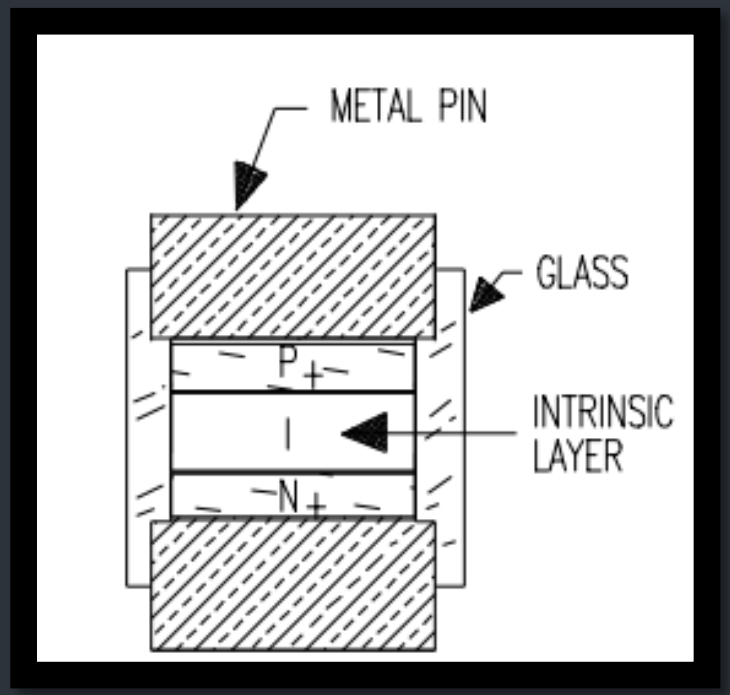
A Whirlwind Tour of PIN Diodes

Nick Cardamone – Fall 2023 – Nonlinear Microwave Devices

(and Circuit Theory 1 Tutorial)

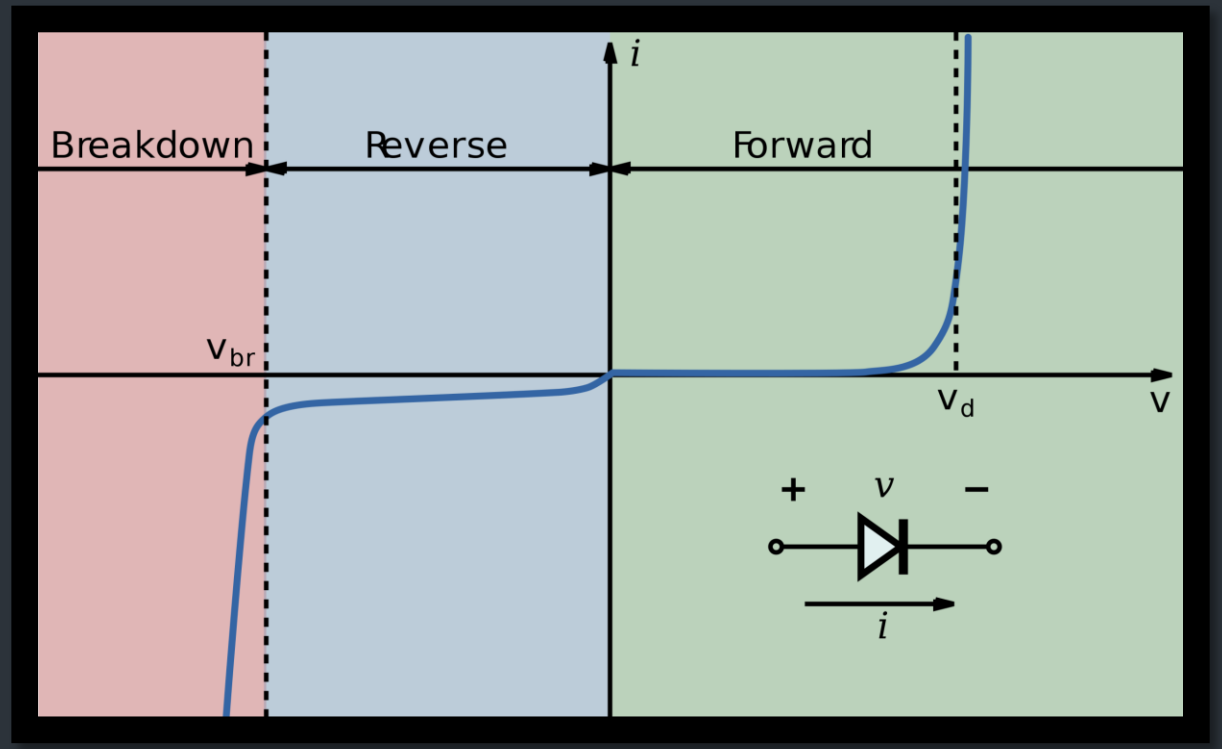
Overview – Applications of PIN Diodes

- What is a diode?
- Diode Models – DC/ Low Frequency, High Frequency
- PIN Diode Overview + Model
- PIN Diode Switches
- PIN Diode Attenuators
- PIN Diode Modulators
- PIN Diode Phase Shifters
- PIN Diode Detectors



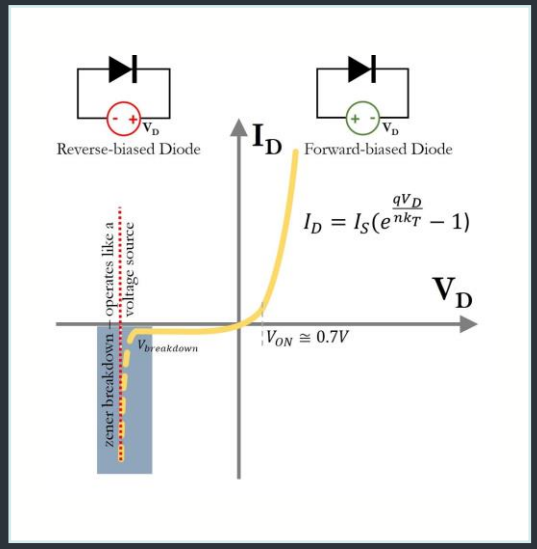
What is a Diode?

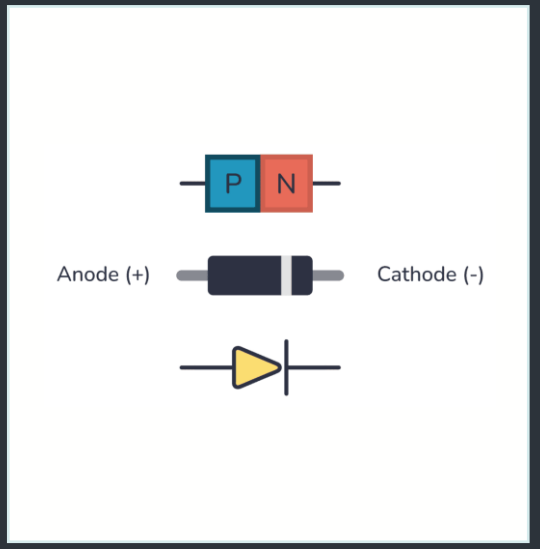
- 2 Terminal Non-Linear Device
- Only allows DC current to flow in 1 direction
- Symbol looks similar to an arrow
- The current is supposed to flow in the direction of the arrow

