The Development of the Electrically Controlled Silicon Switches for Active X-Band High Power RF Compression Systems

Jiquan Guo

SLAC National Accelerator Lab

Outline

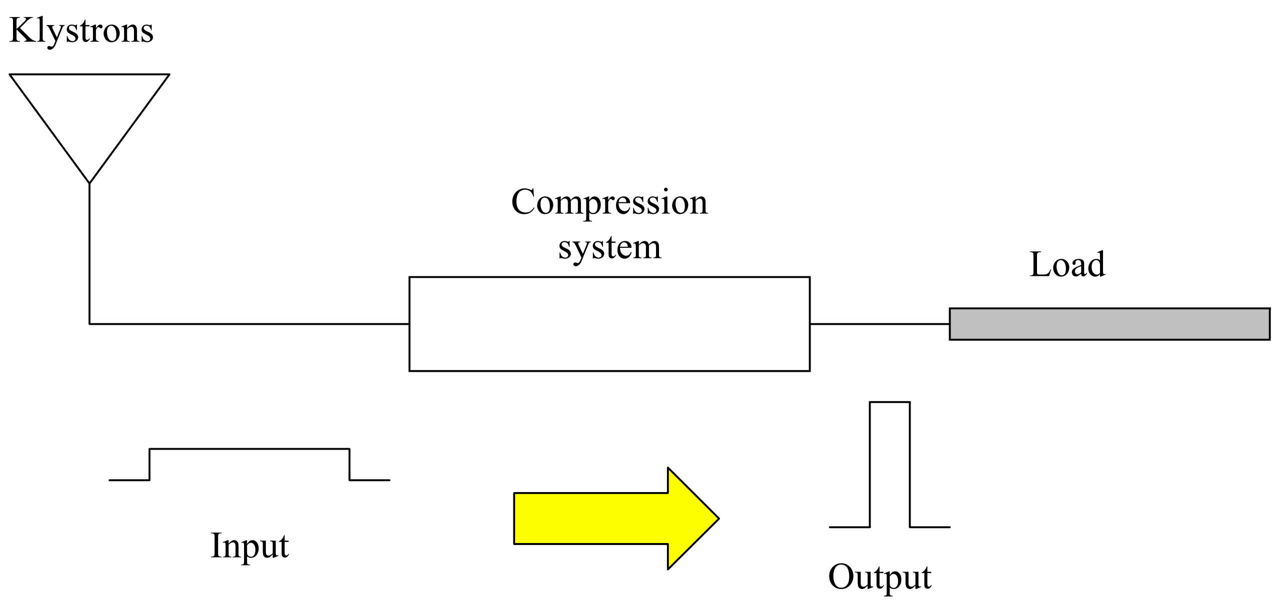
* Introduction
* RF pulse compression systems
* The switch module and the multiple-element switches
* Design and fabrication of the ultra-high power switch window
* Testing setup and results
* Conclusion

Introduction

- High Energy Linear Accelerators
  - Applications
  - Advantages
- Challenges:
  - High gradient and RF field
  - High RF power
- 3 design approaches
  - Super-conducting
  - Normal conducting w/ pulse compression
  - Normal conducting w/ two beam

	NLC Normal conducting	CLIC-G Normal conducting	ILC Super-conducting
CMS Energy	500 GeV	3 TeV	500 GeV
Repetition Rate (Hz)	120	50	5
RF Frequency (GHz)	11.424	12	1.3
Loaded Gradient (MV/m)	55	>100	31.5
Fill Time	104ns	62.9ns	596μs
RF Pulse Length	396ns	240.8ns	1.565ms
Klystron Pulse Length	3.168μs	139μs	1.565ms
Structure peak RF power (MW/m)	~100	295	~0.4
Active Two Linac Length (km)	~12	NA	~20

Function of the RF pulse compression systems



* A klystron operating at a very short pulse width will be inefficient and uneconomical. RF pulse compression systems are preferred to match the longer klystron output to the loads requiring shorter input.
* Application not limited to LINACs.

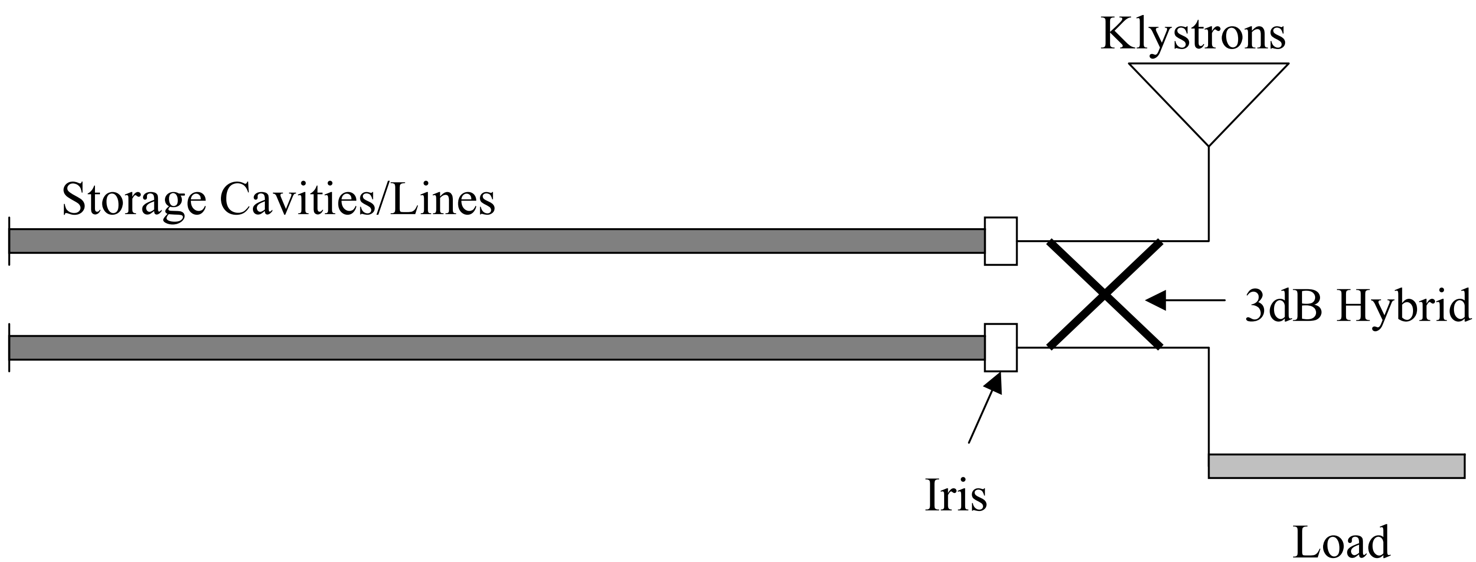
Outline

* Introduction
* RF pulse compression systems
* The switch module and the multiple-element switches
* Design and fabrication of the ultra-high power switch window
* Testing setup and results
* Conclusion

Different Types of RF Pulse Compression Systems

Type of Compression System	Size	Intrinsic Efficiency	High Compression Gain	
SLED	Compact	Low	Max=9	Wilson and Farkas, 1973
SLED-II (Resonant Delay line Compression System)	Compact	Low with high compression ratio	Max = 9	Wilson et al, 1990
BPC (Binary Pulse Compression System)	Needs long delay line	100%	Difficult	Farkas, 1986
DLDS (Delay line Distribution System)	Needs long delay line (shorter than BPC)	100%	Difficult	Mizuno, 1994
Active DLDS	Medium	100%	Possible	Tantawi, 1995
Active SLED-II	Compact	>81.5%	Easy	Tantawi, 1995

