Meta-Resonators in Iron Oxide Enhanced Building Materials for Wireless Communications

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Team

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Contents

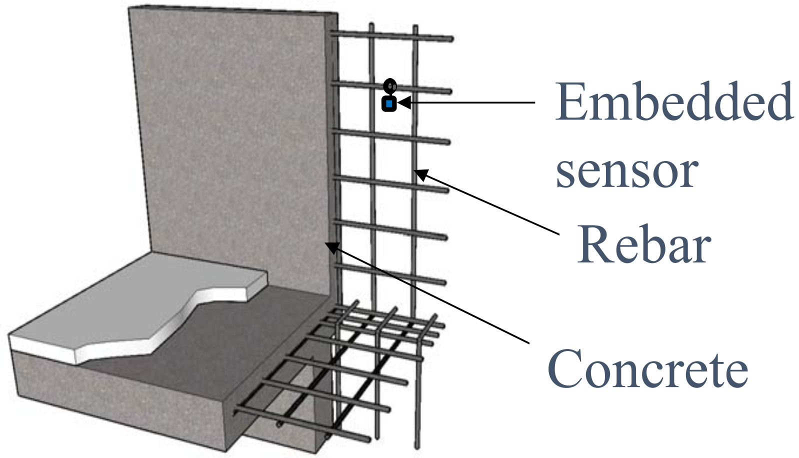
Background

- Increasing urban population drive research in sustainable and smart buildings.
- USGBC and SGBC are certifying buildings with LEED and Green Mark to promote greener buildings
- One key contributor to this goal is to use Wireless Sensor Networks (WSNs) and Massive Internet of Things (MIOT) in the future in buildings for better monitoring and controls.
- Wireless communications is a critical factor affecting design of embedded WSN and MIOT.

Background

- One application of WSN and MIOT is to embed into building materials.

- Wireless sensors can be pre-cast.



- Monitor structural behaviour

- In embedded WSN and MIOT, however, building materials have high shielding effectiveness making wireless communications design challenging.

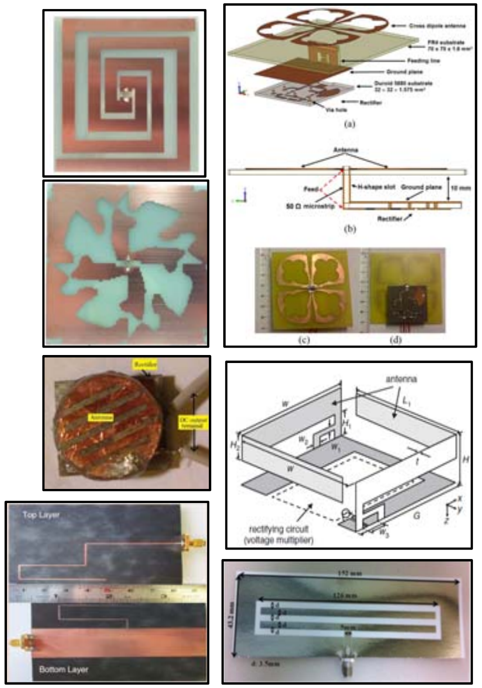
Background

- Concrete: cement, water, aggregates, admixtures
- Admixtures alters the behaviour and properties of concrete
- Admixtures are added to enhance cement such as improving workability and colouring.
- Metal oxides are used to colour cement, example iron oxides colour red.
- Antennas can be improved by synthesising material with metallic particles mixed with the dielectric*.

