Development of TEM High Power RF Vector Modulators

Y. Kang, J. Wilson
M. McCarthy, S-H. Kim, M. Champion, SNS/ORNL
R. Kustom, APS/ANL, B. Chase, FNAL

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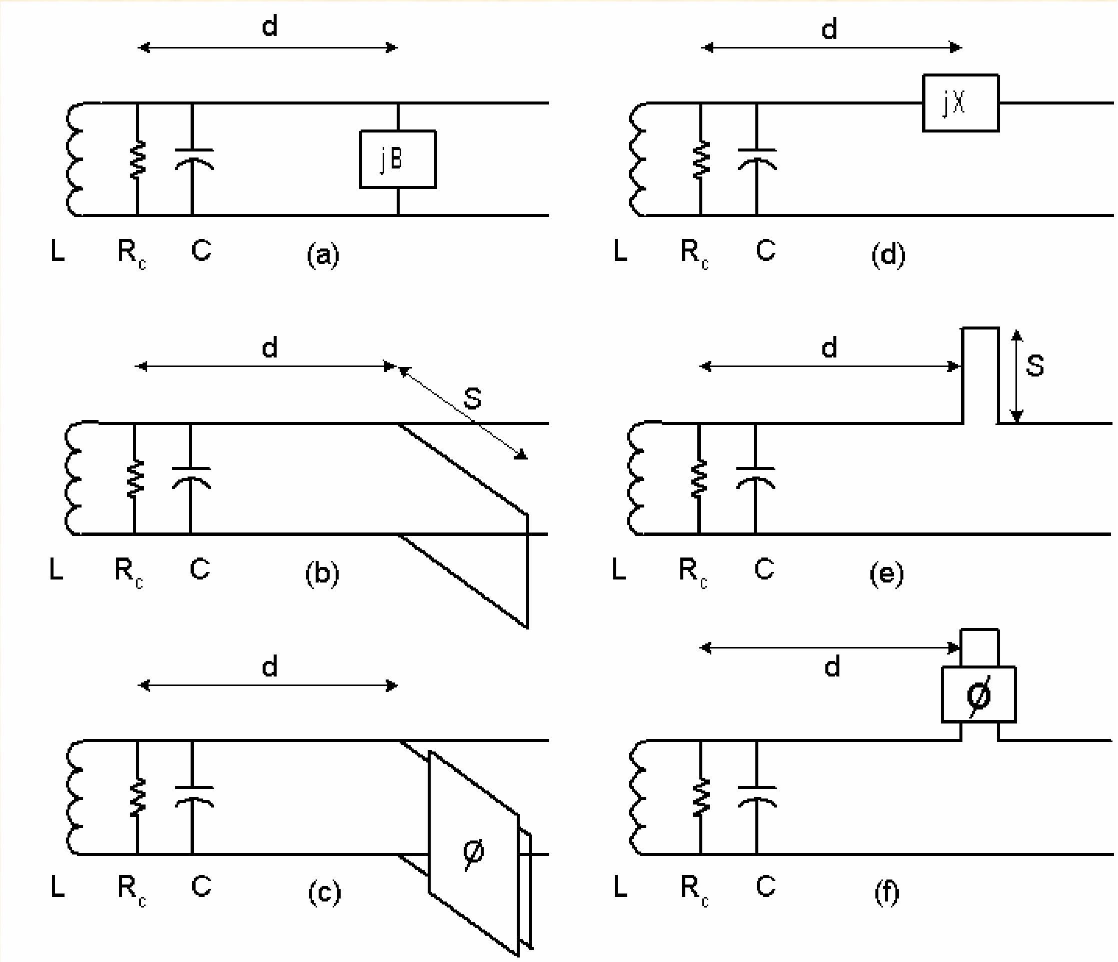
Cavity Tuning with External Reactance

- Cavity tuning is done externally through RF feed transmission line with at 1 or more adjustable reactances.
  - Using one reactance, the cavity can be matched and tuned at the terminal of the reactance
  - Cavity shunt resistance does not change with the detuning
  - The cavity to the reactance need to be N*λ/2



Tuning, RF Voltage Control

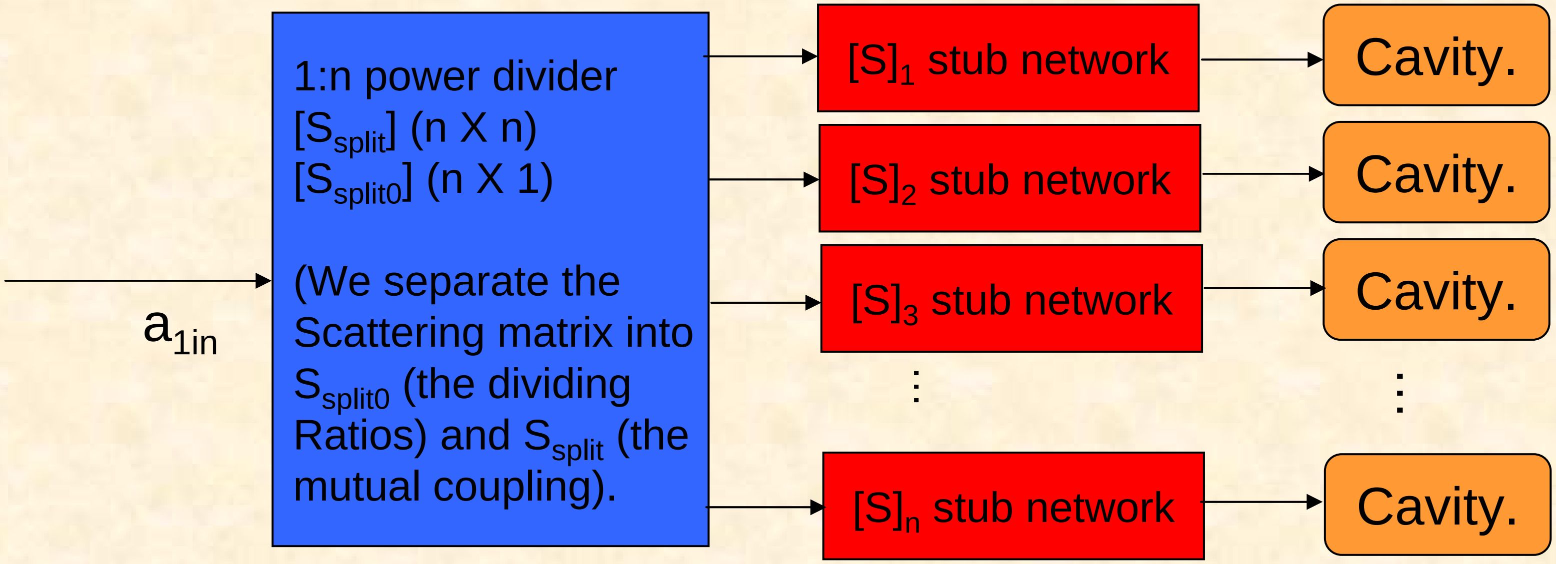
- If the specified amplitude and phase of the voltage in the cavity is delivered, external cavity tuning is already achieved.
- Cavity voltage control is done externally through RF feed transmission line with reactive tuning elements.
- In fan-out RF distribution configuration, having the exact amplitude and phase distributions at cavities gap is important.
- There are advantages and disadvantages to each power splitting scheme, and the splitter itself is an important part of the overall system

Tuning, RF Control, and Matching

- **The voltage vector control (and tuning) can be achieved using 2 or 3 reactive elements (or short stubs for realization)**
  - 2 stubs may provide sufficient range for the control.
- **For a fixed input voltage resulted by fanning out the klystron output, each cavity port will have a reflected wave**
- **The mutual interaction of the reflections from many cavities must be eliminated**
  - **Circulator in each cavity port**
  - **Use an extra tuning element; no circulator or just one circulator at the klystron output for added protection**

A Fan-Out Distribution with Stub Tuners

The terminal voltage at the accelerating cavity can be derived as a matrix equation, which must take into account all mutual coupling.



a_{1in}

1:n power divider
$[S_{split}]$ (n X n)
$[S_{split0}]$ (n X 1)

(We separate the Scattering matrix into S_{split0} (the dividing Ratios) and S_{split} (the mutual coupling).

$[S]_1$ stub network → Cavity.
$[S]_2$ stub network → Cavity.
$[S]_3$ stub network → Cavity.
⋮ ⋮
$[S]_n$ stub network → Cavity.

