\frac{k_{y,\pm1}d}{\rho_0}=\sum_{i=1}^{4}\frac{k_i w\left(a_i-b_i\right)e^{-iG_{\pm1}\alpha_i}}{\rho_i}\mathrm{sinc}\left[\frac{G_1 w}{2}\right],$$

$$t_{\pm1}\,\frac{k_{y,\pm1}d}{\rho_0}=\sum_{i=1}^{4}\frac{k_i w\left(a_i e^{ik_i h}-b_i e^{-ik_i h}\right)e^{-iG_{\pm1}\alpha_i}}{\rho_i}\mathrm{sinc}\left[\frac{G_1 w}{2}\right],$$

At short wavelength $\lambda_0 = 0.6d$

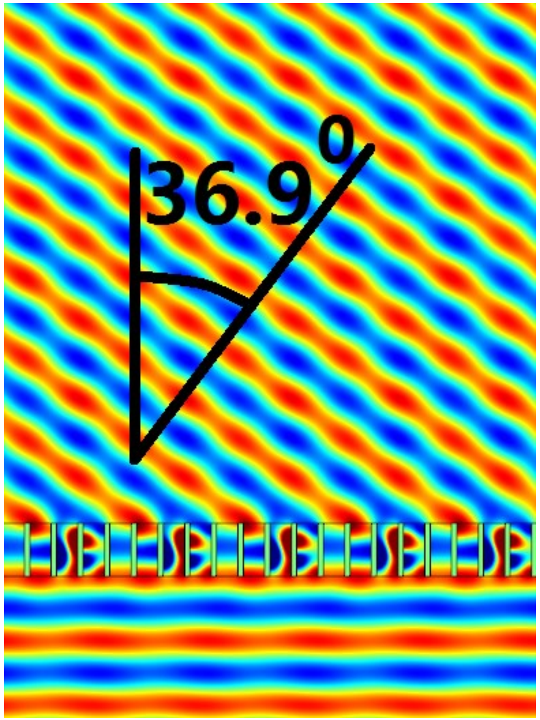
Analytic model prediction

$\theta_t = \arcsin(\lambda_0/d) = 36.9^0$



large t_1, small enough t_{-1} and r_0, while t_0 and $r_{\pm 1}$ are almost 0

