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Tunable Metamaterial-Inspired Resonators for Optimal Wireless Power Transfer Schemes

A. X. Lalas[1], N. V. Kantartzis[1], **T. T. Zygiridis**[2], T. P. Theodoulidis[3]

1. Dept. of Electrical & Comp. Engineering, Aristotle Univ. of Thessaloniki, Thessaloniki 54124, Greece
2. Dept. of Informatics & Telecomm. Engineering, Univ. of Western Macedonia, Kozani 50131, Greece
3. Dept. of Mechanical Engineering, Univ. of Western Macedonia, Kozani 50132, Greece

Motivation and goal

Motivation:

- **Wireless power transfer (WPT)** is considered as a rapidly evolving technology with several stimulating applications.
- **Metamaterials** exhibit extraordinary electromagnetic properties not available in nature.
- WPT systems involve **coupled** magnetic resonances **similar to** those observed in metamaterials.

Objective:

Exclusive exploitation of several **split-ring resonators (SRRs)** as the fundamental resonating elements of a WPT system in an effort to accomplish **enhanced** levels of **power transfer efficiency**.

Wireless power transfer system

Apparatus to transfer energy **wirelessly** between a power source and a consuming device **without physical connection** of solid wires or conductors.

Categories of WPT

Non-radiative (Near field)

- Inductive coupling
- Strongly coupled magnetic resonance

Radiative (Far field)

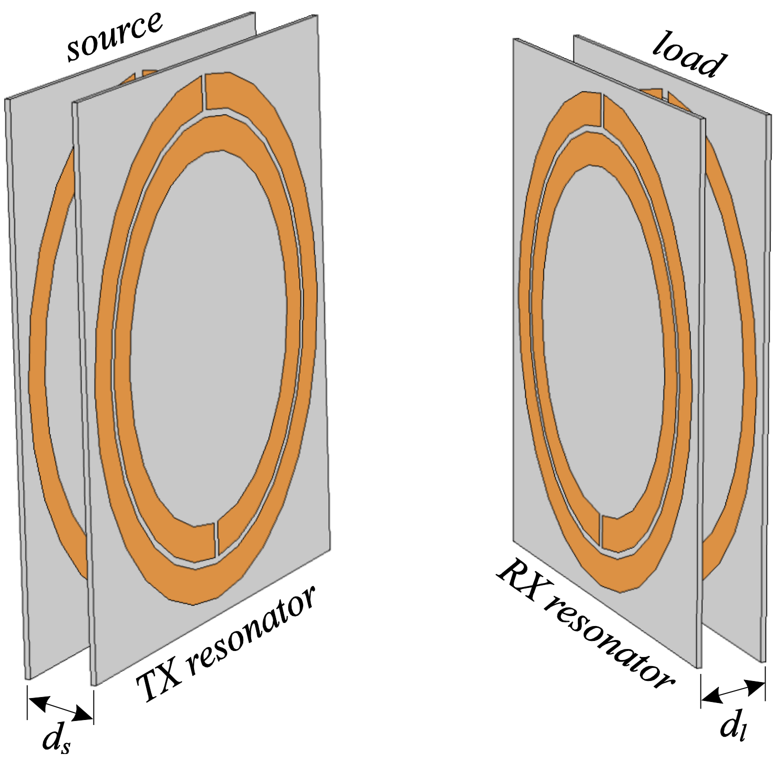
- Microwaves (Rectennas)
- Laser beams

Wireless power transfer system

Strongly coupled magnetic resonance technique provides useful power transfer efficiency at **mid-range distances** through the employment of **evanescent waves**.

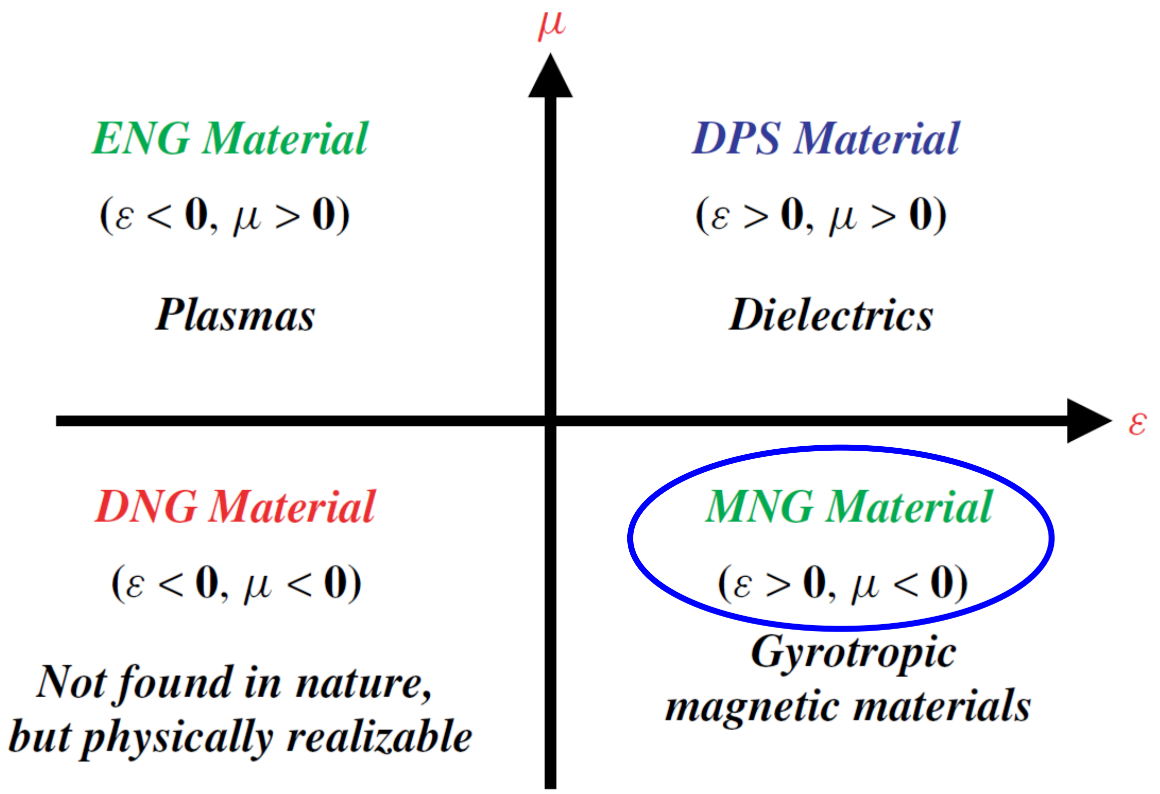
Basic WPT components

- Source loop
- Transmitting (Tx) resonator
- Receiving (Rx) resonator
- Load loop



Metamaterial basics

Characterization of metamaterials

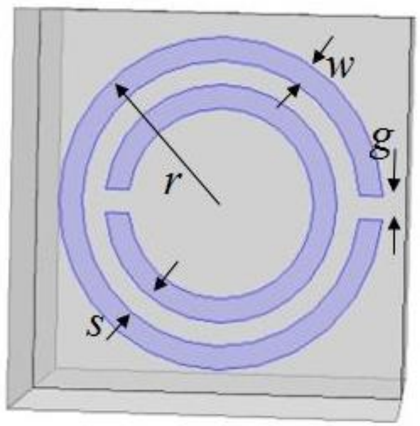


MNG materials involve magnetic resonances that can be used for wireless power transfer.

