Telecommunications
Microwave

PIN Diodes, Microwave Tees,
and Applications

Courseware Sample
39975-F0
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Safety and Common Symbols

The following safety and common symbols may be used in this manual and on the equipment:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="DANGER" /></td>
<td>DANGER indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.</td>
</tr>
<tr>
<td><img src="image" alt="WARNING" /></td>
<td>WARNING indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.</td>
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<tr>
<td><img src="image" alt="CAUTION" /></td>
<td>CAUTION indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.</td>
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<td><img src="image" alt="CAUTION" /></td>
<td>CAUTION used without the Caution, risk of danger sign indicates a hazard with a potentially hazardous situation which, if not avoided, may result in property damage.</td>
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<td><img src="image" alt="Caution, risk of electric shock" /></td>
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<td><img src="image" alt="Caution, risk of danger" /></td>
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<td><img src="image" alt="Earth (ground) terminal" /></td>
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# Safety and Common Symbols

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<th>Symbol</th>
<th>Description</th>
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<tr>
<td><img src="image1" alt="Symbol" /></td>
<td>Protective conductor terminal</td>
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<td><img src="image5" alt="Symbol" /></td>
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<tr>
<td><img src="image6" alt="Symbol" /></td>
<td>Equipment protected throughout by double insulation or reinforced insulation</td>
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<tr>
<td><img src="image7" alt="Symbol" /></td>
<td>In position of a bi-stable push control</td>
</tr>
<tr>
<td><img src="image8" alt="Symbol" /></td>
<td>Out position of a bi-stable push control</td>
</tr>
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</table>

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Please send these to did@de.festo.com.
The authors and Festo Didactic look forward to your comments.
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Courseware Outline

PIN DIODES, MICROWAVE TEES, AND APPLICATIONS

Exercise 1 PIN Diodes


Exercise 2 Wireless Video Transmission System (Optional)

Implementation and testing of a wireless video transmission system that uses a PIN diode as a microwave AM modulator. Effects that constructive and destructive interference has on the strength of the signal received and on the image displayed by the video/TV receiver.

Exercise 3 Hybrid Tees

Introduction to waveguide tees. The hybrid (magic) tee. Using a hybrid tee as a power splitter or a power combiner. Attenuation between the H- and E-plane arms of the tee and each of its lateral arms. Typical applications of hybrid tees.

Appendices

A Common Symbols
B Equipment Utilization Chart
C The Lab-Volt PIN Diode/RF Oscillator Controller, Model 9588
Sample Exercise

Extracted from
PIN Diodes, Microwave Tees,
and Applications
PIN Diodes

EXERCISE OBJECTIVE

Upon completion of this exercise, you will be familiar with the construction and operation of PIN diodes. You will know how to characterize the Lab-Volt PIN diode. You will be able to demonstrate that a PIN diode can be used to switch microwave signals. Finally, you will be able to name various applications for PIN diodes.

DISCUSSION

Introduction

A PIN diode is a semiconductor device that acts like a variable resistor at microwave frequencies. The resistance of the diode is controlled by varying the DC current used to forward bias the diode.

The word PIN is an acronym indicating the three types of materials that form the diode (see Figure 1-1):

- A P layer of highly doped P-type material
- An I (intrinsic) layer of undoped, or slightly doped semiconductor material
- An N layer of highly doped N-type material

At DC or low frequencies, a PIN diode acts like an ordinary PN diode: it has a nonlinear current-versus-voltage response when forward biased; and it blocks current flow when reverse biased.

Figure 1-1. Cross sectional view of a PIN diode.
Operation of a PIN Diode When Forward Biased

A PIN diode is said to be **forward biased** when the polarity of its P layer is **positive** relative to the polarity of the N layer. In that case, a DC bias current can flow through the diode.

When an RF signal is applied to the diode, holes and electrons from the P and N layers move towards the I layer. There, the holes and electrons do not recombine immediately. This occurs because the I layer increases the number of minority carriers, thereby increasing the minority carrier lifetime.

