Some Novel Directions In Metamaterials Engineering

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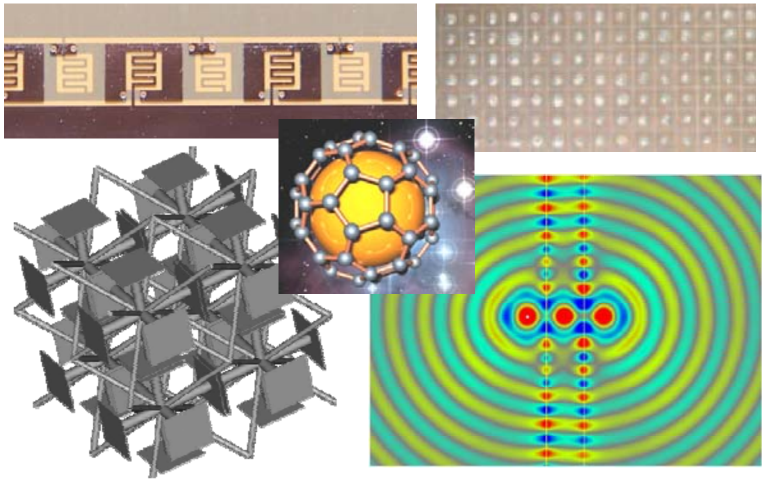

Outline

1. BROADBAND METAMATERIALS
2. INNOVATIONS IN CRLH LEAKY-WAVE ANTENNAS
3. ANALOG SIGNAL PROCESSORS
4. FERROMAGNETIC NANOWIRE COMPOSITES
5. CONCLUSIONS

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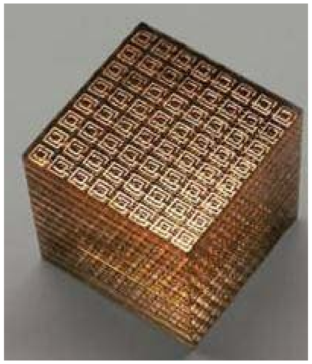
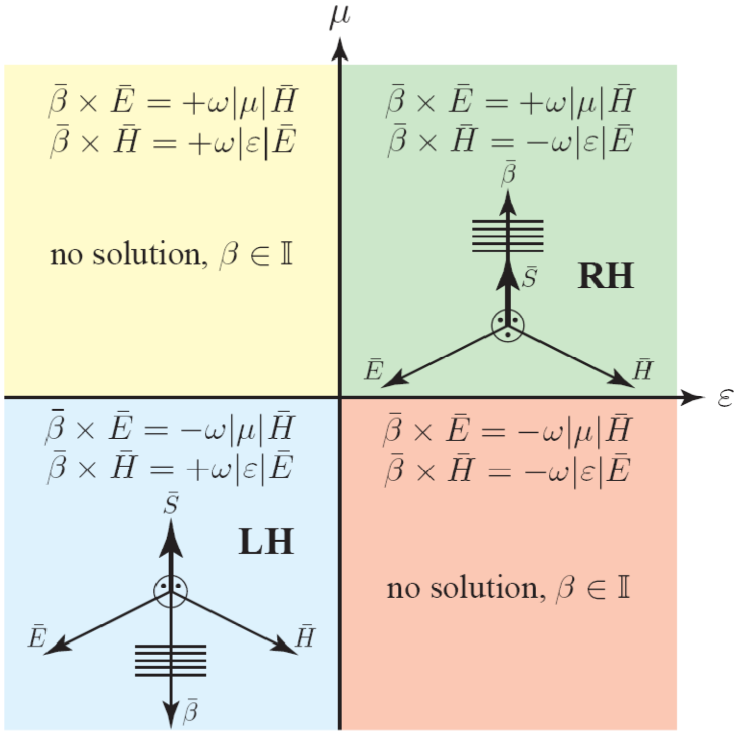
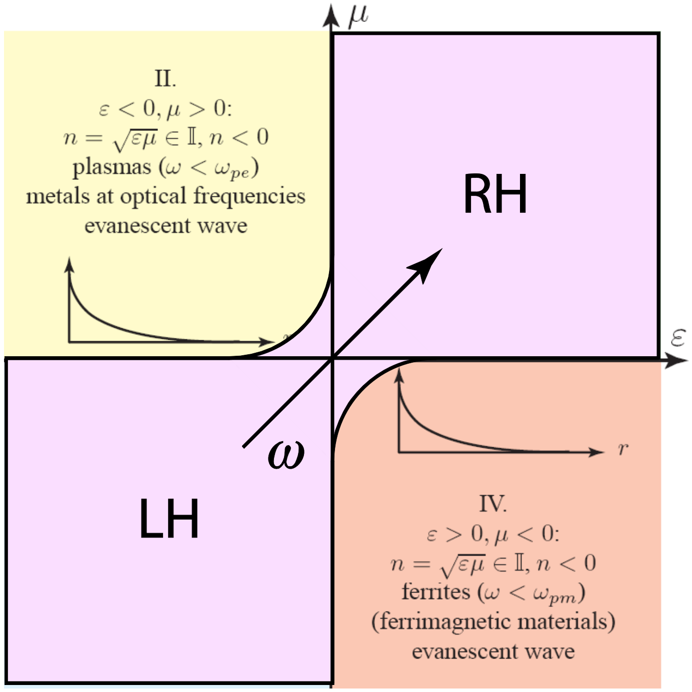
What is a Metamaterial (MTM) ?

Definition: **artificial effectively-homogeneous EM structure with unusual & useful properties:**
negative & less-than-1 refractive index (LH), dispersion, nonlinearity, bi-anisotropy, coord.-transformed GRIN (cloaking), nano-localization, quantum effects, etc.

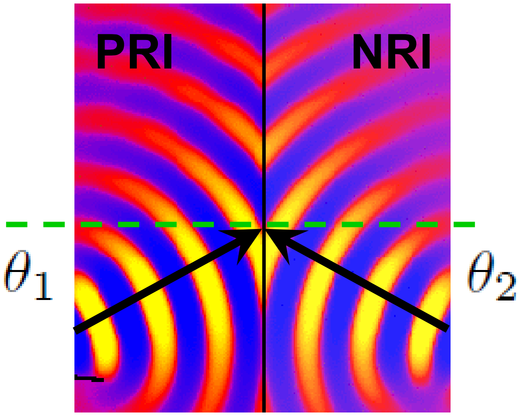




CRLH



Negative refractive index



$$\bar{E} = \bar{E}_0 e^{-j\bar{\beta}\cdot\bar{r}}$$

$$\bar{H} = \frac{\bar{E}_0}{\eta} e^{-j\bar{\beta}\cdot\bar{r}}$$

$$\Rightarrow$$

$$\nabla \times \bar{E} = -j\omega\mu\bar{H}$$

$$\nabla \times \bar{H} = j\omega\varepsilon\bar{E}$$

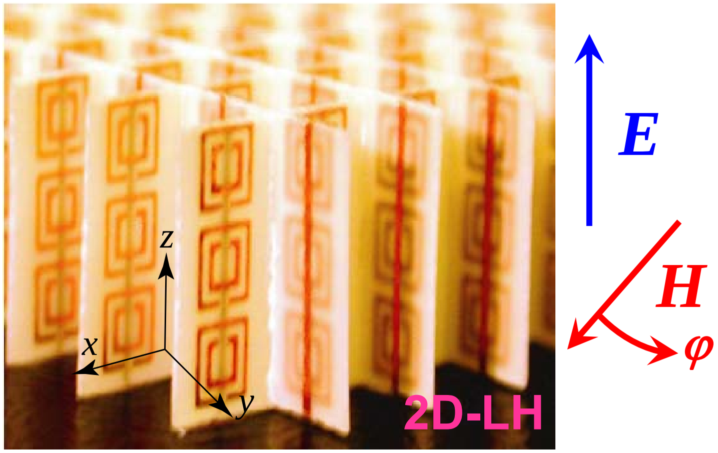
$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$$\theta_2 = \sin^{-1}\left[\frac{n_1}{n_2}\sin\theta_1\right] \overset{\theta_1 \ll 90^\circ}{\approx} \sin^{-1}\left(\frac{n_1}{n_2}\theta_1\right) \overset{n_2/n_1<0}{<} 0$$

Resonant versus Transmission Line Metamaterials

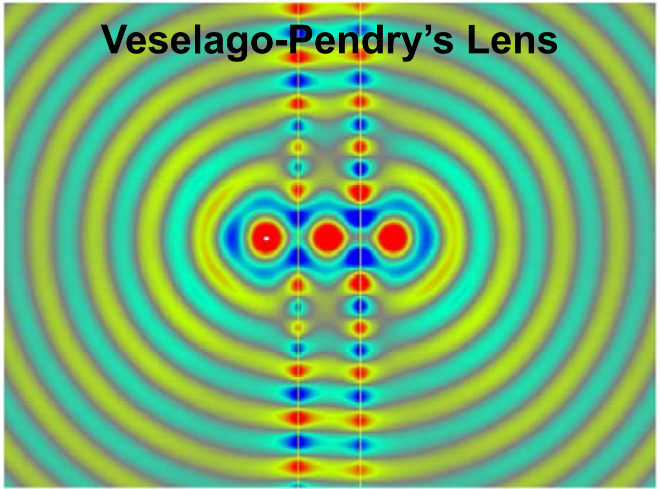
Resonant Particle

Smith et al., 2000-2001



- Narrow band ×
- Highly lossy ×
- Bulky ×

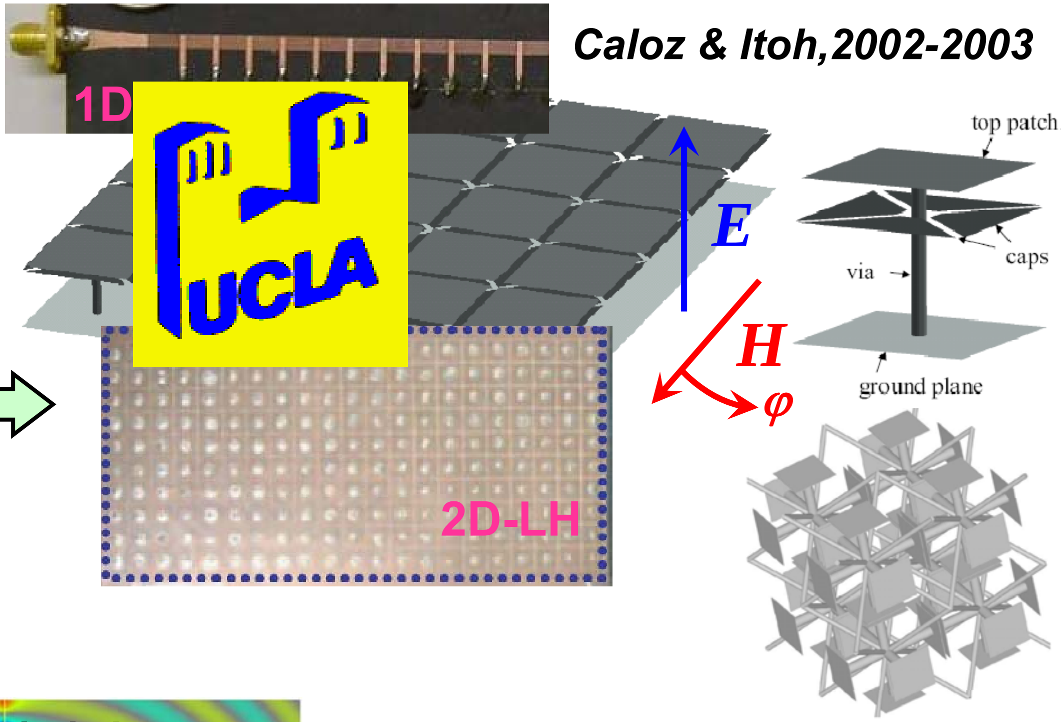
$$Q_l = \frac{f_{res}}{BW_{3\mathrm{dB}}}$$



Veselago-Pendry's Lens

Transmission Line

Caloz & Itoh,2002-2003

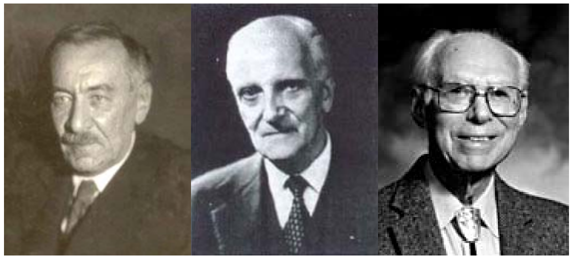


- Broad band → *LC control* ✓
- Low Loss → *Matched* ✓
- Planar → *MIC/MMIC* ✓
- Volumetric → *stacking* ✓
- <u>Dispersion engineering</u> ✓
- Also Optics ✓

Metamaterials (MTMs): Historical Milestones

Artificial Dielectrics = MTMs

- **Bose, 1889:** twisted jute
- **Lindman, 1914:** chiral helixes
- **Kock, Cohn, 1940-60:** dielectric lenses/radoms

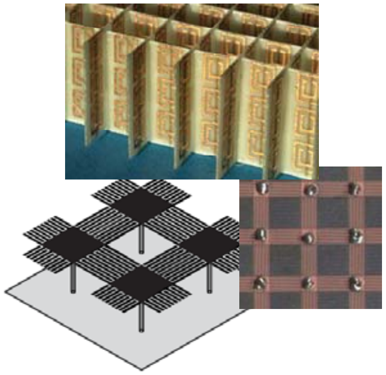


Precursors of LH MTMs:

- **Mandelshtam, 1944:** NRI
- **Brillouin, 1946:** BWD waves in periodic structures
- **Pierce, 1950:** BWD TWT

'Father' of 'LH' MTMs:

Victor Veselago, 1967: fundamentals of LH MTMs



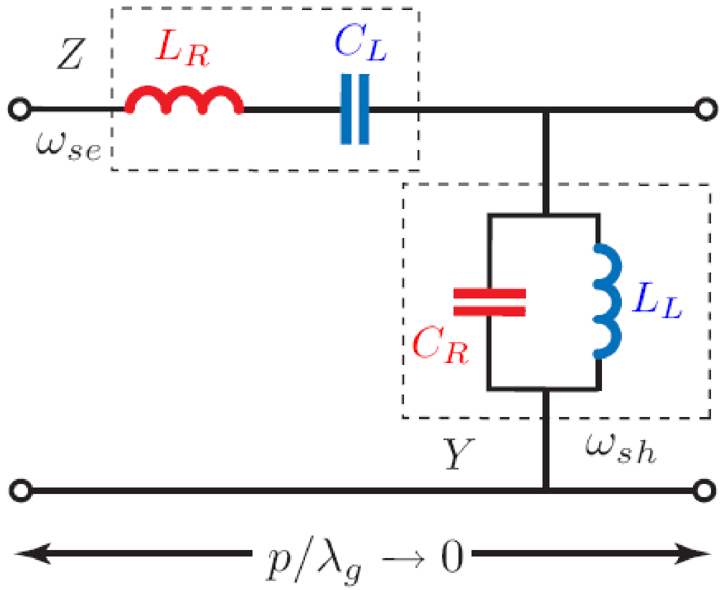
'Modern' NRI MTMs

- **Pendry, 1998-9:** $\varepsilon < 0$ wires & $\mu < 0$ split ring resonators
- **Smith *et al*., 2000-1:** 1st demo of LH MTM
- **Caloz & Itoh, Eleftheriades, Oliner, 2002:** nonresonant TL
- …

time

Transmission Line (TL) Approach

CRLH Model

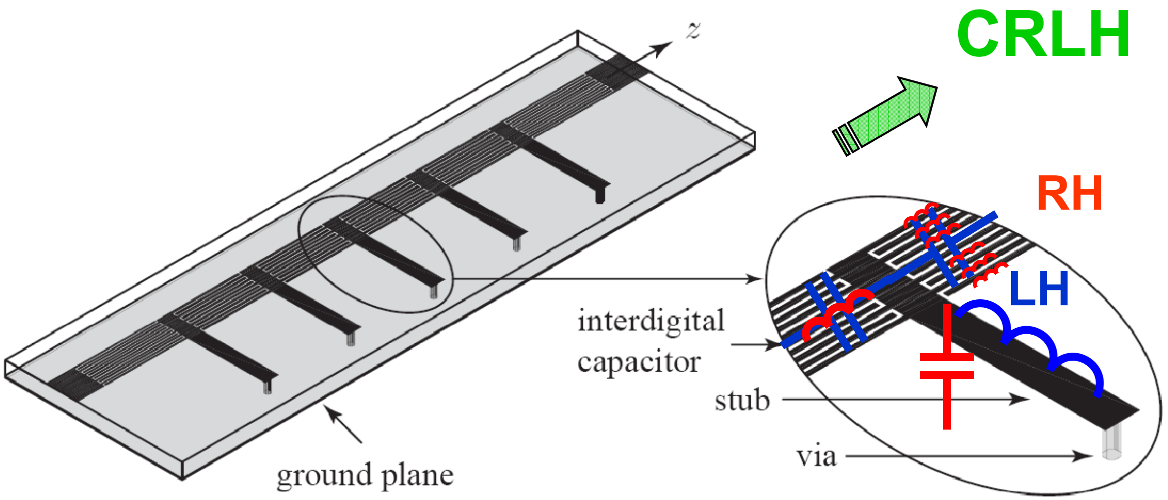


$$\text{balanced resonances: } \frac{1}{L_R C_L} = \frac{1}{L_L C_R}$$

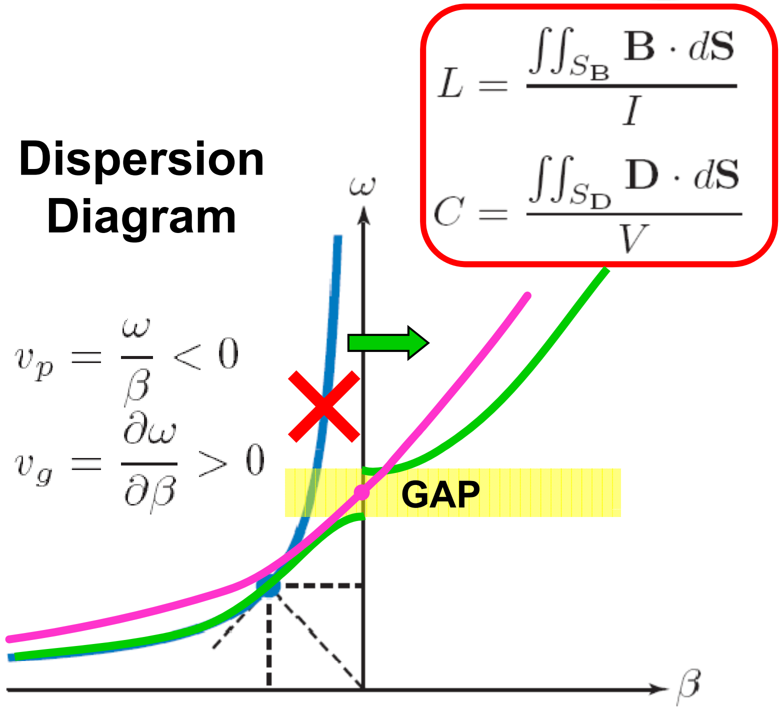
$$\beta(\omega) = \omega\sqrt{L_R C_R} - \frac{1}{\omega\sqrt{L_L C_L}} \rightarrow \text{no gap}$$

$$Z_c(\omega) = \sqrt{\frac{L_R}{C_R}} = \sqrt{\frac{L_L}{C_L}} = Z_0 \rightarrow \text{const}$$

Microstrip Implementation



Dispersion Diagram



$$L = \frac{\iint_{S_\mathbf{B}} \mathbf{B} \cdot d\mathbf{S}}{I}$$

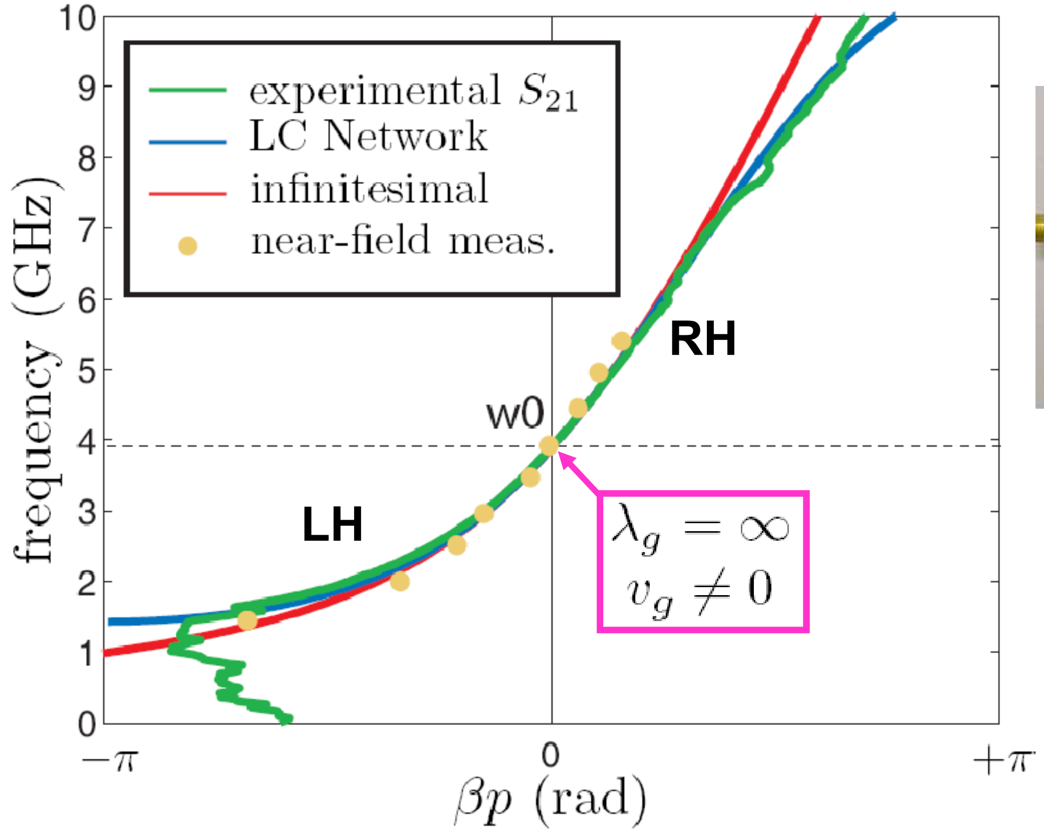
$$C = \frac{\iint_{S_\mathbf{D}} \mathbf{D} \cdot d\mathbf{S}}{V}$$

$$v_p = \frac{\omega}{\beta} < 0$$

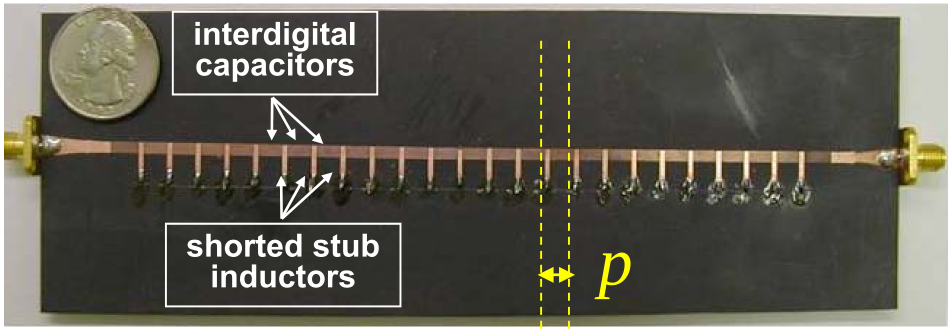
$$v_g = \frac{\partial\omega}{\partial\beta} > 0$$

C. Caloz, H. Okabe, T. Iwai, and T. Itoh, ***IEEE AP-S USNC/URSI***, June 2002.

Unusual $\lambda_g(\omega)$ Behavior



Microstrip CRLH TL

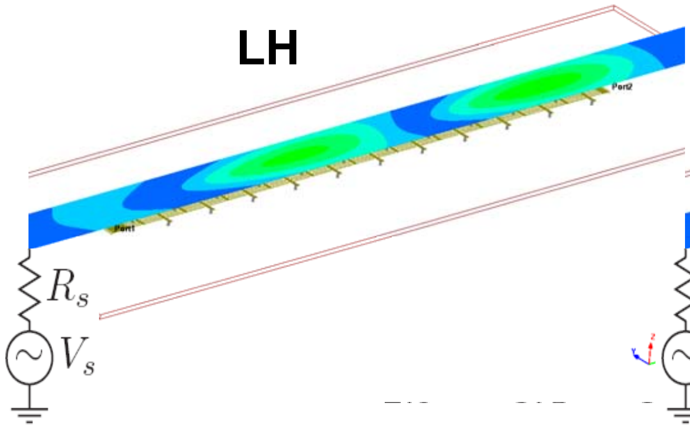


Balanced CRLH guided wavelength

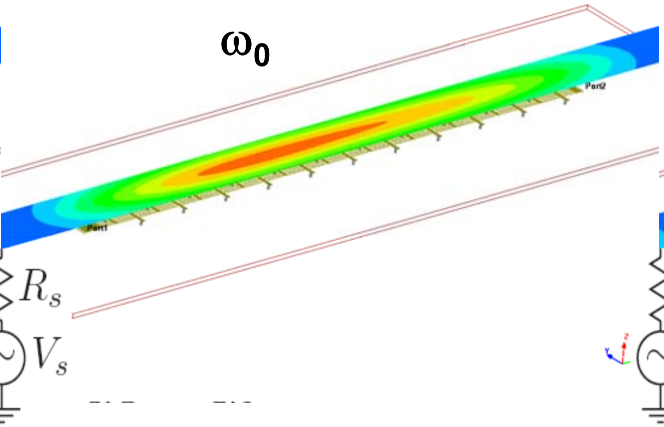
$$\lambda_g(\omega) = \frac{2\pi}{\beta(\omega)}$$

$$= \frac{2\pi}{\frac{1}{p}\left(\omega\sqrt{L_R C_R} - \frac{1}{\omega\sqrt{L_L C_L}}\right)}$$

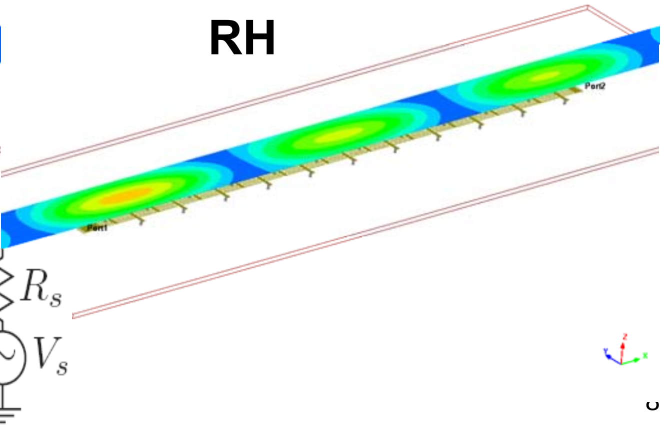
LH



ω_0

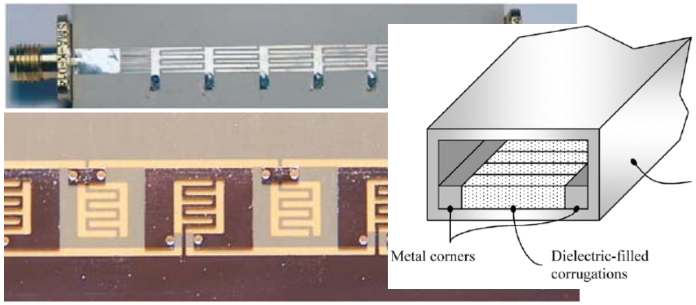


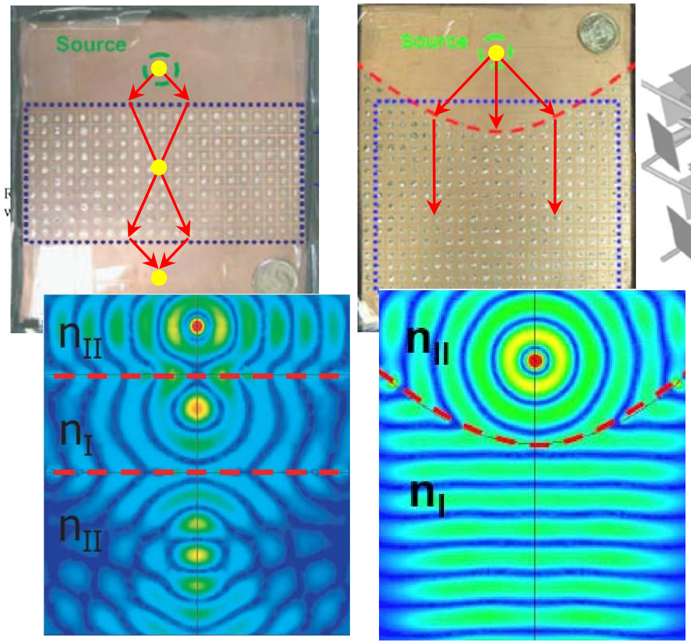
RH

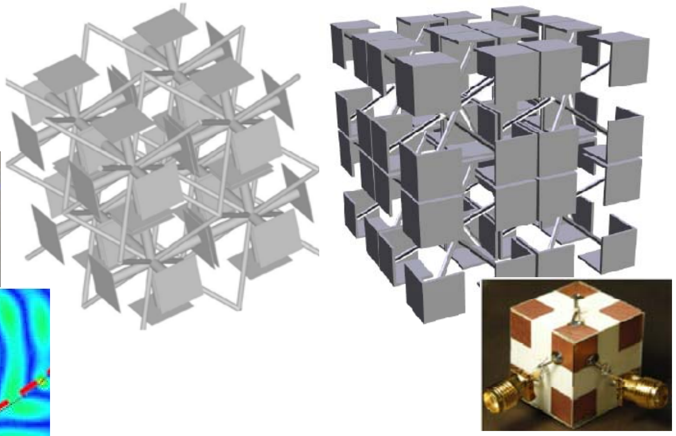


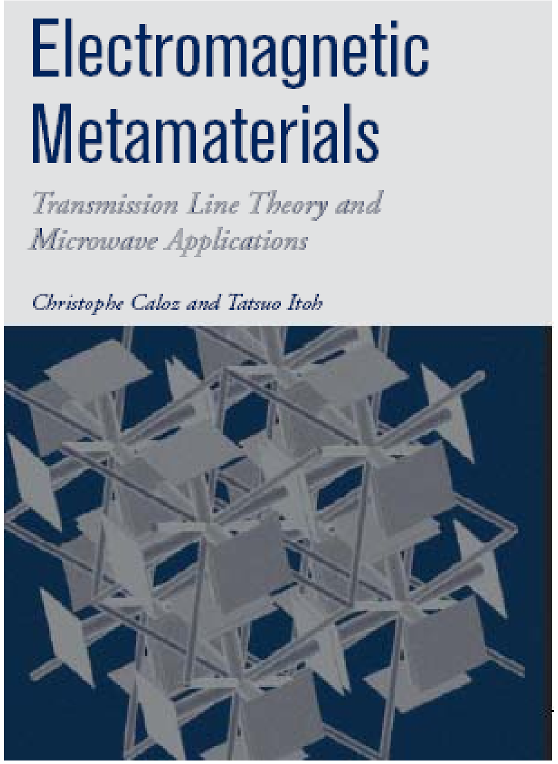
Composite Right/Left-Handed (CRLH)[‡] Metamaterials

1D **2D** **3D**





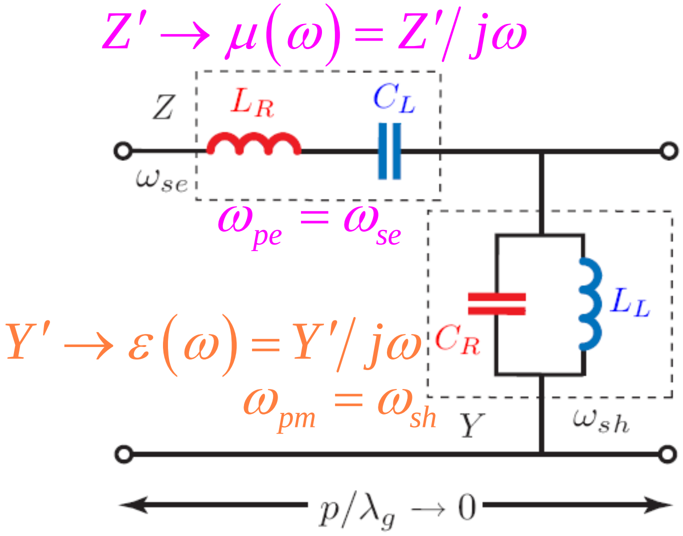




Electromagnetic Metamaterials

Transmission Line Theory and Microwave Applications

Christophe Caloz and Tatsuo Itoh



$Z' \to \mu(\omega) = Z'/j\omega$

$\omega_{pe} = \omega_{se}$

$Y' \to \varepsilon(\omega) = Y'/j\omega$

$\omega_{pm} = \omega_{sh}$

Material Parameters:

$2 \times$ Drude (non-resonant):

$$\mu(\omega) = \mu_\infty \left(1 - \omega_{pm}^2 / \omega^2\right)$$

$$\mu_\infty = L'_R$$

$$\omega_{pm} = 1 / \sqrt{L'_R C'_L}$$

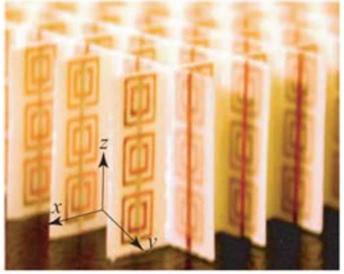
$$\varepsilon(\omega) = \varepsilon_\infty \left(1 - \omega_{pe}^2 / \omega^2\right)$$

$$\varepsilon_\infty = C'_R$$

$$\omega_{pe} = 1 / \sqrt{L'_L C'_R}$$

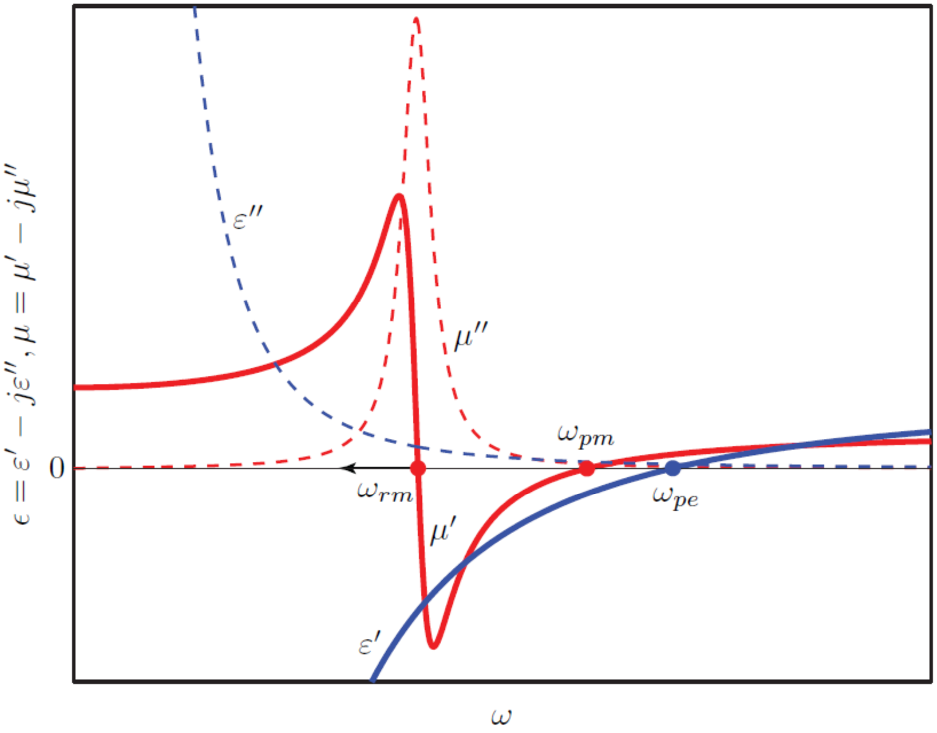
[‡] C. Caloz and T. Itoh, ***IEEE MTT-S Int. Microwave Symp. Dig.***, June 2003, pp. 195-198.

