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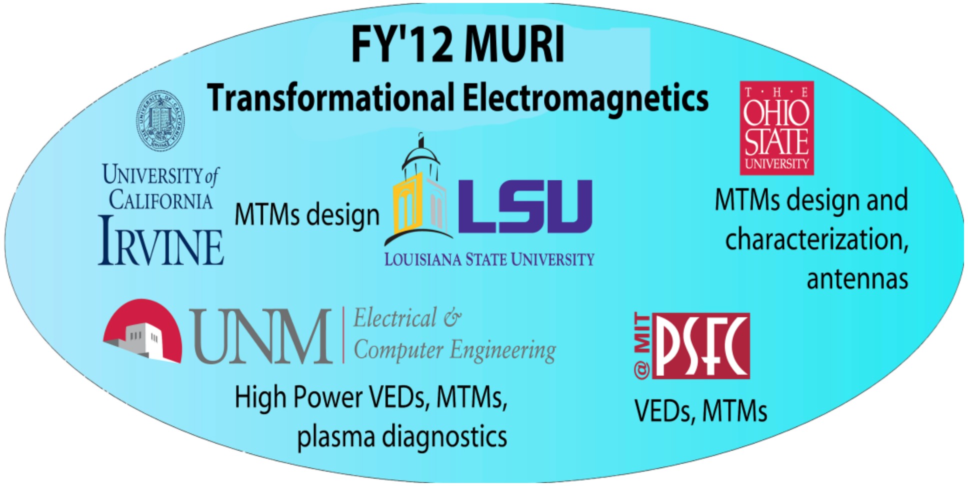
AFOSR
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

ElectroScience LABORATORY

Metamaterial Slow-wave Structures for High-Power Microwave Devices



FY'12 MURI
Transformational Electromagnetics

MTMs design

MTMs design and characterization, antennas

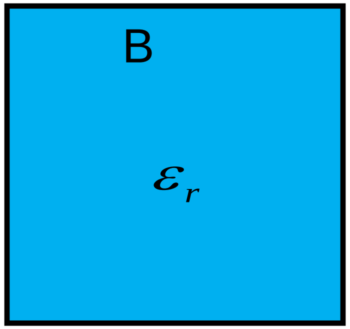
High Power VEDs, MTMs, plasma diagnostics

VEDs, MTMs

Kubilay Sertel
John. L Volakis
Students: Nil Apaydin, Panos Douris & Md. Zuboraj

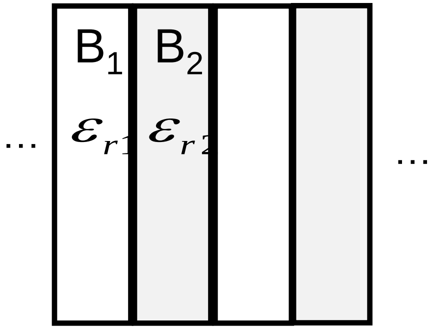
Wave Slow-down Using Anisotropic Materials

