Introduction to Metamaterials: Application to Communications Systems Design

Ignacio Gil

Departament d’Enginyeria Electrònica
Universitat Politècnica de Catalunya, Spain
Outline

- Motivation
- Metamaterials Introduction
- Applications
  - Filtering
  - Couplers, Diplexers, Dividers
- Design Example: RF-MEMS Metamaterials
- Conclusions
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Motivation

IF stages and signal processing
Motivation

New Design Strategies
- Electromagnetic BandGaps
- METAMATERIALS

Technologies
- Micromachining
- RF MEMS
- MCM-D

- Devices isolation
- Filtering
- Espurious suppression
- Miniaturization
- Radiation leakage inhibition
- Tunability
- Efficiency

- Low-losses
- High-Q
- Si Technology
- Reconfigurable devices
- Multi-metal structures
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Metamaterials

Artificially fabricated material, based on periodic (or quasi-periodic) structures, with singular and controllable electromagnetic properties, not present sometimes in natural media.

Types

- Electromagnetic and Photonic Cristals (EBG, PBG)
- Effective media with negative index (LHM, ENG, MNG)

EBG

Period $\sim \lambda_g$
Bragg Effect
Bragg Condition

$$\beta = \frac{\pi}{p}$$

Woodpile structure

LHM

$\varepsilon, \mu$ simultaneiusly negative
Period $\ll \lambda_g$ (miniaturization)
**Metamaterials**

**Effective media metamaterials**
Artificial structures with controllable magnetic permeability and/or dielectric permittivity.

- **Refraction index**
  \[ n^2 = \varepsilon \cdot \mu \]

- **Phase constant**
  \[ \beta = \omega (\varepsilon \cdot \mu)^{1/2} \]

- **LHM**
  \( n, \beta < 0, n \in \mathbb{R} \) (Left Handed Media)

- **ENG**
  \( n, \beta \in \mathbb{I} \) (Plasmas, metals at optical frequencies)

- **RHM**
  \( n, \beta > 0, n \in \mathbb{R} \) (dielectric materials)

- **MNG**
  \( n, \beta \in \mathbb{I} \) (Ferrimagnetic materials)

- **Medios opacos**

- **Transparent medium**
- **Backward waves**
- **Negative refraction index !!!!!!!**
- **Left Handed Media (LHM)**
Metamaterials

Left Handed Materials– LHM (properties)

Maxwell Equations

\[ \nabla \times E = -\frac{1}{c} \frac{\partial B}{\partial t} \]
\[ B = \mu H \]
\[ \nabla \times H = \frac{1}{c} \frac{\partial D}{\partial t} \]
\[ D = \varepsilon E \]

Monochromatic plane wave

\[ \beta x E = \frac{\omega}{c} \mu H \]
\[ \beta x H = -\frac{\omega}{c} \varepsilon E \]

Poynting Vector

\[ S = \frac{c}{4\pi} ExH \]
Metamaterials

Left Handed Materials—LHM (properties)

Doppler effect

Cherenkov radiation

Curved lenses

Flat lenses

Negative refraction

Metamaterials

Synthesis of LHM (superposition of two artificial media)

\[ \varepsilon < 0 \]

\[ \mu < 0 \]

SRR - Pendry

\[ d \ll \lambda_g \]

F: Fractional area.

\[ \omega_o: \text{resonance frequency} \]

\[ \mu < 0 \iff \omega_o < \omega < \omega_o/(1-F)^{1/2} \]

Plasma frequency

First synthesis of a LHM – Smith, 2000
Metamaterials

SRR

Excited by an axial magnetic field

Current loops between the rings

LC tank behaviour

Medium with $\mu < 0$

$C_0 = \pi \cdot r \cdot C_{pul}$

$\omega_o = \frac{2}{\pi \cdot r \cdot C_{pul} L_s}$

$\mu = 1 - \frac{F \omega^2}{\omega^2 - \omega_o^2}$

$F$: fractional area

$\mu < 0 \iff \omega_o < \omega < \omega_o/(1-F)^{1/2}$
Complementary Split Rings Resonator (CSRR)

Excited by an axial electric field

CSRRs can be placed in the ground plane of a microstrip line.

Medium with \( \varepsilon < 0 \)

\[ f_{\text{SRR}} \approx f_{\text{CSRR}} \]

First resonant particle with negative permittivity
Metamaterials

Considered technologies

CPW

- SRRs etched in the slot region
  - Upper metal level
  - Back side of the substrate
- CSRRs etched in the ground plane or in the central strip.

