Metamaterial-Based Electronically-Controlled Leaky-Wave Antenna

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OUTLINE

- Left-Handed Metamaterial (LHM) Approaches
- Composite Right/Left-Handed (CRLH) Transmission Line (TL)
- Leaky-Wave Antenna Application
- Principle of Electronically-Controlled CRLH TL
- Electronically-Scanned Leaky-Wave Antenna Application
- Radiation Angle Controlling & Beamwidth Tuning Capability
- Nonlinear effects of Varactors
- Conclusions

Different Approaches of LHMs

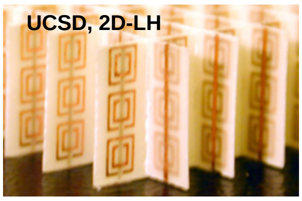
Historical Milestones

- **1968** : theoretical analysis of hypothetical LH materials by **Veselago**
- **1996/9** : introduction of electric (ε<0) / magnetic (μ<0) plasmon by **Pendry**
- **2000** : experimental demonstration of LH structure by **Smith**

LH definition: materials with $\varepsilon < 0 \text{ and } \mu < 0 \;\Rightarrow\; \boxed{v_p - // \, v_g} \;\rightarrow\; n < 0$

and unit-cell << λ → effective / macroscopic / homogeneous

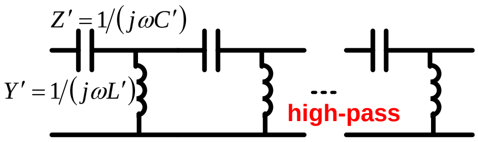
Resonant Structure Approach



- **approach**: no simple/rigorous analysis & no design method
- **structures**: RESONANT ⇨ very lossy & narrow bandwidth & highly dispersive

***BACKWARD WAVES*: S. Ramo, J.R. Whinery and T. Van Duzer, "Fields and waves in communication electronics", Wiley, 1994**

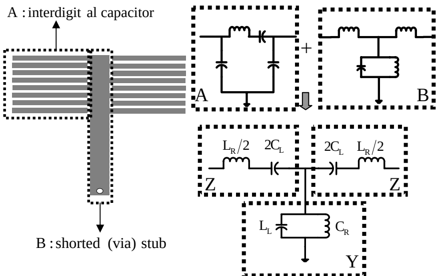
Transmission Line Approach



"*BACKWARD WAVES*"

- **approach**: Transmission line analysis & circuit design methods
- **structures**: *NON*-RESONANT ⇨ low loss & broad bandwidth & moderate dispersion

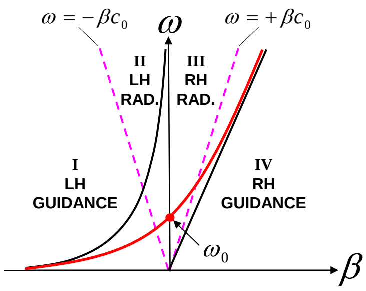
CRLH TL and Dominant Mode LW Antenna Application



$$\beta = \cos^{-1}(1 + Z'(\omega)Y'(\omega))/d$$

$$Z'(\omega) = \frac{1}{2}\left(j\omega L_R + \frac{1}{j\omega C_L}\right)$$

$$Y'(\omega) = j\omega C_R + \frac{1}{j\omega L_L}$$



- Dominant mode operation ($n = 0$)

$$\theta = \sin^{-1}\left(\frac{\beta_0 + 2n\pi/d}{k_0}\right) = \sin^{-1}\left(\frac{\beta_0}{k_0}\right)$$

- Efficient broadside radiation @ ω_0
- Backward (II. LH) and forward (III. RH) radiation

