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ELG 6369 – Project Report

PIN Diodes: Circuits and Applications

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I. ABSTRACT

This report delves into the comprehensive study of PIN diodes, a pivotal component in radio frequency (RF) and microwave engineering. PIN diodes, distinguished by their characteristic intrinsic region sandwiched between the P and N layers, exhibit unique electrical properties that make them highly suitable for a variety of RF applications. The report outlines the fundamental structure and function of PIN diodes, emphasizing their role in devices such as switches, attenuators, phase shifters, and modulators. Key parameters such as series resistance, junction capacitance, carrier lifetime, and their implications on diode performance are thoroughly examined. Challenges related to isolation, power handling, and reverse recovery time are also discussed, providing a balanced view of the capabilities and limitations of these diodes.

Through a blend of theoretical analysis and practical examples, including the latest research developments, the report demonstrates the versatility and importance of PIN diodes in modern RF systems. It underscores the impact of material science and semiconductor technology advancements on the future potential of PIN diodes, particularly in high-speed communications. The report concludes by affirming the indispensable role of PIN diodes in the evolving landscape of RF and microwave engineering, highlighting their adaptability and growing significance in a wide range of applications.

II. ACADEMIC INTEGRITY, LLMS AND GITHUB

The work presented here is solely authored by Nick Cardamone. When writing this work, LLMs (ChatGPT, Bard, Jasper) have been used in the writing. However, the thoughts, opinions and ideas presented in this work have been generated by the author alone. The software used here did not contribute any academic content. That being said, the generated text has been validated and checked for correctness and completeness. All errors are the responsibility of the author and are not the fault of the software that has been used. As a general overview of how this work has been put together, the steps that have been followed are below.

1. Research and gather information (IEEE Explore and Google)
2. Create a short list of supporting documentation
3. Read through the short list and compile notes
4. Feed the LLM samples of the authors previous work to increase the chances of the output sounding human
5. Feed the notes section by section into the LLM and generate text for this document
6. Read through the generated text, making corrections and rewriting (most) parts to conform with the desired writing style
7. Format the final report using the requested template

The resources, notes and rough drafts of this work are available at this GitHub to review: https://github.com/ncardamone10/Nonlinear-Microwave-Modeling

Note* The first reference ([1]) is to a comprehensive document explaining PIN diode circuit design authored by W. E. Doherty, Jr. and R. D. Joos. If there is ever a fact, idea or equation that does not have an associated reference, it is from this work. This work is over 100 pages long and contains many useful pieces of information that have been included in this document. That being said, the main points from that work which have been used in this document have been indicated.

Note* The figures and tables seen in this document have been borrowed from their respective reference

III. PIN DIODE OVERVIEW

The PIN or P-I-N diode is a type of diode that is typically used in RF switches and attenuators. At DC, it behaves identically to the classic PN junction diode and has the same IV curves as well. However, the PIN diode has one major difference to it. In a PIN diode, there is an “intrinsic” region placed in the middle of the P doped and N doped regions of a typical diode.

This intrinsic or “I” region of the PIN diode is usually lightly doped or not doped at all. This effectively turns the I region into the junction of the diode which gives the diode a much larger junction or depletion region depending on the bias conditions. This I region serves as a “bucket” to store extra charge (when forward biased) which has uses when dealing with RF circuits. When the diode is reverse biased, the I region is the depletion region which allows for a much smaller junction capacitance than a regular diode.

In addition to that, the depletion region width is a function of the reverse bias voltage which allows the junction capacitance to change with the voltage allowing the diode to act like a varactor in reverse bias. This variable capacitance can be exploited in circuits that need a controlled way of being tuned, however this isn't the main use of a PIN diode. The main advantage of a PIN diode is that the device acts like a current controlled resistor at a sufficiently high frequency. In addition to that, it can act like a resistor under somewhat large signal conditions provided the "bucket of charge" does not get depleted. The following are some important characteristics, parameters and applications of the PIN diode.

A. PIN Diodes: Important Characteristics and Applications

Structure and Function: At its core, the PIN diode is a PN junction diode with an intrinsic layer wedged in the middle. This structure makes it useful for radio frequency (RF) and microwave circuits. The frequency band that can be used for a particular PIN diode is a function of the diode construction and material. PIN diodes can be made out of pretty much any semiconductor and the typical frequency ranges of the various semiconductors apply to PIN diodes too (such as Si for MHz to lower GHz, GaAs for upper GHz)

Series Impedance: The series impedance of the PIN diode is controlled by the DC bias. When the device is forward biased, it acts like a current controlled resistor (with some parasitic inductance too, which is usually under a nH [2]). When the device is reverse biased, it acts like a (somewhat leaky) voltage controlled capacitor.

Applications: The PIN diode finds its use in various RF applications, such as switches, variable attenuators, phase shifters, modulators, limiters, and detectors. It is particularly good at controlling large RF power signals with small DC bias currents. In addition to that, the typically wider I region in PIN diodes allows for handling larger RF voltages compared to varactors or Schottky diodes, making them ideal for high-power RF switches. [2]

B. Distinctive Features

The "Bucket of Charge": The intrinsic region in the PIN diode acts like a 'bucket of charge', which facilitates the passage of current in the reverse direction for a brief duration, so long as there is some charge left in the I region. This is attributed to the diode's considerably slower reverse recovery time (hundreds of nanoseconds), which enables the passage of sufficiently high frequencies. However, this attribute is contingent on the bias current - the lower the frequency, the higher the required bias current.

Reverse Recovery Time: A critical parameter of the PIN diode is its reverse recovery time, which typically spans hundreds of nanoseconds, as opposed to the nanoseconds or picoseconds for a fast-switching PN Junction diode. For a signal to pass through a PIN diode, the key is not to deplete the stored charge in the diode's junction, i.e., the intrinsic region. The key thing to remember is that the RF signal can propagate both ways through the PIN diode and apply what seems to be a large reverse bias, but this can only happen for a short time (i.e. less than the reverse recovery time). The reverse recovery time is longer than the reverse recovery time of a typical PN junction diode because is takes more time for the electrons and holes to recombined since the I region has been inserted in the middle of the diode.

C. Important PIN Diode Parameters

R_s: Series Resistance under Forward Bias. This resistance is a strong function of the bias current and varies linearly with it.
C_T: Total Capacitance at Zero or Reverse Bias. The total capacitance is significantly influenced by the reverse bias voltage. An undesirable property as it contributes to leakage when the diode is supposed to be open
R_D: Parallel Resistance at Zero or Reverse Bias. An undesirable property as it contributes to leakage when the diode is supposed to be open
V_R: The maximum recommended reverse voltage swing before hitting the breakdown voltage
V_B: Reverse Breakdown Voltage. The voltage at which the junction breaks down and allows a large (uncontrolled) current to pass.
τ: Carrier Lifetime. During forward bias, the non-immediate recombination of holes and electrons (due to the larger physical separation) leads to an increased carrier lifetime, thereby augmenting the stored charge and reducing the effective resistance of the diode.

D. Design Considerations

Intrinsic Region Thickness: A thicker I region contributes to a higher RF breakdown voltage and enhanced linearity/distortion properties, whereas a thinner I region favours faster switching times at the expense of reverse signal swing.

Breakdown Voltage vs. Signal Power: Generally, a lower breakdown voltage correlates with a lower signal power handling capacity and device cost. However, some designs can avoid the diode needing to pass the full RF signal power.