Isotropic Dielectric Medium



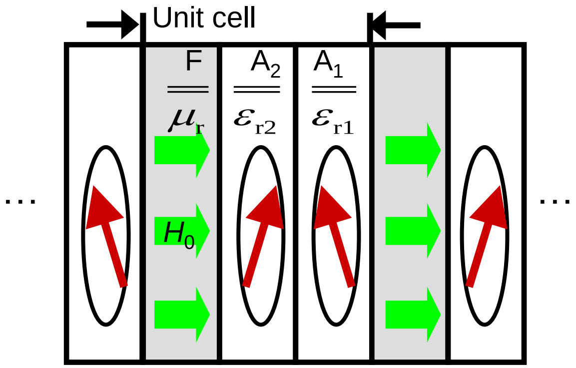
B:Isotropic dielectric

Periodic Isotropic Medium



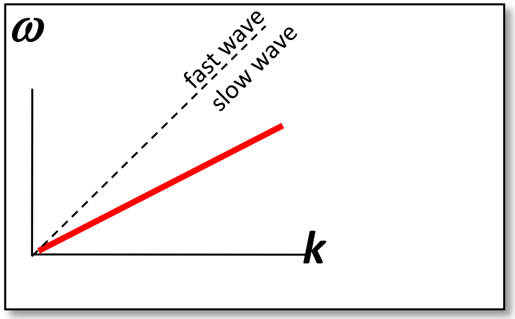
$B_{1,2}$:Isotropic dielectrics

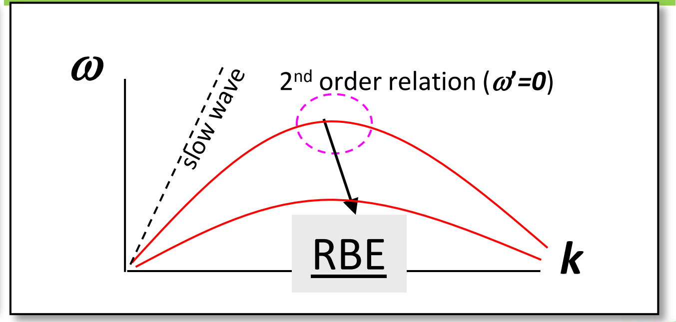
Periodic Magnetic Photonic Crystal

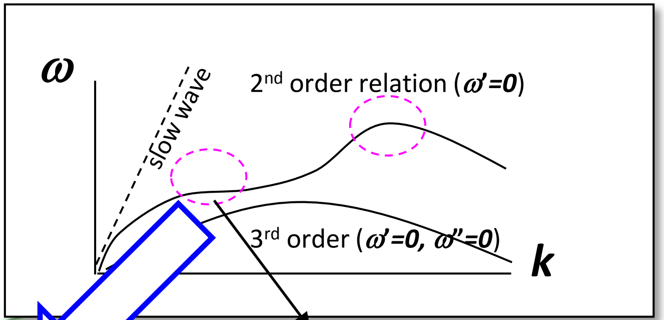


$A_{1,2}$:Anisotropic dielectrics
F: Biased ferrimagnetic layers

Corresponding K-ω diagrams





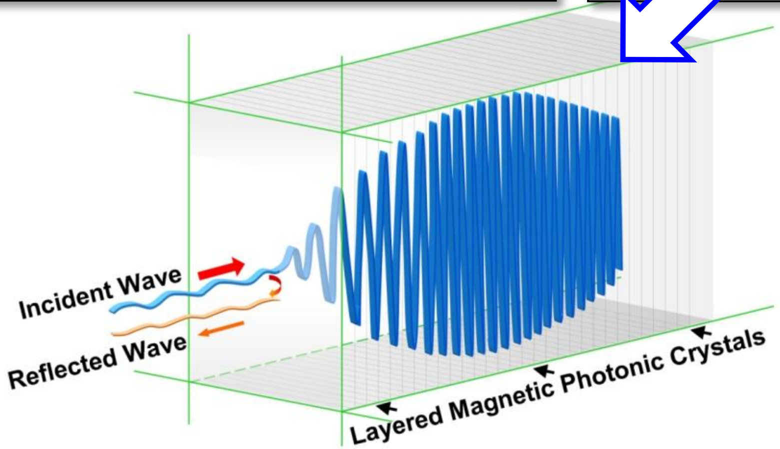


SIP due to anisotropy

Slow-group velocity mode @ SIP

Group velocity: $$\frac{v_g}{c} = \frac{\partial k}{\partial \beta} \approx 0$$

Phase velocity: $$\frac{v_p}{c} = \frac{k}{\beta} \le 1$$

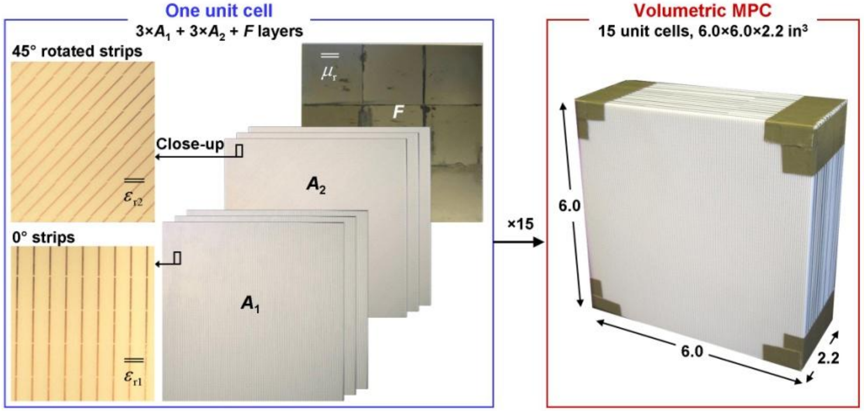


✓Wave slow-down(v_g=0)
✓Field enhancement

Experimental Validation of Wave Slow-Down

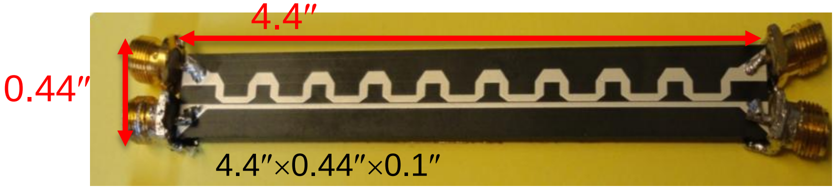
In Volumetric Form

Finite 15-unit-cell Volumetric MPC

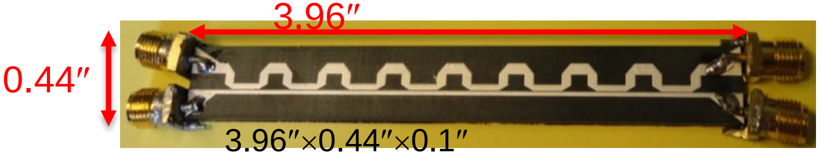


In Printed Form

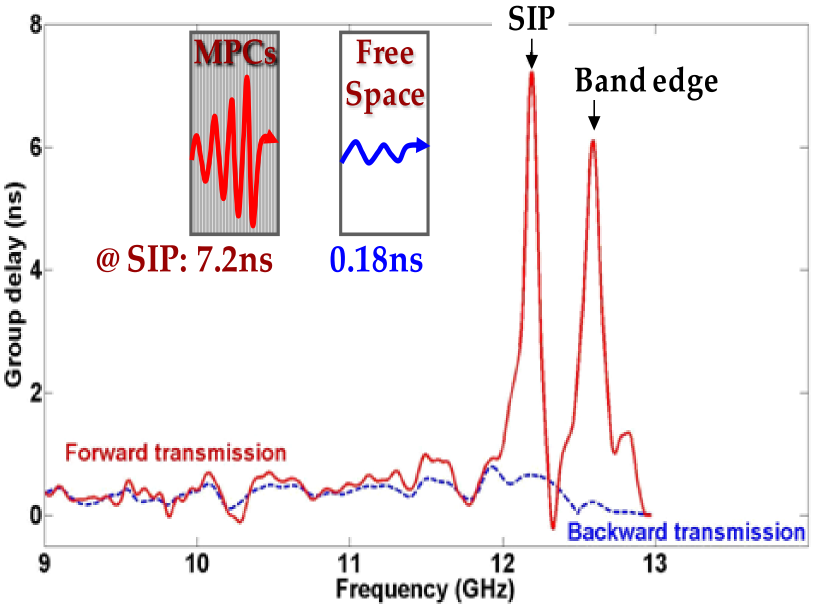
Finite 9-unit-cell Printed MPC

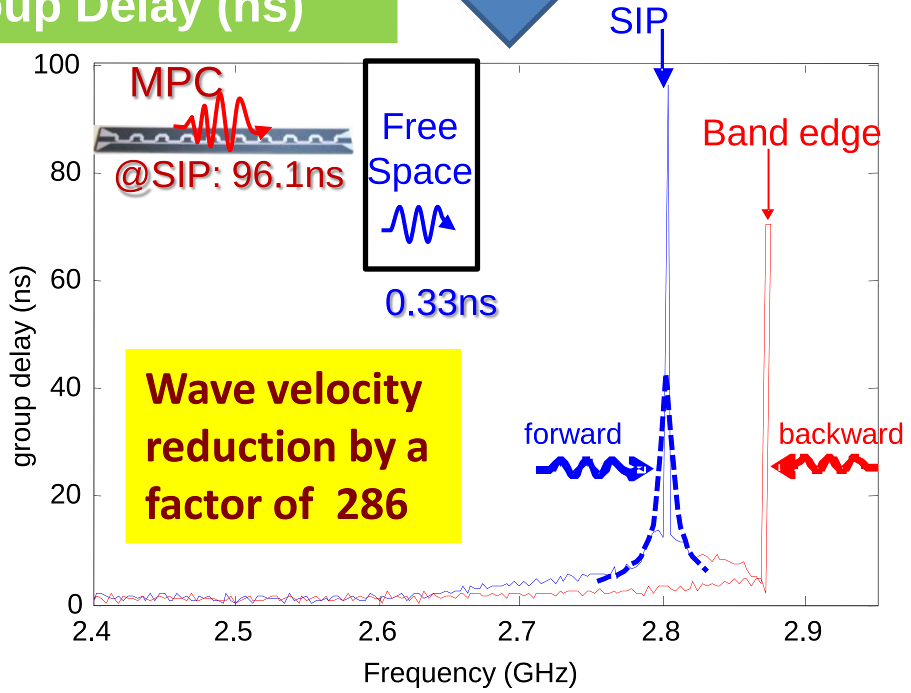


Finite 8-unit-cell Printed MPC



Measured Group Delay (ns)





Wave velocity reduction by a factor of 286

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Novel Slow-wave Structures and Antenna Designs Utilizing Slow Group Velocity Modes

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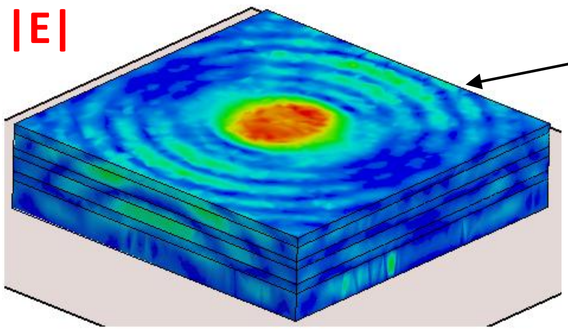
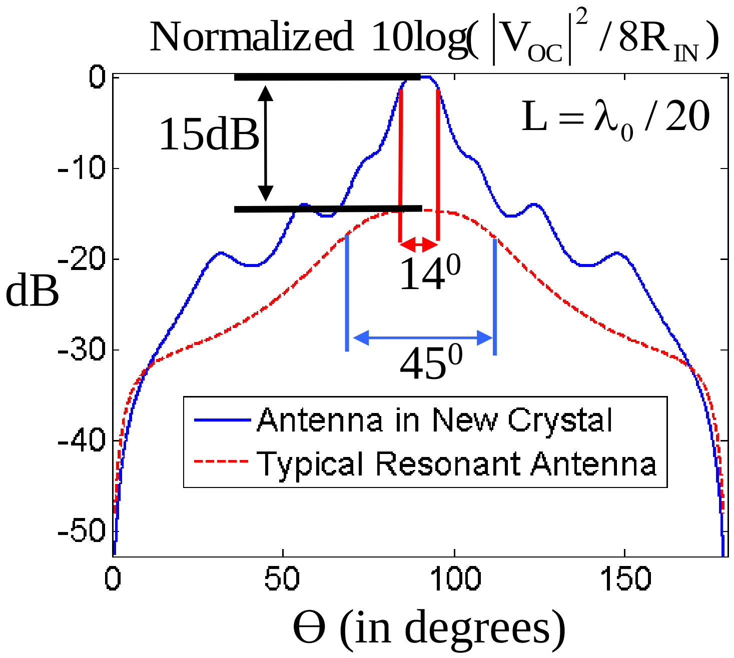
Gain Enhanced Dipole Antenna Embedded in MPC



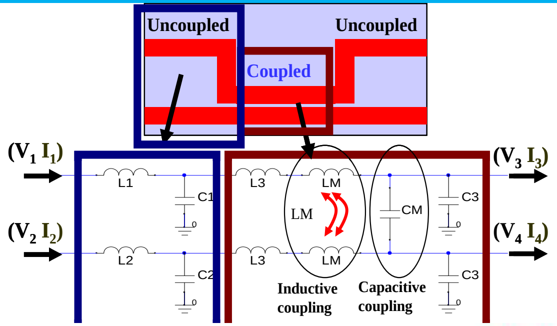
~Uniform Aperture Illumination

High Directivity

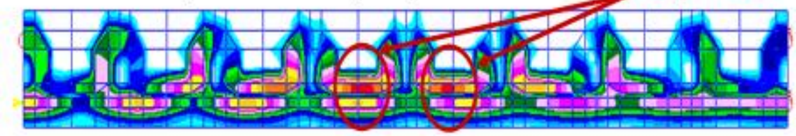
Gain Enhancement via Leaky-waves



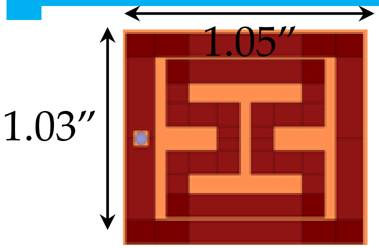
Printed Coupled Lines Emulating Slow Modes



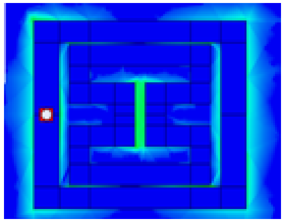
Observed Field along the DBE Microstrip Coupled Lines Indicating Field Amplification



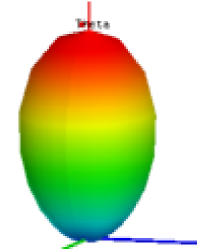
Miniaturized Antennas w/ Optimal Gain × BW



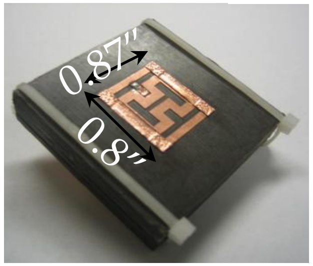
DBE Antenna Element



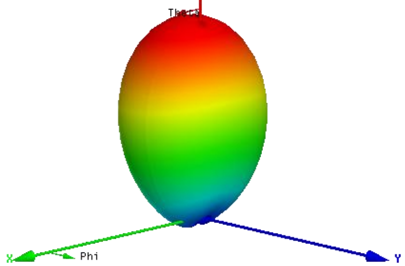
Mode Profile at 2.22 GHz



Broadside 6.5 dB Gain at 2.22GHz



MPC Antenna Element



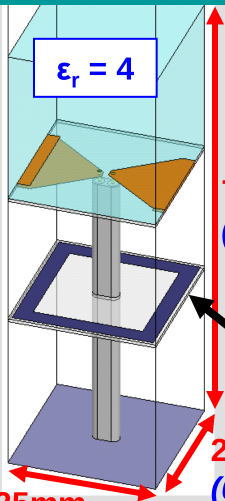
Broadside 6.2 dB Gain at 2.35GHz

Remarkably Large Bandwidth for Thin Conformal Arrays

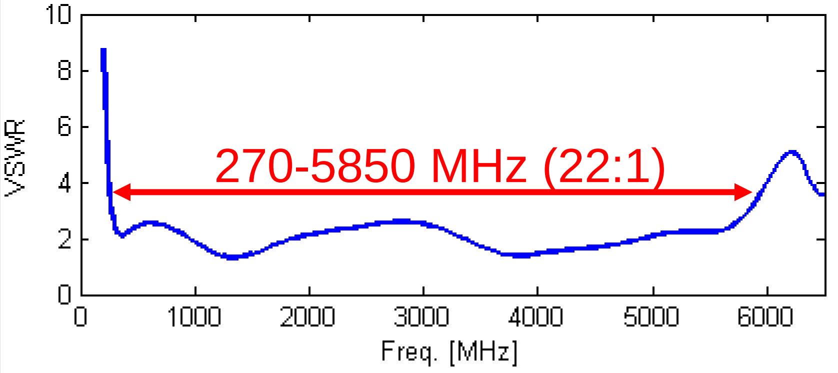
Bowtie Array with FSS in substrate

- 22:1 BW
- Low profile
- Efficiciency. ≥ 69%
- Excellent polarization purity (AR ≥ 43 dB)