Microstrip

- SRRs etched in the upper side of the substrate, beside the conducting strip.
- CSRRs etched in the ground plane or in the conducting strip.
Metamaterials

SRRs $\mu < 0$

Inductors $\varepsilon < 0$

Superposition

LHM Medium

Backward Wave Propagation

$S(2,1)$

SRRs

Wires

$E$

$H$

$S$
Metamaterials

1\textsuperscript{st} LHM planar structure based on SRRs

- Good frequency selectivity
- Small dimensions
- Out of band rejection $> 25\text{dB}$

IL $\approx 3.5\text{dBs}$

BW $\approx 0.6\text{GHz}$

F. Martin \textit{et al.}, \textit{APL}, 2004
Metamaterials

CSRRs
\( \varepsilon < 0 \)

GAPS
\( \mu < 0 \)

SUPERPOSITION

LHM MEDIUM

BACKWARD WAVE PROPAGATION
Metamaterials

I.Gil

2\(C_g\) \quad L/2 \quad C \quad L/2 \quad 2\(C_g\)

\(L_C\) \quad C_C

F. Falcone et al., PRL, 2004

IL \approx 4\text{dBs}

BW \approx 0.4\text{GHz}
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Applications: Narrow Band Pass Filters


Applications: Ultra Wide Band Pass Filters

Bonache et al.,
Applications: Improved Stop Band Filter

Applications: Tunable Filters

I. Gil et al., Electronics Letters, 2004

Infineon BB833
9pF-0.75pF (0V-28V)

Tunable BW

μ<0
Applications: Tunable Filters

Electric simulations (with losses)

Measurement

Tuning range > 30%

Applications: Couplers, Diplexers, Dividers


M. Gil et al., *PIERS*, 2006
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Tunable Metamaterials

- 1-D tunable metamaterials structures implemented in microstrip technology by using VLSRR
- Significant losses due to varactor-metal junction resistance
- Low quality factor, Q~10-30

RF-MEMS Metamaterials
CSRR+RF-MEMS CPW Unit Cell

- CSRR
  - $c=d=10\mu m$
  - $l=480\mu m; w=130\mu m$

- CPW
  - $W=150\mu m; G=30\mu m$

- RF-MEMS bridge
  - $B=80\mu m; b=100\mu m$
  - $H=290\mu m; h=40\mu m$

RF-MEMS modifies the electrical characteristics of CSRR ($f_o$)
CSRR+RF-MEMS CPW Simulation

- 4-stage periodic device
- 50Ω CPW structure
- Agilent Momentum
  - Coplanar mode
  - Mesh frequency = 100GHz
  - Mesh density = 20 cells/λ
- Device length: 2780μm
- Distance between CSRR: 220μm
- No mechanical effects
  - Up-state: MEMS_h = 2μm
  - Down-state: MEMS_h = 0.5μm
CSRR+RF-MEMS CPW Simulation

- $f_0$ at Q-band: 39.2-49.2GHz
- Tuning Range: ~20%
- Rejection Level: IL<-50dB
- No losses simulation
CSRR+RF-MEMS CPW Technology

- Stripped-down RF-MEMS technology
- 3 lithographic steps
  - Al layer sputter-deposited and patterned on AF45 glass substrate (CPW structure)
  - Sacrificial photoresist layer (anchoring regions of the MEMS)
  - Al layer deposited (sacrificial layer removal)
- Electrically floating bridge anchored directly on the substrate in holes of the CPW ground planes
- Down-state: bridge only contacts the centre of CPW strip
- Native Al oxide as interposer to prevent DC shorts

- Al layer thickness: $t_{\text{Al}}=1\ \mu\text{m}$
- AF45 substrate: $\varepsilon_r=5.9$; $h=650\ \mu\text{m}$
- Photoresist Layer: $t_{\text{Ph}}=3\ \mu\text{m}$
CSRR+RF-MEMS CPW Experimental

- Actuation Voltage: 0-17V
- $f_0$ at Q-band: 39-48GHz
- Tuning Range: $\sim$20%
- Rejection Level: IL<-40dB
- Good losses level (<-3dB)
Simulation vs Experimental

- Good agreement
- Approximation validated

I. Gil et al., *Electronics Letters*, 2008
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Conclusions

- **Metamaterials**: Microwave engineering solution in order to achieve compact and miniaturized devices with a significant performance improvement

- **Applications**: Filtering, couplers, diplexers, dividers, etc

- **Performance**:
  - Filtering: **BPF**: high selectivity; **UWBPF**; **RPF**: high rejection
  - Tunable devices: **Tuning range**~20%, **IL**<-40dB, high-Q (low losses)

- **Future work**: RF-MEMS Band pass frequency response (ε,μ<0), electrical modelling
Thanks for your attention!

Questions??