Frequency Range: Although low-frequency PIN diodes are available, they are predominantly used in applications above 1 MHz for Si PIN diodes. GaAs PIN diodes and other higher frequency materials can operate in the neighbourhood of 40 GHz.

A Common Misconception: carrier lifetime is the sole determinant of the cutoff frequency and distortion. In reality, while carrier lifetime is significant, the thickness of the intrinsic region also plays a crucial role. [2]

IV. Large Signal Modeling and IV Characteristics of PIN Diodes

A. IV Curves

For frequencies below the transit time frequency, the PIN diode behaves identically to a regular PN junction diode, exhibiting identical IV curves. The current though a typical (Si) pin diode can be found from the following

$$I = I_0(e^{V/V_T} - 1) \tag{1}$$

Where V is the bias voltage on the diode, V_T is the thermal voltage, I_0 is the current through the diode at the thermal voltage, and I is the bias current through the diode

B. RF Model

In RF applications, it is essential for the charge stored in the intrinsic region (Q) to be significantly greater than the RF current divided by $2\pi f$ to allow the RF current to pass through the diode. Under forward bias conditions, this charge (Q) can be expressed as

$$Q = I_F \tau \tag{2}$$

where I_F is the forward bias current, τ is the carrier lifetime in seconds and Q is the charge in coulombs.

1) Forward Bias Resistance (Model)

$$R_s = \frac{W^2}{(\mu_n+\mu_p)Q} = \frac{W^2}{(\mu_n+\mu_p)\tau I_{fwd}}, for\ f > \frac{1300}{W^2} \tag{3}$$

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

2) Reverse (or No) Bias Model

In reverse bias or no bias conditions, the PIN diode's behavior is influenced by the dielectric constant (ϵ) of the material (Si, GaAs, AlGaAs, etc) and the area of the diode junction (A). The total capacitance (C_T) in this state can be represented as:

$$C_T = \frac{\epsilon A}{W} \tag{4}$$

Which is valid for $f > \frac{1}{2\pi\rho\epsilon}$, where ρ is the resistivity of the intrinsic region

At lower frequencies, the PIN diode can act like a varactor, with its capacitance changing with the reverse bias voltage. In most RF applications, the parallel resistance (R_P) is negligible. The maximum negative voltage swing should not exceed the breakdown voltage (V_B) and ideally the specified maximum reverse voltage V_R.

C. Switching Speed Model

When switching is a critical consideration (transitioning from full on to full off), two different switching speeds need to be considered:

- T_{FR}: Time from Forward Bias to Reverse Bias. This is dependent on the carrier lifetime.
- T_{RF}: Time from Reverse Bias to Forward Bias. This is dependent on the forward bias current (I_F)and the initial reverse current (I_R). The time from forward bias to reverse bias can be calculated using

$$T_{FR} = \tau \ln\left(1 + \frac{I_F}{I_R}\right) \tag{5}$$

V. Advantages of Using a PIN Diode

PIN diodes are advantageous in various applications due to their robustness, high reliability, and versatility in handling high peak voltages and currents. Some of their notable benefits, as seen in [1] include

- **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.

VI. DISADVANTAGES OF USING A PIN DIODE

Even though PIN diodes have many advantages, they also have some 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

VII. RF PIN DIODE SWITCHES

A. *Overview*

PIN diodes are able to conduct in reverse, provided there is an excess charge in the intrinsic region. This leads to three conditions for a PIN diode to act as a switch: sufficient bias current, high enough RF signal frequency, and voltage swings that do not deplete the stored charge in the PIN diode's "bucket."

B. *Frequency Range*

The operational frequency range of a PIN diode switch depends on the material it's made from. For Silicon (Si) PIN diodes, the effective lower frequency limit is around 1 MHz, with upper frequencies reaching into the GHz region. Taking a particular PIN diode example (MA4FCP200 [7]), the diode’s datasheet gives an operating range from 2 GHz to at 40 GHz for this GaAs device.

C. *Challenges in Isolation*

Achieving more than 40 dB of isolation with a single PIN diode switch can be challenging due to factors like radiation, inadequate shielding, and coupling [2]. To address this, compound switches (more than one diode) and tuned switches (reactive and distributed elements) are used. The key principle in using PIN diodes as switches lies in their impedance variation: they act as a low resistance path when forward biased and a high resistance path when reverse biased. Clever circuit topologies can be utilized to exploit this behavior for effective RF signal switching.

D. *Isolation in PIN Diode Switches*

Isolation measures how effectively the switch blocks RF power when it's supposed to be open. It's quantified by the difference in output power between the closed and open states of the switch:

$$Isolation\ (dB) = P_{out,closed}\ (dB) - P_{out,open}\ (dB) \tag{6}$$

The effectiveness of isolation depends on the capacitance of the reverse-biased junction, which impacts how well the switch can prevent signal passage in its off state.

E. *Insertion Loss*

Insertion loss refers to the amount of power dissipated within the switch when it is closed. This aspect is particularly important in communication systems, as it directly affects the system's noise figure by the amount of the switch's insertion loss:

$$IL\ (dB) = P_{out,closed}\ (dB) - P_{in,closed}\ (dB) \tag{7}$$

F. Power Handling in Switching

For a PIN diode switch to handle large power levels effectively, it often needs to be configured to reflect power when in the open state. This design consideration is important for ensuring the switch can manage the power without succumbing to damage or excessive loss (i.e. with out releasing the magic smoke).

G. Single Pole Single Throw (SPST) PIN Diode Switches

1) Series Implementation

In a series implementation of an SPST switch, the PIN diode acts as the switching element which is in series with the two circuits that either need to be part of the signal path, or need to be isolated. These switches operate on the idea of reflections

a) Basic Operating Principle (Figure 6):

- When $V_{c1} > V_{c2}$, the diode conducts (forward bias), closing the switch.
- When $V_{c1} < V_{c2}$, the diode is reverse biased, opening the switch.
- Increasing the forward bias current decreases *RS*, thereby reducing insertion loss.
- In reverse bias, the switch appears open with some capacitance, reflecting the RF signal back.

b) Bias Circuitry:

This typically involves a bias tee and some method for creating bias current. This can be realized by using series resistors or current mirrors. One important advantage of this topology is that a negative voltage is not necessary and a 0V bias will work.

c) Usage:

This configuration is preferred when minimal insertion loss is needed over the signal bandwidth. This is simpler to realize on a single-sided PCB layout as no vias are needed [2]

d) Key Equations:

$$IL = 20\log\left(1 + \frac{R_S}{2Z_0}\right) \tag{8}$$

$$Isolation = 10log\left[1 + \frac{1}{(4\pi fCZ_0)^2}\right] \tag{9}$$

$$P_D = \frac{4R_SZ_0}{(2Z_0+R_S)^2}P_{AVS}, P_{AVS} = \frac{V_{gen}^2}{4Z_0} \tag{10}$$

$$P_D = \frac{R_S}{Z_0}P_{AVS}\ for\ Z_0 \gg R_s \tag{11}$$

$$I_{peak,RF} = \sqrt{\frac{2P_{AVS}}{Z_0}}\left(\frac{2VSWR}{VSWR+1}\right) \tag{12}$$

$$V_{peak,RF} = \sqrt{8Z_0P_{AVG}} \tag{13}$$

Note* The equations for the power dissipated by the diode (P_D) are only valid for the simplifying assumption of perfect matches, which is never the case with these types of switches. To correct for this, multiply by $(\frac{2VSWR}{VSWR+1})^2$

