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# Anomalous propagation of EM waves in structured metamaterial


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PHOTON FRONTIER NETWORK

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# Outline

- Highly conceptual discussion struggling to see the “anomalous propagation” in a “normal” way.
  - more of a 'call-for-discussion' than a talk

- To begin from the very end:

  I would like to shed more light on

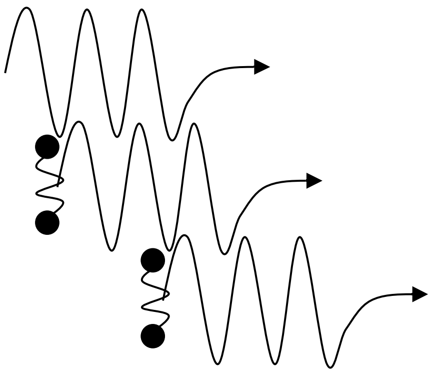
  “confined states” (resonators)

  when we talk about propagation

- views of phenomena as phase interferences of propagators & resonators

# Propagators (extended modes)

- plane waves (propagators)
  - periodic or uniform system
  - electronic: crystals: band diagram
  - photonic: permittivity and permeability

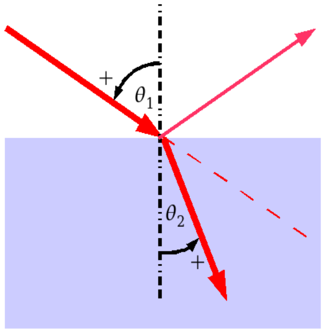


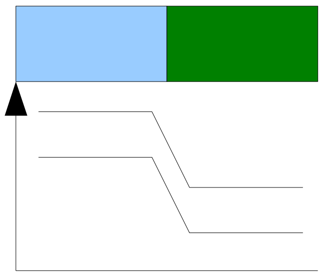
$$\epsilon = \epsilon_0 (1 + \chi)$$
$$k_0 \rightarrow k$$

- They were and are important:
  - extraction (detection) are with propagators:
    - electric currents (dc/ac), light beams
  - numerous "confined states" are renormalized into small number of propagators -> analytical soltn.
    - the rest (nearfields) of the "confined states" can be forgotten

# Boundaries

- photonic interface:
  - Snell's law, Fresnel formula, ....
    relation between propagators at the interface



- electronic interface: as in diodes
  .... more conceptual  cf. decoherence

At the bleeding edge:
  nano-optics, structured media, ultrafast dynamics ...

--- full of boundaries, in space and time

analysis involves large number of propagators:
  very-high-order components of Fourier spectra $(k, \omega)$
  and with dispersion taken into account

Why expansion, when they are accumulated again?
  ---> resonators

# Layering of resonators and propagators

Large extreme: K. Y. Bliokh *et al*, RMP **80,** 1201-1213 (2008).

- mutual layering of resonators and propagators
- Propagator: delocalized, indexed by $\boldsymbol{k}$

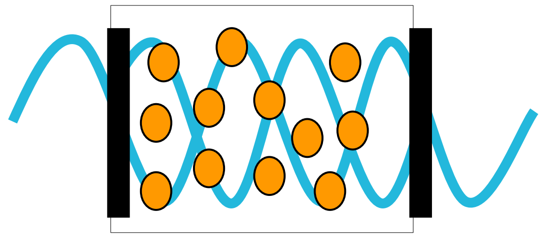
relevance for coupled state

0

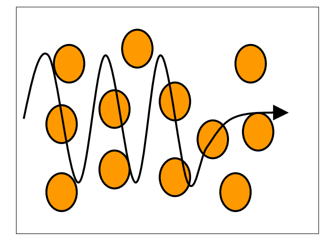
Q

∞

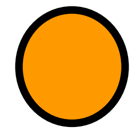
- Resonator: localized, indexed by $\omega_0$
- carriers of phase, where it is
  open - propagator
  or
  fedback - resonator