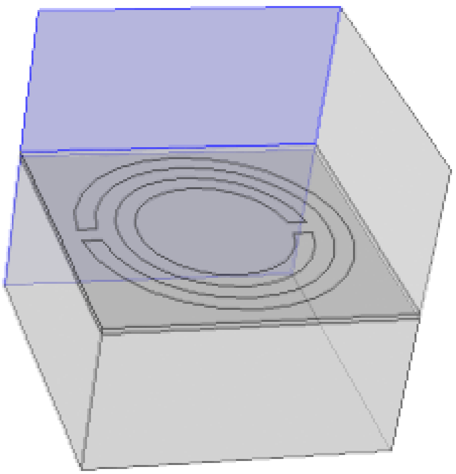
Edge-coupled split-ring resonator (EC-SRR) – Characterization

Retrieval of effective constitutive parameters via COMSOL

Geometry

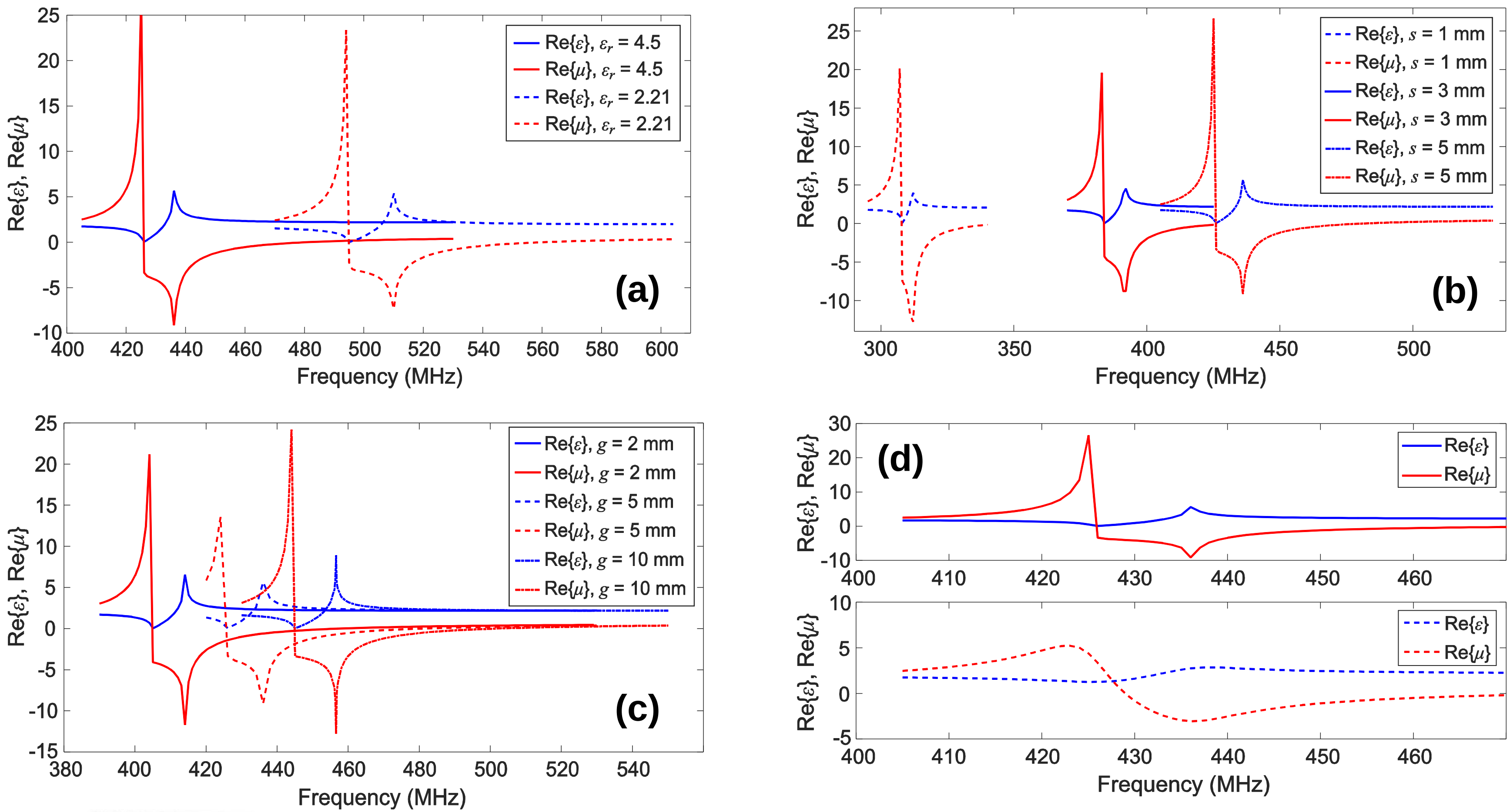


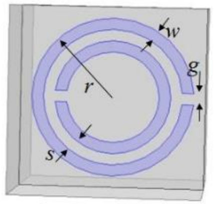
Unit cell



- Typical dimensions: $r = 35$ mm, $w = g = s = 5$ mm.
- The resonance frequency can be estimated via an equivalent LC circuit. We extract the **shift** of the resonance frequency for different dimensions and dielectric slab properties.
- The effective constitutive parameters are retrieved via a homogenization technique.
- These SRRs are then placed as **resonators** in the featured WPT system, which is excited at the region of the estimated **optimal frequency**, with the expectation to exhibit a high performance in this region.
- So, a parametric sweep for various dimensions or media characteristics unveils the **stability** of the **efficiency level** under changes in the environment of the system.

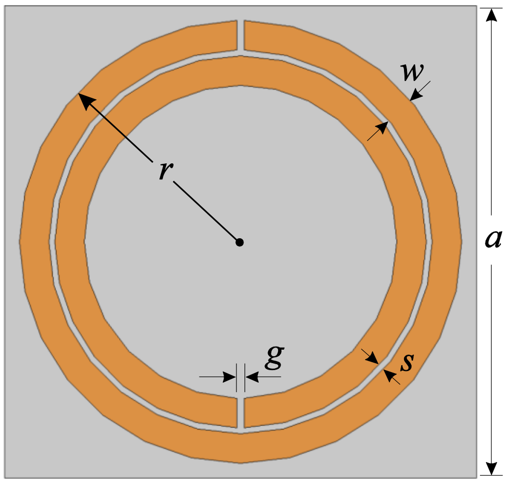
Edge-coupled split-ring resonator (EC-SRR) – Effective parameters





Real parts of the EC-SRR effective constitutive parameters for diverse dimensions and substrate characteristics. **(a)** ε_r, **(b)** s, **(c)** g, and **(d)** lossless and lossy (FR4; σ = 0.004 S/m) substrate with the same ε_r = 4.5.

