# 메타구조 기반의

# 고효율 무선전력전송 공진기 설계

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경북테크노파크

무선전력전송기술센터

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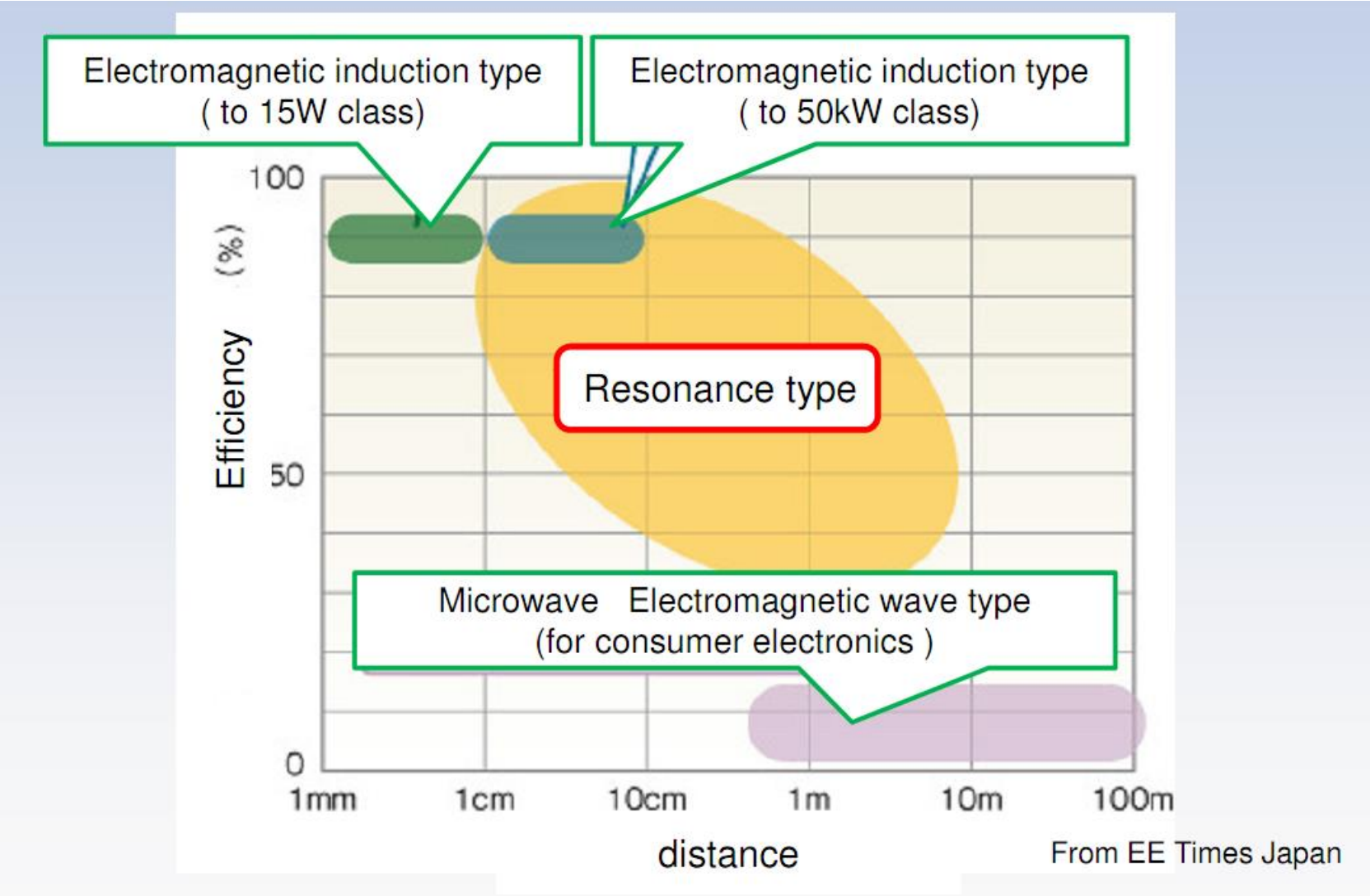
## 1. Wireless Power Transfer

- **Nicola Tesla (1856-1943)**
  - Wireless power transmission experiments at Wardenclyffe (1899)
    - Able to light lamps over 25 miles away without using wires
    - High frequency current, of a Tesla coil, could light lamps filled with gas

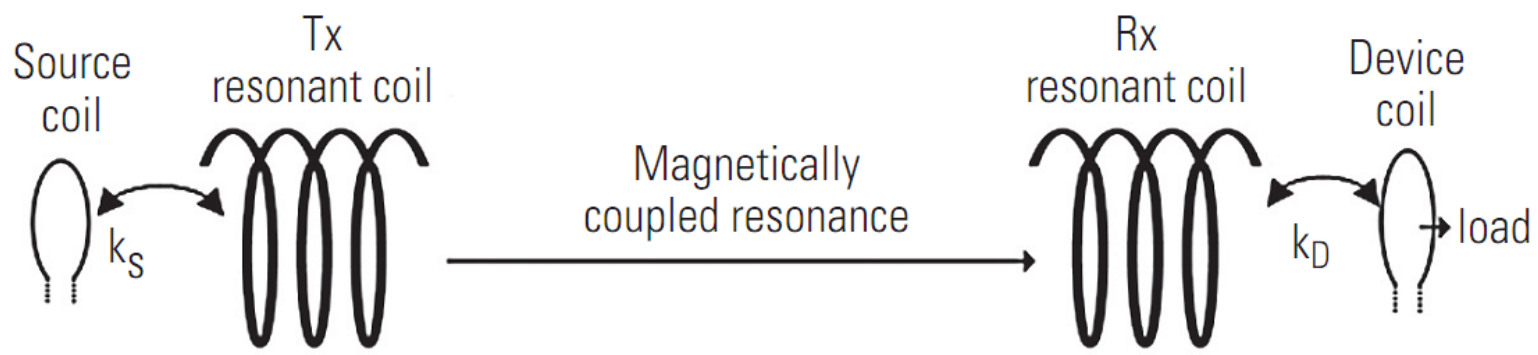
- **1940's to Present**
  - World War II developed ability to convert energy to microwaves using a magnetron, no method for converting microwaves back to electricity.
  - 1964 William C. Brown demonstrated a rectenna which could convert microwave power to electricity.
  - Recently, high interest in technology development for using solar power from satellites (SPS).

## 1. Wireless Power Transfer



## 1. Wireless Power Transfer

- **Resonance**
  - If two resonators are placed in proximity to one another such that there is coupling between them, it becomes possible for the resonators to exchange energy.
  - The efficiency of the energy exchange depends on the characteristic parameters for each resonator and the energy coupling rate , between them.
  - The dynamics of the two resonator system can be described using coupled-mode theory or from an analysis of a circuit equivalent of the coupled system of resonators.



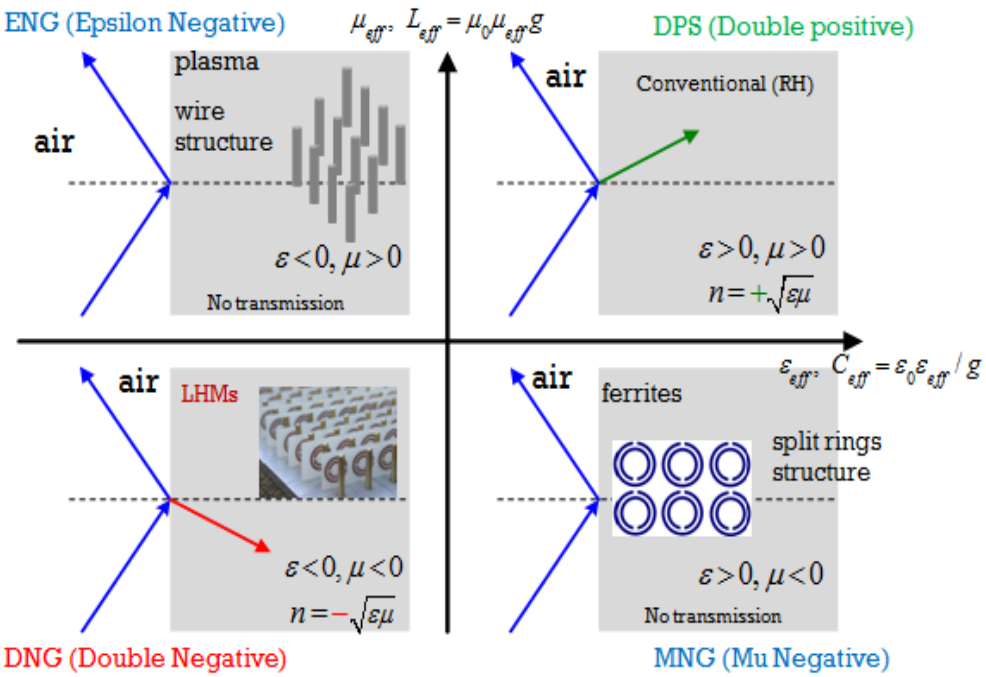
# Contents

## 2. Metamaterial

- *Metamaterial* is broadly defined as artificial and effective homogeneous materials with unusual electromagnetic properties.

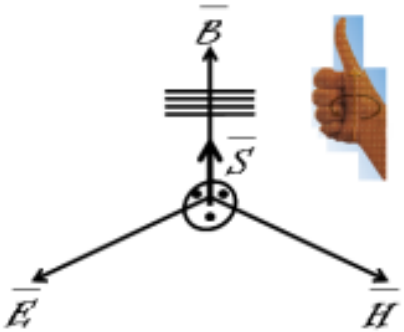
- Metamaterials that provide a structure with an effective negative index of refraction
  - First conceptualized by V.G Veselago in 1968
  - Pendry proposed physical structures in 1996 and 1999 that lead to the their physical realization
  - First physically realized by Smith.

- Metamaterials can be classified as
  - Double PoSitive material (DPS)
  - Epsilon NeGative material (ENG)
  - Mu NeGative material (MNG)
  - Double NeGative material (DNG)

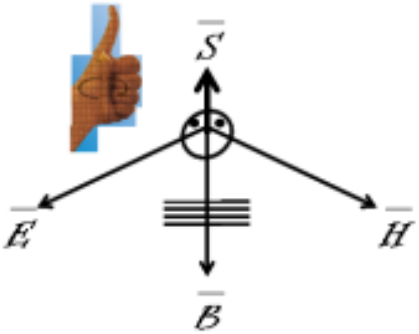


## 2. Metamaterial

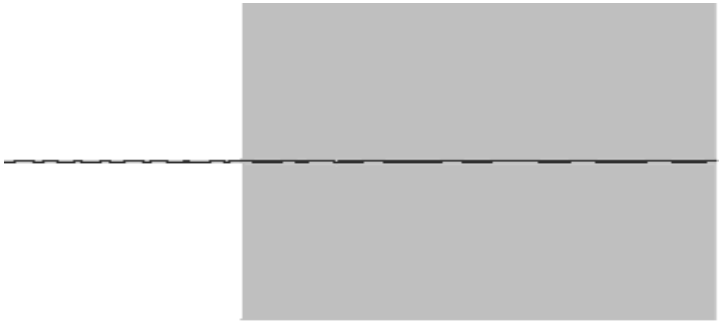
- A type of metamaterial with simultaneous ***negative permittivity*** and ***permeability***, and a ***negative index of refraction***.
- Left-handed refers to the Left Hand Triad (*E, H, k*) obtained from Maxwell equations
- In the case of LHMs, **poynting vector is anti-parallel to phase-velocity vector due to negative permittivity and permeability**.
- Science magazine listed LH materials as one of the ten greatest scientific breakthroughs in 2003




**Conventional Material**




**Metamaterial**

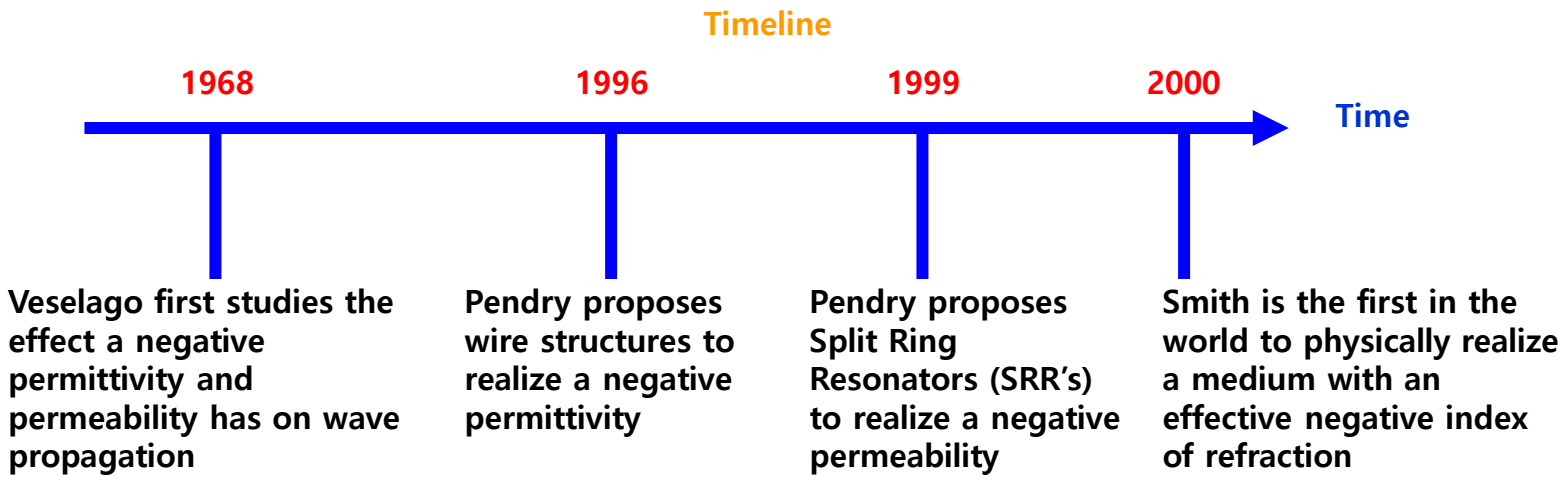


**Positive Index Medium** **Negative Index Medium**

## 2. Metamaterial

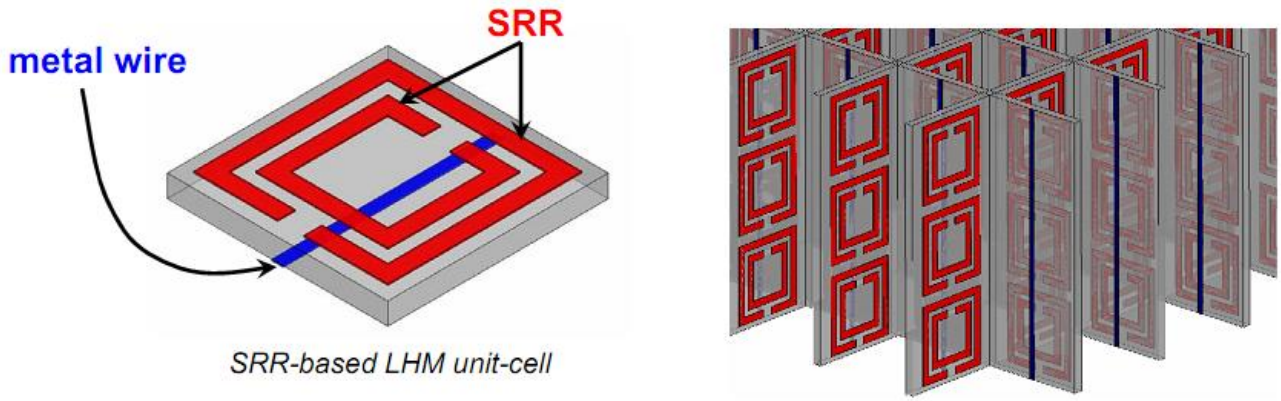
- Metamaterials that provide a structure with an effective negative index of refraction
  - First conceptualized by V.G Veselago in 1968
  - Pendry proposed physical structures in 1996 and 1999 that lead to the their physical realization
  - First physically realized by Smith, et. al. in 2000