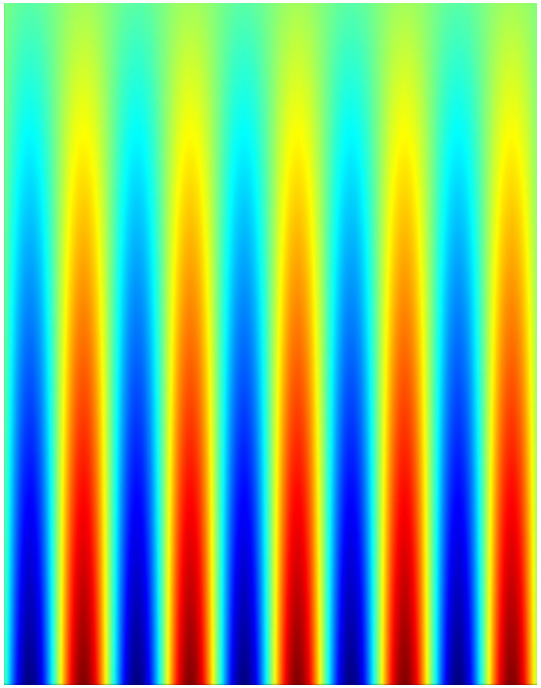
COMSOL Simulation



At critical point: $\lambda_0 = d$

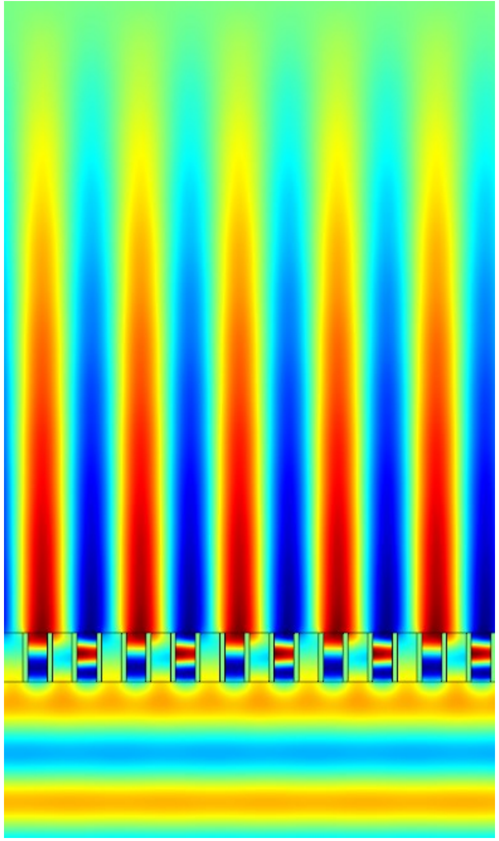
Analytic model prediction

$$k_{y,\pm 1} = \sqrt{k_0^2 - \left(2\pi/d\right)^2} = 0$$



large r_0 and $t_{\pm 1}$

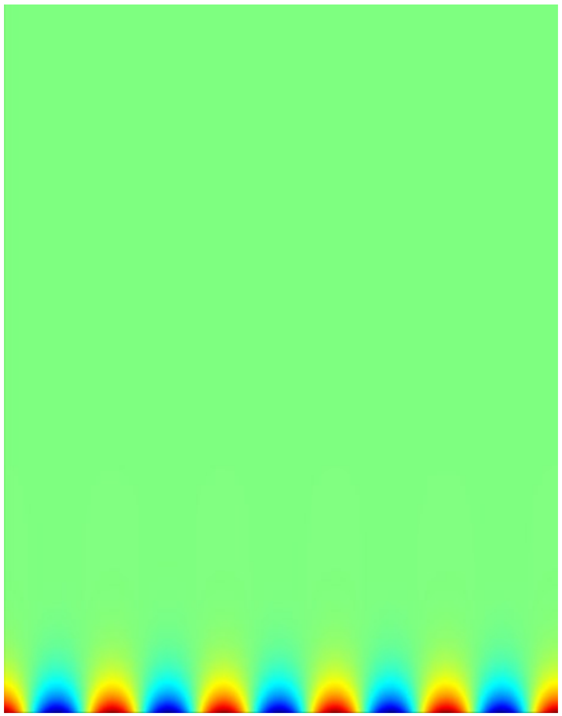
COMSOL Simulation



At long wavelength $\boldsymbol{\lambda_0 = 1.6d}$

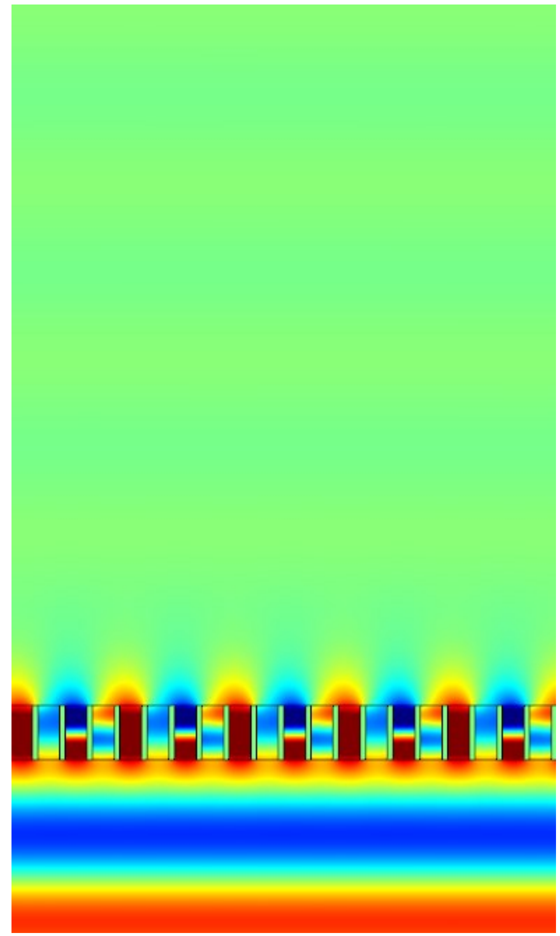
Analytic model prediction

$k_{y,\pm 1}$ are purely imaginary



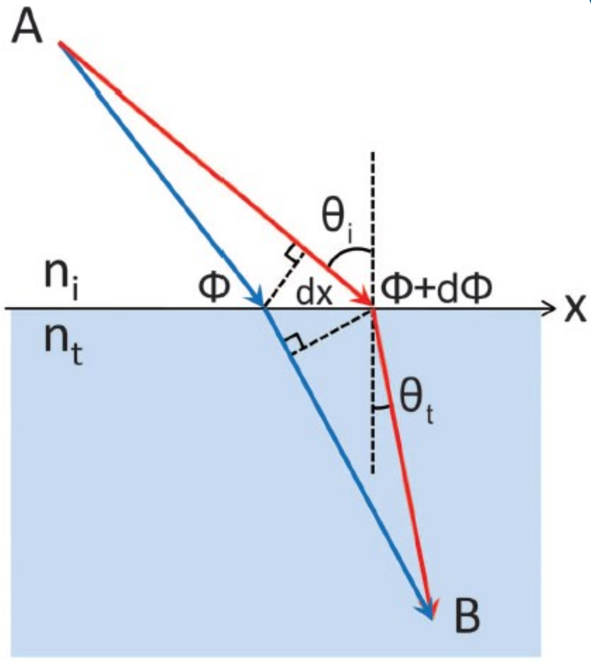
large r_0 and $t_{\pm 1}$, while
t_0 and $r_{\pm 1}$ are almost 0