2) Shunt Implementation

The shunt implementation of an SPST switch offers higher isolation and power handling capabilities.

a) Basic Operating Principle (Figure 7):

- When the diode is forward biased, it shunts the RF signal to ground, thus acting as an open circuited switch
- When the diode is reverse biased, it acts as closed switch as far as the RF signal is concerned

b) Advantages Over Series:

- Provides higher isolation over a broader bandwidth. The switch isn't in series with the two circuits. This means that when the diode is off, it's parasitics appear in parallel with the input impedance of the load circuit, which makes this parasitic capacitance insignificant
- Is able to handle more power due to better sinking into the diode. [1]

c) Key Equations:

$$IL = 10\log\left[1 + \frac{1}{(\pi f C_T Z_0)^2}\right] \tag{14}$$

$$Isolation = 20\log\left(1 + \frac{Z_0}{2R_S}\right) \tag{15}$$

$$P_D = \frac{4R_S Z_0}{(Z_0 + 2R_S)^2} P_{AVS} \tag{16}$$

$$P_D = \frac{4R_S}{Z_0} P_{AVS}\ for\ Z_0 \gg R_S \tag{17}$$

$$I_{peak} = \sqrt{\frac{8P_{AVS}}{Z_0}} \tag{18}$$

$$V_{peak,RF} = \sqrt{2Z_0 P_{AVS}}\left(\frac{2VSWR}{VSWR+1}\right) \tag{19}$$

H. Single Pole Multi Throw Switches

Multi throw switches are more commonly used and are often challenging to realize using only shunt diodes. These types of switches are typically made by combining SPST switches (one diode per branch). If branches are symmetric, they can be analyzed as SPST equivalents, but isolation increases by 6 dB.

A. Compound Switches:

This is the most common form of a RF PIN diode switch as the performance can be enhanced using compound switches (both series and shunt elements). The analysis of these kinds of switches can be done by considering each switch as a unique “cell” and cascading those to find the insertion loss and isolation. There are two main types of compound switches, the “series shunt” and the “TEE” or “ELL” type. The advantage of these types of switches is they provide a higher degree of isolation but this can be at the cost of an increased insertion loss and VSWR degradation due to mismatching. In addition to that, the bias circuit tends to be more complex.

A. Tuned Switches

Tuned switches use a reactive or distributed element to boost the performance of a simple or compound switch. The disadvantage of these types of switches is they are usually somewhat narrowband.

1) Theory of Operation

The operation of these switches is fairly straight forward. The diode element either acts as a short or open circuit depending on the bias condition. The tuned element is inserted in such a way as to rotate the diode impedance across the smitch chart as to produce a favourable matching condition seen from either the common or the input/ output port. For example, in a SPDT shunt switch configuration, quarter wave transmission lines can be placed separating the two branches. When one of the diodes at the end of the circuit is forward biased, it acts as a short circuit to ground. On the other side of the quarter wave transformer, the impedance seen is an open circuit which can further boost the insertion loss and isolation of the switch for a narrow bandwidth. If the frequency is too low for a quarter wave transmission line transformer, the pi equivalent circuit can be used.

2) Antenna TX/RX PIN Diode Switch Example

As seen in figure 11, a PIN diode switch can be used to switch between the transmitter and receiver at the port of an antenna, thus allowing the antenna to be used for both TX and RX. In this circuit, when the DC supply is sufficiently positive, both diodes are on and appear as low resistance paths. This allows the signal from the transmitter to reach the antenna. The catch is, is that the short circuit at the receiver end is reflected to look like an open circuit at the antenna port, which allows the antenna to act as the transmitter. When the bias conditions are inverted, both diodes act as an open circuit. This means that the transmitter is isolated from the antenna. At the receiver end, the diode is in parallel with the receiver, which looks like a matched load (assuming the receiver is matched). This matched load is unaffected by the quarter wave transformer and now the antenna can be used to receive a signal. It is also possible to use a PIN diode to switch between antenna elements to modify the radiation pattern [3]

1) Research Paper Example

As seen in [4] a W-band SPDT switch is implemented using PIN diodes in a new 90 nm SiGe BiCMOS technology. This SPDT switch is able to achieve a minimum insertion loss of 1.4 dB and an isolation of 22 dB at 95 GHz. Over a 77 to 134 GHz span, the insertion loss is always less than 2 dB. In the span of 79 to 133 GHz, the isolation is always greater than 20 dB. The input and output return losses are greater than 10 dB from 73-133 GHz. By reverse biasing the off-state PIN diodes, the P1dB is larger than 24 dBm. From this example, it can be seen that not only are PIN diodes realizable and effective, their frequency of operation can be pushed well above 100 GHz, but the material and structure of the diode will need to change to accommodate this region of operation.

VIII. RF PIN DIODE VARIABLE ATTENUATORS

A. Overview

Attenuators are networks designed to introduce a predetermined amount of loss into a signal path. PIN diodes serve effectively as current-controlled resistors (attenuators when considering the voltage divider formed from with the input/ output impedances). The series resistance (*Rs*) of the diode, which is inversely proportional to the forward bias current ($I_{forward}$), plays an important role in the attenuation. This resistance, combined with a shunt impedance, forms a voltage divider responsible for the attenuation. The dynamic range of the attenuator is influenced on the range of R_s. In many PIN diodes, R_s can vary from 10 kΩ to 1 Ω depending on the bias current. The following are important points to consider when designing a PIN diode attenuator:

- **Distortion Sensitivity**: Attenuators tend to be more distortion-sensitive than switches, particularly when the bias current results in a lower amount of stored charge. This extra sensitivity comes from how the bias current is used in a somewhat continuous fashion instead of the binary fashion to control a switch.

- **Intrinsic Region Thickness**: The thickness of the I region in PIN diodes influences their performance. A thin I region operates at lower forward bias currents, saving DC power, but a thicker region generates less distortion, exhibiting better third-order intermodulation and compression point.

One of the big use cases of PIN diode attenuators is in automatic gain control (AGC) or leveling control loops to ensure consistent output power, regardless of variations in input power, within practical limits.

B. Reflective Attenuators:

Reflective attenuators are similar to reflective PIN diode switches but with more continuously controlled bias currents. Reflective attenuators work by introducing a mismatch into the signal path, which causes reflections and thus a power loss as far as the output is concerned. This is generally the most simple way of creating a PIN diode attenuator, but the drawback is the signal reflections. Since PIN diodes can handle a lot of power, these reflections can be a problem for the input circuit.

1) Key Equations

Attenuation equations for series and shunt connected attenuators:

- Series connected: $A = 20\log\left(1 + \frac{R_S}{2Z_0}\right)$ (20)

- Shunt connected: $A = 20\log\left(1 + \frac{R_S}{2Z_0}\right)$ (21)

Note* This assumes the reactive part of the PIN diode impedance is insignificant.

C. Matched Attenuators:

In contrast to reflective attenuators, matched attenuators provide nearly a constant impedance across the entire attenuation range. These are implemented using multiple PIN diodes (using compound formation) with different biasing conditions or bandwidth-limited circuits using resonant/tuned elements. In the circuits with multiple diodes at different biasing conditions, the biases of each diode must track each other to maintain match, which is an increase of complexity.