Lorentz vs Drude Responses

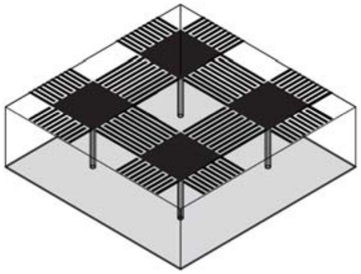


Resonant Particle MTMs: e-Drude & m-Lorentz

$$\varepsilon(\omega)=\varepsilon_0\left[1-\frac{\omega_{pe}^2}{\omega^2-j\omega\Gamma_e}\right],\quad \mu(\omega)=\mu_0\left[1-\frac{\omega_{pm}^2}{\omega^2-\omega_{rm}^2-j\omega\Gamma_m}\right]$$



BROADBAND



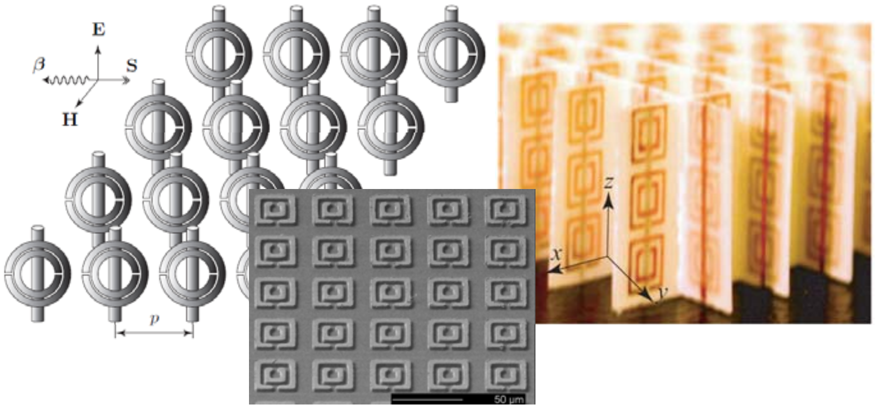
Transmission Line MTMs: 2x Drude

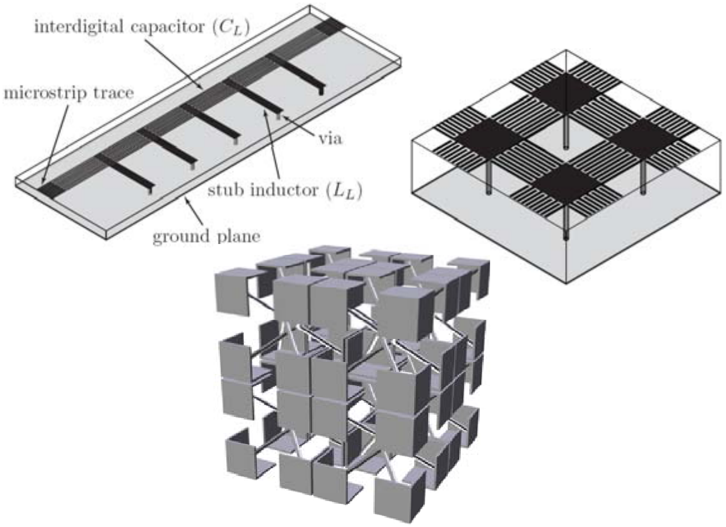
$$\varepsilon_0=\frac{C_R}{p},\ \omega_{pe}=\frac{1}{\sqrt{L_L C_R}},\quad \mu_0=\frac{L_R}{p},\ \omega_{pm}=\frac{1}{\sqrt{L_R C_L}},\ \boxed{\omega_{rm}=0}$$

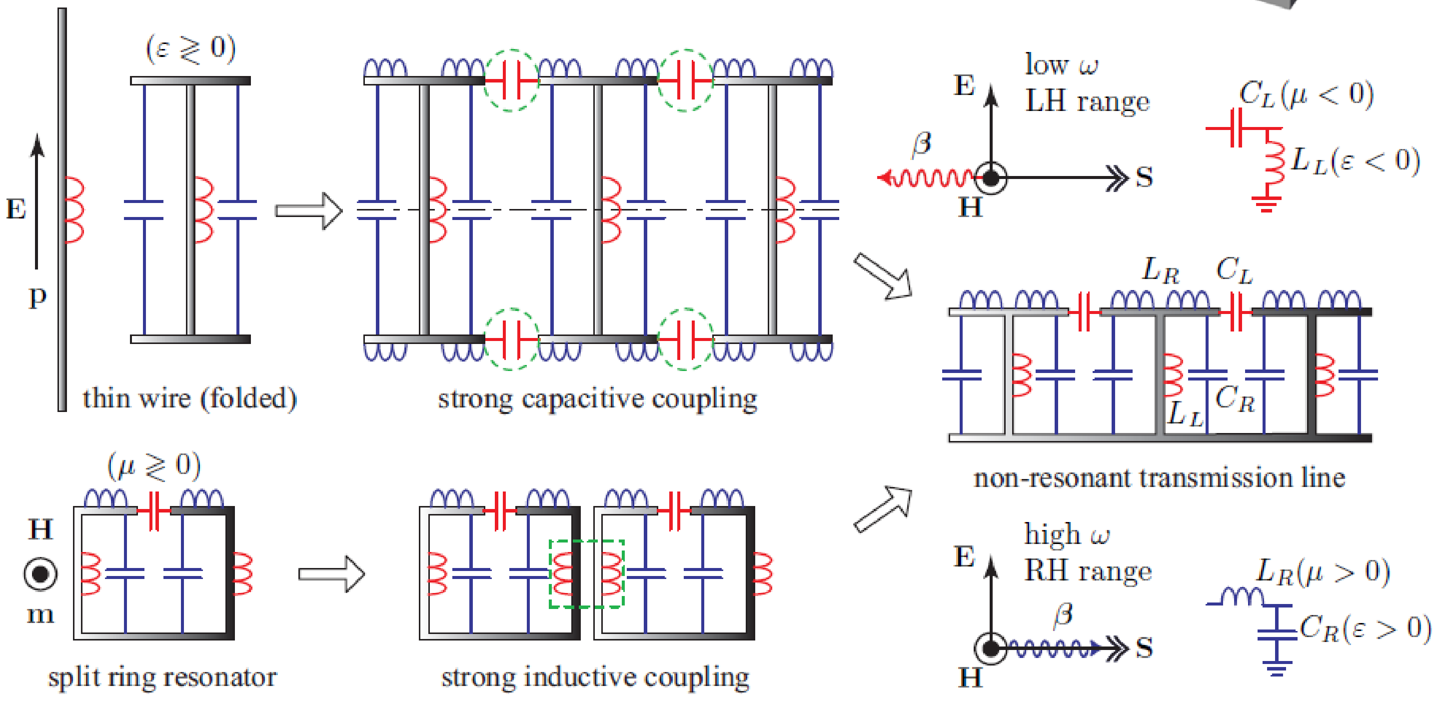
Relation Resonant Particle and Transmission Line MTMs

Resonant Particle MTMs

Transmission Line MTMs

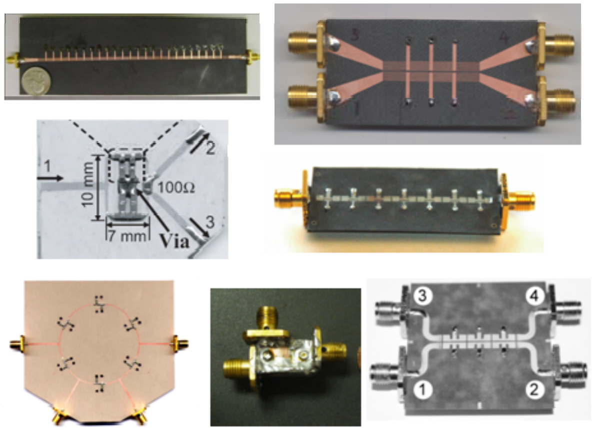






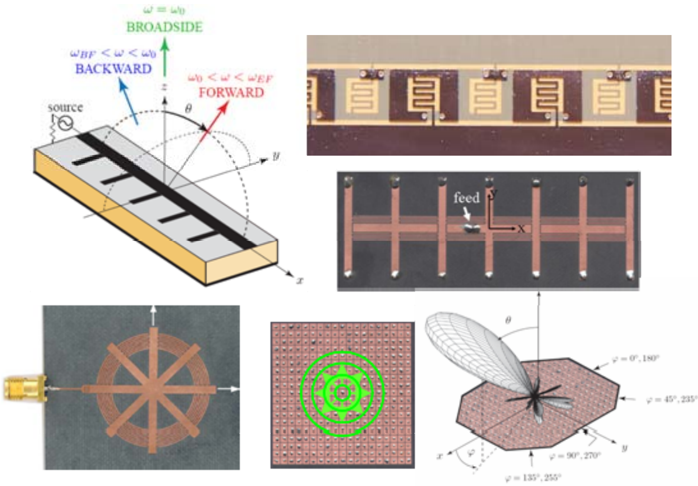
C. Caloz, *Materials Today*, March 2009.

Overview of Applications



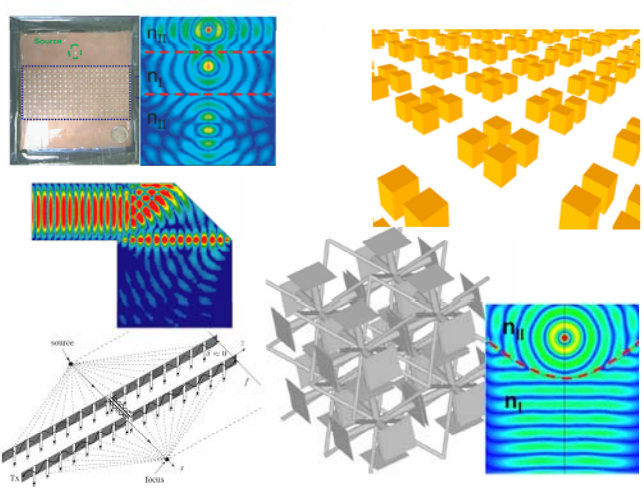
GUIDED WAVES

- Enhanced-bandwidth components
- Multi-band (2,3,4) devices
- Tight broadband couplers
- UWB filters
- Small/high-Q resonators
- Beam-forming networks
- Distributed amplifiers
- Transceivers
- Impulse-regime devices
- Analog signal processors



RADIATED WAVES

- Leaky-wave antennas (LWA)
- Backfire-to-endfire scanning
- Conical beam 2D antennas
- 'Smart' Reflectors
- Compact/high-gain antennas
- Multi-band antennas
- Low-profile monopoles
- Active digital beam-shaping
- Direction of Arrival
- MIMO
- Real-Time Spectrum Analysers



REFRACTED WAVES

- TL distributed NRI slab
- 3D isotropic NRI MTM
- Perfect parabolic refractor
- Endfire antennas
- Surface plasmon waveguide
- NRI meta-interface
- Anisotropic spatial filters
- Artificial plasmas
- Artificial dielectrics
- Ferromagnetic nanowires
- Meta-substrates

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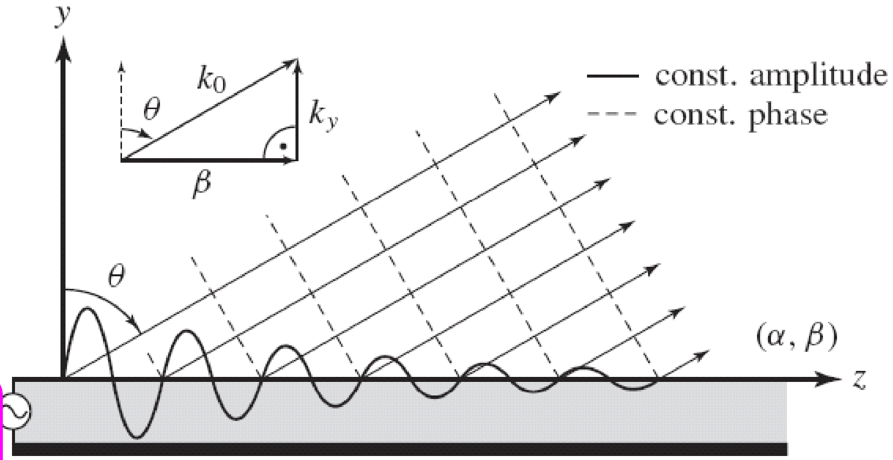
Leaky-Wave Antennas (LWAs)

LWA: wave guiding structure that allows energy to leak out as it propagates along a direction of propagation

$$\psi(x,z) = \psi_0 e^{-\gamma z} e^{-jk_y y}$$

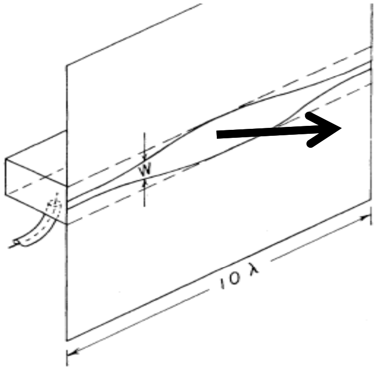
$$= \left(e^{-j\beta z} e^{-\alpha z}\right) e^{-jk_y y}$$

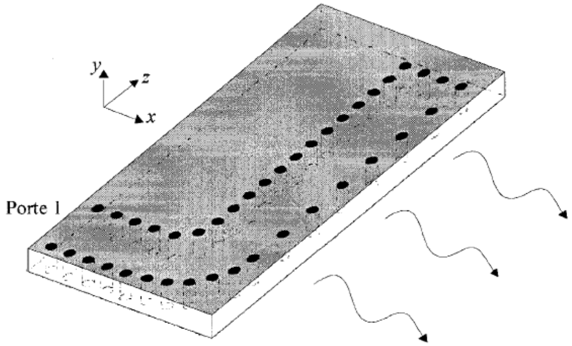
$$k_y = \sqrt{k_0^2 - \beta^2} \qquad \boxed{\theta_{MB} = \sin^{-1}(\beta/k_0)}$$



Advantages

1. Simple and single feed
2. Highly directive
3. Frequency scanning





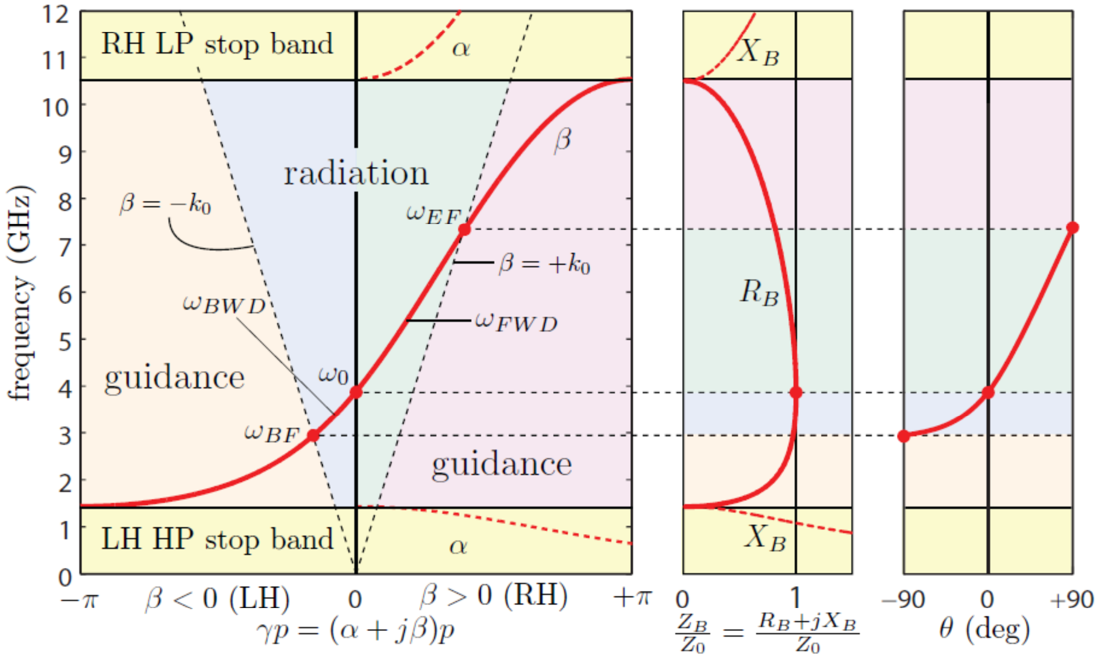
Limitations

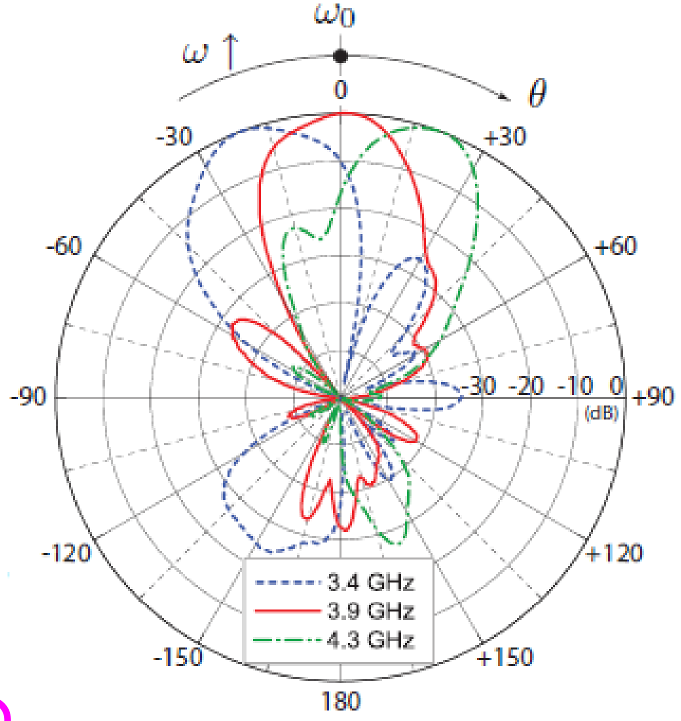
1. Limited scanning range
2. Radiation efficiency η ~ size

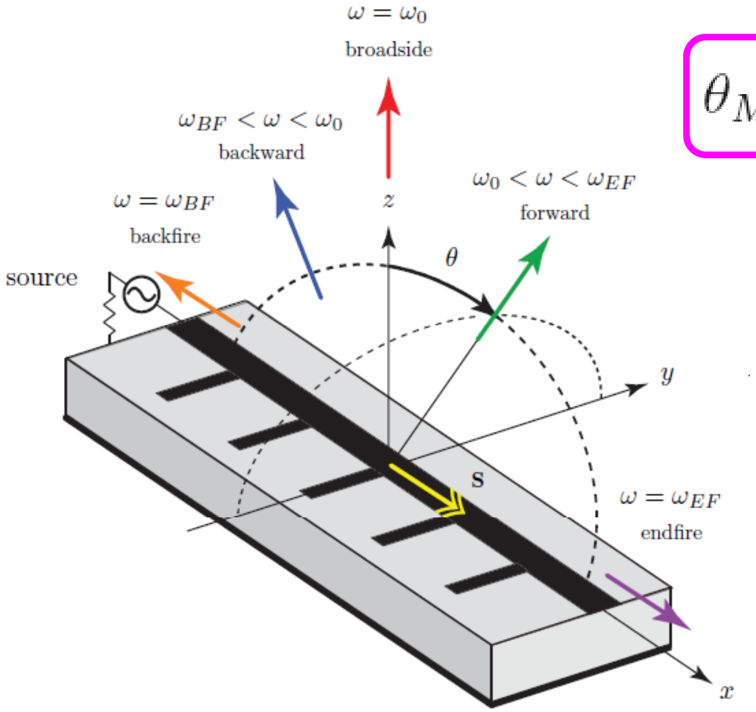
	Uniform	Periodic
Quadrants	FW	BW + FW
Broadside	NO	NO

A. Oliner and D. R. Jackson, “Leaky-wave Antennas,” in Antenna Engineering Handbook, 4th ed., J. L. Volakis, Ed. McGraw-Hill, 2007, ch. 11.

CRLH Backfire-to-Endfire Leaky-Wave Antennas



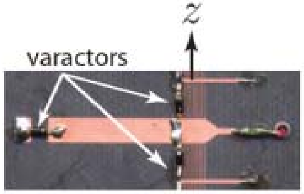




$$\boxed{\theta_{MB} = \sin^{-1}(\beta/k_0)}$$

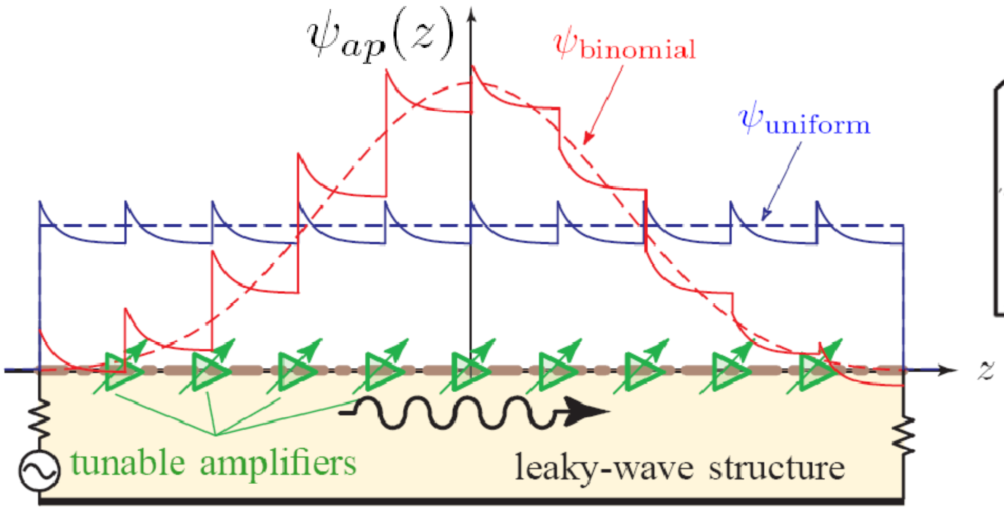
- fund. mode ⇒ simple & efficient feed
- full-space scanning
- traveling-wave @ $\beta = 0$

  ⇒ also BROADSIDE !
- ω- and e- scanning
- breakthrough LW antenna!

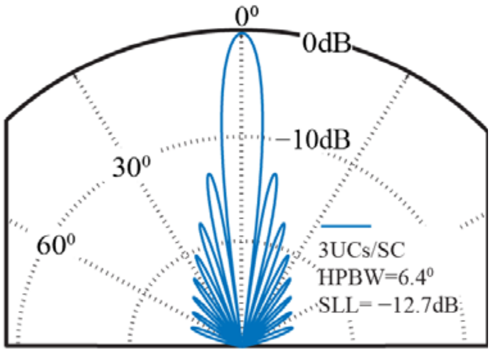


Active Aperture-Digitized Beam-Formers

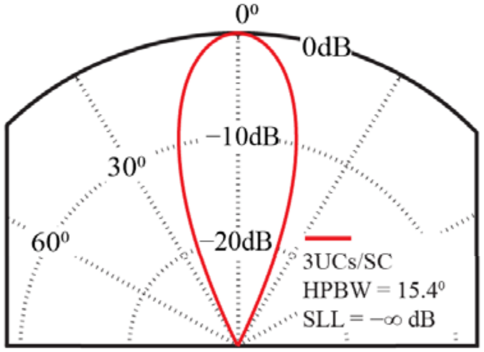
$$\psi_{\mathrm{FF}}(\theta) = \int_{-\ell_\lambda/2}^{+\ell_\lambda/2} \psi_{\mathrm{ap}}(z_\lambda) e^{j2\pi x_\lambda \sin\theta} \, dz_\lambda$$

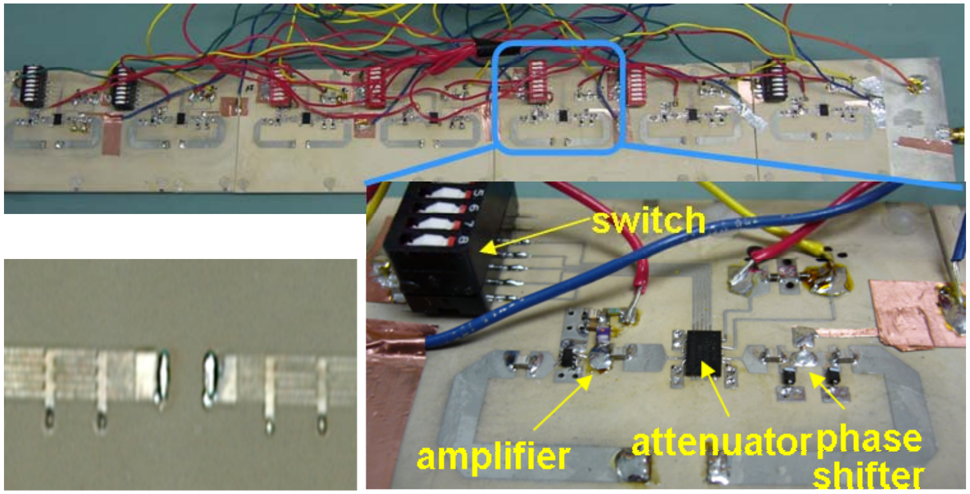


Uniform ⇒ Maximum Directivity



Binomial ⇒ Minimum Slidelobes



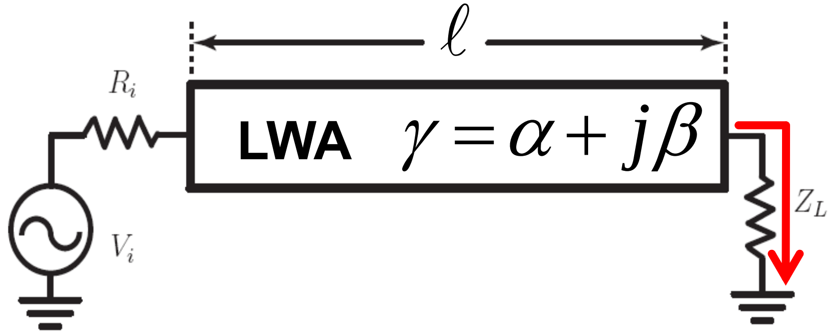


- **Any aperture distribution**
  - ⇒ **beam shaping**
- **tunable amplifiers (VGA)**
  - → **real-time scanning & shaping**
- **'aperture digitization'**
- **real-time DSP: DOA & MIMO**

F. P. Casares, C. Camacho, and C. Caloz, ***IEEE T-AP***, vol. 54, no. 8, pp. 2292-2300, Aug. 2006.
S. Abielmona, H. V. Nguyen, F. P Casares, and C. Caloz, ***IEEE AP-S***, June 2007, 5593-5596.