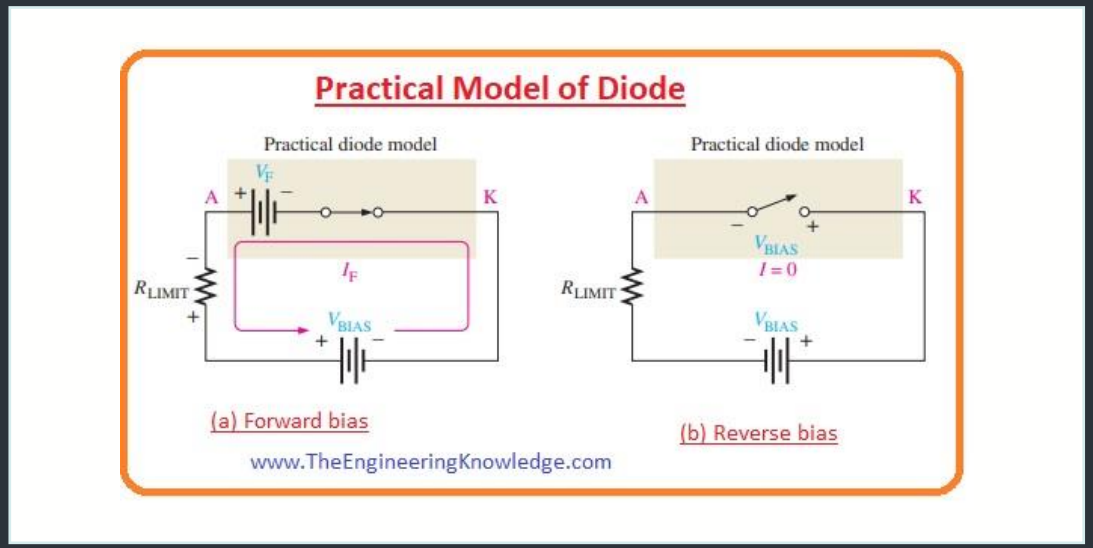


Diode Modeling (Low Frequency/ DC)

- A Diode acts like a voltage controlled switch
- If the DC voltage supplied to the diode is sufficiently positive the diode acts as a short circuit (forward bias)
- If the DC voltage supplied to the diode is negative the diode acts like an open circuit (reverse bias)
- The DV voltage supplied to the diode is called the bias voltage
- In forward bias, the DC voltage across the diode will be constant regardless of the current

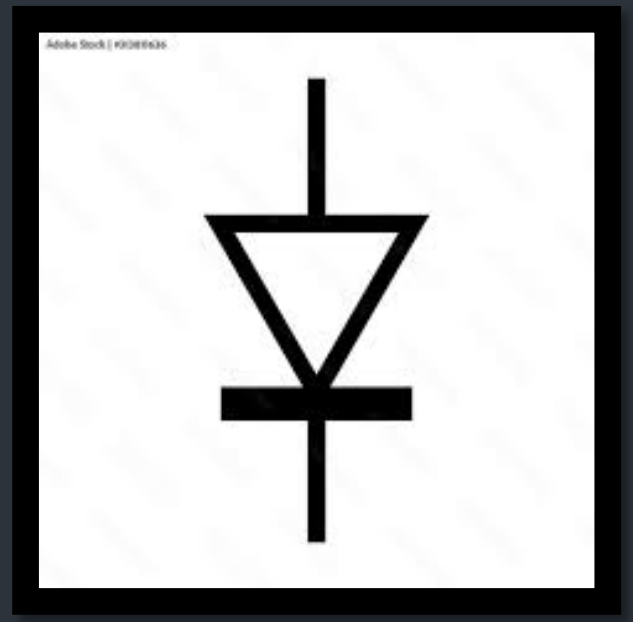


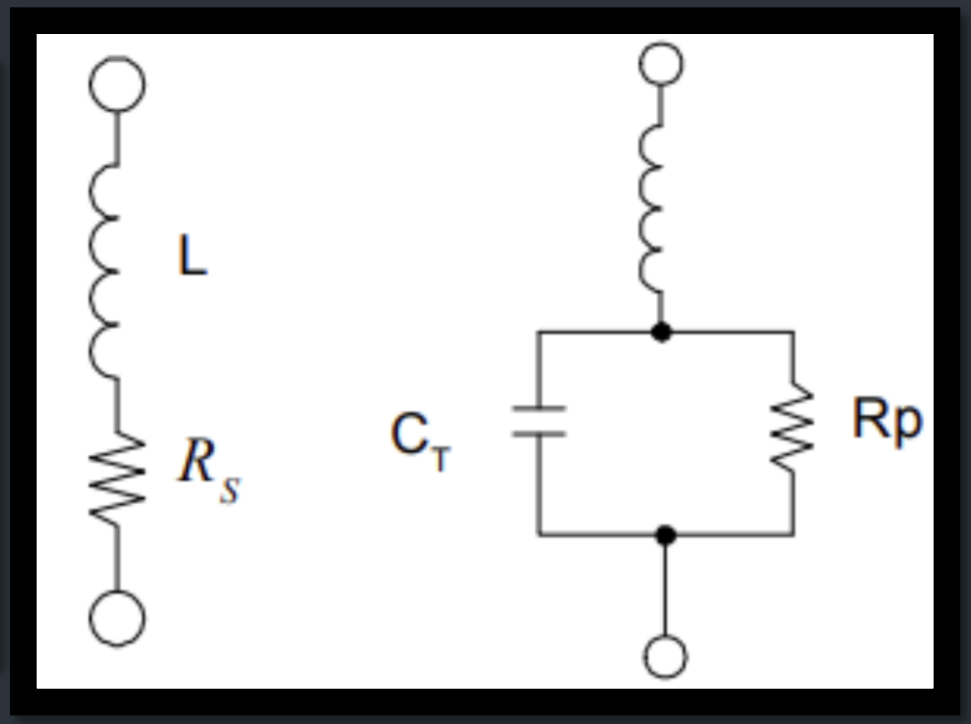




Diode Modeling (High Frequency)

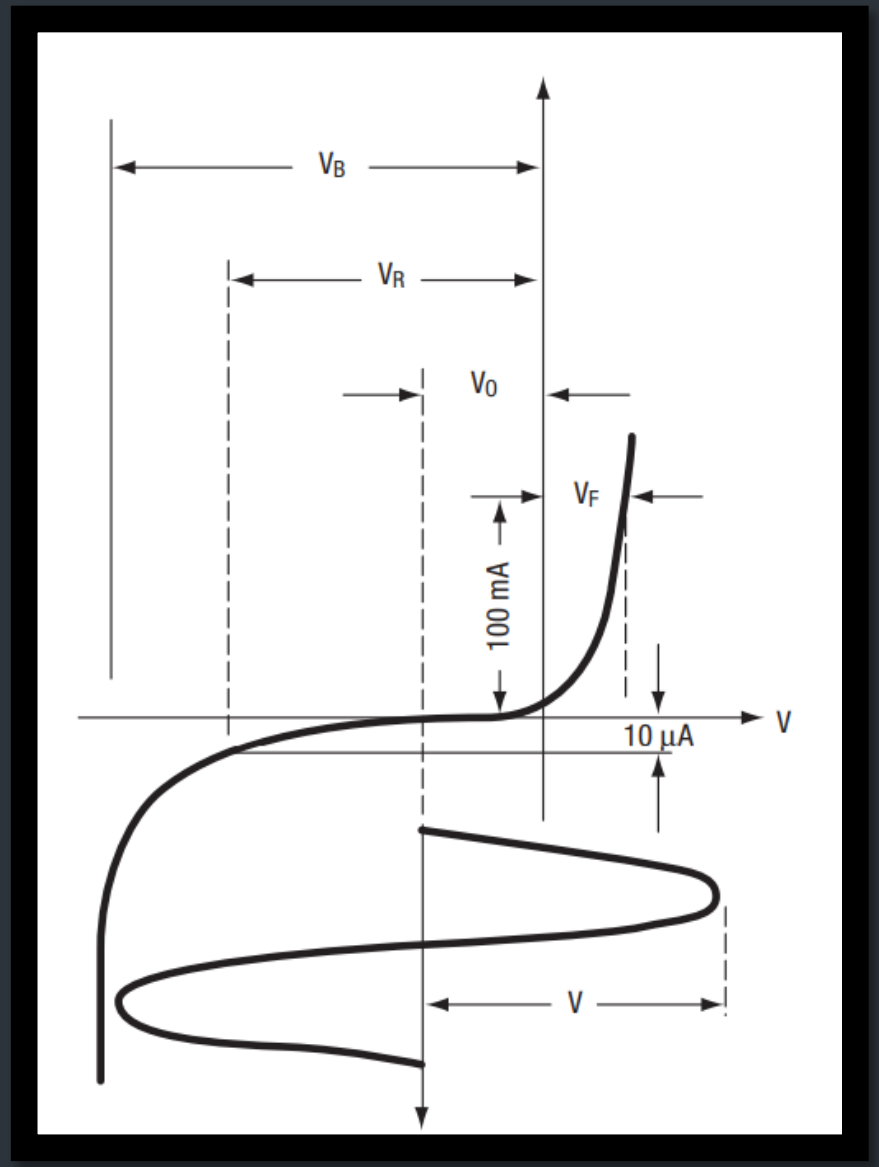
- When the diode is forward biased, it acts like a series inductor and resistor
- When the diode is in reverse bias, it acts like a parallel resistor and capacitor (similar to a varactor)