1) Quadrature Hybrid Attenuators:

These attenuators use a 90 degree/ 3 dB quadrature hybrid as their tuned element to ensure matching when the diodes are providing attenuation. These types of attenuators are capable of handling twice the input power compared to circulator-based reflective design since the hybrid divides the power by 2. One important consideration is that the load resistor must be able to dissipate half of the max input power at the full attenuation

a) Theory of Operation

The matching is a result of how the 90 degree hybrid works in figure 16 and 17. Power from port A goes to port B and C with 90 degree phase shift (D is isolated). Then the power is reflected back to port A and D from port B and C. Power reflected to port A cancels (from port B and C from the phase shifting). Which gives the circuit a matched input port. The diodes at port B and C are still doing the attenuation.

It is possible to get rid of the load resistors by the diodes. This lets there be more bias current which allows for more stored charge in the diode which gives less distortion. However, the purpose of the load resistors is to make the circuit less sensitive to device variation and mismatch. Plus having those resistors doubles the power handling capability of the attenuator for the same PIN diodes.

b) Key Equations

Attenuation equations for quadrature hybrid attenuators:

- Shunt connected: $A = 20\log\left(1 + \frac{2R_S}{Z_0}\right)$ (22)

- Series connected: $A = 20\log\left(1 + \frac{2Z_0}{R_s}\right)$ (23)

2) *Quarter Wave Attenuators:*

These attenuators are implemented using a quarter wave transformer as the tuned element. This attenuator will remain matches with both diodes have the same series resistance, which can be a problem with devices that aren't on the same die (device variation). Typically, the series configuration is better for higher attenuation settings and the shunt is better for lower attenuation settings/ use cases. [1]

a) Key Equations

Attenuation equations for quarter wave attenuators:

- Shunt connected: $A = 20\log\left(1 + \frac{R_s}{Z_0}\right)$ (24)

- Series connected: $A = 20\log\left(1 + \frac{Z_0}{R_s}\right)$ (25)

3) *Pi and Bridged Tee Attenuators:*

These are suitable for broadband applications where matched attenuators are required. The bias currents through the diodes need to be adjusted to maintain matching conditions for various attenuation levels.

a) Key Equations

- Bridged Tee: $A = 20\log\left(1 + \frac{Z_0}{R_{s1}}\right), When\ Z_0 = \sqrt{R_{s1}R_{s2}}\ the\ attenuator\ is\ matched$ (26)
- Pi: $A = 20\log\left(\frac{R_{s1}+Z_0}{R_{s1}-Z_0}\right), When\ R_{s3} = \frac{2R_{s1}Z_0^2}{R_{s1}^2-Z_0^2}\ and\ R_{s1} = R_{s2}\ the\ attenuator\ is\ matched$ (27)

Note* only the unbalanced networks are shown. To convert to a balanced network, simply reflect the circuit across a line of symmetry and divide the component values by two.

IX. MODULATORS USING PIN DIODES

A. *Overview*

PIN diodes find extensive use in high-power modulator circuits. Their ability to switch and attenuate allows them to function effectively in amplitude modulation (AM), square wave/pulse modulation (ASK, QPSK), and linear modulation schemes. In these applications, PIN diodes can act like mixers, where the bias current carries the information signal, and the RF signal functions as the local oscillator (LO). However, because the PIN diodes have a rather large reverse recovery time compared to the typical fast switching diode that could be found in a gilbert cell, the modulation bandwidth is rather limited for some materials. As seen below, it is possible to create high speed modulators out of the right material.

B. *Applications and Design Considerations*

AM Modulation: Here, the modulation of the bias current alters the RF signal's amplitude. The design closely resembles that of switches and attenuators, where the bias current modulation depth determines the AM depth.
Square Wave/Pulse Modulation: Utilizing the switching capabilities of PIN diodes, this application is ideal for amplitude-shift keying (ASK) or quadrature phase-shift keying (QPSK) modulation. PIN diode switches can rapidly alternate the signal's presence or absence, effectively encoding digital information.
Linear Modulation: In this application, a PIN diode attenuator is employed. The smooth variation of the diode's resistance with the bias current allows for fine control over the signal's amplitude, suitable for more complex modulation formats such as M level ASK or M-PSK

C. *Key PIN Diode Modulator Properties*

The following are some important points to consider when using a PIN diodes as a modulator.

- **Thick Intrinsic Regions**: PIN diodes used in modulators should have thick intrinsic regions to reduce distortions and handle higher powers.

- **Configuration**: Series or back-to-back configurations of PIN diodes can significantly reduce distortion.

- **Modulation Limitations**: The trade-off in using PIN diodes as modulators is a lower modulation bandwidth due to the high reverse recovery time/ carrier lifetime. This can be mitigated with the material choice and careful construction and design of the diode. In addition to that, the modulation current required is far less than a traditional modulator/ mixer.

D. Microwave Power Modulators

When designing a modulator that needs to put out a lot of power, using PIN diodes is the preferred choice [1]. However, when outputting a significant amount of power, linearity and distortion can become a problem. To avoid modulator non linearities, the depth of the modulation must be chosen carefully as to not deplete that “bucket of charge” which is stored in the I region of the device. Another way of looking at it is to say the carrier lifetime can not be too long as to hinder the modulation process. At the same time, it needs to be long enough to suppress intermodulation distortion [1].

A typical circuit that can be used to do modulation (with PIN diodes) is the 90-degree hybrid attenuator, provided the hybrid covers the necessary bandwidth. The modulation signal is fed into the bias port of the attenuator, the RF signal is fed into the input of the 90 degree hybrid and the output IF is taken from the output of the hybrid.

E. Demodulators

A 90-degree hybrid attenuator can technically demodulate signals by feeding the LO and RF into the hybrid, with the intermediate frequency (IF) emerging from the bias port. However, this is not the most efficient approach. A better method involves using carrier synchronizer which is really just a fancy phase-locked loop (PLL) for demodulation, offering much better performance. It is possible to make the mixers in a carrier synchronizer using PIN diodes, but that is out of the scope of this document.

F. Research Paper Example: Low LO Power Monolithic BPSK Modulator

A monolithic BPSK modulator has been constructed covering 25 to 65 GHz, with GaAs PIN diodes, that demonstrates the versatility of PIN diodes in high-frequency applications. It was able to operate with an LO power of -15 dBm and a modulation bandwidth of over 500 MHz. The error vector magnitude (EVM) at the output of the modulator is 1.8% at 30 GHz and has a good eye opening up to 500 Mbps

This practical example illustrates the high performance and wide operational bandwidth achievable with PIN diode-based modulators, especially in advanced communication systems, however, more expensive materials are needed and the design is far more complex.

X. Phase Shifters Using PIN Diodes

A. Overview

Phase shifters are useful circuit components that can as the name suggests, insert a prescribed amount of phase shift in the signal path. One important applications is in phased array systems, where they control the phase of each antenna element. These devices can consist of PIN diode switches combined with reactive elements that can be dynamically engaged or disengaged to achieve the desired phase shift.

B. Phase Shifter Basics

The fundamental concept of a phase shifter involves incorporating a reactive element into the signal path. The amount of phase shift a single phase shifter can provide is limited. Therefore, multiple phase shifters are often arranged in cascading "cells," each contributing a portion of the total phase shift. This arrangement allows for discrete phase adjustments, with each cell functioning as a "bit" that can be activated or deactivated.