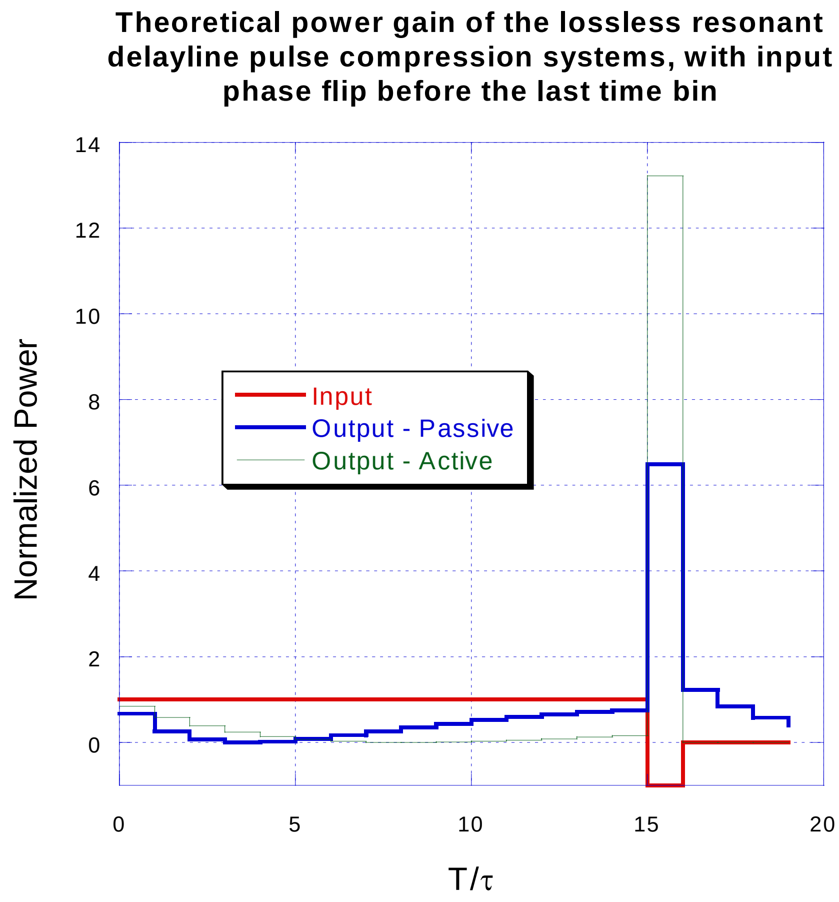
Resonant Delayline Pulse Compression System SLED-II



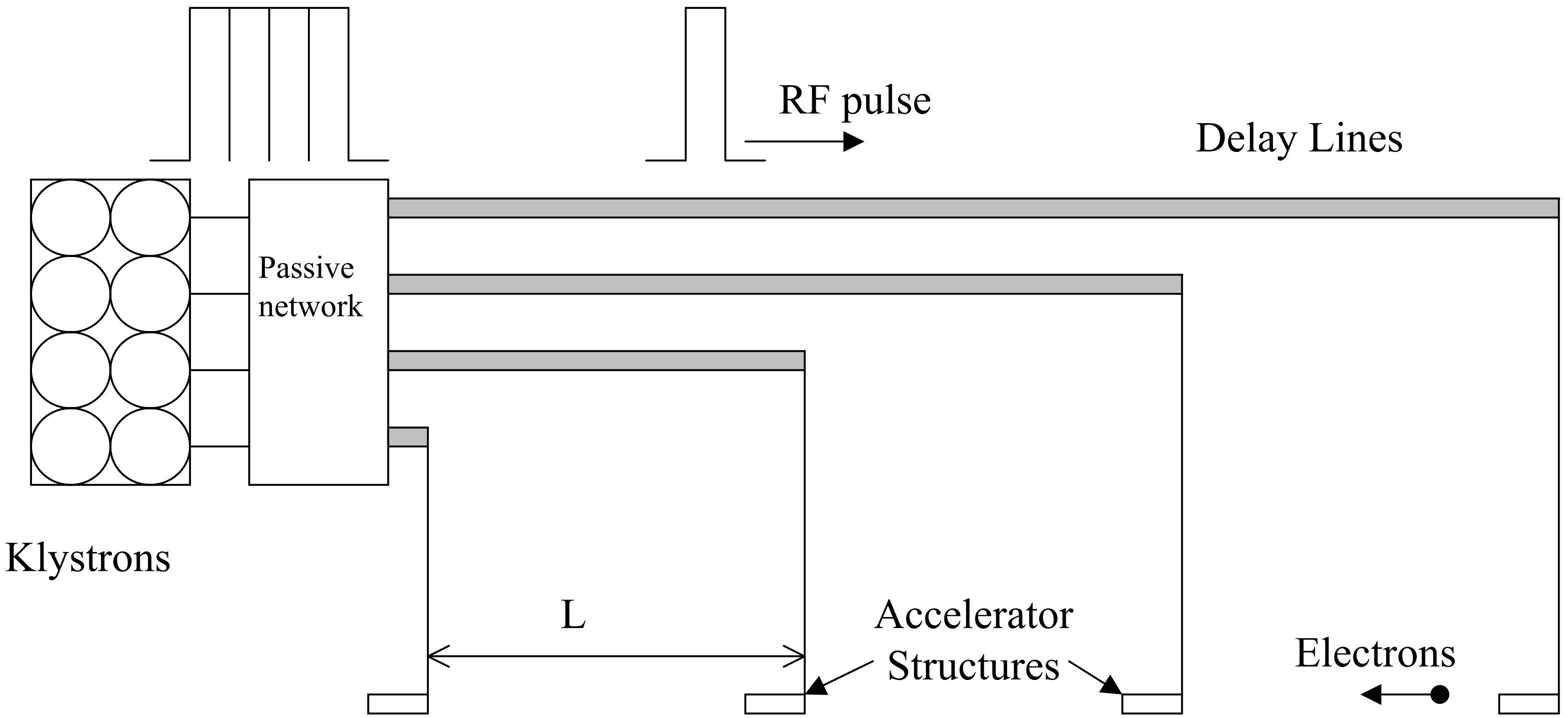
* Use over-moded delayline. Overcoupled for high compression ratio operation.
* In the charging phase, RF energy transmits through the iris and is accumulated in the delayline.
* In the discharging phase, the input RF can be turned off, getting a maximum output gain of 4. Or the input keeps on but with phase flipped, the maximum gain can be 9.

Active Resonant Delayline Pulse Compression System

* A passive SLED-II type system has low efficiency due to
  - RF emission during charging
  - The delayline can not be fully discharged
* An active SLED-II type compression system uses a switchable iris, which can change the transmission coefficient during discharging.
  - reduce emitted power during the charging.
  - fully discharge the delayline.