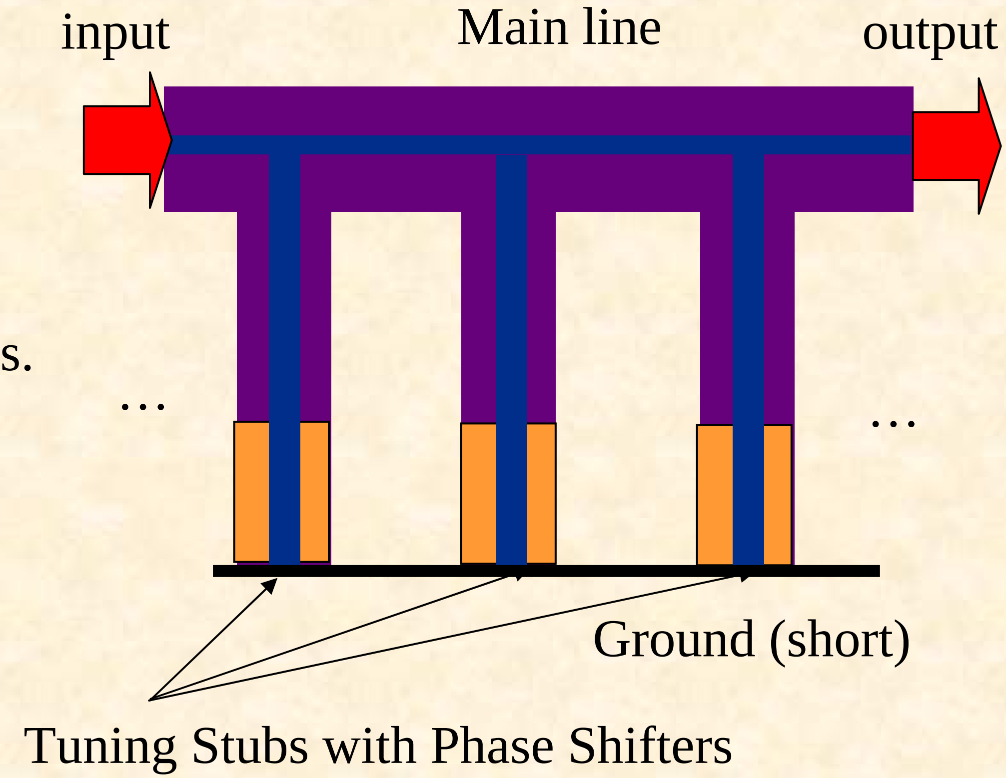
The terminal voltage: $V_L = Q\left(1 - S_{split}\Psi\right)^{-1} S_{split0} a_{1in}$

$$Q_{mn} = \frac{S_{n21}\left(\Gamma_{Ln} + 1\right)}{1 - S_{n22}\Gamma_{Ln}}\delta_{mn} \qquad \Psi_{mn} = \left(S_{n11} + \frac{S_{n12}S_{n21}\Gamma_{Ln}}{1 - S_{n22}\Gamma_{Ln}}\right)\delta_{mn}$$

A Different Vector Modulator Idea

Quadrature hybrid + 2 half-wavelength tunable slabs

vs.

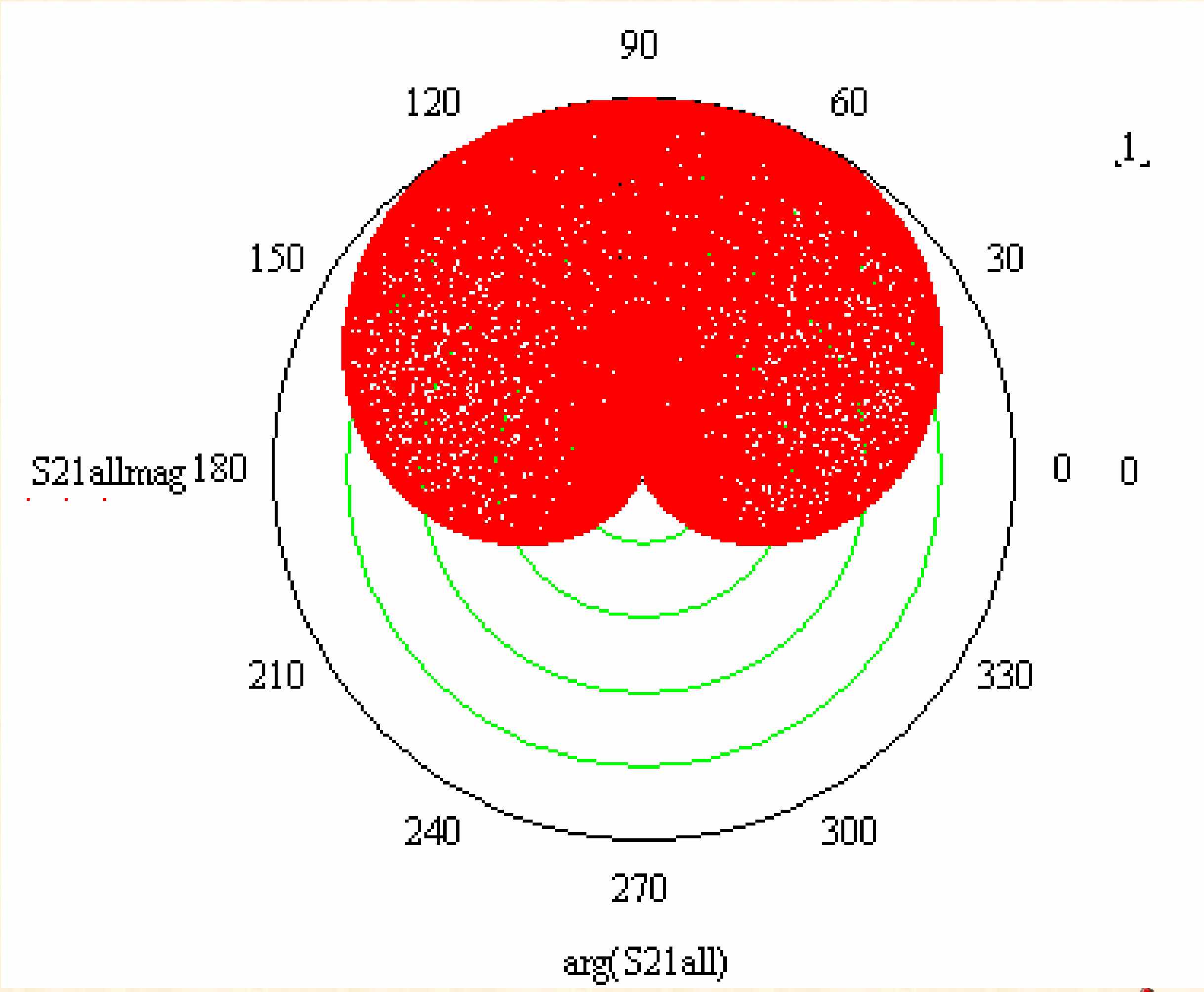


Tuning Stubs with Phase Shifters

- Advantages:
  - The power can be distributed over a larger volume of tunable material. This leads to easier cooling.
  - The need for the hybrid is eliminated.

Load Terminal Voltages for stub tuners (no loss case)

0.25 λ spacing, 2 stubs from 0 to 0.5 λ. $Z_{stub}/Z_{line}=1$

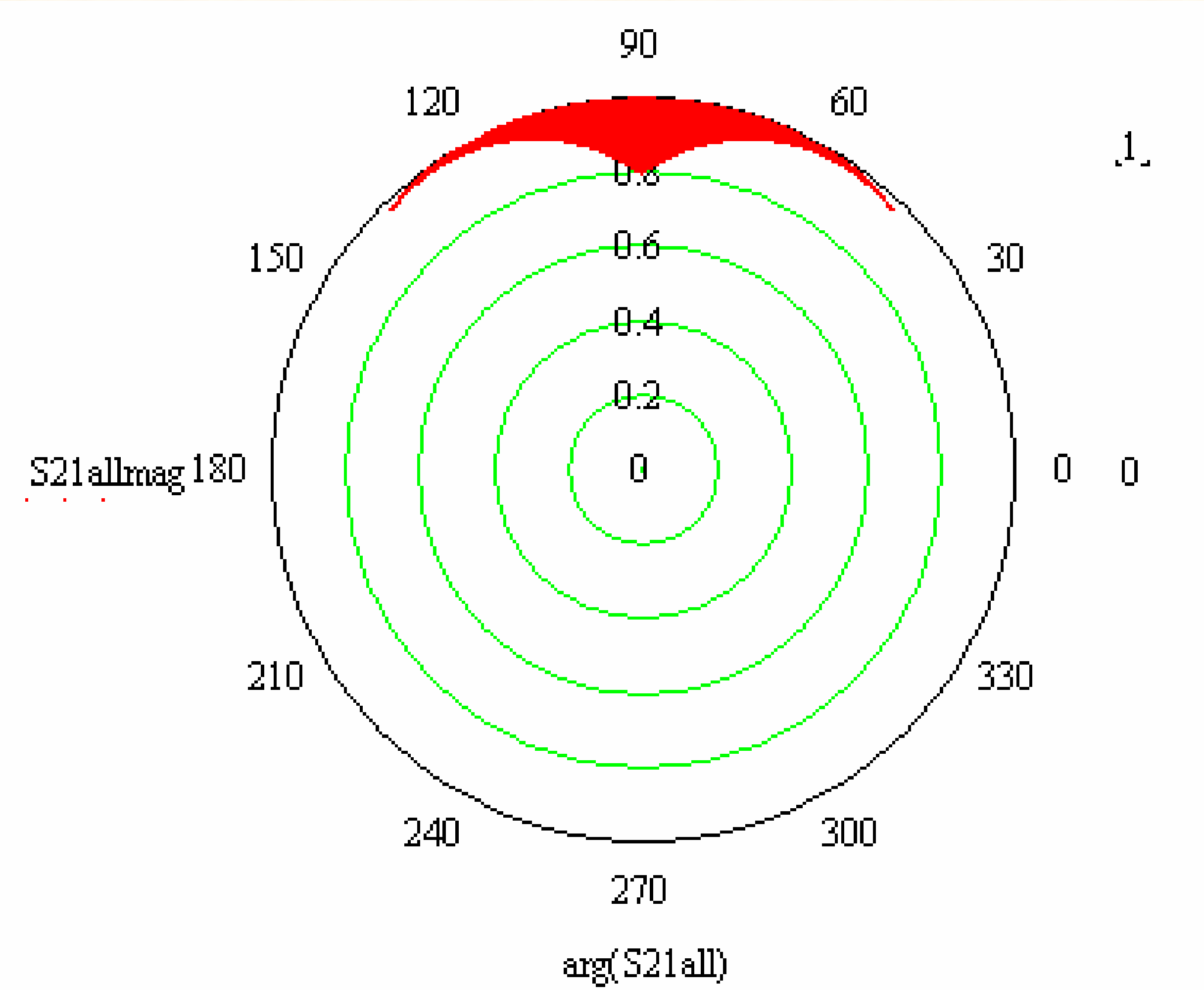


This represents the theoretical MAXIMUM tuning range.