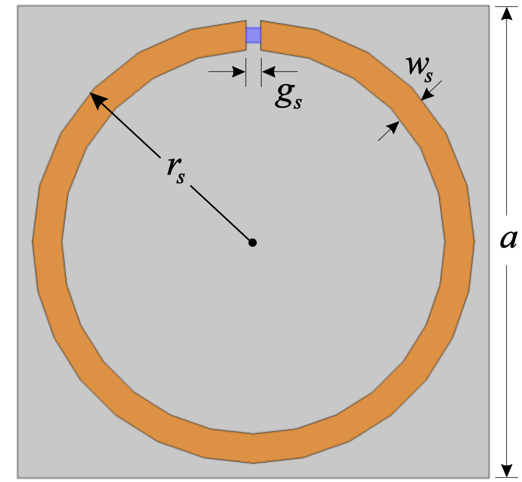
Edge-coupled split-ring resonator (EC-SRR) – Design parameters



The EC-SRR

A capacitance between adjacent loops is created due to the edge-coupled geometry

Transfer power to Tx resonator and retrieve power from the Rx resonator via inductive coupling



Source/load loops

Implementation materials

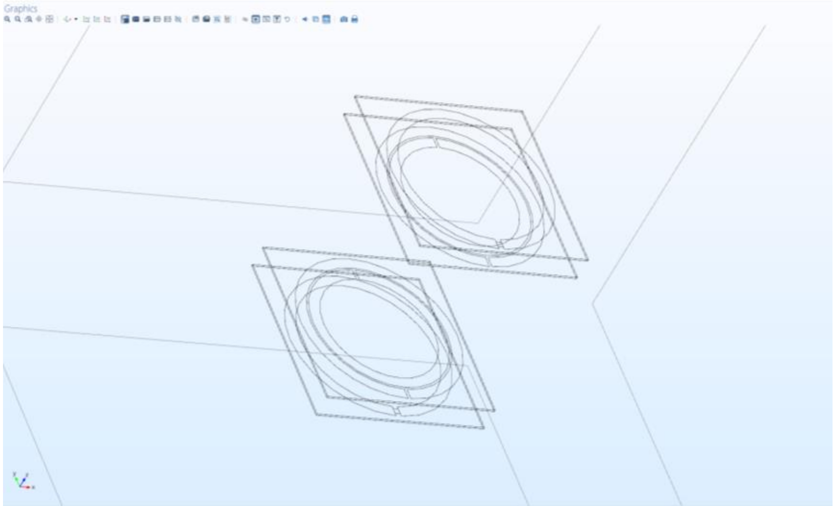
Metal parts: Copper
Dielectric material:
Taconic™ TLY5 substrate

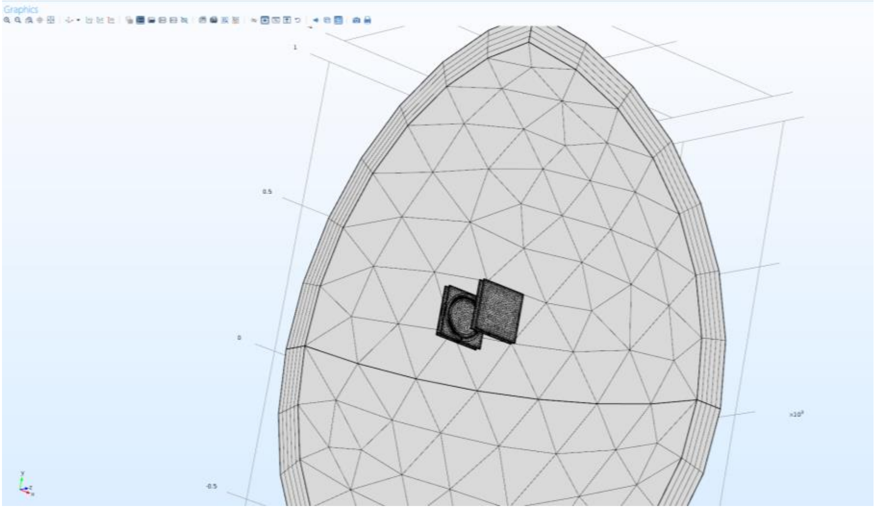
Design parameters

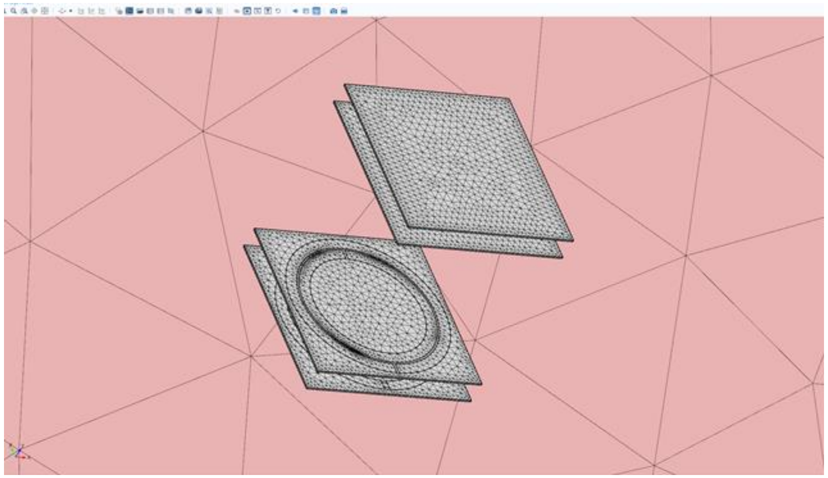
$r = r_s = 75$ mm, $w = w_s = 10$ mm,
$g = g_s = 2.5$ mm, $s = 2$ mm,
$a = 160$ mm, $d_s = d_l = 20$ mm

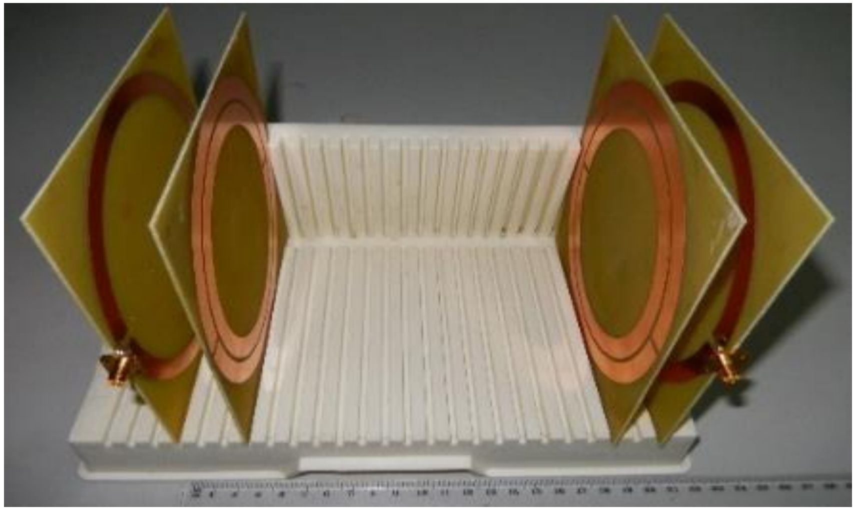
Performance described an equivalent **LC network**