PIN Diodes

- An Intrinsic layer is inserted in between the P and N regions of a typical diode
- That intrinsic layer is lightly doped or not doped at all
- This allows the junction to store extra charge which increases the reverse recovery time of the diode significantly
- This means that the diode can conduct in both directions provided the stored charge is not depleted
  - i.e. either the frequency needs to be high enough or there need to be enough bias current



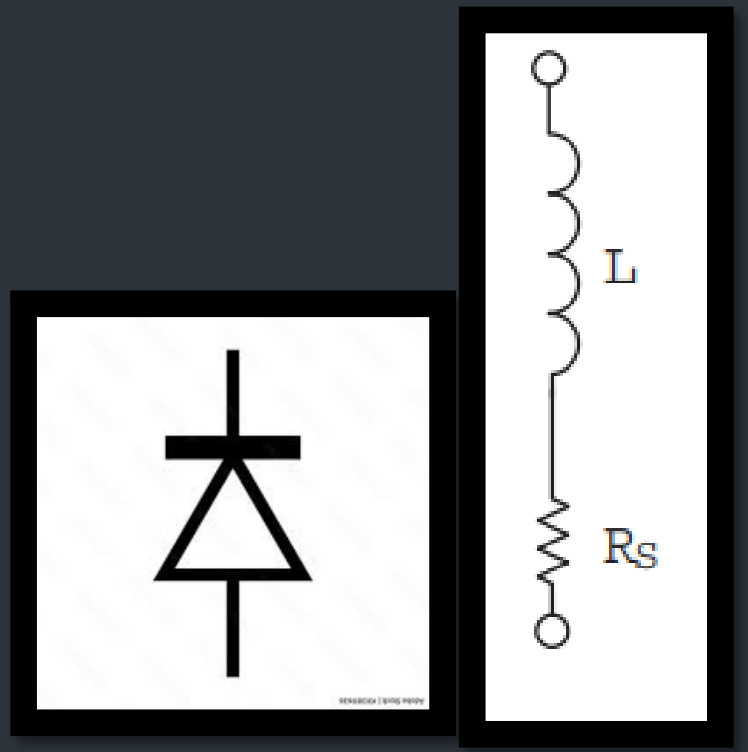
PIN Diode Forward Bias

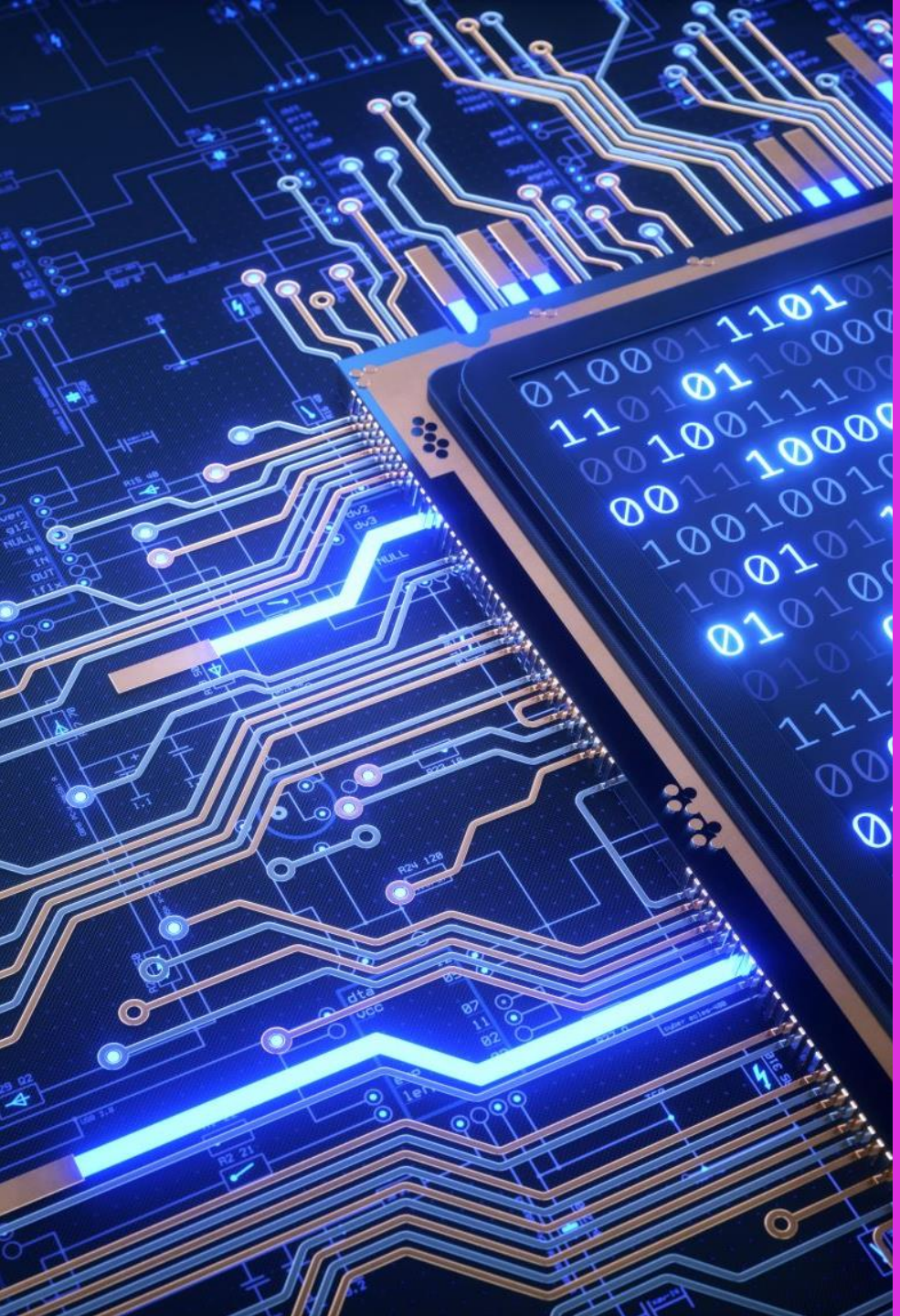
The PIN diode acts as a current controlled resistor in forward bias
Also acts like a voltage controlled capacitor in reverse bias

$$R_s = \frac{W^2}{(\mu_n + \mu_p)Q} = \frac{W^2}{(\mu_n + \mu_p)\tau I_{fwd}}, for\ f > \frac{1300}{W^2}$$

Where:

- R_s is the series resistance of the PIN diode (Ω)
- W is the width of the intrinsic region (μm)
- f is the frequency of operation (MHz)
- τ is the carrier lifetime
- μ_n is the electron mobility
- μ_p is the hole mobility