*Here, Γ_{load} = 0, so at the terminal $V_{terminal}$ / V_{input} = S_{21}

Load Terminal Voltages for stub tuners (no loss case)

0.25 λ stub spacing, 2 stubs from 0.15 to 0.35 λ. $Z_{stub}/Z_{line}=1$

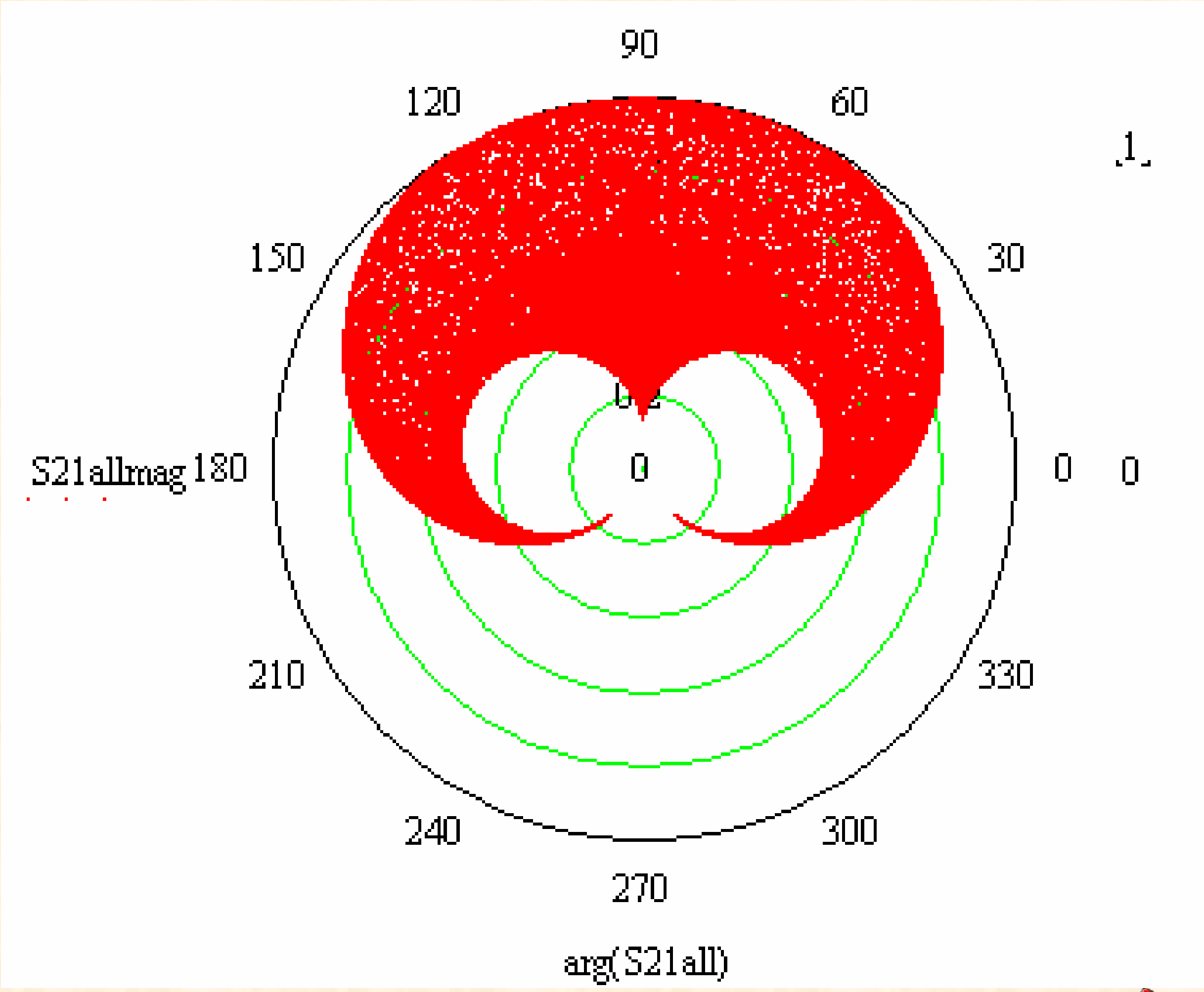


Since a change in the electrical length of the stub of 0 to 0.5 λ is not feasible, we limit our range to 0.15 to 0.35 λ.

Load Terminal Voltages for stub tuners (no loss case)

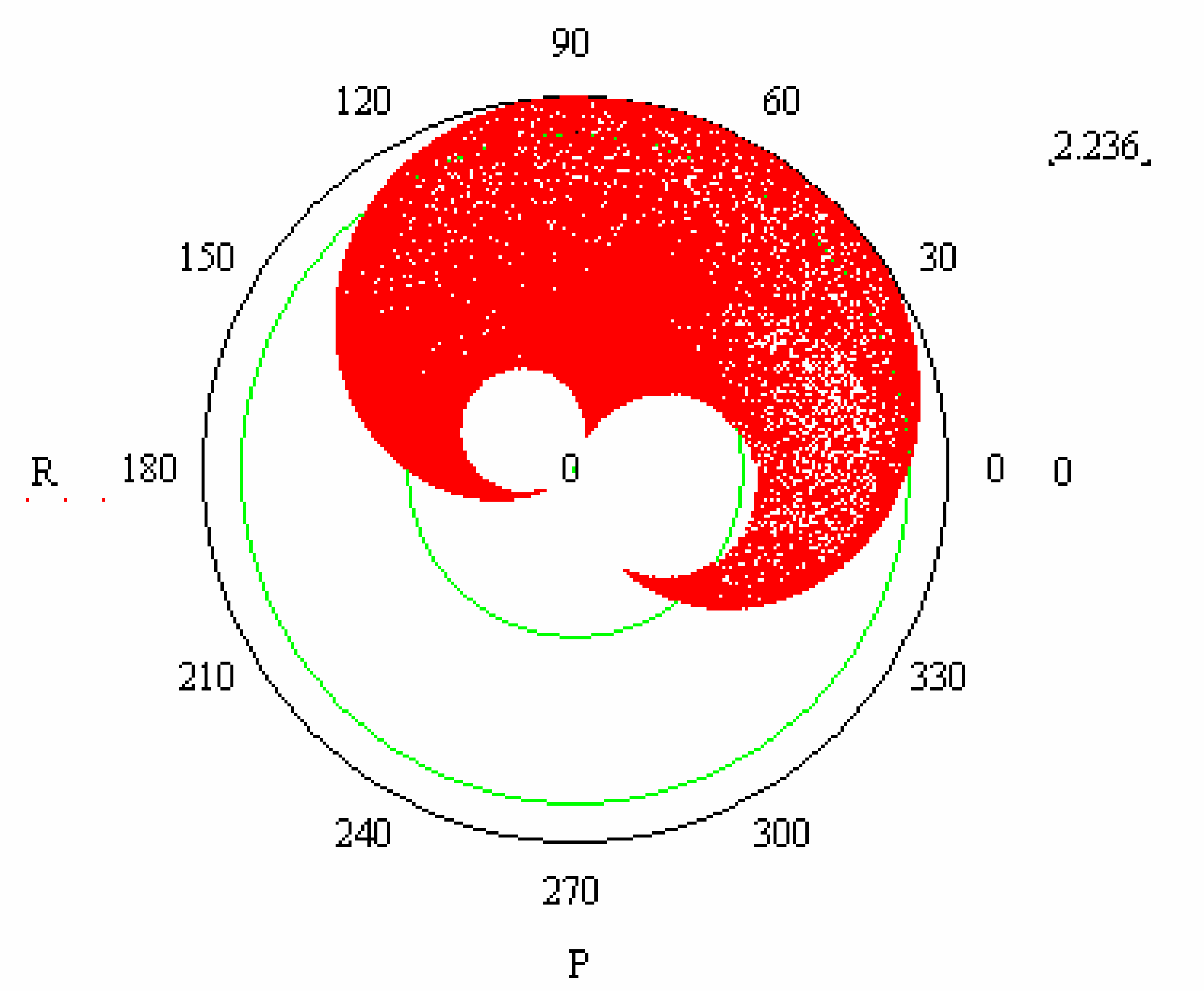
By changing the coupling to the stub (i.e. changing Z_{stub}/Z_{line}) we can dramatically improve the tuning range.

0.25 λ stub spacing, 2 stubs from 0.15 to 0.35 λ. $Z_{stub}/Z_{line}=0.2$



Load Terminal Voltages for stub tuners (no loss case)