- Since metamaterials were first physically realized in 2000, many research groups have exploited these synthetic structures to create novel devices and components



## 2. Metamaterial

- **LHM – Resonant Approach**
  - 1967 : LHM were first proposed by Russian Physicist Victor Veselago
  - 2001 : LHM realized based on split ring resonators : **Resonant Approach** towards LHMs




*SRR-based LHM unit-cell*

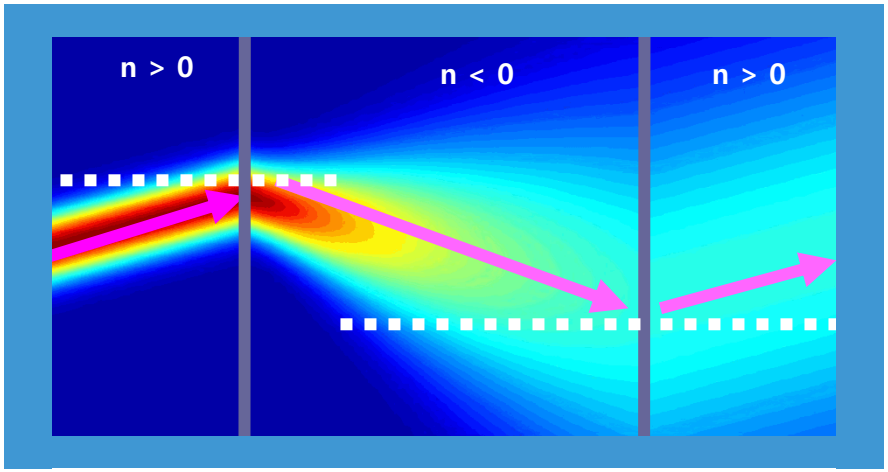
**SRR**: at ***resonance*** provides μ<0

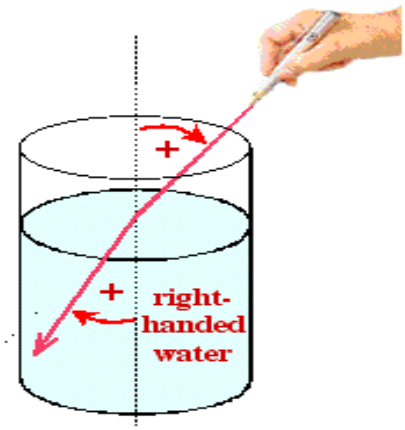
**metal wire**: provides ε<0

  - SRR-based metamaterials only exhibit LH properties at **resonance** – inherently ***narrow-band*** and ***lossy***
  - SRR-based LHMs are bulky – not practical for microwave engineering applications

## 2. Metamaterial

- Snell's Law at the interface between a negative index material and a positive index material :




$$n_1 \sin\theta_i = n_2 \sin\theta_t,$$

$$\theta_t = \sin^{-1}\left(\frac{n_1}{n_2}\sin\theta_i\right)$$

- **Light Bending the Wrong Way?**
  - $n_1 > 0$ and $n_2 < 0$,
  - Refracted beam will be opposite to the normal as shown in the animation above

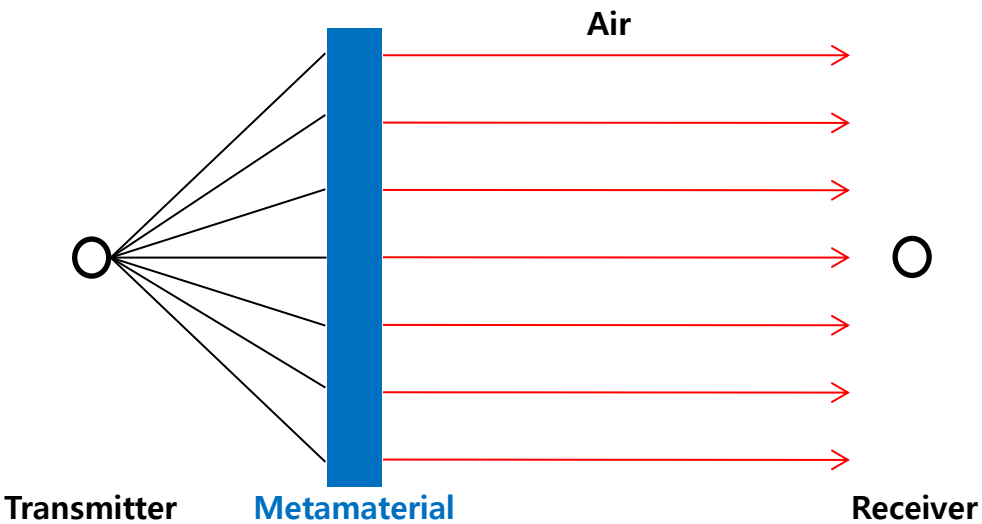
## 2. Metamaterial

- High-Q resonators is essential to achieve high transfer efficiency.
  → Coupling coefficient is important, as higher coupling coefficient leads to higher efficiency.

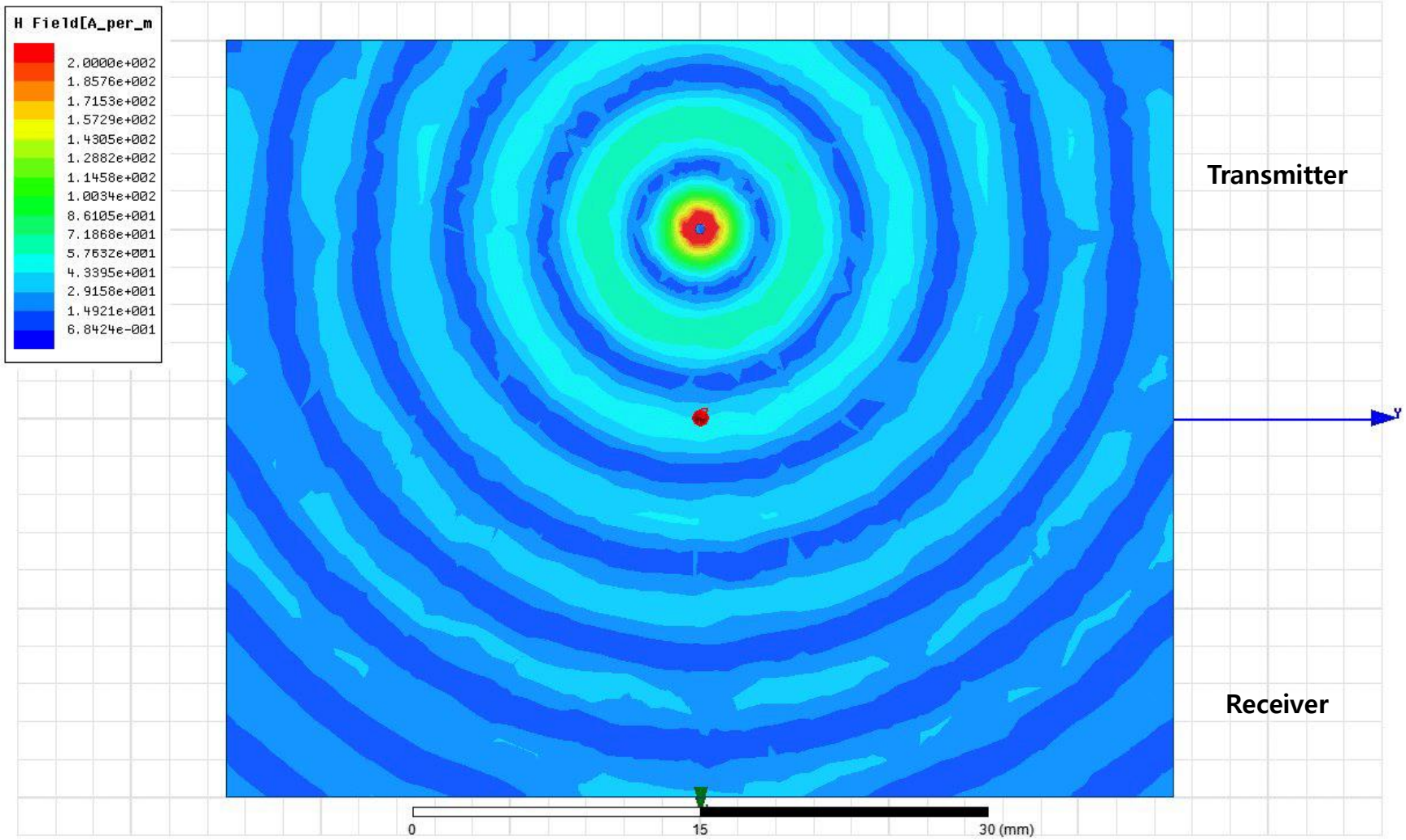
- We have proposed the use of metamaterials to enhance the coupling coefficient of transmitter and receiver, and improve the WPT efficiency.

- We designed a WPT resonator with a metamaterial for zero refractive index (ZRI) to improve th e power transfer efficiency of a WPT system based on resonant coupling.

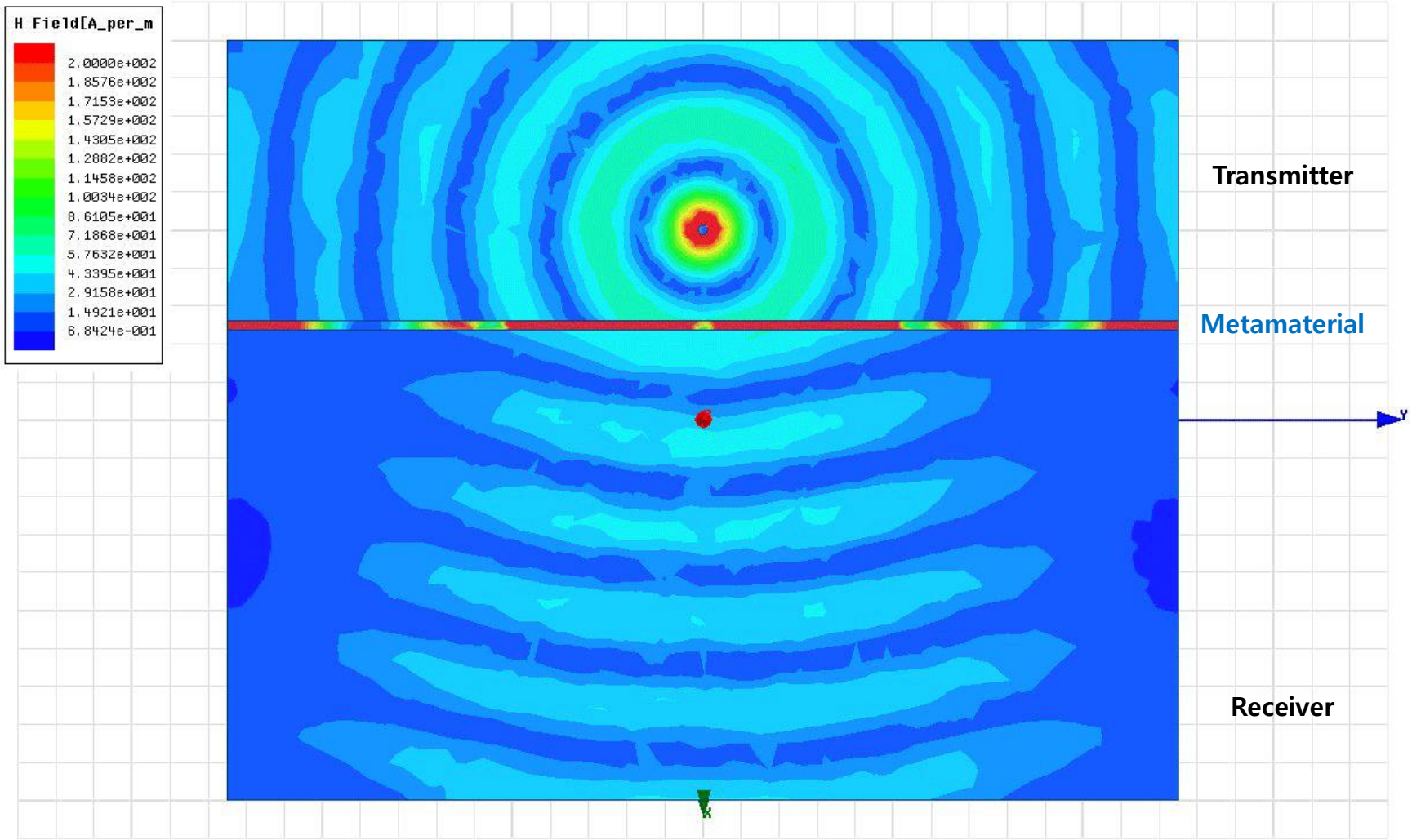
$$\varepsilon_{eff} = 0, \mu_{eff} = 0 \quad \Rightarrow \quad n = \sqrt{\varepsilon\mu} = 0$$