Motivation of Voltage–Scanned LW Antenna

Conventional LWA
- Frequency dependent scanning

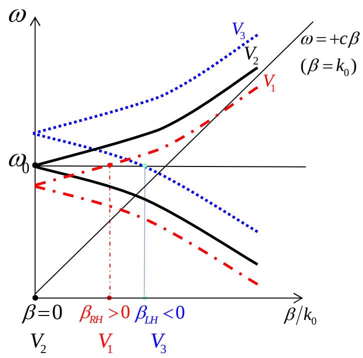
Conventional Electrically-Scanned LWA
- Frequency independent scanning
- Only two discrete states are possible
- Waveguide configuration with PIN diode

Conventional Magnetically-Scanned LWA
- Frequency independent scanning
- Biasing DC magnetic field ➔ NOT practical
- Waveguide configuration

Novel Electronically–Scanned LWA
- Frequency independent scanning ➔ Efficient Channelization
- Continuous scanning capability
- Microstrip technology ➔ Low profile

R. E. Horn, et. al, "Electronic modulated beam steerable silicon waveguide array antenna," *IEEE Tran. Microwave Theory Tech.*
H. Maheri, et. al, "Experimental studies of magnetically scannable leaky-wave antennas having a corrugated ferrite slab/dielectric layer structure," *IEEE Trans. AP.*
L. Huang, et. al, "An electronically switchable leaky wave antenna," *IEEE Trans. AP.*

Principle of Voltage–Scanned Leaky–Wave Antenna

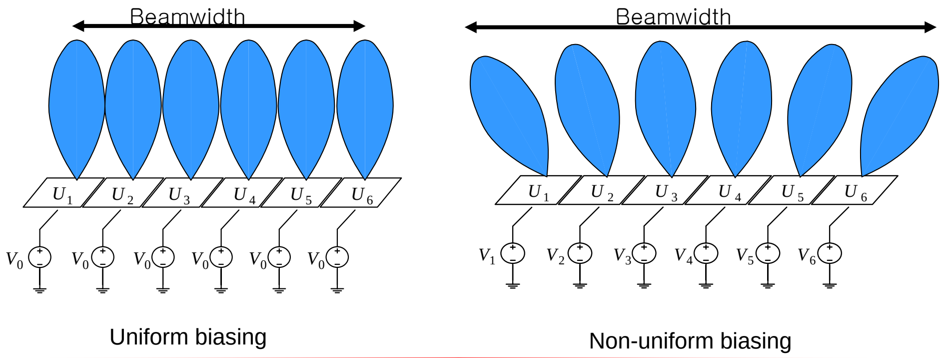


$$\theta(V) = \sin^{-1}\left[\frac{\beta}{k_0}\right]$$

$$\theta(V) = \sin^{-1}\left[\frac{\beta(V)}{k_0}\right]$$

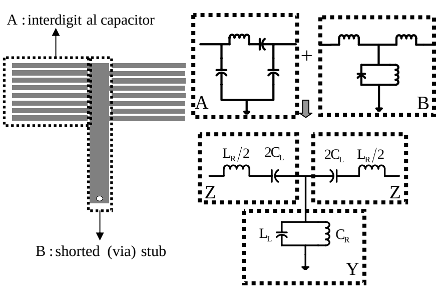
- ❑ Scanning angle is dependent on inductances and capacitances
  ➔ Introducing varactor diodes
- ❑ Capacitive parameters are controlled by voltages
  ➔ Dispersion curves are shifted vertically as bias voltages are varied
  ➔ Radiating angle becomes a function of the varactor diode's voltages