A. Switched Line Phase Shifters:

The idea with these configurations is to split the signal path among multiple branches. Each one of these branches can be switched in and out (typically with series diodes) and also has a different electrical length (figure 24). The following is how to calculate the phase shift from a single cell, two branch phase shifter

$$\Delta\theta = \frac{2\pi\Delta l}{\lambda} \tag{28}$$

Where Δl is the difference in electrical length of the branches (delay line length)

A. Loaded Line Phase Shifters:

In this phase shifter configuration, shunt diodes are typically used to switch in and out reactive or tuned elements. Since the diodes are in shunt, the power ability of this configuration is larger than the previous one since not all the RF power passes through the shunt diodes. The practical limit on the amount of phase shift this can supply is 45 degrees so more than one cascaded cell is needed. [1] The following is how to calculate the amount of phase shift introduced by the loaded line phase shifter:

$$\tan\left(\frac{\theta}{2}\right) = \frac{B_n}{1-\frac{B_n^2}{8}} \tag{29}$$

$Where\ B_n\ is\ the\ susceptance\ introduced\ by\ the\ diodes$

A. *Reflective Phase Shifters:*

In the reflective phase shifter, the circuit is often designed around a 90 degree hybrid. With this configuration, the phase shifter can handle the largest amount of RF power (twice the peak power for the same number of diodes) and give the most incremental phase shift out of the configurations presented in this document. The following is the equation for how to find the induced phase shift

$$sin\left(\frac{\theta_{max}}{2}\right) = \frac{V_B I_{fwd}}{8P_{RF}} \tag{30}$$

A. *Research Example*

A notable implementation of PIN diode-based phase shifters is seen in a research paper where MACOM's MA4FCP200 PIN diode was used to create a 4-bit phase shifter based on a hybrid coupler design. The device, fabricated on Taconic TLX8 PCB material, outperformed its comparisons in terms of lower insertion loss and effective phase shifting capabilities. [6]

XI. CONCLUSION

This report has extensively explored the functionalities and applications of PIN diodes in RF systems, underscoring their integral role in handling high-frequency signals. Characterized by their unique intrinsic region, PIN diodes are adaptable components used in a variety of applications, including switches, attenuators, phase shifters, and modulators. The adaptability of PIN diodes stems from key parameters like series resistance, total capacitance, and carrier lifetime, influencing their performance in different RF applications. Despite their versatility, PIN diodes face challenges such as isolation and maximum reverse voltage, necessitating careful design considerations.

Looking ahead, the potential of PIN diodes in RF and microwave systems is promising, particularly with advancements in material science and semiconductor technology. As the demand for high-speed communication and radar systems grows, PIN diodes are poised to play an even more critical role. In summary, PIN diodes, with their unique properties and growing applications, remain indispensable in the rapidly evolving field of RF and microwave engineering.

APPENDIX A: REFERENCES

[1] W. E. Doherty and R. D. Joos, The Pin Diode Circuit Designers' handbook , https://www.qsl.net/n9zia/pdf/pin_diode_handbook.pdf (accessed Nov. 21, 2023).

[2] Skyworks Solutions, Inc., Application note design with PIN diodes , https://www.digikey.com/Site/Global/Layouts/DownloadPdf.ashx?pdfUrl=AF319B62D6FD4AD182C38082595F3B28 (accessed Nov. 21, 2023).

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[5] X. Lin, H. -E. Liu, H. -Y. Chang and Y. -C. Wang, "A 25–65 GHz broadband low-LO-driving wide-modulation-bandwidth monolithic BPSK modulator in GaAs PIN diode MMIC process," 2017 IEEE Asia Pacific Microwave Conference (APMC), Kuala Lumpur, Malaysia, 2017, pp. 910-913, doi: 10.1109/APMC.2017.8251597.

[6] K. T. Trinh, J. Feng and N. C. Karmakar, "18.7 GHz 4-Bit PIN Diode Reflection Type Phase Shifter for Radiometer Phased Array Antenna," 2021 2nd International Conference on Robotics, Electrical and Signal Processing Techniques (ICREST), DHAKA, Bangladesh, 2021, pp. 504-509, doi: 10.1109/ICREST51555.2021.9331208.

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APPENDIX B: FIGURES

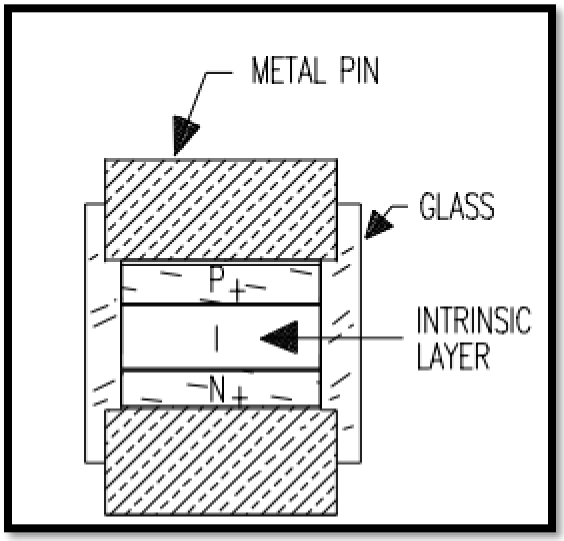

Figure 1: PIN Diode Construction [1]

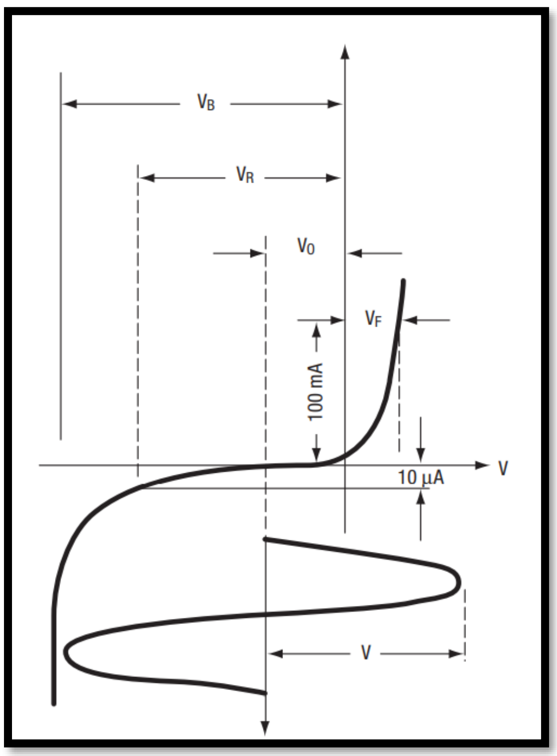

Figure 2: PIN Diode Labeled IV Curve [2]

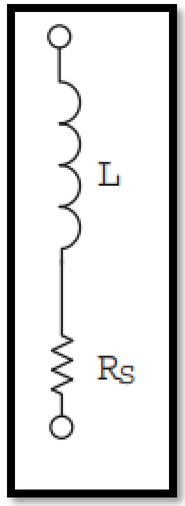

Figure 3: PIN Diode Forward Bias Model [2]

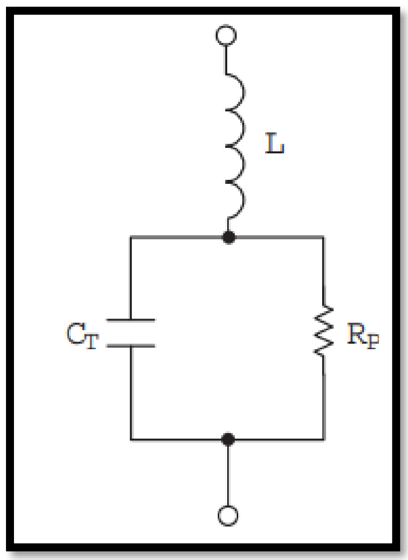

Figure 4: PIN Diode Reverse Bias Model [2]