## 2. Metamaterial



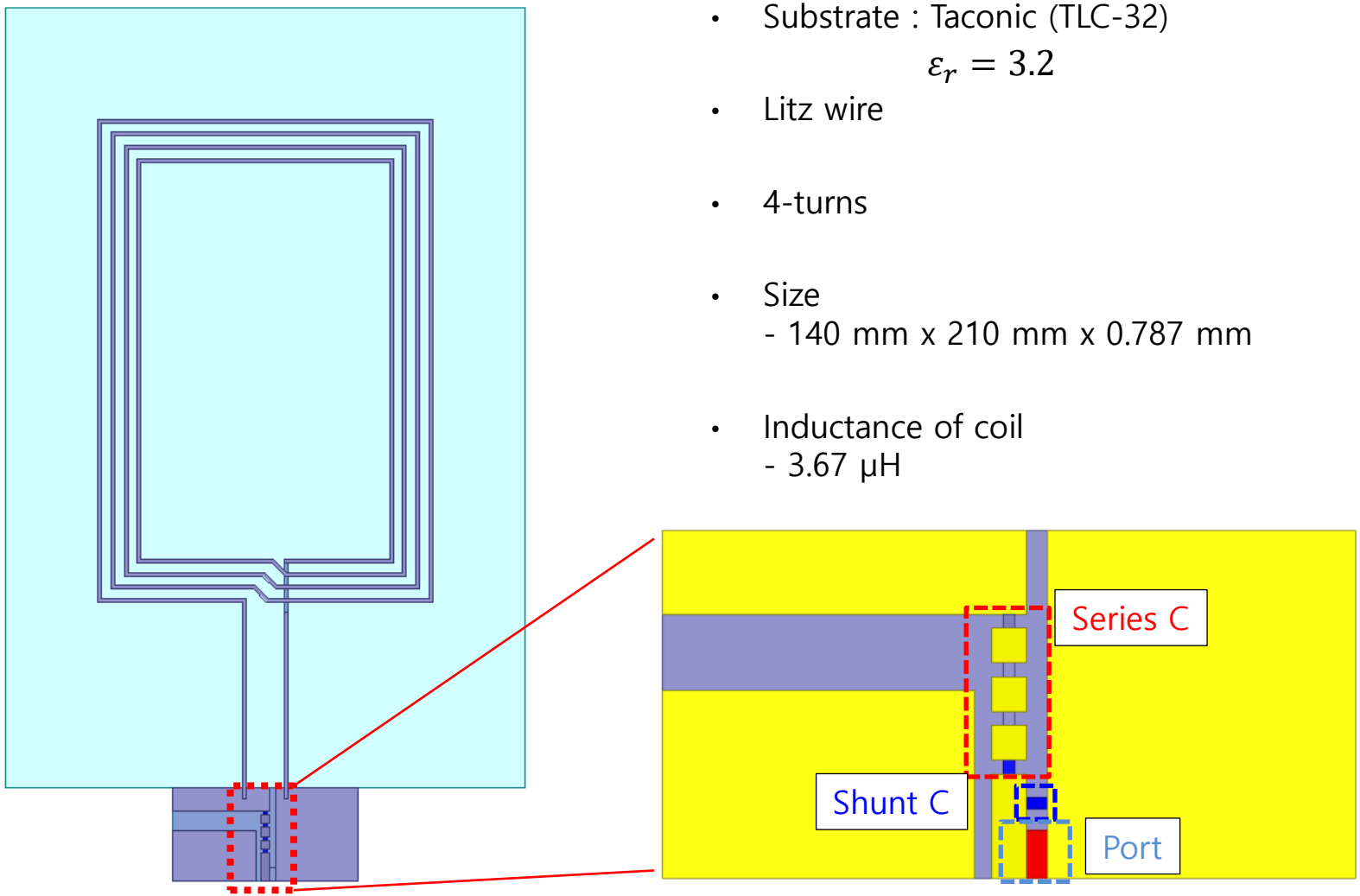
## 2. Metamaterial



# Contents

## 3. Conventional WPT Resonator

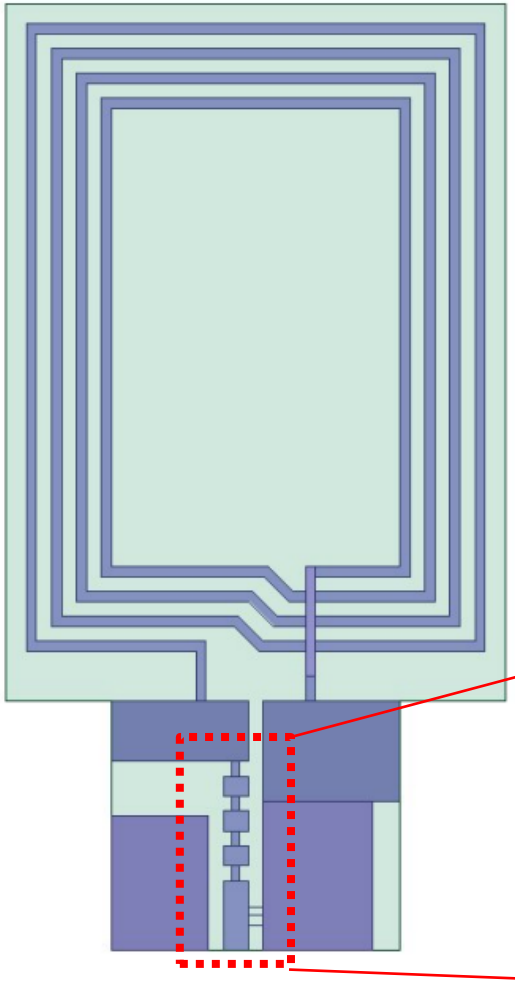
- Transmitting loop



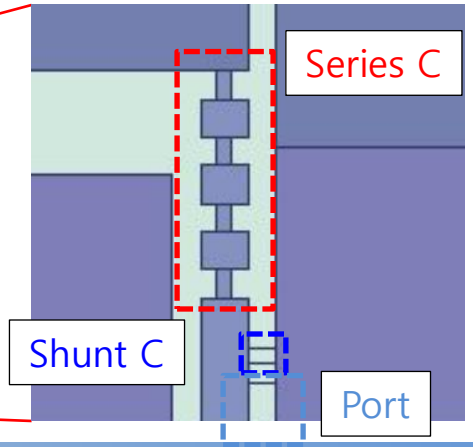

- Substrate : Taconic (TLC-32)
  $\varepsilon_r = 3.2$
- Litz wire
- 4-turns
- Size
  - 140 mm x 210 mm x 0.787 mm
- Inductance of coil
  - 3.67 μH

## 3. Conventional WPT Resonator

- Receiving loop

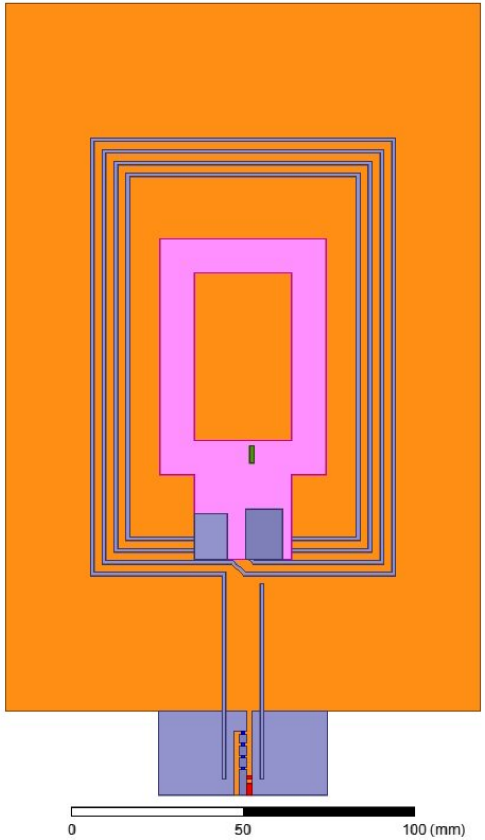


- Substrate : Taconic (TLC-32)
  $\varepsilon_r = 3.2$
- Litz wire
- 4-turns
- Size
  - 50 mm x 700 mm x 0.787 mm
- Inductance of coil
  - 1.14 μH

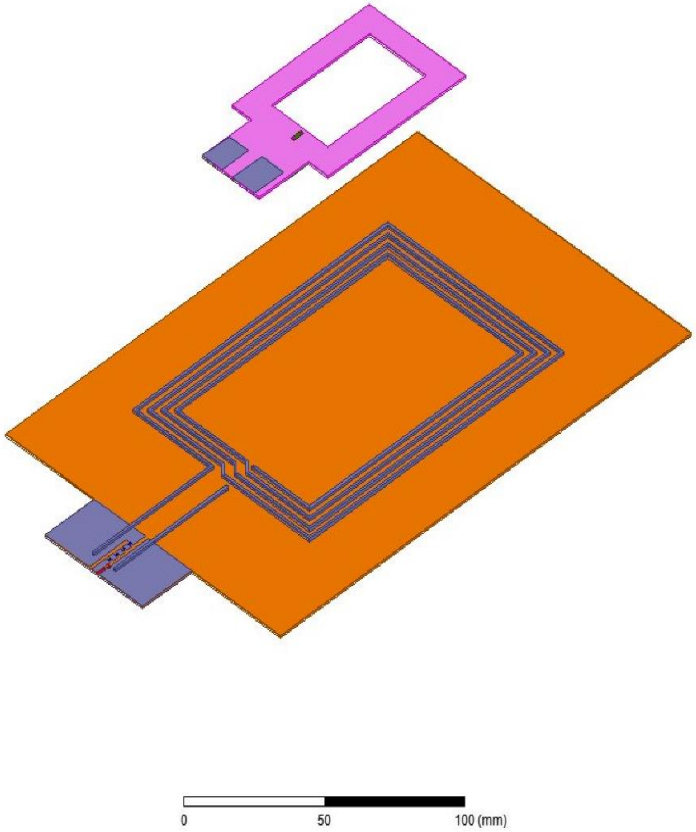


## 3. Conventional WPT Resonator

- Simulation



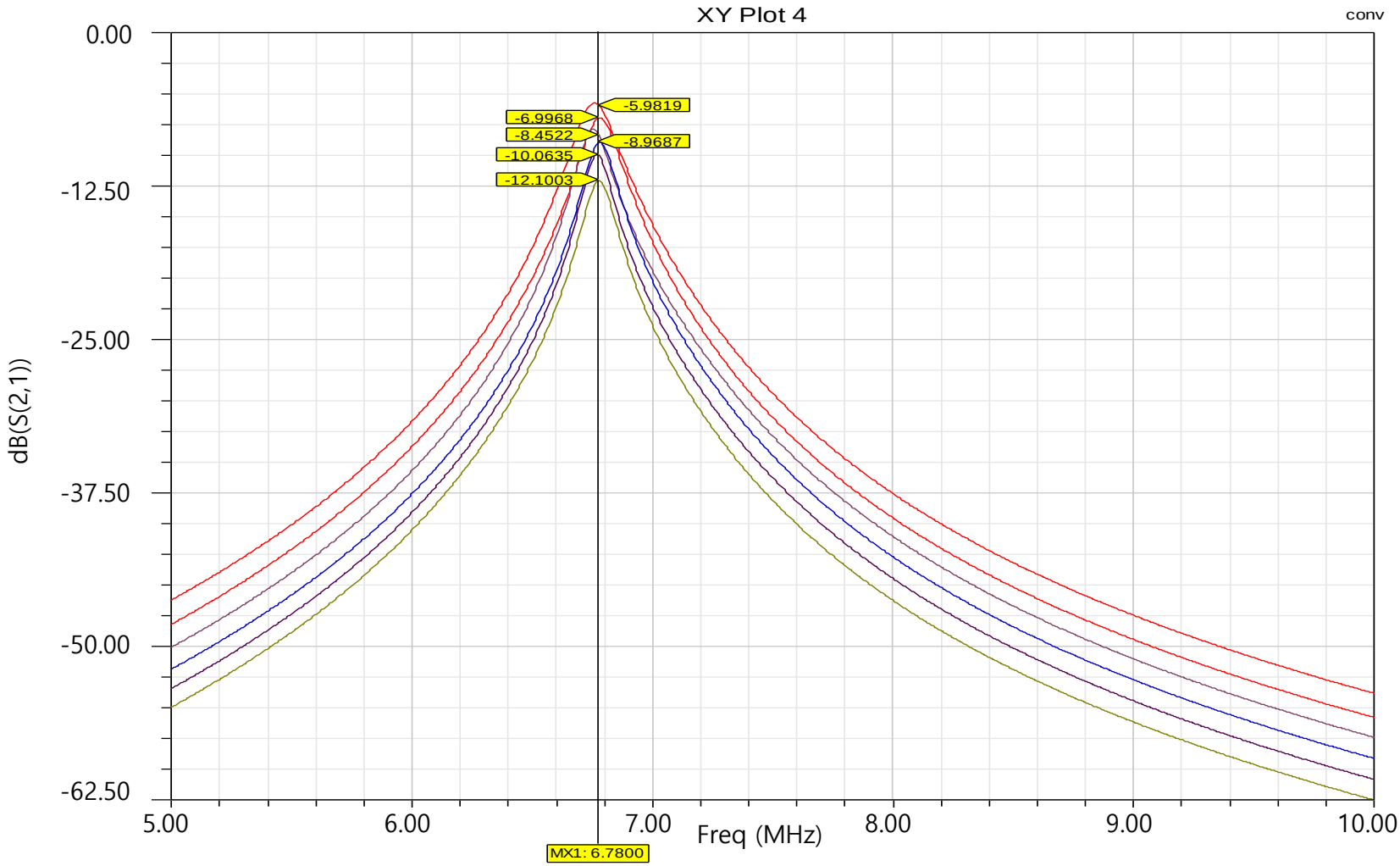

- Front -




- Side -

## 3. Conventional WPT Resonator

- Simulation



## 3. Conventional WPT Resonator

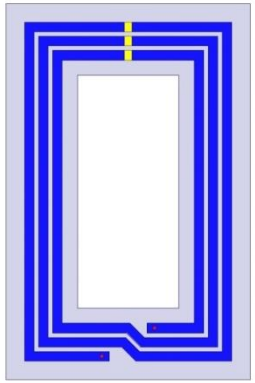
- Simulation

| Distance (mm) | $S_{21}$ (dB) (@ 6.78 MHz) | Efficiency (%) (@ 6.78 MHz) |
|---|---|---|
| 100 | -5.98 | 25.2 |
| 110 | -6.99 | 19.99 |
| 120 | -8.45 | 14.2 |
| 130 | -8.97 | 12.67 |
| 140 | -10.06 | 9.86 |
| 150 | -12.1 | 6.16 |