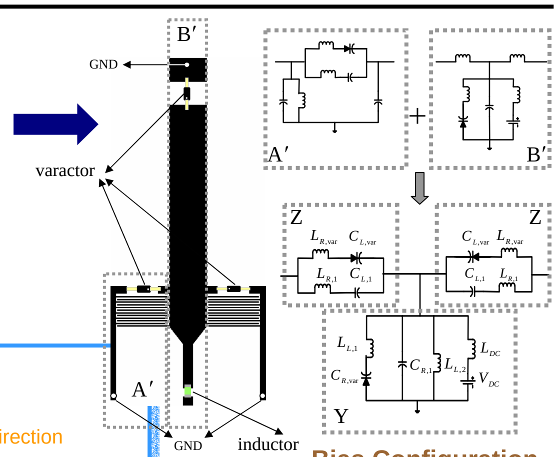
Beamwidth Control Capability: Principle



- ❑ Uniformly biased periodic TL
  - ➔ Each unit cell radiates toward the same angle
  - ➔ High directivity
- ❑ Non-Uniformly biased periodic TL
  - ➔ Each unit cell radiates toward different angles
  - ➔ Beamwidth is determined by the superposition of each cell
  - ➔ Broader beamwidth

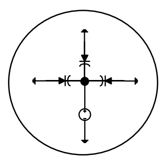
Unit Cell Implementation



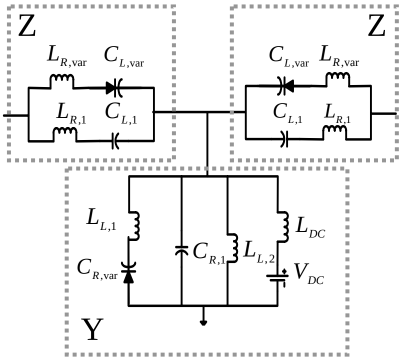


- ❑ Reverse biasing to Varactors
  - ➔ Anodes of varactors : GND
  - ➔ Cathodes of varactors: Biasing
- ❑ The cathodes of three varactors in the same direction
  - ➔ Only one bias circuitry in unit cell
- ❑ Series and Shunt Varactors
  - ➔ Fairly constant characteristic impedance
  - ➔ Additional degree of freedom for wider scanning range
- ❑Back to back configuration of two series varactors
  - ➔ Fundamental signals : in phase and add up
  - ➔ Harmonic signals: out of phase and cancel

Bias Configuration



Analysis with Parameter Extraction



ABCD Transmission Matrix

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{Unit\_Cell} = \begin{bmatrix} 1+Z'(V)Y'(V) & Z'(V)\{1+Z'(V)Y'(V)\} \\ 1 & 1+Z'(V)Y'(V) \end{bmatrix}$$

Bloch-Floquet Theorem

$$\begin{pmatrix} V_1 \\ I_1 \end{pmatrix} = \begin{pmatrix} e^{-j\beta d} & 0 \\ 0 & e^{-j\beta d} \end{pmatrix} \cdot \begin{pmatrix} V_2 \\ I_2 \end{pmatrix}$$

$$\beta(V) = \cos^{-1}(1 + Z'(V)Y'(V))/d$$

$$Z'(V) = \left\{ \left(j\omega L_{R,var} + \frac{1}{j\omega C_{L,var}(V)} \right) \Big\| \left(j\omega L_{R,1} + \frac{1}{j\omega C_{L,1}} \right) \right\} \Big/ d$$

$$= \left\{ \frac{j\omega \cdot \left(L_{R1}C_{L1} + L_{Rvar}C_{Lvar}(V) - \omega^2 L_{R1}C_{L1}L_{Rvar}C_{Lvar}(V) - \frac{1}{\omega^2} \right)}{C_{L1} + C_{Lvar}(V) - \omega^2 (L_{R1} + L_{Rvar})} \right\} \Big/ d$$

$$Y'(V) = \left\{ \left(\frac{1}{j\omega L_{L,1}} \| j\omega C_{R,var}(V) \right) + j\omega C_{R,1} + \frac{1}{j\omega L_{L,2}} \right\} \Big/ d$$

$$= \left(\frac{j\omega}{-\omega^2 L_{L,1} + 1/C_{R,var}(V)} + j\omega C_{R,1} + \frac{1}{j\omega L_{L,2}} \right) \Big/ d$$