Infinite Unit Cell



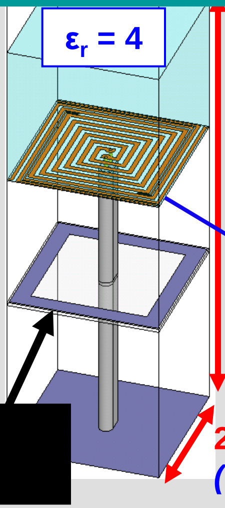
FSS in substrate:
R_s = 25Ω/□

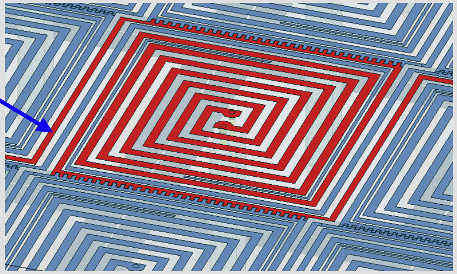


Interweaved Spiral Array (ISPA) w/ FSS in Substrate

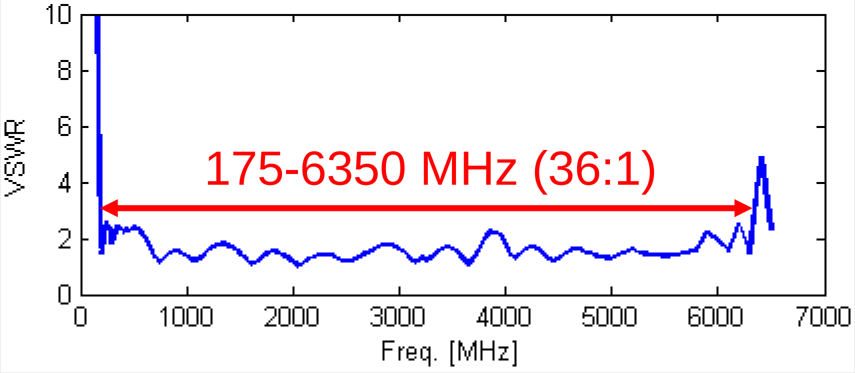
- 36:1 BW
- Low profile
- Efficiency ≥ 63%
- Circular polarization

Infinite Unit Cell

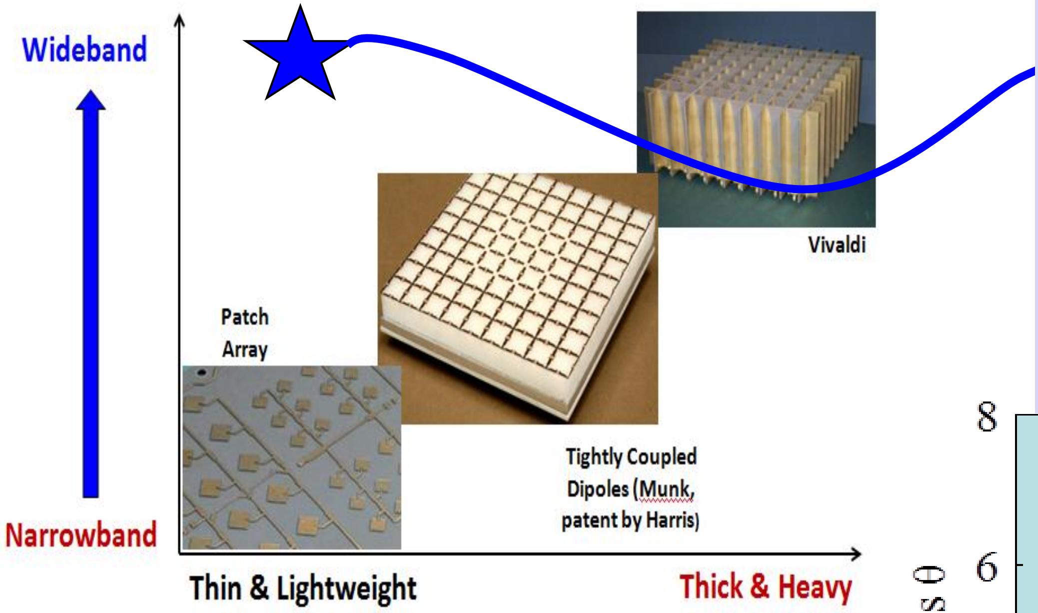




FSS in substrate:
R_s = 25Ω/□



Integrated UWB Balun and Demonstrated Meta-structured Array Benefits

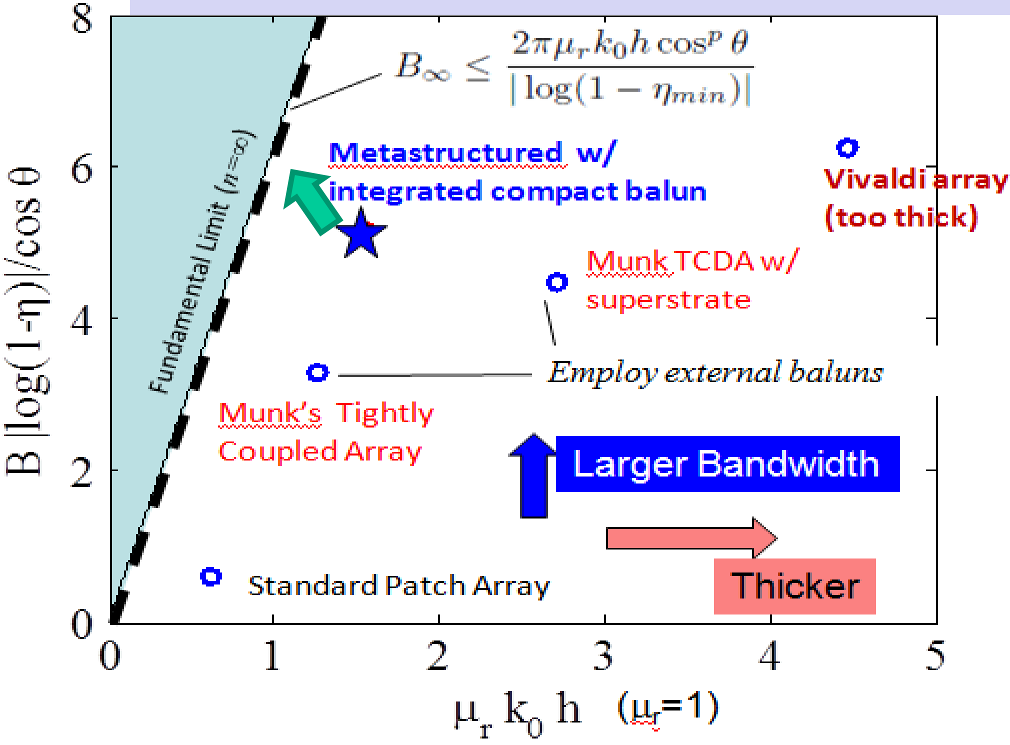


New thin Metastructured Array is

- Thinner
- Much greater bandwidth
- Has integrated balun and feed
  (several balun/feed options)
- Lightweight 600-4500MHz
- Military datalinks:
- Link-16, DWTS, DDL, TTNT, TACAN, etc.
- Almost all commercial telecom waveforms
- Wideband SAR, TWRI

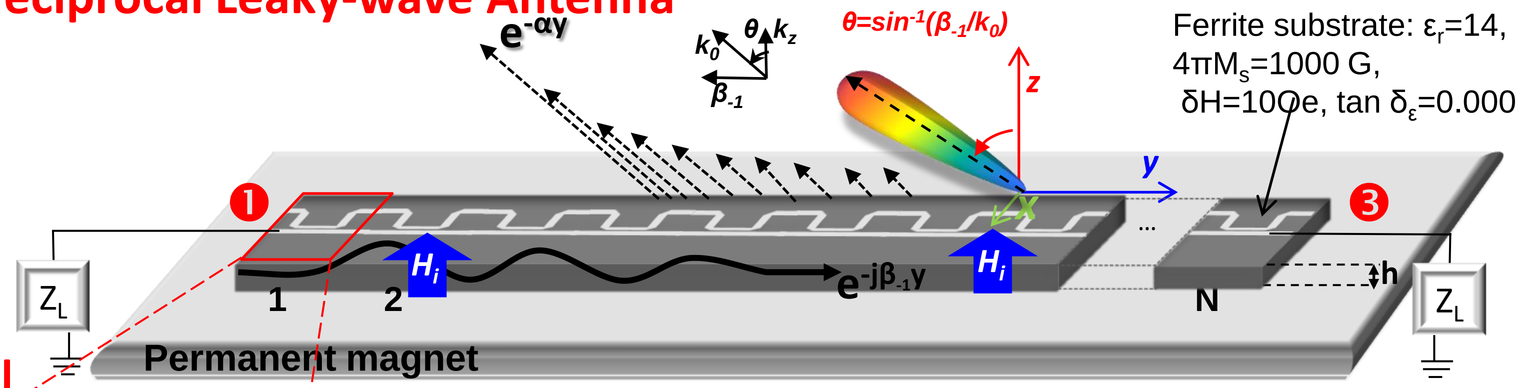
Measured Metastructured Aperture

- Much thinner integrated printed balun (trivial cost); as thin as $\lambda/15$ at 600MHz, lowest operational frequency.
- Measured array was 8x8 and had 7.3:1 VSWR<2 bandwidth with no FSS in substrate.
- Aperture: 9.4”x9.4” (89in^2)
- Scanning verified to 60° with no sidelobes or surface waves
- Beam steering over entire band (digital or optimal beam formers required).



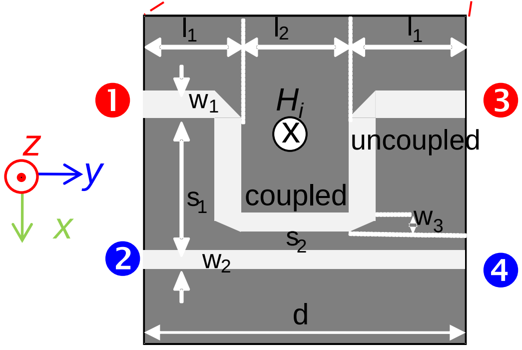
Nonreciprocal Leaky Wave Antenna Using Coupled Microstrip Lines

Nonreciprocal Leaky-wave Antenna



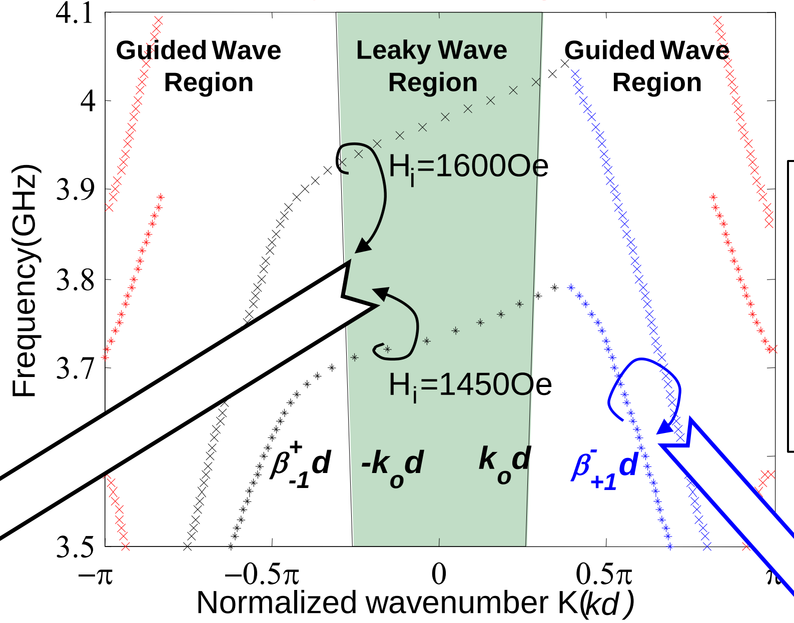
Ferrite substrate: $\varepsilon_r=14$, $4\pi M_s=1000$ G, $\delta H=10$Oe, $\tan\delta_\varepsilon=0.0002$