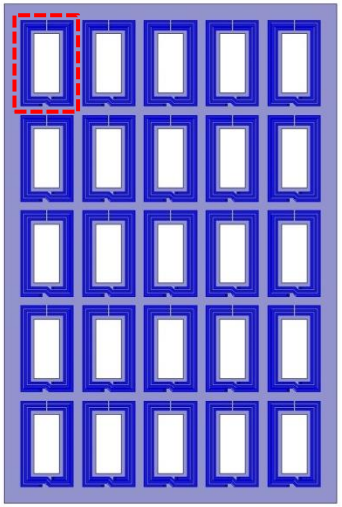
# Contents

## 4. Proposed WPT Resonator

- Metamaterial



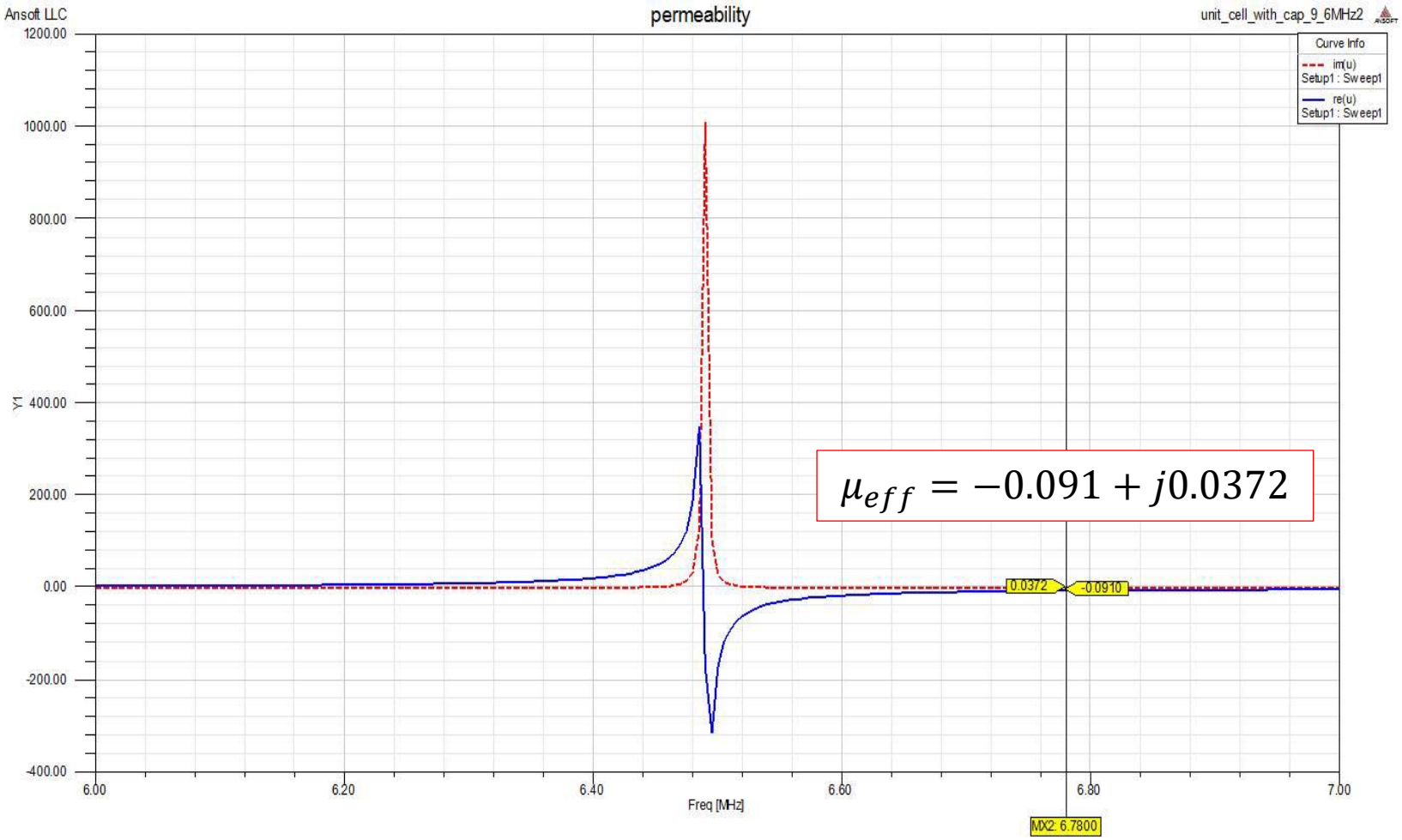
- Substrate : Taconic (CER-10)
  $\varepsilon_r = 10.2$
- Size
  - 26 mm x 40 mm x 0.64 mm
- 3-capacitors : 1500 pF



- Substrate : Taconic (CER-10)
  $\varepsilon_r = 10.2$
- Size
  - 140 mm x 210 mm x 0.64 mm
- 5 × 5 array
- 2-layer with 3mm gap

## 4. Proposed WPT Resonator

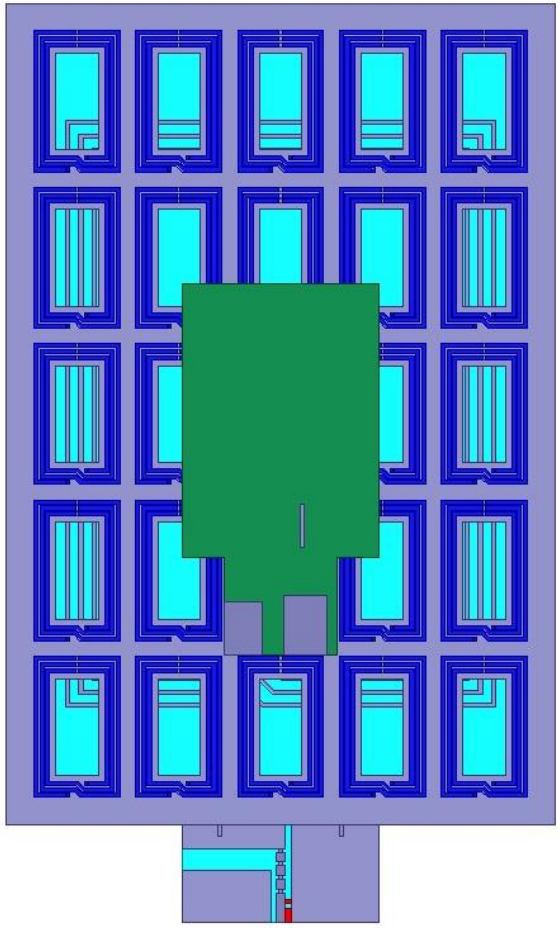
- Metamaterial



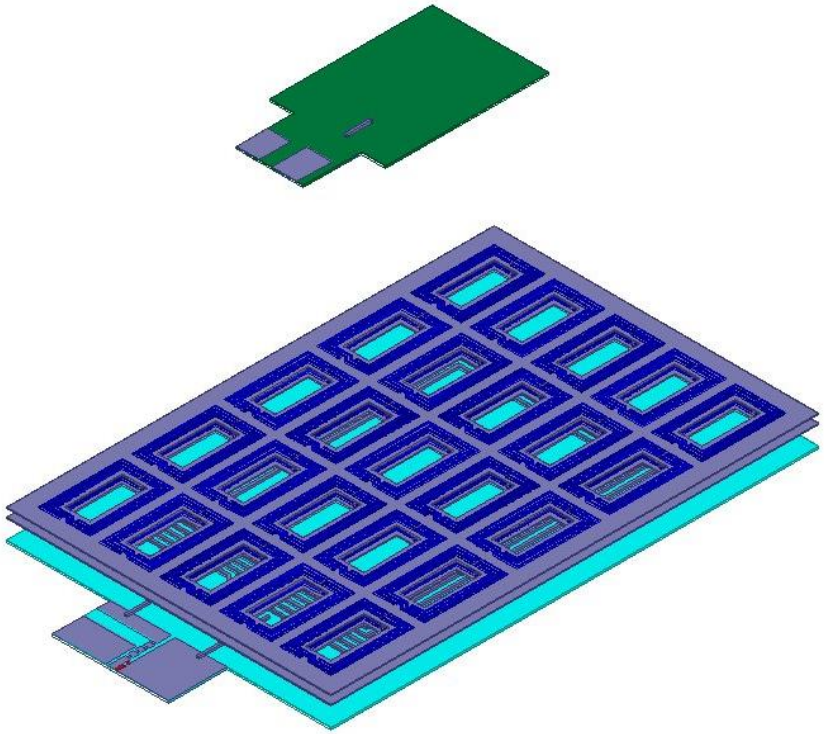

$$\mu_{eff} = -0.091 + j0.0372$$

## 4. Proposed WPT Resonator

- Simulation



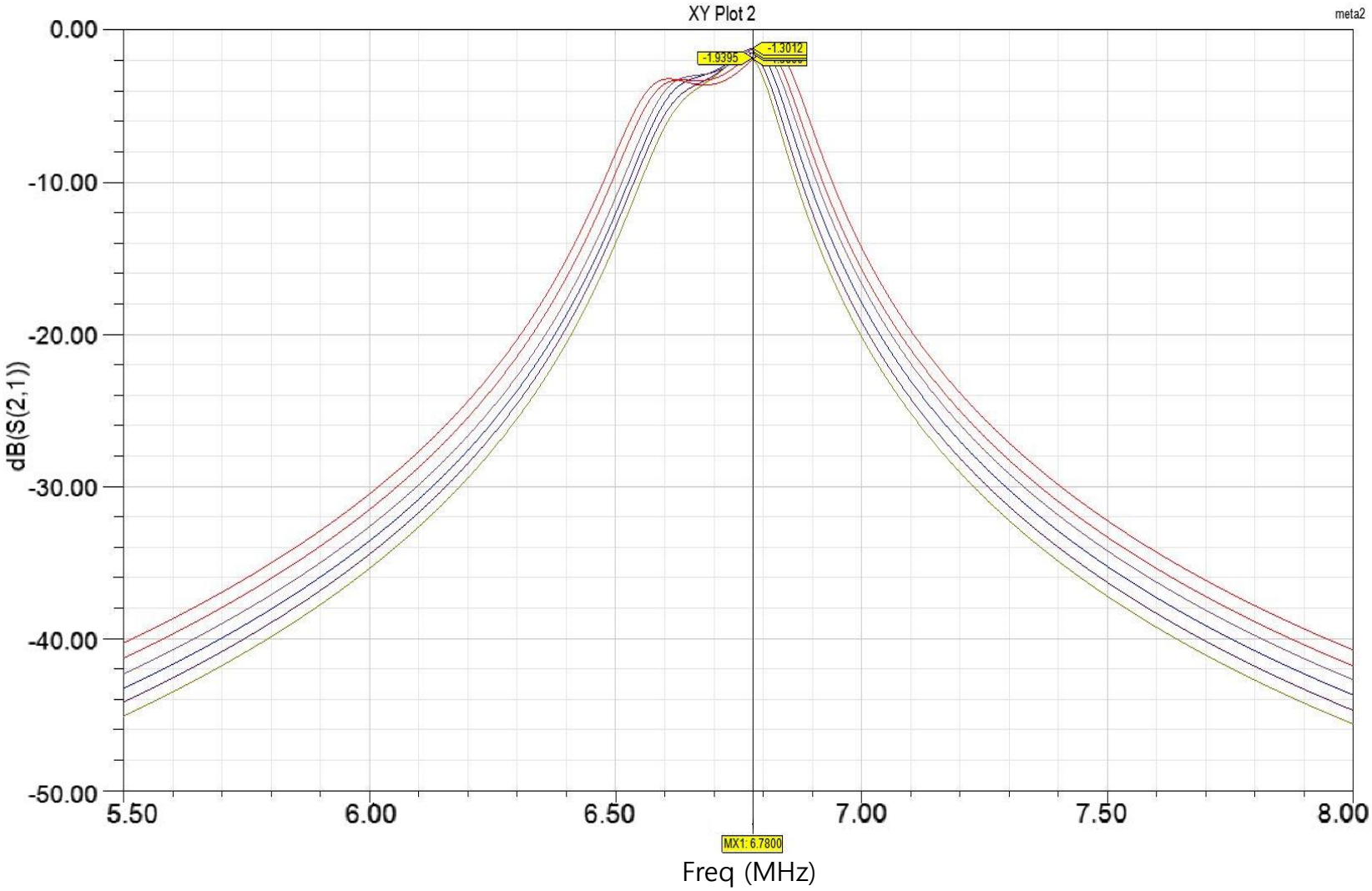
- Front -



- Side -

## 4. Proposed WPT Resonator

- Simulation



## 4. Proposed WPT Resonator

- Simulation

| Distance (mm) | $S_{21}$ (dB) (@ 6.78 MHz) | Efficiency (%) (@ 6.78 MHz) |
|---|---|---|
| 100 | -1.3 | 74.1 |
| 110 | -1.31 | 73.9 |
| 120 | -1.51 | 70.6 |
| 130 | -1.62 | 68.8 |
| 140 | -1.94 | 63.9 |
| 150 | -1.96 | 63.7 |