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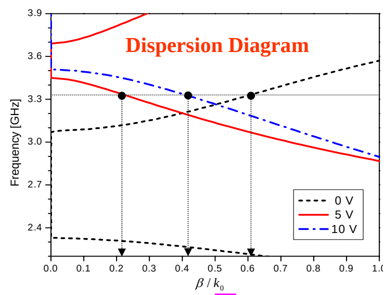
Analysis with Parameter Extraction

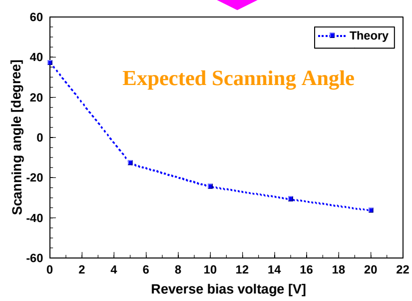
Extracted Circuit Model Parameters @ 3.33 GHz and *d* = 1.2 *cm*

Parameters \ Voltage	0 V	5 V	15 V
$L_{R,var}$ [nH]	1.840	2.029	1.768
$C_{R,var}$ (=$C_{L,var}$) [pF]	2.544	0.916	0.765
L_{L1} [nH]	5.168	6.165	6.524
C_{R1} [pF]	1.230	1.018	0.900
L_{L2} [nH]	4.597		
C_{L1} [pF]	0.485		
L_{R1} [nH]	2.027		



$$\beta(V) = \cos^{-1}(1 + Z'(V)Y'(V))/d$$

$$\theta(V) = \sin^{-1}\left(\frac{\beta(V)}{k_0} \right)$$



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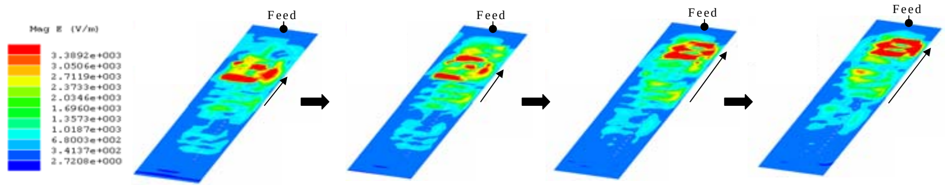
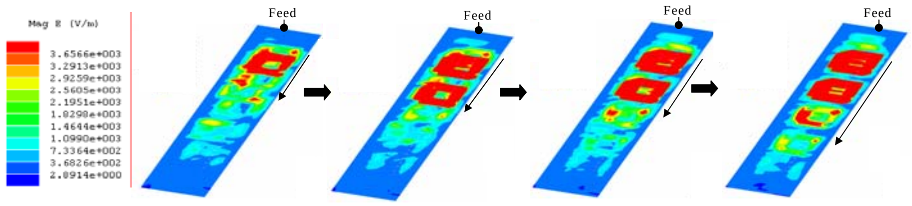
MoM Full-Wave Simulation

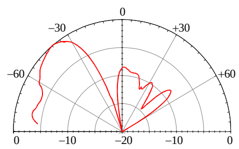


❑ Backward Propagating Capability @ higher applied voltage (15 V)

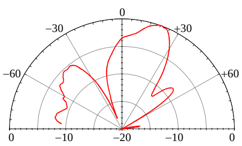


❑ Forward Propagating Capability @ lower applied voltage (0 V)

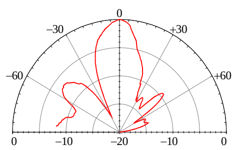
30 Cell Leaky–Wave Antenna Implementation



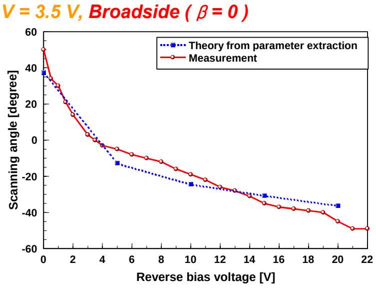
V = 18 V, LH (β < 0)