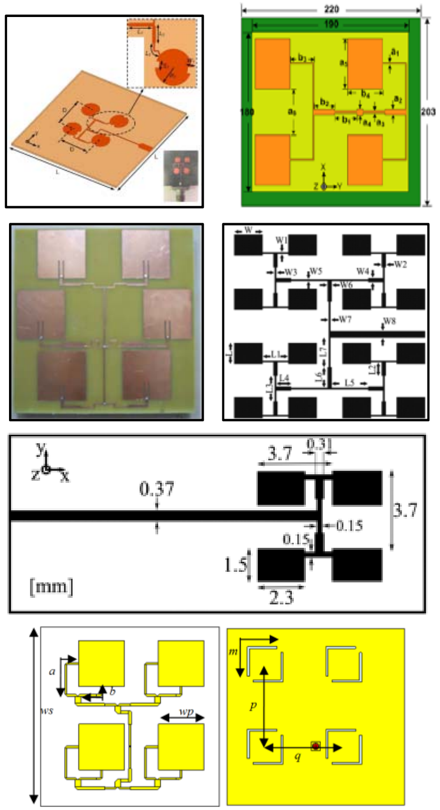
* M. Fallahpour and R. Zoughi, "Antenna Miniaturization Techniques: A Review of Topology- and Material-Based Methods," *IEEE Antennas and Propagation Magazine*, vol. 60, no. 1, pp. 38-50, Feb. 2018.

Background

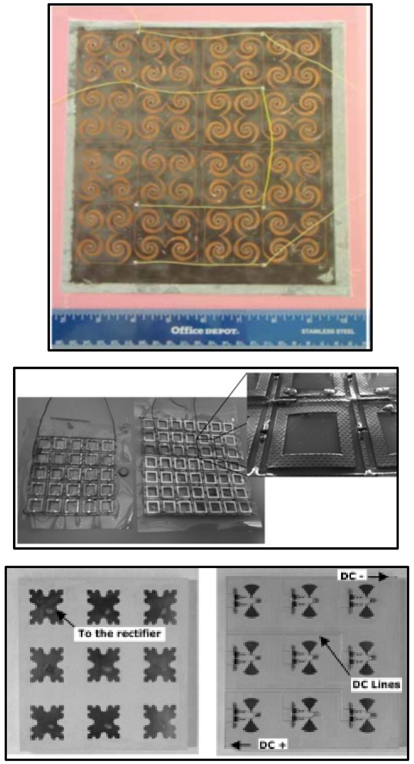
Single Antenna



Array Antenna



RF Rectenna



Limitations

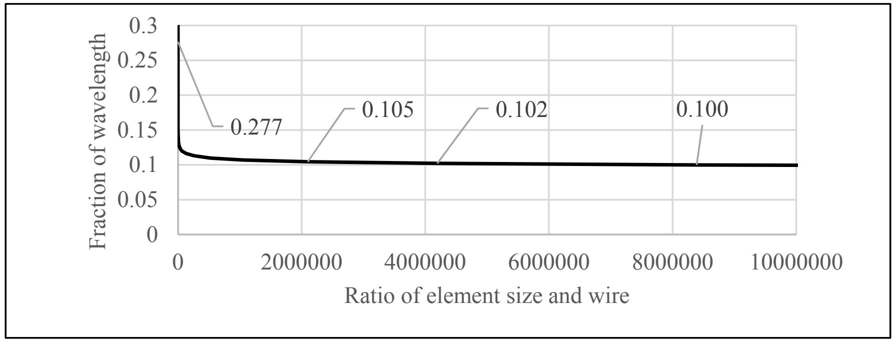
- Low area utilisation with element size ≥ 0.15λ and element spacing of ≥ 0.3λ.
- Non-tunable.
- Possibly expensive to scale.
- Not suitable for embedding in building materials.

Background

Metamaterial is defined as "**artificial** effectively **homogeneous** electromagnetic structures with unusual properties not readily available in nature… an effectively homogenous structure is a structure whose structural average cell size p is **much smaller** than a quarter of wavelength, $\mathbf{p} < \frac{\boldsymbol{\lambda}_\mathbf{g}}{\mathbf{4}}$"[1]

Pendry[2]
$a \ll \lambda = 2\pi c_0 \omega^{-1} < \frac{\lambda}{\sqrt{2\pi \ln\left(\frac{a}{r}\right)}}$*

*plasma frequency is equal to the resonance frequency



$a < 0.1\lambda$ → Electrically small antenna can be used as unit cell or element

[1]C. Caloz and T. Itoh, Electromagnetic metamaterials: transmission line theory and microwave applications: John Wiley & Sons, 2005.