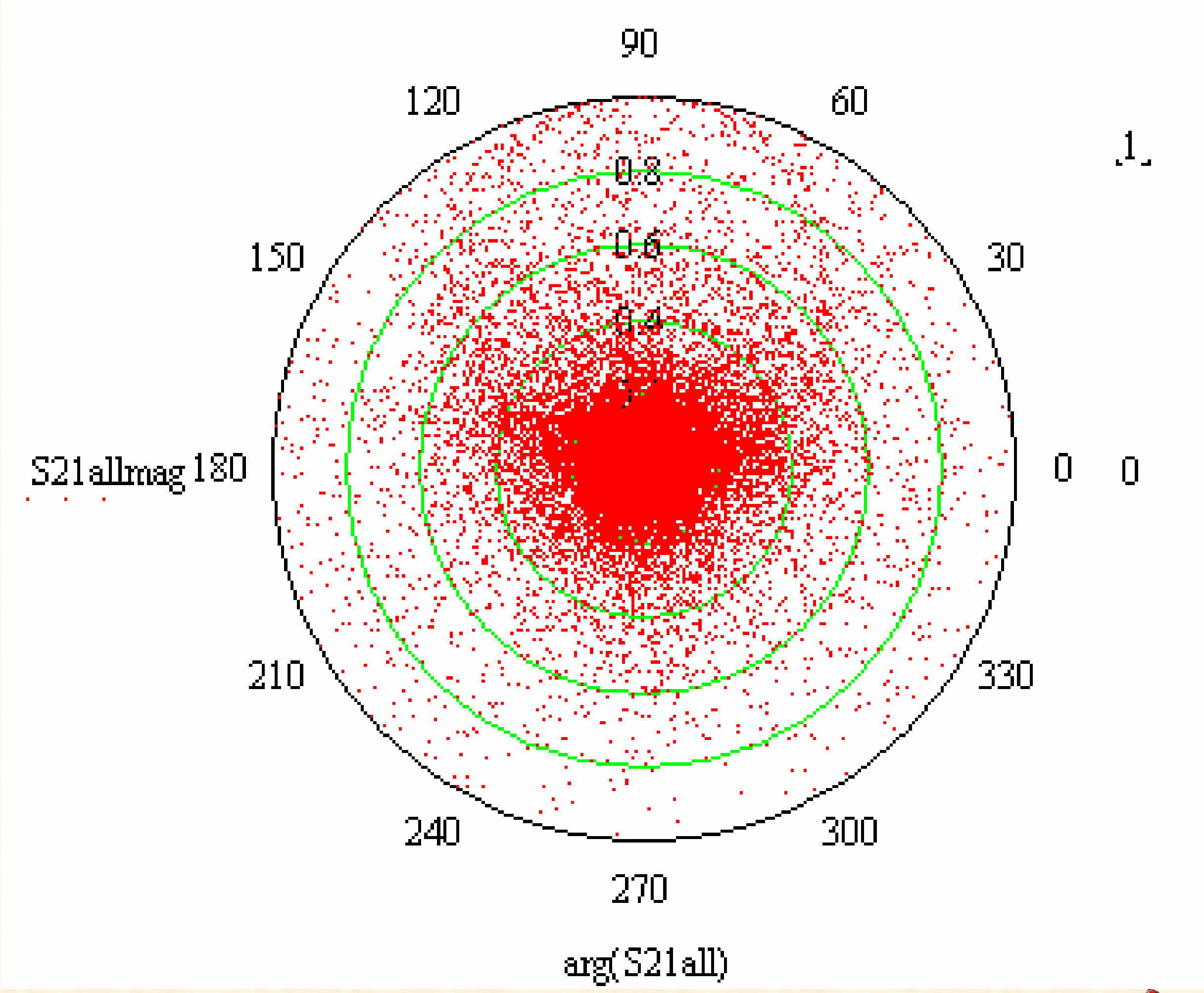
0.25 λ stub spacing, 2 stubs from 0.15 to 0.35 λ. $Z_{stub}/Z_{line}=0.2$



As could be expected, changing Gamma, load to 0.5+j0.5 will shift the tuning range slightly, as shown.

Load Terminal Voltages for stub tuners (no loss case)

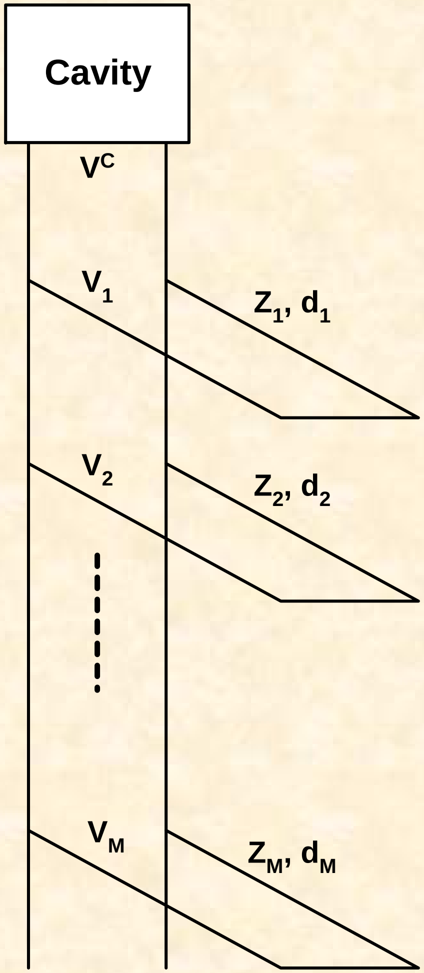
0.25 λ stub spacing, 3 stubs from 1 to 0.5 λ. $Z_{stub}/Z_{line}=0.2$

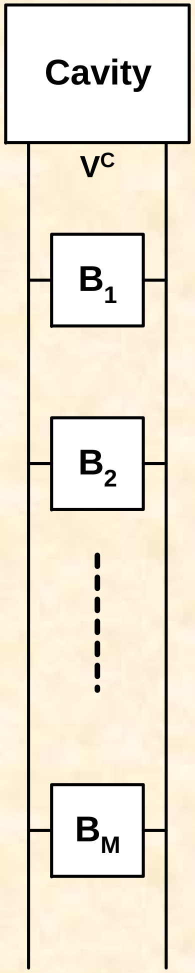


Using 3 stubs can provide FULL vector control. However, this is not typically required in accelerator applications.

Applying RF Voltage to a Cavity

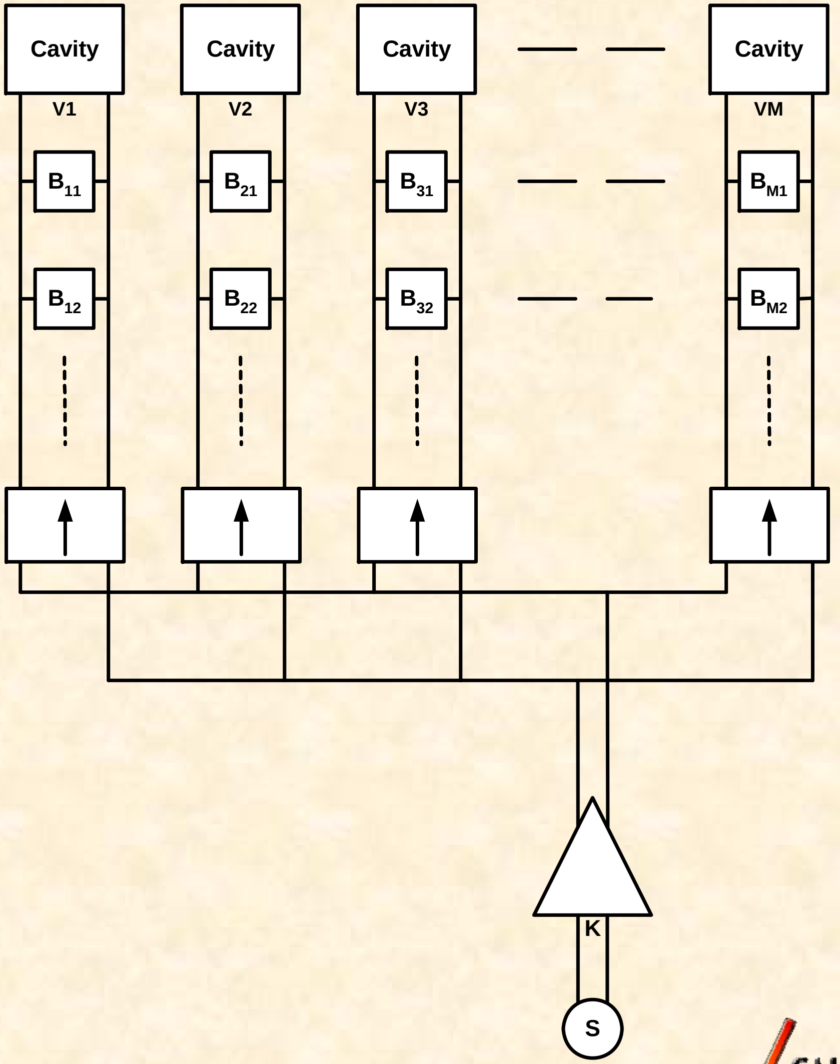
- The cavity can have a specified voltage using two or more reactances in the feed transmission line
- The reactances are realized with short circuited transmission line sections
- Two tuning elements can deliver a limited range of voltage vector control
- Three tuning elements can deliver full range of voltage vector control





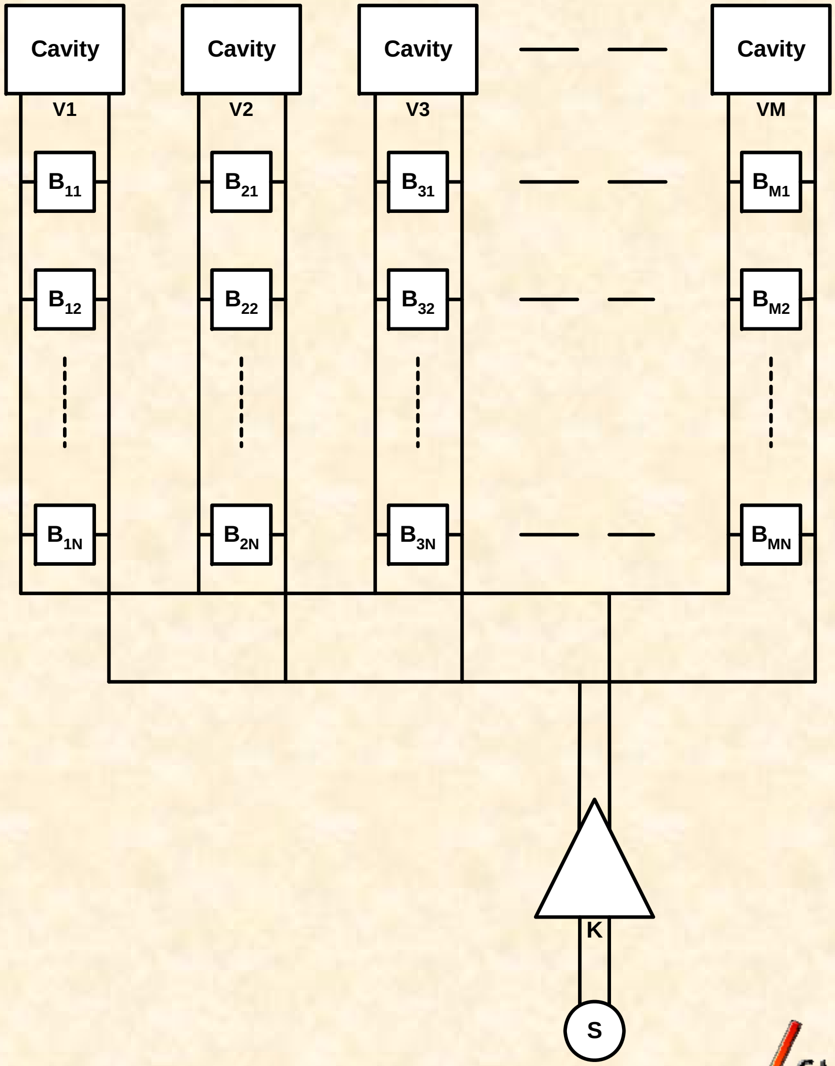
Determining Reactive Elements for Fan-Out Multicavity Operation