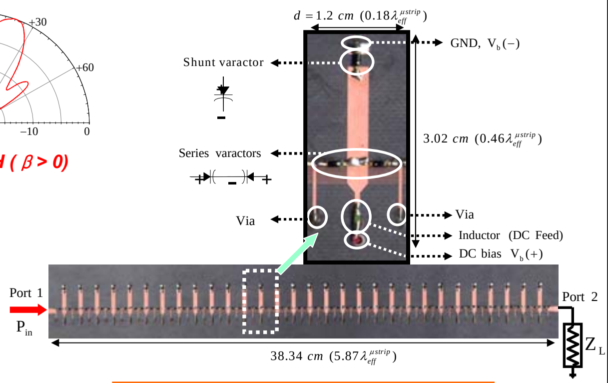


V = 1.5 V, RH (β > 0)



V = 3.5 V, Broadside (β = 0)



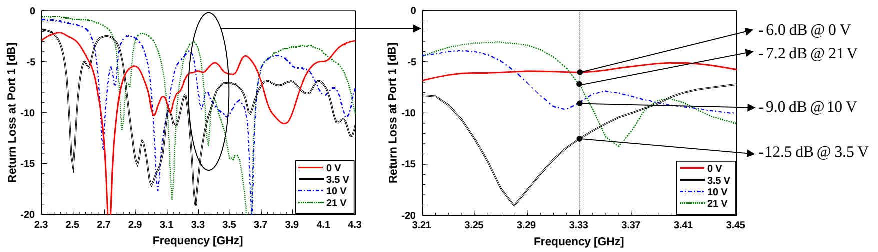


❑ Scanning Range $\Delta\theta$ = 99º (-49º to +50º)
➔ Backward, forward, and broadside
❑ Biasing Range ΔV = 21 V (0 to 21 V)
❑ Fixed operating frequency : 3.33 GHz
❑ Maximum Gain: 18 dBi at broadside
❑ Antenna dimension:

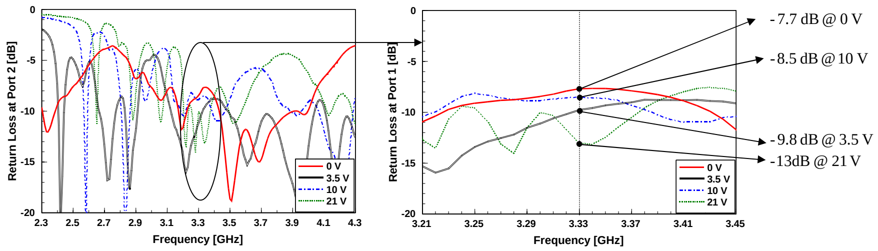
$38.34\ cm\ (5.87\lambda_{eff}^{\mu strip})$

Measured S Parameters versus Frequency

Port 1: Excitation Port



Port 2: Termination Port



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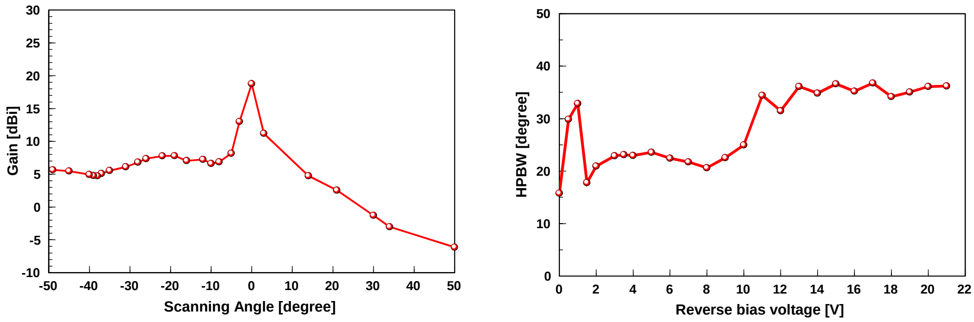
Performance as a LW Antenna