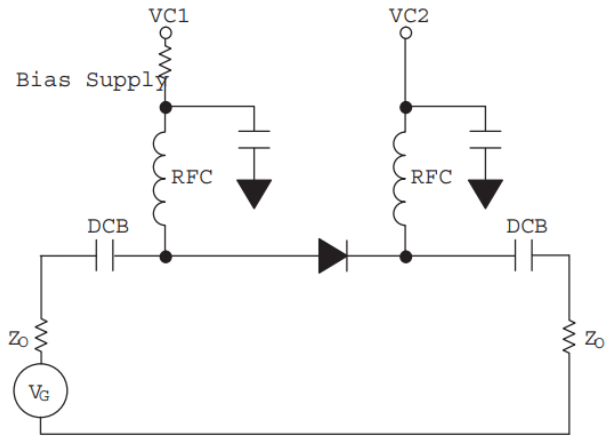


PIN Diode Applications

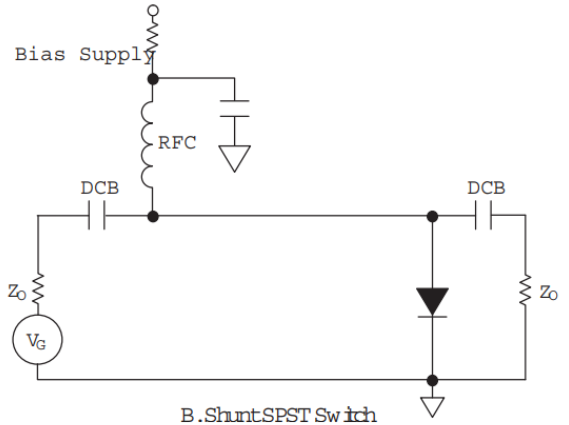
- RF (High Frequency) Switches – great for switching large RF powers with small bias currents
- Variable Attenuators (variable voltage dividers – controlled by bias current)
- Modulators
- Phase Shifters
- Optical Detectors (used in fiber communication systems)

PIN Diode Switches

- Diodes can either be used in series or in parallel (shunt)
- These type of switches either transmit the signal or reflect it back
- Isolation is a problem with series switches