Unit-cell



$l_1=110$, $l_2=120$, $w_1=60$, $w_2=20$, $w_3=30$, $s_1=105$, $s_2=10$, $h=100$, $d=440$(mils)

Dispersion Diagram



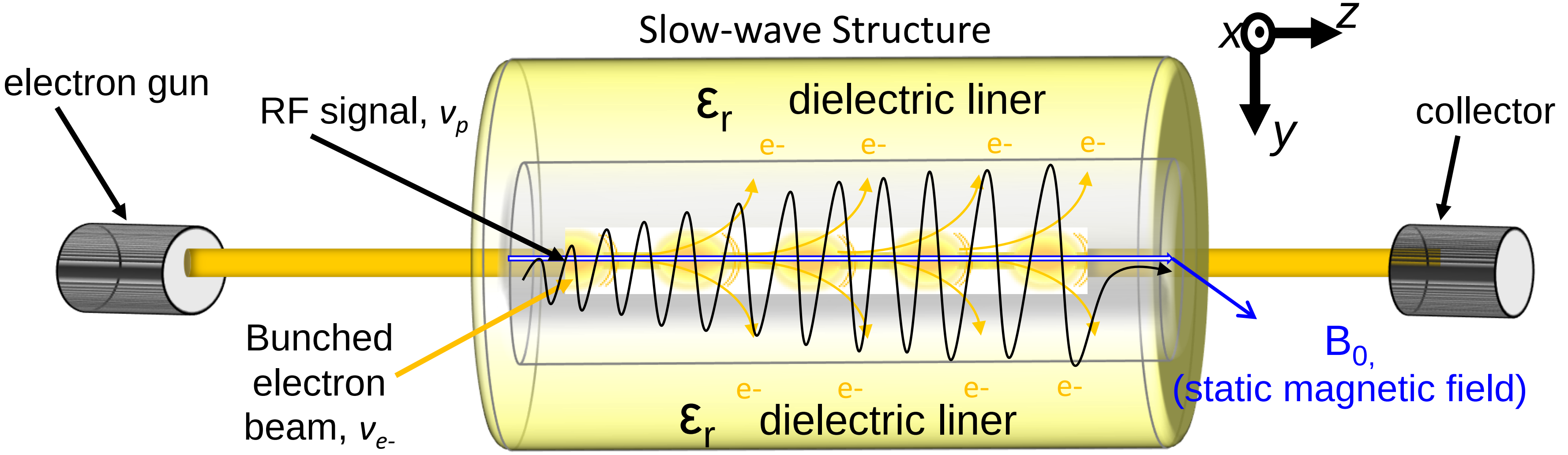
Beam-steering capability without frequency modulation
due to tunable dispersion properties with bias field strength, H_i

Nonreciprocal Transmitting and Receiving Properties

- leaky/fast wave: $|\beta_{-1}/k_0|<1$ →radiates
- guided/slow wave: $|\beta_{+1}/k_0|>1$ →does not radiate

Traditional Slow-wave Structure for Travelling Wave Tubes

Cerenkov Maser: Dielectric Lined Cylindrical Waveguide



Cherenkov Radiation Condition

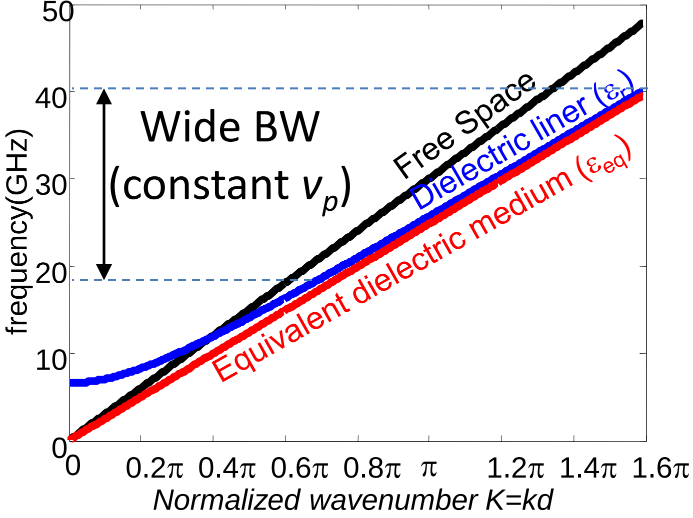
1)Microwave signal v_p ≈electron velocity v_{e-}

$$v_p = \frac{c}{\sqrt{\varepsilon_{eq}}} = v_{e-} = \sqrt{eV_0 / m}$$

**e* and *m* are electron charge and mass.
V_0 =voltage applied to electron gun.

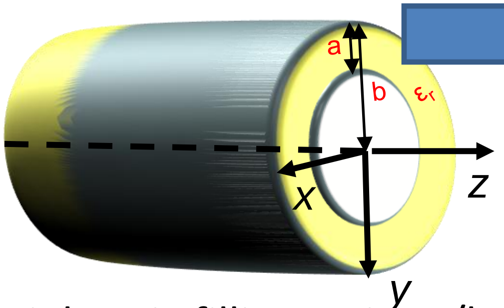
2)Strong longitudinal E-field at waveguide center (TM_z modes) for mode coupling

Corresponding K-ω diagram



Issues to be Addressed in Designing High-Power Microwave Devices

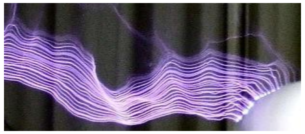
Cerenkov Maser



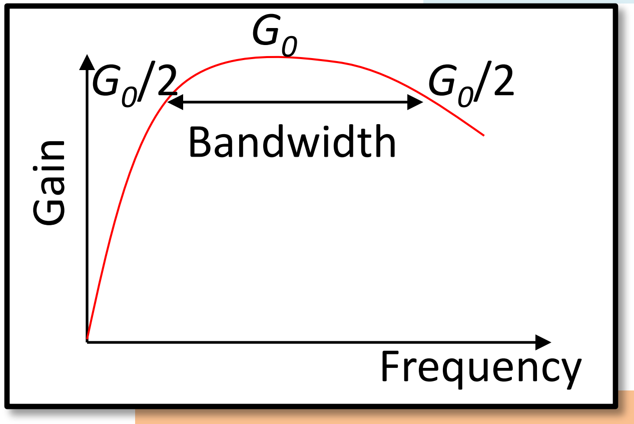
Dielectric filling ratio=a/b

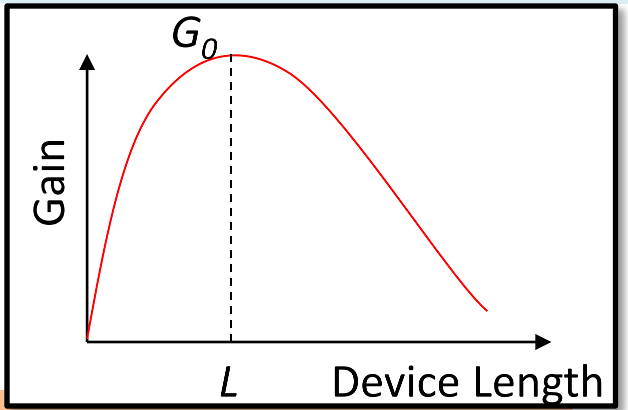
Advantages:
- Simple geometry
- Wider bandwidth
- Tunable operation
- Several MWs of output microwave power
- Validated performance

Shortcomings:
- Limited wave slow-down (depends on the filling ratio (*a*/*b*) and ε_r)
- Dielectric charging
- Surface breakdown
- Bulky design



Goal:
- Larger amplification ($G_0 \Uparrow$)
- Smallest configuration ($L \Downarrow$)
- Wide bandwidth
- Avoid charging





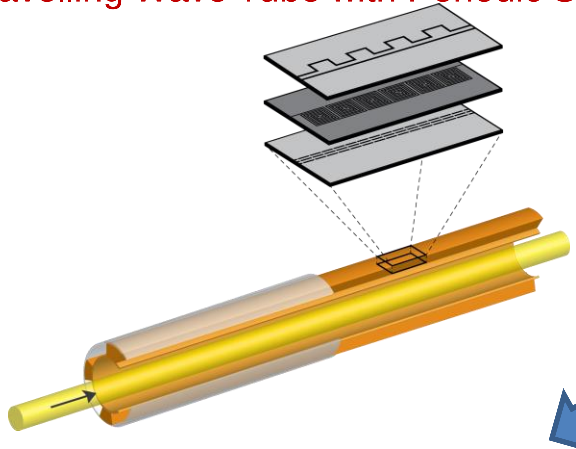
Solution
- Purely metallic slow-wave metamaterial structures

Metallic construction

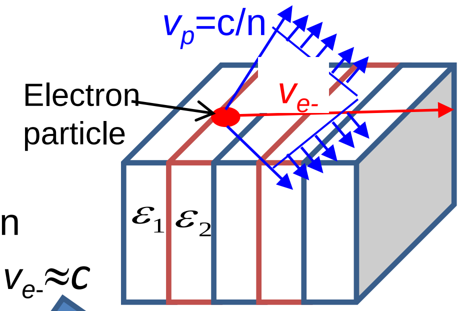
Additional wave slow-down ($L \Downarrow$)

