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Wireless Power Transfer with Metamaterials

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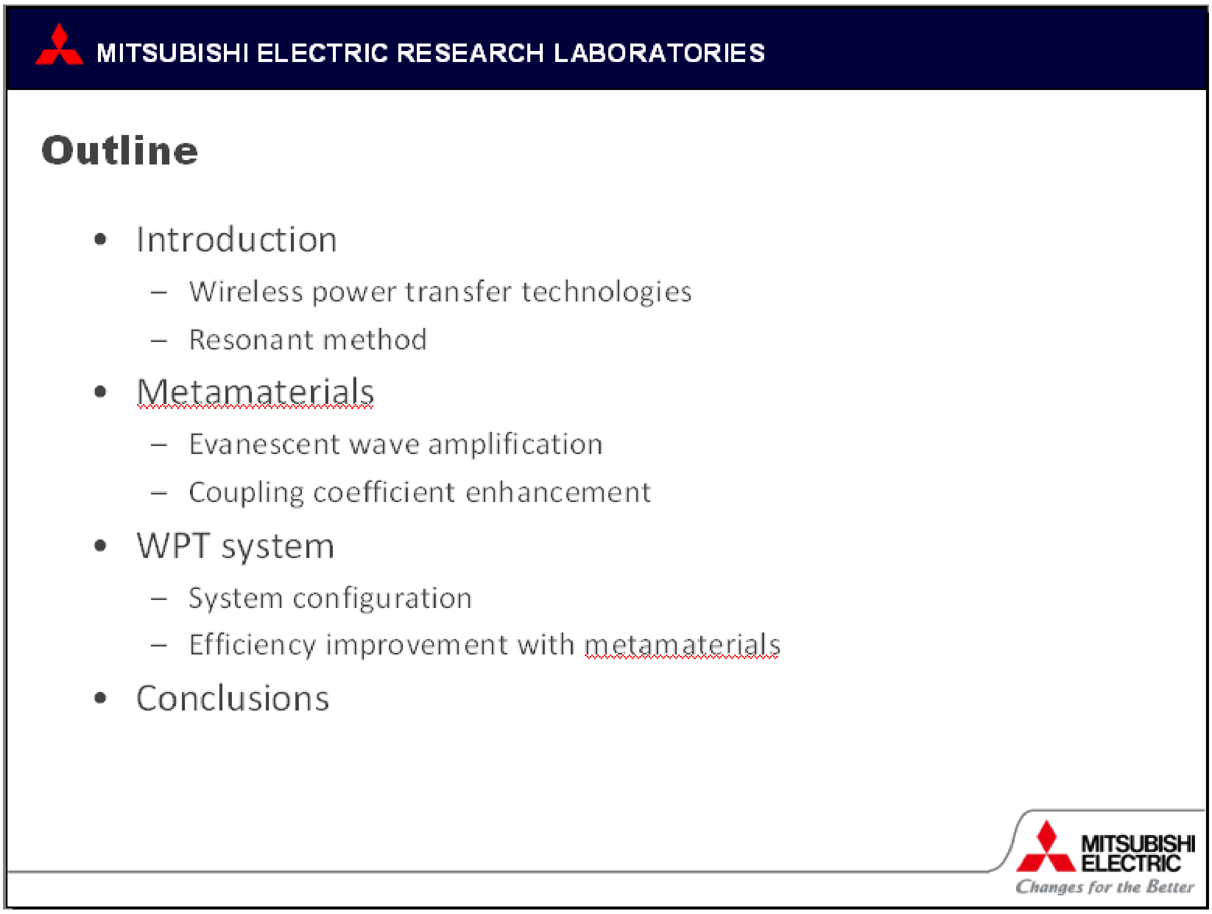
Abstract In this paper, we introduce the resonant type wireless power transfer technology and the way to enhance the efficiency by using the metamaterial between them. The theory was proven by the numerical simulation.