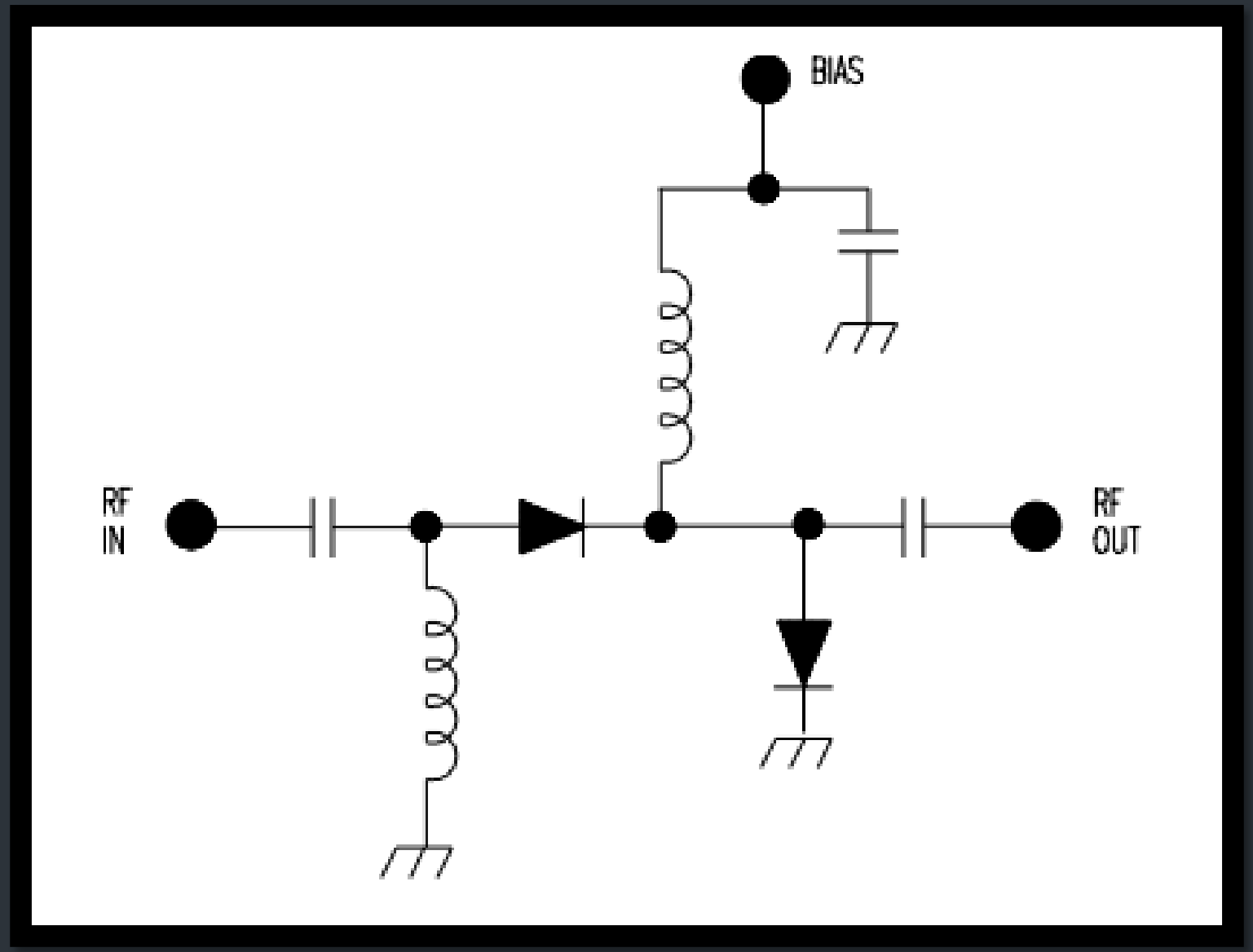
A. Series SPST Switch



B. Shunt SPST Switch

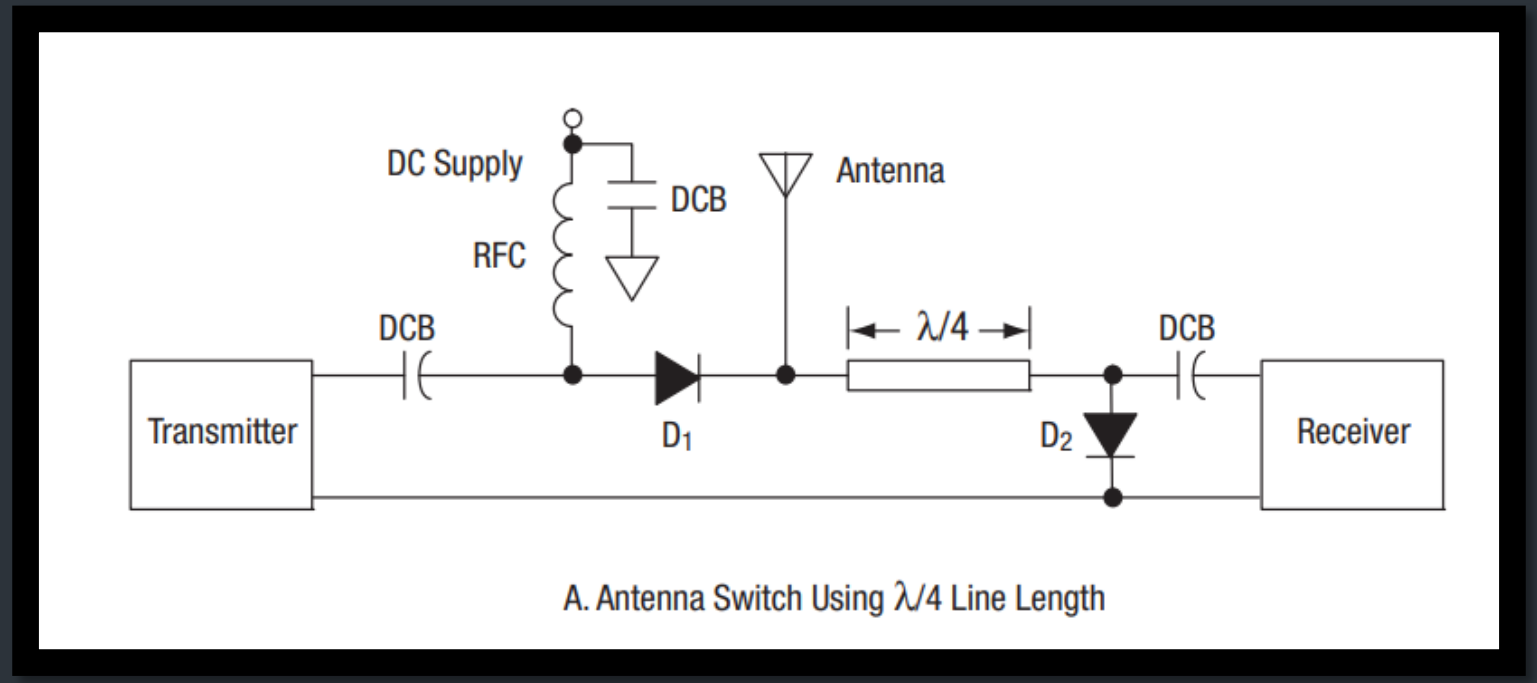
Compound Switches

- Multiple diodes can be used to improve the isolation



PIN Diode TX/ RX Switch Example

- Single pole double throw
- Quarter wave transformer is used to do impedance transformation



A. Antenna Switch Using λ/4 Line Length

High Frequency Switch Example

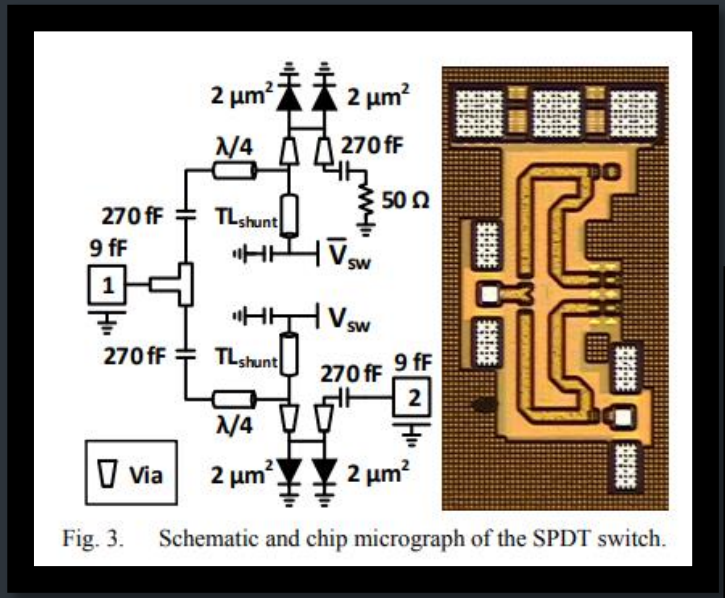
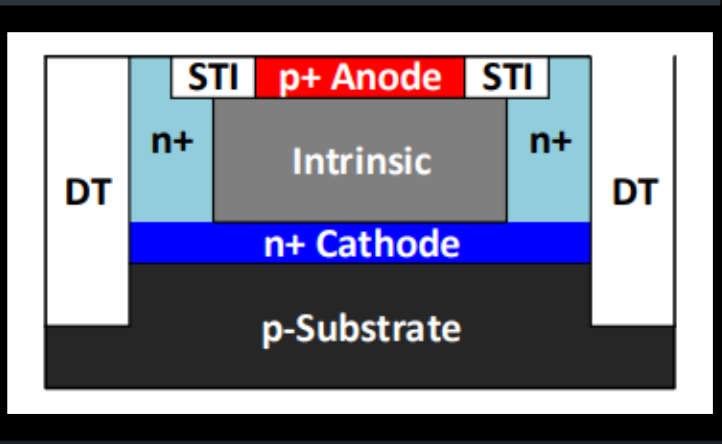


Fig. 3. Schematic and chip micrograph of the SPDT switch.