Edge-coupled split-ring resonator (EC-SRR) – Modelling/fabrication

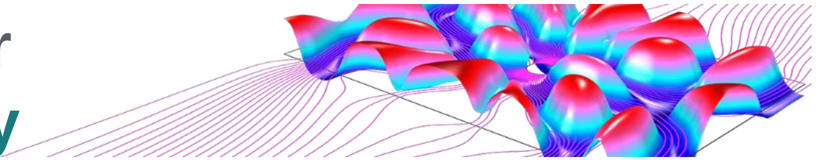


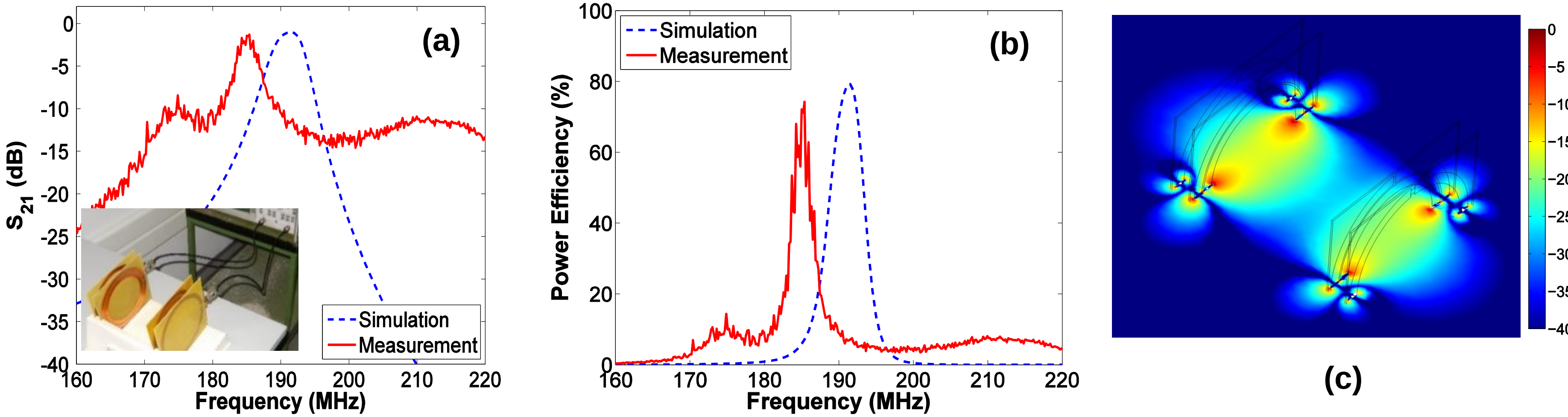




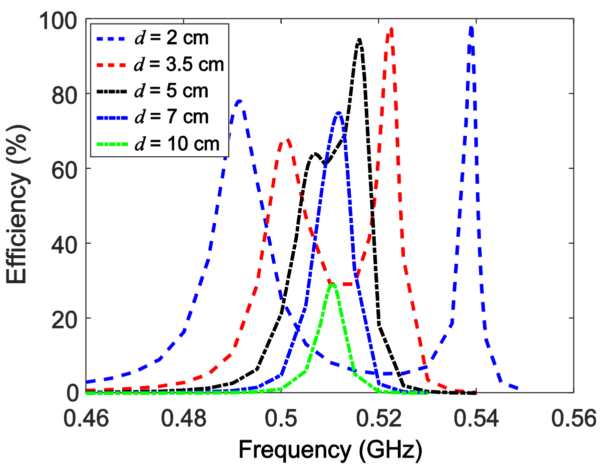


Edge-coupled split-ring resonator (EC-SRR) – Results and efficiency

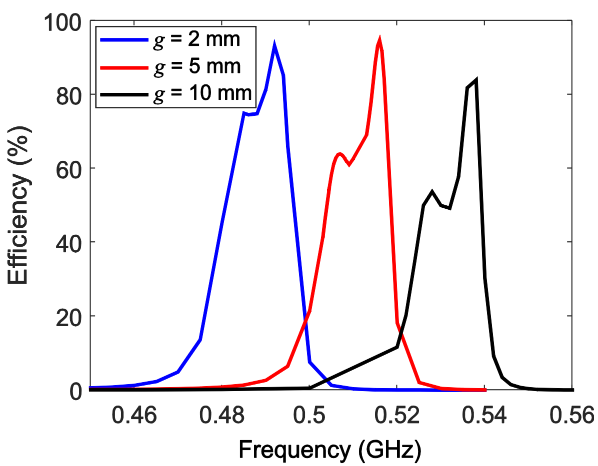




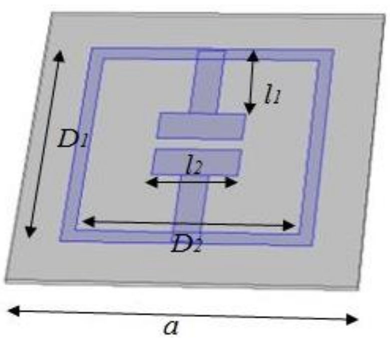
Performance of the proposed metamaterial-based WPT device in terms of **(a)** the S_{21}-parameter (inlet photo: measurement setup), **(b)** power efficiency, and **(c)** magnetic field intensity (in dB) at 191 MHz.

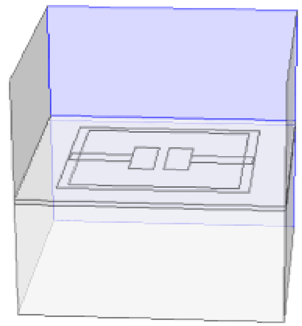


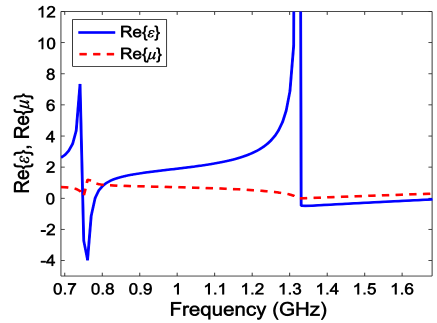
- **Very satisfactory** for most cases, exceeding the level of **80%** or even reaching the promising value of **99.03%** for $d = 2$ cm.
- The structure is suitable for **small/ medium** distances (up to 7 cm).