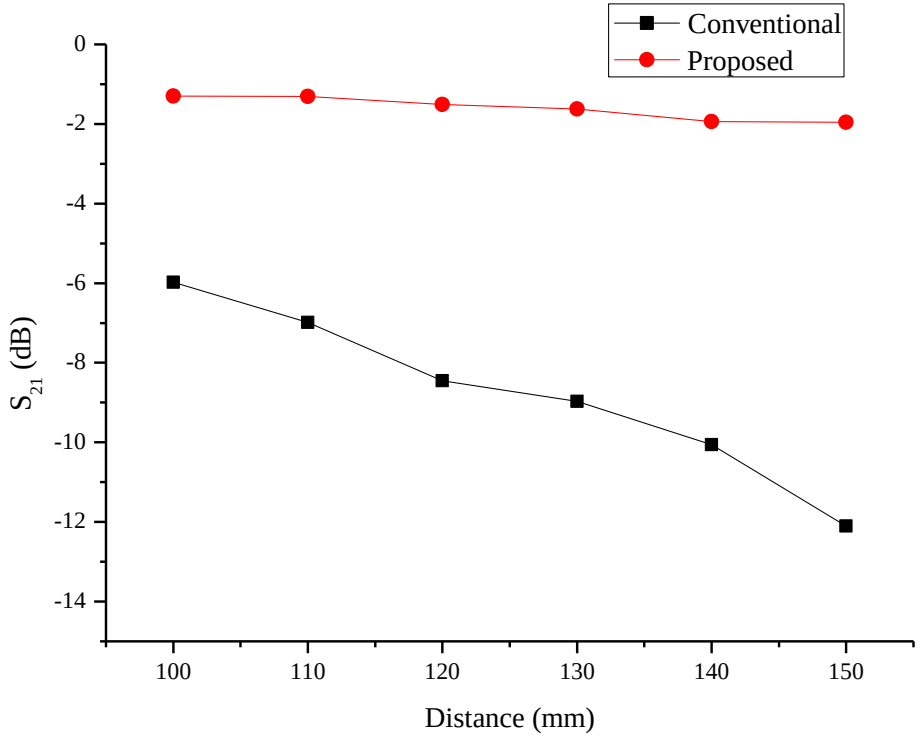
## 4. Proposed WPT Resonator

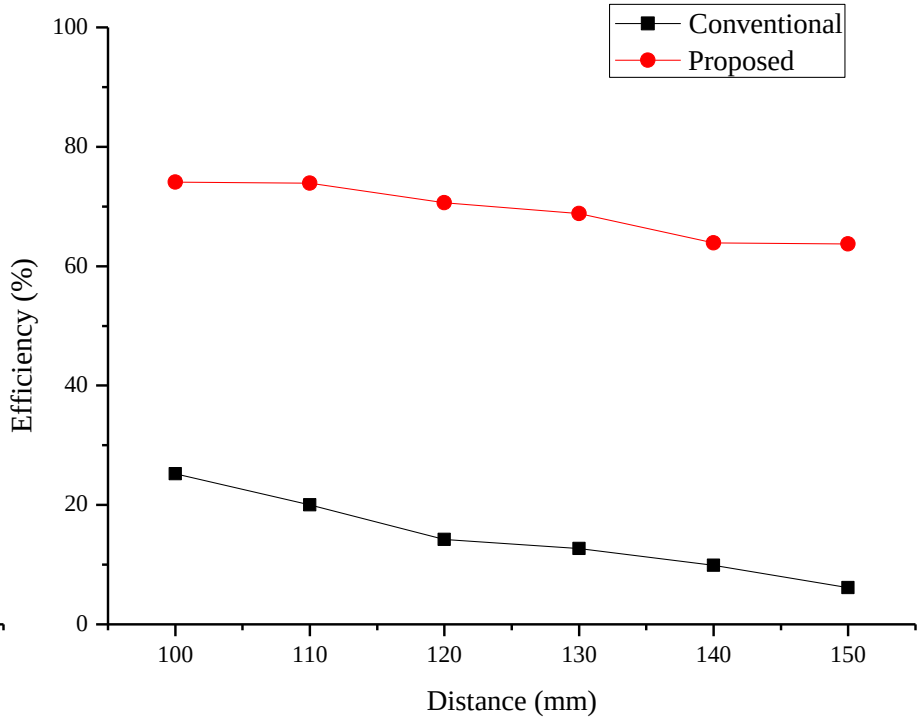
- Simulation - Comparison

| Distance (mm) | Conventional Resonator | | Proposed Resonator | |
|---|---|---|---|---|
| | $S_{21}$ (dB) | Efficiency (%) | $S_{21}$ (dB) | Efficiency (%) |
| 100 | -5.98 | 25.2 | -1.3 | 74.1 |
| 110 | -6.99 | 19.99 | -1.31 | 73.9 |
| 120 | -8.45 | 14.2 | -1.51 | 70.6 |
| 130 | -8.97 | 12.67 | -1.62 | 68.8 |
| 140 | -10.06 | 9.86 | -1.94 | 63.9 |
| 150 | -12.1 | 6.16 | -1.96 | 63.7 |

## 4. Proposed WPT Resonator

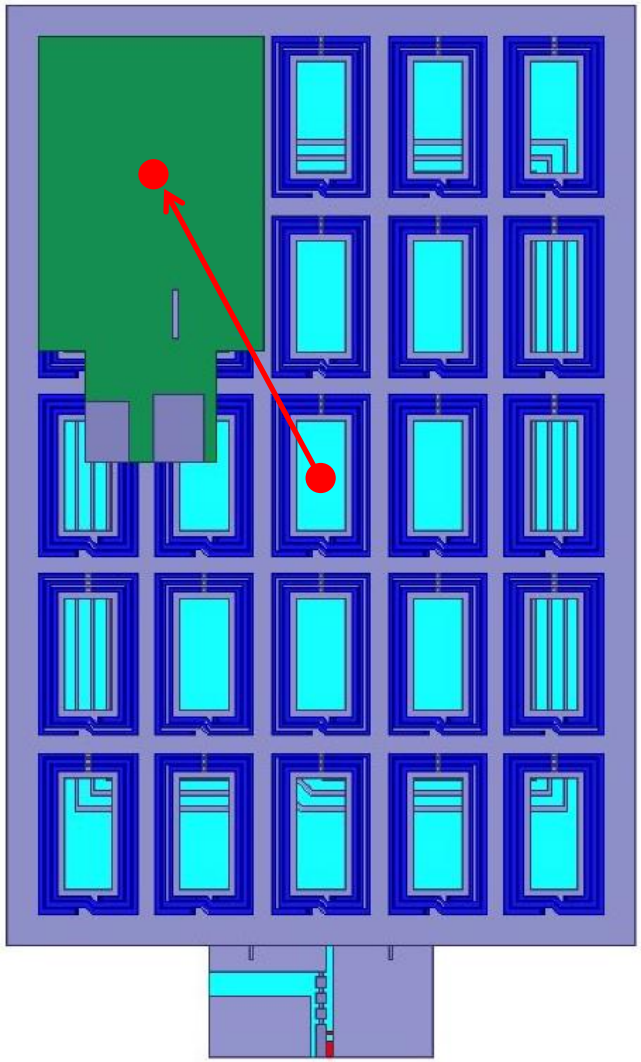
- Simulation - Comparison



## 4. Proposed WPT Resonator

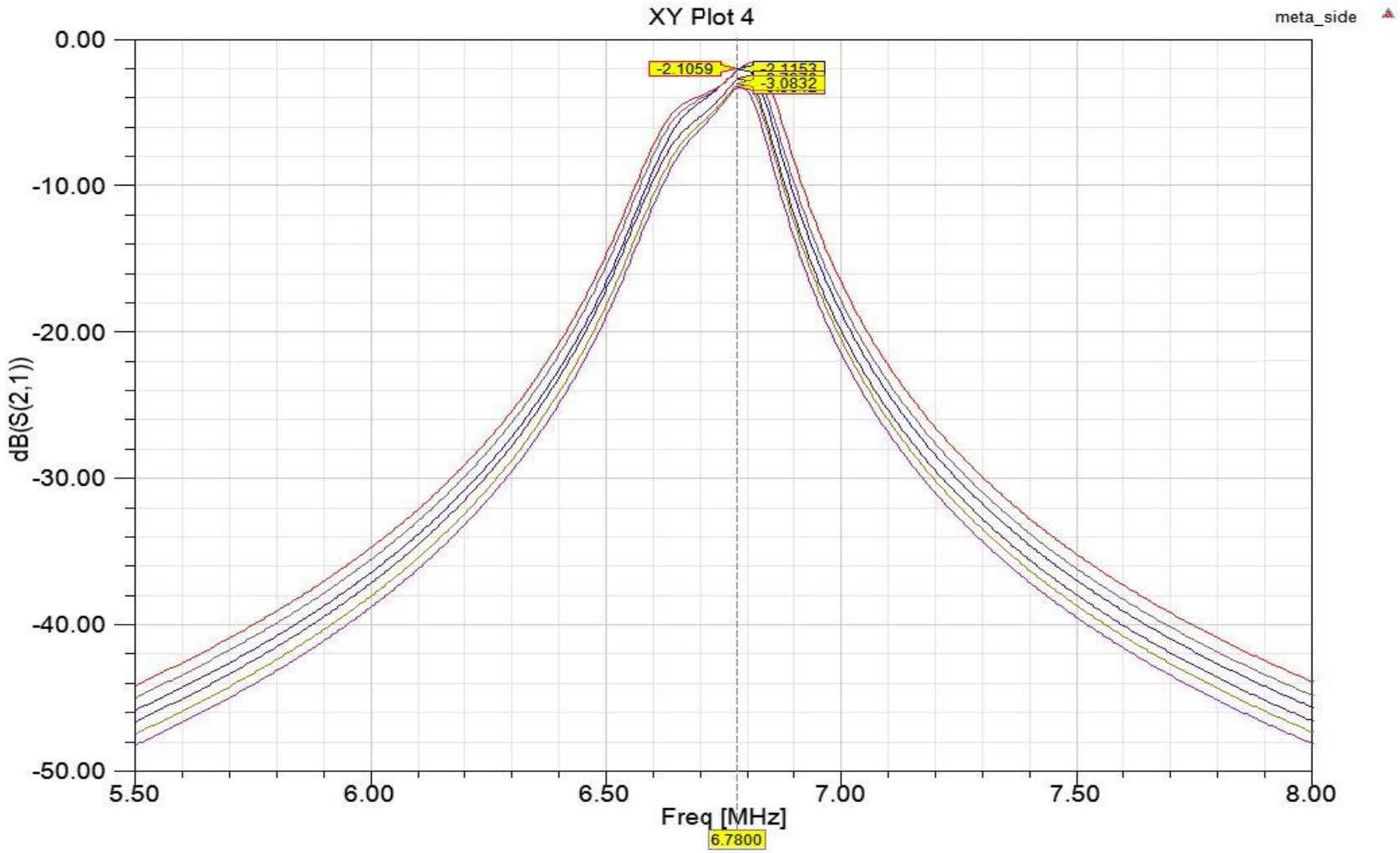
- Edge



x - axis : 35 mm
y - axis : 50 mm

## 4. Proposed WPT Resonator

- Simulation



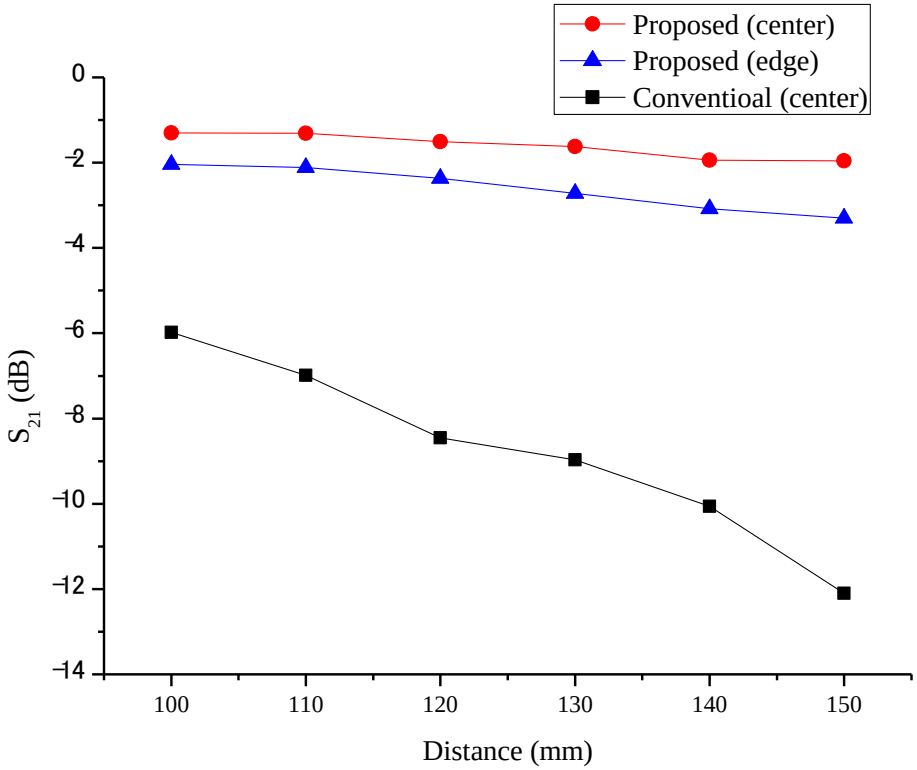
## 4. Proposed WPT Resonator

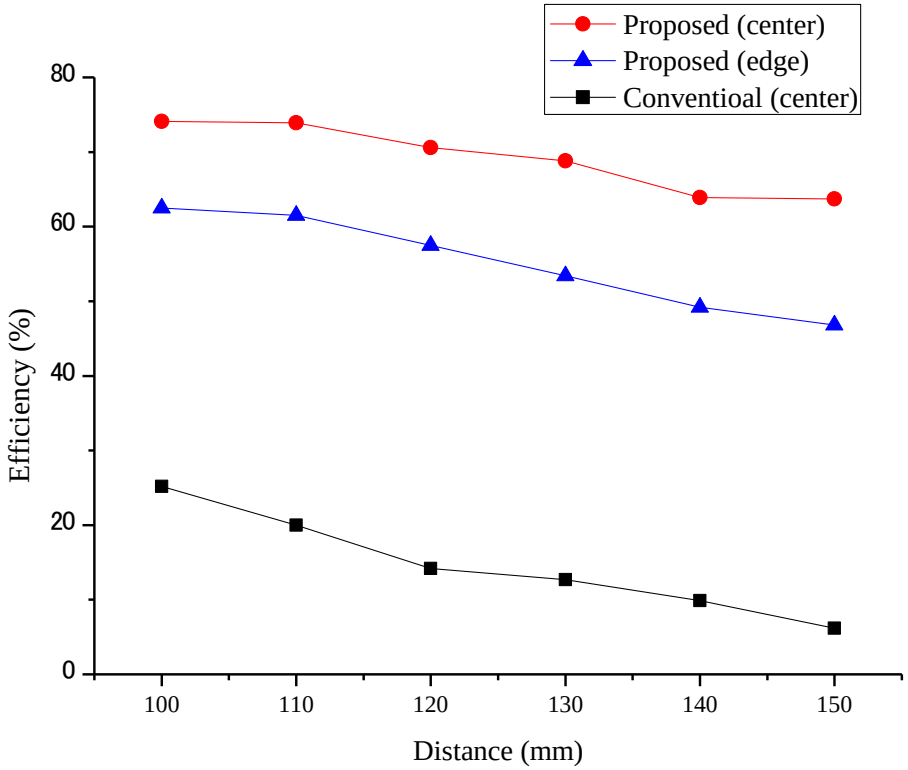
- Simulation - Comparison

| Distance (mm) | Center | | Edge | |
|---|---|---|---|---|
| | $S_{21}$ (dB) | Efficiency (%) | $S_{21}$ (dB) | Efficiency (%) |
| 100 | -1.3 | 74.1 | -2.04 | 62.5 |
| 110 | -1.31 | 73.9 | -2.11 | 61.5 |
| 120 | -1.51 | 70.6 | -2.37 | 57.5 |
| 130 | -1.62 | 68.8 | -2.72 | 53.4 |
| 140 | -1.94 | 63.9 | -3.08 | 49.2 |
| 150 | -1.96 | 63.7 | -3.3 | 46.8 |