- **Cavities are driven through transmission line stub networks**
- **For a specified set of voltage vectors, each stub network will have reflected power**
- **Each splitter output must be protected with an isolator (or a circulator), since the mutual interaction can cause disruptions in the voltage vector control**
- **Additional reactances at the splitter ports may tune out the reflection at the klystron amplifier output**
- **The reactances can be found setting up a system admittance matrix**



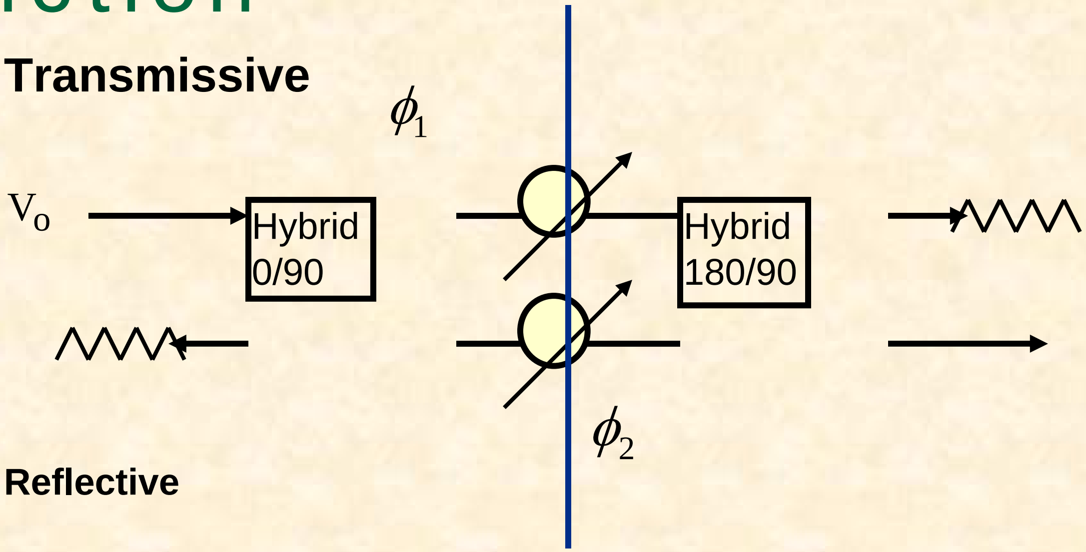
Determining Reactive Elements for Fan-Out Multicavity Operation

- **Reactive tuning is done at each splitter output port**
- **Additional reactances at the splitter ports may tune out the reflection at the klystron amplifier output**
- **The reactances can be found setting up a system admittance matrix**



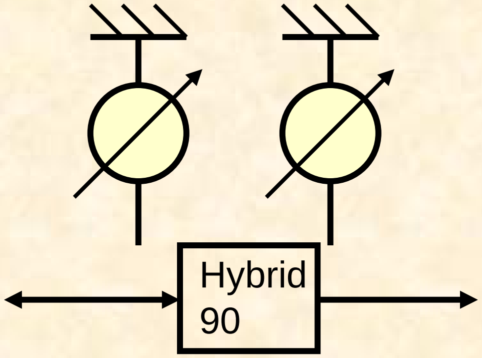
The Vector Modulation Using Hybrid Junction

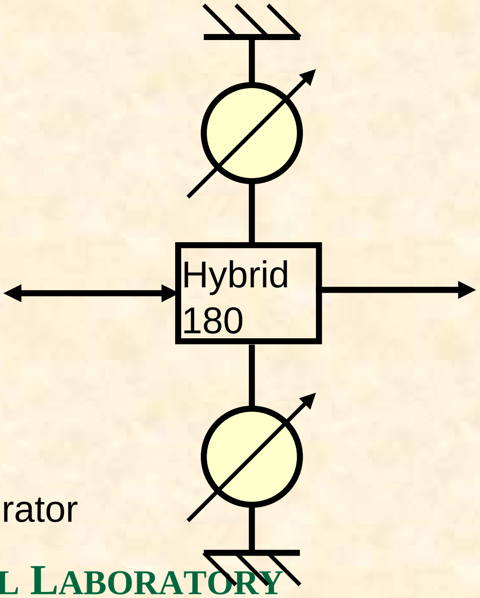
- **Transmissive**



$$V_{out}(\phi_1,\phi_2) = V_o\cos\left(\frac{\phi_1-\phi_2}{2}\right)e^{-j\left(\frac{\phi_1+\phi_2}{2}\right)}$$

- **Reflective**

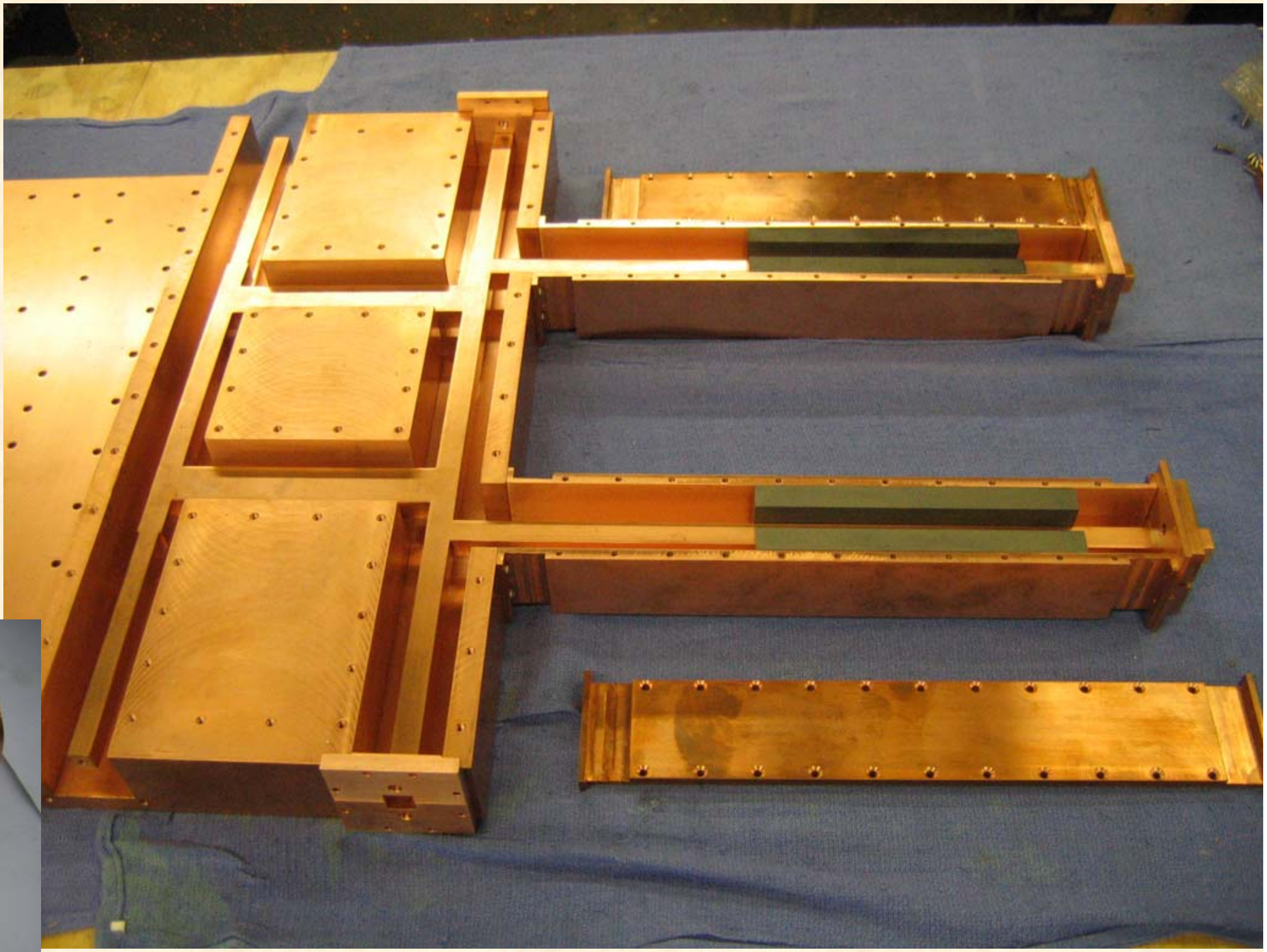




  - Standingwave is formed
  - Reflected wave must be trapped before the RF generator (klystron): circulator