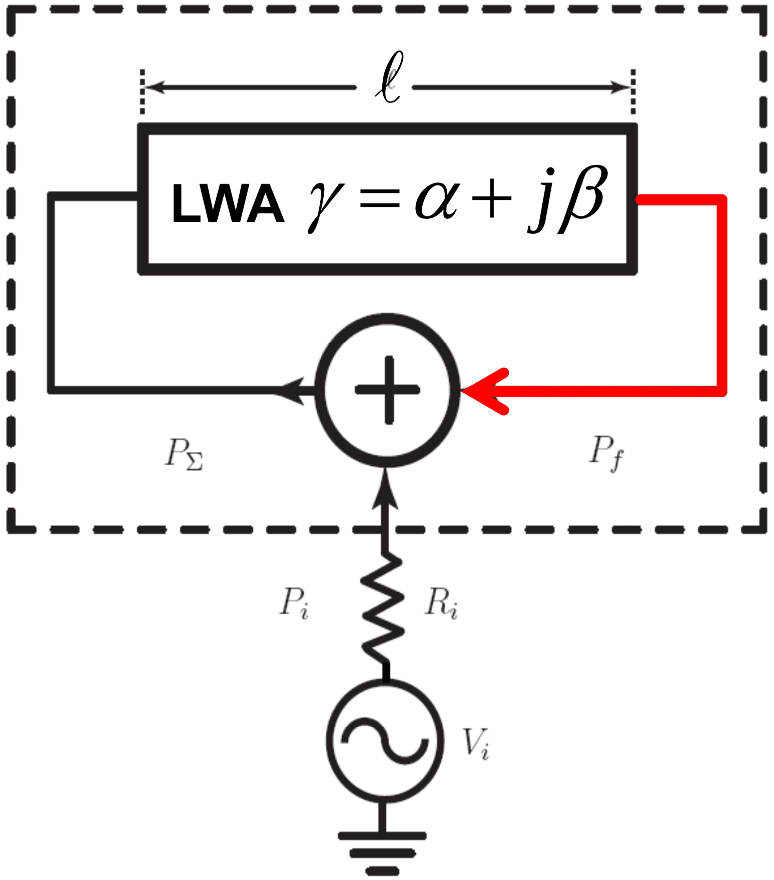
Self Power-Recycling Principle

Conventional LWA



$$P_{rad} = \eta_0 P_i \qquad \eta_0 = 1 - e^{-2\alpha\ell}$$

Power-recycling LWA



Operation and Radiation Efficiency

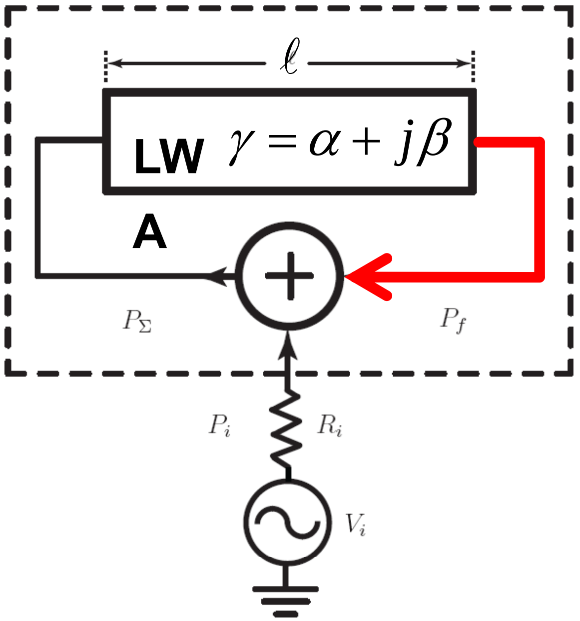
1. $P_\Sigma = P_i + P_f$

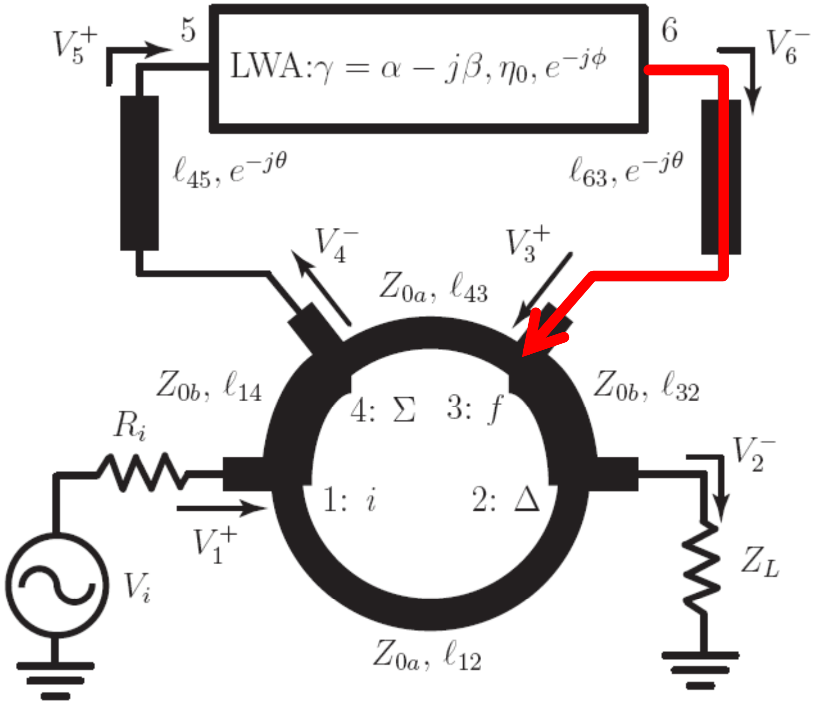
2. $P_{rad} = \eta_0 P_\Sigma$

3. $$\eta_s = \frac{P_{rad}}{P_i} = \frac{\eta_0 P_\Sigma}{P_i} = \frac{\eta_0\left(P_i + P_f\right)}{P_i} = \boxed{\eta_0\left(1 + \frac{P_f}{P_i}\right) \quad P_f > 0 \Rightarrow \eta_s > \eta_0}$$

H. V. Nguyen, A. Parsa and C. Caloz, ***IEEE T-MTT***, *to be published.*

Self Power-Recycling Implementation





Amplitude & Phase Conditions

$$V_2^- = S_{21}V_1^+ + S_{23}V_3^+ = 0$$

$$\boxed{\begin{gathered} a = \sqrt{1-\eta_0} \qquad b = \sqrt{\eta_0} \\ \theta = -\frac{\phi}{2} + \frac{3\pi}{4} + m\pi, \end{gathered}}$$

Rat-race implementation benefits

☺ Isolation between 2 input ports

☺ Arbitrary power coupling ratio P_f / P_i

☺ Termination port ⇒ power regulation

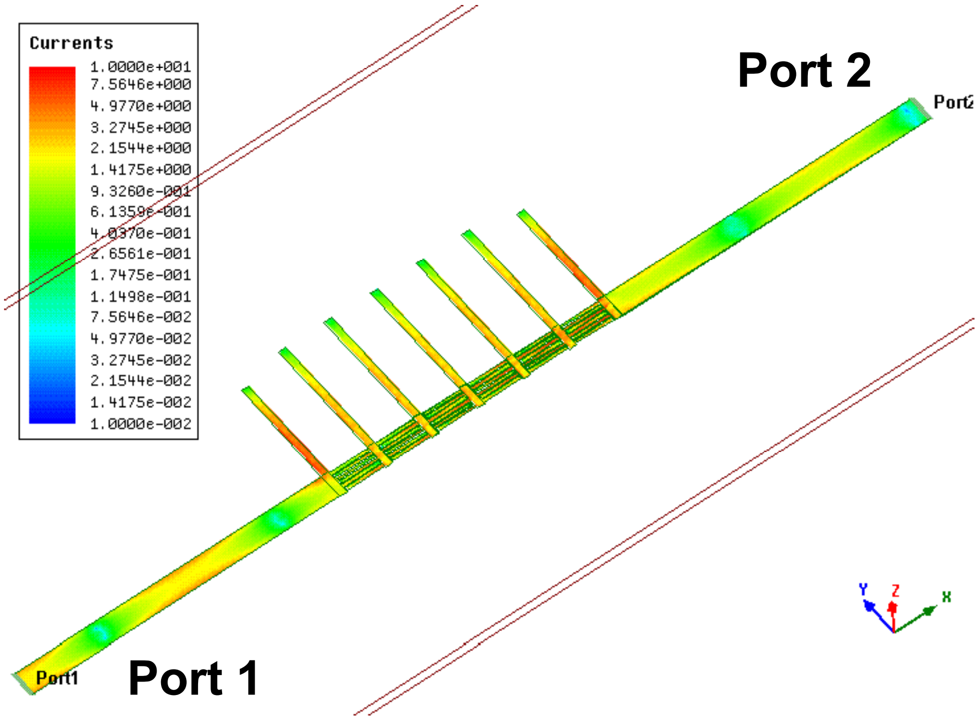
during transient regime

H. V. Nguyen, A. Parsa and C. Caloz, ***IEEE T-MTT***, *to be published.*
H. V. Nguyen, S. Abielmona, A. Parsa and C. Caloz, *patent filed*.

3-dB LWA Full-wave Results

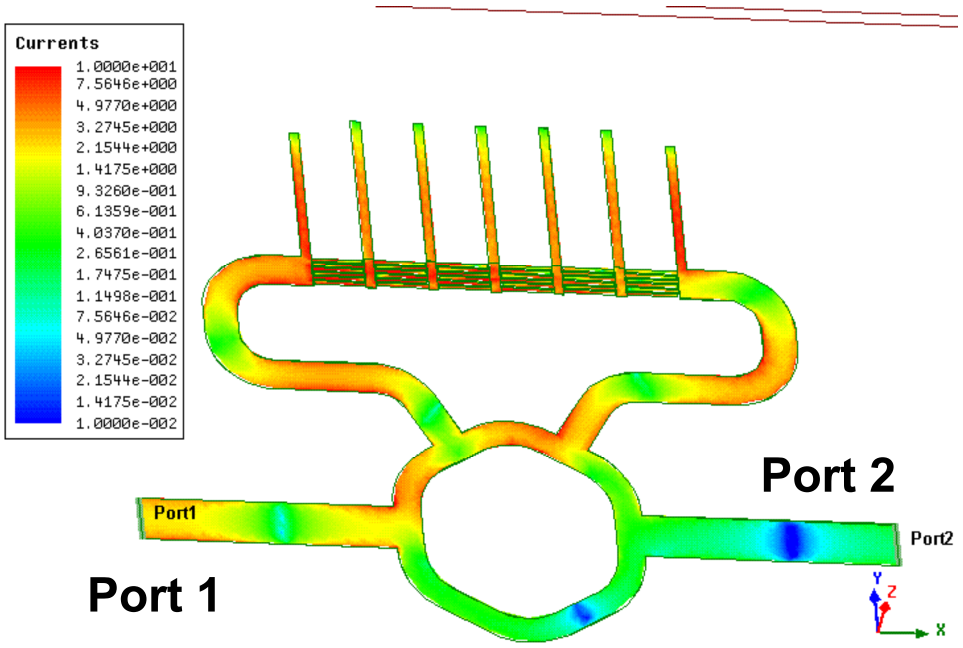
Open-loop LWA

- 3-dB LWA → η_o = **50%** (lossless)
- $P_2 = P_1/2$



Power-recycling LWA

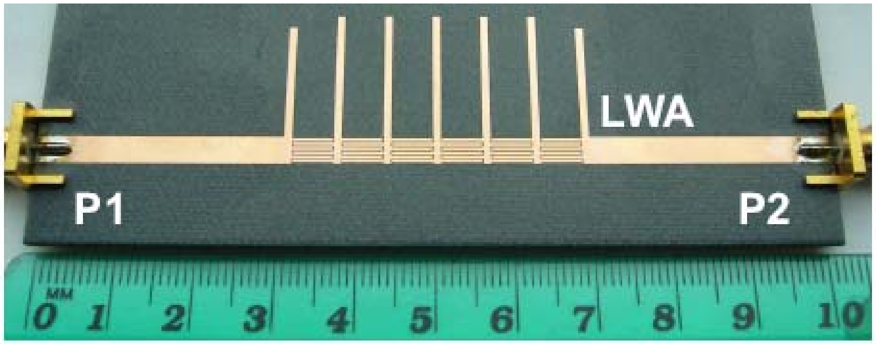
- 3-dB feedback LWA system
- $P_2 = 0$



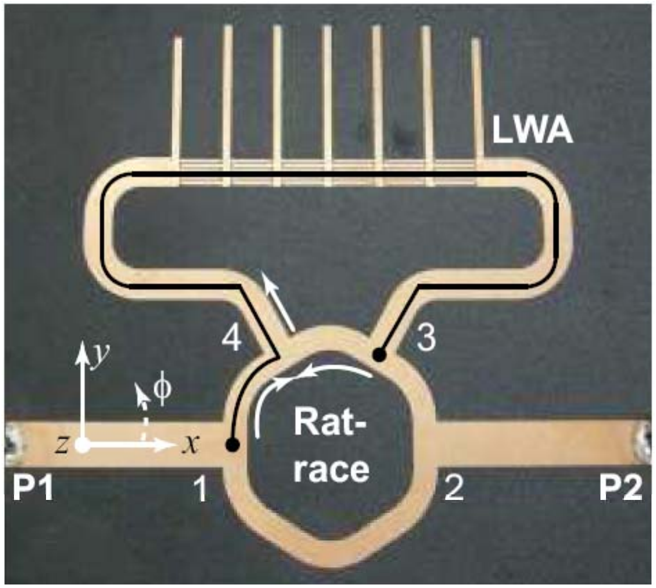
$$\eta_s = \eta_0\left(1+\frac{P_f}{P_i}\right) \overset{P_f=P_i}{=} 2\eta_0 \overset{\eta_0=50\%}{=} 100\%$$

3-dB LWA Performance Comparison

Open-loop LWA

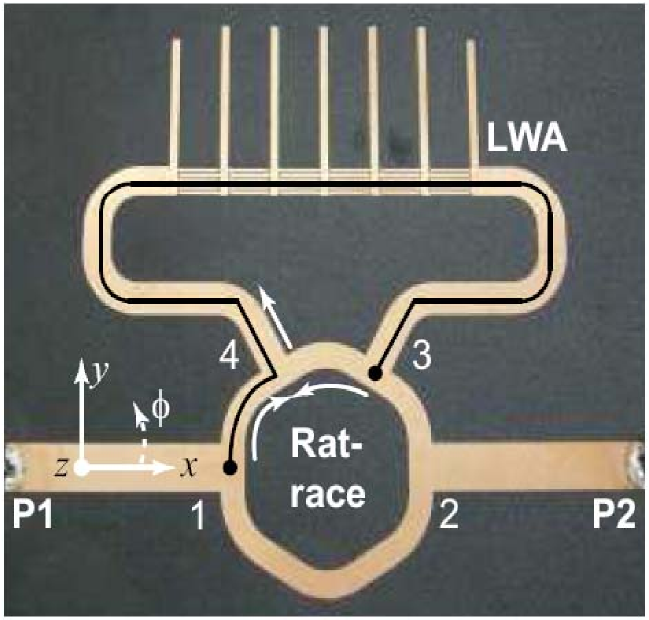


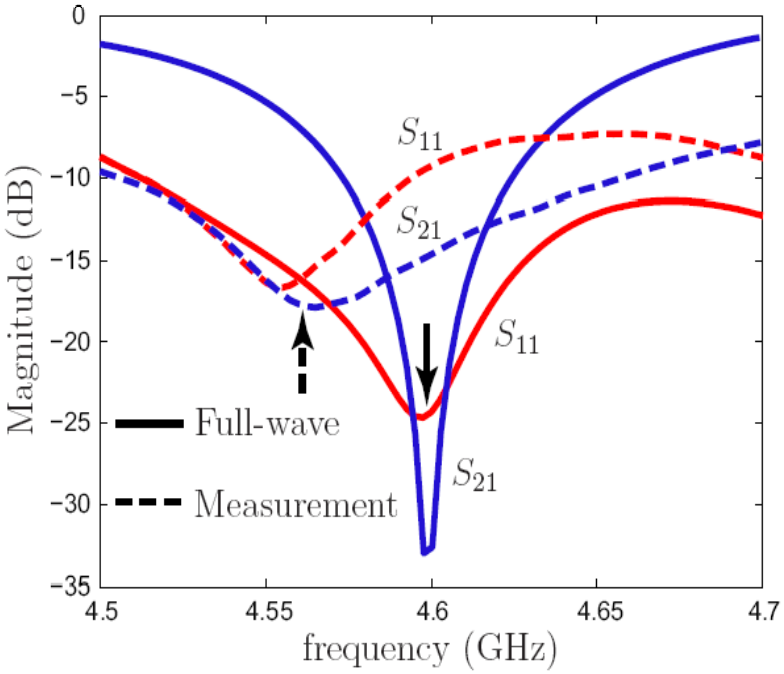
Power-recycling LWA

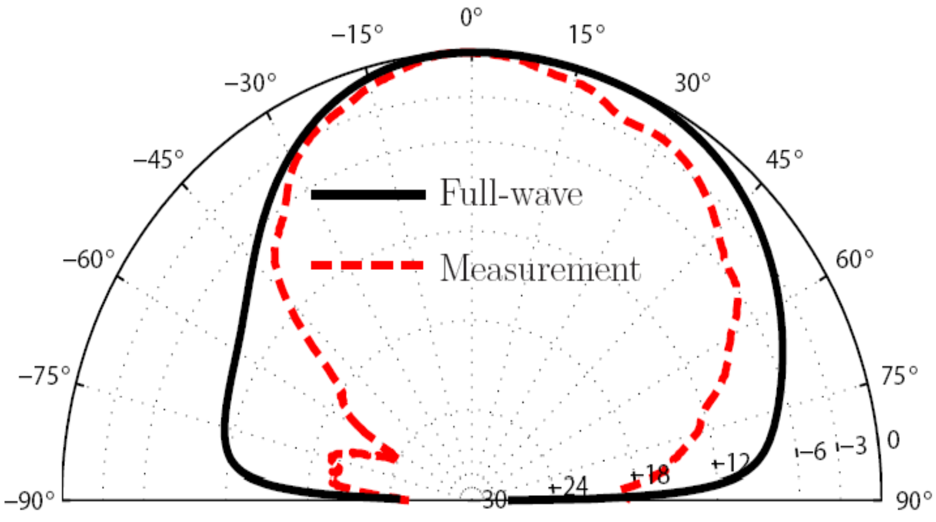


	Conventional LWA ($\eta = \eta_0$)		Power Recycling LWA ($\eta = \eta_s$)	
	FW	Measured	FW	Measured
G	3.68 dB	3.70 dB	6.73 dB	5.77 dB
D	7.84 dB	7.88 dB	7.85 dB	7.42 dB
η	38.36%	**38.00%**	77.27%	**68.45%**

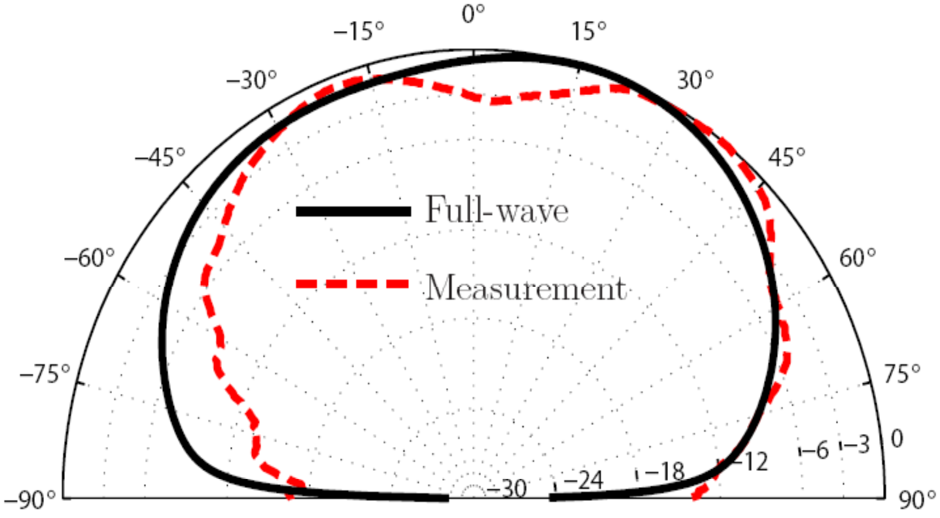
Prototypes and Results







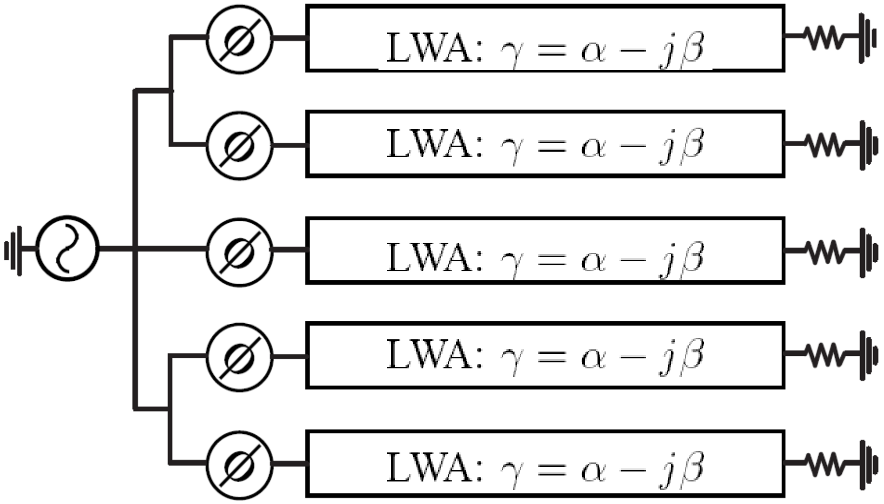
(a) $\phi = 0^o$ plane



(b) $\phi = 90^o$ plane

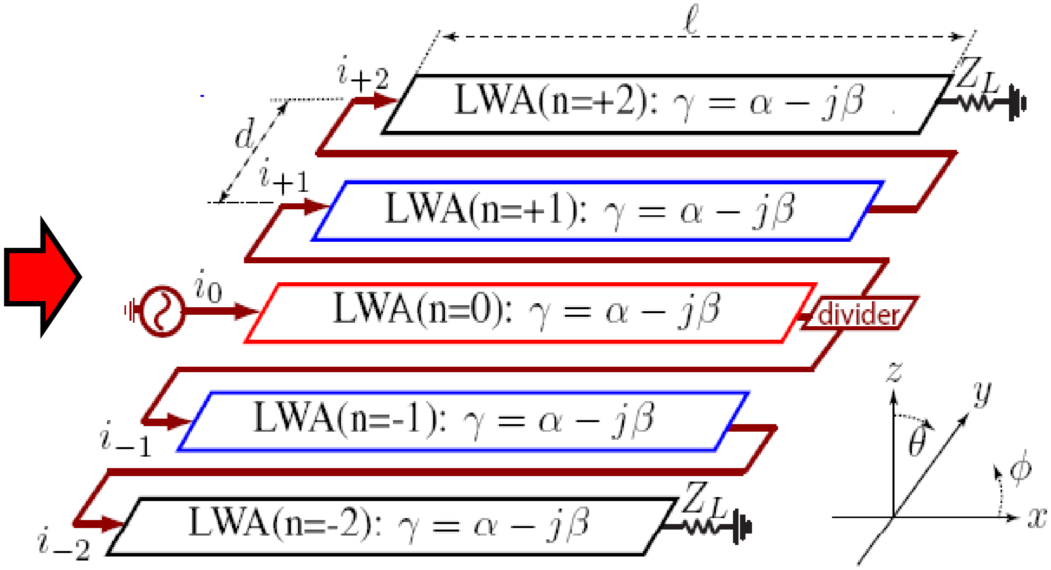
Cross Power-Recycling Principle

Conventional LWA array

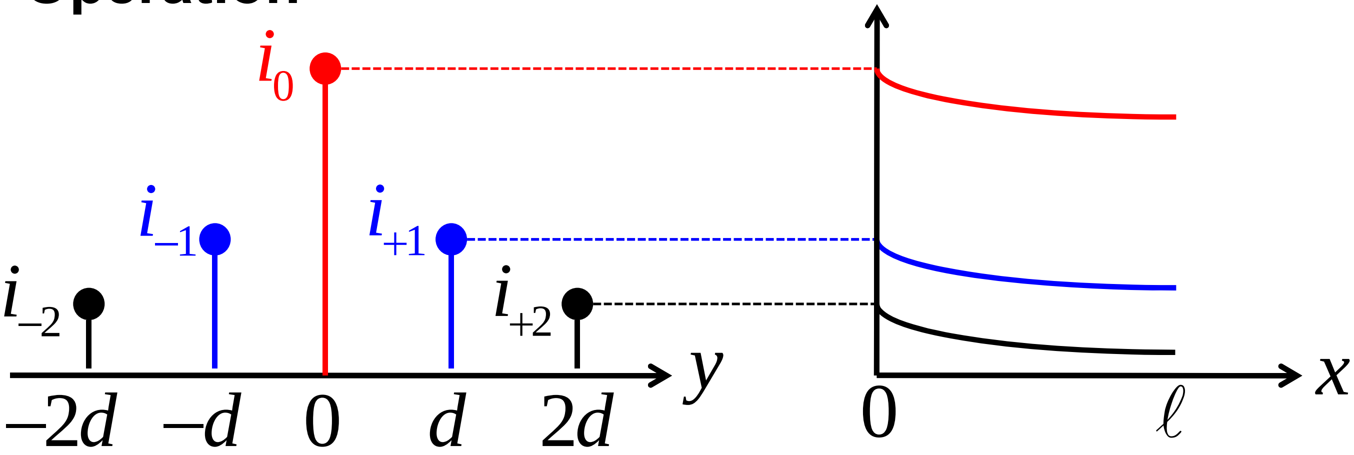


$$\eta_{array} = \eta_0 = 1 - e^{-2\alpha\ell}$$

Power-recycling LWA array



Operation



1. $i_{0(0,0)} = i_i$
2. $i_{\pm1(0,\pm d)} = i_{0(\ell,0)}/2$
3. $i_{\pm2(0,\pm 2d)} = i_{\pm1(\ell,\pm d)}/2$
4. $i_{n(\ell,nd)} = i_{n(0,nd)} e^{-\alpha\ell}$

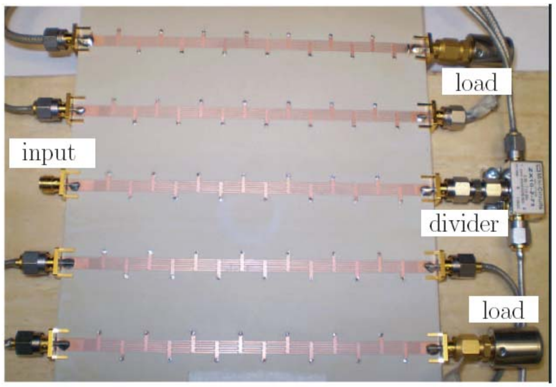
H. V. Nguyen, S. Abielmona and C. Caloz, ***IEEE AWPL***, vol. 8, pp. 441-444, March 2009.

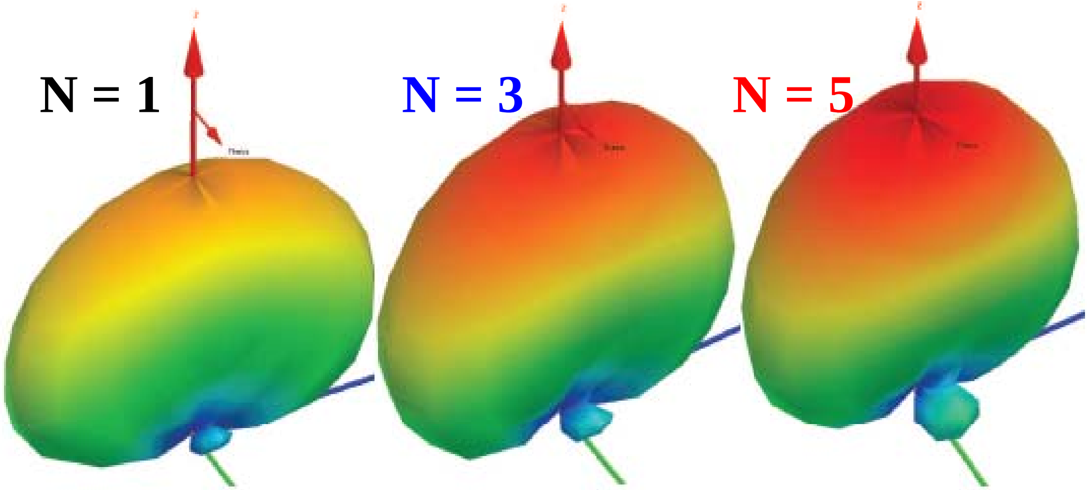
Radiation Efficiency

$$\eta_{array} = \frac{P_{rad}}{P_i} = \frac{P_i - P_L}{P_i}$$

$$\eta_{array} = \frac{i_0^2 - i_{\pm N}^2\left(\ell, \pm Nd\right)}{i_0^2}$$

$$\boxed{\eta_{array} = 1 - \frac{e^{-2(N+1)\alpha\ell}}{2}}$$





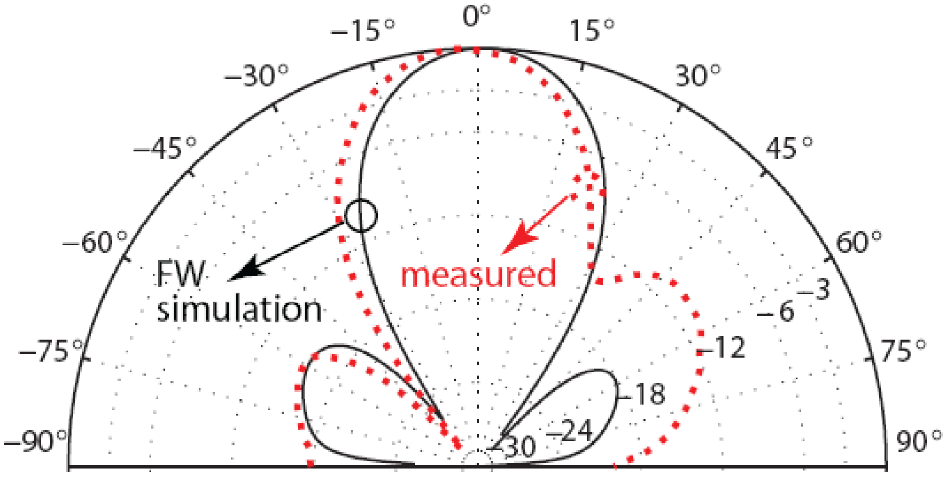
	Conventional LWA array	Power-recycling LWA array
Length of elements	☺	☺
Number of elements	☹	☺

H. V. Nguyen, S. Abielmona, A. Parsa and C. Caloz, ***patent filed.***

Results

Full-wave Results

N	G (dB)	D (dB)	HPBW		η_{array}
			$\phi = 0^o$	$\phi = 90^o$	
1	6.84	11.15	30^o	96^o	37.60%
3	10.72	12.53	31^o	62^o	65.89%
5	12.45	13.51	31^o	45^o	78.29%

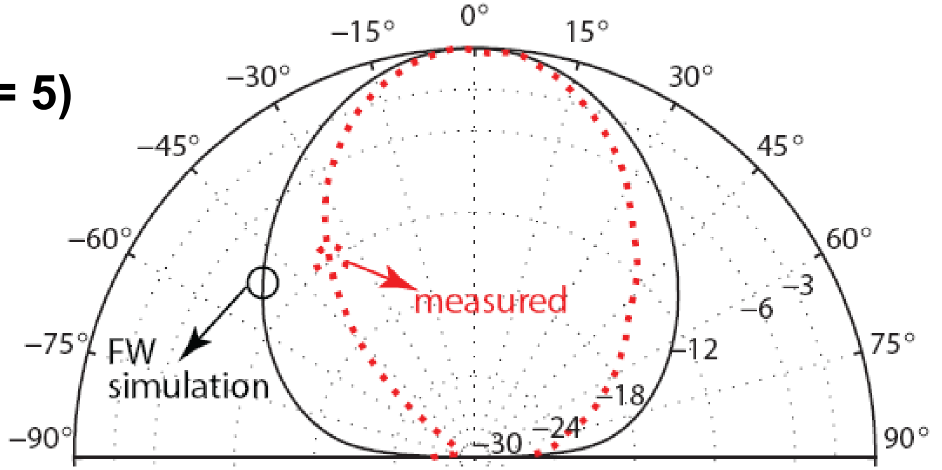


(b) zx-plane cut at broadside frequency.