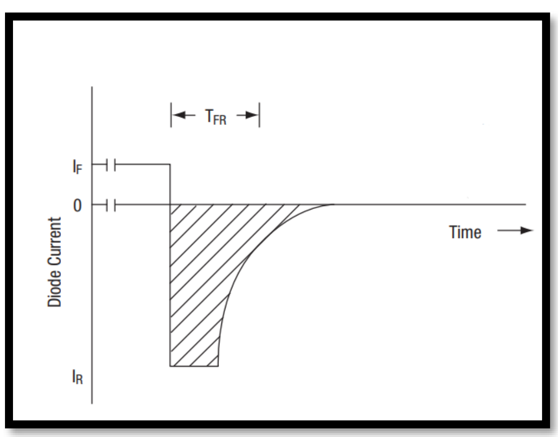

Figure 5: PIN Diode Switching Current [2]

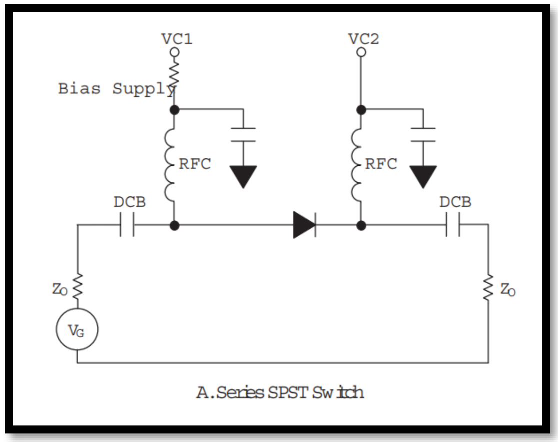

Figure 6: Single Pole Single Throw Series Switch [2]

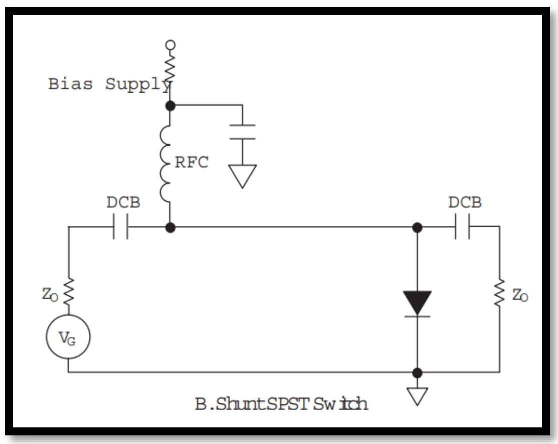

Figure 7: SPST Shunt Switch [2]

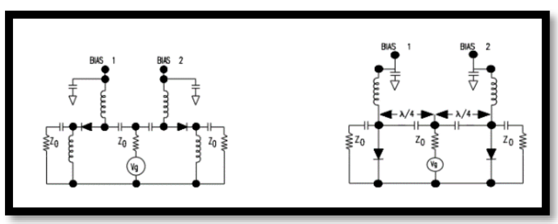

Figure 8: Multi Throw Switches [1]

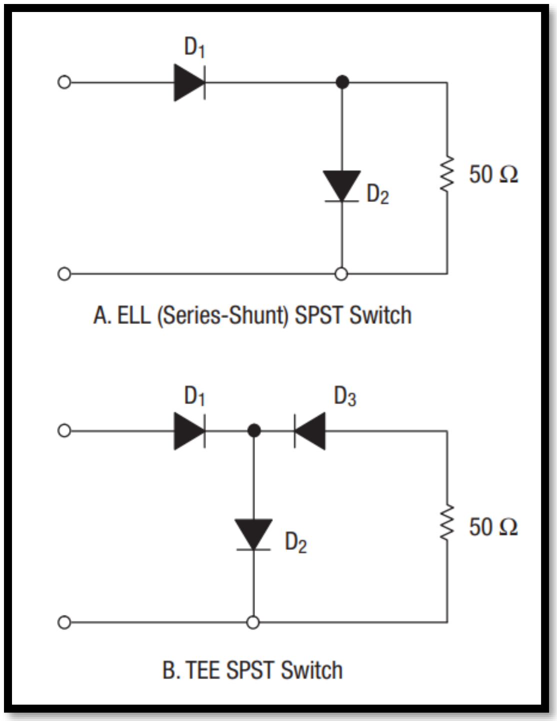

Figure 9: Compound Switches [2]

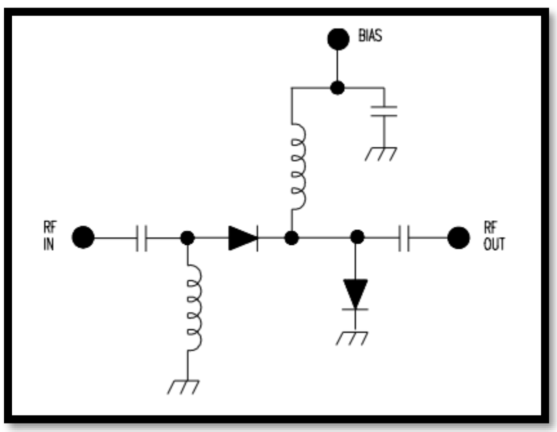

Figure 10: Series Shunt Compound Switch [1]

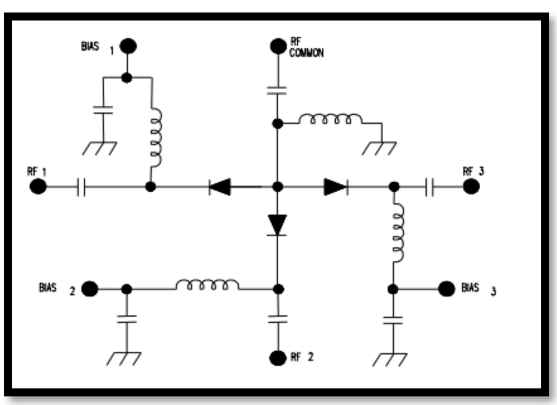

Figure 11: Compound TEE Switch [1]

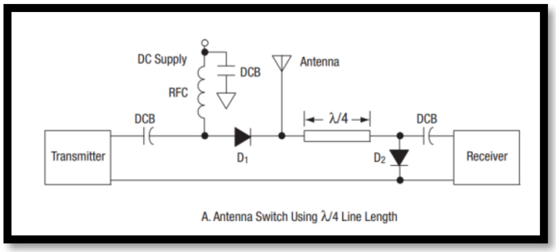

Figure 12: TX/RX Switch Example

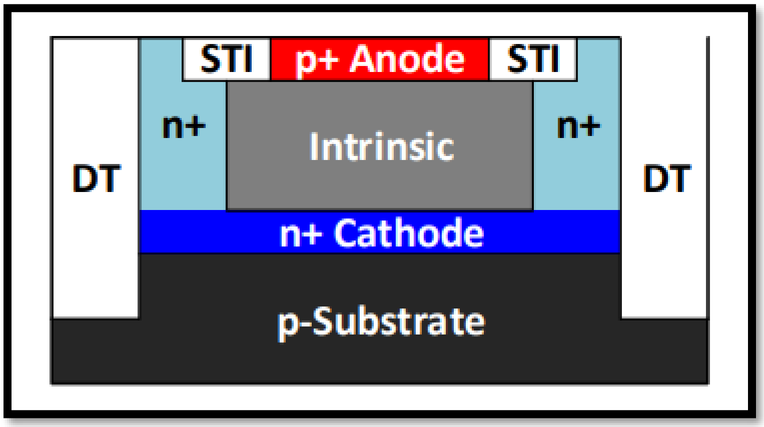

Figure 13: PIN Diode Structure in [4]