## 4. Proposed WPT Resonator

- Simulation - Comparison



# Contents

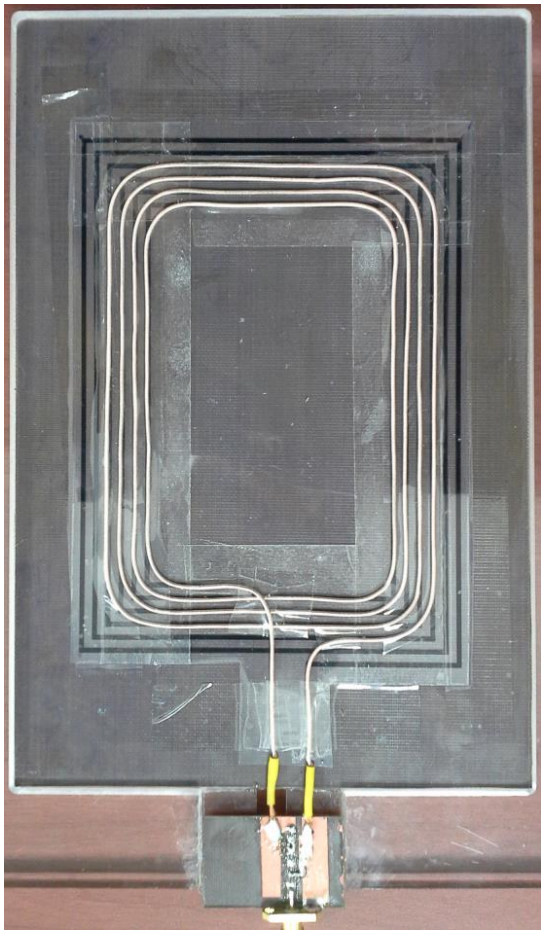
## 5. Measurements

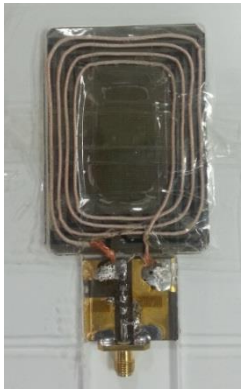
- Fabrications

$L = 3.67\ uH$

$R = 0.65\ \Omega$

$Q = \frac{\omega_0 L}{R} = 240$





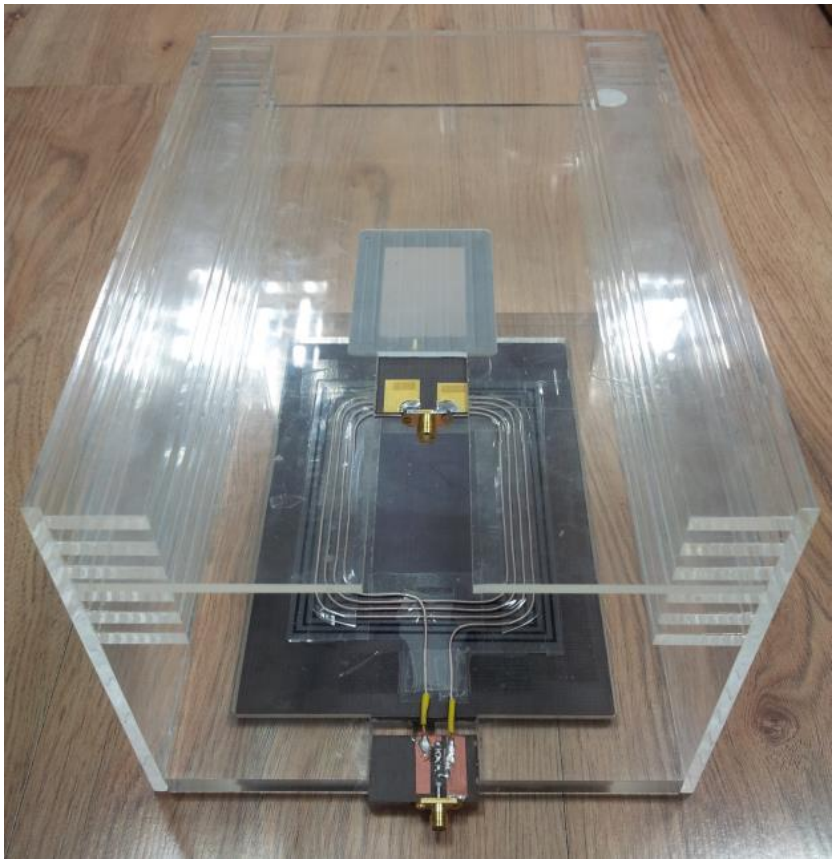
$L = 1.57\ uH$

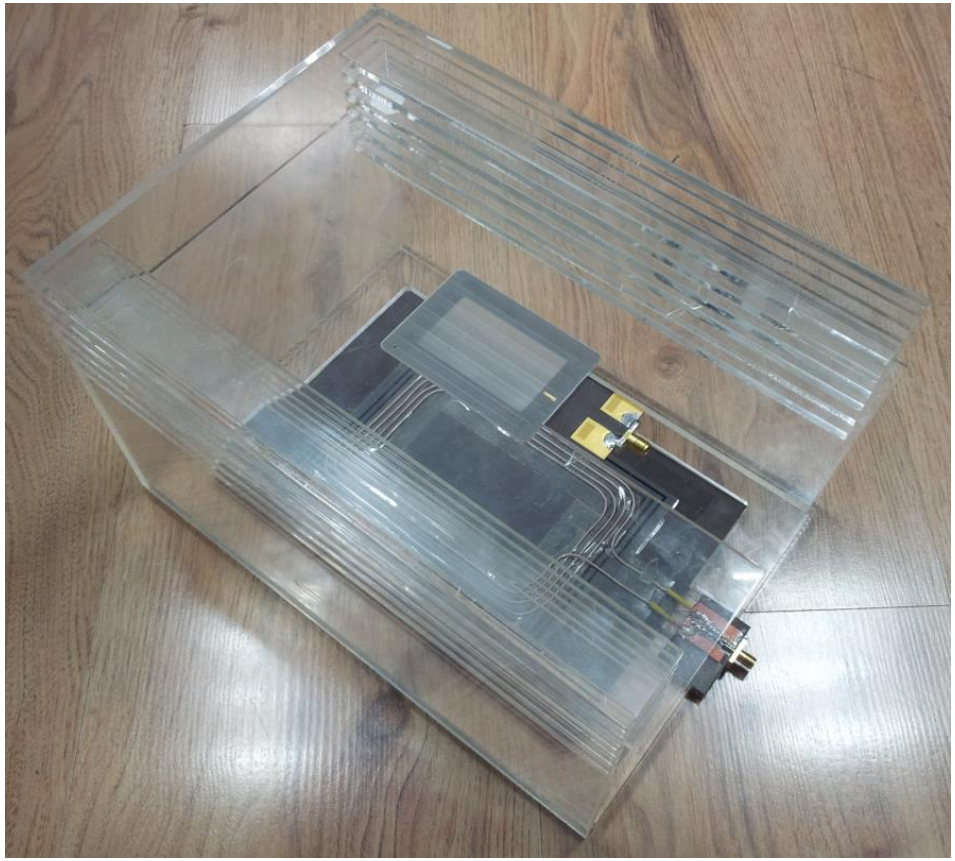
$R = 0.34\ \Omega$

$Q = \frac{\omega_0 L}{R} = 196$

## 5. Measurements

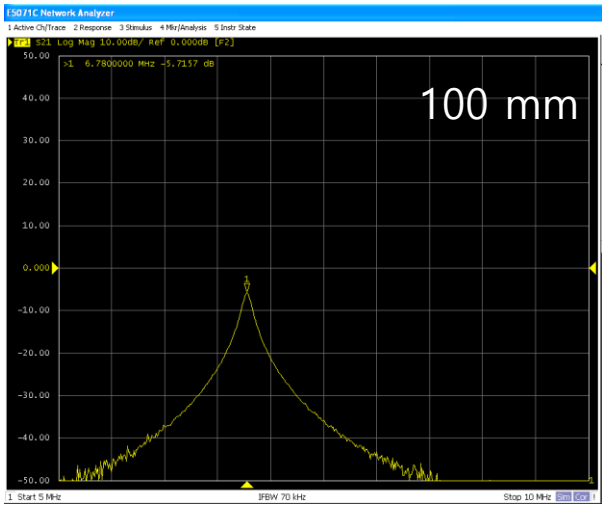
- Fabrications

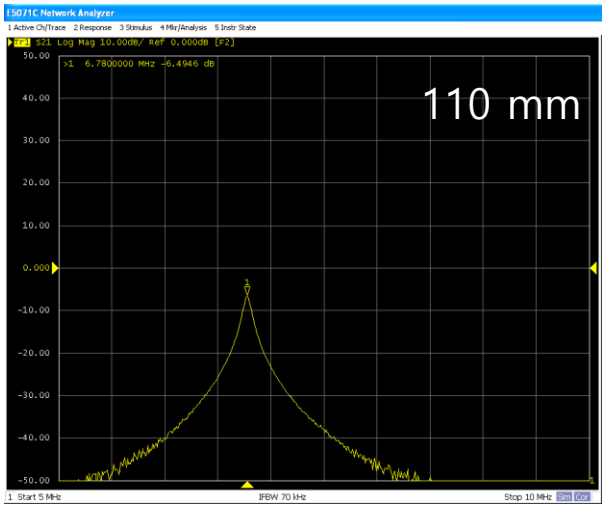


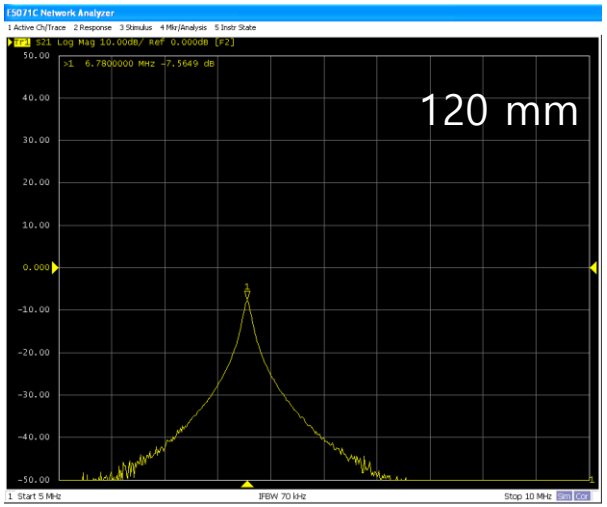


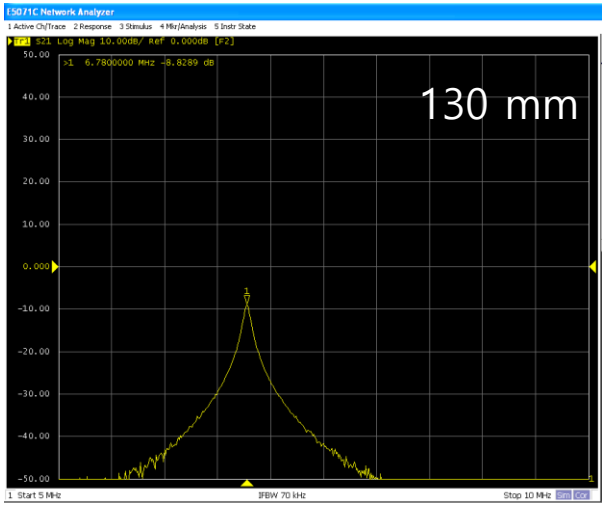
## 5. Measurements

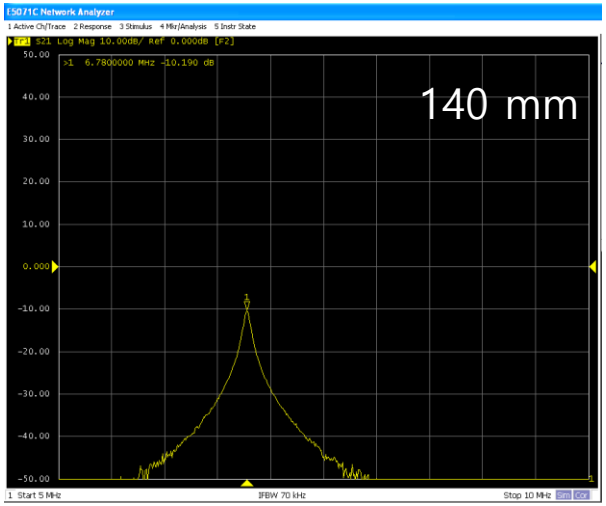
- S-parameter($S_{21}$)