- High directivity : One of attractive characteristic of LW antenna

  : Achieved by increasing the number of cells ➔ Large radiation aperture
- Antenna dimension : $38.34\ cm\ (5.87\lambda_{eff}^{\mu strip})$

  ➔ Maximum Gain : 18 dBi at broadside (V = 3.5 V)

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Beamwidth Control Capability: Prediction

Approximation method

➔ Superposition of each beam pattern

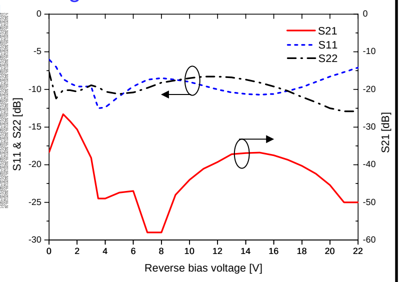
$$f_{total}\left(\theta_{V_1};\cdots;\theta_{V_n}\right) \simeq \sum_{n=1}^{N} A_n \cdot w_n(\theta_{V_n})\cdot f_n(\theta_{V_n})$$

Beam pattern at the applied bias of V_n

$$= \sum_{n=1}^{N} e^{-\alpha_n n d}\cdot w_n(\theta_{V_n})\cdot f_n(\theta_{V_n})$$

Exponentially decreasing as n is increasing

N: the number of elements
d: the distance of unit cell
$f_n(\theta_V)$: the normalized beam pattern function
A_n: the attenuation factor
$w_n(\theta_V)$: the weighting factor
α_n: the attenuation constant at the *nth* cell
Since the amplitude factor exponentially decreases as n increases, $\theta_{v,n}$'s from the onset cells are dominant factors.

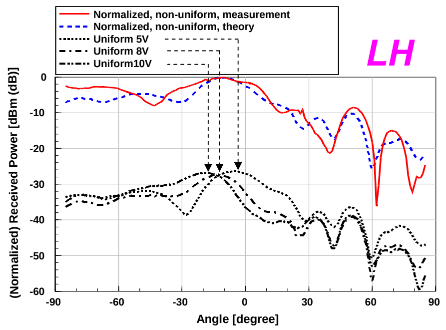


Insertion Loss Versus Reverse Voltage

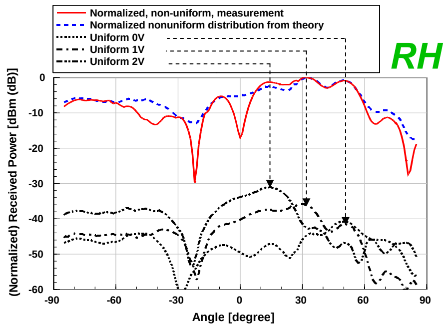
Voltage [V]	Insertion loss per a single varactor [dB]
0	0.974
5	0.964
10	0.944
15	0.926
20	0.909

Beamwidth Tuning Capability: Measurement

5	5	5	6	6	6	7	7	8	8	8	9	9	9	10
10	10	11	11	11	12	12	12	13	13	13	14	14	14	15



0	0	0	0.5	0.5	0.5	1	1	1	1.5	1.5	1.5	2	2	2
6	6	6	7	7	7	8	8	8	9	9	9	10	10	10



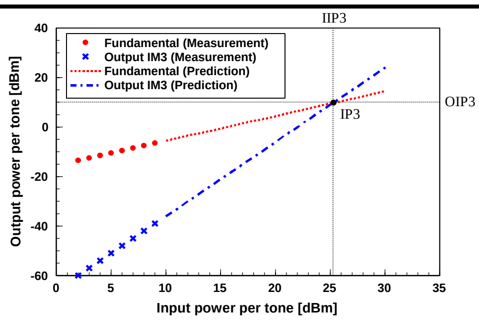
❑ Less power is radiated at the end of LW antenna