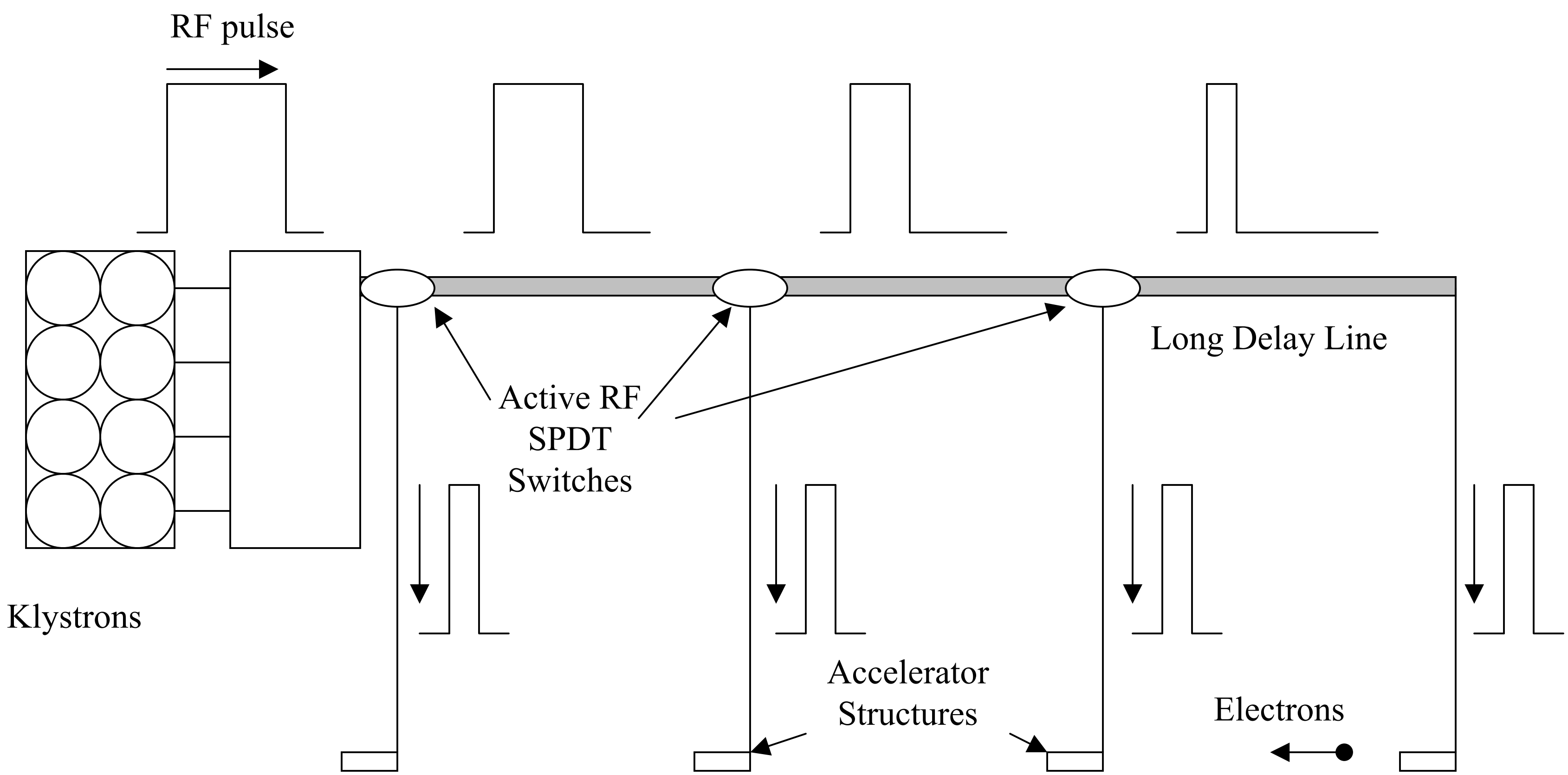


Passive DLDS



The particle beam provides about 1/2 of the delay

Active DLDS


RF pulse
Long Delay Line
Active RF
SPDT
Switches
Klystrons
Accelerator
Structures
Electrons

Outline

* Introduction
* RF pulse compression systems
* The switch module and the multiple-element switches
* Design and fabrication of the ultra-high power switch window
* Testing setup and results
* Conclusion

Possible choices of the high power RF switch

* Plasma switch: uses high voltage(100KV) to generate conducting plasma
* Ferroelectric switch: applies high voltage(100KV) to build the electric field and change the dielectric permittivity.
* Ferromagnetic switch: uses magnetic field and change the permeability.
* Semiconductor optical switch: uses a high power laser pulse to generate carriers and changes the conductivity
* Semiconductor electrical switch: uses PIN diodes to inject carriers

* We have chosen the silicon electrical switch.

Basic physics of the semiconductor active window

RF losses in a conductor

$$P_l = \left|H_{short}\right|^2 R_s = 4P_{in}\frac{R_s}{Z_g}$$

Surface resistance

$$R_s = \sqrt{\frac{\omega\mu}{2\sigma}}$$

Conductivity in a semiconductor

$$\sigma = e(\mu_n n + \mu_p p)$$

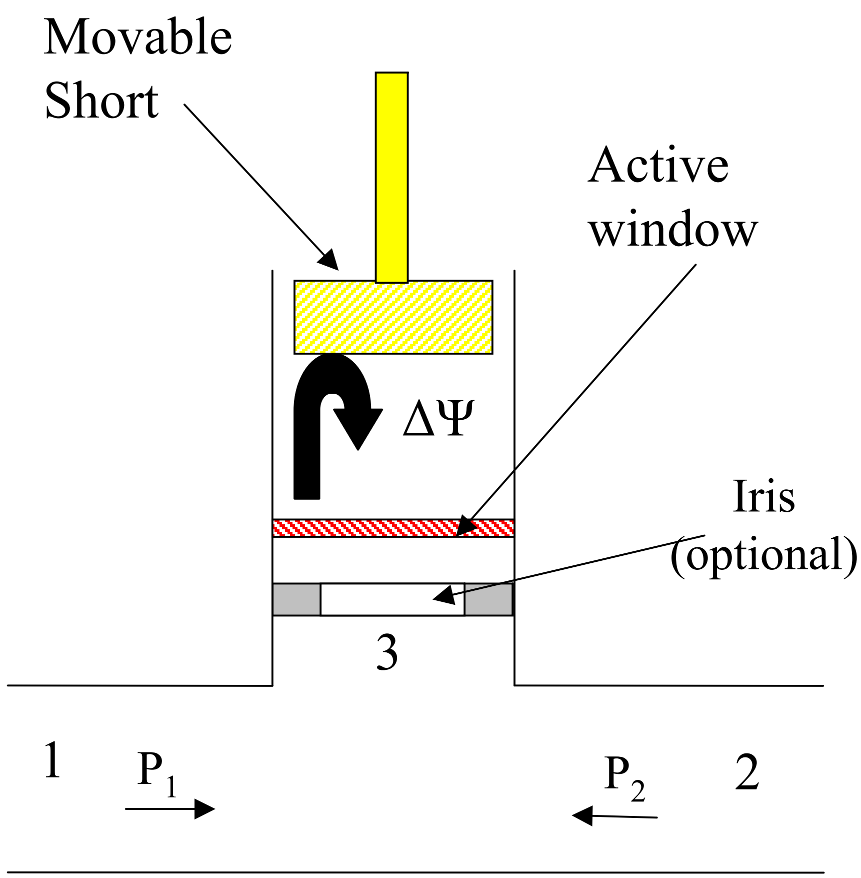
$$= 2e\mu_{eff} n$$

Skin depth

$$\delta_s = \sqrt{\frac{2}{\omega\mu\sigma}}$$

Design of the active switch module

* Switch the S-matrix of the two port network by changing the reflection phase in the 3rd arm
* The S-matrix of the *ON* state (when the active window becomes reflective) is tuned by changing the position of the active window .
* The S-matrix of the *OFF* state is tuned by the movable short.
* The *ON* state loss can be matched by the iris



Equivalent power handling capacity of the module

$$P_{in} = \left(\sqrt{P_1} + \sqrt{P_2}\right)^2$$

$$= \frac{AGL_{on}}{4R_s \sin^2(\psi_1 - \psi_0)} E_{max}^2$$

$$= \frac{GL_{on} Ne\mu_{eff}}{2\sin^2(\psi_1 - \psi_0)} E_{max}^2$$

E_{max}: Maximum *off* state E-field

G: Geometric factor, ~0.25

A: Waveguide cross-section area

μ_{eff}: Semiconductor effective mobility

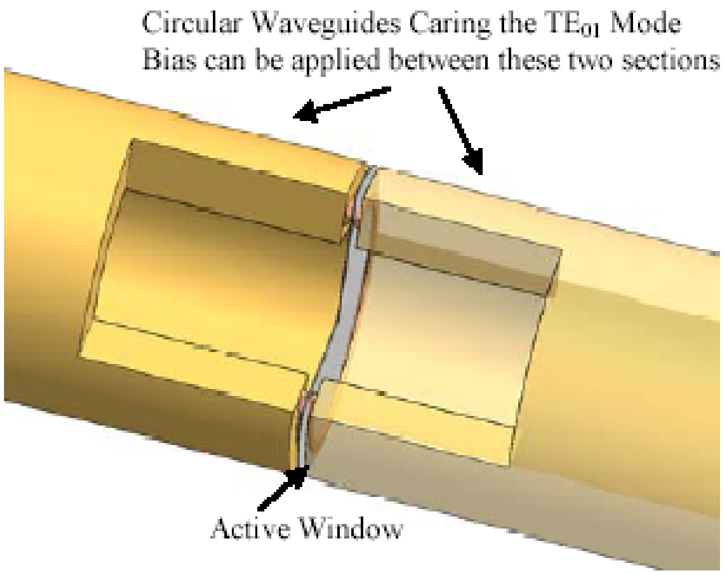
P_1 and P_2: Incoming power from port 1 and 2