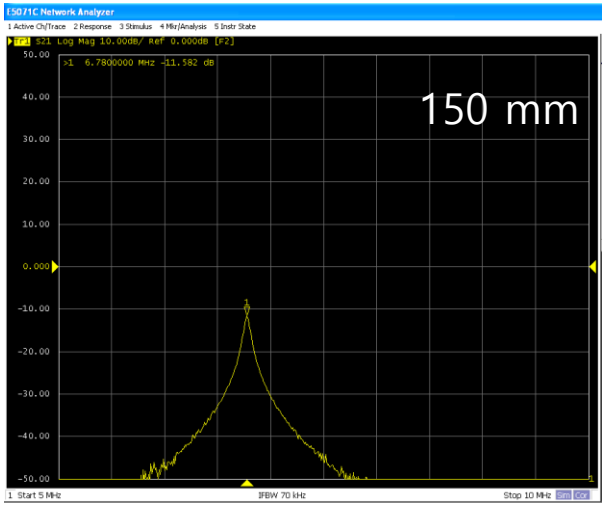


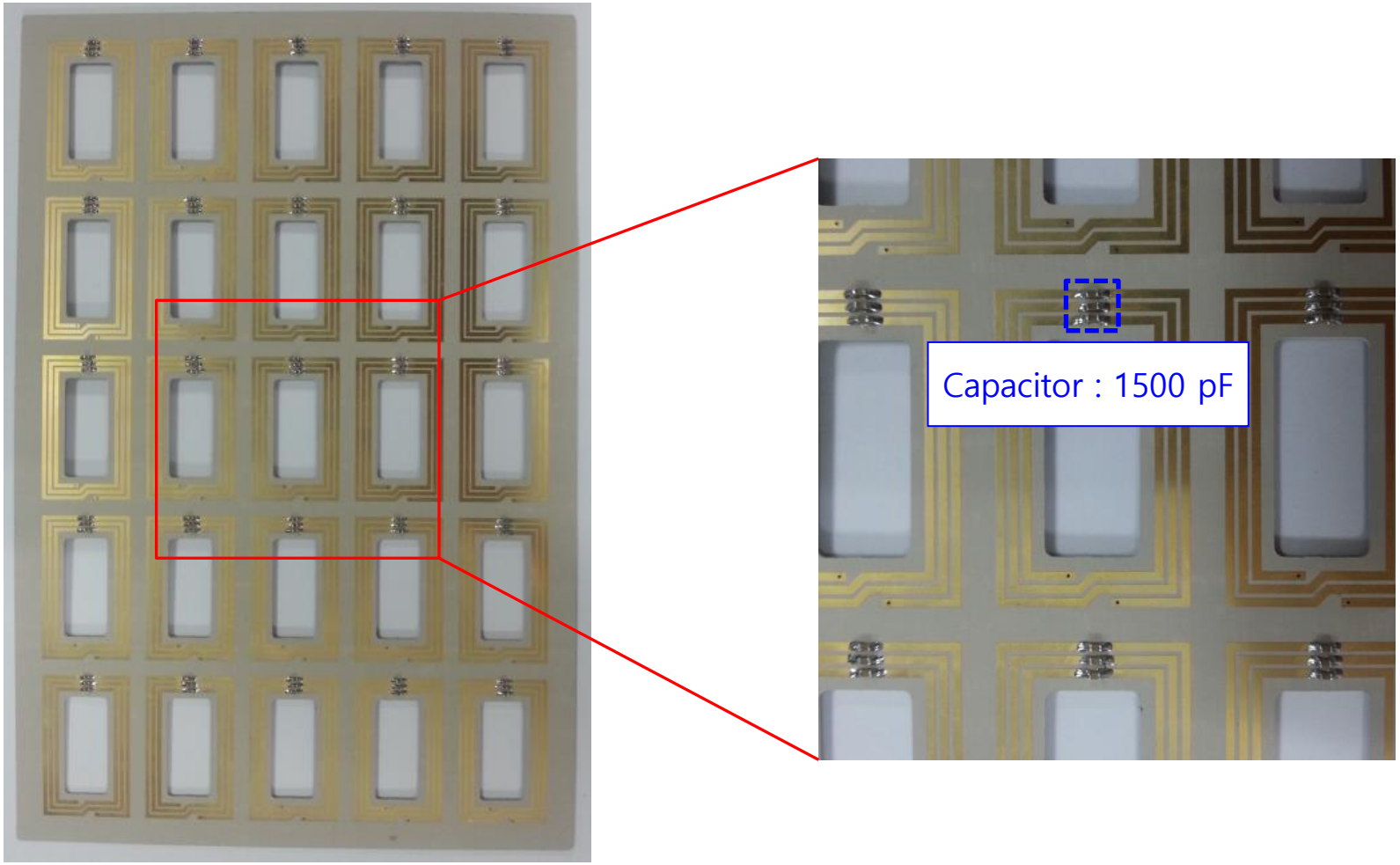



## 5. Measurements

- Fabrications - Metamaterial



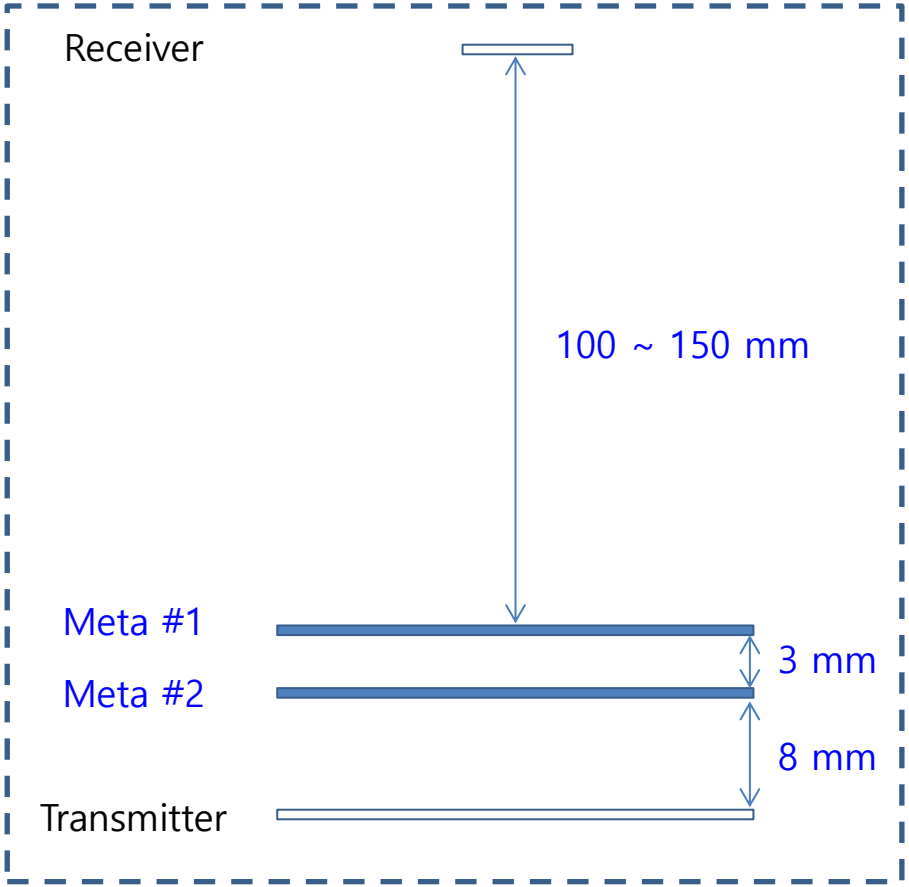
## 5. Measurements

- Fabrications

- 2-layer
- 3 mm between layers
- 8 mm between transmitter

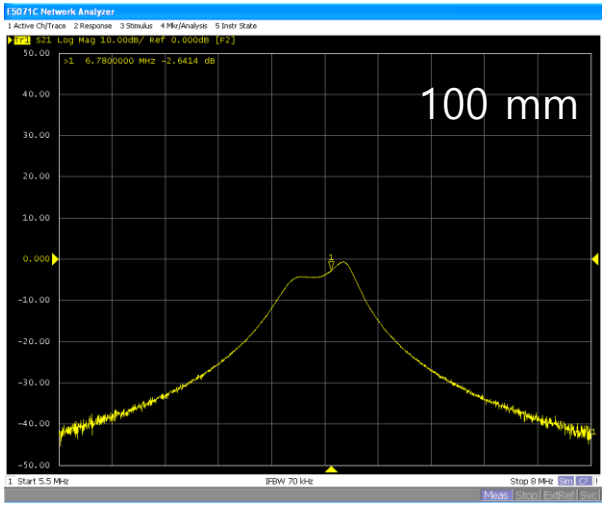
## 5. Measurements

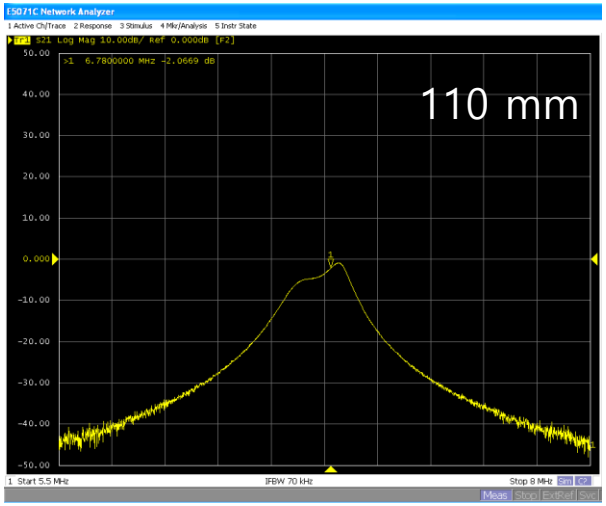
- Fabrications

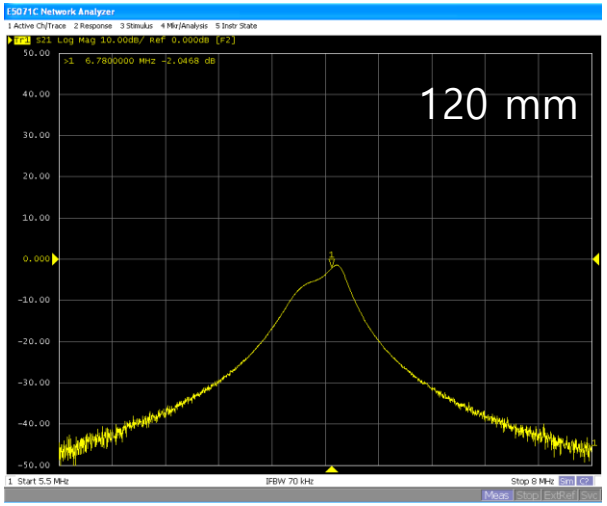


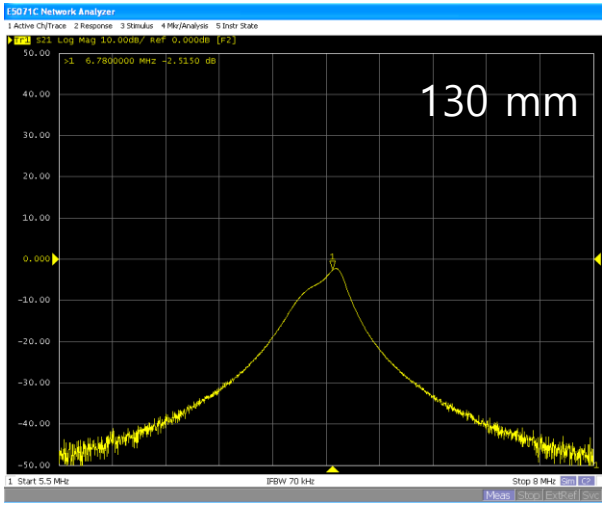
## 5. Measurements

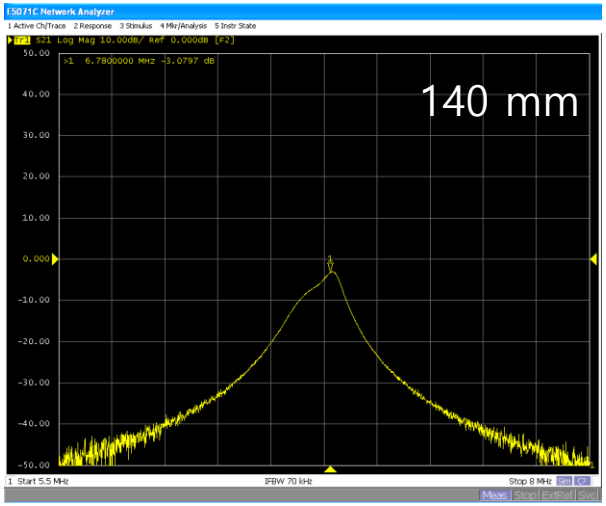
- S-parameter($S_{21}$) - Center

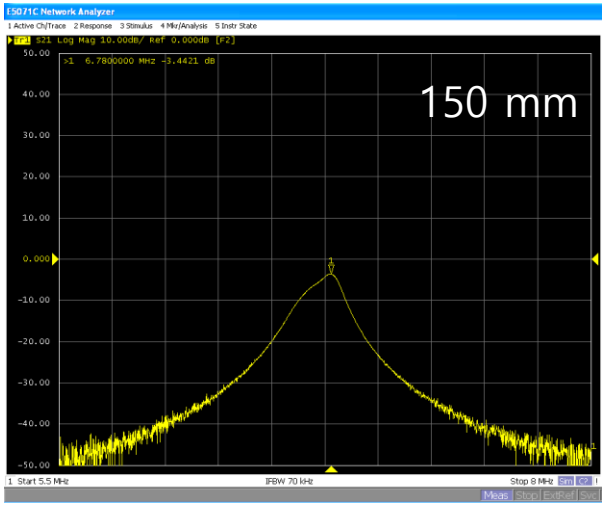


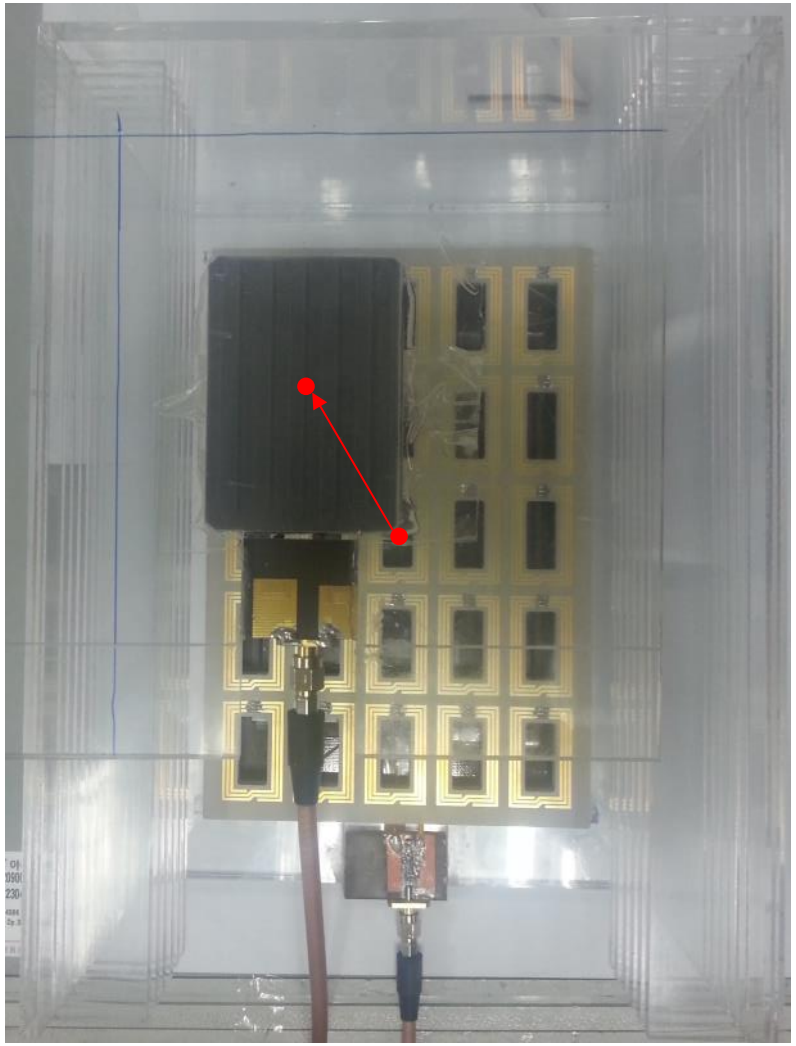



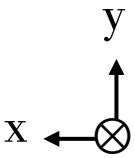



## 5. Measurements

- Measurements - Edge

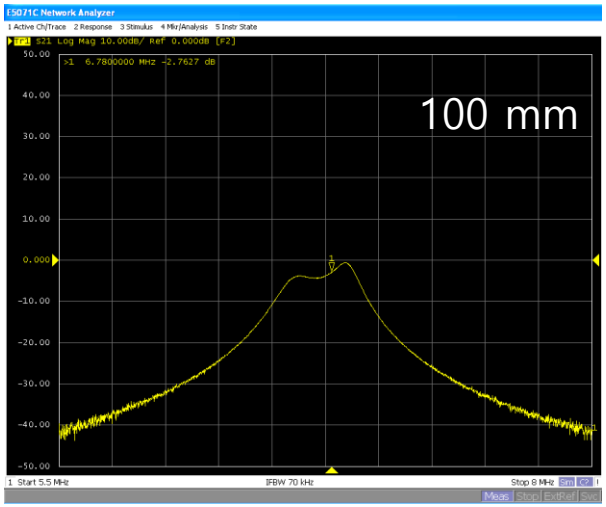


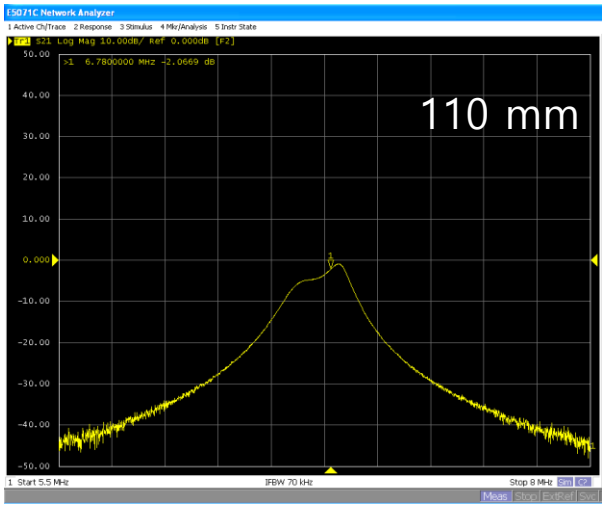
x - axis : 35 mm
y - axis : 50 mm

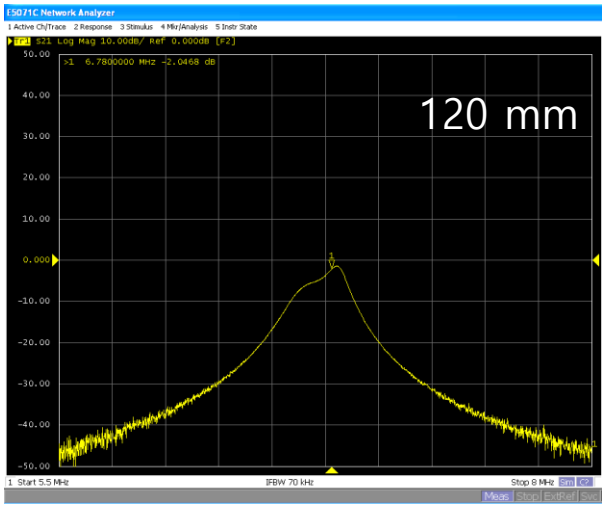


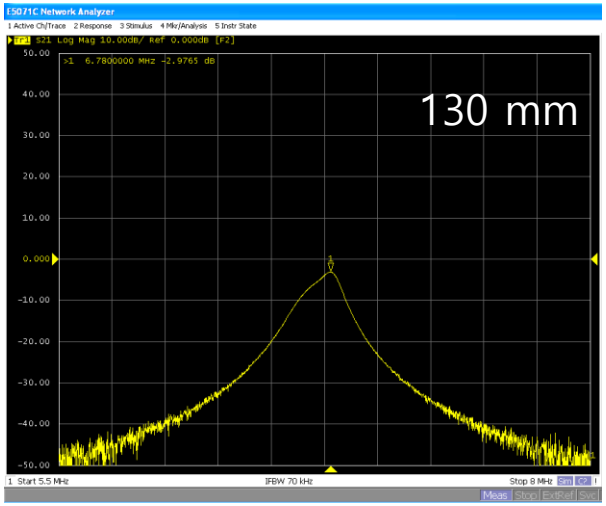
## 5. Measurements

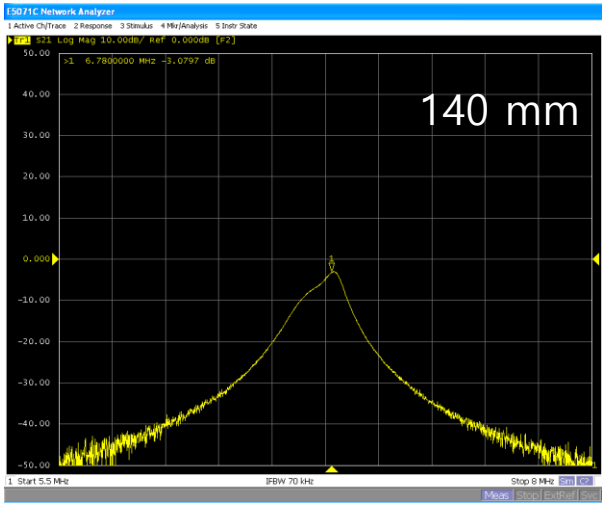
- S-parameter($S_{21}$) - Edge