Full-wave and Measurement Comparison (N = 5)

	G (dB)	D (dB)	HPBW		η_{array}
			$\phi = 0^o$	$\phi = 90^o$	
FW	12.45	13.51	31.00^o	45.00^o	78.29%
Measure	12.35	14.57	31.06^o	36.42^o	60.06%

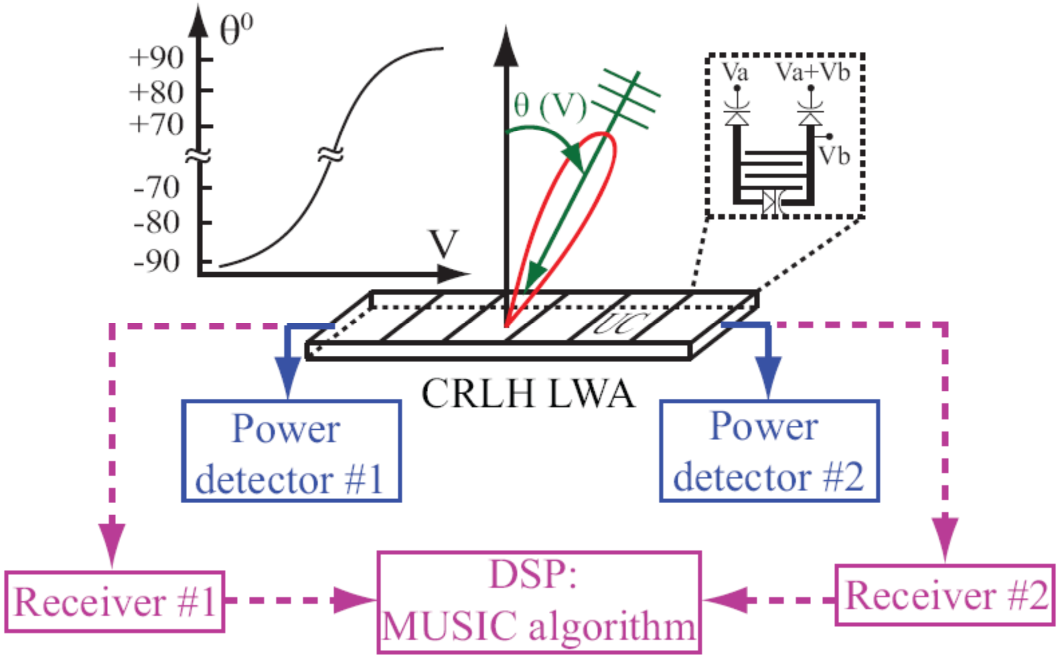
$$\eta_{array} = \frac{G}{D}$$



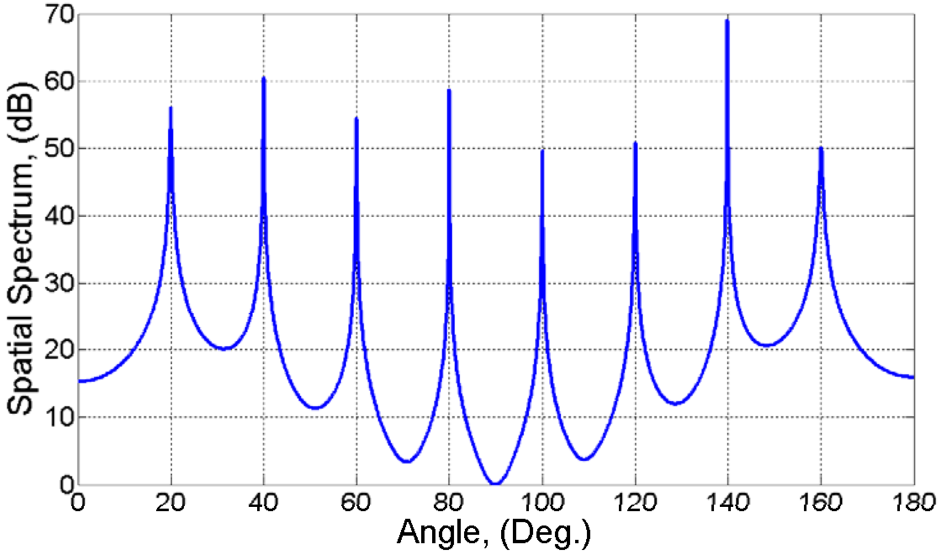
(c) zy-plane cut at broadside frequency.

Direction of Arrival Estimation using E-Scanned CRLH LWA

Principle



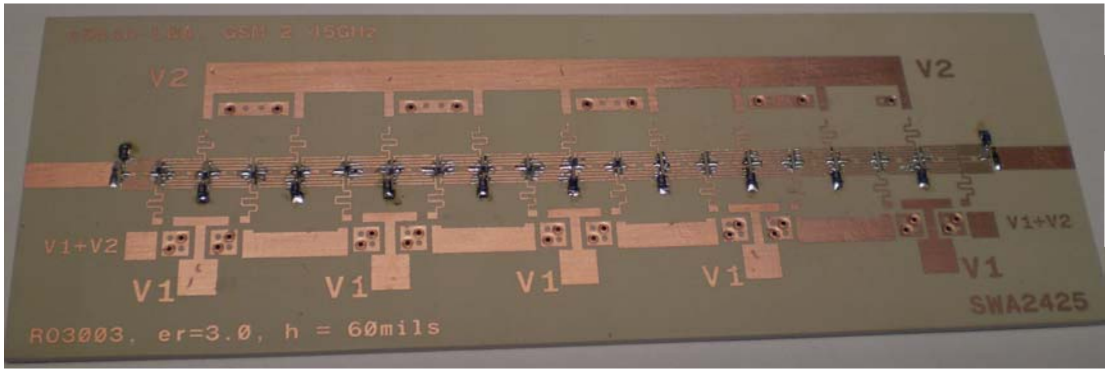
Angular Spectrum



Two modes of operation:

- **Analog : Power detectors**
  - → **max Rx power**
- **Digital : MUSIC**
  - → **S/N decomposition**

Full-space electronically-scanned CRLH LWA

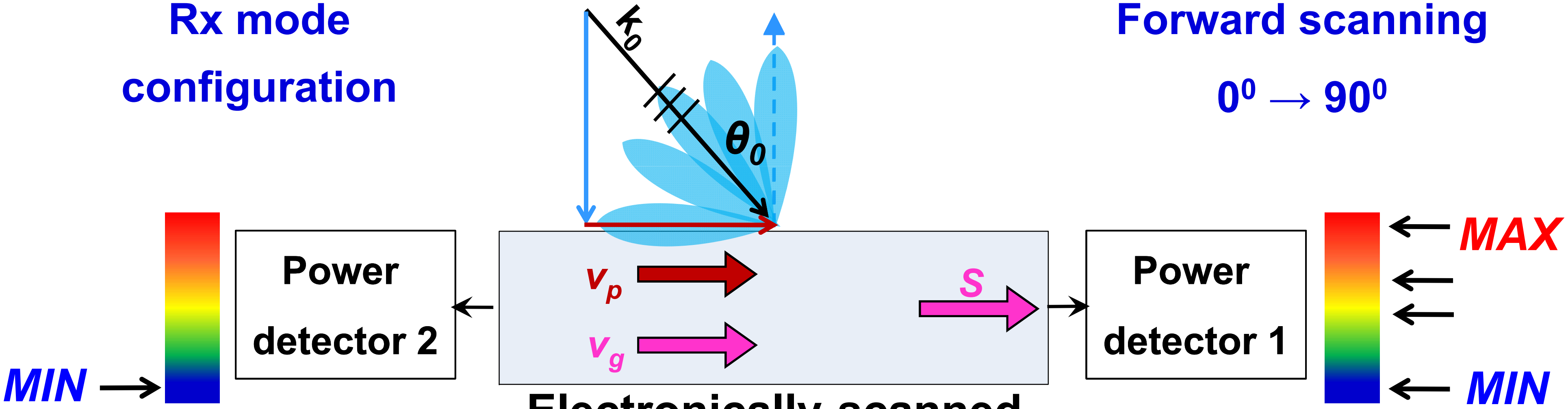


DoA Estimation using CRLH LWA: Right Quadrant

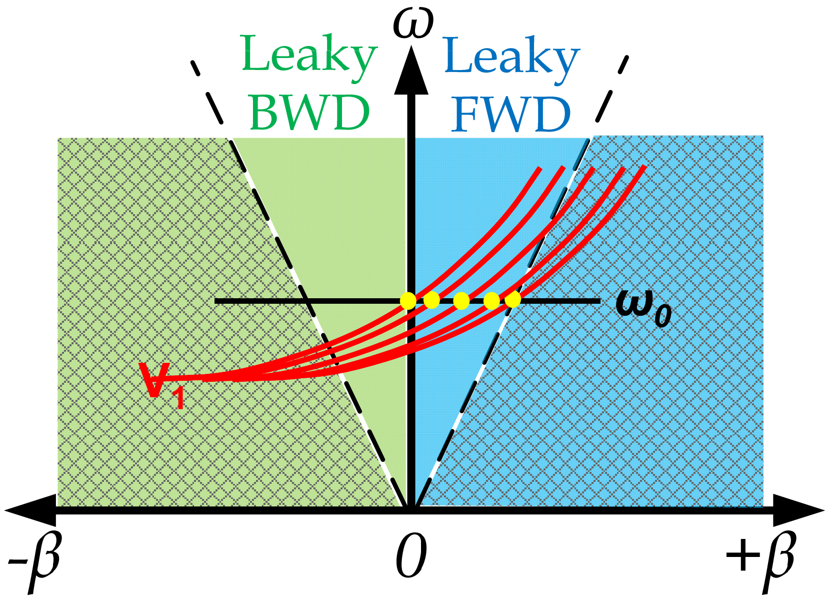
Rx mode configuration

Forward scanning

$0^0 \rightarrow 90^0$

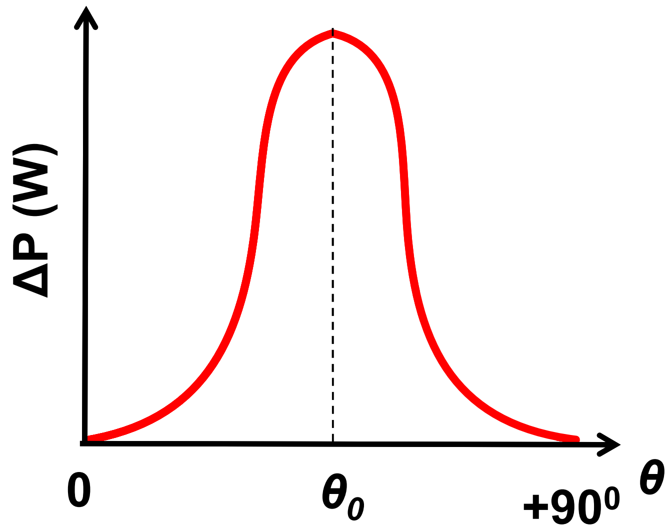


Electronically-scanned CRLH LWA



Differential Power Measurement

$$\Delta P = PD1 - PD2$$

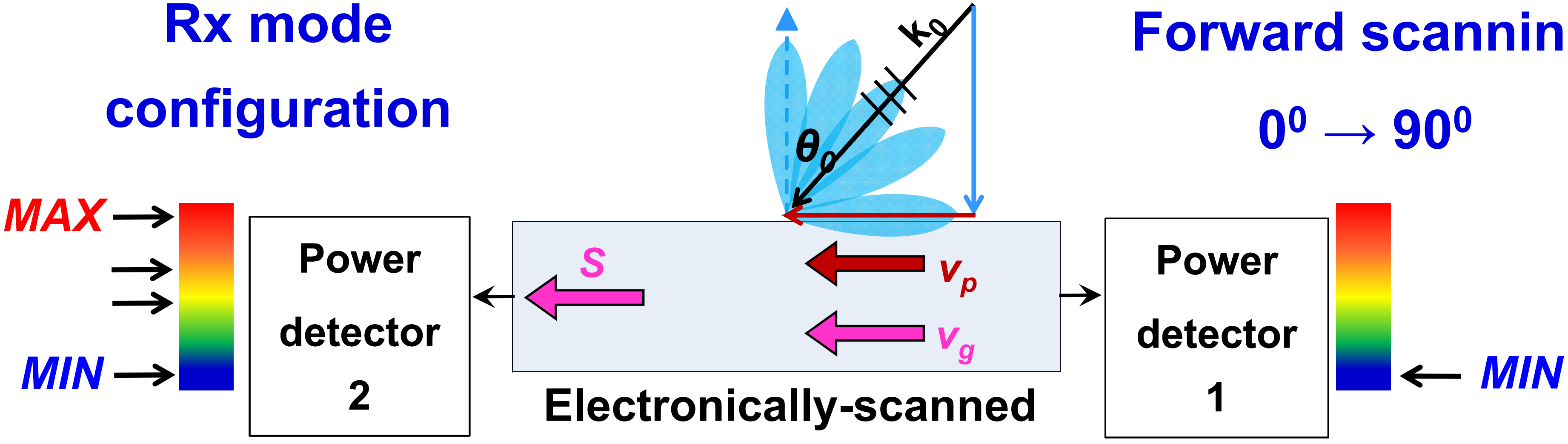


DoA Estimation using CRLH LWA: Left Quadrant

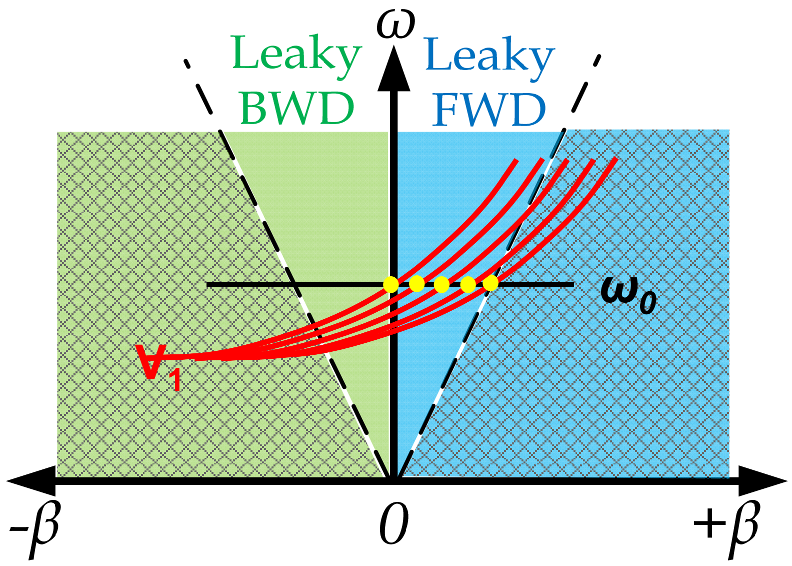
Rx mode configuration

Forward scanning

$0^0 \rightarrow 90^0$

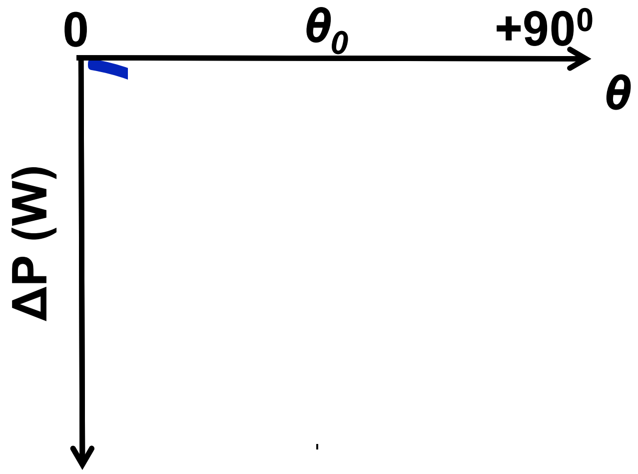


Electronically-scanned CRLH LWA

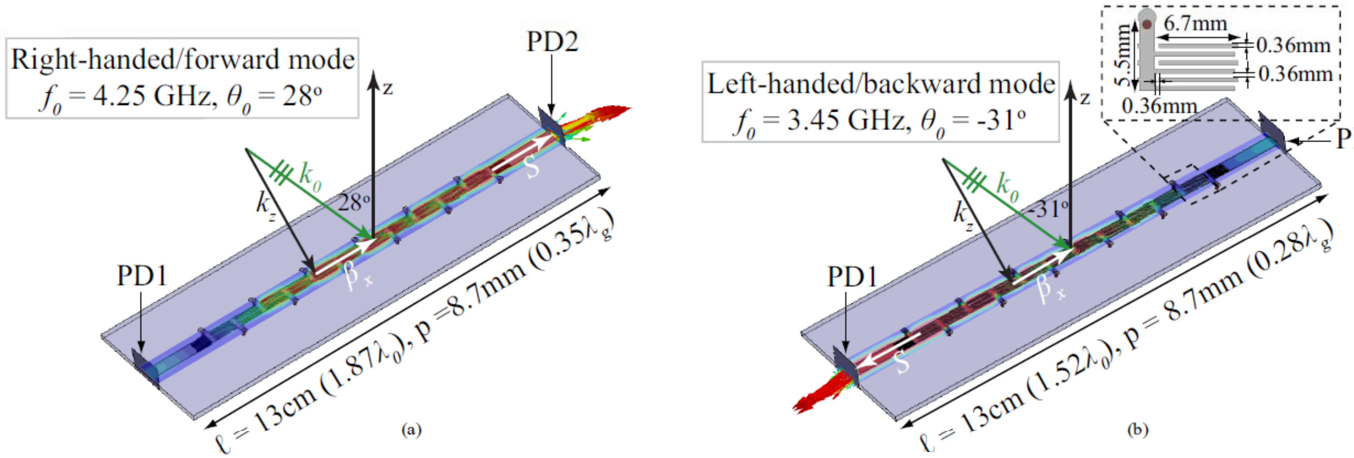


Differential Power Measurement

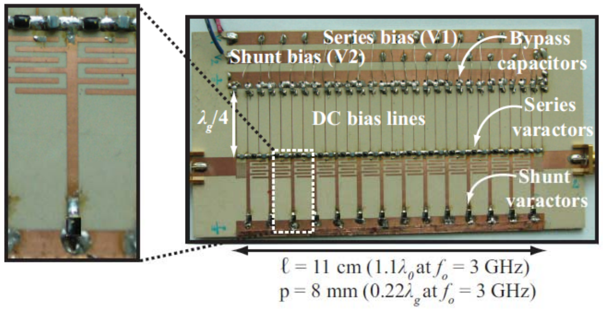
$$\Delta P = PD1 - PD2$$

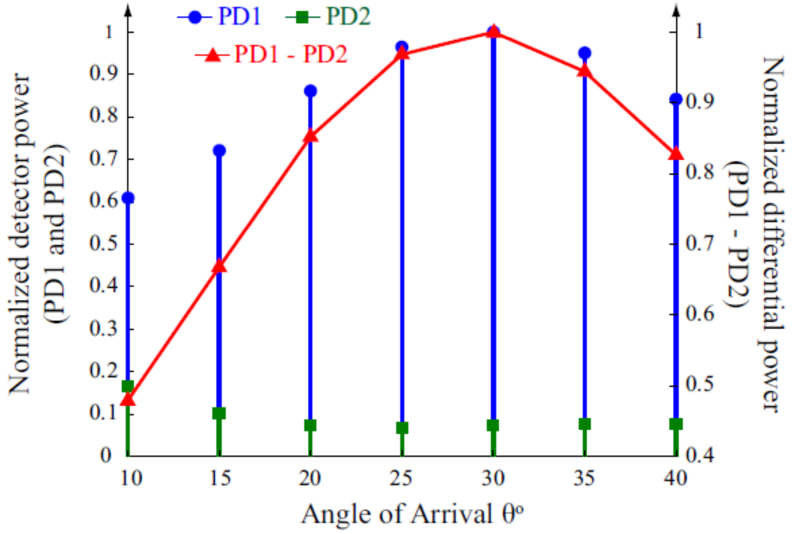


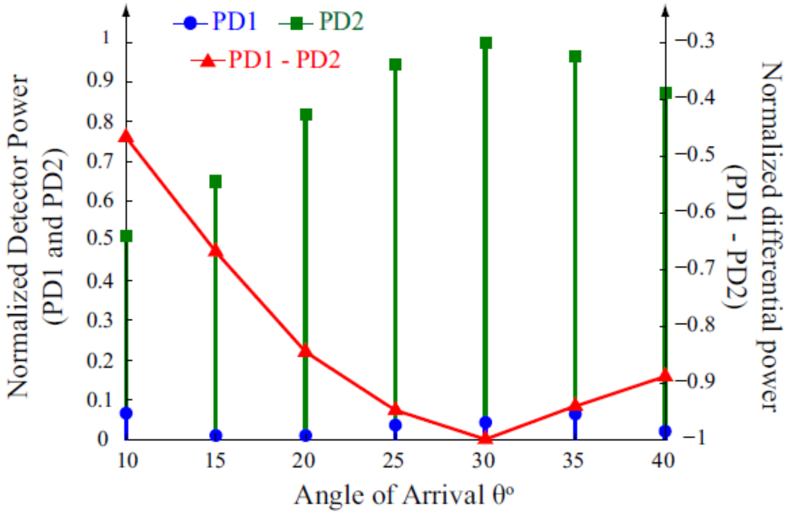
Analog DoA Estimation using CRLH LWA



(a) (b)







S. Abielmona, H. V. Nguyen, and C. Caloz, ***IEEE T-AP***, *to be published*.

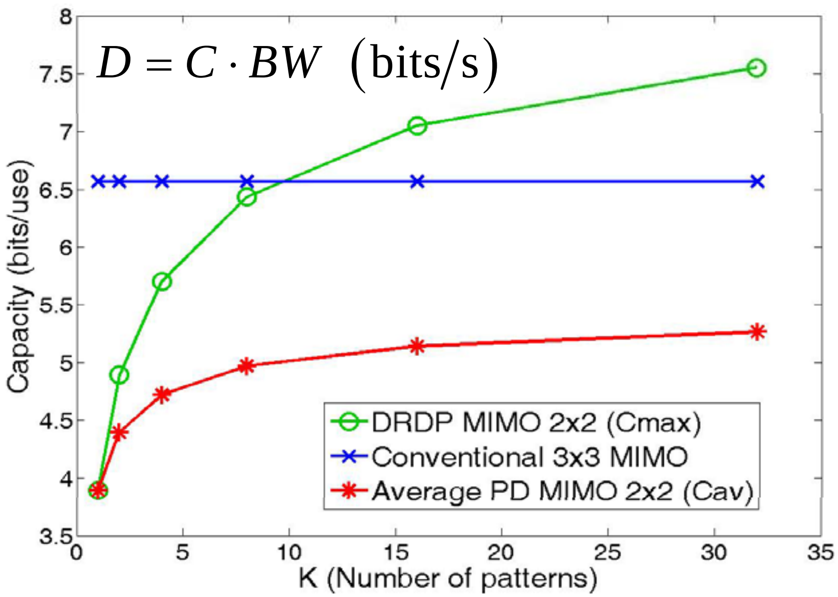
MIMO Dynamic Radiation Pattern Diversity

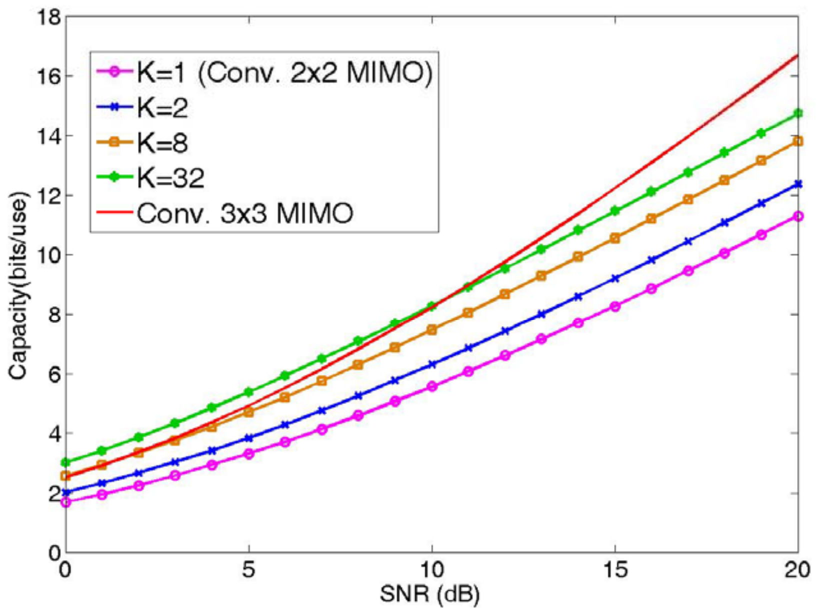
"Search and Lock" → Real-time calibration of best channel → *Smart* MIMO

Capacity

$$C_{\max} = \max_{k=0,\ldots,K-1}\left[\log_2\left(\left|I_M + \frac{\rho}{M}\mathbf{H}_k\mathbf{H}_k^*\right|\right)\right]$$

$$C_{\text{ave}} = \frac{1}{K}\sum_{k=0}^{K-1}\log_2\left(\left|I_M + \frac{\rho}{M}\mathbf{H}_k\mathbf{H}_k^*\right|\right)$$





J.-F. Frigon, C. Caloz and Y. Zhao, *in Proc.* ***IEEE RWS***, Jan. 2008.

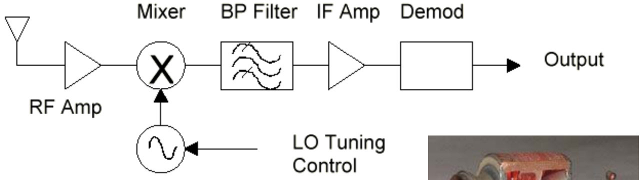
Outline

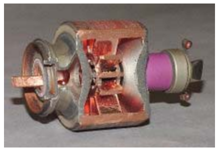
1. BROADBAND METAMATERIALS
2. INNOVATIONS IN CRLH LEAKY-WAVE ANTENNAS
3. ANALOG SIGNAL PROCESSORS
4. FERROMAGNETIC NANOWIRE COMPOSITES
5. CONCLUSIONS

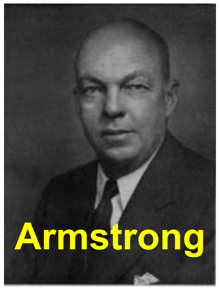
Magnitude Engineering at Microwave Frequencies

Magnitude Engineering

superheterodyne receiver (1918)



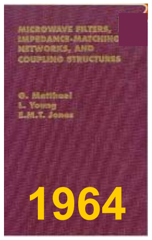




+ signal generators

Impulse-Narrowband radio ⇒ filters

μwave filters



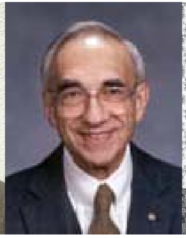
MICROWAVE FILTERS, IMPEDANCE-MATCHING NETWORKS, AND COUPLING STRUCTURES

G. Matthaei
L. Young
E.M.T. Jones

1964

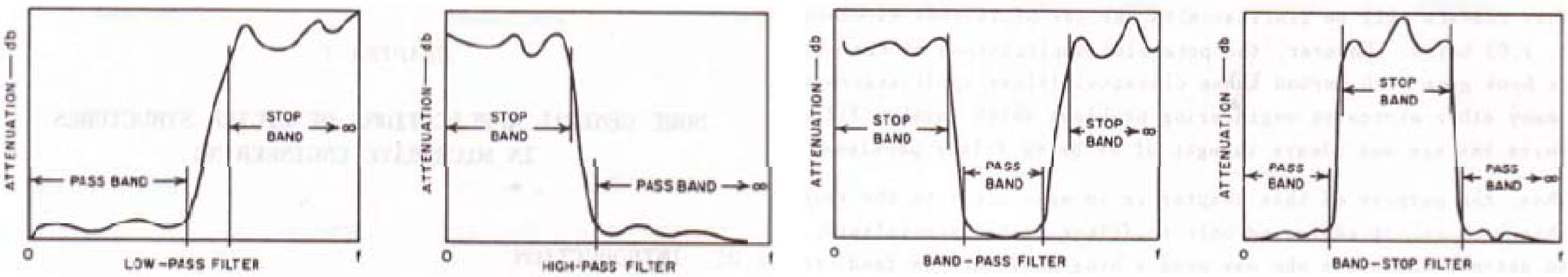
Matthaei

Young



Jones

Long history of “magnitude engineering” → FILTERS



- **Little “phase engineering”, except all-pass filters (τ_g equalization)**
- **No systematic exploration for exploiting richer dispersion**

→ analog signal processing devices & systems

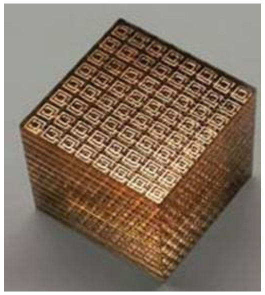
e.g. millimeter-wave analog signal processors

Dispersion Engineering in EM & Radio

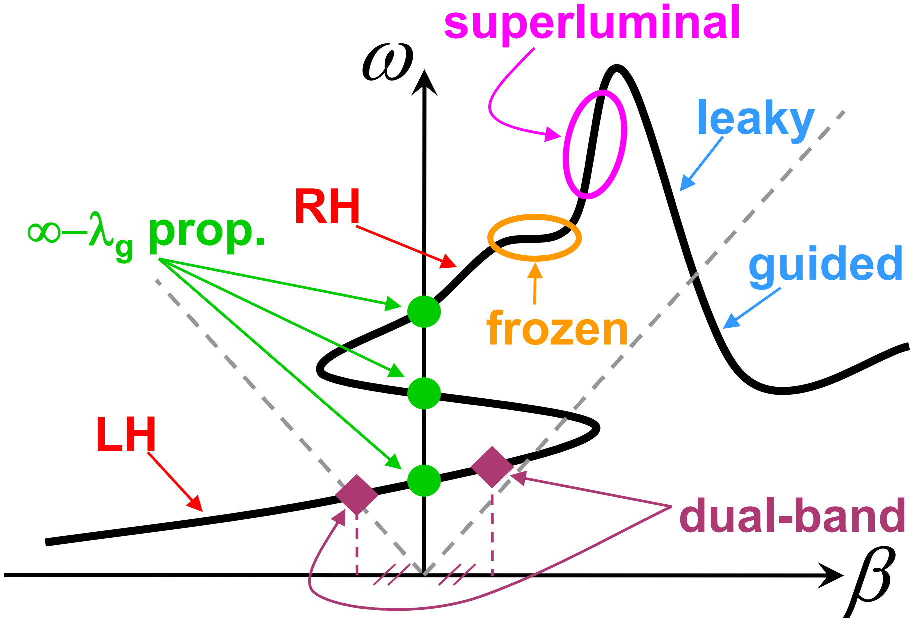
Dispersion (Phase) Engineering

broadband wireless (e.g. UWB)

METAMATERIALS



Pulse-broadband radio ⇒ ‘phasers’