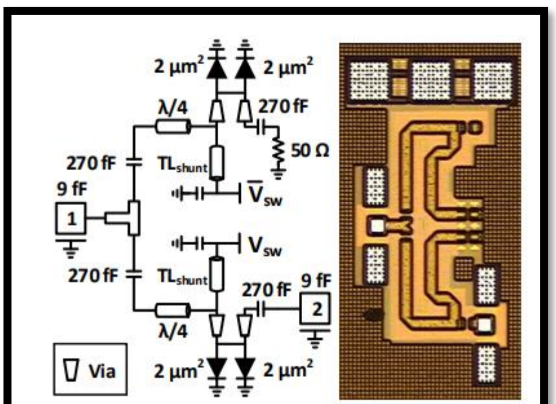

Fig. 3. Schematic and chip micrograph of the SPDT switch.

Figure 14: Switch Layout in [4]

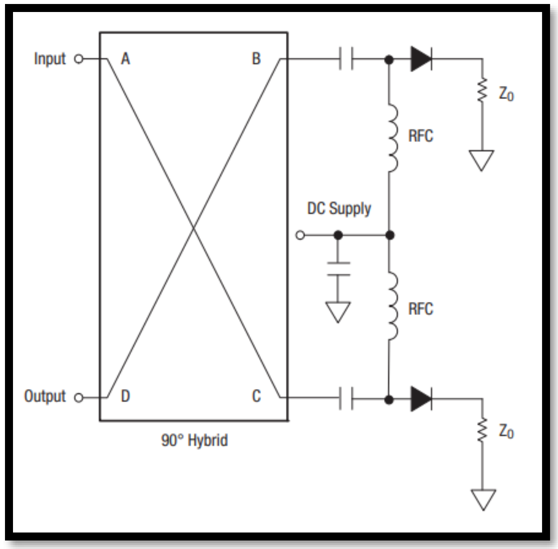

Figure 15: Series 90 Degree Hybrid Attenuator [2]

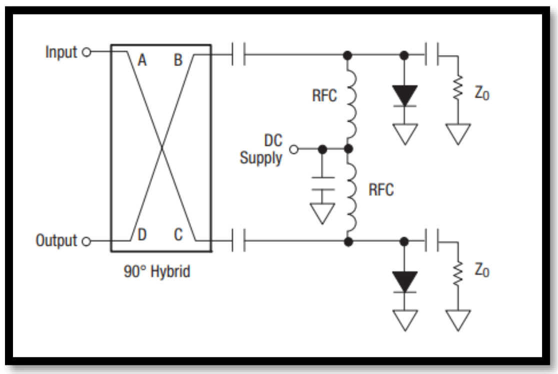

Figure 16: Shunt 90 Degree Hybrid Attenuator [2]

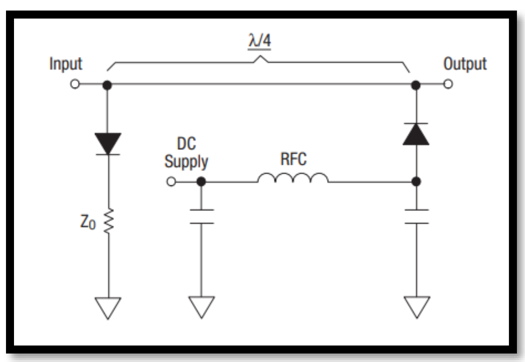

Figure 17: Quarter Wave Series Connected Matched Attenuator

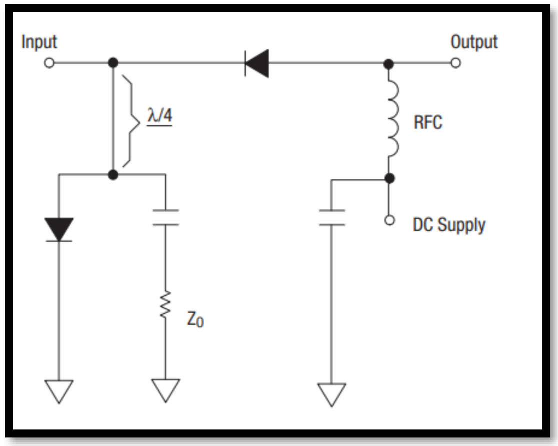

Figure 18: Quarter Wave Shunt Connected Matched Attenuator

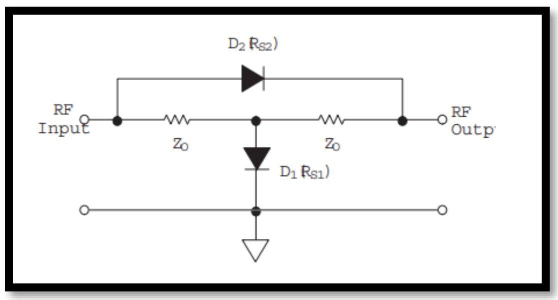

Figure 19: Bridged TEE Attenuator

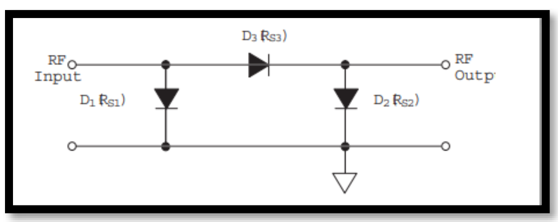

Figure 20: Pi Attenuator

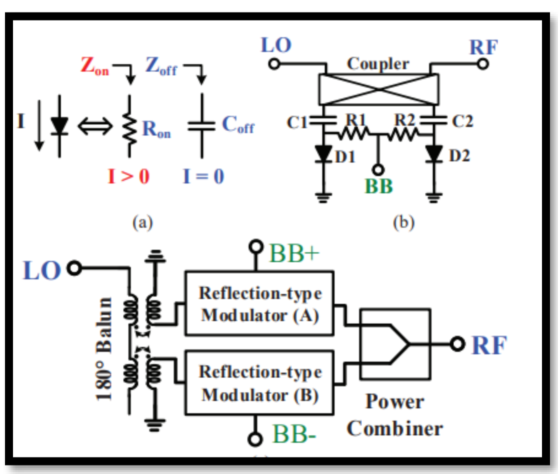

Figure 21: Modulator Circuit in [5]