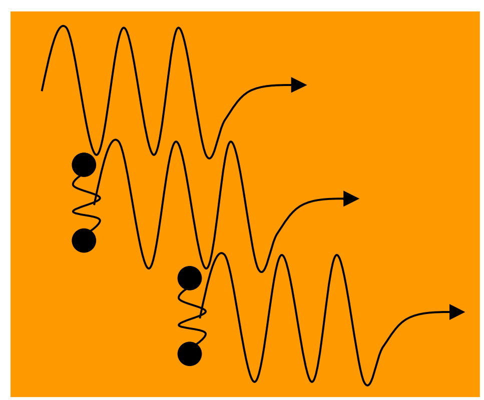
resonator: cavity



propagator: effective media

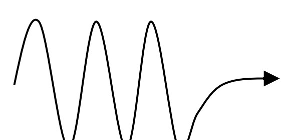


resonator: cavity

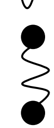


$\epsilon = \epsilon_0 (1 + \chi)$

propagator: resonator renormalized (permittivity)



propagator: incident light



resonator: Lorentz osc.

# S.Foteinopoulou (2003)

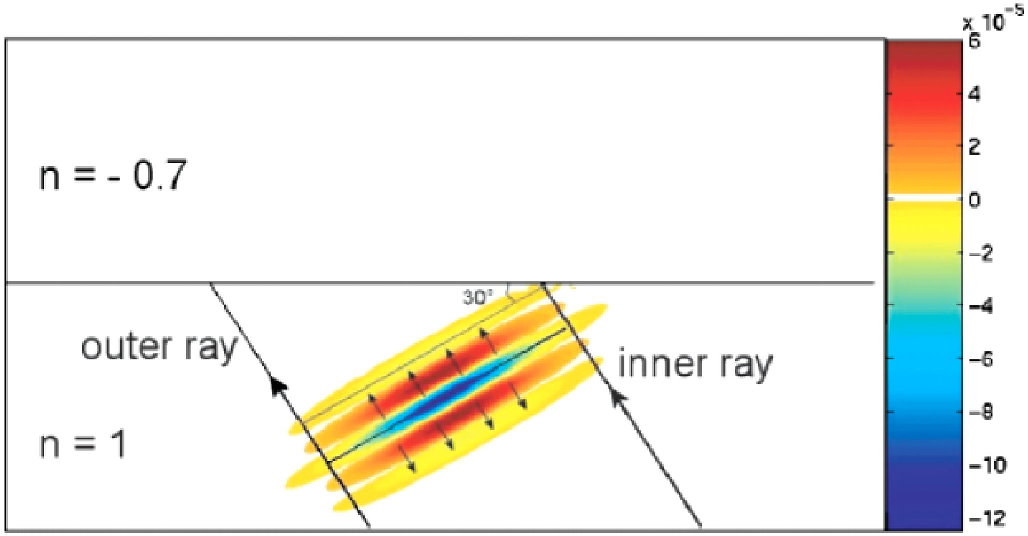
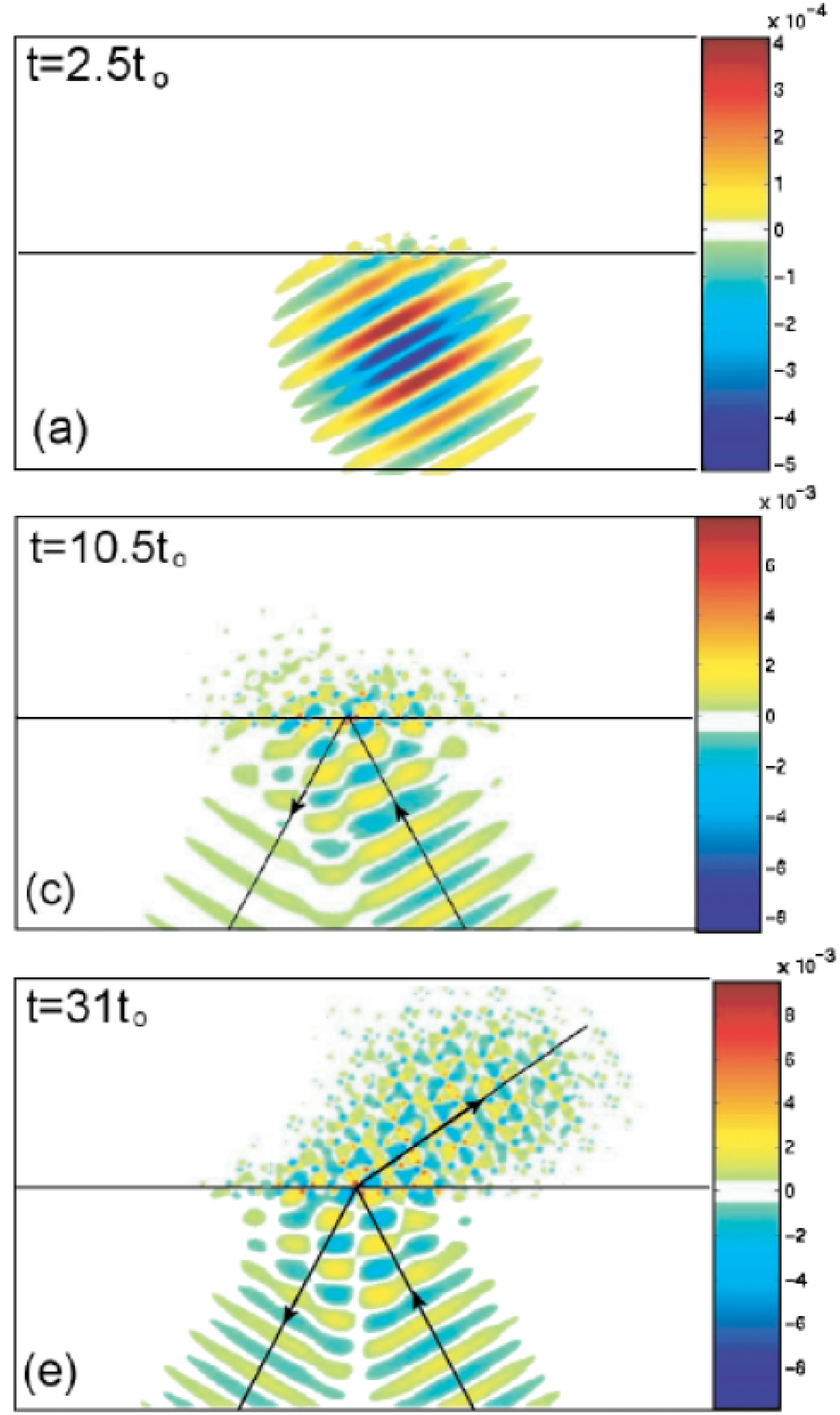