COMSOL Simulation



Generalized Snell's law

Manipulate wave front by engineering the phase



- Fermat's principle:

$$[k_0 n_i \sin(\theta_i)dx + (\Phi + d\Phi)] -$$
$$[k_0 n_t \sin(\theta_t)dx + \Phi] = 0$$

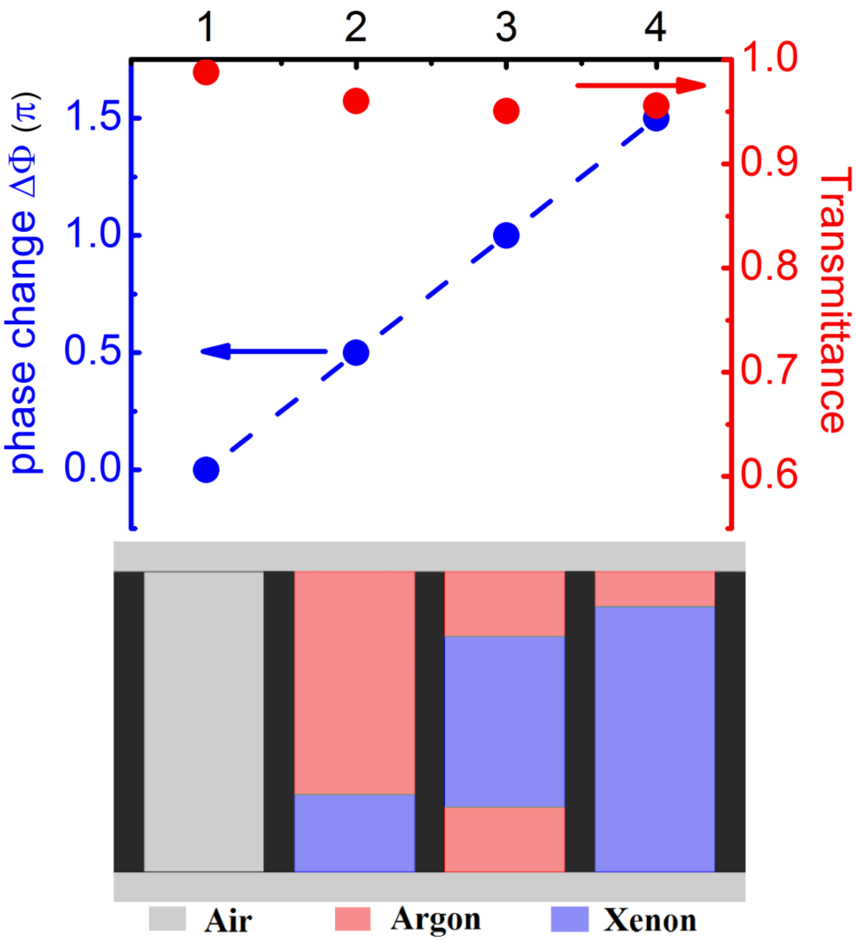
when $n_t = n_i$, we get

$$k_0 sin\theta_t - k_0 sin\theta_i = \frac{d\Phi}{dx}$$

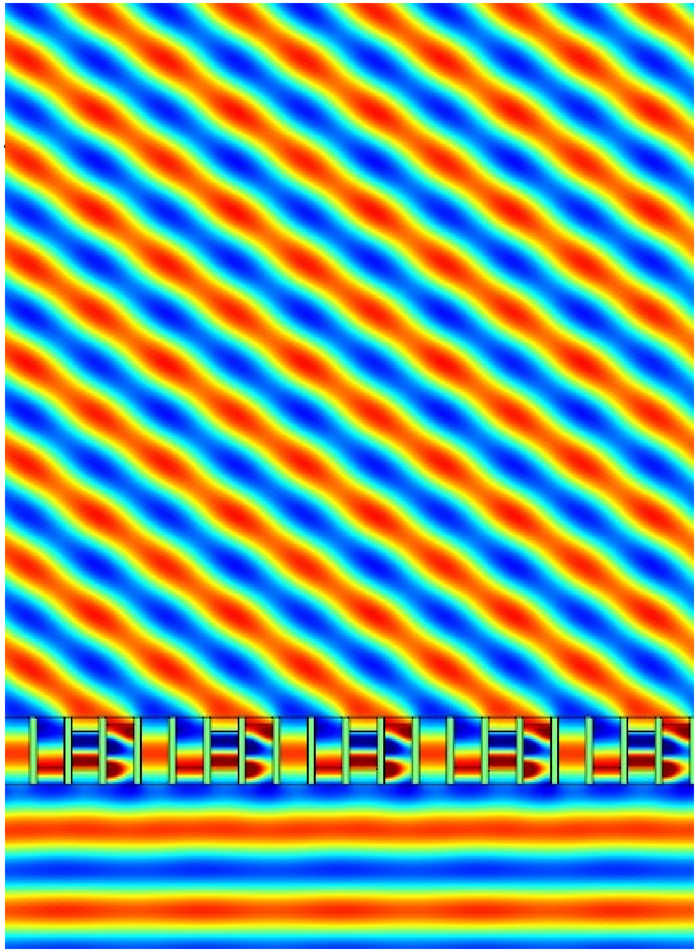
- For our metasurface $\frac{d\Phi}{dx} = \frac{2\pi}{d}$

$$\theta_t = arcsin\left(\frac{\lambda_0}{d}\right)$$

One Realization