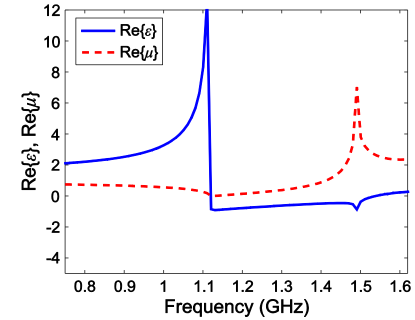


E2 SRR – Alternative design

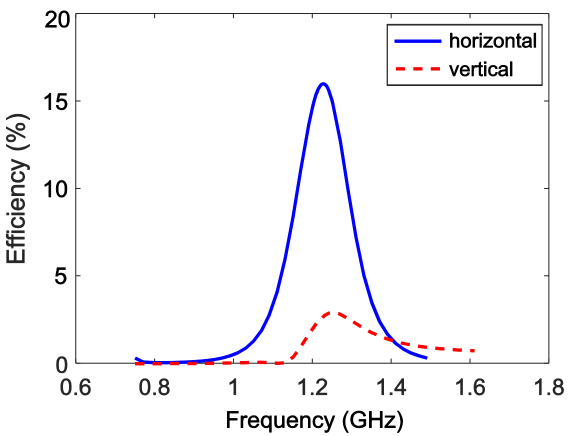






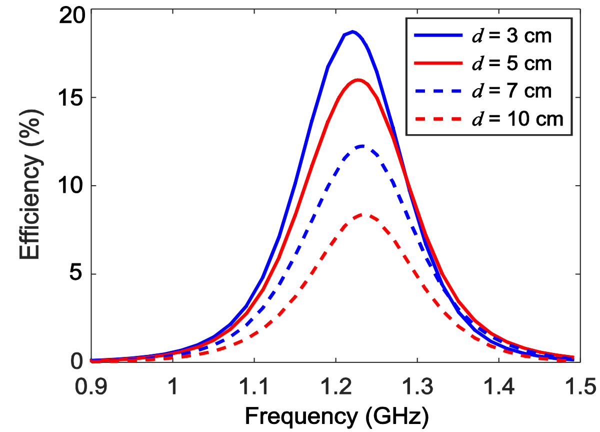


The E2 SRR and the unit cell. It can be excited either through the blue face (horizontal polarization) or the shaded face (vertical polarization). Effective constitutive parameters for a horizontally and a vertically polarized excitation.



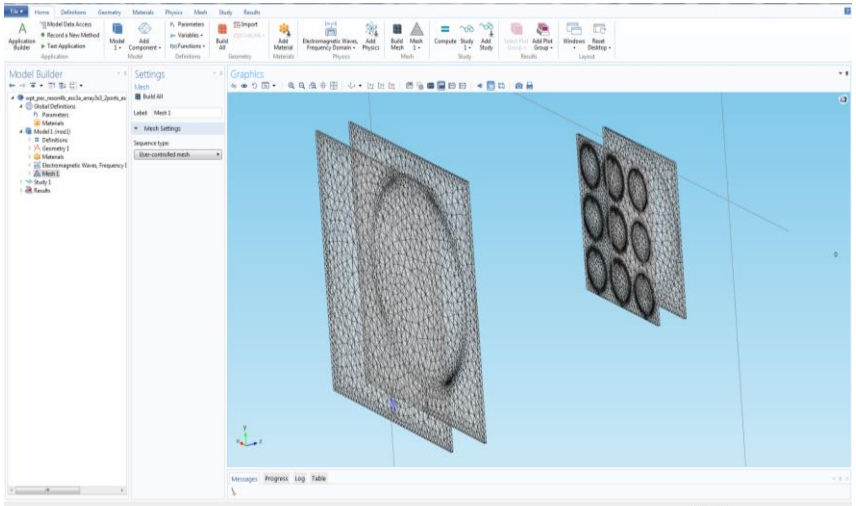
Main dimensions

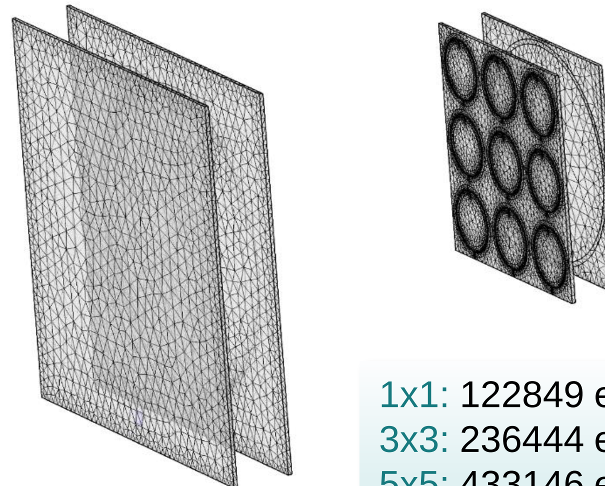
$D_1 = 57.6$ mm, $D_2 = 51.2$ mm,
$l_1 = 19.2$ mm, $l_2 = 20$ mm,
$\alpha = 8$ cm,



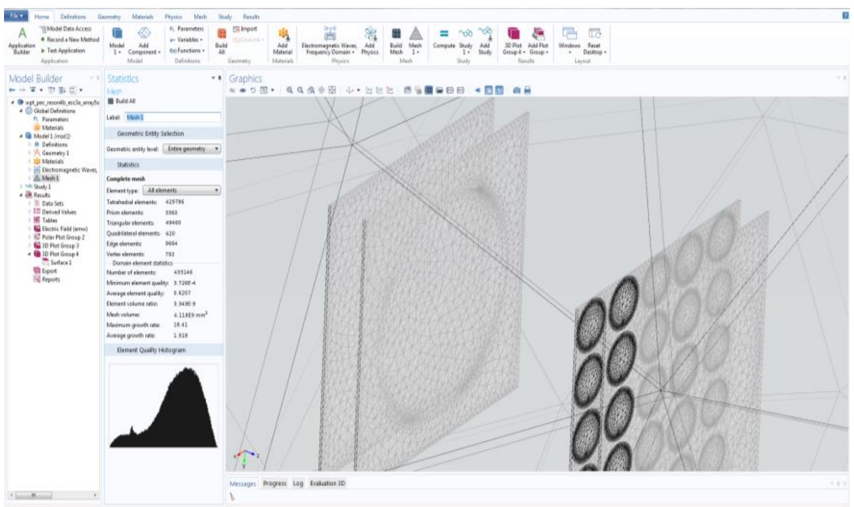
Rather small efficiency (not exceeding 19%), confirming initial expectations.

Efficiency enhancement via metasurfaces – Modeling



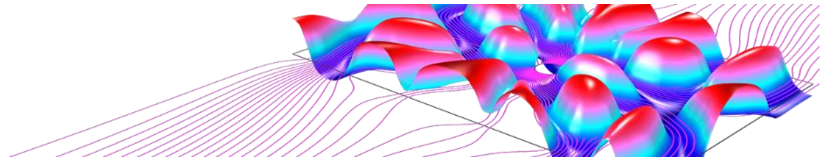


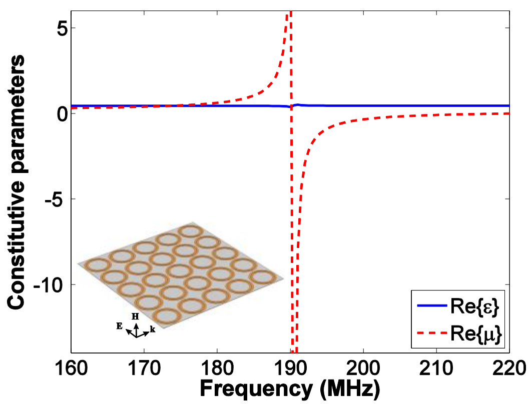
1x1: 122849 elements
3x3: 236444 elements
5x5: 433146 elements