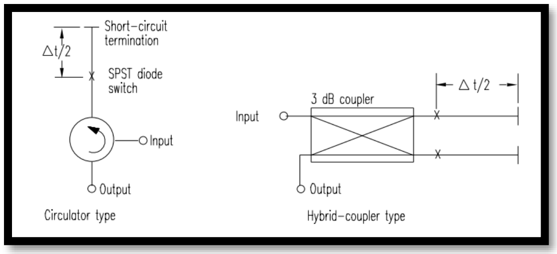

Figure 22: Simple Phase Shifter Example

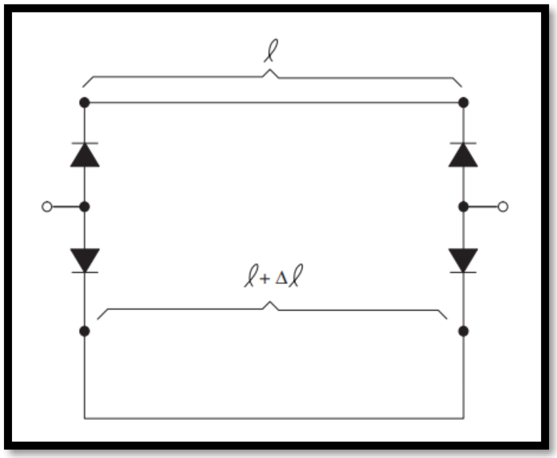

Figure 23: Two Branch Switched Line Phase Shifter

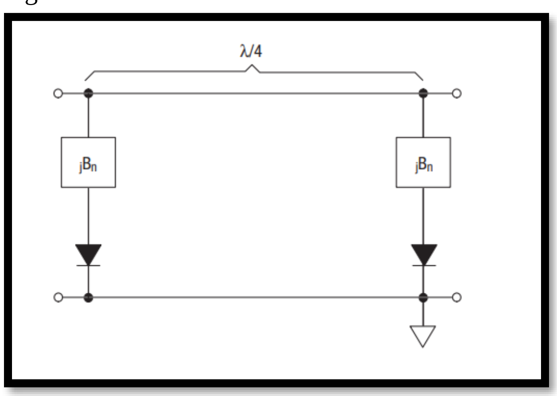

Figure 24: Loaded Line Phase Shifter

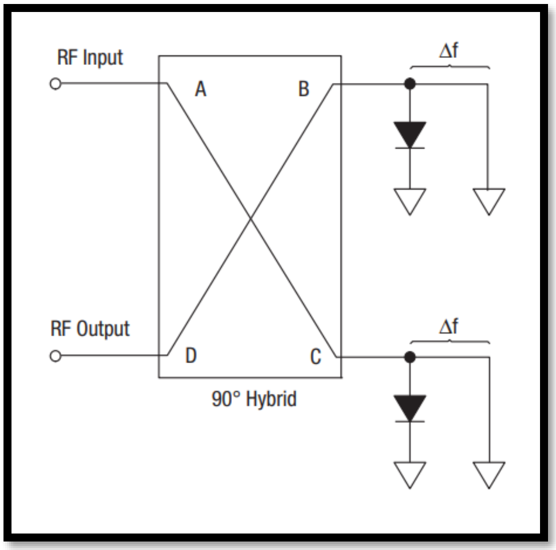

Figure 25: Reflective Phase Shifter using 90 Degree Hybrid [2]

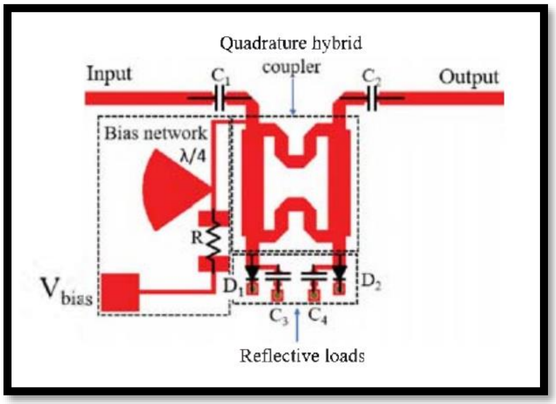

Figure 26: Layout used in [6]

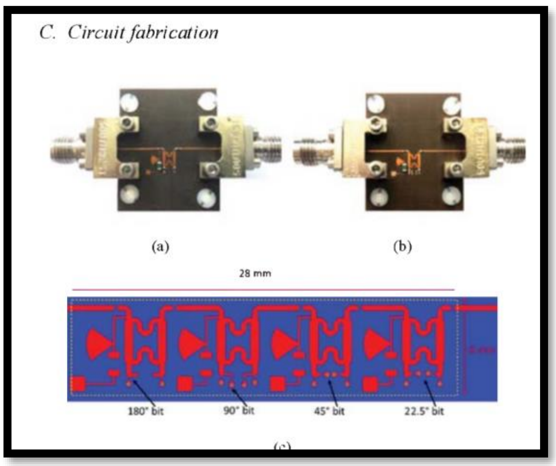

Figure 27: Realization in [6]

APPENDIX C: TABLES

Table 1: Switch Equation Summary [1]

TYPE	ISOLATION (dB)*	INSERTION LOSS (dB)
SERIES	$10\log\left[1+\frac{1}{\left(4\pi fC_T Z_0\right)^2}\right]$	$20\log\left(1+\frac{R_S}{2Z_0}\right)$
SHUNT	$20\log\left(1+\frac{Z_0}{2R_S}\right)$	$10\log\left[1+\left(\pi fC_T Z_0\right)^2\right]$
SERIES-SHUNT	$10\log\left[\left(1+\frac{Z_0}{2R_S}\right)^2 + \frac{1}{4\pi fC_T Z_0}\left(1+\frac{Z_0}{R_S}\right)^2\right]$	$10\log\left[\left(1+\frac{R_S}{2Z_0}\right) + \left(\pi fC_T\right)^2\left(Z_0+R_S\right)^2\right]$
TEE	$10\log\left[1+\left(\frac{1}{2\pi fC_T Z_0}\right)^2\right] + 10\log\left[\left(1+\frac{Z_0}{2R_S}\right)^2+\left(\frac{1}{4\pi fC_T R_S}\right)^2\right]$	$20\log\left(1+\frac{R_S}{2Z_0}\right) + 10\log\left[1+\left(\pi fC_T\right)^2\left(Z_0+R_S\right)^2\right]$

* For SPNT Switch, Add 6 dB

Table 2: Comparison of W-Band SPDT Switches in [4]

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 (mm^2)	0.94	0.05	0.11	0.14	**0.14**

* Aluminum pads have not been de-embedded.

** Limited by available source power.

Table 3: Performance Summary Seen in [5]

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**

Table 4: Comparison Summary in [6]

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

Table 5: Circuit Conclusions Summary Table

Circuit Variant	Advantages	Disadvantages
Switches - Series	Minimal insertion loss; simple bias circuitry; easier PCB layout	Lower isolation; limited power handling
Switches - Shunt	Higher isolation; can handle more power	Signal is shunted to ground
Switches - Compound (Series-Shunt)	Higher degree of isolation; can combine benefits of series and shunt	Increased insertion loss; complex bias circuits; potential VSWR degradation from mismatches
Switches - Tuned	Enhanced performance; can be optimized for specific frequencies	Usually narrowband; more complex design
Phase Shifters - Switched Line	Simple design; direct control over phase shift	Limited to the phase shift range of individual branches; typically requires multiple cells
Phase Shifters - Loaded Line	Can handle higher power; more robust	Limited phase shift (max 45 degrees); requires cascading for higher shifts
Phase Shifters - Reflective (90 Degree Hybrid)	Handles the largest RF power; significant incremental phase shift	Complexity in design
Attenuators - Reflective	Simple design; effective for certain applications	Signal reflections can be problematic; not matched across bandwidth
Attenuators - Matched	Provides constant impedance; can be finely tuned	Complex design; requires careful bias tracking
Attenuators - Quadrature Hybrid	Good matching; higher power handling capability	Complexity
Attenuators - Quarter Wave	Matched impedance; good for specific attenuation settings	Device variation can affect performance; typically for narrow bandwidth