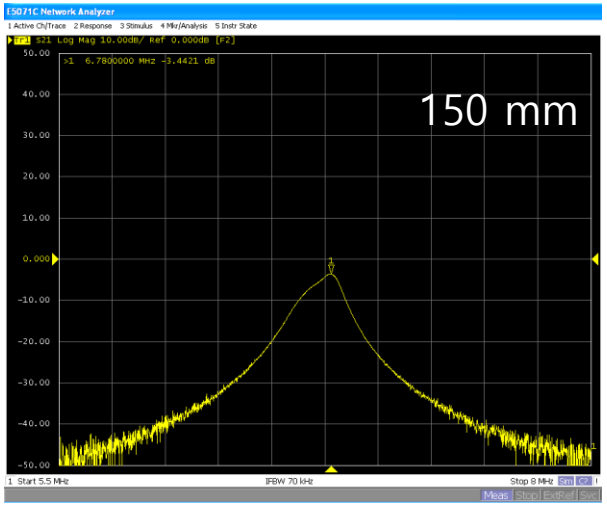


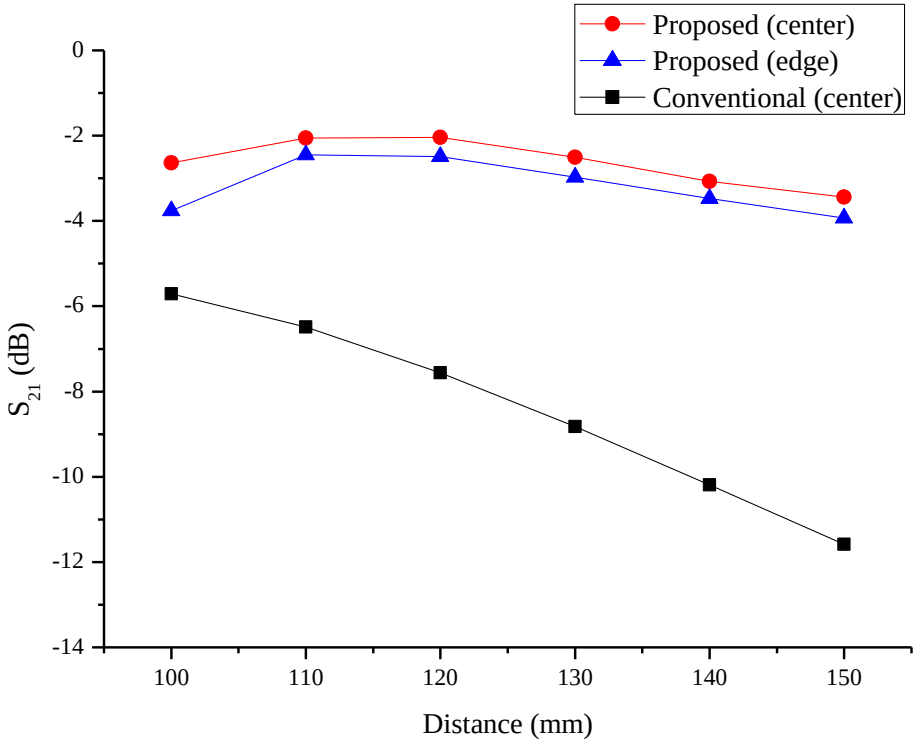
## 5. Measurements

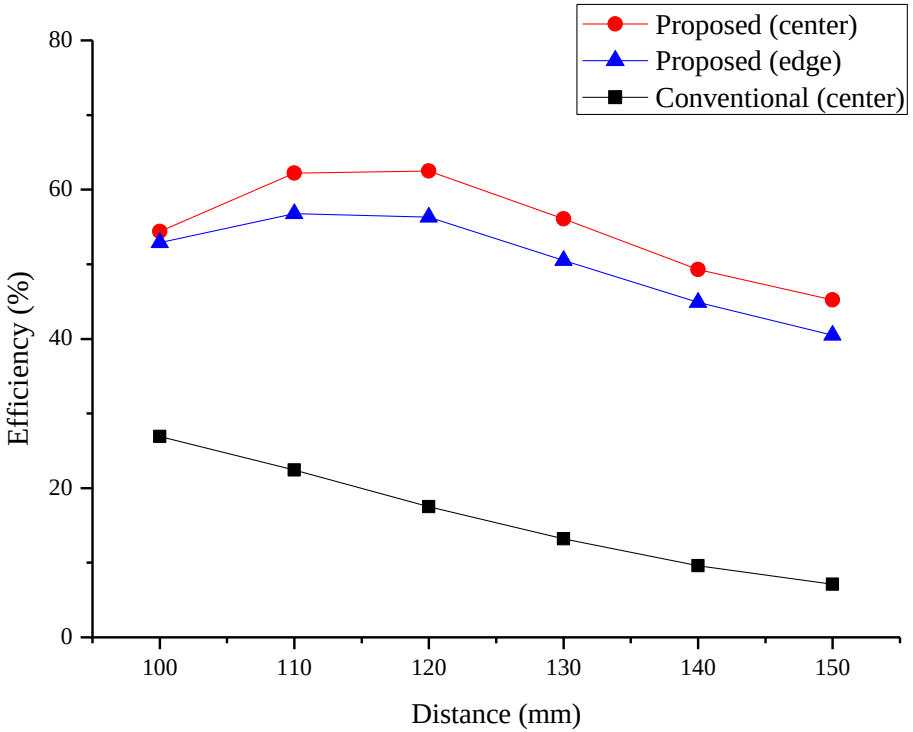
- Measurements - Comparison

| Distance (mm) | Conventional structure | | Proposed structure | | | |
|---|---|---|---|---|---|---|
| | | | Center | | Edge | |
| | $S_{21}$ (dB) | Efficiency (%) | $S_{21}$ (dB) | Efficiency (%) | $S_{21}$ (dB) | Efficiency (%) |
| 100 | -5.71 | 26.9 | -2.64 | 54.4 | -2.76 | 52.9 |
| 110 | -6.49 | 22.4 | -2.06 | 62.2 | -2.45 | 56.8 |
| 120 | -7.56 | 17.5 | -2.04 | 62.5 | -2.49 | 56.3 |
| 130 | -8.82 | 13.2 | -2.51 | 56.1 | -2.97 | 50.5 |
| 140 | -10.19 | 9.6 | -3.07 | 49.3 | -3.47 | 44.9 |
| 150 | -11.58 | 7.1 | -3.44 | 45.2 | -3.93 | 40.5 |

## 5. Measurements

- Measurements - Comparison



# Contents

## 6. Conclusion

- 메타구조를 이용하여 제로굴절률 특성 설계 및 구현
  - Spiral structure & Capacitor

- 제로 굴절률 메타구조를 이용하여 원거리에서도 고효율 특성 확인

- 송수신 공진기 거리에 따른 효율 측정
  - $S_{21}$ : -2.04 dB ~ -3.44 dB
  - 효율 : 45.2 % ~ 65.2 %

- 수신 공진기의 위치가 중심에서 벗어나도 고효율 특성 유지 확인

# Thank you

# Q & A