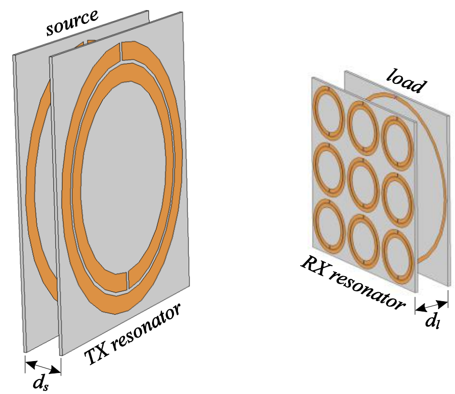


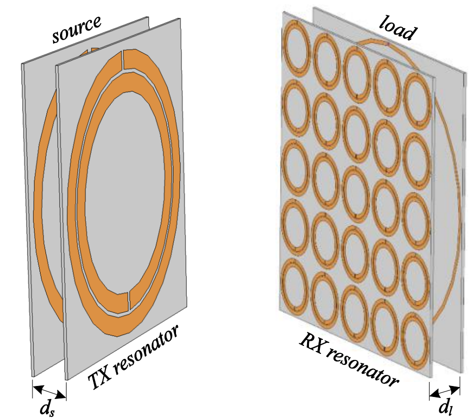
- The properties of the WPT system can be further improved via **metasurfaces**, i.e. planar periodically-repeated metamaterial structures.
- As compact dimensions constitute a critical issue in WPT research, our initial efforts concentrate on the **minimization of the Rx component**.
- So, we obtain the magnitude of the ***S_{21}*-parameters** and the **power transfer efficiency** of the featured structures.

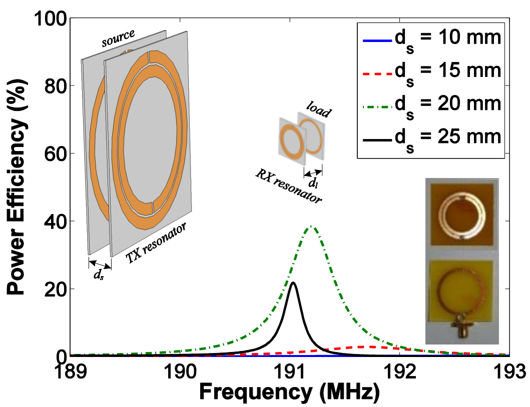
Efficiency enhancement via metasurfaces – Comparison

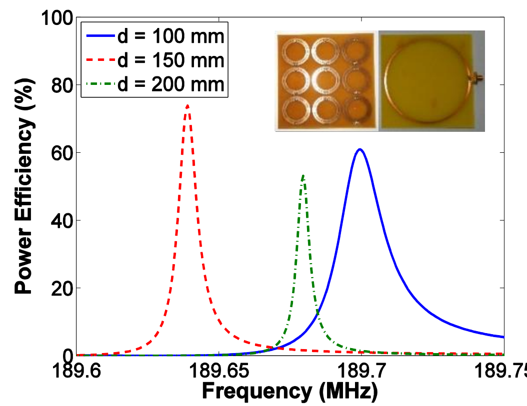


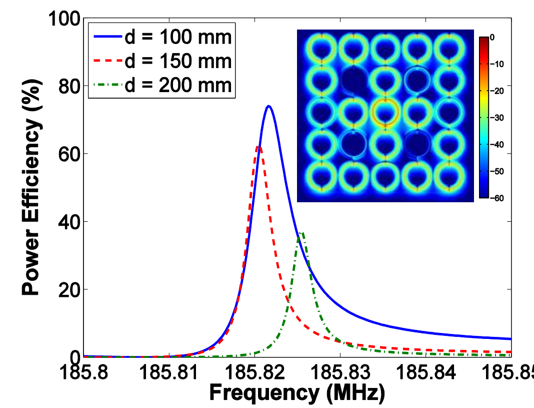










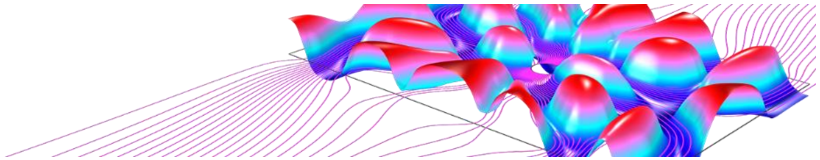


1x1 EC-SRR metasurface
(a) Constitutive parameters real parts and (b) power efficiency of the WPT system

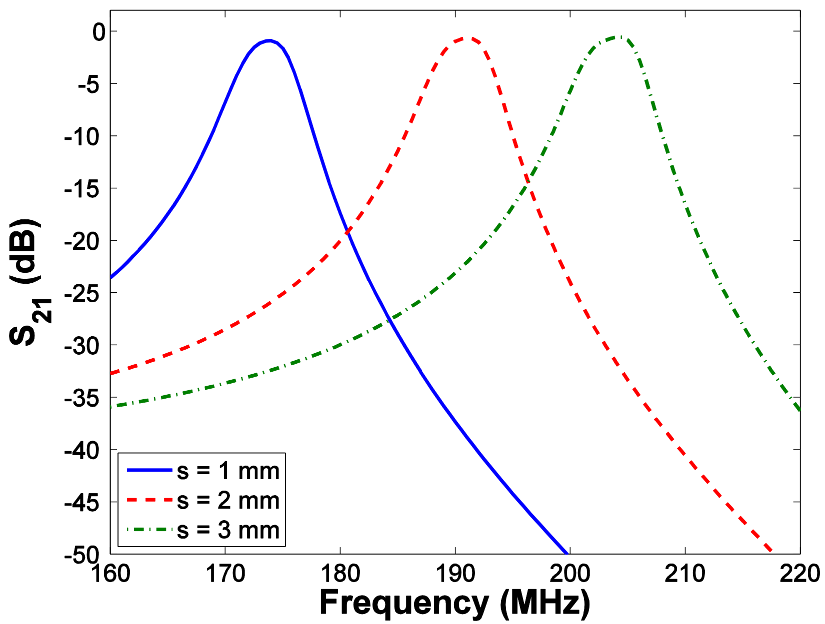
3x3 EC-SRR metasurface
(a) Setup of the device and (b) power efficiency of the WPT system

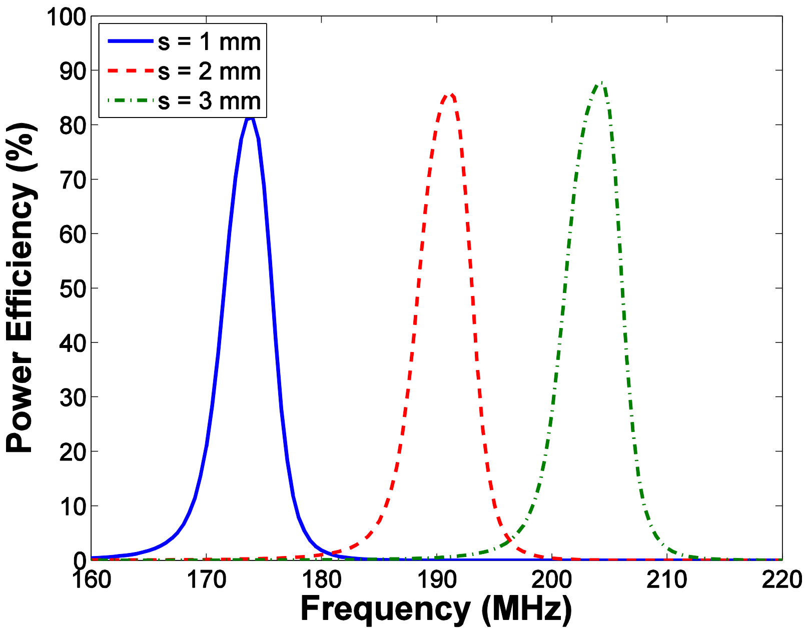
5x5 EC-SRR metasurface
(a) Setup of the device and (b) power efficiency of the WPT system