Power handling capacity is determined by

* Material constants
  - E_{max}, μ_{eff}
  - System requirements
  - L_{on}: module *on* state loss
  - $\cos\psi_1$ and $\cos\psi_0$: Module reflection coefficients for on/off states
* Number of carrier pairs N (when the thickness of the carrier layer is optimized as 1 skin depth)

Independent of waveguide size and impedance, if the module's *on* state loss is matched to the system requirement

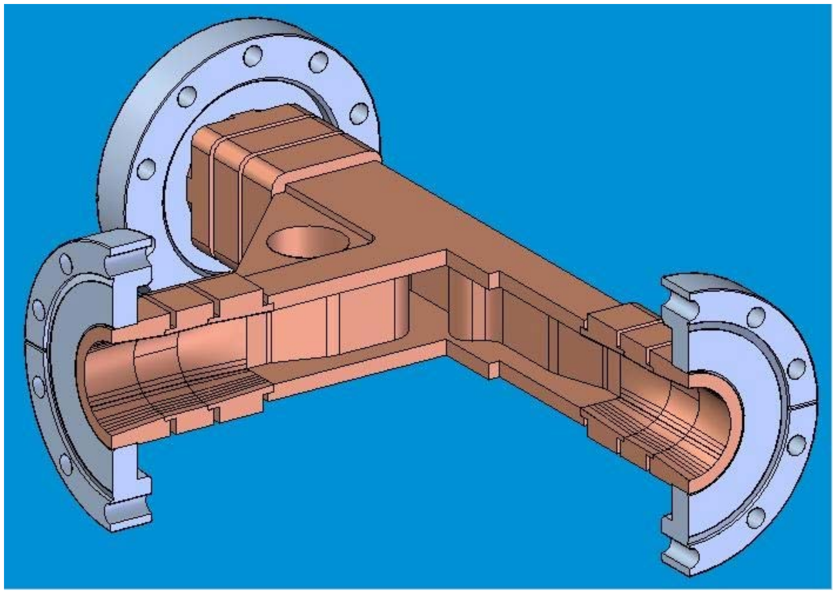
Active window in a Circular Waveguide

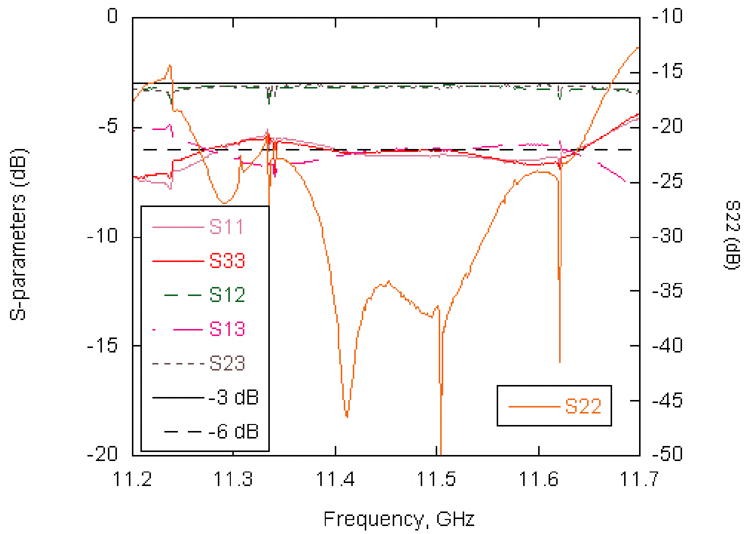


* Working under TE_{01} mode in a circular waveguide
* No radial electric field and no azimuthal magnetic field/axial current
  – Minimize RF leaking
* TE_{01} mode has lower attenuation (at high frequency) and lower field, common choice for X-band high power RF transmission

The Circular Waveguide Tee

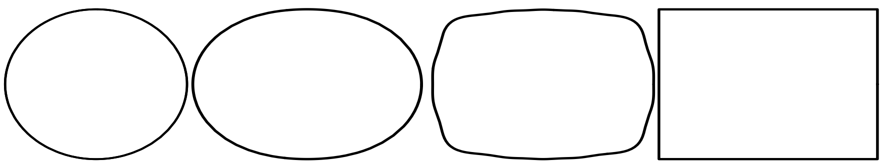
* Applications
* Constructed with one rectangular TE_{20} Tee and three circular TE_{01} to rectangular TE_{20} mode converters
* Novel, compact design, low loss

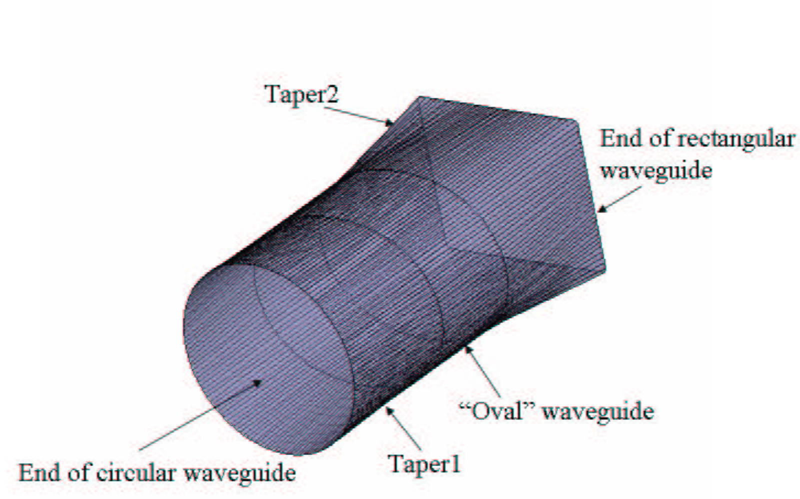




Circular-rectangular mode-converter

- Composed of three sections
  - Rectangular to oval taper
  - Oval section
  - Oval to circular taper
- Mechanism
  - Rec TE_{20} is excited into two modes M_1/M_2 through Taper2
  - Phase of M_1/M_2 adjusted in straight oval section
  - M_1/M_2 can excite cir TE_{21} and TE_{01} mode through Taper1; with proper phase, TE_{21} eliminated.
- Much smaller than conventional designs



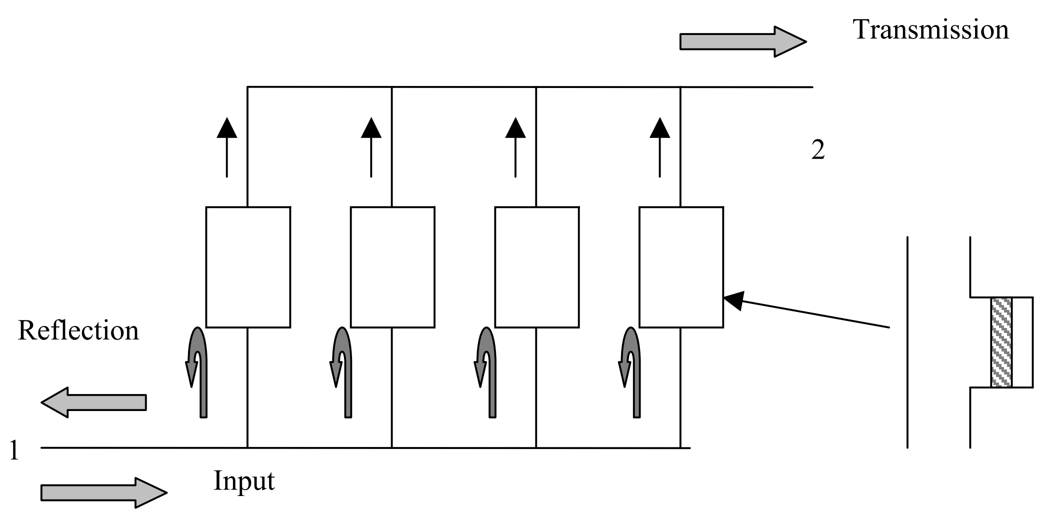


Multi-element Switch

* Combine several switches to provide higher power handling capacity
* Two options: parallel switch array, cascaded phase shifter
* Each option can compose a switchable iris or an SPDT switch

Parallel switch array:

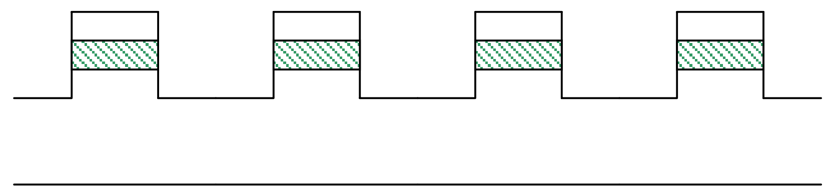
- Elements in parallel
- Power distributed and recombined
- S-parameter/loss same as single element



Cascaded phase shifter

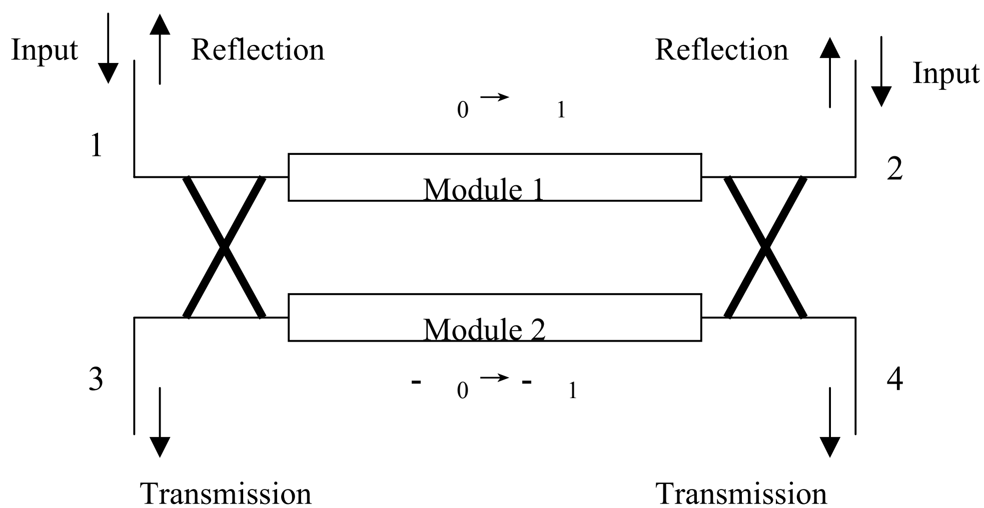
Phase shifter module:

- Elements in serial
- Each element provide small
- When the active window is off, the window is close to standing wave node with lower E-field



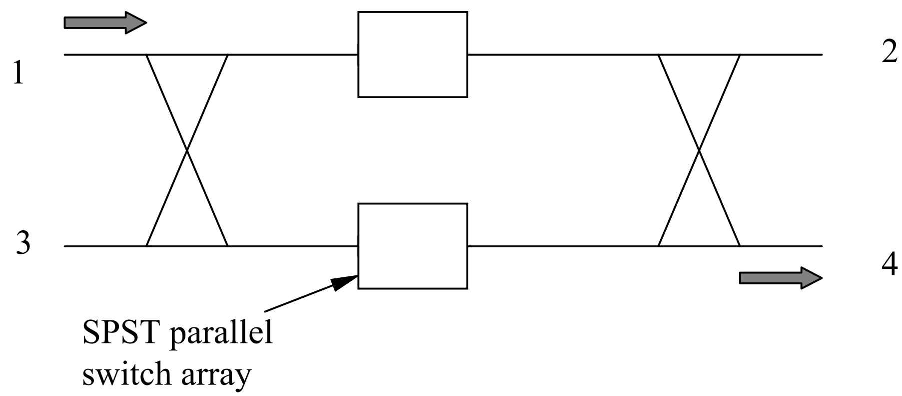
Switchable iris using phase shifter:

$$S = j\begin{pmatrix} \sin\psi & \cos\psi \\ \cos\psi & -\sin\psi \end{pmatrix}$$

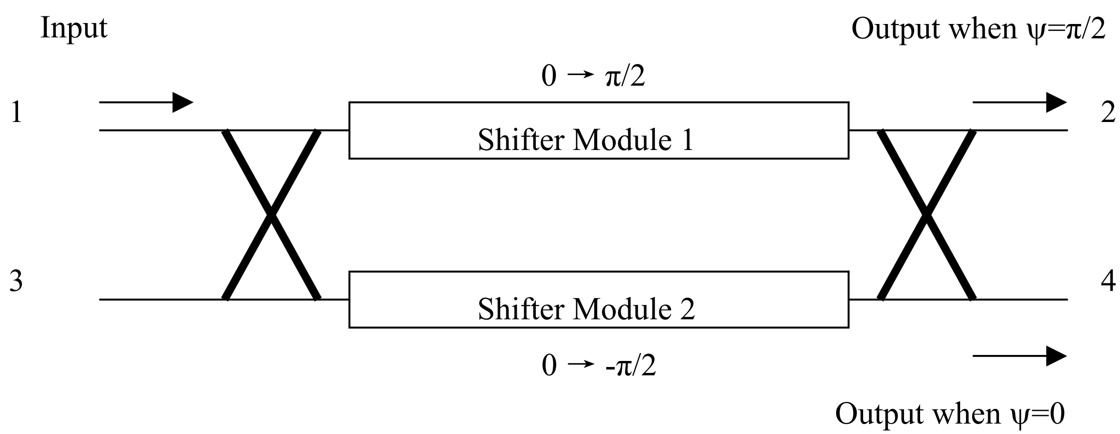


SPDT switches (for DLDS)

Using parallel switch array



Using cascaded phase shifter



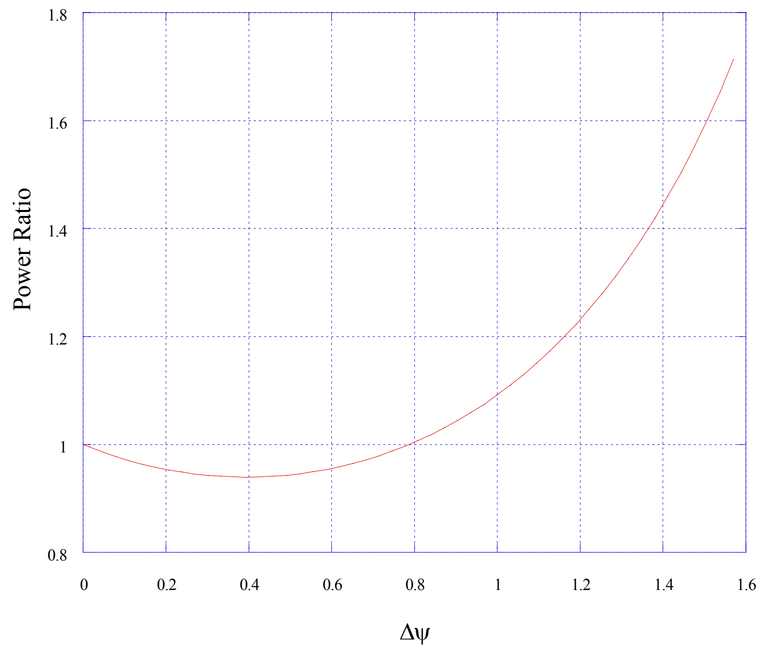
Scaling of the parallel switch array and the cascaded phase shifter

* Parallel switch array:

$$P_{sys} = nP_{ele}$$

* Cascaded phase shifter

$$P_{par}/P_{cas} = \frac{4(\psi_1 - \psi_0)^2 (1 + \frac{\pi}{\pi + \psi_1 - \psi_0})^2}{\sin^2(\psi_1 - \psi_0)}$$



Ratio between the power handling capacity of the parallel switch array and the cascaded phase shifter