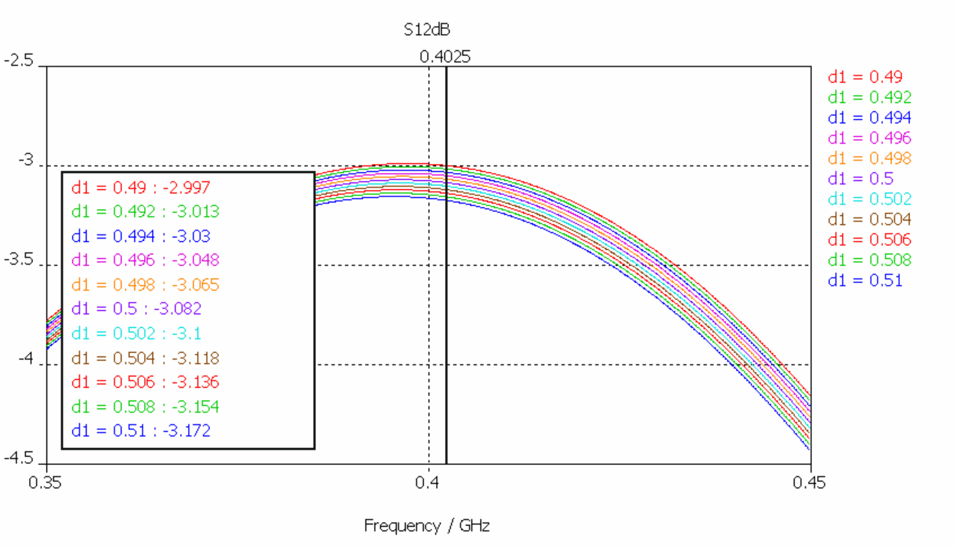
Prototype Vector Modulator

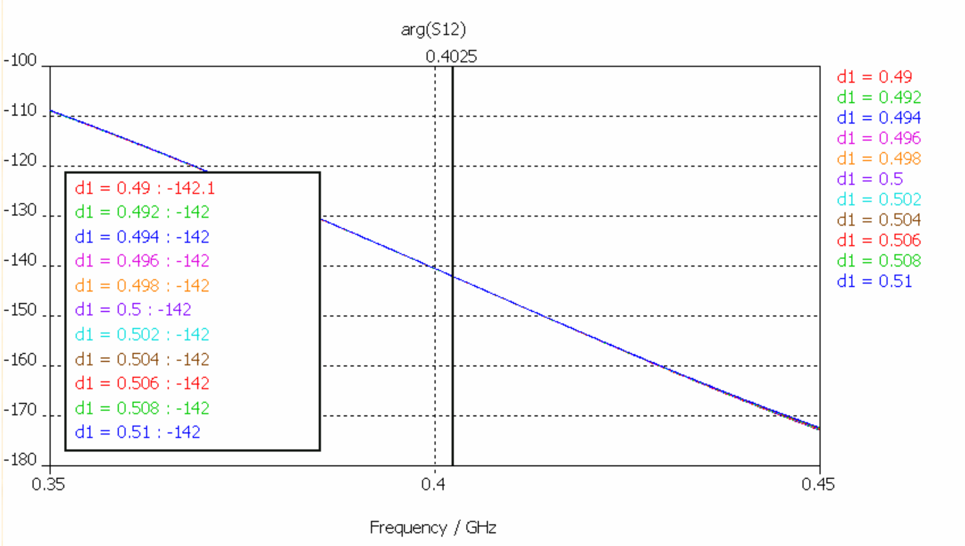
- Manufacturing parts completed and assembling is under way
- Center conductor is supported by two λ/4 stubs for cooling
- RF testing to be performed



Square coax dimensional Sensitivity Hybrid Junction (50Ω section)

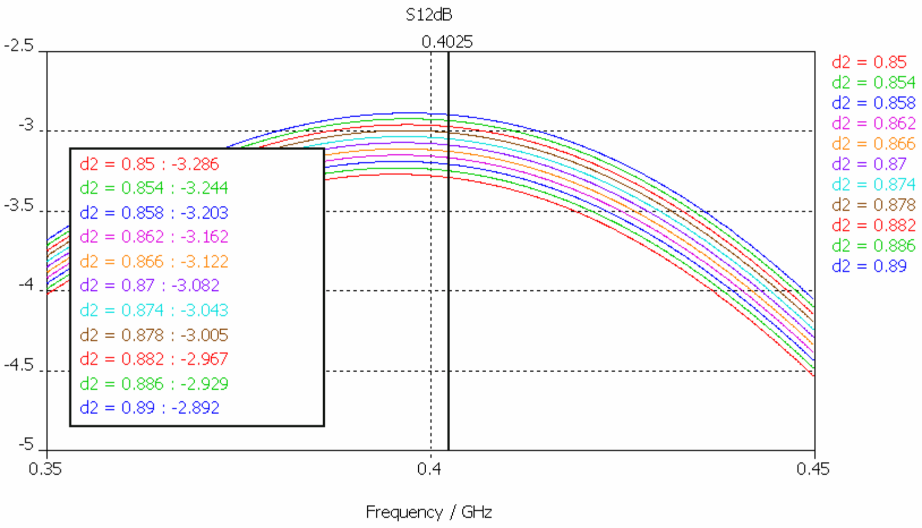
- 50Ω section center conductor width ranging from 0.49…0.51 inches

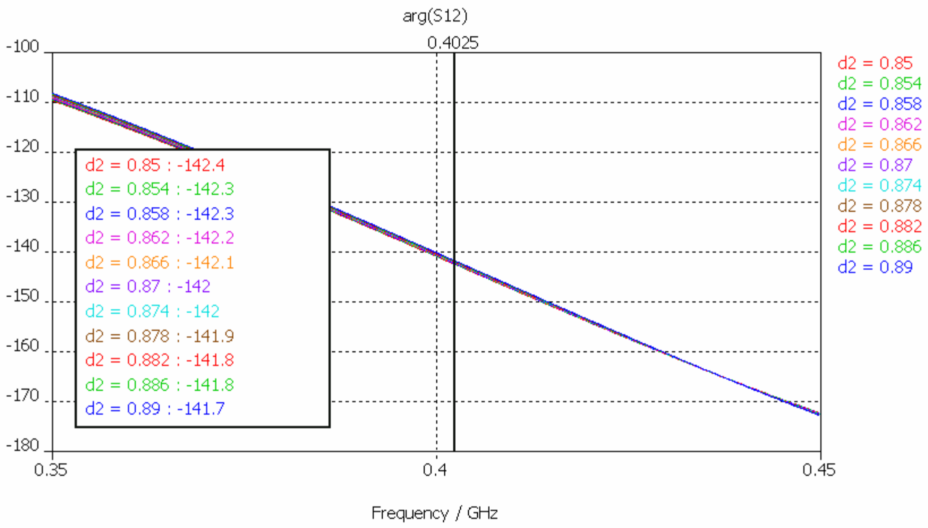




Square coax dimensional Sensitivity Hybrid Junction (50Ω section)

- 35Ω section center conductor width ranging from 0.85…0.89 inches





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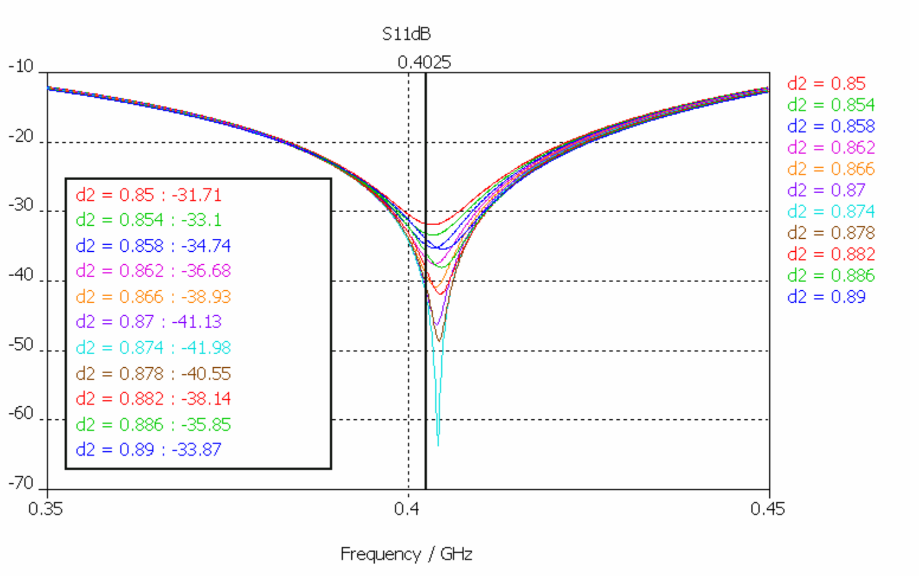
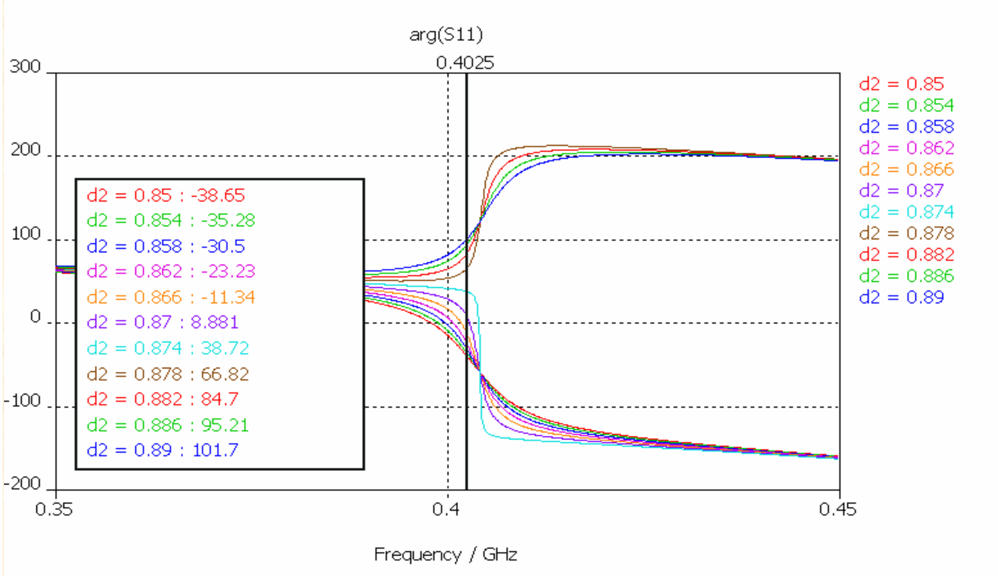




Ferroelectric materials

Ferroelectrics can be tuned with an external *electric* field

The relationship between the electric field and flux density can be approximated (in the lossless case) by

$$E = \alpha D + \beta D^3$$

where a and b are functions of temperature.