FIG. 2 (color online). An incident EM wave is propagating along a 30° direction. The time is 200 simulation steps.




S. Foteinopoulou, *et al., Phys. Rev. Lett.* **90,** 107402 (2003).

# F.J.Rachford (2002)

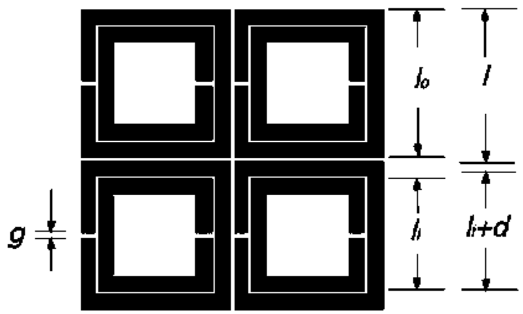



FIG. 1. Square double ring geometry. Lattice constant $l = 1.04$ cm, ring's outer dimensions $l_o = 0.99$ cm, etched linewidth 1 mm, inner ring's outer dimensions $l_i = 0.75$ cm, inter-ring gap of 0.2 mm, and ring gap $g = 0.04$ cm.

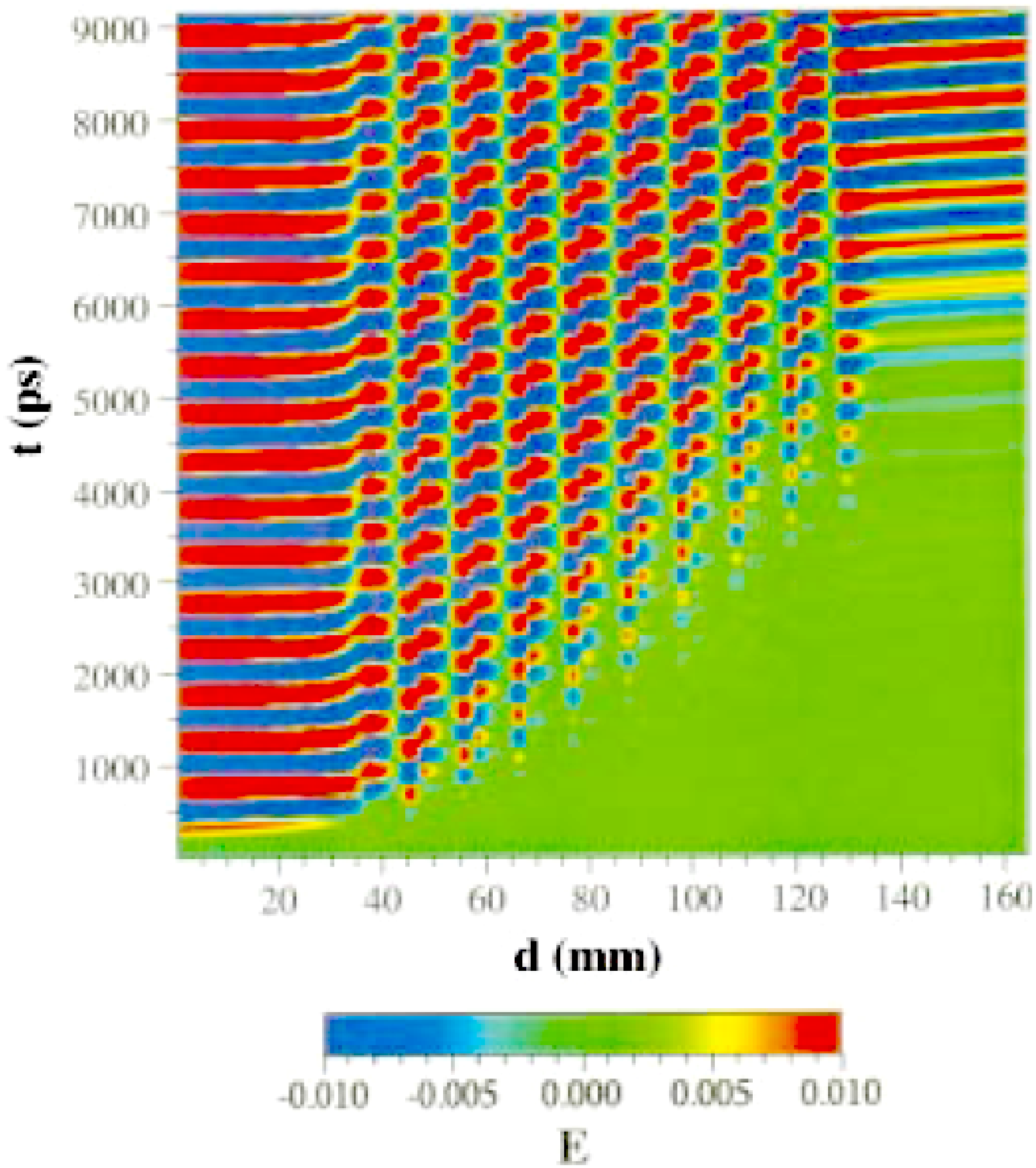



FIG. 4. (Color) Propagation of 1.96-GHz microwave radiation through our ring/wire composite media. A plane wave is assumed to enter from the left. Time is plotted on the vertical axis while distance is plotted on the horizontal axis. From 0 to 35 mm the wave is in free space. The wave enters the ring/wire medium with $E$-field polarization along the direction of the wires. It takes several cycles before the resonant response of the medium settles into a steady state. At 129 mm, the radiation exits from the medium. The color scale is saturated to highlight the position of successive $E$-field crests and troughs. In this case resonances at the ring locations are pronounced and the apparent index of refraction is ambiguous: $n = +11.8$ is for rising phase slope and $n = -3.6$ for decreasing phase slope.