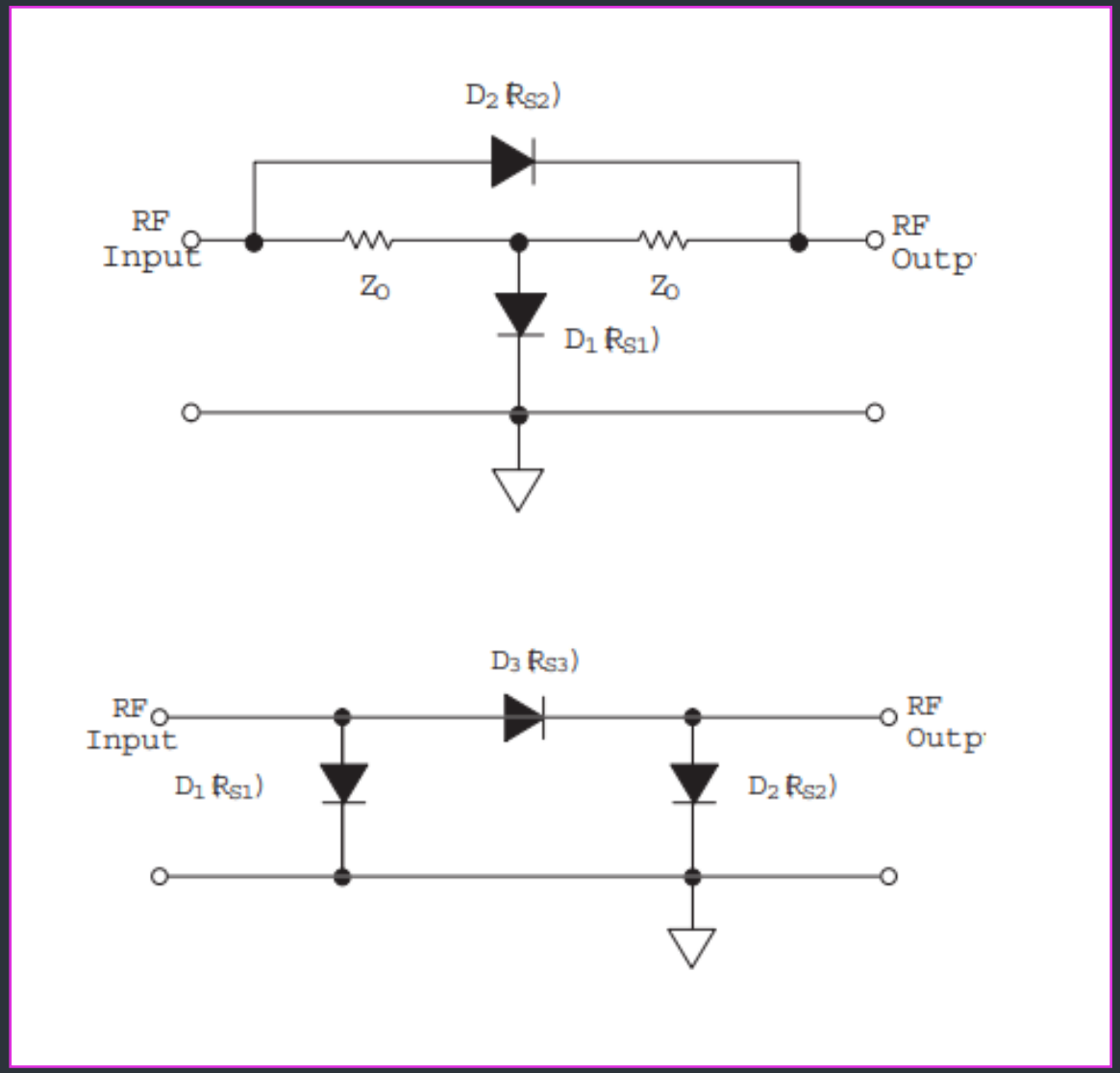


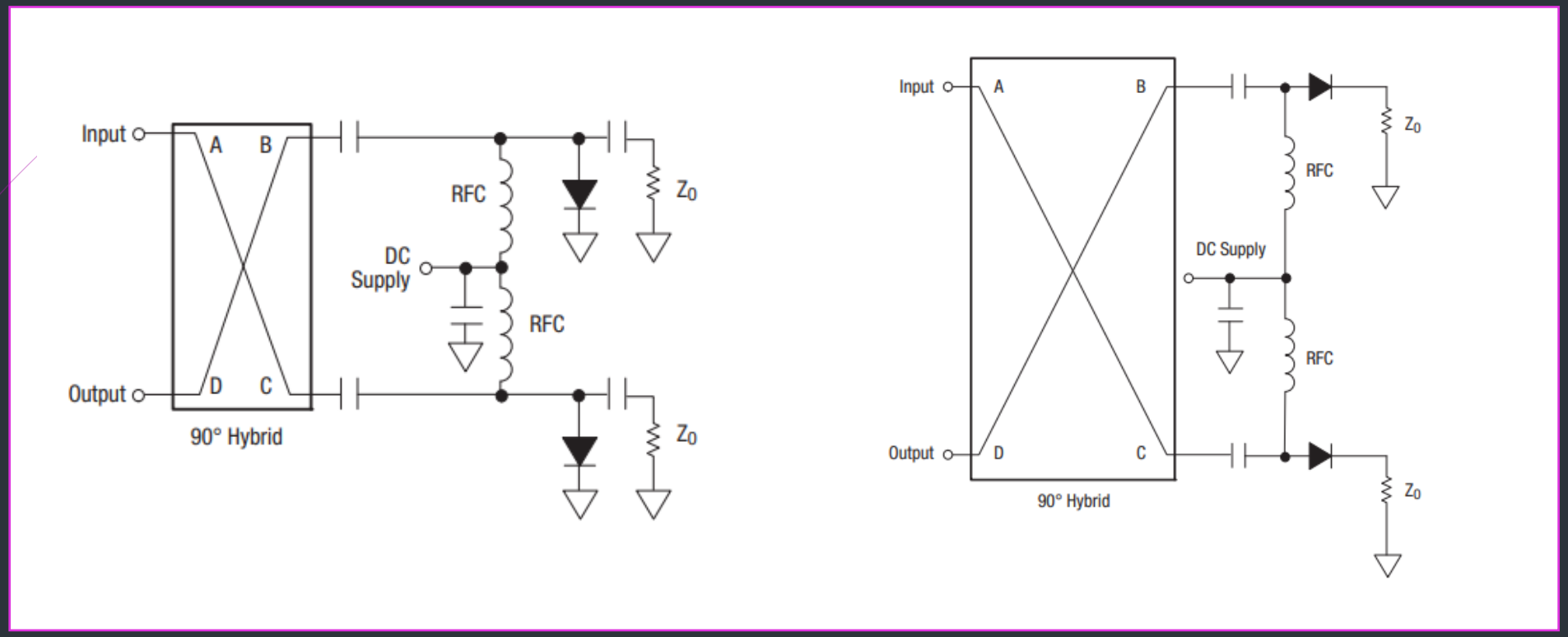
Reference	[5]	[6]	[7]	[8]	**This Work**
Technology	GaAs	130nm SiGe	130nm SiGe	90nm SiGe	**90nm SiGe**
Device	PIN	nMOS	PIN	HBT	**PIN**
Topology	λ/4 shunt	λ/4 shunt	Series-shunt	λ/4 shunt	**λ/4 shunt**
Freq. (GHz)	75-110	85-105	50-78	77-110	**73-133**
Insertion Loss (dB)	1.1-1.6	2.3-3.0	2.0-2.7	1.4-2.0	**1.4-2.0***
Isolation (dB)	21-22	20-21	25-35	17.5-19	**19-22**
P_{1dB} (dBm)	-	-	-	+19	**> +24****
Area (mm²)	0.94	0.05	0.11	0.14	**0.14**

* Aluminum pads have not been de-embedded.
** Limited by available source power.

Matched PIN Diode Attenuators

- An attenuator is just a voltage divider
- Which is meant to add some loss in the circuit to make the voltages smaller at the output
- Any PIN diode switch can be used as an attenuator, all that is needed is to control the bias current more finely
- In the matched attenuator, each diode is biased at a different current level
- The bias of each diode must track one another at all attenuation levels to maintain matching
- The bias circuit is not shown



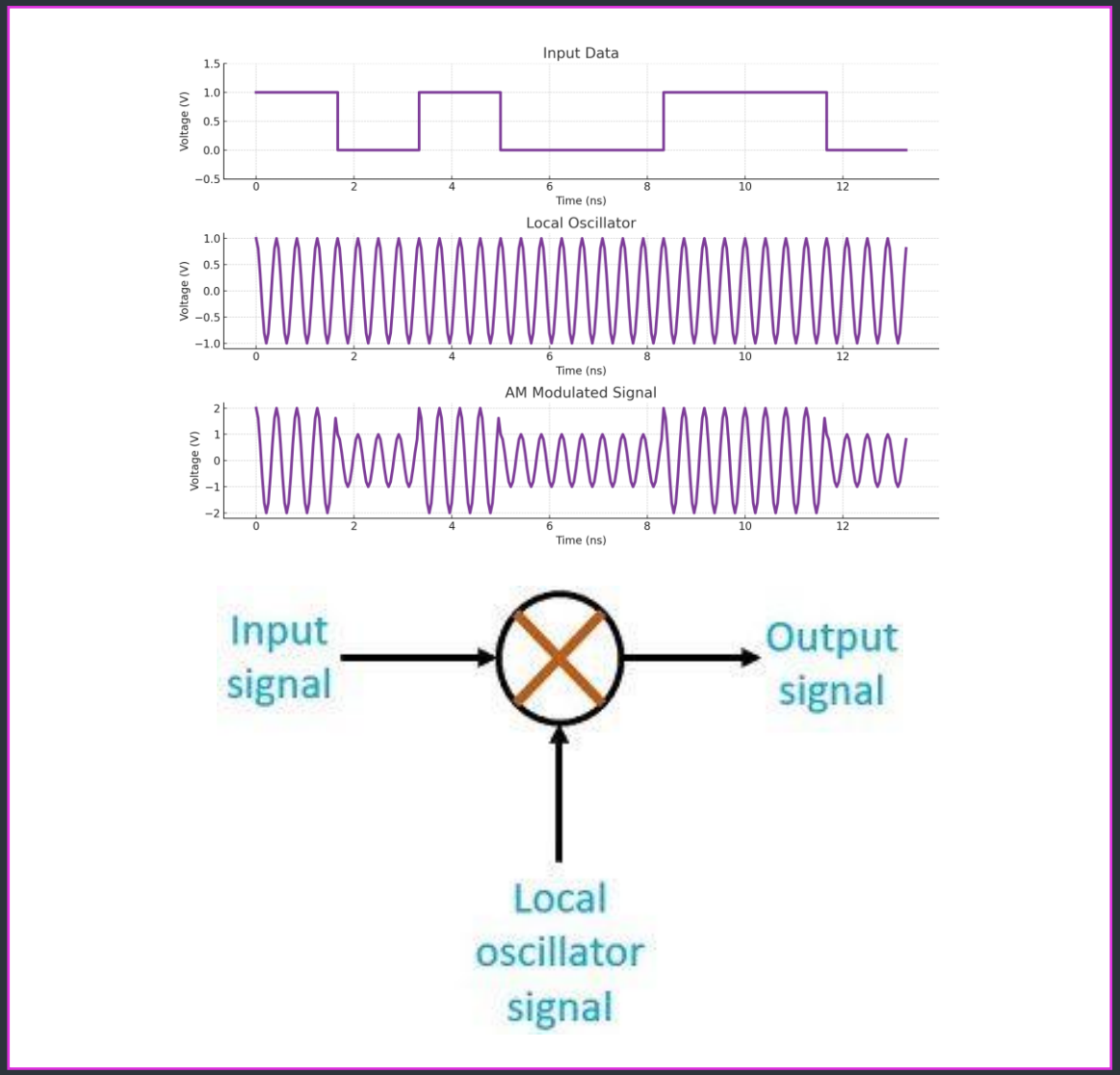


Tuned PIN Diode Attenuators

The matching is from the 90 degree hybrid (coupler)