The definition of (ac) permittivity, then, is

$$\varepsilon' = \frac{dD}{dE}$$

For small ac signals, this quantity can be approximated by a constant, and the system behaves linearly.

Shepard Roberts, "Dielectric and Piezoelectric Properties of barium titanate," Phys. Rev. 71, 890 (1947).

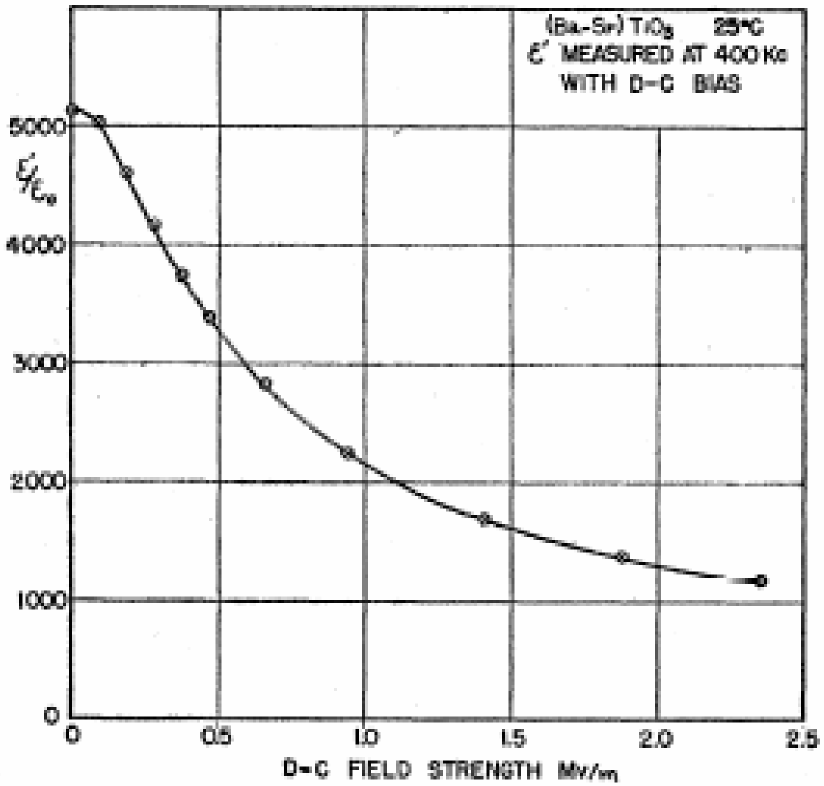


FIG. 4. Dielectric constant of $(Ba\text{-}Sr)TiO_3$ *versus* d.c. field strength.

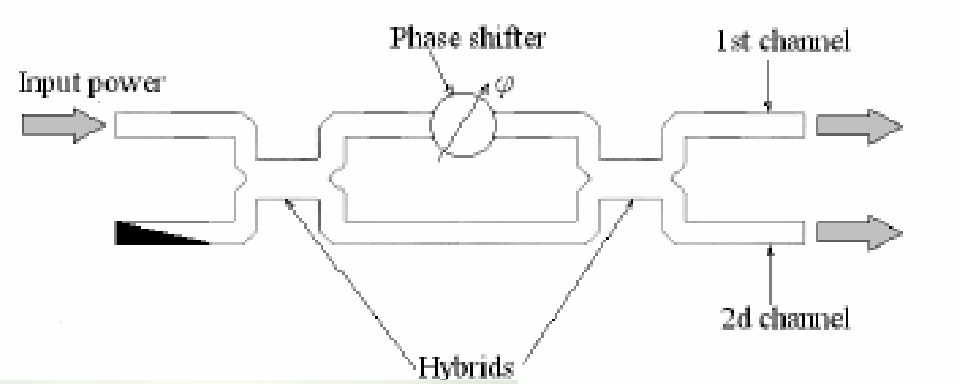
***New ferroelectric materials have been developed recently with excellent microwave properties**

A look at previous research

We would like to explore a structure that could also be used at lower frequencies.

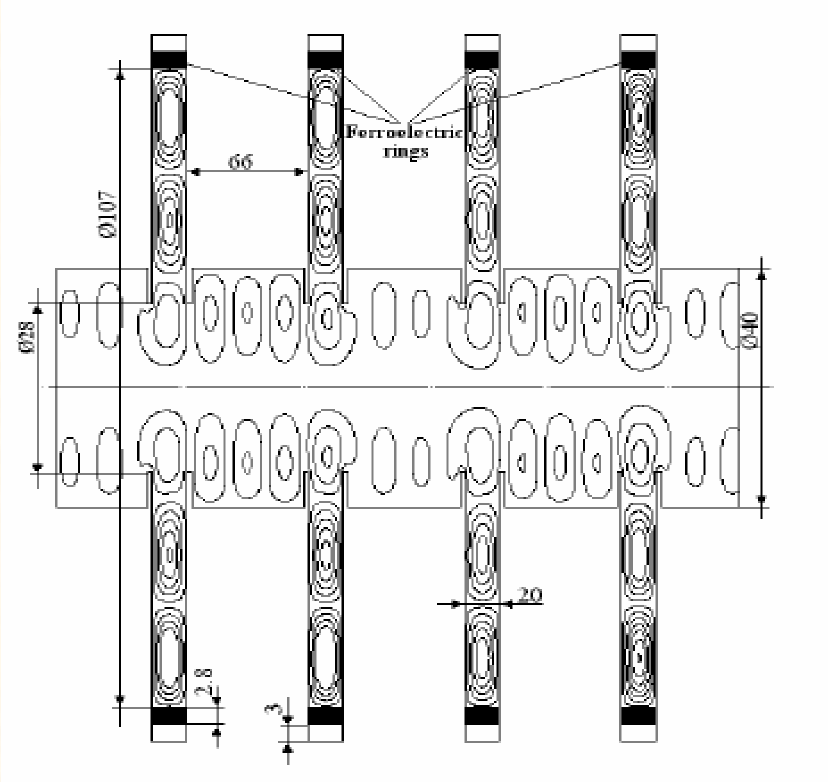
- Frequency: 11.424 GHz (X-Band)
- >96% efficient at 250 MW
- 200 degree phase shift, 100kV bias

- Uses 4 partially filled resonant cavities placed a quarter-wavelength apart.
- Cavities are partially loaded with BST ceramic.



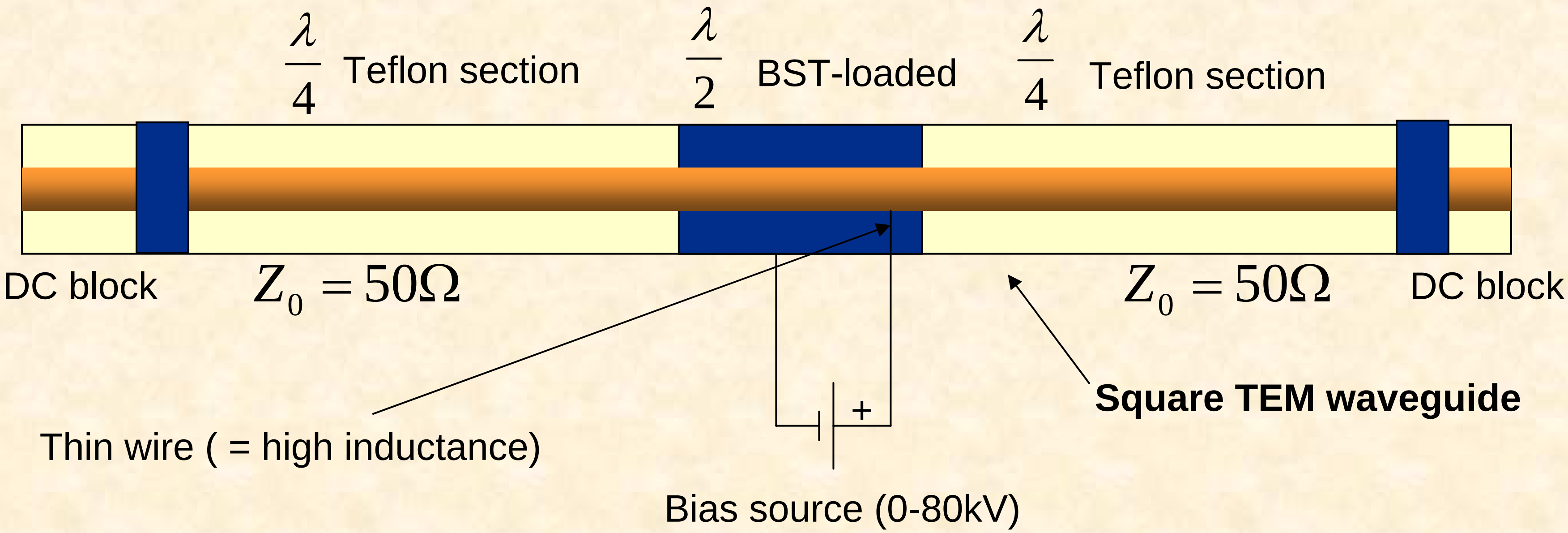
Architecture of RF switch

BST Ceramic
OD: 34 mm
ID: 20 mm
Thickness: 8mm



V.P. Yakovlev, O.A. Nezhevenko, and J.L. Hirshfield
11th Advanced Accelerator Concepts Workshop 2004.