Energy

$$\overline{W} = \frac{1}{4}\left[\frac{d(\omega\varepsilon)}{d\omega}\overline{\mathcal{E}^2} + \frac{d(\omega\mu)}{d\omega}\overline{\mathcal{H}^2}\right] > 0$$

$$\Downarrow$$

$$\frac{d(\omega\varepsilon)}{d\omega} > 0 \qquad \frac{d(\omega\mu)}{d\omega} > 0$$

$$\varepsilon < 0 \quad \Downarrow \quad \mu < 0$$

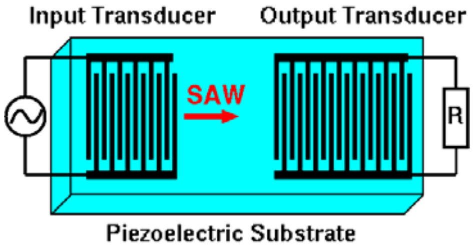
$$\varepsilon = \varepsilon(\omega) \qquad \mu = \mu(\omega)$$

$$\Downarrow$$

DISPERSION ENGINEERING

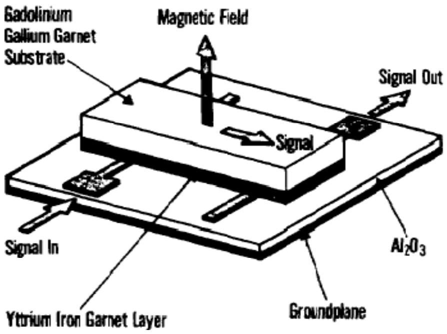
ANALOG SIGNAL PROCESSING (ASP)

Technologies for Analog Signal Processing (ASP)



Size ↓ + Delay ↑ : ☺
f_o+ BW ↓ : ☹

SAW

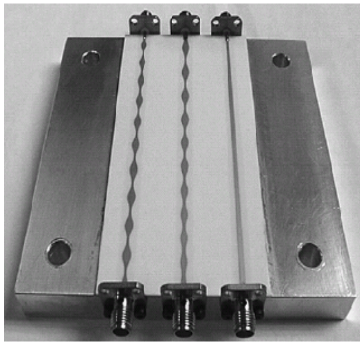


f_o + BW + Delay ↑ : ☺
Magnet + Loss : ☹

MSW

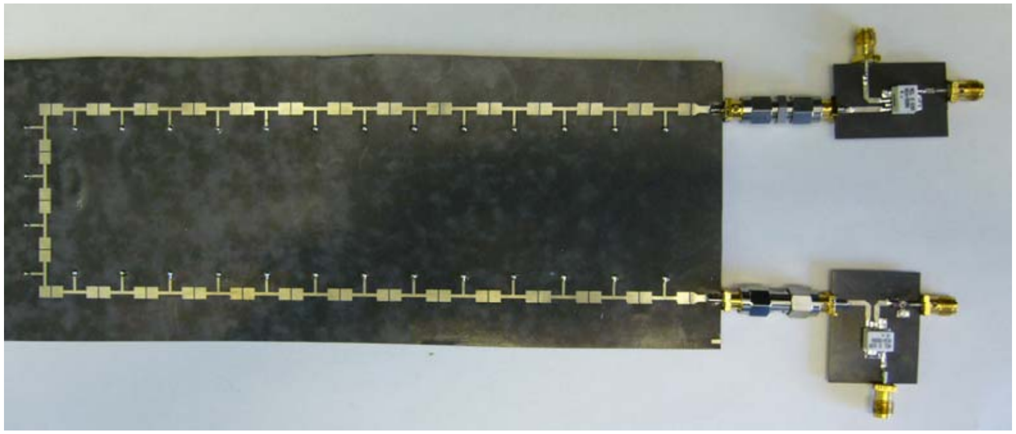
BW + delay ↑ : ☺
Size ↑ + Cryogenics : ☹

Coupler chain



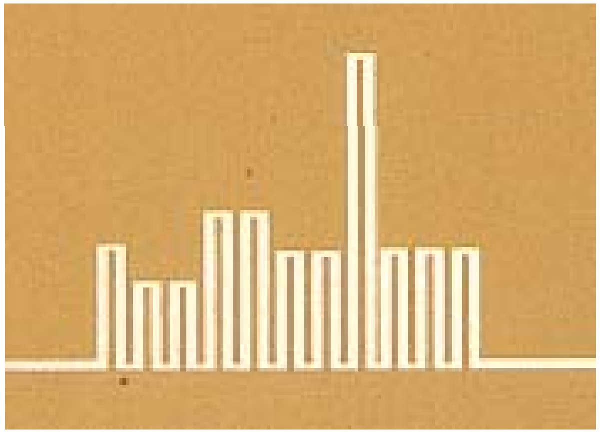
BW + Delay ↑ : ☺
Size ↑ : ☹ Ripples : ☹

Chirped TL



BW + Delay ↑ : ☺; Ripples : ☺; f_o ↑ : ☺; Design : ☺
Fixed profile : 😐; Size ↑ : ☹

CRLH TL



BW + Delay ↑ : ☺ ; Ripples: ☺
Engineerable: ☺; Size : 😐

All-pass network DDL

CRLH Impulse Regime Dispersion Properties

- **2-Port transmission (reflection) phase:**

$$\Phi(\omega)\Big|_{\omega=\omega_0} = \Phi_0 + \dot{\Phi}_1(\omega-\omega_0) + \frac{1}{2}\ddot{\Phi}_2(\omega-\omega_0)^2 + \ldots$$

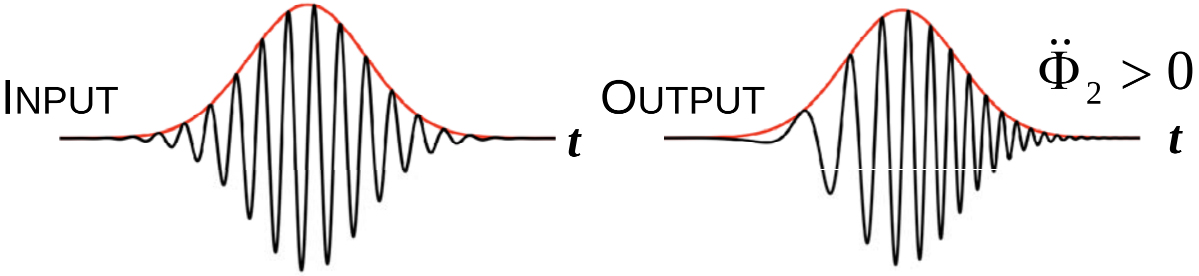
PHASE DELAY PARAMETER

GROUP DELAY PARAMETER

DISPERSION PARAMETER

- **Transfer function & impulse response for a signal envelope in a retarded frame:**

$$H(\omega) = |H(\omega)|\exp\left[j\frac{1}{2}\ddot{\Phi}_2\omega^2\right] \qquad h(t) \propto \exp\left[j\frac{1}{2\ddot{\Phi}_2}t^2\right]$$



- **For effective medium (e.g. CRLH)**

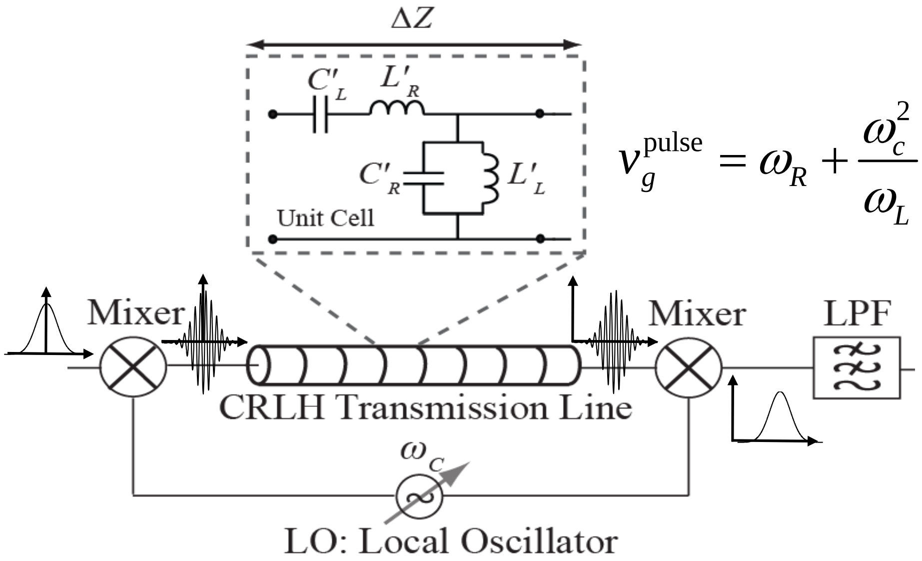
$$\beta(\omega)\Big|_{\omega=\omega_0} = \frac{\omega}{\omega_R} - \frac{\omega_L}{\omega}\Bigg|_{\omega=\omega_0} = \beta_0 + \beta_1(\omega-\omega_0) + \frac{1}{2}\beta_2(\omega-\omega_0)^2 + \ldots$$

$$\beta_0 = \left(\frac{\omega_0}{\omega_R} - \frac{\omega_L}{\omega_0}\right), \quad \beta_1 = \frac{1}{v_g} = \frac{1}{\omega_R} + \frac{\omega_L}{\omega_0^2} = \frac{\tau_g}{\ell}, \quad \beta_2 = -\frac{2\omega_L}{\omega_0^3} < 0 \text{ (anomalous)}$$

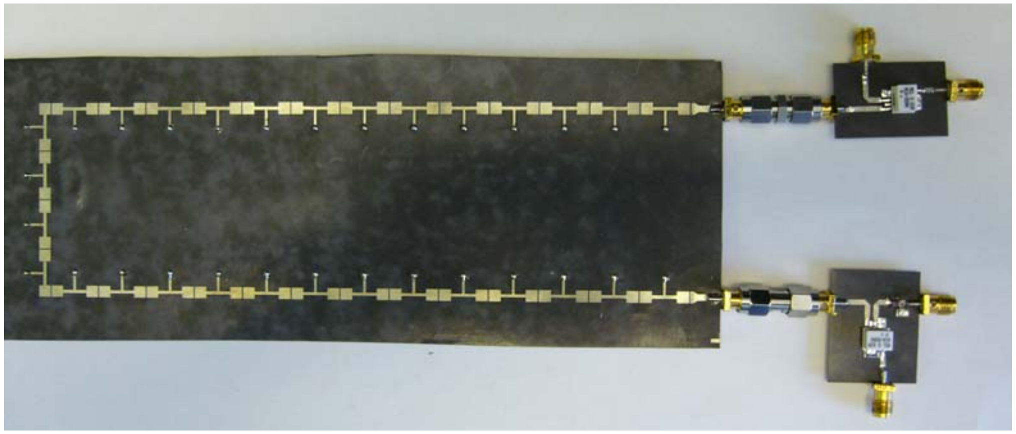
Analog Signal Processing (ASP) Applications

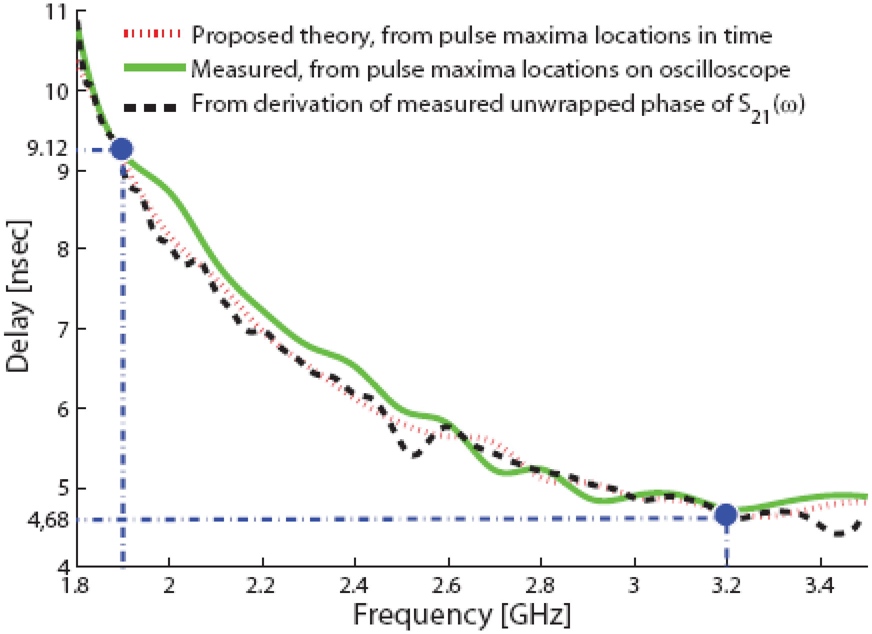
PHASE VELOCITY PARAMETER: β_0	GROUP VELOCITY PARAMETER: β_1	GROUP VELOCITY DISPERSION PARAMETER: β_2
Multi-band components	Tunable delay line	Real-time Fourier Transformer (RTFT)
Bandwidth enhancement	Dispersion compensator	Frequency discriminator
Coupling enhancement	Pulse position modulator	Real-time spectrum analyzer (RTSA)
Flexible combiner/divider	Tunable pulse generator	Temporal Talbot Effect
Direction of Arrival (DoA)	True time delayer	Spatio-Temporal Talbot Effect
Active systems		Convolvers and correlators
…	…	Solitons/Shock Waves…

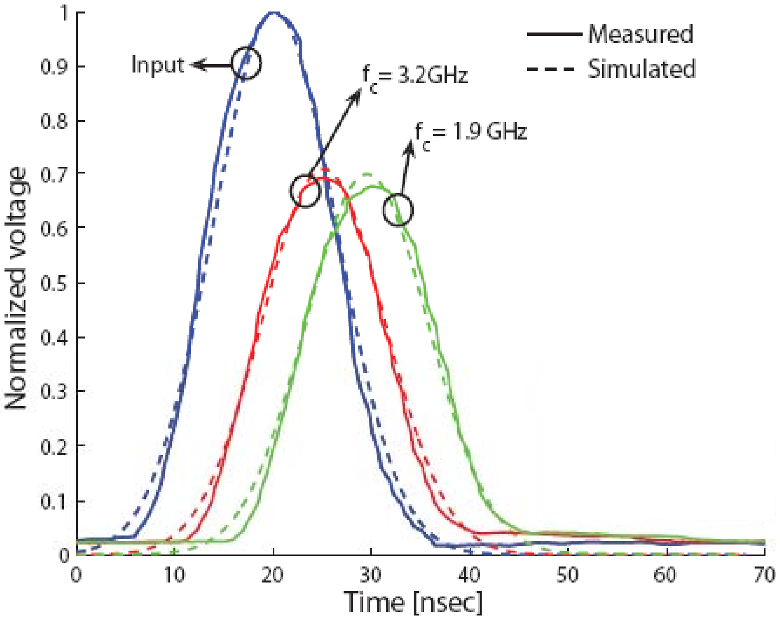
Tunable CRLH Delay Line



$$v_g^{\text{pulse}} = \omega_R + \frac{\omega_c^2}{\omega_L}$$

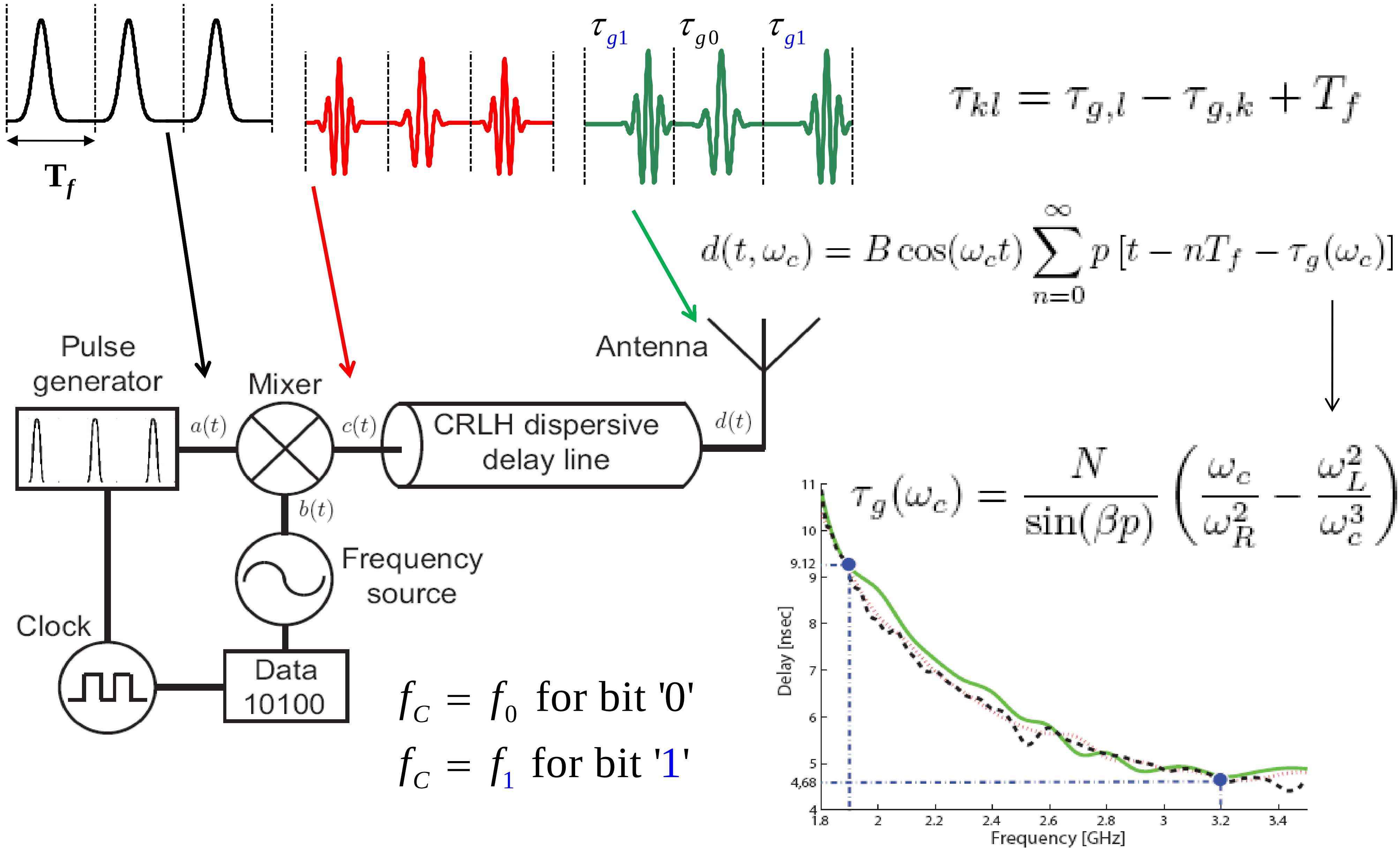






S. Abielmona, S. Gupta, and C. Caloz, ***IEEE MWCL,*** vol. 17, no. 12, pp. 864-6, Dec. 2007.

UWB – Pulse Position Modulator (PPM): Principle



$$\tau_{kl} = \tau_{g,l} - \tau_{g,k} + T_f$$

$$d(t,\omega_c) = B\cos(\omega_c t)\sum_{n=0}^{\infty} p\left[t - nT_f - \tau_g(\omega_c)\right]$$

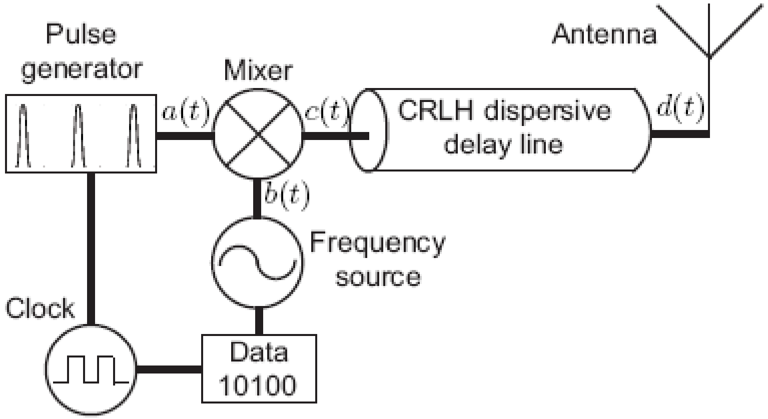
$$\tau_g(\omega_c) = \frac{N}{\sin(\beta p)}\left(\frac{\omega_c}{\omega_R^2} - \frac{\omega_L^2}{\omega_c^3}\right)$$

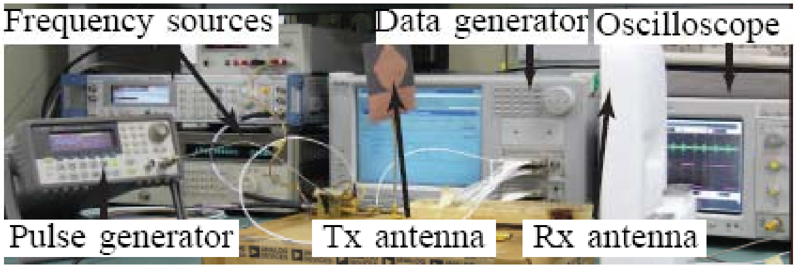
$f_C = f_0$ for bit '0'

$f_C = f_1$ for bit '1'

H. V. Nguyen, and C. Caloz, ***IEEE MWCL***, vol. 18, no. 6, pp. 527-529, Aug. 2008.

UWB – PPM Result





(a)

(b)

Quaternary PPM

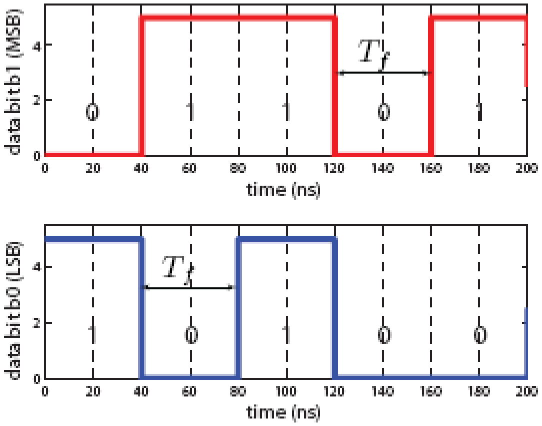
State	Data bits		f_c (GHz)	τ_g (ns)
s	b_1	b_0		Eq. (2)
0	0	0	2.500	10.948
1	0	1	2.050	15.339
2	1	0	1.850	19.529
3	1	1	1.725	23.769

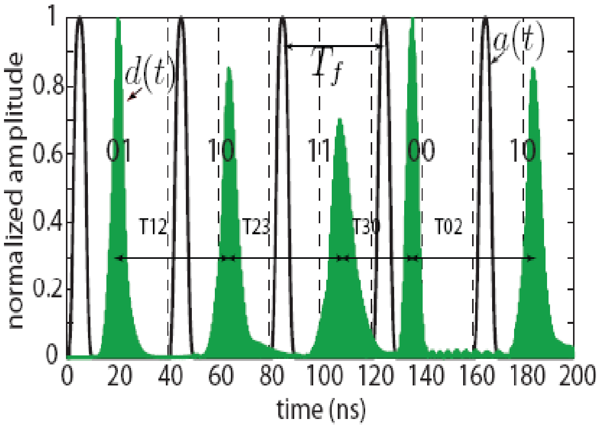
$f_c = f_{00}$ for bit '00'

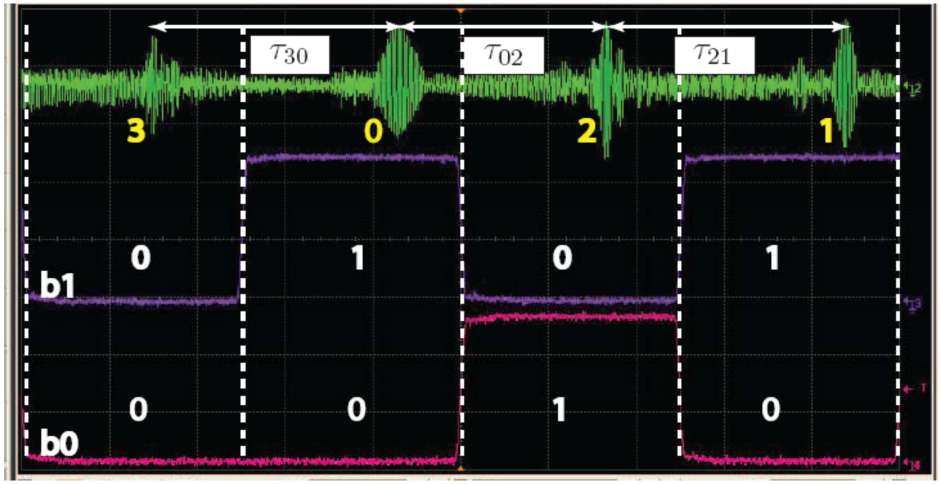
$f_c = f_{01}$ for bit '01'

$f_c = f_{10}$ for bit '10'

$f_c = f_{11}$ for bit '11'

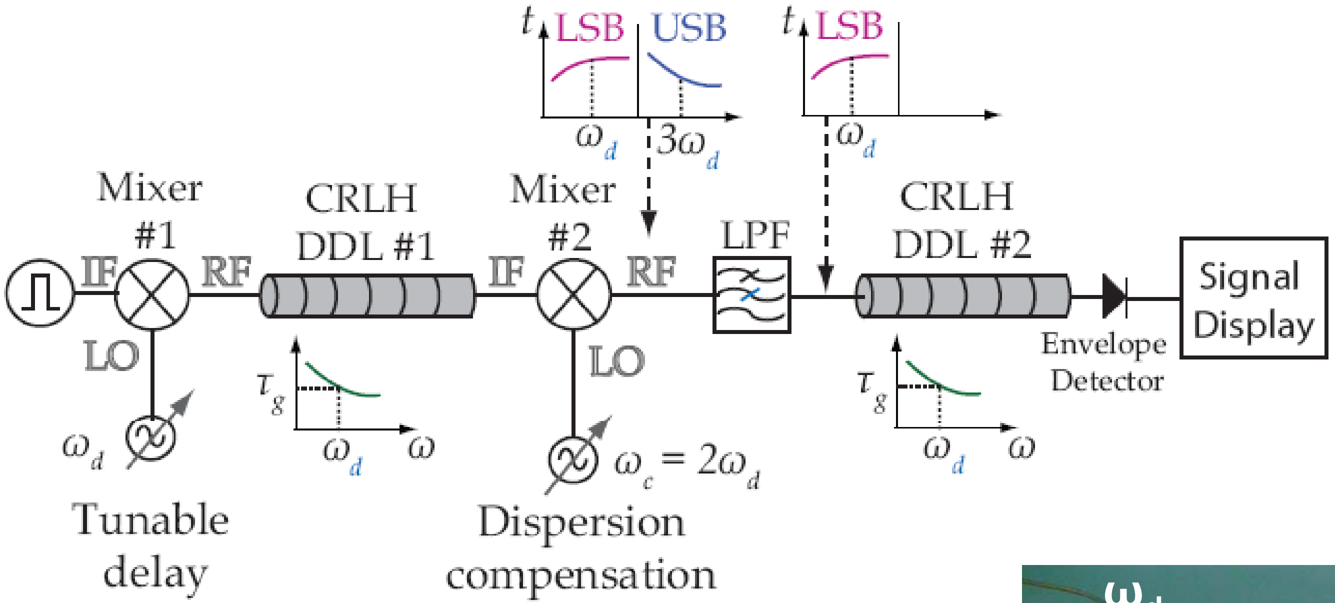


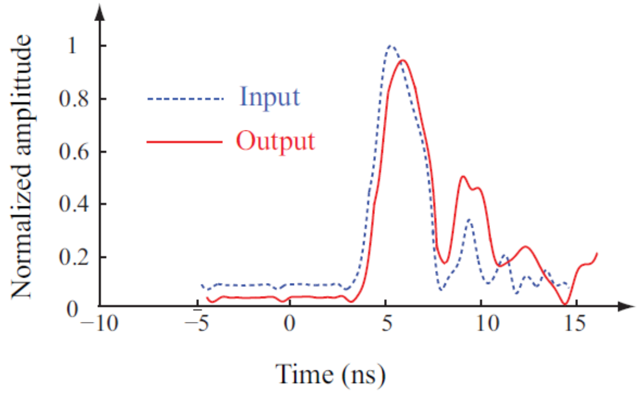


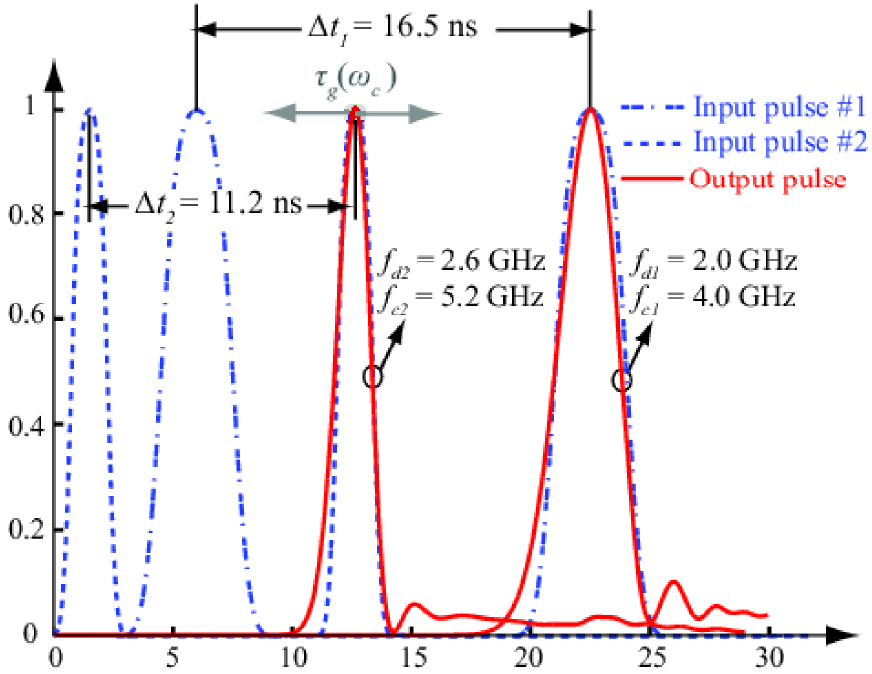


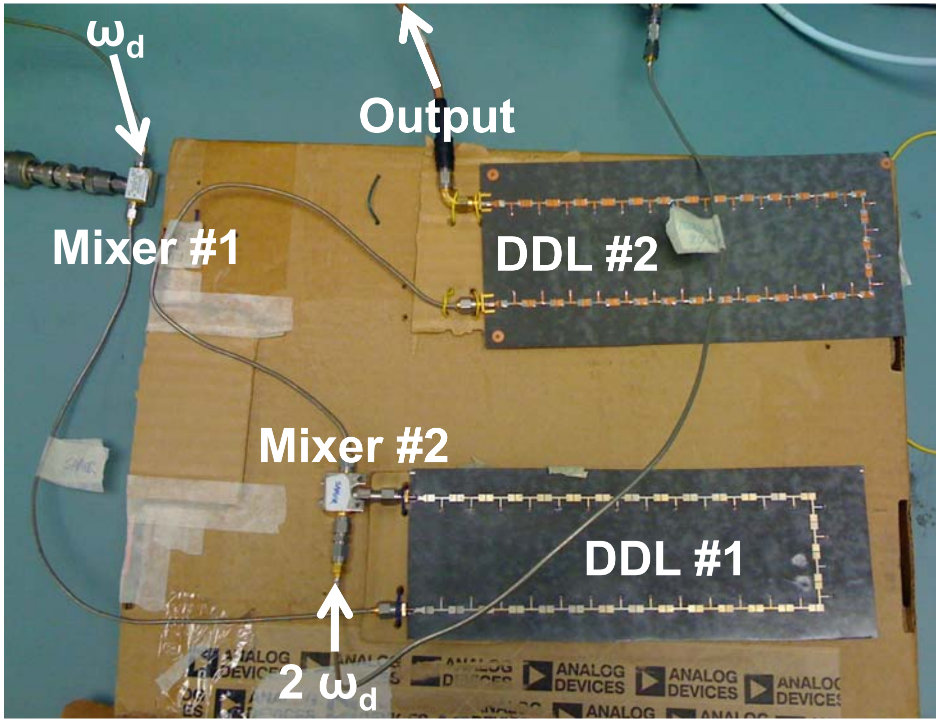
H. V. Nguyen, and C. Caloz, ***IEEE MWCL***, vol. 18, no. 6, pp. 527-529, Aug. 2008.