Possible Slow-wave Structures for Travelling Wave Tubes

Travelling Wave Tube with Periodic Slow-wave Liner



Cherenkov Radiation in Periodic Media

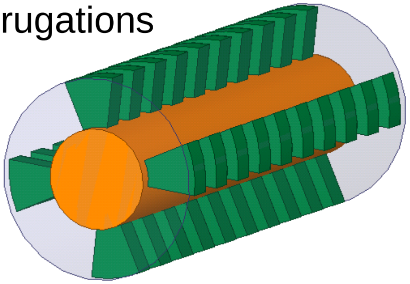


n=effective refractive index of the medium

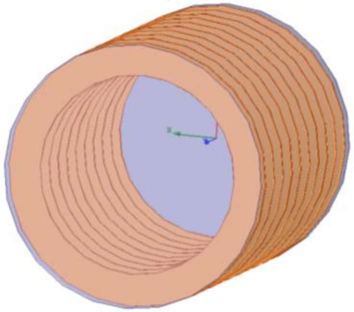
- Limited wave slow-down

good for relativistic e-beams, $v_{e-}\approx c$

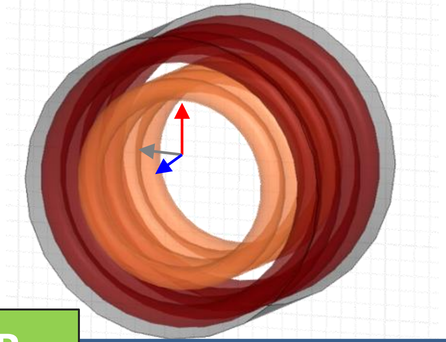
Dielectric/Ferrite Corrugations



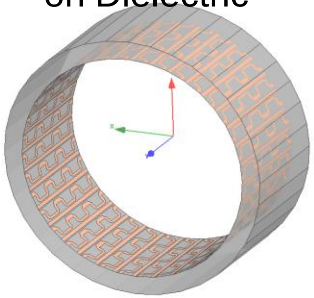
Metal Corrugations



Concentric Metallic Rings

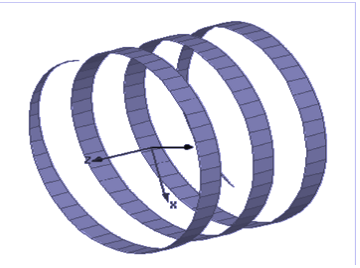


Coupled Transmission Lines on Dielectric

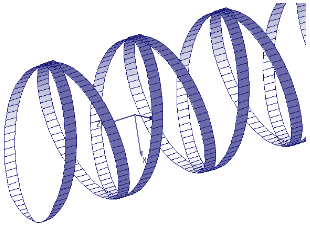


OR

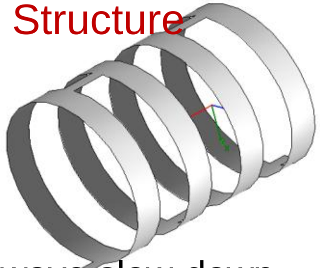
Helix



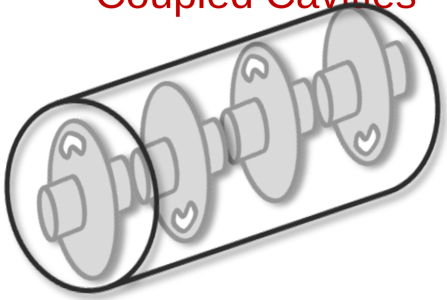
Double Helix



Ring-Bar Structure



Coupled Cavities

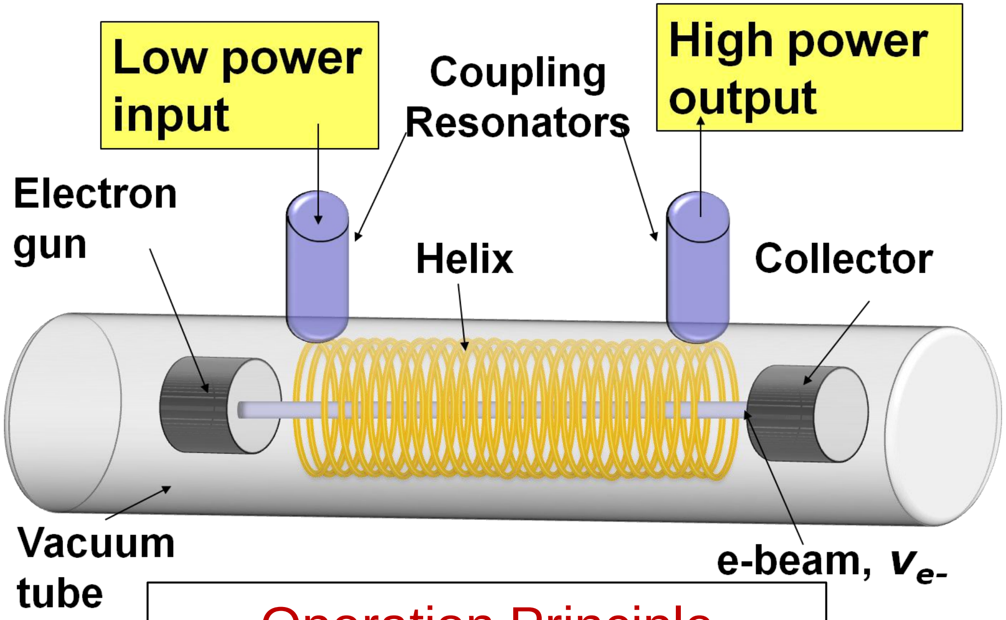


- Enormous wave slow-down

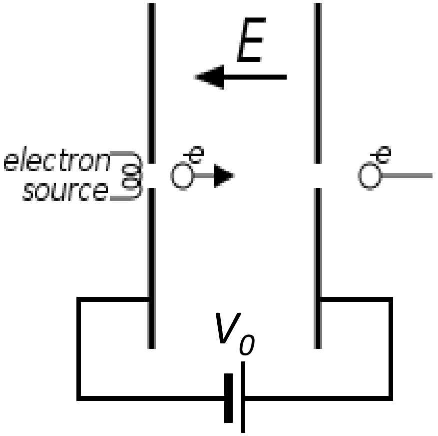
(good for slower e-beams, $0.1c<v_{e-}<0.3c$)

Metallic Slow Wave Structures Based on Helical Waveguide

Travelling Wave Tube



Electron gun



$v_{e-} = (eV_0/m)^{1/2}$

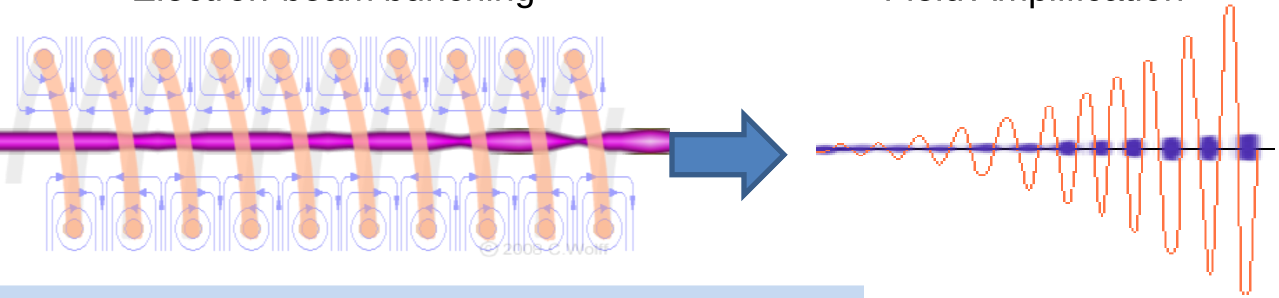
e and *m* are electron charge and mass.

V_0 =voltage applied to electron gun.

Operation Principle

Electron-beam bunching

Field Amplification



Advantages of Helix WG

- Considerable wave slow down.
- Purely metallic construction.
- Wide BW operation.

Gain≅-9.54+47.3×C×*N* (dB)

(* J. R. Pierce, *Travelling Wave Tubes*, NY: D.Van Nostrand Co, 1950)

N=number of wavelengths

$$C = \sqrt[3]{\boxed{\frac{E_{axial}^{2}}{2\beta^{2}P}}\boxed{\frac{I_0}{4V_0}}}$$

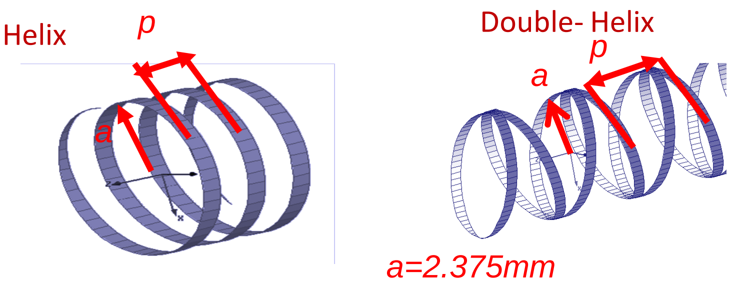
Needs to be as large as possible to obtain high gain.

Key Performance Parameters for Helical Waveguides

1)Phase velocity of EM wave=electron velocity

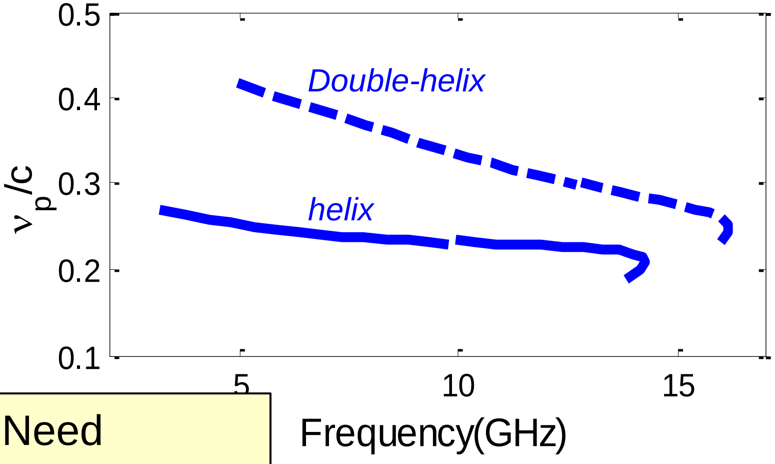
$v_p = c \times \sin\psi = v_{e-} = (eV_0/m)^{1/2*}$ $\Psi = \cot^{-1}(2\pi a/p)$

*e and m are electron charge and mass,
V_0 is the voltage applied to electron gun.



a=2.375mm
p=3.52mm

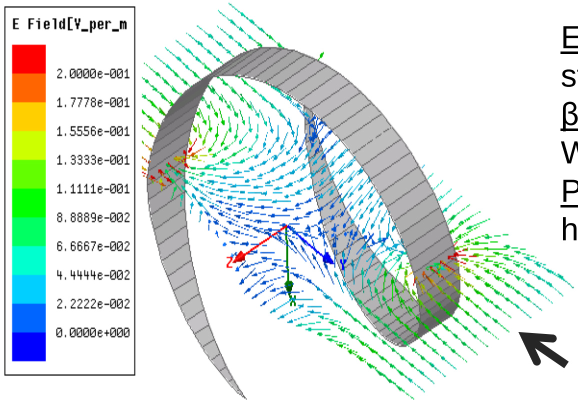
Normalized Phase velocity



Need constant v_p for wider BW

2)Interaction Impedance: $K_0 = E_z^2/(2\beta^2 P)$

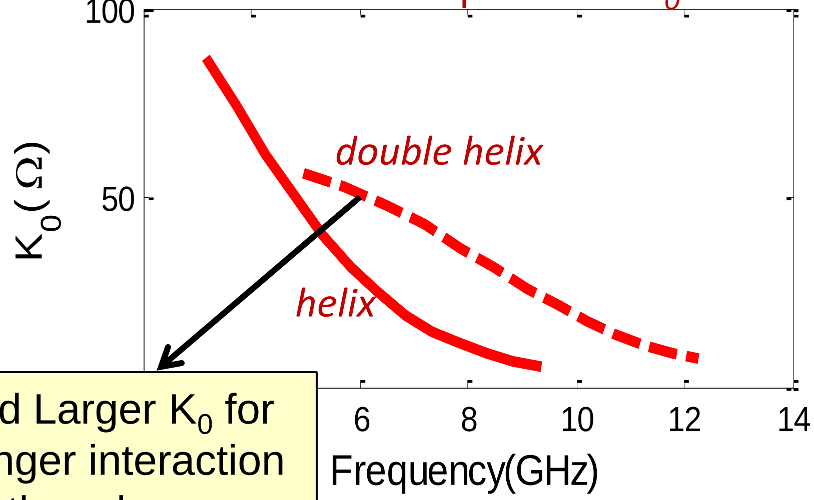
(*J. R. Pierce, *Travelling Wave Tubes*, NY: D.Van Nostrand Co, 1950)



E_z: Longitudinal field strength along *z* axis
β:phase constant within WG
P:net power flow along helix

Strong transverse electric field!

