Analysis and Design of Left-Handed Metamaterial Lenses Using Ansoft HFSS

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Introduction: Left-Handed Metamaterials

Historical Milestones

• 1968: theoretical analysis of hypothetical LH materials by Veselago
• 1996/9: introduction of electric ($\varepsilon < 0$) / magnetic ($\mu < 0$) plasmon by Pendry
• 2000: experimental demonstration of LH structure by Smith

LH definition: $\varepsilon < 0$ and $\mu < 0 \Rightarrow n < 0$ and $v_p - || v_g$

$\rightarrow$ unit-cell $<< \lambda \rightarrow$ effective / macroscopic / homogeneous

Resonant Structure Approach

• approach: no simple/rigorous analysis & no design method
• structures: RESONANT $\Rightarrow$ lossy & narrow bandwidth & highly dispersive

Transmission Line Approach

• approach: Transmission line analysis & circuit design methods
• structures: NON-RESONANT $\Rightarrow$ low loss & broad bandwidth & moderate dispersion

“BACKWARD WAVES”
(e.g. Brillouin, Pierce)
Negative Refractive Index Lenses

RH medium
refractive index \( n_{RH} \)

LH medium
refractive index \( n_{LH} \) (\(<1\))

Plane Wave ↔ Cylindrical Wave

HFSS Simulations: Effective Medium (\( \varepsilon < 0, \mu < 0 \))

flat lens

parabolic lens

magnitude

phase

magnitude

phase
Composite Right/Left-Handed TL

CRLH metamaterial includes LH and unavoidable RH parasitic effects.

LH at low frequencies
RH at high frequencies

1-D unit cell

\[ \begin{align*}
C_L & \quad L_R \\
C_R & \quad L_L
\end{align*} \]

2-D unit cell

\[ \begin{align*}
p & \quad \text{period of unit cell}
\end{align*} \]

patch

via

ground plane

\[ \begin{align*}
\omega & \quad \beta \\
\omega_{se} & \quad \omega_{sh} \\
-\beta_c & \quad +\beta_c
\end{align*} \]
HFSS Characterization of 2-D CRLH TL

HFSS Eigenmode Simulation w/PBCs

CRLH unit cell → master/slave boundaries on all 4 sides

Dispersion Diagram (HFSS)

\[
(p=5.0 \text{ mm}, \ g=1.0 \text{ mm}, \ h=1.27 \text{ mm}, \ \varepsilon_R=10.2)
\]

\[
\text{RH: } \lambda_g \sim \frac{1}{f} \quad \text{LH: } \lambda_g \sim f
\]

17x17 Mushroom Array

17x17 Mushroom Array

Measured E-Field Phase Atop 17x17 Array

RH:
5.50 GHz
6.50 GHz
6.90 GHz

LH:
3.55 GHz
3.75 GHz
4.00 GHz
RH/LH Interface Matching Conditions

Dispersion Diagram

Refractive Index

$n_{CRLH} = -3.2 \ @ \ f = 3.77 \ GHz$

need $n_{RH} = - n_{CRLH} = 3.2$
HFSS Simulation of NRI Lenses

* CRLH and RH regions interchanged for simulation
Measured Results

$\tilde{f}_0 = 3.79 \text{ GHz}$

Mushrooms (21x10 cells)
* Entire structure built on $\varepsilon_R = 10.2$ substrate

$\tilde{f}_0 = 3.77 \text{ GHz}$

~ Mushrooms (23x16 cells) in outlined area