[2]J.B. Pendry, A.J. Holden, D. J. Robbins, and W. J. Stewart, "Magnetism from conductors and enhanced nonlinear phenomena," *Trans. Microw. Theory Tech.*, vol. 47, no. 11, pp. 2075–2084, 1999.

[3]H. A. Wheeler, "The Radiansphere Around a Small Antenna," in *Proc. IRE*, vol. 47, no. 8, pp. 1325–1331, 1959.

Objective

- Key Objective:

  Enabling WSN sensors to communicate wirelessly in building materials for MIOT.

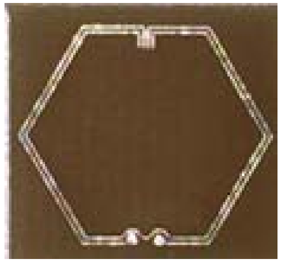
- Challenges and motivations:

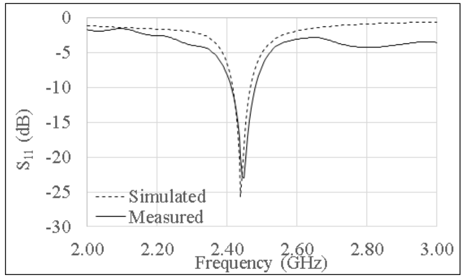
  A method of embedding antenna in building materials to enhance the RF performance of embedded antenna and materials.

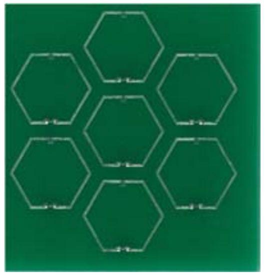
Motivation and Contribution

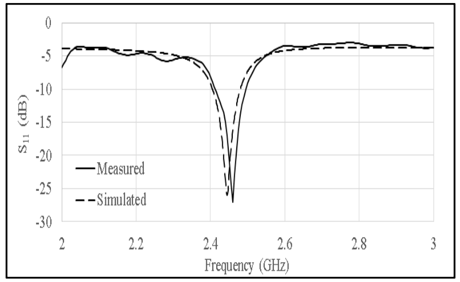
Motivation

1. Main shortcoming of metaresonators and metaresonator arrays have narrow bandwidth of less than 3%.
2. Building materials do not benefit but degrade the performance of antennas embedded in them.









Objective

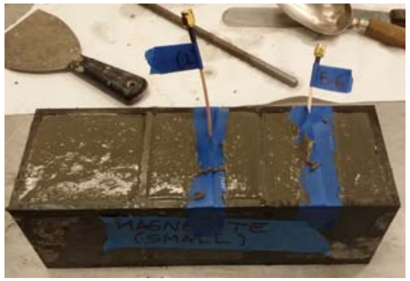
Use the surrounding dielectric of the building materials to enhance the performance of the embedded antenna and the material.