Tunable Delay with Dispersion Compensation



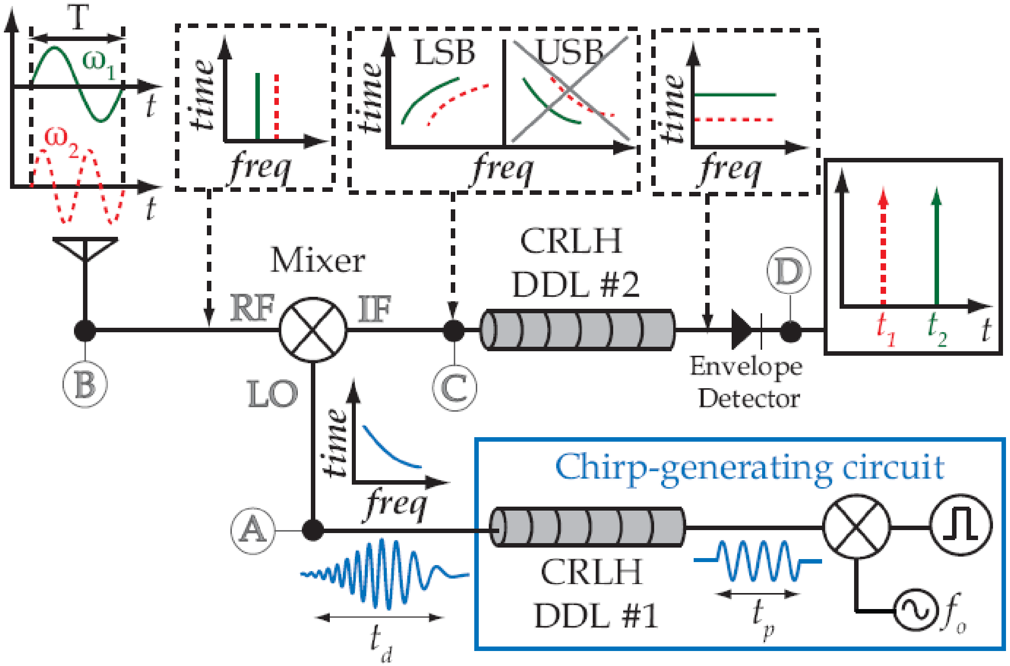


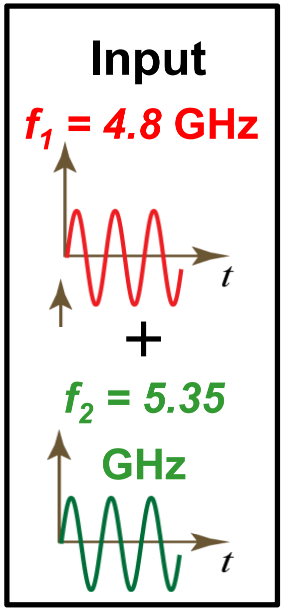




S. Abielmona, S. Gupta, and C. Caloz, ***IEEE T-MTT***, vol. 57, no. 11, pp. 2617-2618, Nov. 2009.

Real-Time Frequency Discriminator (RTFT + Mixer Inv.)

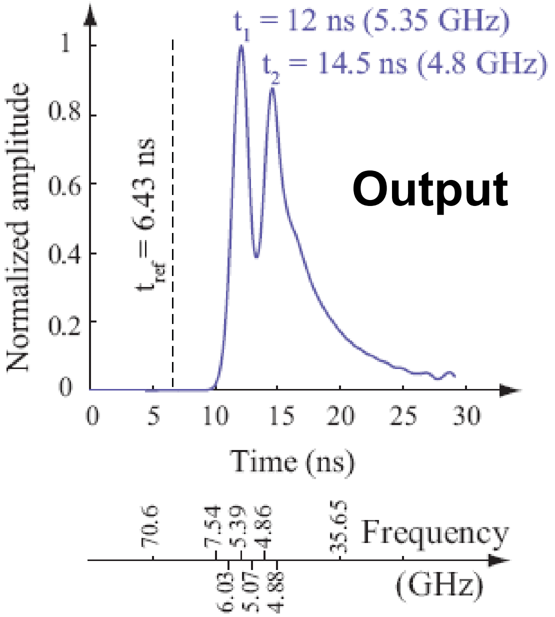


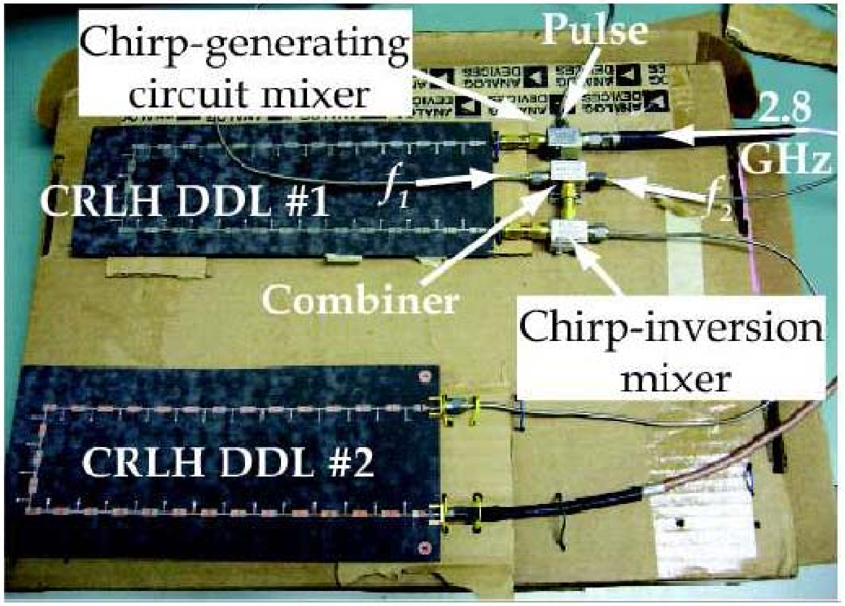

Input

f_1 = 4.8 GHz

+

f_2 = 5.35 GHz

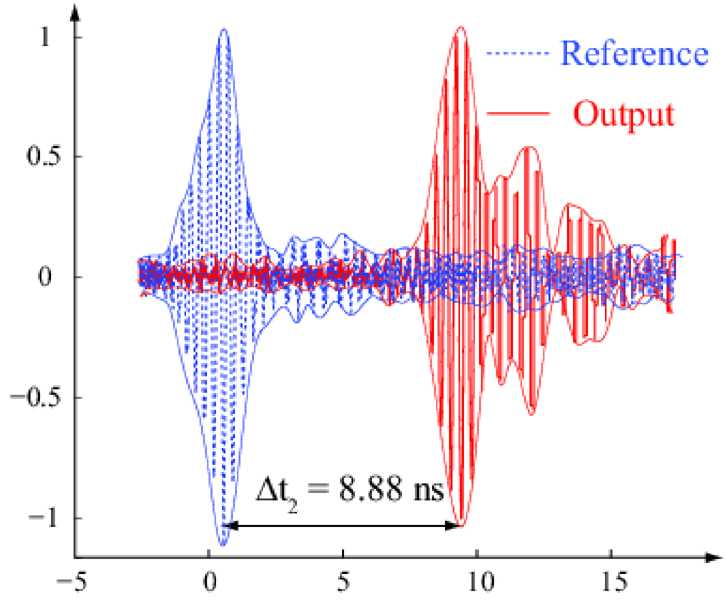

Output

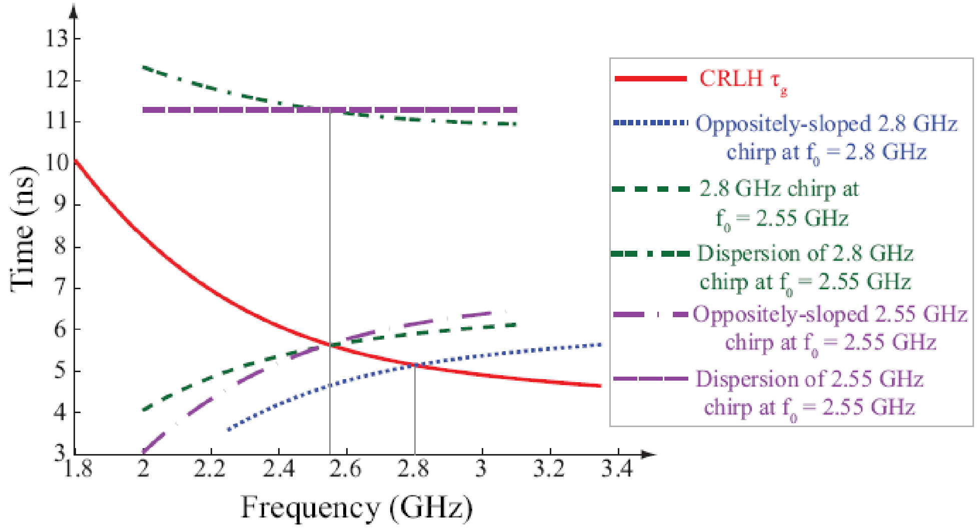


S. Abielmona, S. Gupta, and C. Caloz, ***IEEE T-MTT***, no. 11, vol. 57, Nov. 2009, *to be published.*

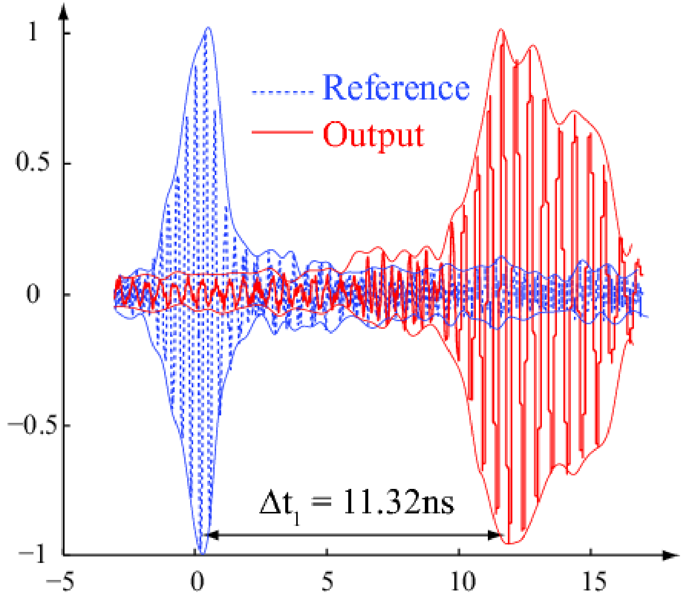
Effect of CRLH DDL on Signal Compression

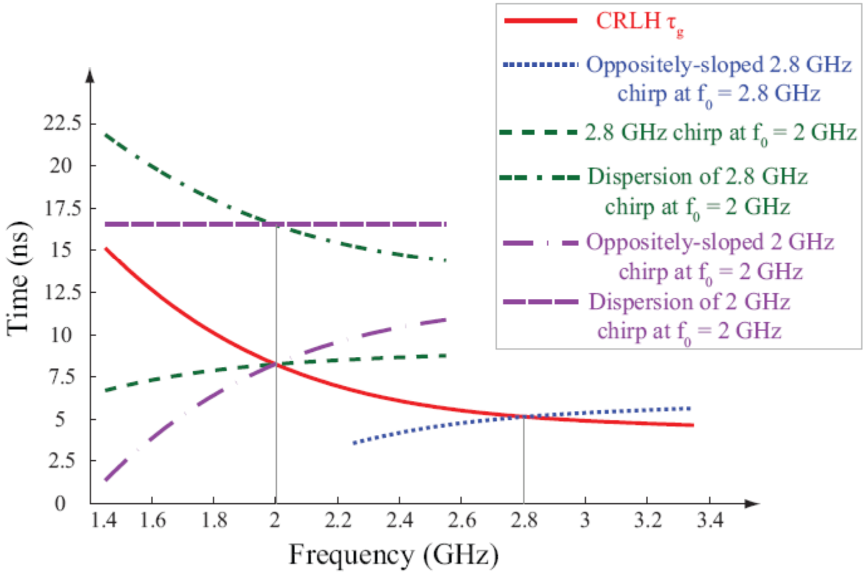
f_0 = 5.35 GHz
Near-optimal compression





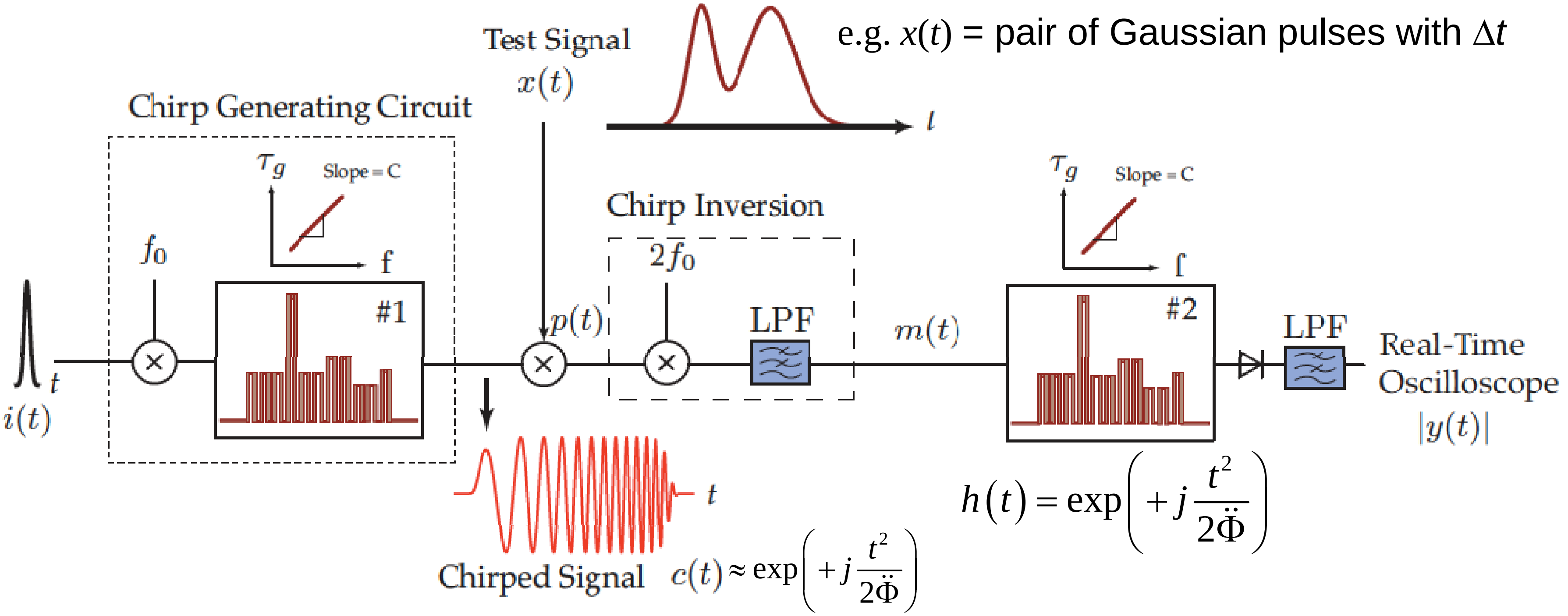
f_0 = 4.8 GHz
Sub-optimal compression





S. Abielmona, S. Gupta, and C. Caloz, ***IEEE T-MTT***, no. 11, vol. 57, pp. 2617-2618, Nov. 2009.

Real-Time Fourier Transformer (RTFT)



e.g. $x(t)$ = pair of Gaussian pulses with Δt

$$h(t) = \exp\left(+j\frac{t^2}{2\ddot{\Phi}}\right)$$

$$c(t) \approx \exp\left(+j\frac{t^2}{2\ddot{\Phi}}\right)$$

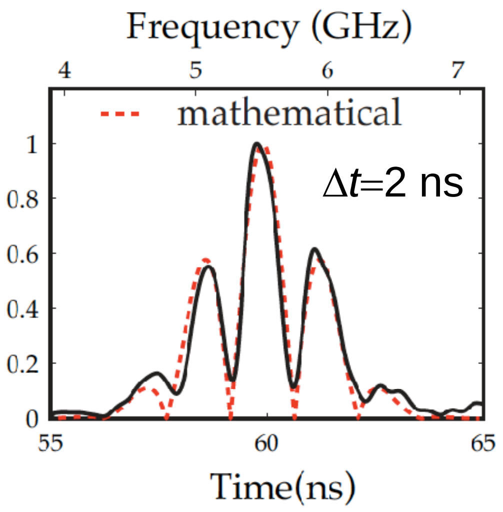
$$y(t) = \left[x(t)c(t)\right] * h(t)$$

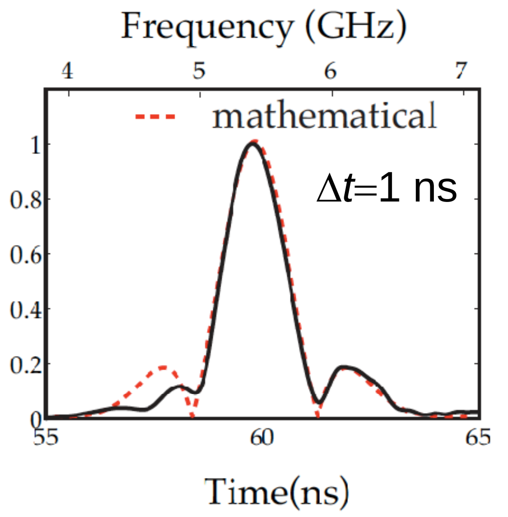
$$\boxed{\left|y(t)\right| = \int x(\tau)\exp\left(-j\frac{t}{\ddot{\Phi}}\right)d\tau}$$

FOURIER TRANSFORM INTEGRAL

$$\omega = \frac{t}{\ddot{\Phi}}$$

TIME TO FREQUENCY MAPPING

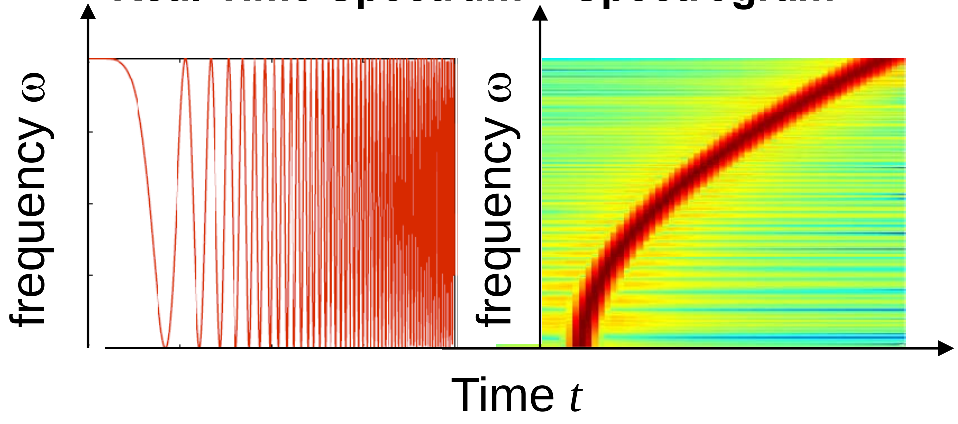




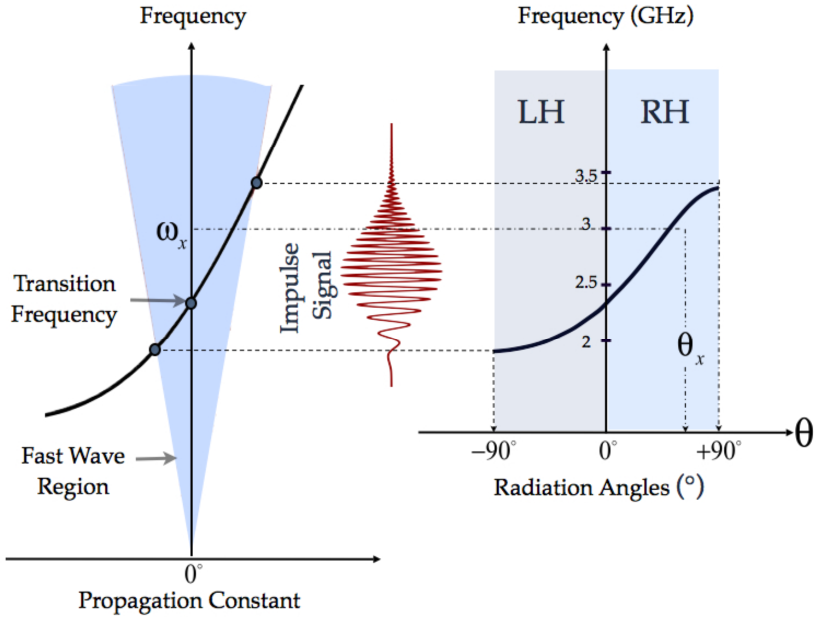
S. Abielmona, S. Gupta, and C. Caloz, ***IEEE T-MTT***, no. 11, vol. 57, Nov. 2009.

Analog Spectrogram Analyzer (1/2)

Real-Time Spectrum = Spectrogram

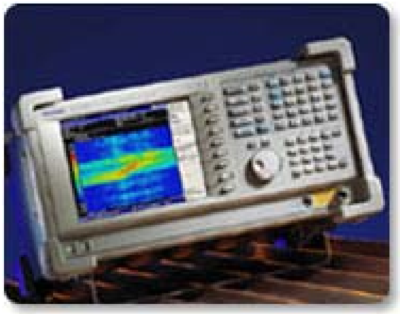


CRLH Frequency-Space Mapping

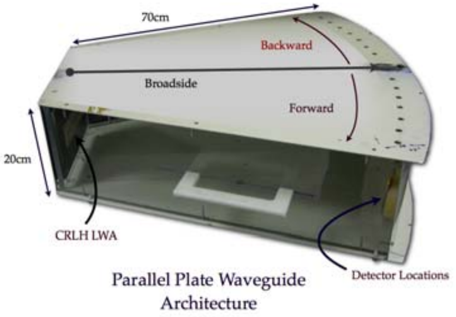


State of the Art

(Tektronix RSA6000)

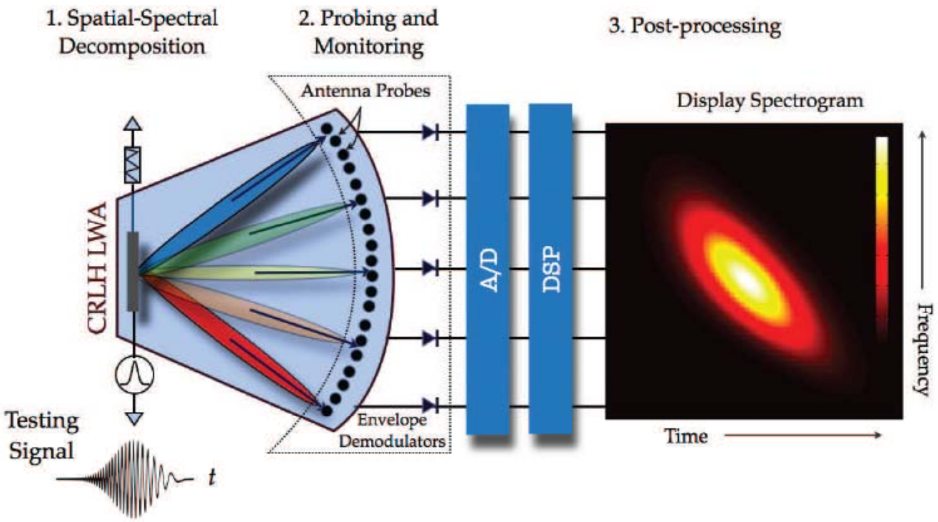


CRLH LWA Solution



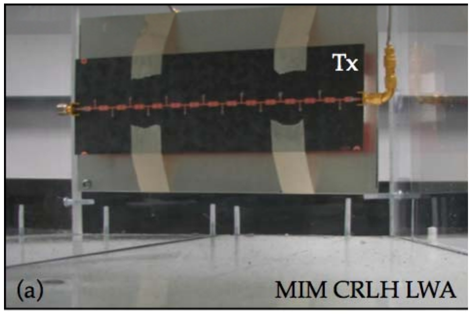
- light post-processing
- short acquisition time
- broadband UWB
- ω-scalable to mm-wave

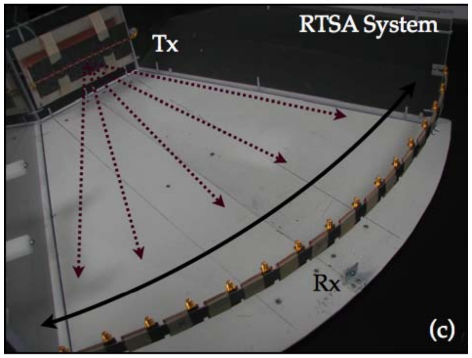
Principle

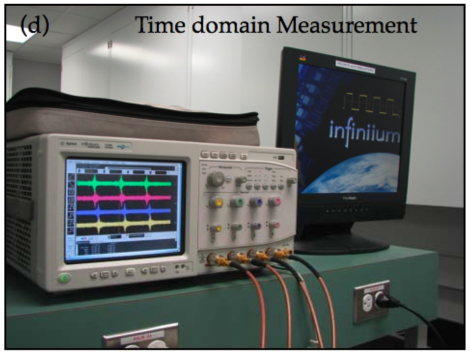


S. Gupta, S. Abielmona and C. Caloz, ***T-MTT***, vol. 57, no. 12, Dec. 2009.

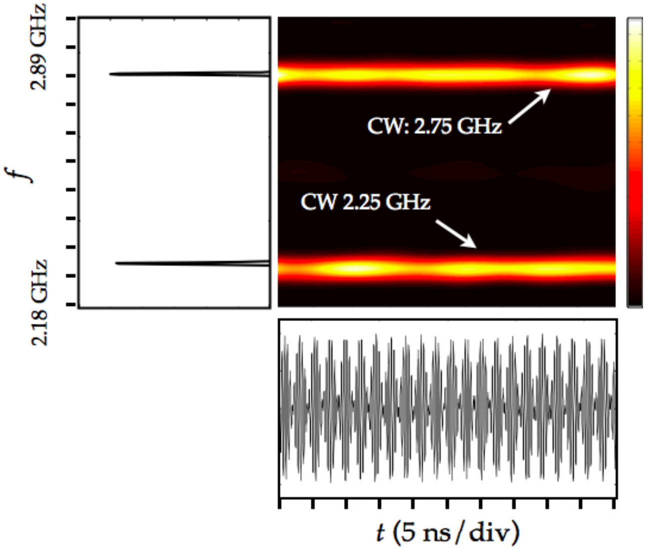
Analog Real-Time Spectrum Analyzer (2/2)