Efficiency enhancement via metasurfaces – Results

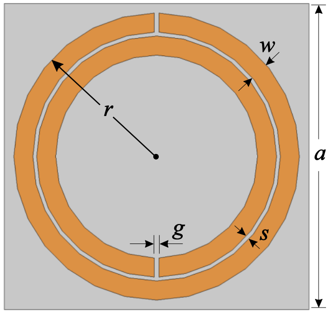


Investigation on the **variation of distance *s*** of the gap between the adjacent loops

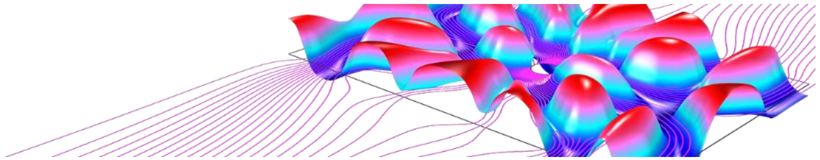




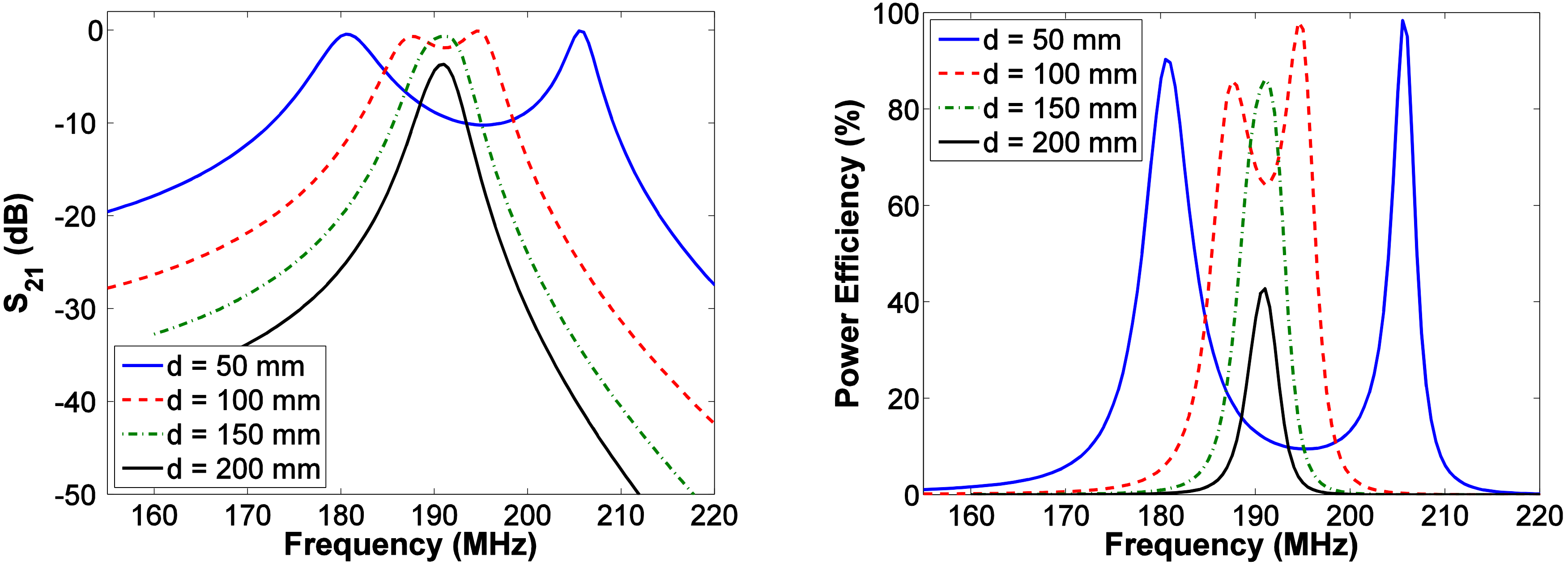
- A frequency shift towards greater frequencies is discerned, when *s* **increases**.
- The length of the gap can be used to establish the operational frequency of the WPT device.



Efficiency enhancement via metasurfaces – Results

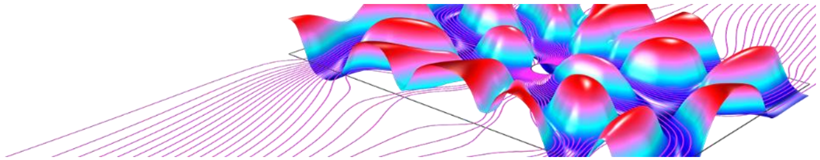


Investigation on the **variation of distance *d*** between the Tx and Rx components of the system