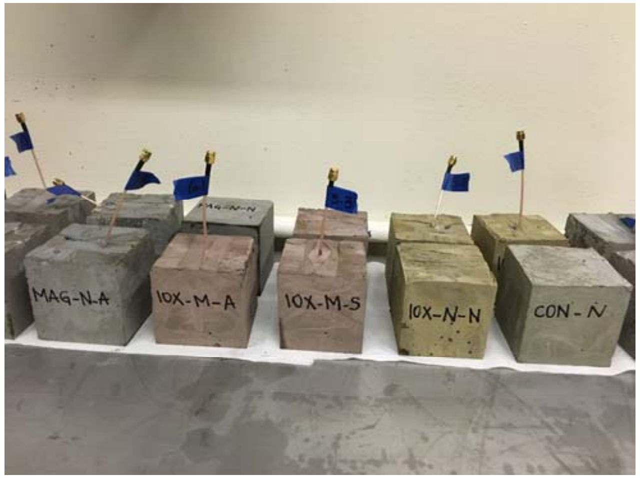
Contribution

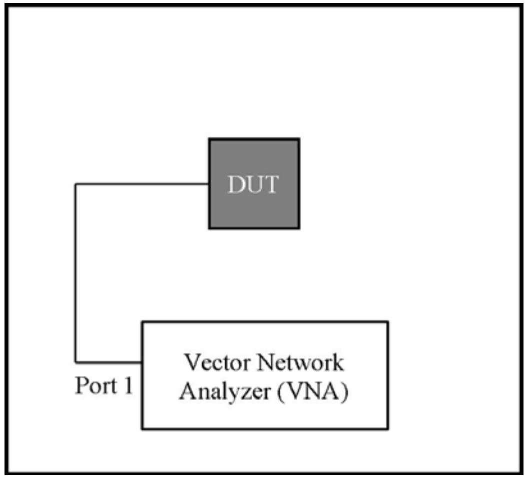
Determined micro-sized iron (III) oxide enhanced cement paste improves the impedance matching and bandwidth of antenna, and RF transparency of cement paste.

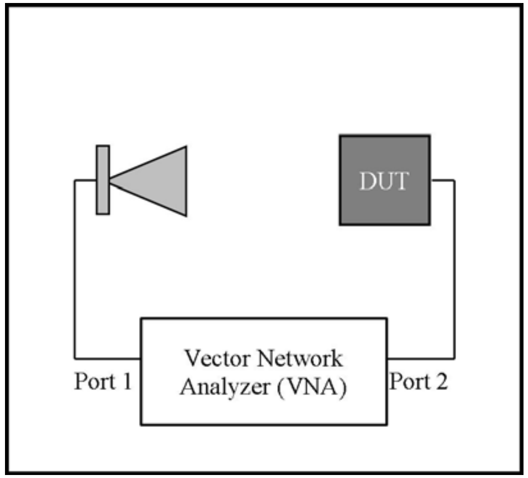
Methodology

Sample type	Size	Percentage by weight	Label
Micro-sized magnetite	$< 5\ \mu m$	0.5%	MAG-M
Nanosized magnetite	$5 - 100\ nm$	0.5%	MAG-N
Micro-sized iron (III) oxide	$< 5\ \mu m$	0.5%	IOX-M
Nanosized iron (III) oxide	$< 50\ nm$	0.5%	IOX-N









Understanding

On the effects of quality factor and bandwidth

$$Q > \frac{1}{(ka)^3} + \frac{1}{ka}$$

where $k = \frac{2\pi}{\lambda}$, and a is the radius of the sphere enclosing the antenna.[1]

Thus ESA has high Q.

However, we want to lower the Q to increase power radiated as

$$Q = \frac{\omega W}{P_{rad}}$$

where ω is the angular frequency, W is the average stored energy, and P_{rad} is the radiated power.[2]

[1]Chu, L. J., "Physical limitations of Omni-Directional Antennas," *J. Appl. Phys.*, vol. 19, pp. 1163–1175, 1948
[2]D. M. Pozar, *Introduction to Microwave Systems in Microwave Engineering,* 4th Ed, Wiley, 2011, pp. 670–671

Understanding

On the effects of quality factor and bandwidth

[1]If a transverse electromagnetic is considered, TEM wave propagation on a two-wire conductor, and assuming sinusoidal steady-state, the complex propagation constant can be obtained as

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}$$

where α is the attenuation constant, $\beta = k_0\sqrt{\mu_r \varepsilon_r}$ is the phase constant, $k_0 = \sqrt{\mu_0 \varepsilon_0}$ is the propagation constant (wave number) of a plane wave in free space, R is the series resistance per unit length $(\frac{\Omega}{m})$, L is the series inductance per unit length $(\frac{H}{m})$, G is the shunt conductance per unit length $(\frac{S}{m})$, and C is the shunt capacitance per unit length $(\frac{F}{m})$.