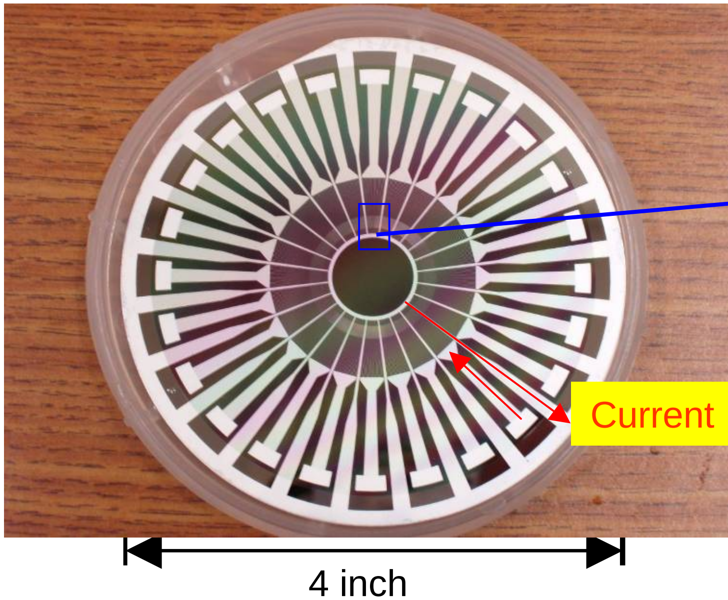
Outline

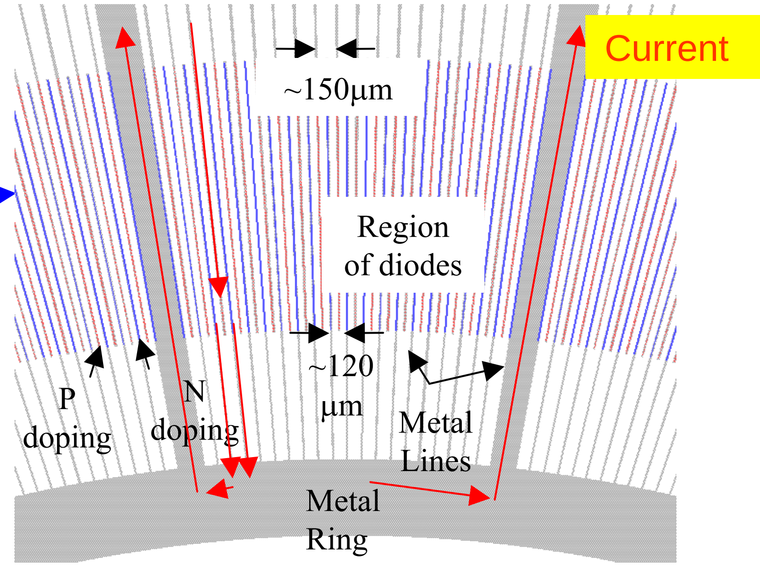
* Introduction
* RF pulse compression systems
* The switch module and the multiple-element switches
* Design and fabrication of the ultra-high power switch window
* Testing setup and results
* Conclusion

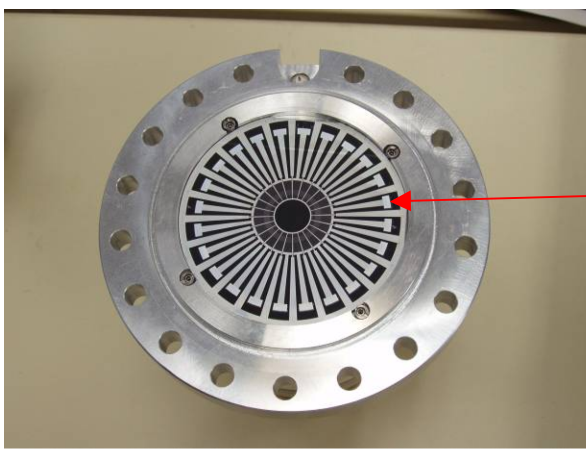
Design of the switch window

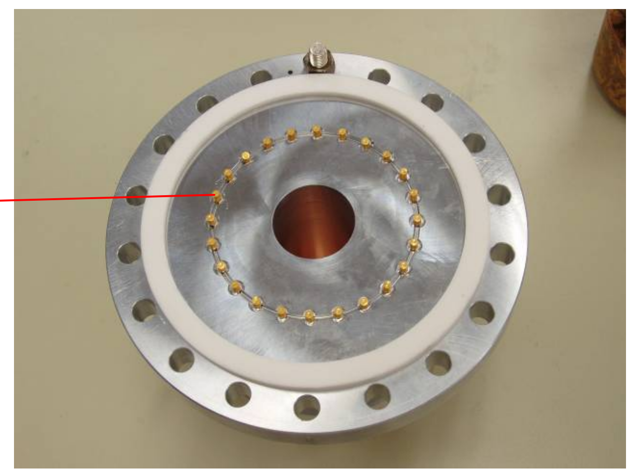
* Optimized at 11.424GHz
* Works in a 1.299 inch circular waveguide under TE_{01} mode
* Minimize the number of carriers required for switching
  - Close to cutoff, high Z_g (at the cost of power handling capacity)
  - Inject carriers into a ring where the field is the highest
  - The thickness of the carrier layer is 30-50μm
* Minimize the *OFF* state loss by using high purity silicon
  - Uses 90KΩcm resistivity silicon wafer, 525μm thick
* A metal ring on the window
  - Supplying bias
  - Reducing the amount of carriers required for switching
  - Eliminating reflection during the *OFF* state

The switch window and holder







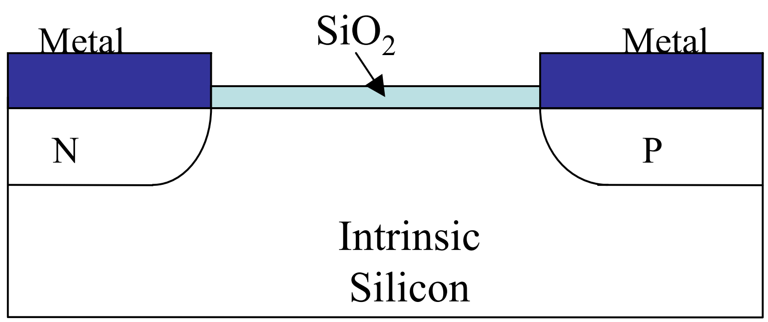


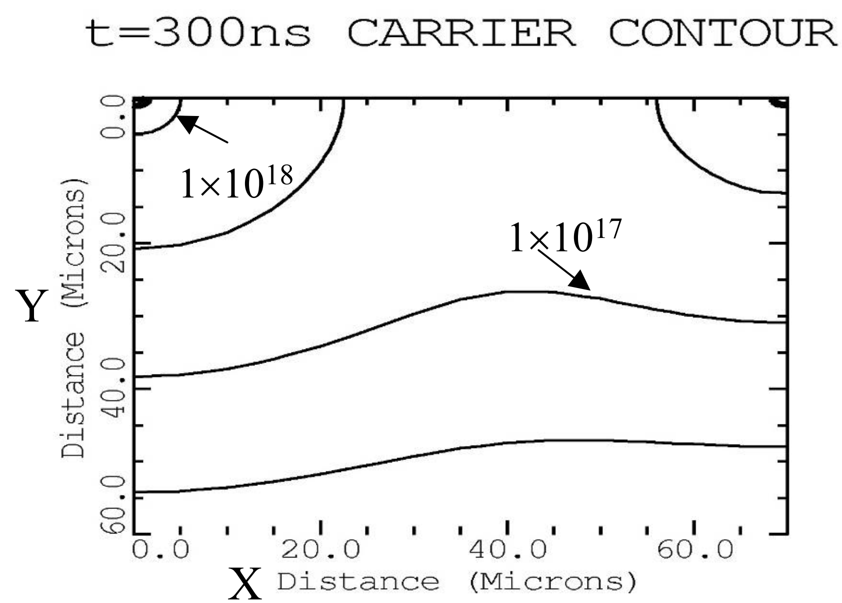
Simulated RF properties of the switch window

* *OFF* state:
  - S_{11} is close to 0.1
  - One-pass setup loss is about 0.1% in the 90KΩcm silicon and 0.6% in the aluminum ring
* *ON* state:
  - filled with carrier pairs at 1×10^{17}/cm3, 50μm in depth
  - The total number of carrier pairs is 8.8×10^{14}, with 140μC charge
  - S_{12} is close to 0.15
  - Loss is about 6.8%
* Estimated equivalent power handling capacity

Assumed Maximum E-Field (MV/m)	Estimated Power Handling Capacity (MW)
10	12
30	108