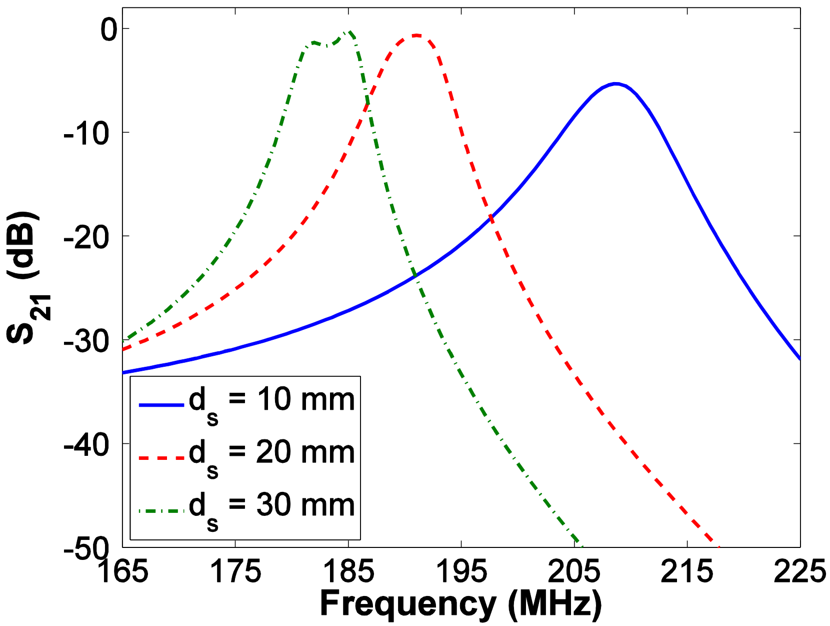


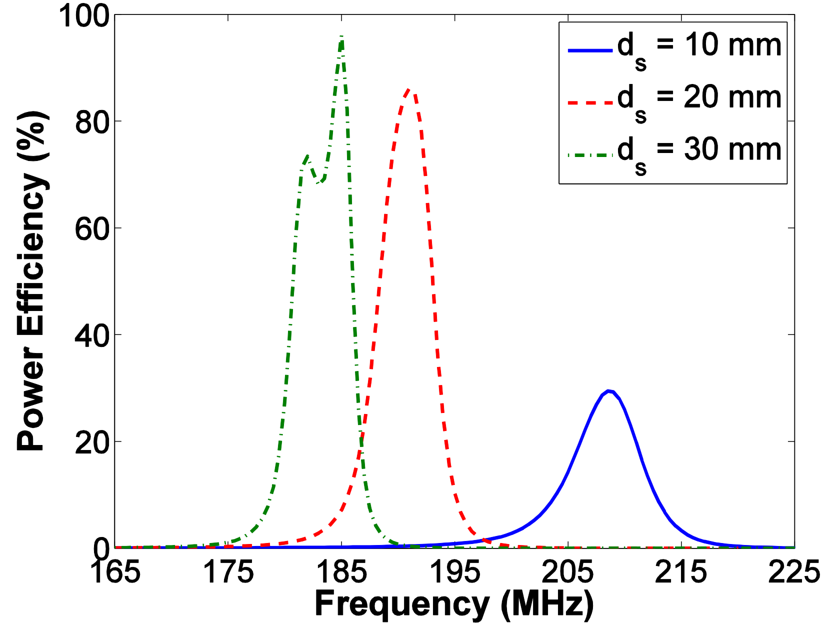
- Two discrete frequencies of maximum efficiency are discerned, when the resonators are close enough.
- Transfer efficiency levels are decreased when *d* **augments**.

Efficiency enhancement via metasurfaces – Results

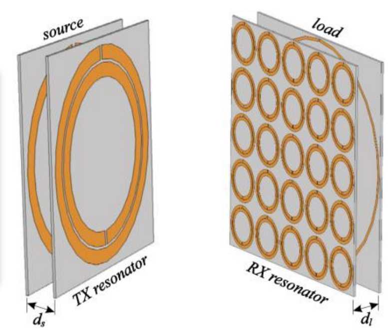


Investigation on the **variation of distance d_s** between the source, or load, loop and the EC-SRR

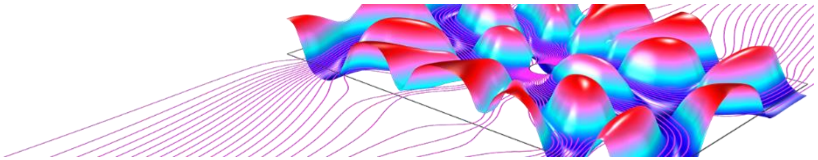




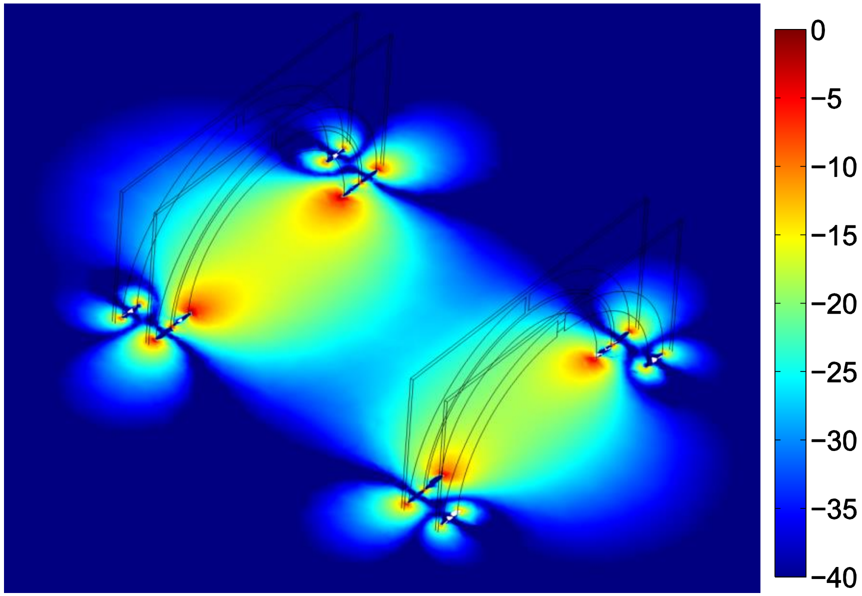
- A frequency shift towards lower frequencies is observed, when d_s **increases**.
- The resonance is replaced by two discrete resonances, while the maximum **power efficiency is enhanced**.
- Tuning of d_s affects the matching of the input and output ports of the system.

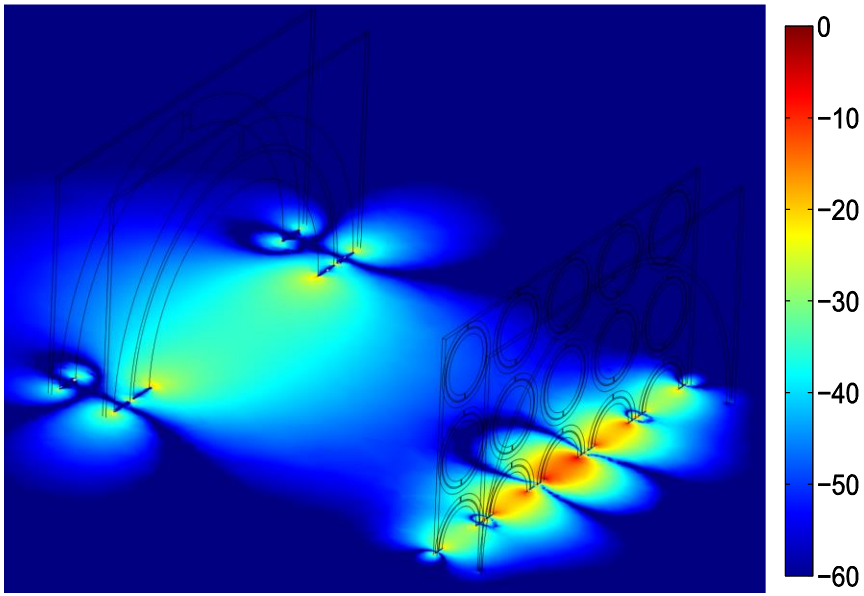


Efficiency enhancement via metasurfaces – Results



Magnetic field snapshots





Maximum values observed in the area of the resonators

Conclusions and future aspects

- A novel design incorporating various SRRs into a WPT system has been successfully proposed, achieving enhanced energy delivered to the load and eliminating lumped element restrictions.

- Additional overall efficiency has been attained via metasurfaces.

- The properties of the proposed device enable its potential employment in realizing several implementations.

- Future investigation involves modeling of multiple Tx and Rx components.

- A detailed study extended in more complex metamaterial resonators.