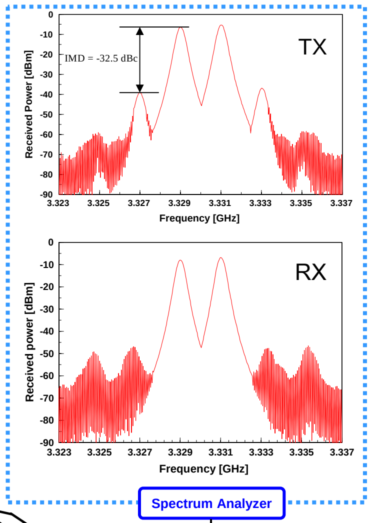
➔ The first row becomes dominant

Uniform biasing		Non-Uniform biasing (0 V to 2 V, 6 V to 10 V)
HPBW min	HPBW max	HPBW
16º @ 0V	33.5º @ 1 V	48º (43 to 200 % increased)

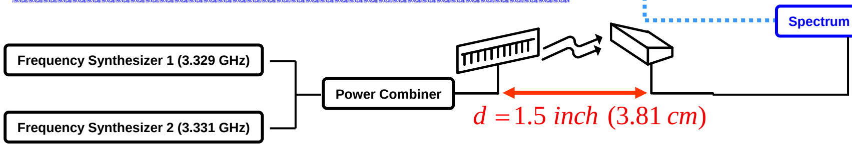
Uniform biasing		Non-Uniform biasing (5 V to 10 V, 10 V to 15 V)
HPBW min	HPBW max	HPBW
20.61º @ 8 V	24.95º @ 5 V	37º (48 to 80 % increased)

Nonlinear Effects of Varactors: Two Tone Test

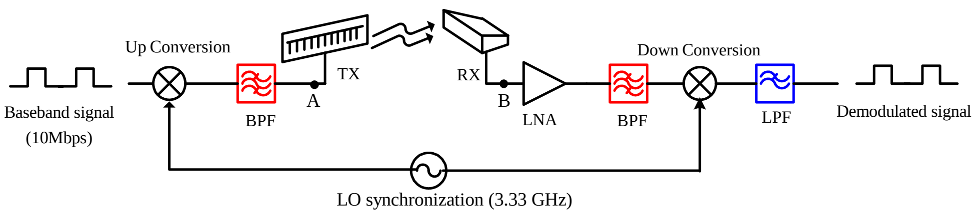


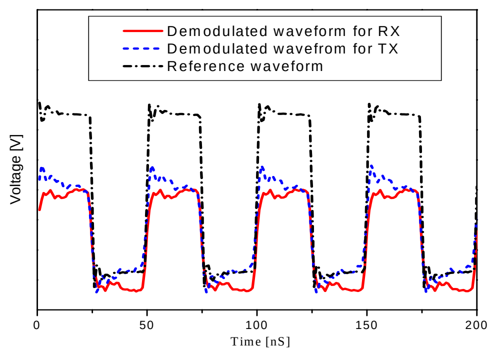


- ❑ Two tone (3.329 GHz and 3.331 GHz) Test
  - ➔ at broad side (V = 3.5 V)
  - ➔ the proposed antenna used as both TX and RX
  - ➔ IIP3 = 25.3 dBm as TX antenna



Nonlinear Effects of Varactors: BPSK Data Transmission





- ❑ BPSK (10 Mbps) Data Transmission Test
  - ➔ at broad side (V = 3.5 V)
  - ➔ the proposed antenna used as TX and RX
  - ➔ successfully recovered in both cases
- ❑ Nonlinear effects are negligible as antenna applications in the far field region

Conclusions

- ❖ Novel Metamaterial-Based ***Electronically-Controlled*** TL
- ❖ ***Continuous*** Scanning Leaky-Wave Antenna
- ❖ Radiation Angle Control at ***Uniform Biasing***
- ❖ Beamwidth Control at ***Non-uniform Biasing***
- ❖ Nonlinear Effects of Varactors ➔ ***Negligible***