Interaction Impedance K_0

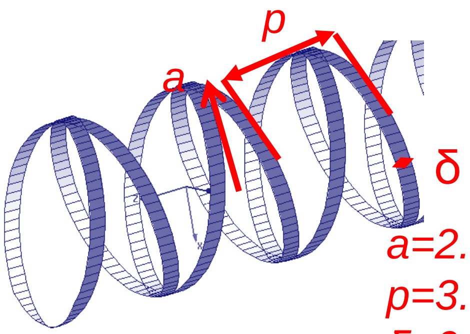


Need Larger K_0 for stronger interaction with the e-beam

- Double-helix allows for more energy transfer from the e-beam to the RF signal.

Simplified Double-Helix : Ring-bar Structure

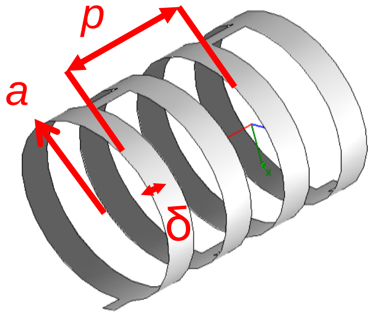
Double-Helix



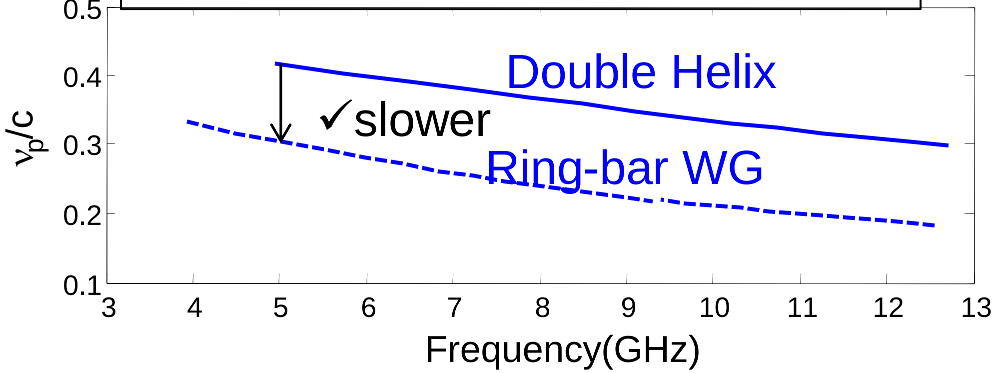
Simpler =

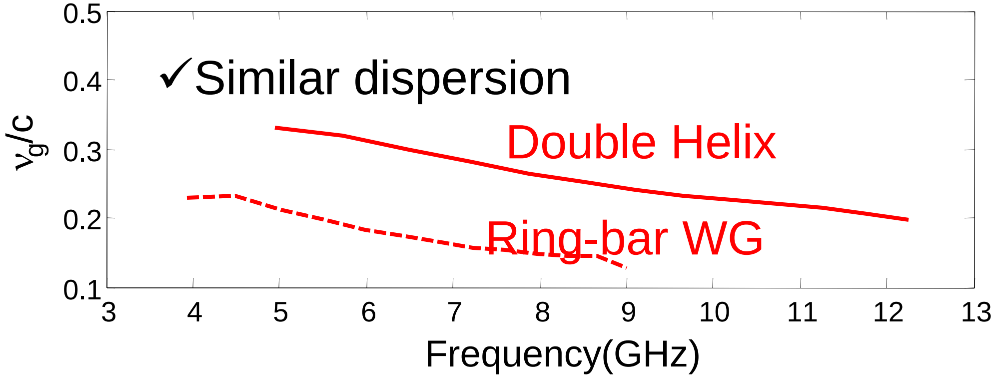
a=2.375mm
p=3.52mm
δ=0.15mm

Ring-bar Structure

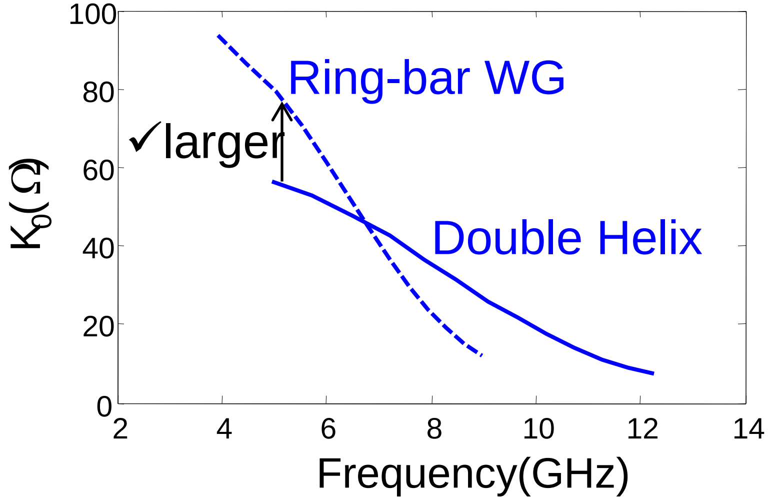


Normalized Phase &Group Velocity



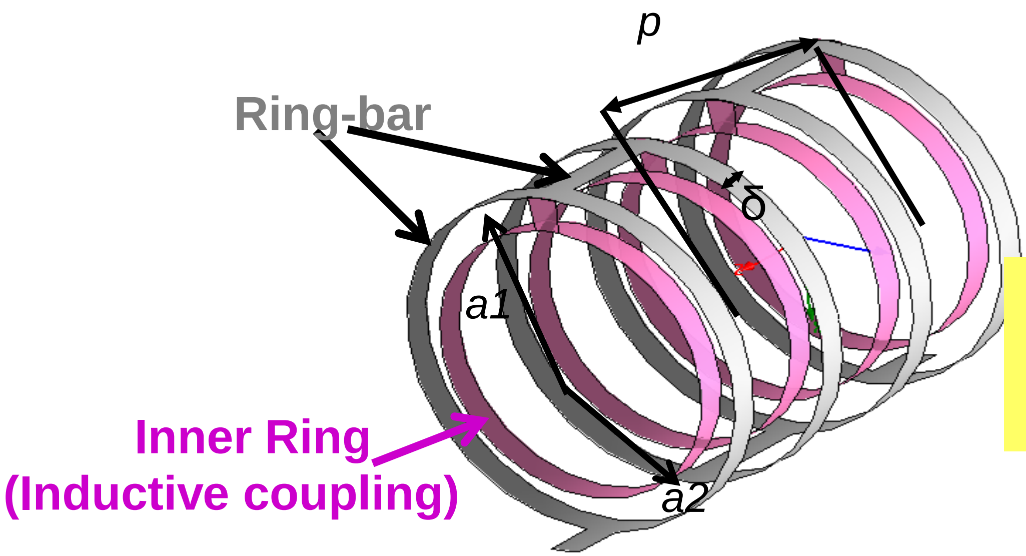


Interaction Impedance $K_0(\Omega)$



- Easier to fabricate
- Extra wave slow-down
- Higher $K_0(\Omega)$ → larger gain

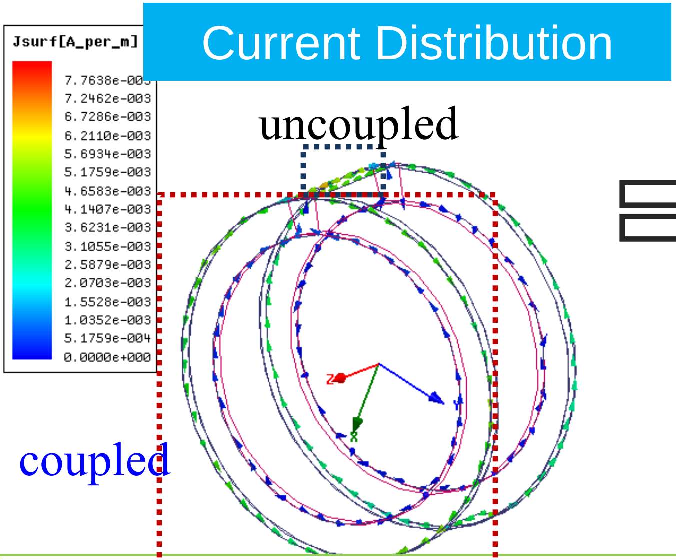
Design 1:
Double Ring-bar Structure for Miniaturization



a1=2.375mm
a2=1.9mm
p=3.52mm
δ=0.15mm

✓Purely metallic construction
✓Connected inner and outer rings (no charging or arcs)