New Ferroelectric Phase Shifter –Test Structure



$\frac{\lambda}{4}$ Teflon section

$\frac{\lambda}{2}$ BST-loaded

$\frac{\lambda}{4}$ Teflon section

DC block

$Z_0 = 50\Omega$

$Z_0 = 50\Omega$

DC block

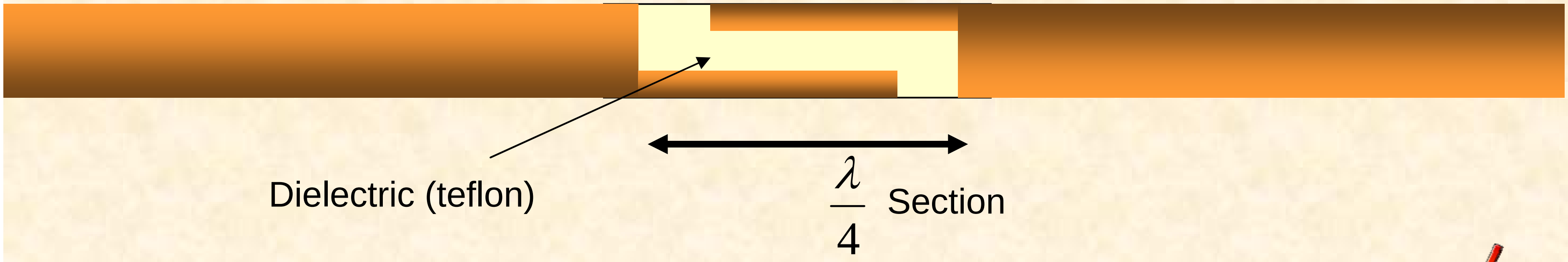
Square TEM waveguide

Thin wire (= high inductance)

+

Bias source (0-80kV)

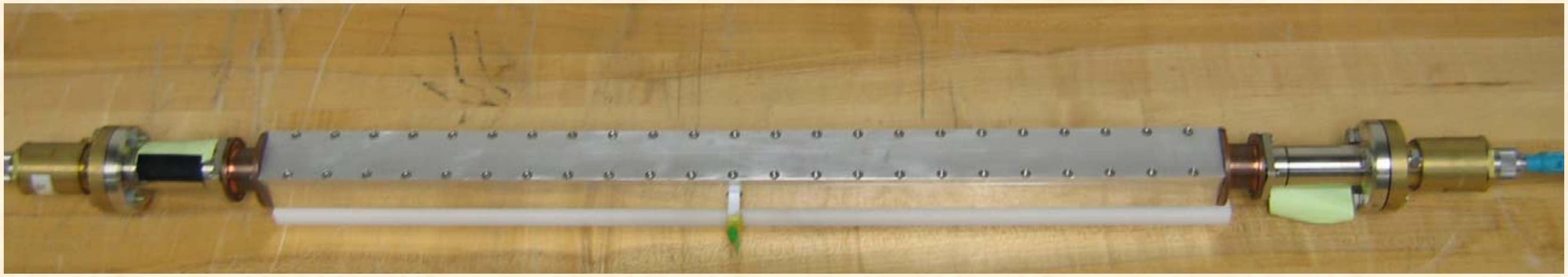
Coupled line DC block – also acts like 402.5 MHz filter!

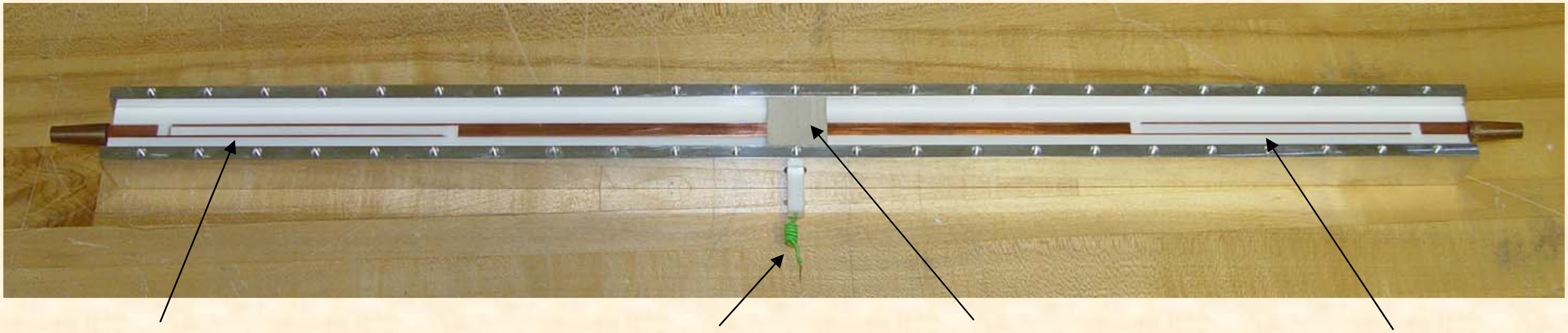


Dielectric (teflon)

$\frac{\lambda}{4}$ Section

Ferroelectric Phase Shifter Structure





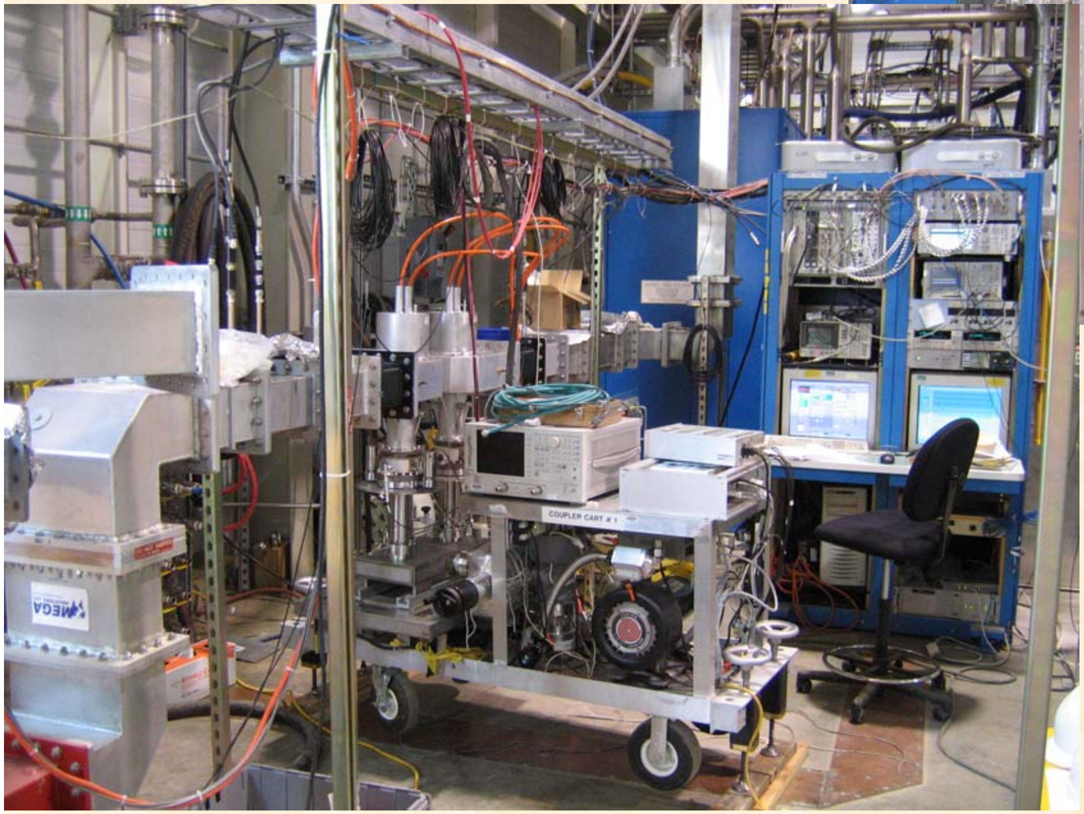
* A small 6 degree phase shift has been measured with a 2 kV biasing potential.
* An alumina matching section is being developed to improve performance by lowering insertion loss.

SNS RF Test Facility (RFTF)

- The prototype VM will be tested in the SNS RFTF
- RFTF has been used for various cavity power coupler RF conditioning
  - SNS SRF couplers were conditioned using a 550 kW, 805 MHz klystron
  - Presently a 5 MW klystron is being used for BNL SRF photoinjector couplers
- The two klystrons have been installed completely – April, 2006
  - 402.5 MHz, 2.5 MW peak, 1.3 msec, 8% DC
  - 805 MHz, 5 MW peak, 1.3 msec, 8% DC
- HV Converter Modulator
  - 10 MW capacity that can drive the SNS klystrons
- RFTF
  - The existing building is being reconfigured
  - Test cave is being equipped
- SRF facility
  - An additional SRF building is under construction – completion by Sep. 2007
  - Vertical and horizontal testing of SRF structures and more

RFTF

- Two klystrons installed and tested (402 MHz and 805 MHz)



- Coaxial couplers under RF processing (805 MHz)

Summary

- RF vector modulation and tuning methods
  - For fan-out RF power distribution
  - Elimination of circulators
- Development of phase shifters
  - Ferrite phase shifter
  - Ferroelectric phase shifter
- Prototype vector modulator being built
  - Hybrid coupled design
  - High power RF testing to be performed
  - Will demonstrate the ferrite phase shifter performance