$$h_{Arg} + h_{Xen} = h$$



$$\lambda_0 = 0.6d$$

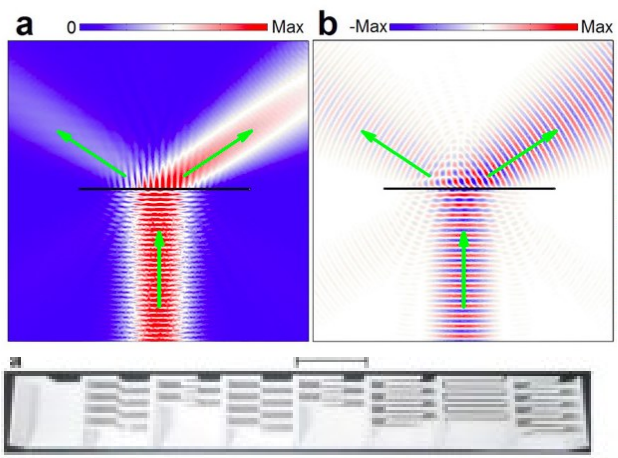
$$\Phi_i = k_{Arg} h_{Arg} + k_{Xen} h_{Xen} = \Phi_1 + (i-1)\pi/2 = k_0 h + (i-1)\pi/2$$

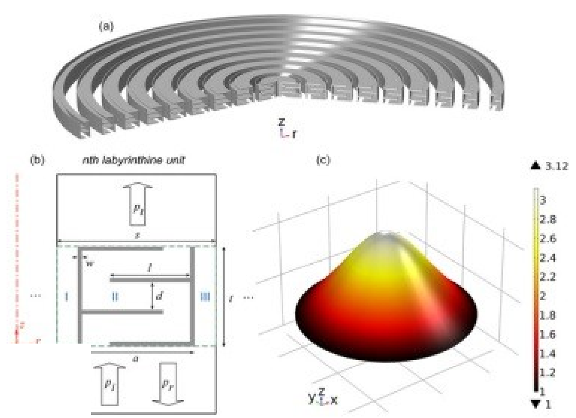
Conclusions

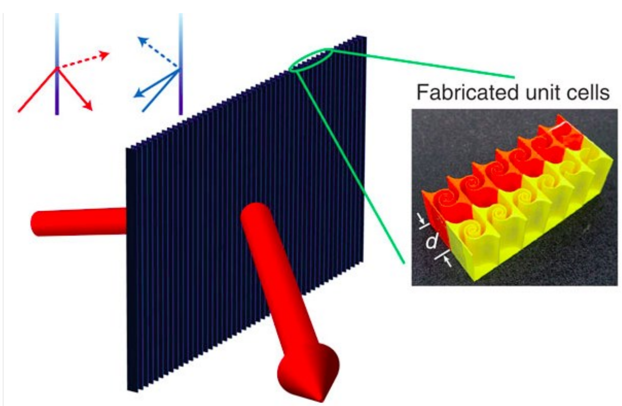
Acoustic metasurface can manipulate acoustic waves

- From normal incidence to oblique transmission or surface bound wave
- Coupled mode theory

Thank you !







Sci. Rep. 4, 6517 (2014)

Sci. Rep. 4, 6830 (2014)

Nat. Commun. 5, 5553 (2014)