Design of the PIN diode





* Planar structure compatible with CMOS process
* Diodes length 60-75micron
  – Short diodes has better uniformity in carrier distribution
  – Simulated on time 200-300ns for PIN diodes driven by a 1KA driver with ~50ns rise time.
  – Simulated carrier layer thickness ~50μm

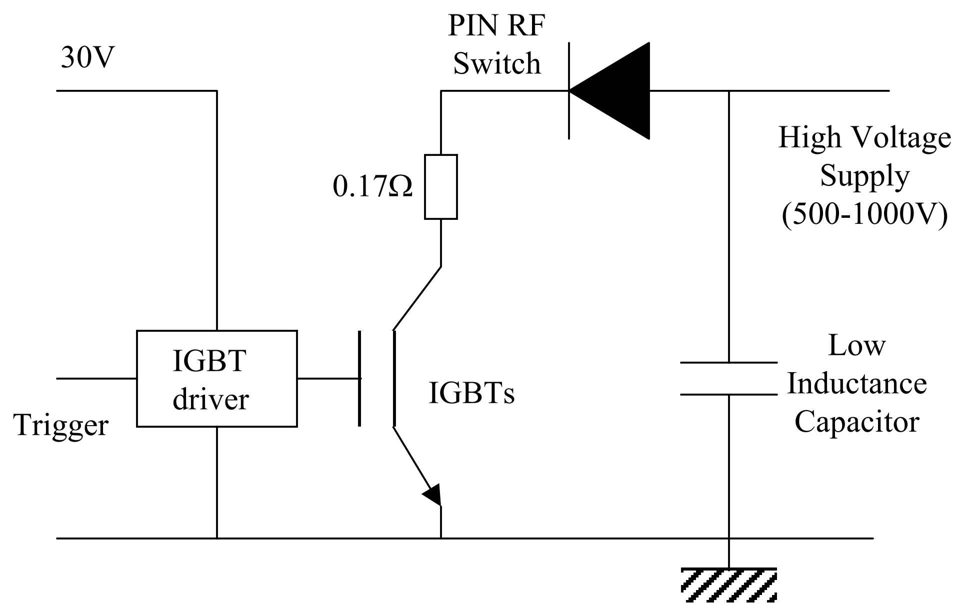
Fabrication of the diode array

- * Fabricated at Stanford Nanofabrication Facility
- * Using CMOS compatible technology
- * Process simulated with TSuprem, and the results are exported to the electrical simulation with Medici
- * Several rounds of revisions

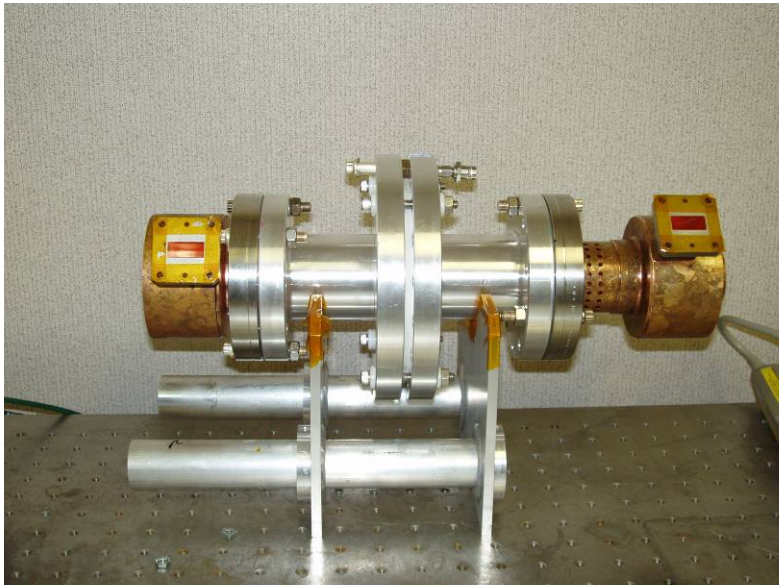
Outline

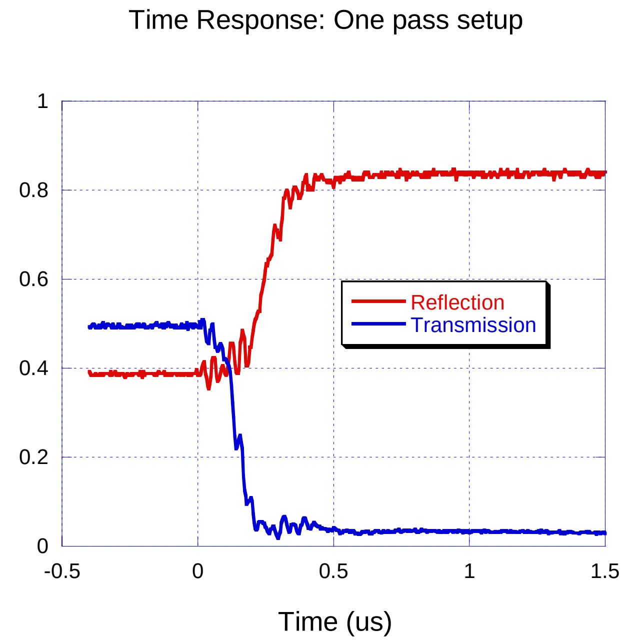
* Introduction
* RF pulse compression systems
* The switch module and the multiple-element switches
* Design and fabrication of the ultra-high power switch window
* Testing setup and results
* Conclusion

Driver circuit



One Pass Test





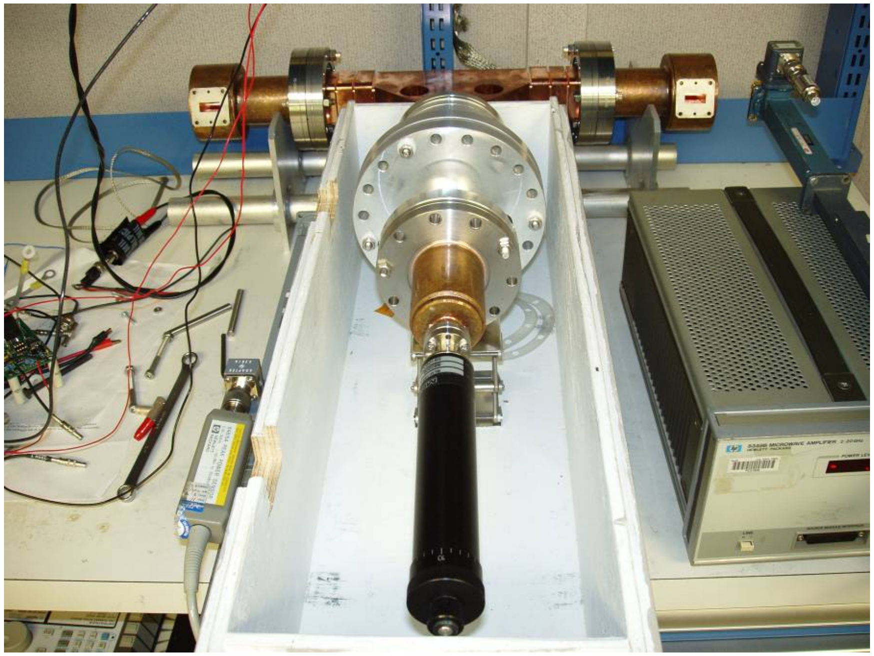
NWA measurement for *off* state:

- S_{12}=0.939,
- S_{11}=0.267,
- loss~4.7% (2.3% on silicon window)

Switching test:

- Driver current ~1KA
- Switch time 200-300ns
- *On* state loss ~10%

Switch Module Setup with the Circular Tee

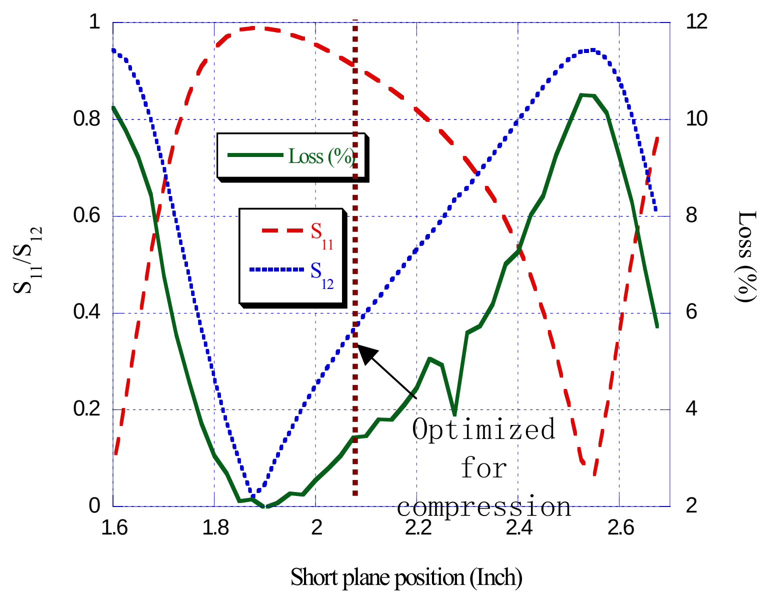


- Connect 3rd port of the Tee with active window and a movable short
- On state S-parameters adjusted by adding spacers between the window and Tee.
- Off state S-parameters scanned with short plane at different, different scans were made with different spacers between the window and Tee.

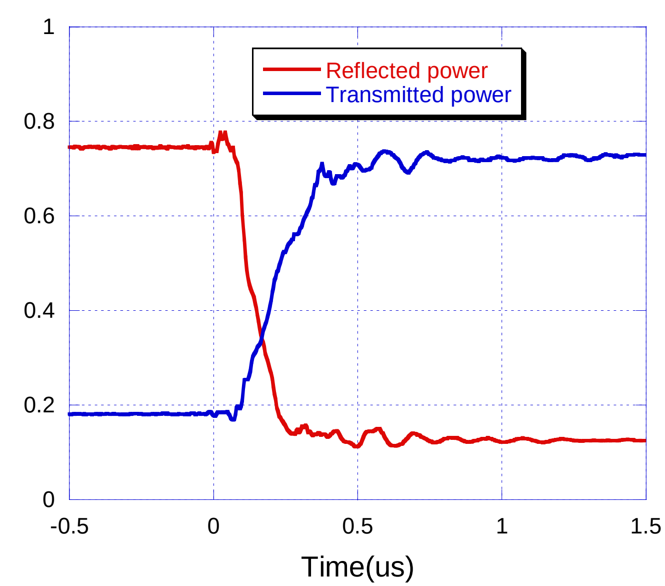
Switch module test results

* Off state S-parameters were scanned with short plane at different locations
* In the active switching, S-parameters during on/off states were tuned close to values optimized for active compression
  – Switch time 200-300ns

S-parameters/losses vs. short location

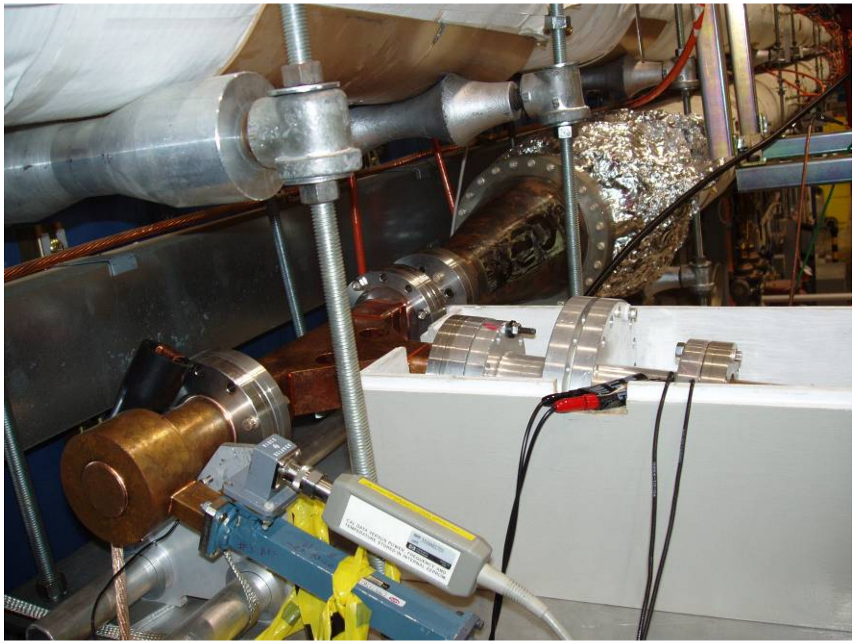


Time Response: Switch Module



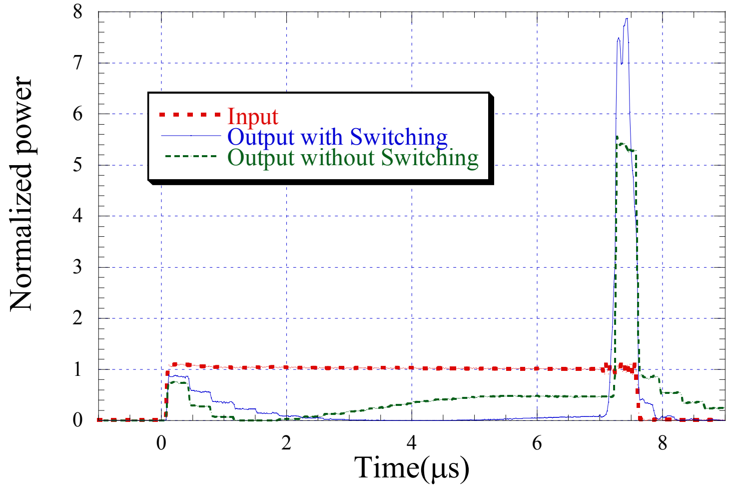
Active compression experiment

* Connect the switch module to a 375ns overmoded delay line
* Low power RF input, pulse width ~20 times delay time
* Two experiments carried out:
  – Window switched and input phase flip before the last time bin (375ns before the end)
  – Window switched at the end of input pulse without phase flip.
* Driver current ~1.5KA

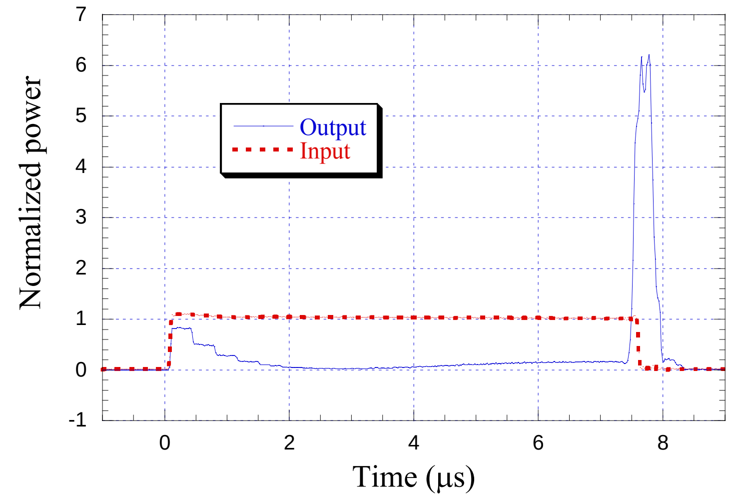


Active compression experiment results

with input phase flip



without input phase flip



* With phase flip, 8 times gain observed. Improvement over passive compression,
* Without phase flip, 6 times gain recorded. Impossible for passive systems.

Conclusion

* Active Window
  - The S Matrix for both the *on* and *off* states of the active window are close to the desired value. 200-300ns switch time has been achieved with ~10% loss.
  - The switch module has successfully performed the function of tuning the S-matrix of both *on* and *off* states.
* Related RF components
  - Active window holder
  - Circular waveguide Tee and circular-rectangular modeconverter
* Active pulse compression system
  - 8 times gain has been recorded, improvement against passive.
  - 6 times gain in the case that input phase cannot be flipped, possible to use magnetron as the RF source, which is impossible for passive systems
* Possible improvements:
  - Faster switching: higher driver current; laser; reversed bias
  - Lower *off* state loss

Acknowledgements