F. J. Rachford, *et al.*, *Phys. Rev. E* **66,** 036613 (2002).

# Phase interference

- “Functions” of a system:
  results of interferences of phase
- Propagators do not interfere with each other:

  propagator interferes with resonators, and

  resonators interferes with multiple propagators

  - scattering, reflection, refraction...

  -> these are easier to renormalize into propagator - propagator interaction

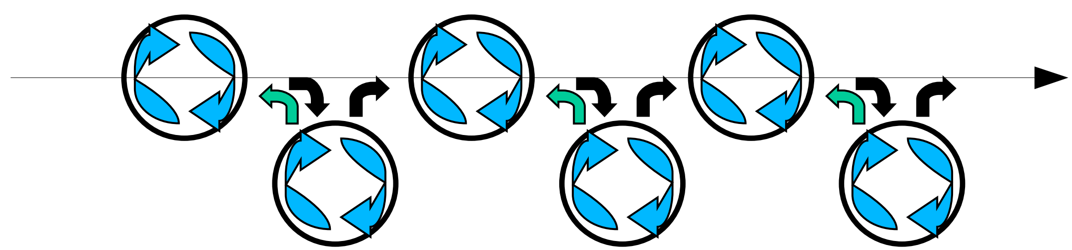
- The more interesting are:
  “double-resonator” systems

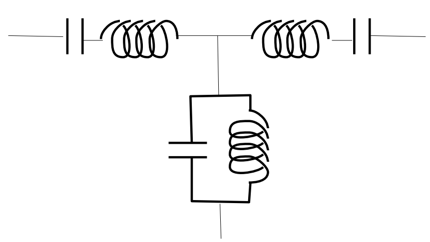
# Double resonators

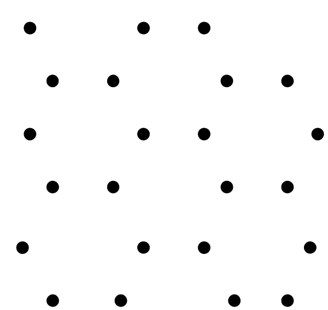
Under this framework, most of the interesting phenomena are in “double resonator” systems:

- Band crossing (in contrast to anti-crossing):
  - CRLH-Transmission line
  - electronic band structure of graphene

-> Two “tuned” resonators with different topology



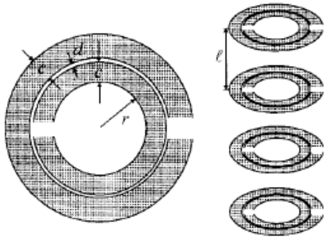




# Double resonators

- Negative refractive index
  - Split ring resonator
    - electronic (metal material)
    - photonic (ring structure)
  - Photonic crystal with backward wave
    - photonic (particle itself)
    - photonic (periodicity, Bloch, Umklapp)