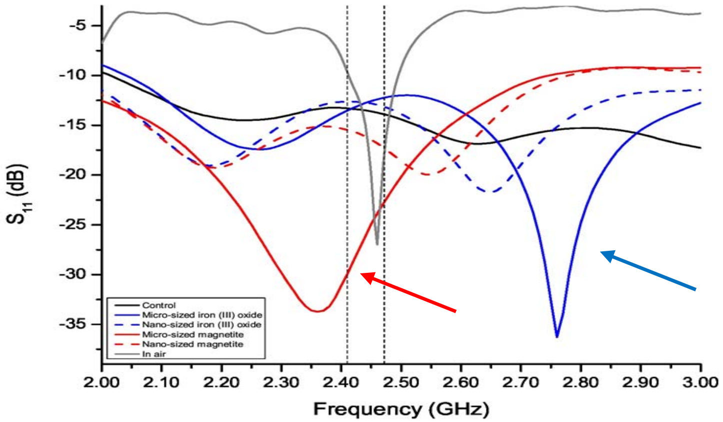
$$Q = \frac{\beta}{2\alpha} = \frac{k_0\sqrt{\mu_r \varepsilon_r}}{2\alpha}$$

[1]D. M. Pozar, *Introduction to Microwave Systems in Microwave Engineering,* 4th Ed, Wiley, 2011, pp. 670–671

Results

Comparison of S_{11}

Sample type	Change in S_{11} (dB)	Frequency shift (%)
Cement paste only (Control)	−2.01	23.20
Cement paste with micro-sized magnetite particles	−17.26	−3.87
Cement paste with nanosized magnetite particles	−6.19	3.66
Cement paste with micro-sized iron oxide particles	−19.28	12.20
Cement paste with nanosized iron oxide particles	−9.07	8.35

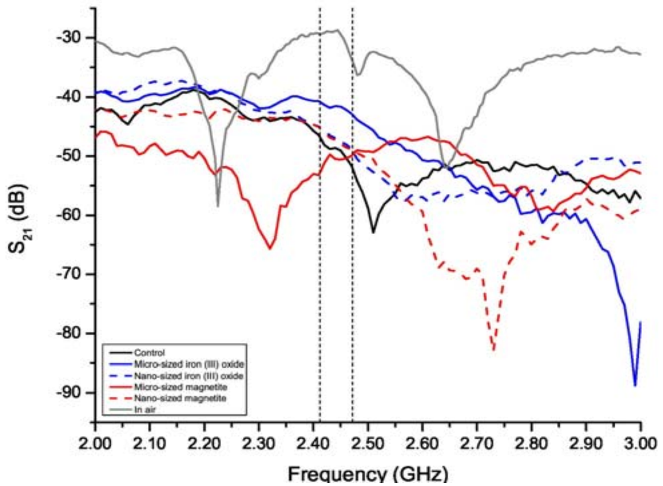


- Micro-sized particles have a better effect on S_{11} than nano-sized particles.
- The shape of S_{11} is maintained for micro-sized particles, while the shape for nano-sized particles are distorted.

Results

Comparison of S_{21}

Sample type	S_{21} (dB)		Change in S_{21} (dB)	
	Channel 1	Channel 13	Channel 1	Channel 13
Cement paste only (Control)	−46.47	−54.21	-	-
Cement paste with micro-sized magnetite particles	−53.23	−49.46	−6.76	4.75
Cement paste with nanosized magnetite particles	−45.10	−49.35	1.37	4.75
Cement paste with micro-sized iron oxide particles	−40.49	−43.88	5.98	10.33
Cement paste with nanosized iron oxide particles	−45.20	−49.52	1.27	4.69



- Within the WiFi spectrum, micro-sized iron (III) oxide particles improves the S_{21} more than control sample and other samples.