Current Distribution



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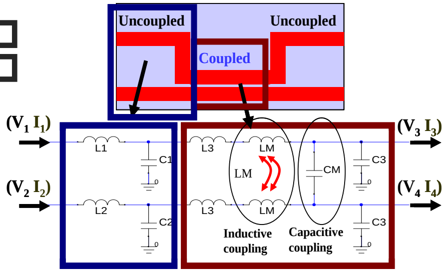
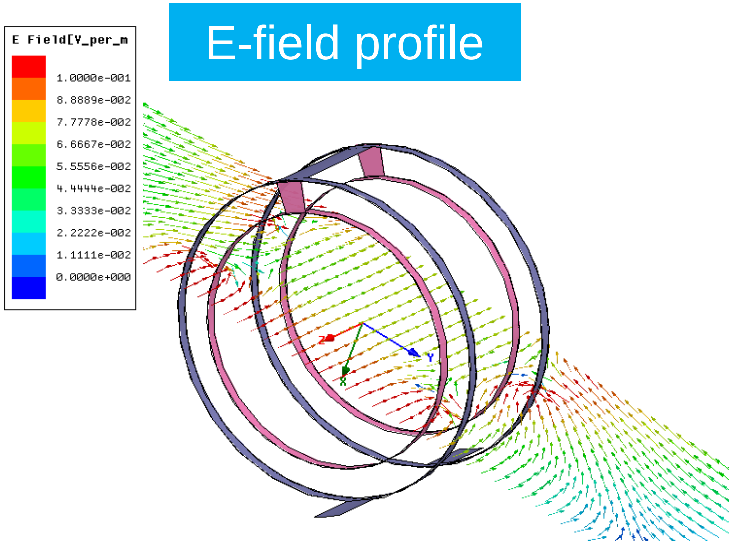


E-field profile

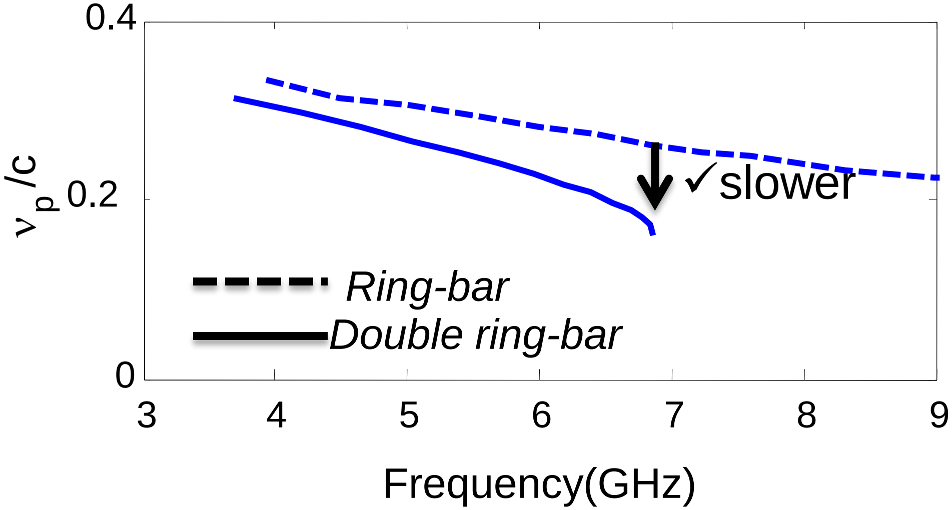


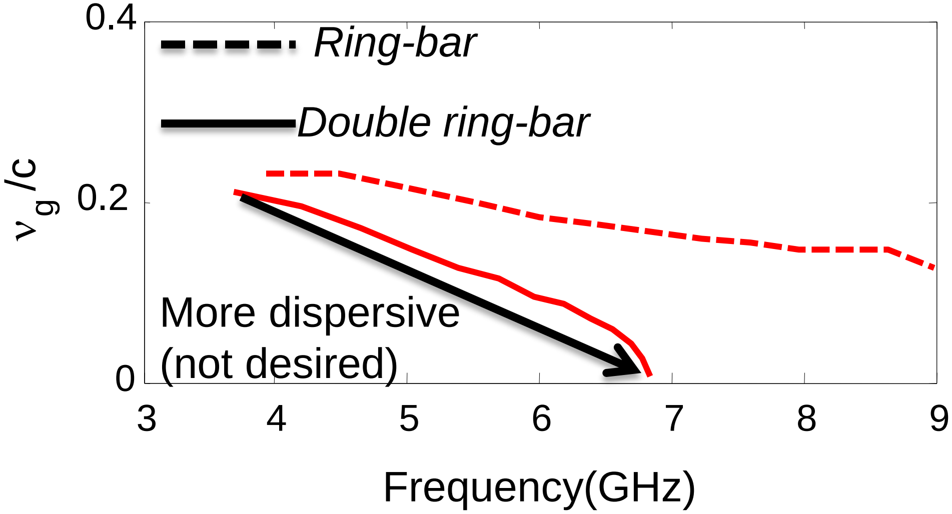
✓Inductive&capacitive coupling → extra wave slow-down&miniaturization

✓Strong longitudinal field→ stronger coupling between the RF signal and e-beam

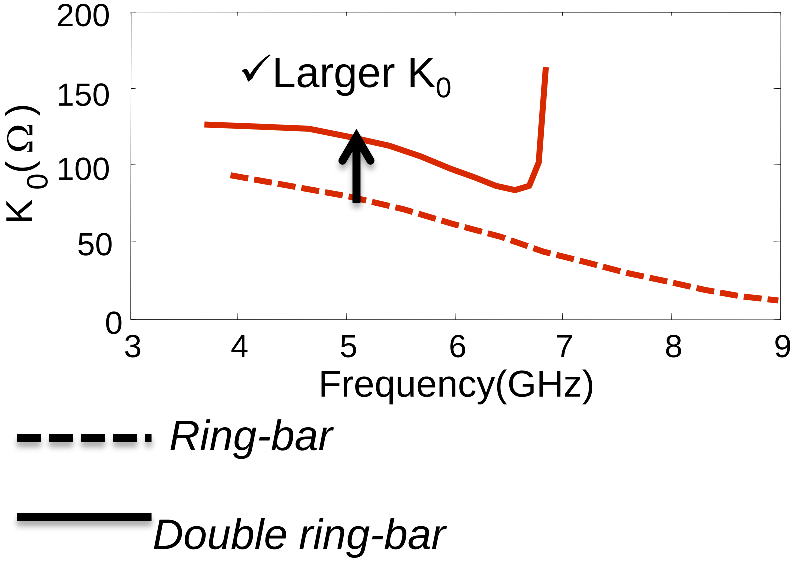
Performance of Double Ring-bar Structure

Phase & Group Velocities





Interaction Impedance

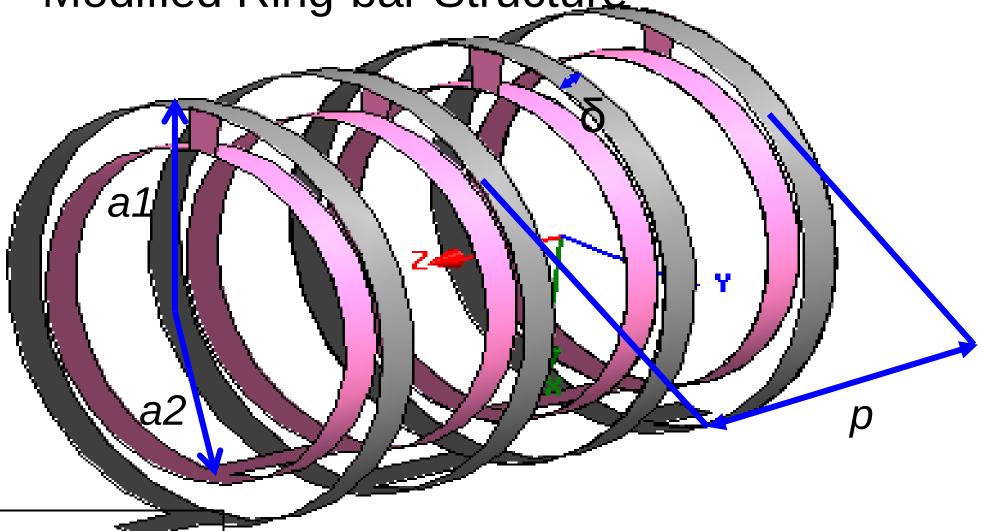


- ✓Extra wave slow-down $(0.18c<v_p<0.32c)$
- ✓Larger K_0 over the bandwidth $(90\Omega<K_0<150\ \Omega)$
- ✓More dispersive (not desired)
- ✓Operates between 3-7GHz $(v_p=0.25c\pm0.07c)$

Design 2: Modified Ring-bar Structure for Additional Miniaturization

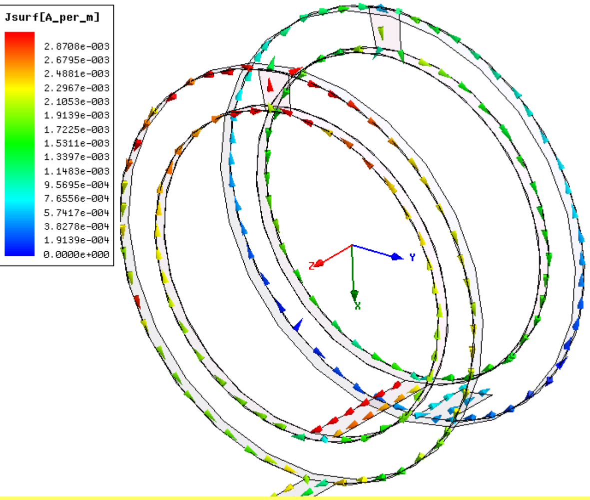
Concentric ring-bars increase the current path and leads to miniaturization.