Keyword Wireless Power Transfer, Metamaterials, Evanescent wave, Resonant method



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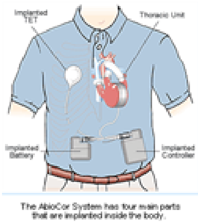
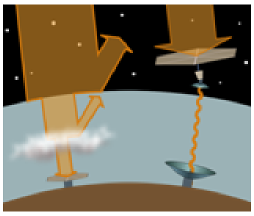
Applications of Wireless Power Transfer

- Wireless power transfer is useful for applications where wires are inconvenient or impossible
  - Provide power wirelessly to devices
  - Wireless charging





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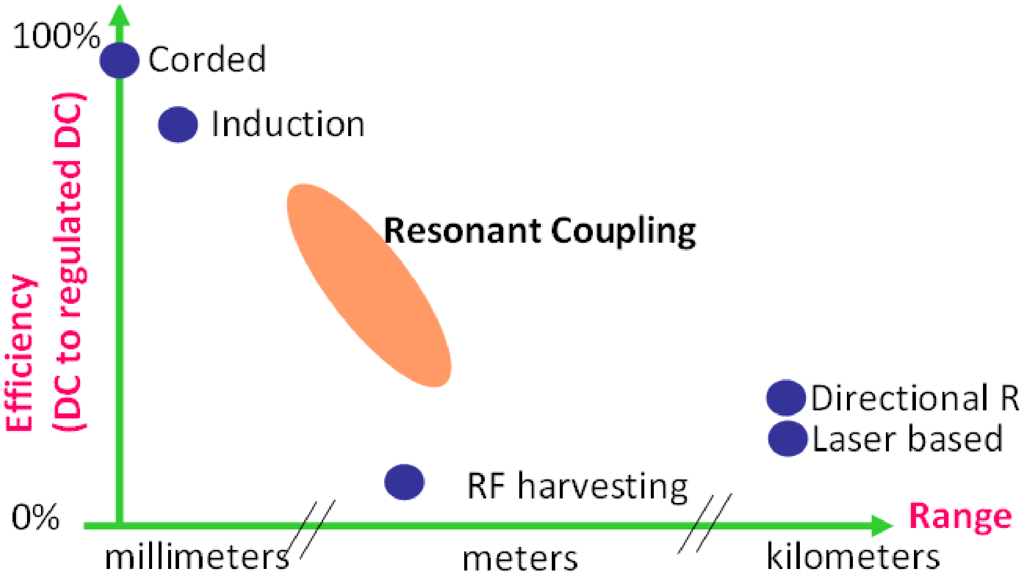
Wireless Power Transfer Technologies



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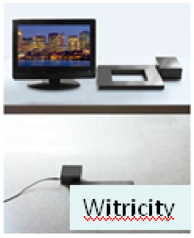
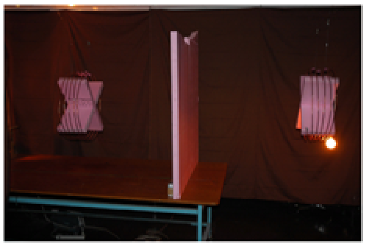
Resonant Type Wireless Power Transfer

- Proposed and experimentally demonstrated by MIT (2007)
  - Mid-range (Distance > device size)
  - Near-field coupling, non-radiative
  - Moderate efficiency (transferred 60W with efficiency~40% over a distance of ~2m)





Kurs *et al.* Science **317**, 83 (2007)

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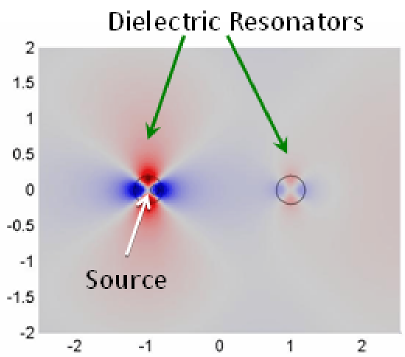
Coupled Resonators