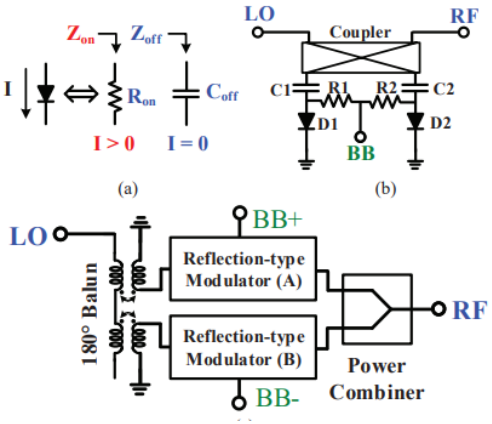
Modulators and Modulation

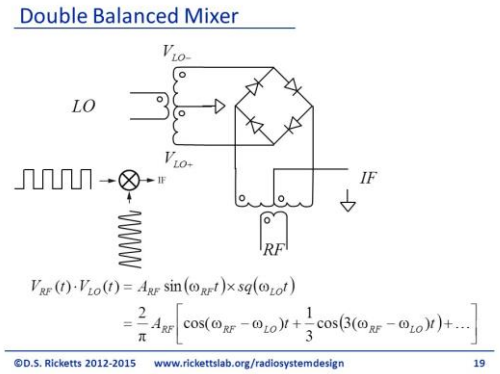
- To modulate a signal, just use a multiplication bloack (called a mixer)
- We modulate signals because it is easier to transmit higher frequency signals with antennas
- $v_{out}(t) = (bias + data(t)) * \mathrm{V_0}\cos(2\pi f_0 t)$



PIN Diode Modulators

- Since the Rs of a PIN diode is a function of the bias current, this can be used for modulation
- Modulation Bandwidth can be limited due to the (relatively long reverse recovery time)

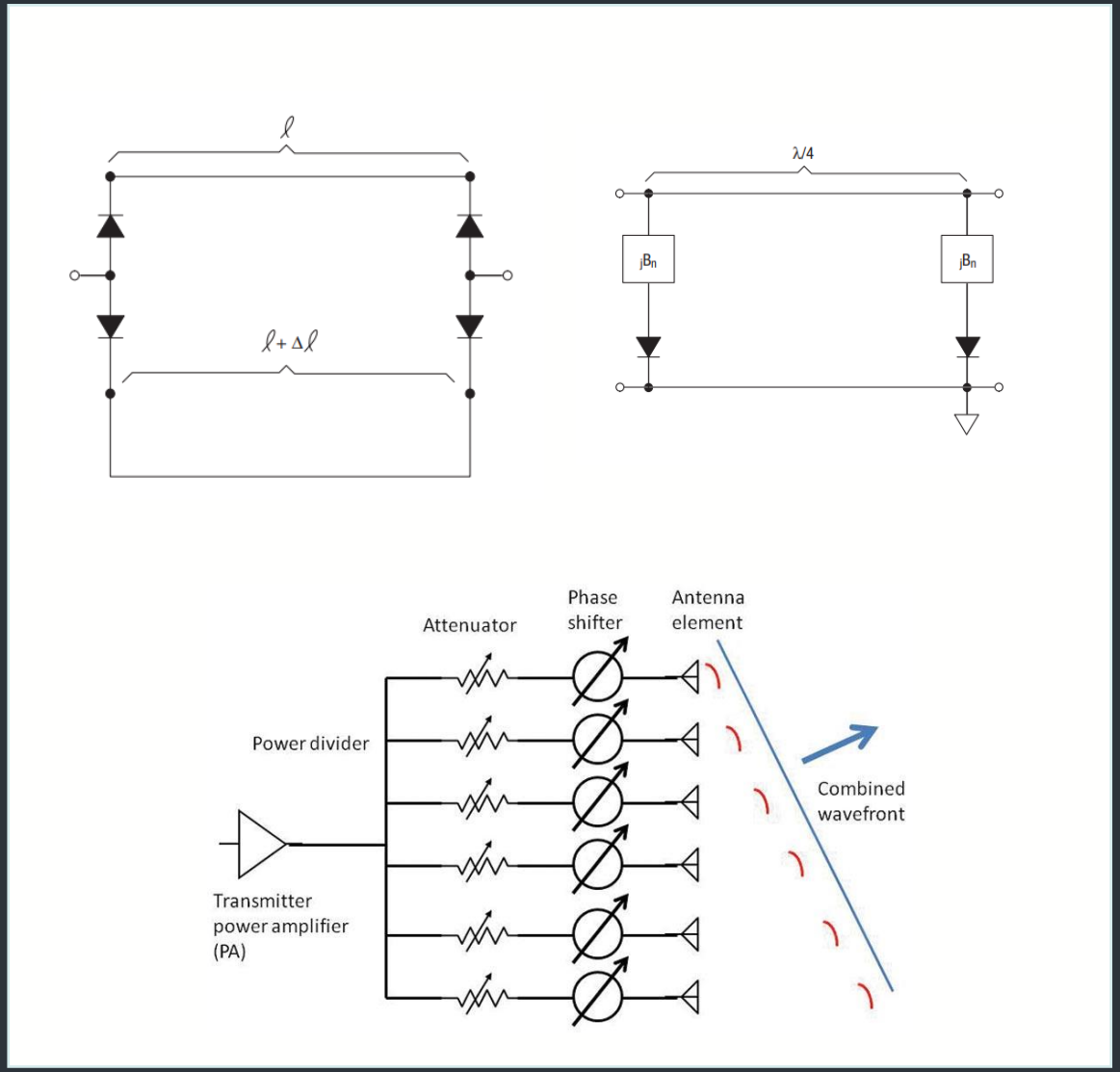




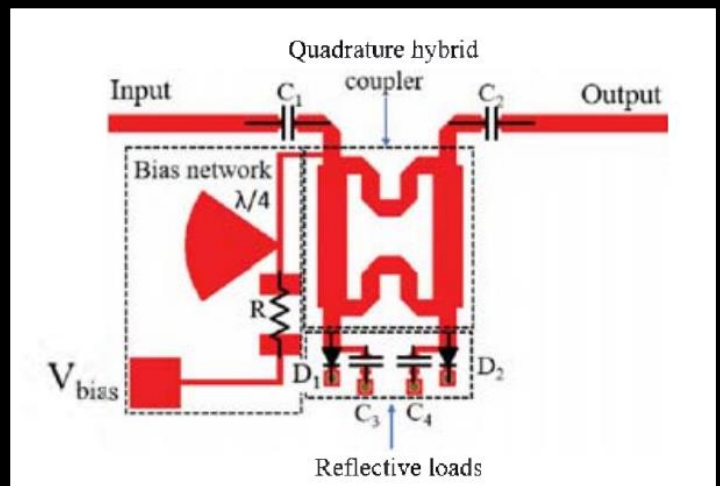
Reference	MMIC Process	Frequency (GHz)	LO Driving Power (dBm)	Modulation BW (MHz)	Phase Im. (°)	Amplitude Im. (dB)	EVM @ symbol rate 1 MS/s (%)	Chip Size (mm^2)
[5]	1-μm HBT	50 - 110	-8	3	5	2.5	<6	1×1
[6]	0.13-μm CMOS	25 - 55	12	15			4	0.64×0.67
[7]	2-μm GaAs	30 - 50	0	3000			<11	1×1
[8]	0.13-μm CMOS	15 - 75	4	>1000	3	0.5	3	0.5×0.35
[9]	0.5-μm GaAs HEMT	30 - 130	-10	>1000	5	0.8	<5	0.8×0.7
[10]	0.1-μm InP HEMT	115 - 135		10000	5	0.2	5	1×2
This work	**GaAs PIN Diode**	**25 - 65**	**-15**	**>500**	**<6**	**<0.9**	**<4**	**0.7×0.8**