Modified Ring-bar Structure



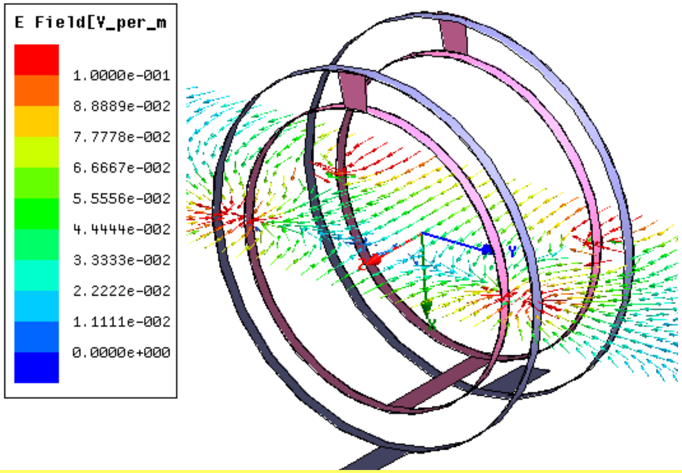
a1=2.375mm
a2=1.9mm
p=3.52mm
δ=0.15mm

$J_{surface}$ Distribution (A/m)



Longer current path → miniaturization

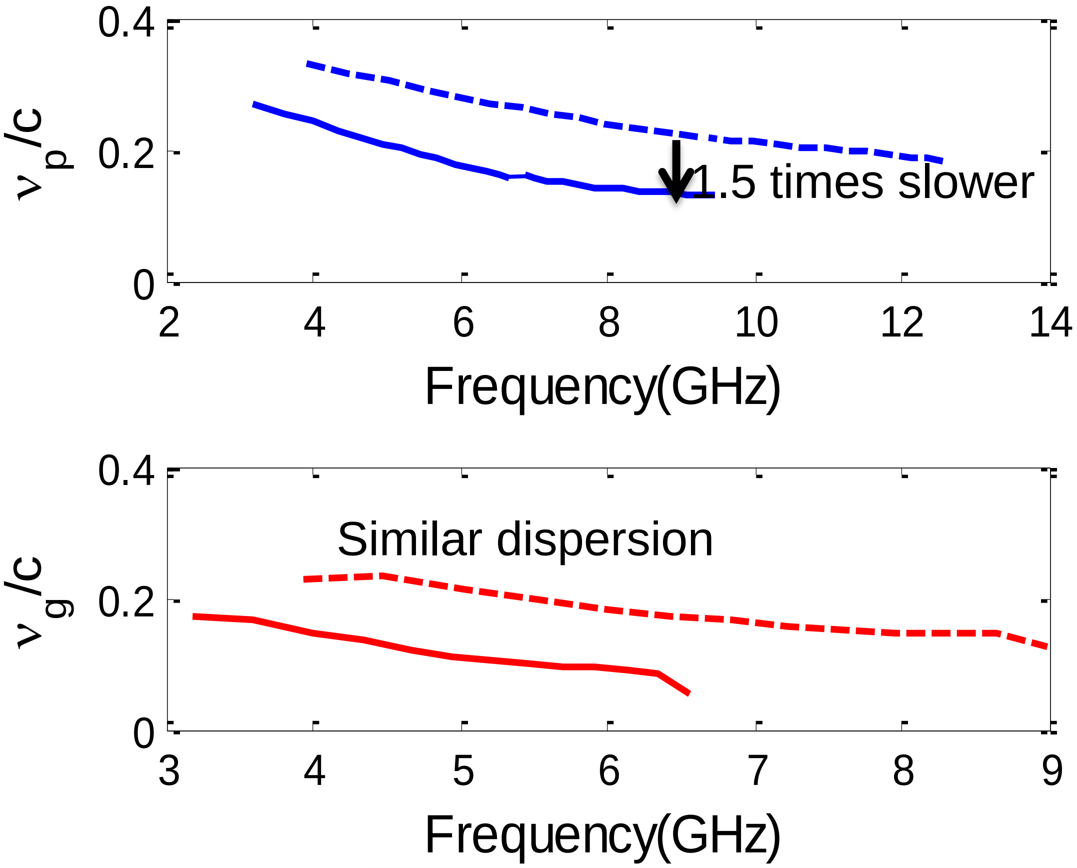
E-field Distribution (V/m)



Strong axial E-field → strong radiation

Performance Using Modified Ring-bar Structure

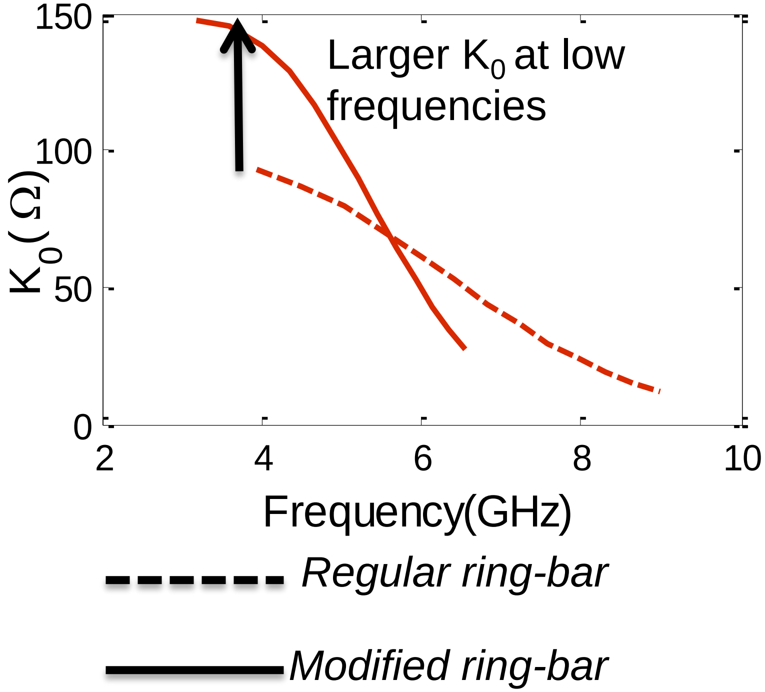
Phase & Group Velocities



1.5 times slower

Similar dispersion

Interaction Impedance

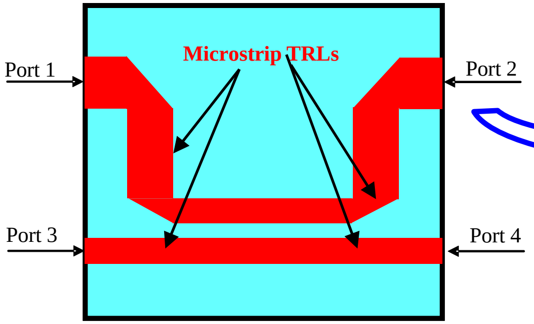


Larger K_0 at low frequencies

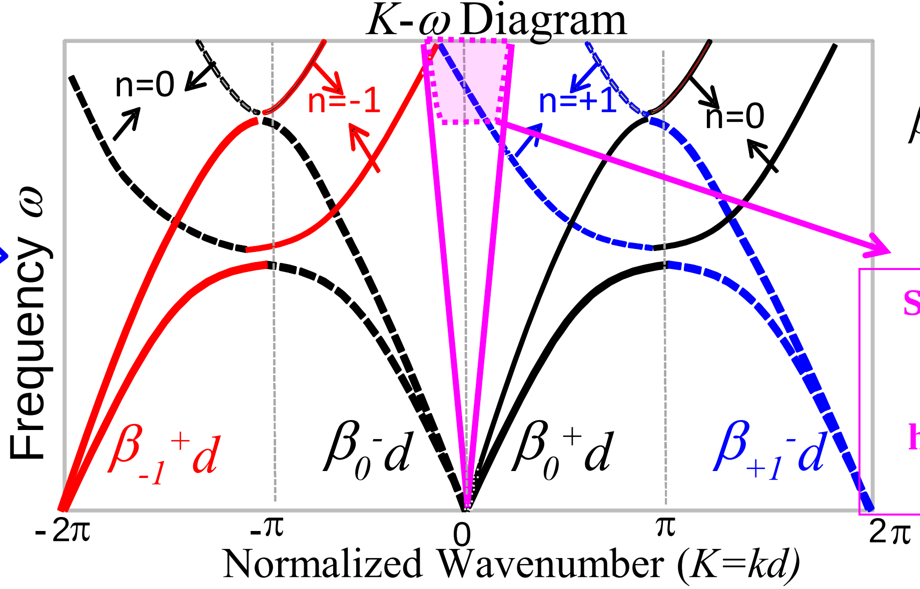
- ✓**1.5 times more wave slow-down (0.18c<vp<0.25c)**
- ✓Larger K_0 up to 5.8GHz($75\Omega < K_0 < 150\ \Omega$)
- ✓Similar dispersion
- ✓Operates between 3-7GHz(v_p=0.215c±0.035c)

Further Miniaturization Using CRLH Concept

Coupled Transmission Lines



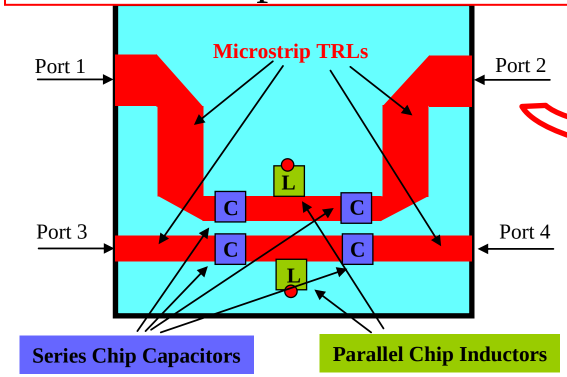
- Artificial anisotropy
- Nonreciprocal behavior
- Leaky-wave radiation from n=±1 harmonics



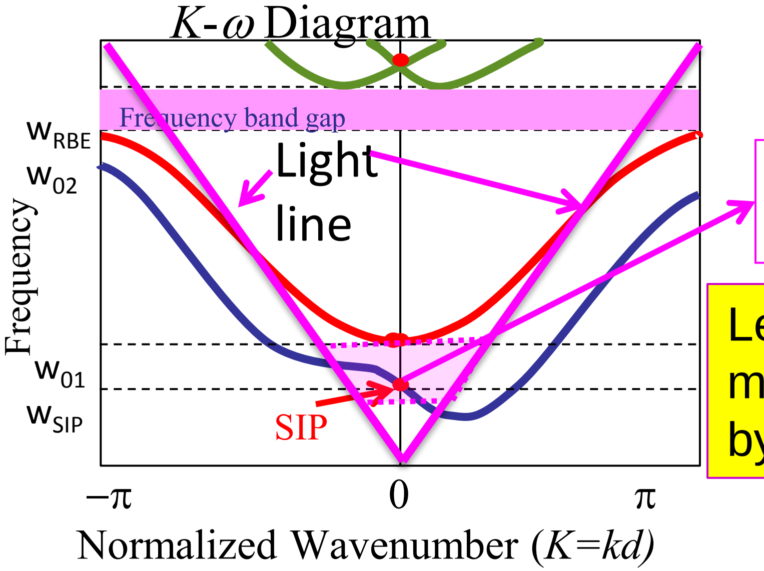
$\beta_{+1}=\beta_0^{-}+2\pi/d$

Strong Spectral Asymmetry but high frequency resonance

Coupled Transmission Lines w/ Lumped Elements



- Leaky-wave radiation from n=0 mode



low frequency resonance

Leads to miniaturization by a factor of 3!

Ohio State's Research

- **Design slow wave structures using a variety of metamaterial liners**
  Purely metallic is our first focus
  Material loading to be considered as well and examine their potential
  Coupling, Power & Group Velocity consideration

- **Demonstration and applications**

-------------------Immediate Steps--------------------------------------

- **Calculate interaction of SWS with e-beams using PIC code simulations.**
  - E-beam bunching
  - Cherenkov radiation
  - Field amplification

- **Final prototype and performance evaluation for high power microwave source.**
  - Output power
  - Power efficiency
  - Bandwidth of operation