J. B. Pendry, *et al., IEEE T Microw. Theory* **47,** 2075 (1999).

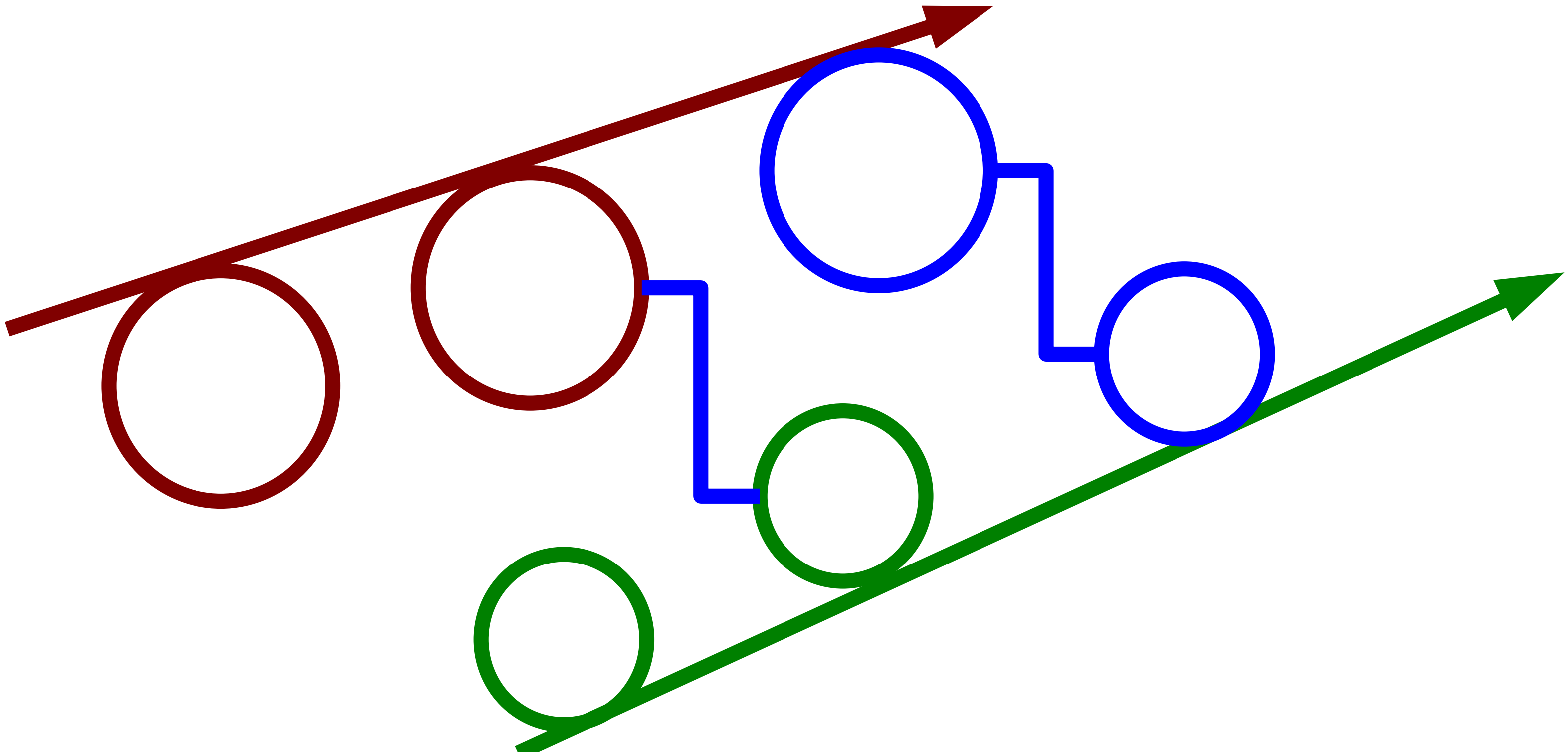


-> Two strong just-above-resonance resonators with different topology

cf: crystal themselves are “double resonance”

# “Anomalous” propagation

- “Anomalous” effects tend to occur when resonators that are renormalized into propagators independently, start to interact “directly”.
  -- renormalization order has to be inverted



# Analogies?

- Resonators
- Near-field
- Voltage
- Kinetic potentials
- Scalar potentials
- Position

⋮

- Propagators
- Far-field
- Current
- Kinetic energy
- Vector potentials
- Momentum

⋮

# Metamaterials

Metamaterials under this picture:

- Materials:
  systems with electronic resonators
- Photonic crystals:
  systems with photonic (incl. polaritonic, SPP) resonators
- Metamaterials:
  systems with electronic/photonic resonators

“Implementations” of the “abstraction” of phase-interaction network

# Terminology considerations

- electronic reso. + photonic prop. ..... polaritons?
- photonic reso. + photonic prop. ..... open cavity
- photonic reso. .... cavity, near-field photon
- electronic reso. + photonic reso. ..... ?

- resonator + propagator .... ?

# Summary

- Conventionally, we are used to work with plane waves as our base, and have learned to renormalize all other effects into this "propagator."

  "Resonators" are the counterpart to propagators, which become more insightful when the system has more "space and time boundaries" than bulk.

- The pair is a candidate to make abstraction of materials and metamaterials under the same framework, in that "function" is abstracted by phase interaction, and the "carrier" of the phase (electrons, photons, polaritons, ...) is made implementation detail.