- At resonant frequency, the system oscillates with a large amplitude, which can be excited by a small driving force
- A second resonator can be excited by a first resonator even they are far apart, thus transfer energy efficiently
- The electromagnetic energy is strongly localized within resonators: non-radiative
- The electromagnetic wave outside resonators decays exponentially: evanescent wave
- Keys to efficient transfer
  - High-Q resonators to reduce ohmic and radiation loss
  - Improve the coupling coefficient



Field distribution of the resonant coupling between two dielectric resonators

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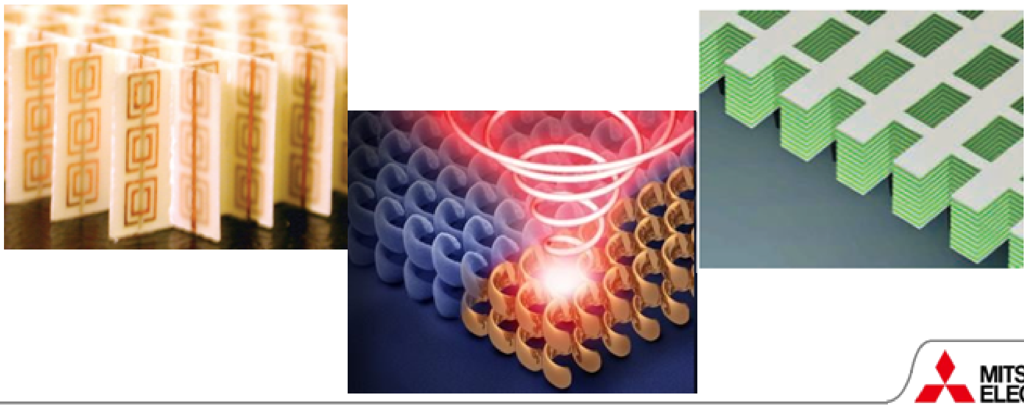
Introduction to Metamaterials

- Metamaterials are artificially engineered structures that have properties not attainable with naturally occuring materials
- The structure size in metamaterials are much smaller than the driving wavelength
- The pecculiar properties of metamaterials come from the response of the artificial structures instead of the constituting materials



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Negative Index of Refraction

$$\bar{k} \times \bar{E} = \omega\mu_0\mu\bar{H}$$
$$\bar{k} \times \bar{H} = -\omega\varepsilon_0\varepsilon\bar{E}$$

Poynting vector

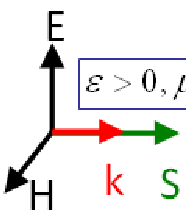
$$\bar{S} = \bar{E} \times \bar{H}$$

Maxwell's equations allow two propagation regions

$$k^2 = \omega^2\varepsilon\mu > 0$$

ε: permittivity
μ: permeability

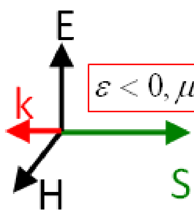
k: wave vector
ω: angular frequency
E: electric field strength
H: magnetic field strength



$$\varepsilon > 0, \mu > 0$$

Phase change in same direction as energy flux

n>0



$$\varepsilon < 0, \mu < 0$$

Phase change in opposite direction to energy flux

n<0

n: index of refraction

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Negative Index of Refraction

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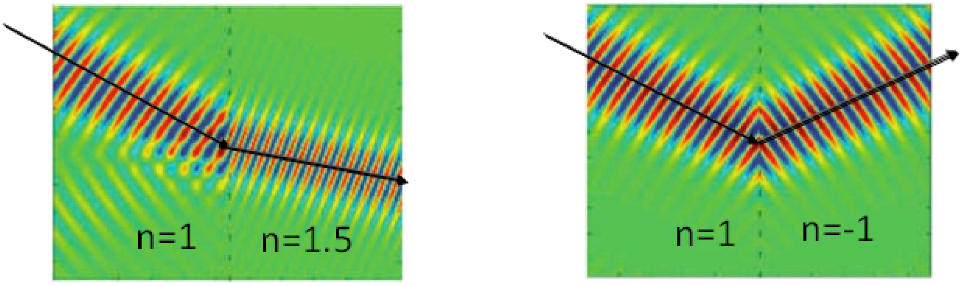