PIN Diode Phase Shifters

- A phase shifter is a device that introduces some phase shift into a circuit/ signal
- Idea is to introduce some switched in reactive element to provide some phase shift
- Delay lines also work
- If we have an array of antennas, adding phase shifts can steer the beam

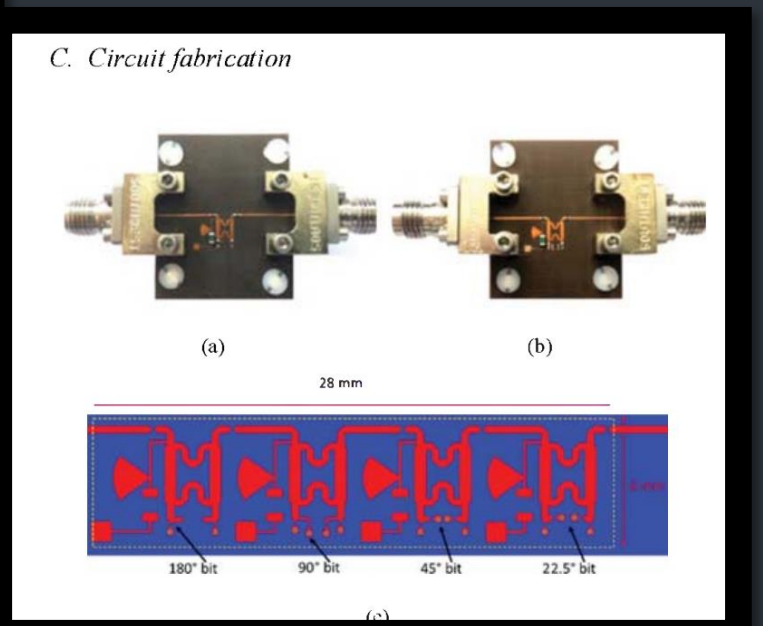


Phase Shifter Example

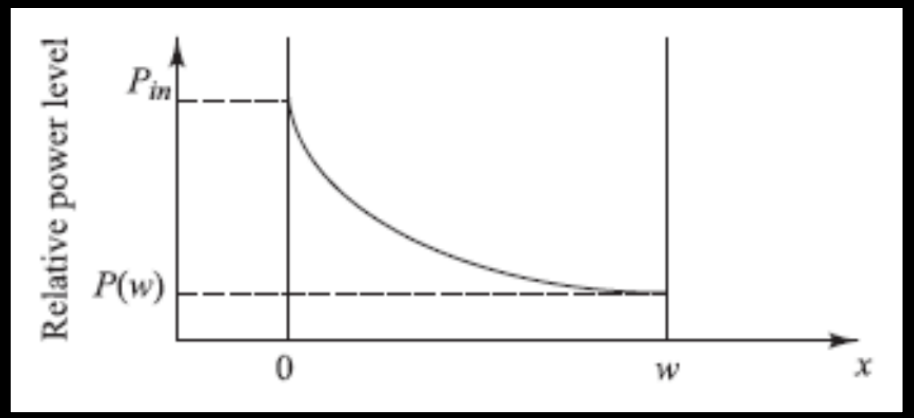


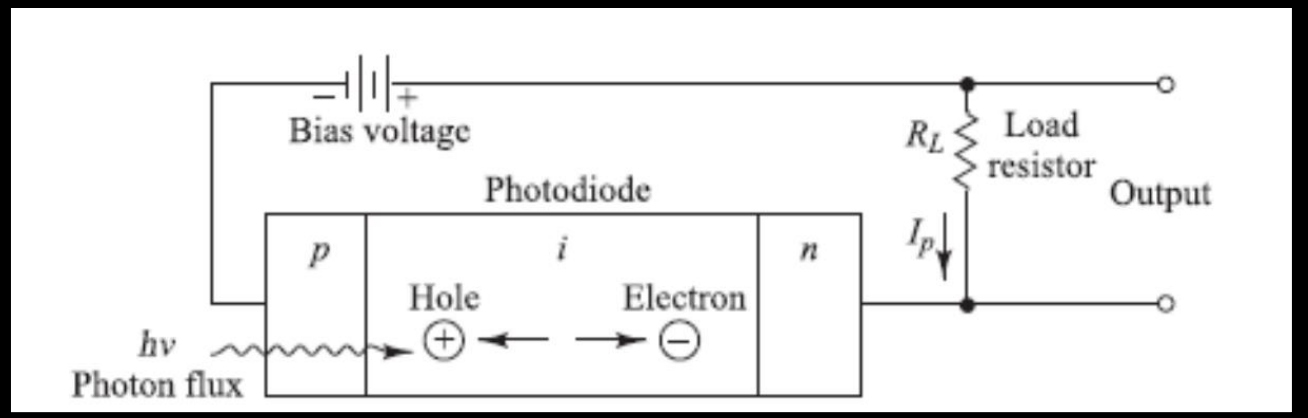
Ref.	[8]	[9]	[10]	This work*
Technology	CMOS	GaAs	CMOS	**PIN diode PCB**
Freq. (GHz)	26 - 30	33 -35	29 - 37	**18.7**
Bits	5	4	4	**4**
RL (dB)	NA	>12	>11	**>15**
IL (dB)	<16.5	<14.2	<12.8	**4.7**
RMS phase error (°)	<3.3	<5	<8.8	**1@18.7 GHz**

* Simulated results



PIN Diode Detectors





Parameter	*Symbol*	*Unit*	*Si*	*Ge*	*InGaAs*
Wavelength range	λ	nm	400–1100	800–1650	1100–1700
Responsivity	$\mathscr{R}$	A/W	0.4–0.6	0.4–0.5	0.75–0.95
Dark current	I_D	nA	1–10	50–500	0.5–2.0
Rise time	τ_r	ns	0.5–1	0.1–0.5	0.05–0.5
Modulation (bandwidth)	B_m	GHz	0.3–0.7	0.5–3	1–2
Bias voltage	V_B	V	5	5–10	5

PIN Diode Advantages

- **Ruggedness and High Reliability:** Capable of withstanding high voltage and current peaks and thermal impulses.
- **High Voltage and Current Capabilities:** Suitable for applications requiring voltages greater than 2000 volts and continuous currents exceeding 25 amperes.
- **High Surge Current Capability:** Can handle surge currents over 500 amperes for short durations.
- **Low Distortion:** Exhibits less than -60dBc distortion at 455 KHz.
- **High Power Gain:** Offers a power gain exceeding 10,000:1.
- **Switching Speed:** Capable of switching speeds under 100 ns, depending on construction.
- **Compact Size:** Its small physical size makes it ideal for various applications.
- **Variety of Thermal Packaging Options:** Offers flexibility in thermal management.
- **RF Relay Replacement:** Can replace mechanical (sometimes Hg containing) relays in RF applications.

PIN Diode Disadvantages

- **Isolation:** Since there is parasitic capacitance in the junction, there will always be some level of leakage when the diode is isolating two different circuits which is usually more than an RF relay, but it really depends on the devices that are being used
- **Repeatability:** The PIN diode is not as repeatable as the RF relay
- **Maximum Power/ Voltage:** The PIN diode does have a maximum power and voltage ratings, which are typically lower than an RF relay
- **Switching Speed:** The reverse recovery time limits the switching speed of the PIN diode. In high speed applications, not all PIN diodes will be acceptable

Questions?

References

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