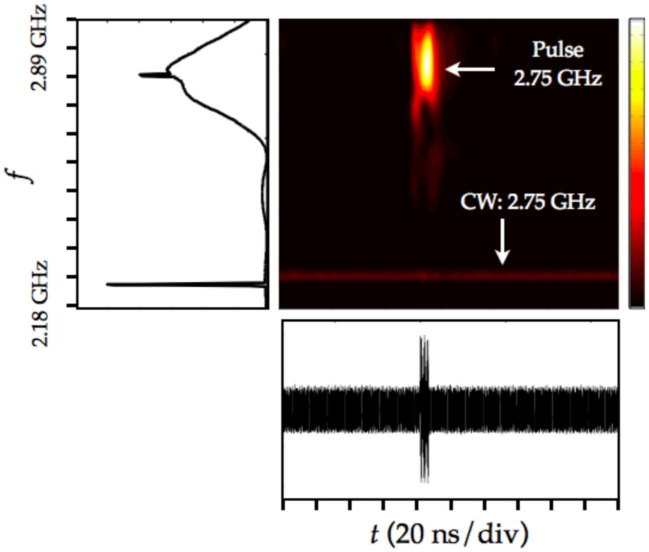




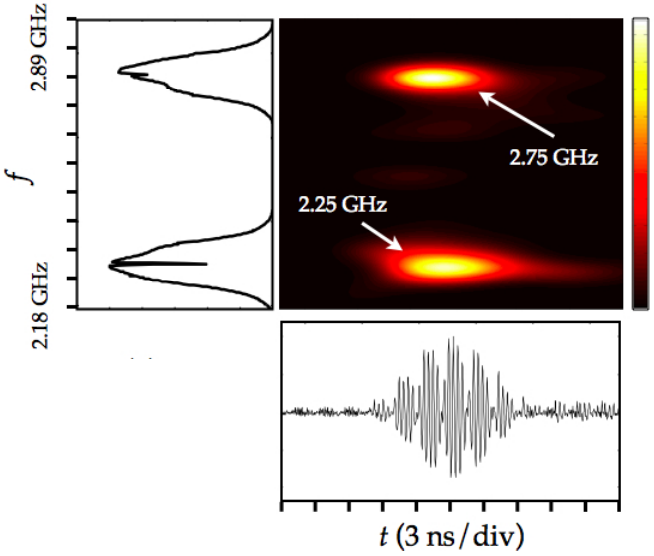
Measured Spectrograms



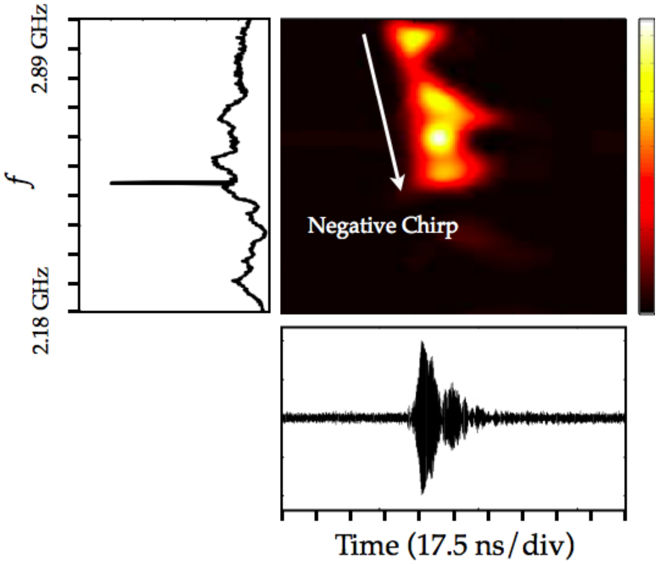
CW + CW



CW + Pulse

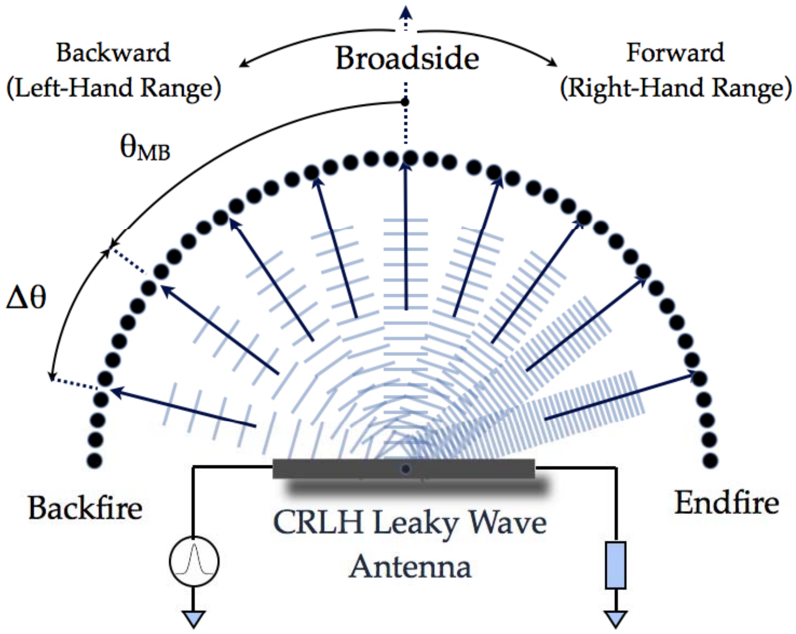


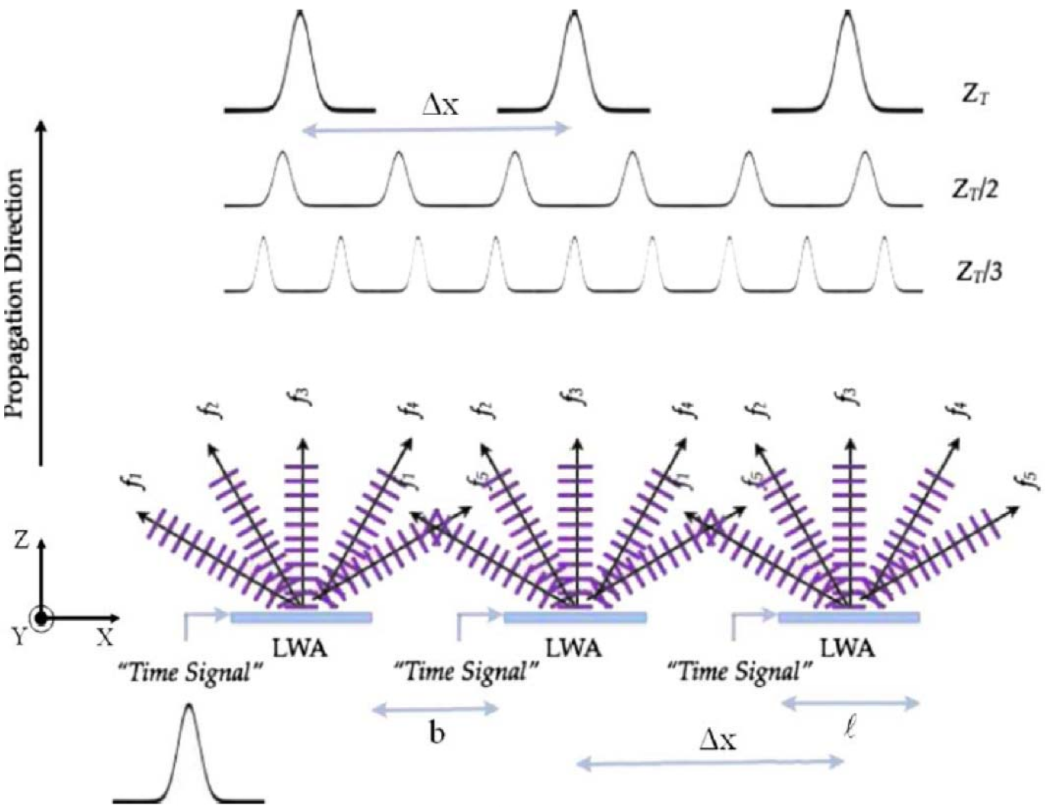
Pulse + Pulse

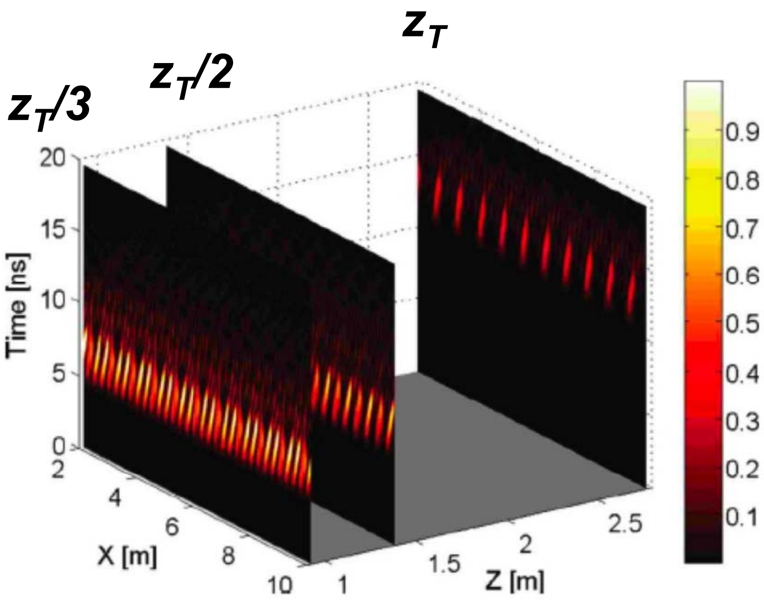


Distorted Chirped Pulse

Spatio-Temporal Talbot Effect (1/2)

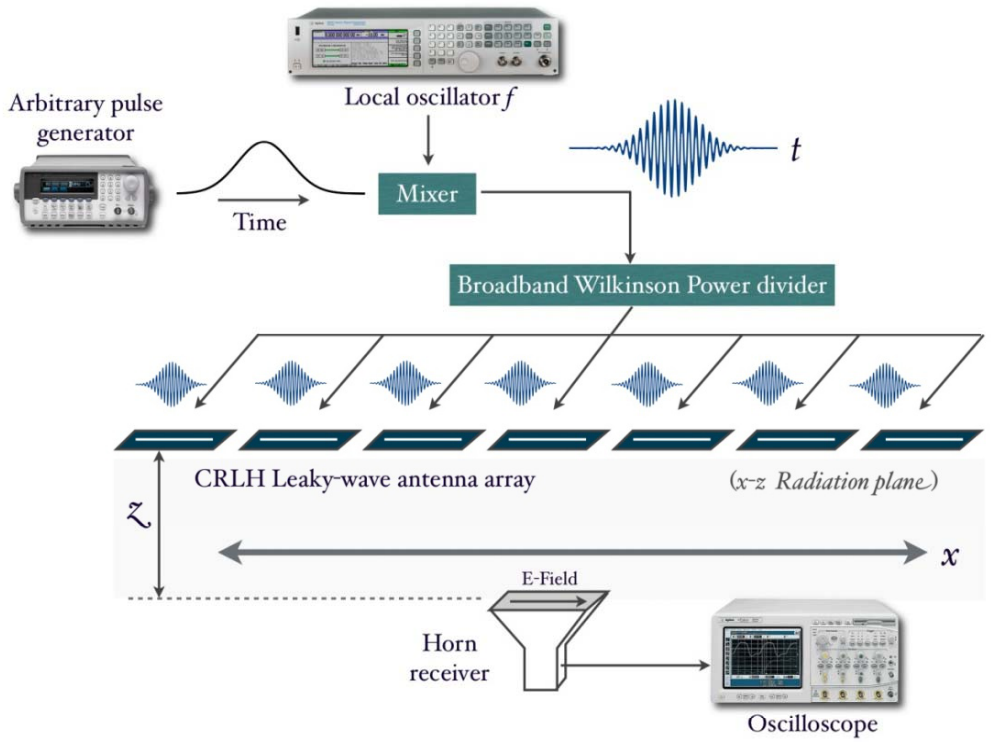






- **Spatial Talbot self-imaging localised in time**
- **Pulse radiation interference due to spectral-spatial decomposition property of the LWA**
- **Formation of Talbot zones due to impulse operation** $z_T = 2X^2 / \lambda_0 \cos^3\theta$
- **Carrier frequency Tunable Talbot distance**

Spatio-Temporal Talbot Effect (2/2)

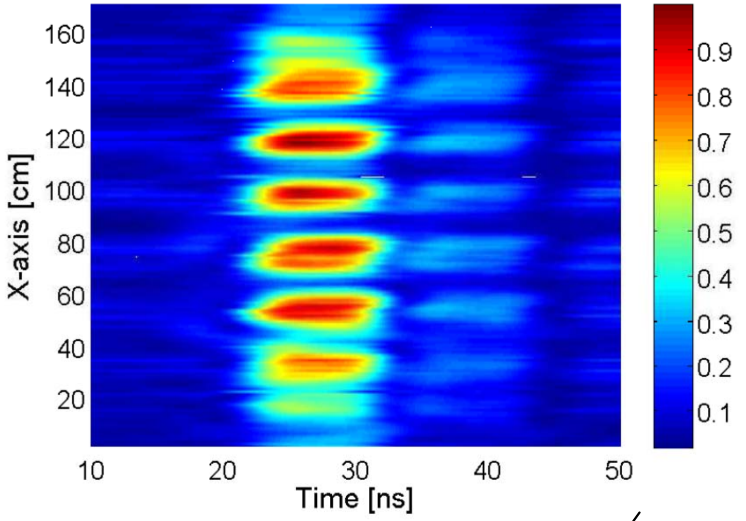


Experimental Setup

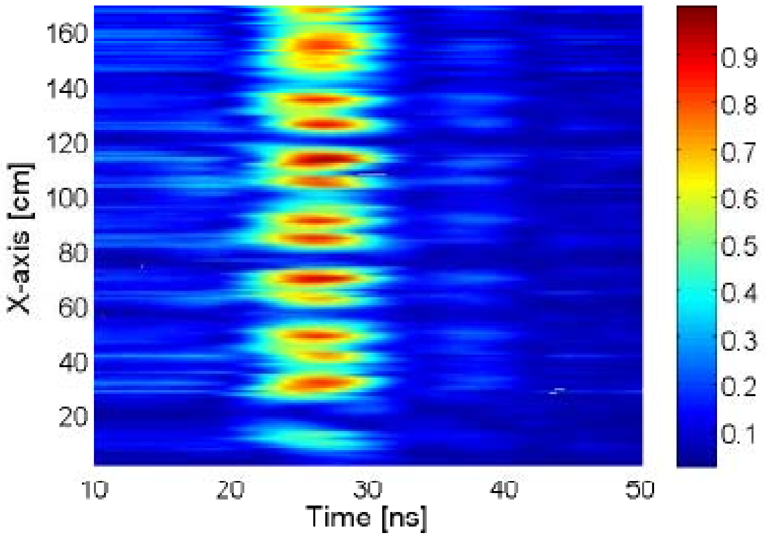
- **Self-imaging exists for backward, broadside and forward radiations.**

J. S. Gómez-Díaz, A. Alvarez-Melcon, S. Gupta, and C. Caloz, "Novel spatio-temporal Talbot phenomenon using metamaterial composite right/left-handed leaky-wave antennas " *J. App. Phys.*, vol. 104, pp. 104901:1-7, Nov. 2008.

$z = z_T$



$z = {z_T}/{2}$



Broadside Radiation

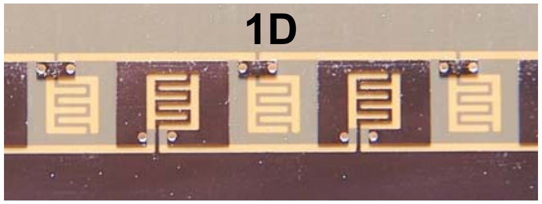
Outline

1. BROADBAND METAMATERIALS
2. INNOVATIONS IN CRLH LEAKY-WAVE ANTENNAS
3. ANALOG SIGNAL PROCESSORS
4. FERROMAGNETIC NANOWIRE COMPOSITES
5. CONCLUSIONS

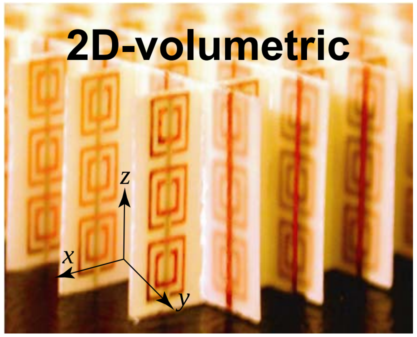
Multiscale “Ingredients” for Future Metamaterials

μ-Scale

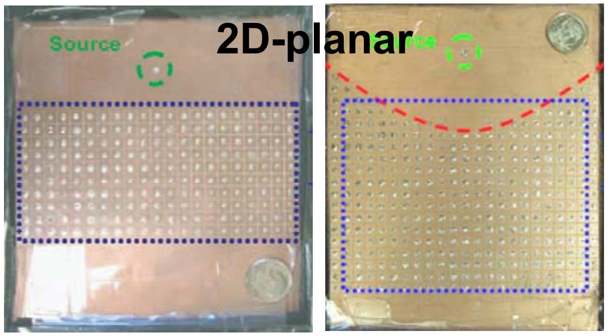
1D



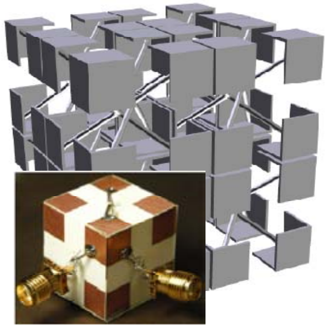
2D-volumetric



2D-planar

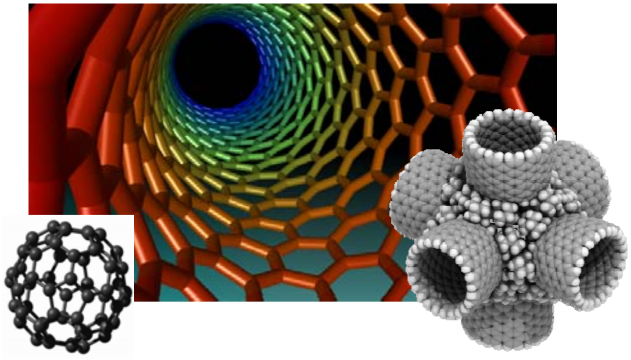


3D

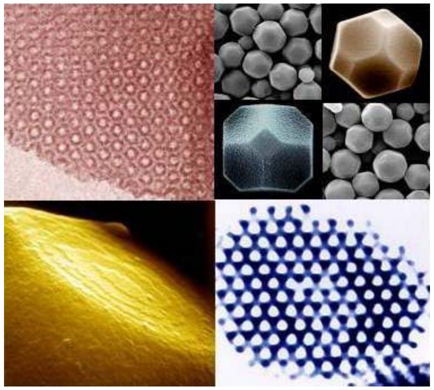


n-Scale

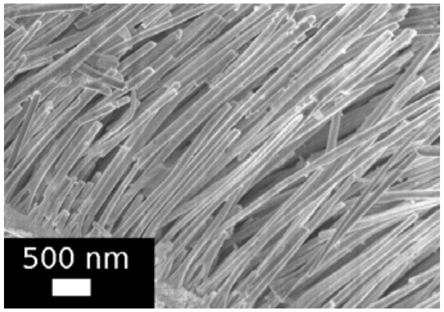
Carbon Nano-Tubes



Nano-Polymers

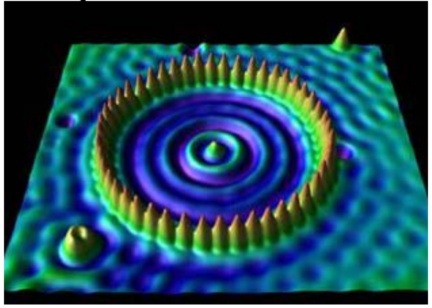


Magnetic Nano-Wires

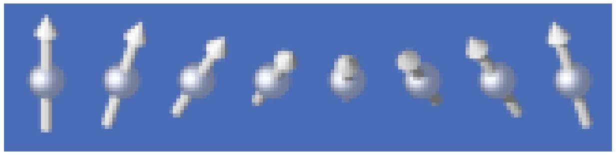


a-Scale

Quantum Dots

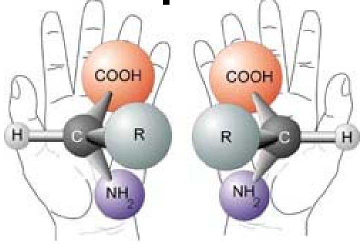


Spins



Anisotropic Materials

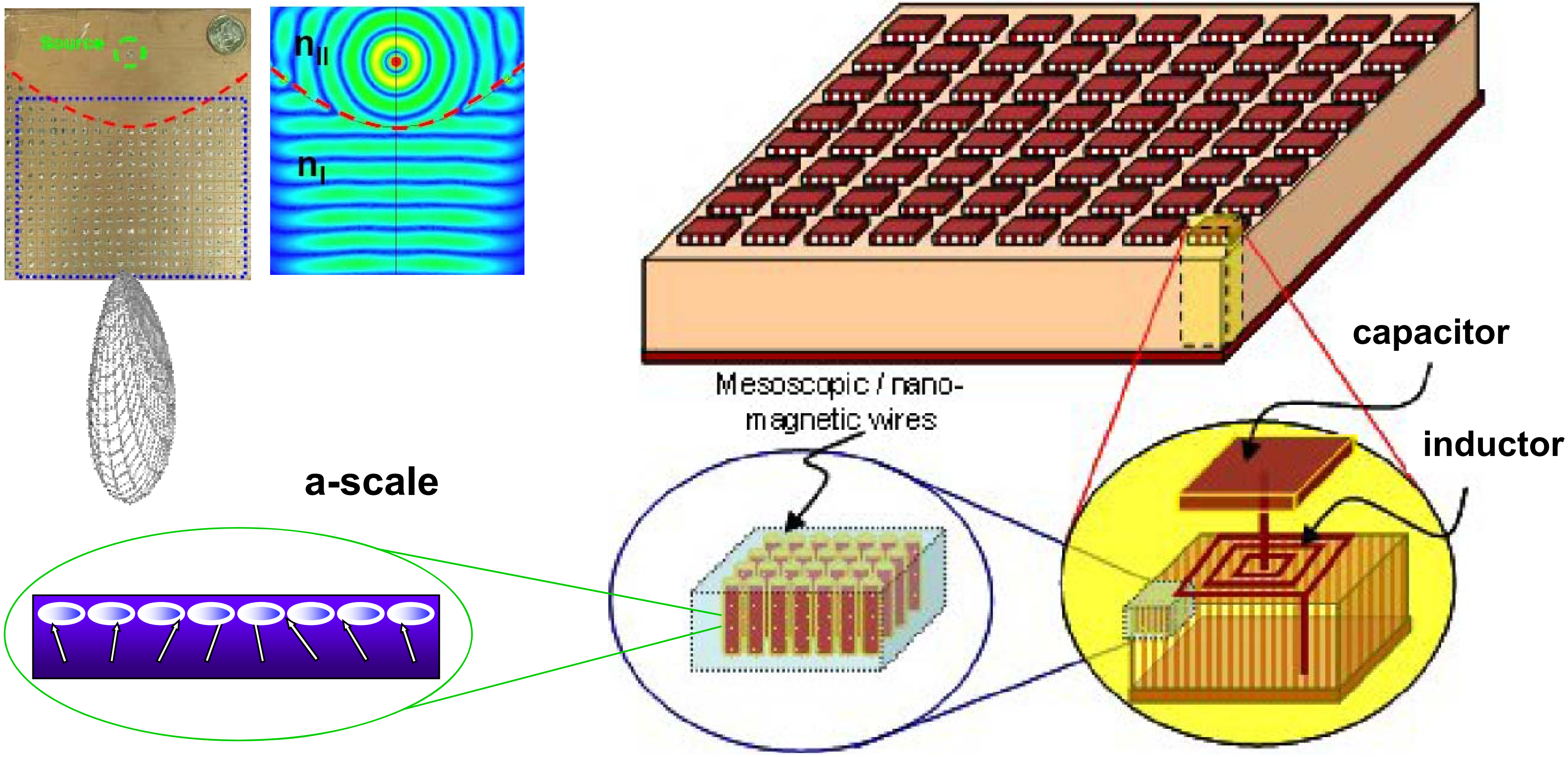
Bi-anisotropic Substances



Multiscale Metamaterial

MTM Device

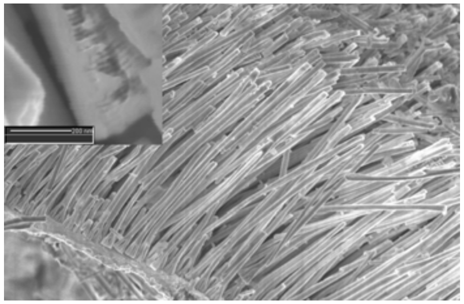
Overall MTM



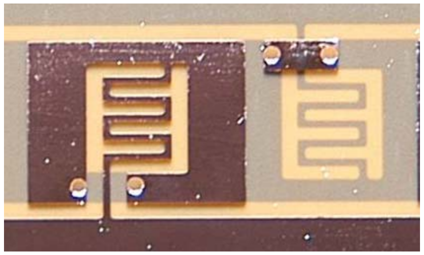
$$\overline{D} = \overline{\overline{\varepsilon}}(\omega) \cdot \overline{E} + \overline{\overline{\xi}}(\omega) \cdot \overline{H}$$

$$\overline{B} = \overline{\overline{\zeta}}(\omega) \cdot \overline{E} + \overline{\overline{\mu}}(\omega) \cdot \overline{H}$$

n-scale



μ-scale

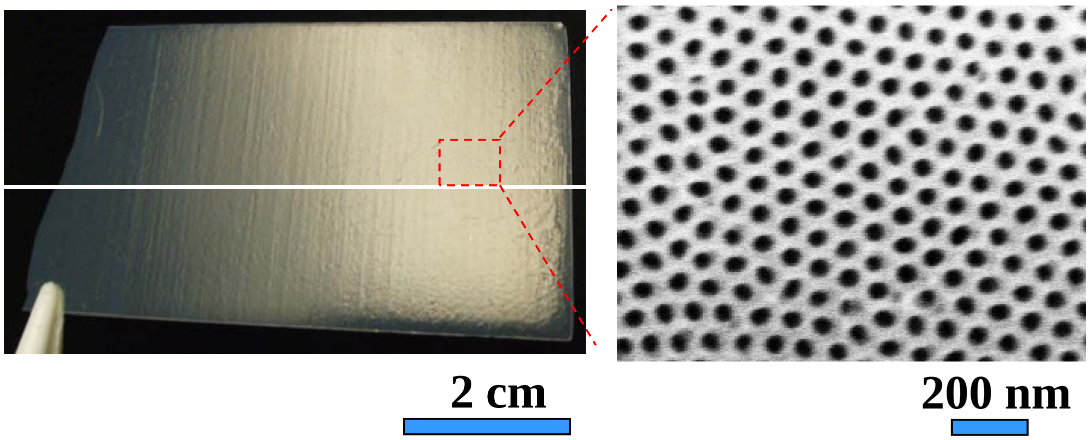


Ferromagnetic Nanowire (FMNW) Metamaterial

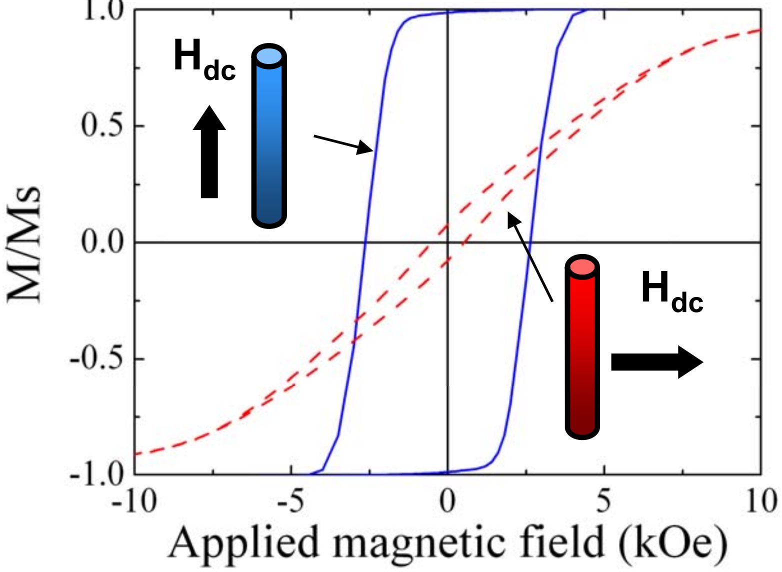
Fabrication Process of FMNW

Anodization of Al :
nanoporous Al_2O_3

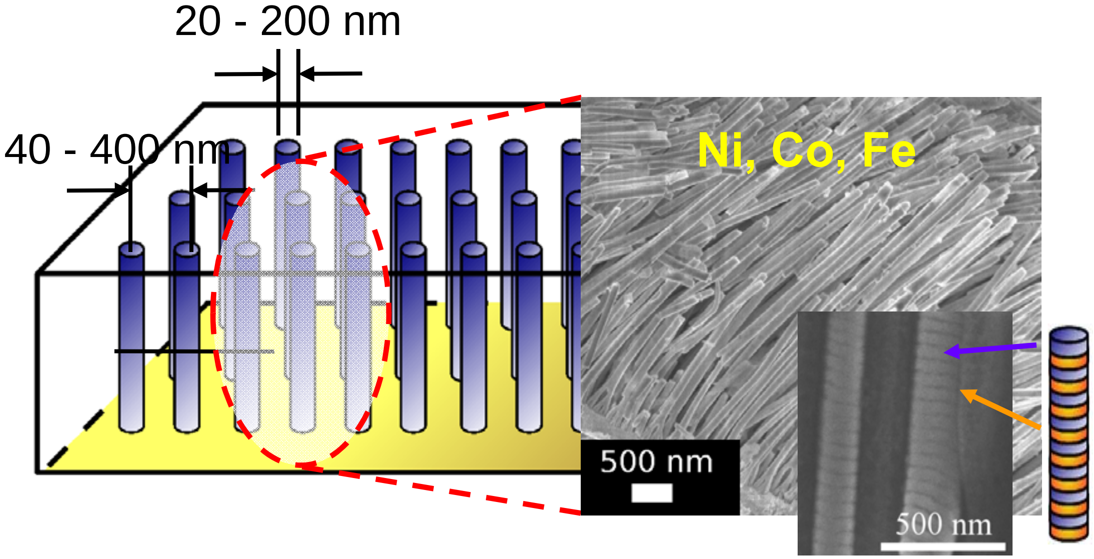
Nanoporous template
Ferromagnetic plating



Hysteresis



FMNW Structure

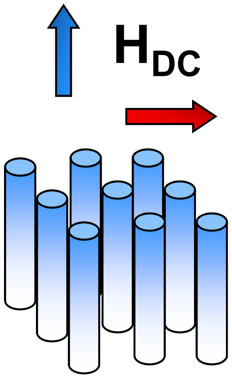


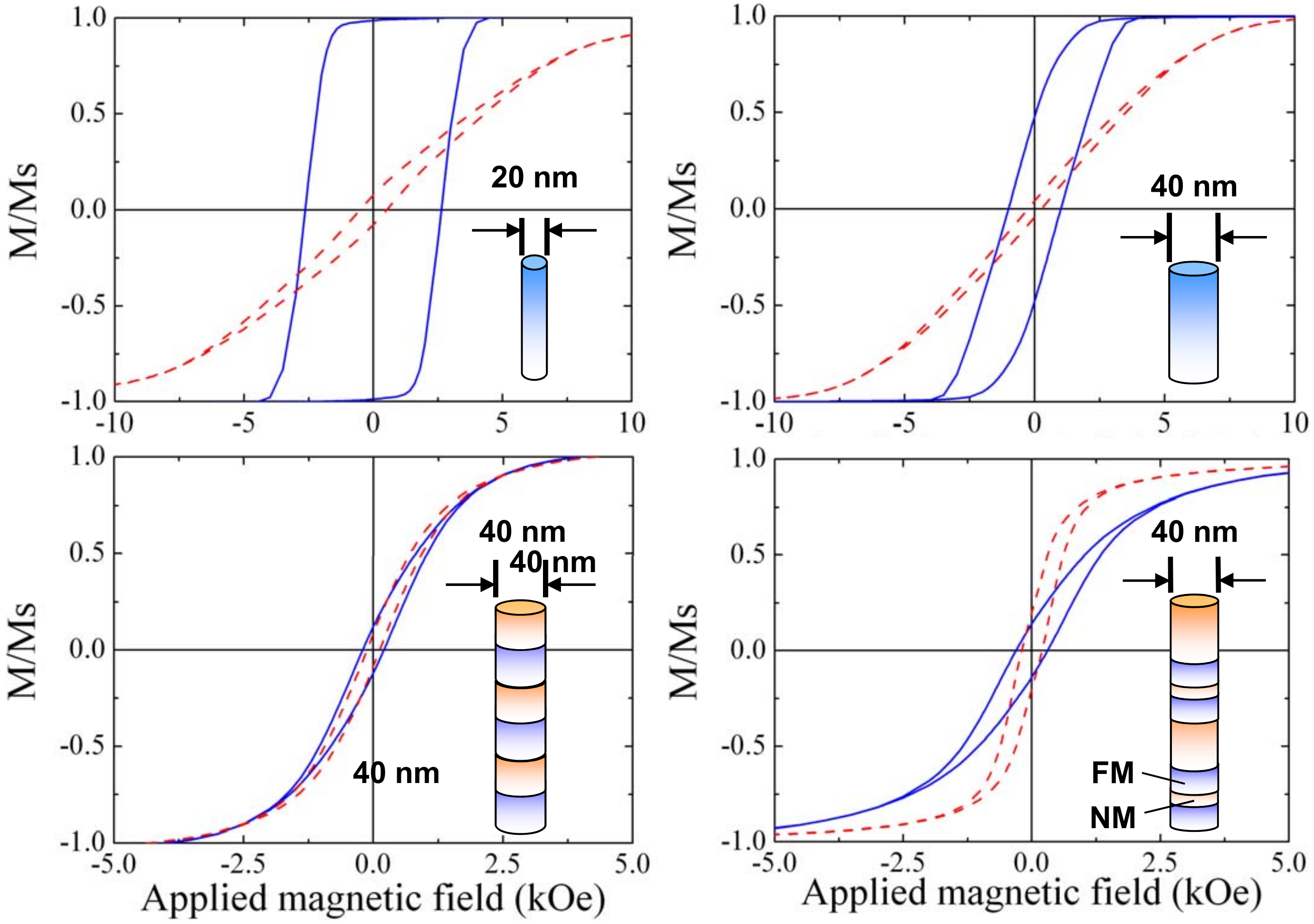
Unique Properties

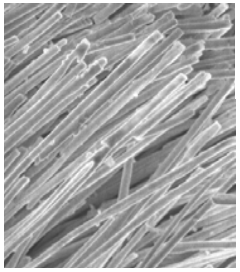
- Highly homogeneous ($p << \lambda_g$)
- Self bias
- High ω (> 35 GHz)
- Integrated magnetics
- Dispersion eng. $(\bar{\bar{\varepsilon}}, \bar{\bar{\mu}})$
- Double FMR
- High power handling
- High T stability (high T_c)

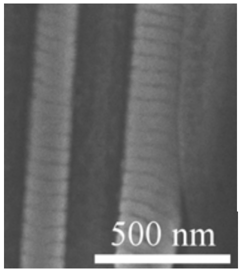
L.-P. Carignan, M. Massicotte, C. Caloz, A. Yelon, and David Ménard., ***IEEE T-Mag.***, vol. 45, no. 10, 4070-4073, Oct. 2009.