n: index of refraction

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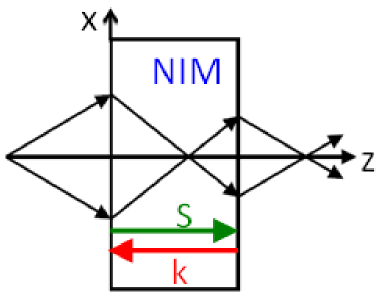
Evanescent Wave Enhancement

Negative-index metamaterial (NIM):
Double negative with both ε <0 and μ <0

$$\varepsilon = -1, \mu = -1$$
$$n = -\sqrt{\varepsilon\mu} = -1$$

Propagating wave components refract negatively at the interfaces, form two focusing points.

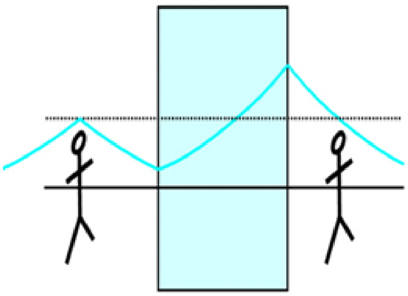


Near-field evanescent wave decays in the propagating direction

$$k_z = i\sqrt{k_x^2 + k_y^2 - \frac{\omega^2}{c^2}}, \frac{\omega^2}{c^2} < k_x^2 + k_y^2$$

Transmission coefficient for near-field

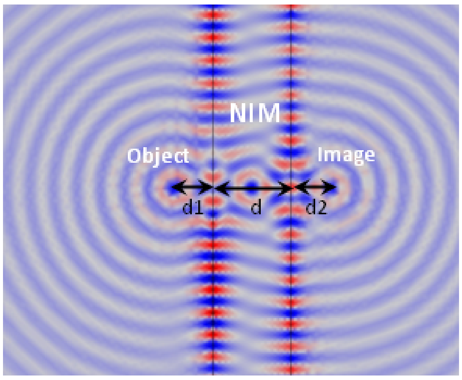
$$\lim_{\varepsilon,\mu \to -1} T_S = e^{-ik_z' d} = \exp(\sqrt{k_x^2 + k_y^2 - \omega^2/c^2}d)$$



Exponential increase in the NIM slab!

J.B.Pendry, Phys. Rev. Lett. 85, 3966 (2000)

NIM and Perfect Imaging

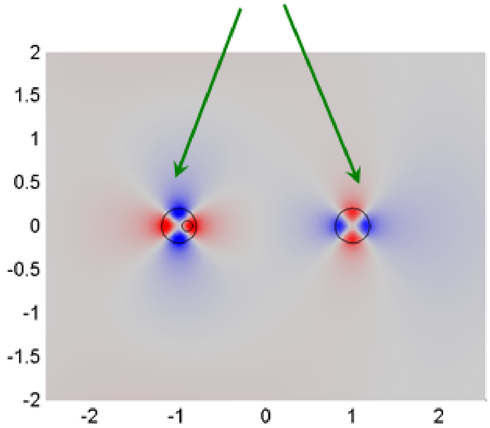


Perfect imaging with NIM lens:
Distance of image to source is exactly 2d

- Both propagating wave and evanescent wave components are recovered as the image: perfect image
- Effectively, the lens laterally transports the object to the other side of the lens
- Metamaterials could increase the coupling of resonators by making them virtually closer!