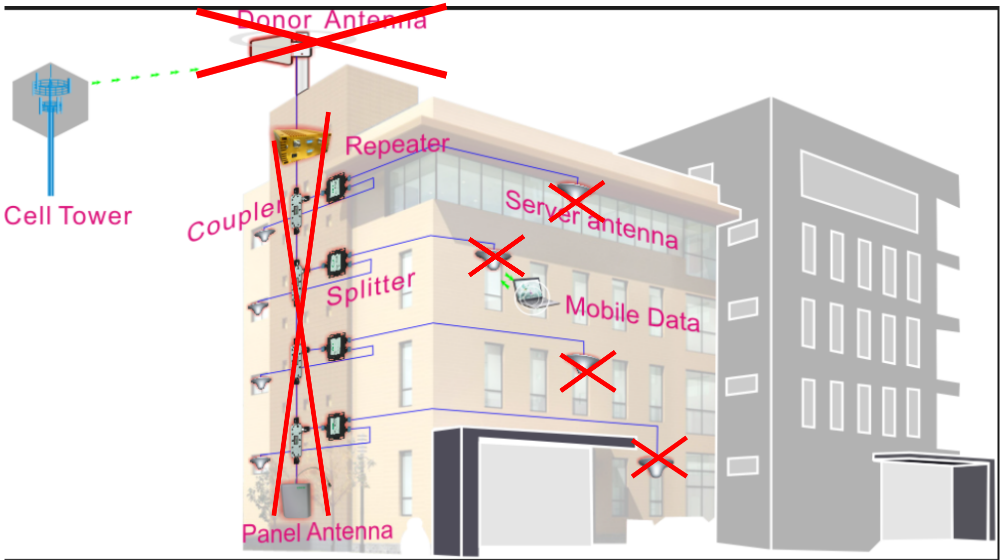
Future Work

5G network

3.5 GHz

26 GHz

28 GHz



https://www.signalbooster.com/products/hiboost-pro-quint-4g-lte-industrial-cell-booster-f27-5s

- Improve reception of 4G / 5G mobile and digital TV signals in buildings.
- Reduce mobile network capital cost for buildings

Concluding Remarks

Motivation

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Publication

- Y.L. Sum, V. Rheinheimer, B.H. Soong, P.J.M. Monteiro, "Effects of Cement Paste Enhanced with Iron-Based Magnetic Particles on an Embedded Small Resonator Antenna," Nature Scientific Report, 7, Article number: 15185, 2017. **(Published)**

Contributions

Contributions	Outcome	Results
Combining concepts from MM, ESA, and antenna array to select a suitable element size	• Determined element size of 0.1λ	• Y.L. Sum, B.H. Soong, K.J. Tseng, "Selection of Unit Cell Size for RF Energy Harvesting Metaresonator Array," in *5th IET International Conference on Renewable Power Generation (RPG)*, London, 2016, pp. 1-6. **(Published)**
Design and fabrication of 0. 1λ 2.4 GHz ESA	• ESA of size 0.1λ • Planar • FR-4 • No external loading • Tunable	• Y.L. Sum, B.H. Soong, "Design of 2.45 GHz ESA Metaresonator," in *2017 International Workshop on Antenna Technology: Small Antennas, Innovative Structures, and Applications (iWAT),* Athens, 2017, pp. 281-284. **(Published)**
Design and fabrication of 2.4 GHz antenna array	• Using 0.1λ ESA to form antenna array • Higher area utilisation • Tunable	• Y.L. Sum, V. Rheinheimer, B.H. Soong and P.J.M. Monteiro, "Scalable 2.45 GHz Electrically Small Antenna Design for Metaresonator Array," in *The Journal of Engineering*, vol. 2017, no. 5, pp. 170-174, 5 2017. **(Published)** • Y.L. Sum, B.H. Soong, K.J. Tseng, "Metamaterial Split Ring Resonator, Metamaterial Split Ring Resonator Array and Energy Harvesting Apparatus", *Patent Cooperation Treaty, PCT/SG2017/050384*, 28th July 2017**. (Filed)**
Embedding antenna array in enhanced building materials	• Identified 4 wt% micro sized iron (III) oxide to be beneficial	• Y.L. Sum, V. Rheinheimer, B.H. Soong, P.J.M. Monteiro, "Effects of Cement Paste Enhanced with Iron-Based Magnetic Particles on an Embedded Small Resonator Antenna," Nature Scientific Report, 7, Article number: 15185, 2017. **(Published)** • Y.L. Sum, V. Rheinheimer, B.H. Soong, P.J.M. Monteiro, "Antenna In Enhanced Building Composites", *US Provisional Patent Application No. 62/430,172*, 5th December 2016. **(Filed)**

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