FMNW Metamaterial Anisotropy Engineering





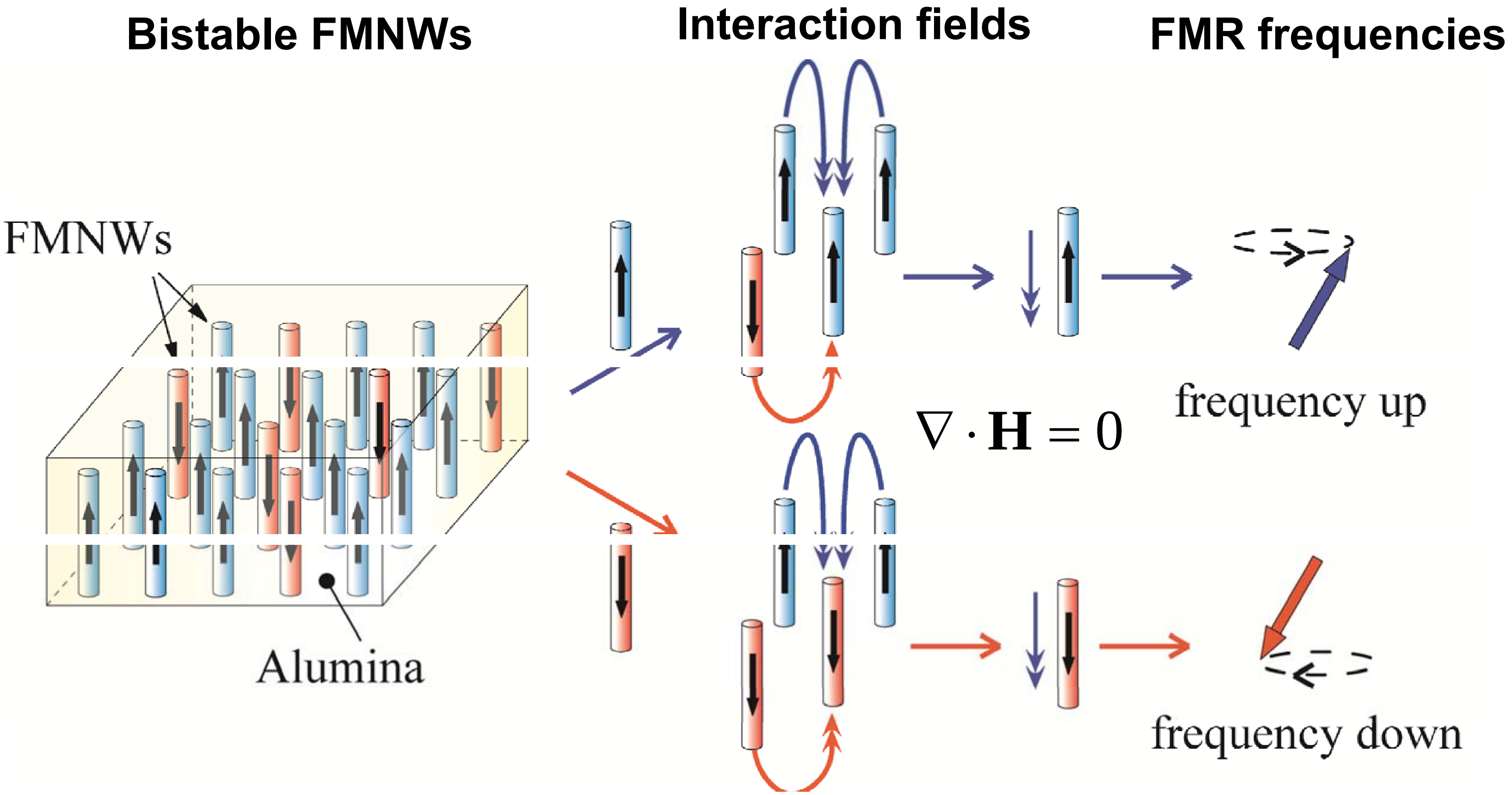




Magnetic properties tuned via:

- **wire diameter: 10 - 100 nm**
- **material composition: NiFe and CoFeB alloys**
- **nano-disk thicknesses: 5 nm – 500 μm**

Double ferromagnetic resonance in FMNWs



- 2 peaks associated with the 2 magnetization states (↑ and ↓)
- Applications: dual-band microwave devices

L.-P. Carignan, C. Caloz, and D. Ménard, *IMS* (2009).

FMNW Double FMR: Maxwell-Garnett Modeling

Landau-Lifshifz-Gilbert (LLG) equation for $\mathbf{M}_\uparrow$ & $\mathbf{M}_\downarrow$

$$\frac{\partial \mathbf{M}_{\uparrow,\downarrow}}{\partial t} = -\mathbf{M}_{\uparrow,\downarrow} \times \left(\underbrace{\mu_0 |\gamma| \mathbf{H}_{w\uparrow,\downarrow}}_{\text{effective field}} - \underbrace{\frac{\alpha}{M_s} \frac{\partial \mathbf{M}_{\uparrow,\downarrow}}{\partial t}}_{\text{loss}} \right)$$

$$\boxed{\mathbf{H}_{w\uparrow,\downarrow}} = \mathbf{H}_{w0} + \mathbf{h}_{w\uparrow,\downarrow} = (H_0 - \Delta P M_s)\hat{\mathbf{z}} + \mathbf{h}_{\text{loc}} - \tfrac{1}{2}\mathbf{m}_{\uparrow,\downarrow}$$

DC bias field

DC inter-wire field

AC field

AC demagnetizing field

$$\boxed{\mathbf{M}_{\uparrow,\downarrow}} = \pm M_s \hat{\mathbf{z}} + \mathbf{m}_{\uparrow,\downarrow}$$

LLG equations ➡ $\mathbf{m}_{\uparrow,\downarrow} = \overleftrightarrow{\eta}_{w\uparrow,\downarrow} \mathbf{h}_{\text{loc}}$

Maxwell-Garnett mixing rule

$$\langle \mathbf{b} \rangle = \underbrace{P[f_\uparrow \langle \mathbf{b}_{w\uparrow} \rangle + f_\downarrow \langle \mathbf{b}_{w\downarrow} \rangle]}_{\text{FMNWs}} + \underbrace{(1-P)\langle \mathbf{b}_m \rangle}_{\text{Matrix}}$$

➡ $\langle \mathbf{b} \rangle = \overleftrightarrow{\mu}_{\text{eff}} \langle \mathbf{h} \rangle$

$$\frac{\overleftrightarrow{\mu}_{\text{eff}}}{\mu_0} = \overleftrightarrow{I} + P[\overleftrightarrow{\eta}_w^{-1} - P\overleftrightarrow{N}_w]^{-1}$$

$$\overleftrightarrow{\eta}_w = f_\uparrow \overleftrightarrow{\eta}_{w\uparrow} + f_\downarrow \overleftrightarrow{\eta}_{w\downarrow}$$

MG and LLG equations ➡

$$\overleftrightarrow{\mu}_{\text{eff}} = \mu_0(\overleftrightarrow{I} + \overleftrightarrow{\chi}_{\text{eff}}) = \begin{pmatrix} \mu_{\text{eff}} & -i\mu_{\text{eff},t} & 0 \\ i\mu_{\text{eff},t} & \mu_{\text{eff}} & 0 \\ 0 & 0 & \mu_0 \end{pmatrix}$$

$$\Delta P = \Delta f P = P_\uparrow - P_\downarrow$$

➡ **poles of μ_{eff}** ➡

$$\omega_{\text{res}\pm} = \frac{\omega_M}{2} \left\{ \left[1 - P + \left(\frac{\Delta P}{2} \right)^2 \right]^{\frac{1}{2}} \mp \frac{\Delta P}{2} \right\} \pm \omega_H$$

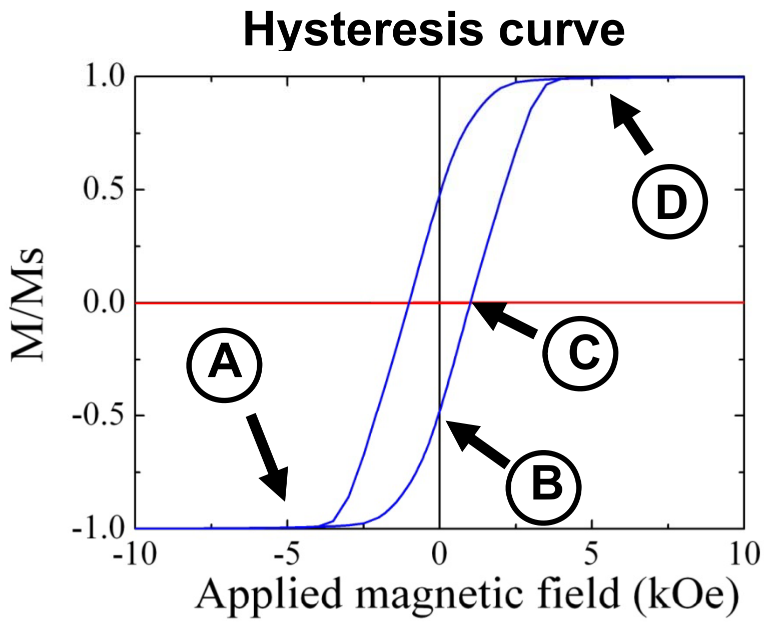
$$\Delta P = P_\uparrow - P_\downarrow$$

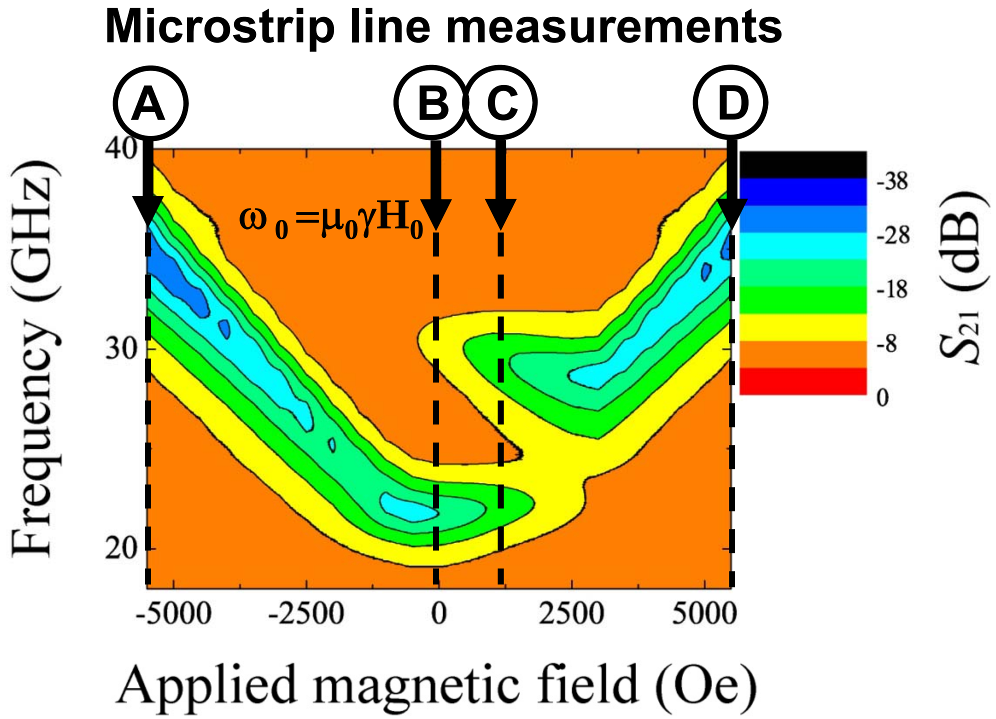
$$\omega_M = \mu_0 |\gamma| M_s$$

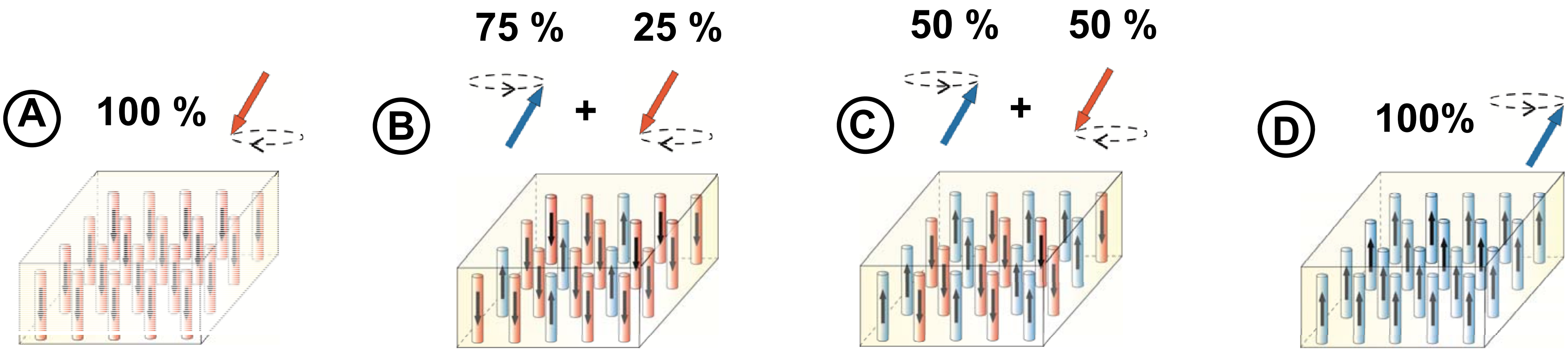
$$\omega_H = \mu_0 |\gamma| (H_0 - \Delta P M_s)$$

V. Boucher, L.-P. Carignan, T. Kodera, C. Caloz, A. Yelon, D. Ménard, ***Phys. Rev. B***, vol. 80, 224402 1:11., Dec. 2009.

FMNW Double FMR: Experimental Demonstration

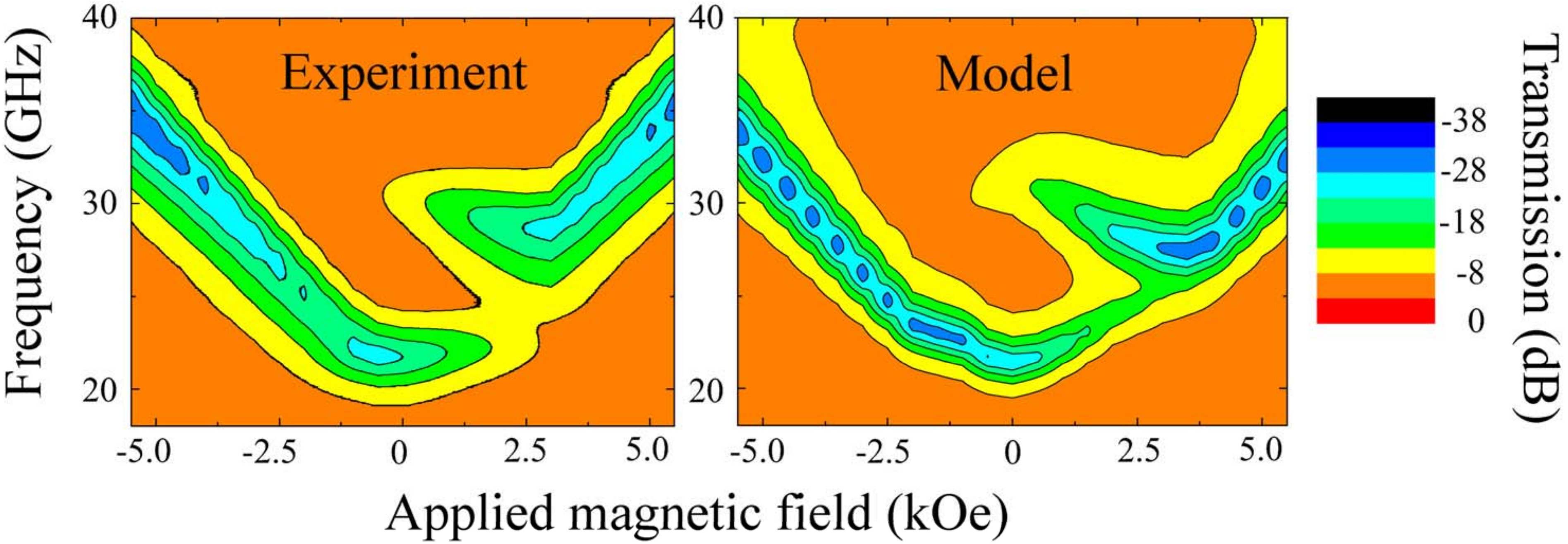

Hysteresis curve


Microstrip line measurements



L.-P. Carignan, V. Boucher, T. Kodera, C. Caloz, A. Yelon, and D. Ménard, ***Appl. Phys. Lett.***, vol. 52, pp. 062504-1:3, Aug. 2009.

FMNW Double FMR: Model vs Experiment

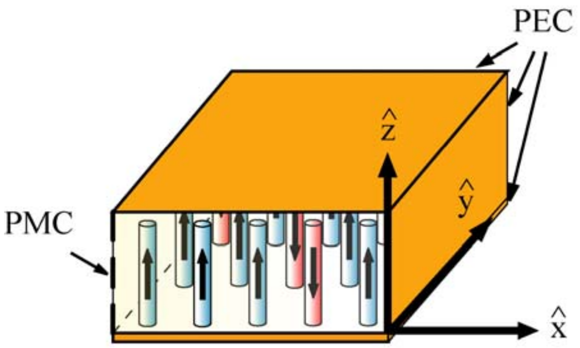


Good agreement between experiment and model

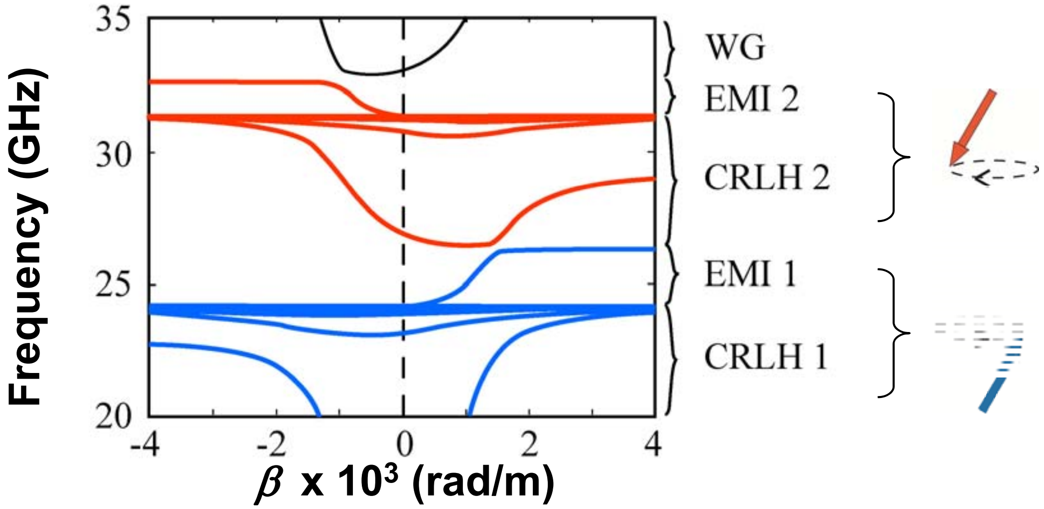
L.-P. Carignan, V. Boucher, T. Kodera, C. Caloz, A. Yelon, and D. Ménard, ***Appl. Phys. Lett.***, vol. 52, pp. 062504-1:3, Aug. 2009.

Double-Band Edge-Guided Mode Isolator

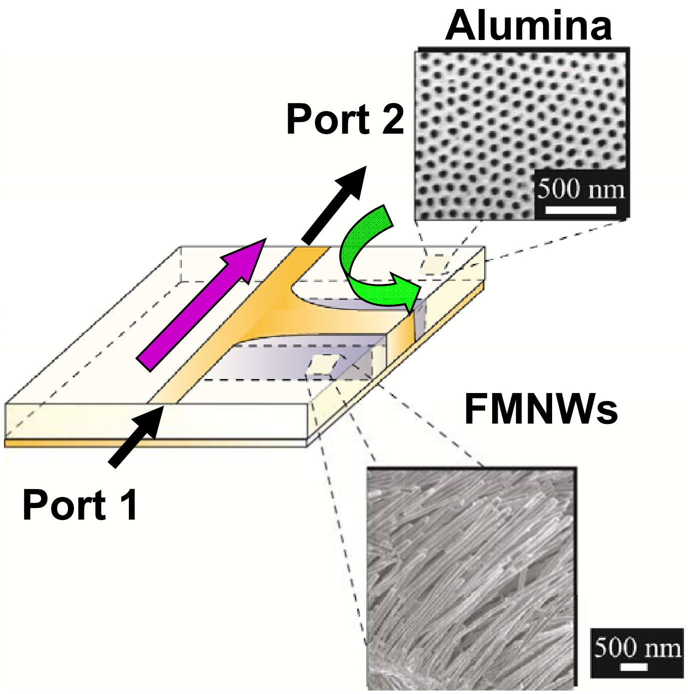
Idealized Structure



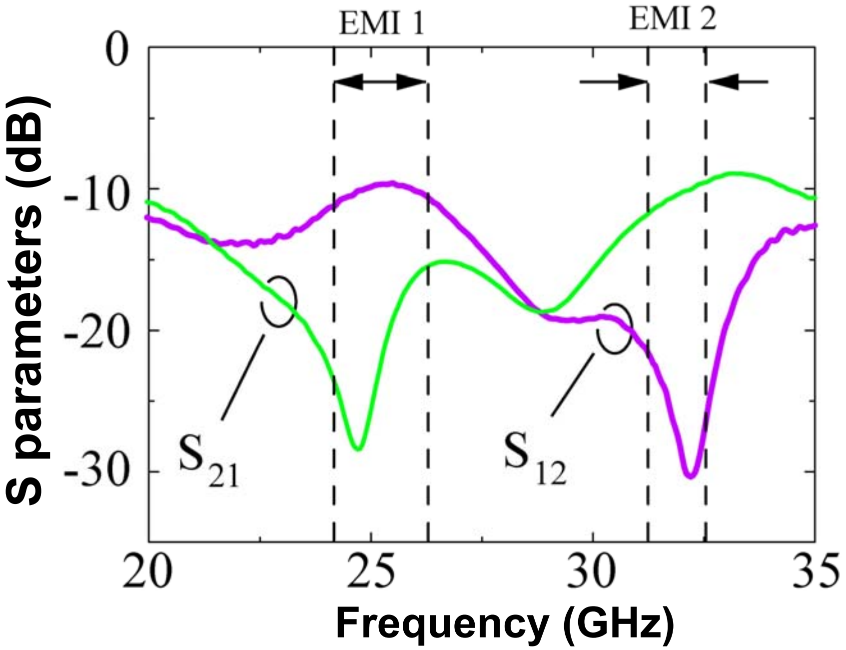
Dispersion relation calculation



Fabricated structure

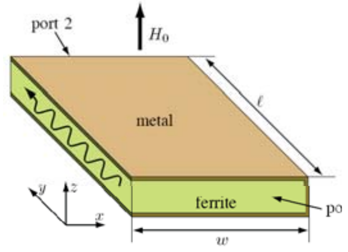


Measurement



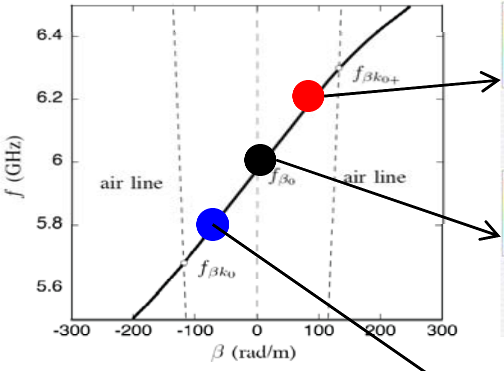
L.-P. Carignan, C. Caloz, and D. Ménard, *IMS* Conference, Session TH3B-1, May 2010.

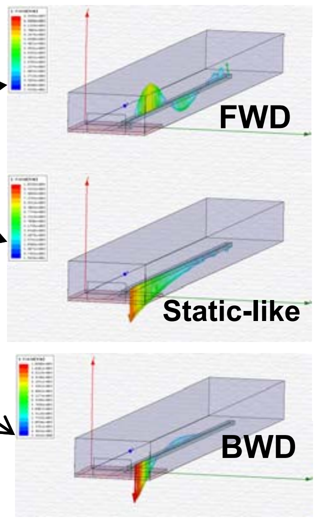
CRLH Ferrite Waveguide Leaky-Wave Antenna



Dispersion Relation

$$\tan(k_x w) = -\frac{\mu k_x}{\beta\kappa}$$

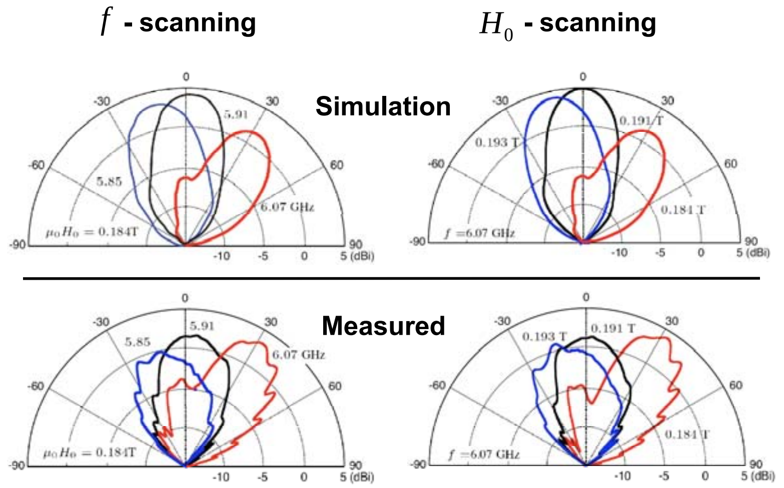




☺ Uniform

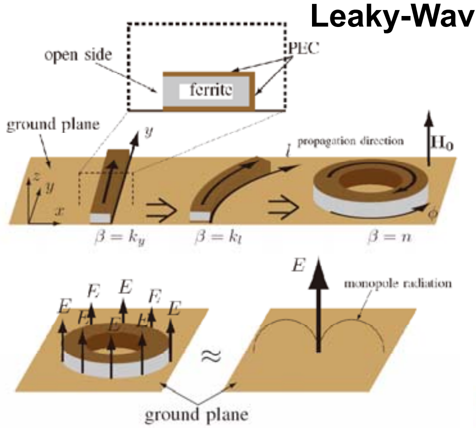
☺ Inherently balanced

☺ Scanning ⇒ H_0



T. Kodera and C. Caloz, "Uniform ferrite-loaded open waveguide structure with CRLH response and its application to a novel backfire-to-endfire leaky-wave antenna," *IEEE T-MTT*, vol.57, No.4, pp.784-795, April 2009.

Leaky-Wave Electronic Monopole Loop Antenna



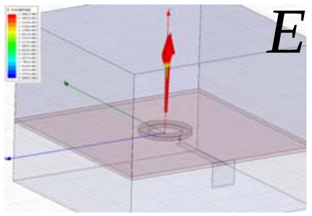
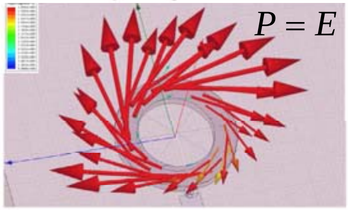


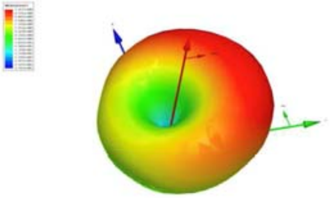
Fig. 15. Ferrite ring machined by a Nd-YAG laser from a ferrite slab.

(a) (b)

Fig. 16. Prototype corresponding to structure of Fig. 8 and using the ring of Fig. 15. (a) Top view. (b) Bottom view.



$P = E \times H$



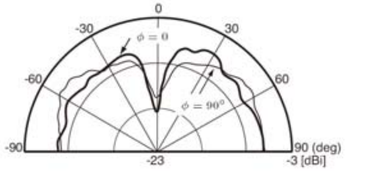
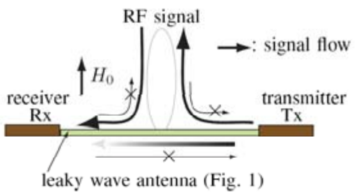


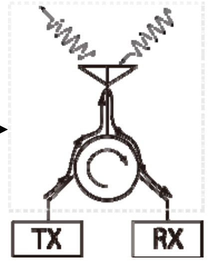
Fig. 18. Measured elevation radiation pattern at 4.38 GHz for $\phi = 0$ and 90°.

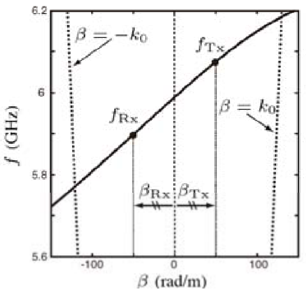
T. Kodera and C. Caloz, "Low-profile leaky-wave electric monopole loop antenna using the regime of a ferrite-loaded open waveguide," *IEEE T-AP, to be published*.

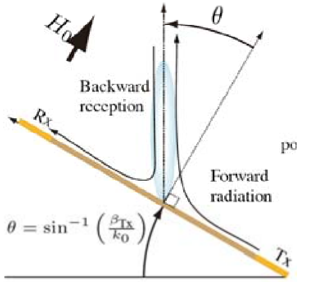
Diplexer/Duplexer integrated LWA



same! ⟷







T. Kodera and C. Caloz, *IMS2009, June 2009*.
T. Kodera and C. Caloz, *IEEE T-AP, sub.*

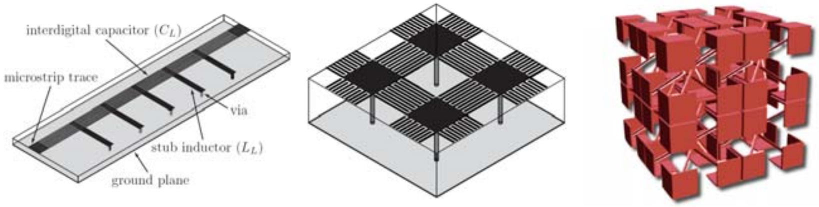
Outline

1. BROADBAND METAMATERIALS
2. INNOVATIONS IN CRLH LEAKY-WAVE ANTENNAS
3. ANALOG SIGNAL PROCESSORS
4. FERROMAGNETIC NANOWIRE COMPOSITES
5. CONCLUSIONS

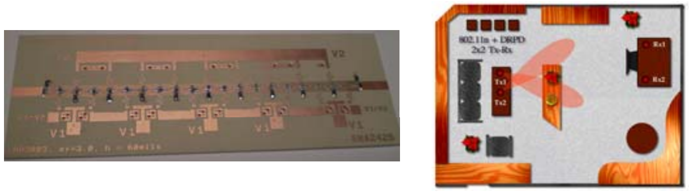
General Conclusions on Metamaterials

- 2000 → 2010: from fiction to reality !

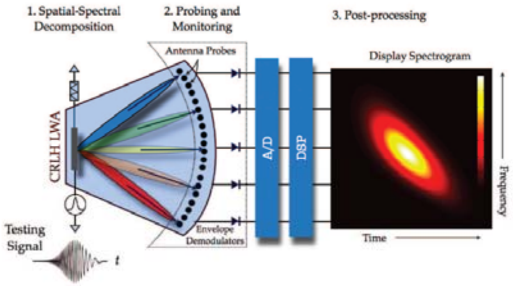
- Novel concepts & applications with 1D, 2D & 3D MTMs



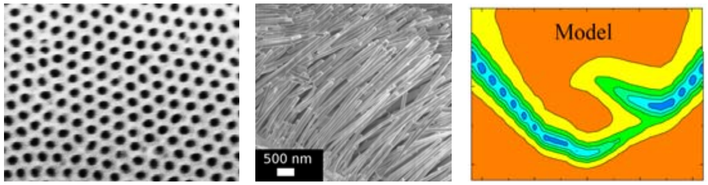
- TL MTMs ≡ low-loss:
  - Smart antennas



- TL MTMs ≡ broad-band & dispersive:
  - Analog signal processors



- Nostructured MTMs:
  - FMNW composites



- Future: multiscale & multiphysics MTMs