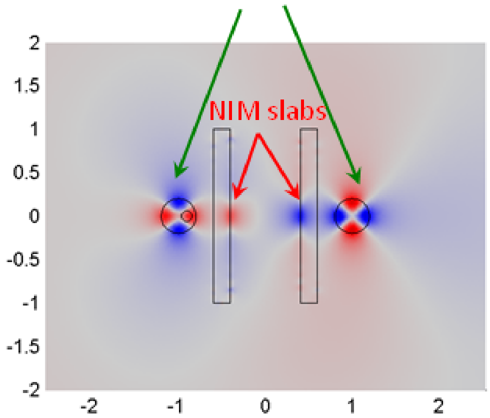
Enhanced Coupling with NIMs

Resonators



Resonant coupling of two dielectric resonators

Resonators



Resonant coupling of two dielectric resonators with metamaterial slabs

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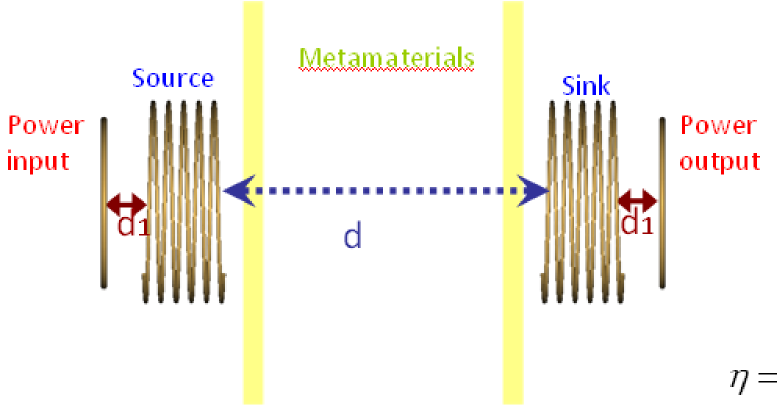
Wireless Power Transfer System



$$\eta = \frac{P_{out}}{P_{in}}$$

Start with the MIT demo system, and add metamaterials in.
System works at 10 MHz

d: Transfer distance between source and sink;
d1: Distance between small supply/load loop and source/sink coil.

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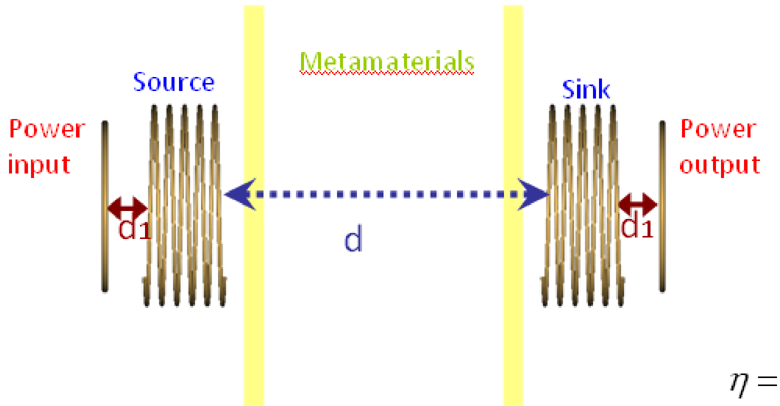
Wireless Power Transfer System



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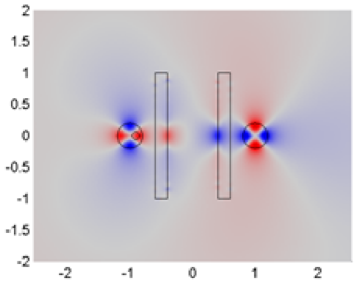
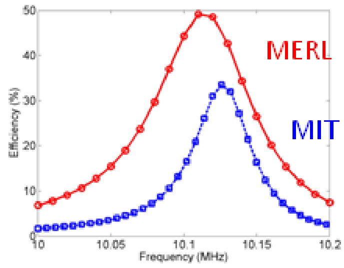
Conclusions

- Investigated the background of resonant type wireless power transfer
- Proposed the use of metamaterials to improve the transfer efficiency
- Showed the coupling coefficient and transfer efficiency improvement with metamaterials by theory and numerical simulations





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