If the period of the RF signal is shorter than the minority carrier lifetime, the diode will lack sufficient time to pass from the "on" (conducting) state to the "off" (blocked) state. Therefore, the diode will allow the RF signal to pass through during the entire signal's period, offering a certain resistance to the passing of this signal.

At RF frequencies, therefore, a PIN diode does not behave like an ordinary PN diode, but like a **linear variable resistor**, even in the presence of strong RF signals.

The frequency at which a PIN diode stops acting like a PN diode and starts acting like a linear variable resistor is called the **transition frequency**. The transition frequency is a function of the thickness of the I layer.

The advantage of a PIN diode at or above the transition frequency becomes a disadvantage at lower frequencies: thus, the PIN diode cannot be used as a rectifier at lower frequencies.

Typical Resistance-Versus-Bias Current Response of a Forward Biased PIN Diode

Figure 1-2 shows the typical resistance-versus-bias current response of a forward biased PIN diode at microwave frequencies. The higher the bias current is, the lower the resistance of the I layer to the passing of microwave signals will be.

As the bias current increases, the resistance of the diode decreases rapidly. Beyond a certain bias current, the diode resistance becomes quite constant: the PIN diode can be considered as fully "on" (conducting).

Note that a PIN diode will not conduct if the bias current is below some minimum level. Below this level, the resistance of the I layer remains very high.
Figure 1-2. Typical resistance-versus-forward bias current response of a PIN diode at microwave frequencies.

**Equivalent RF Circuit of a Forward Biased Diode**

The equivalent RF circuit of a forward biased PIN diode is dependent upon the way the diode is constructed (structure and packaging), and the quality of the coupling between the diode and the waveguide (if it is used in a waveguide).

Figure 1-3 shows the construction of the Lab-Volt PIN Diode, Model 9358, and its equivalent RF circuit with and without shunt compensation.

- As Figure 1-3 (a) shows, the Lab-Volt PIN Diode is coupled to the waveguide through metal posts.

- The metal posts act like an inductor in series with the diode. This forms a series RL circuit across the waveguide, as Figure 1-3 (b) shows. $jX_L$ is the sum of the inductance reactances of the metal posts and diode stud.

- The series RL circuit can be converted into the equivalent parallel circuit shown in Figure 1-3 (c).

  In this condition, $X_L$ is not high enough, relative to the characteristic impedance ($Z_0$) of the waveguide, to prevent significant absorption and reflection losses.

- To reduce these losses to a minimum, a capacitive metal disk is added to the diode assembly [see Figure 1-3 (a)].

  The addition of the disk connects a capacitive reactance, $-jX_C$, in parallel (shunt) with the circuit of Figure 1-3 (c), giving the equivalent circuit of Figure 1-3 (d).

- The capacitive reactance is tuned so that, at the operating (resonant) frequency, $jX_C = jX'_L$. The tuning is performed with the resistance of the PIN diode at the minimum (forward bias current set to the maximum).

  At resonance, $X'_L = X_C$, so that the equivalent circuit becomes a shunt impedance, $R'$, across the waveguide, as Figure 1-3 (e) shows. Since $R'$ is much greater than $Z_0$, the attenuation provided by the diode is negligible below a minimum forward bias current.
Note: The explanations and circuits provided in this section apply specifically to the Lab-Volt PIN Diode, Model 9538. Since PIN diodes can be mounted in several different ways (e.g. parallel mounting, series mounting, etc.), their equivalent RF circuits will change accordingly.

Figure 1-3. Equivalent RF circuit of the Lab-Volt PIN Diode (forward biased) with and without shunt compensation.
PIN Diodes

Operation of a PIN Diode When Reverse Biased

A PIN diode is said to be reverse biased when the polarity of its P layer is negative relative to the polarity of the N layer. In this condition, the diode acts essentially like a capacitance, providing a high resistance independently of the reverse voltage across it.

Figure 1-4(a) shows the equivalent RF circuit of the Lab-Volt PIN Diode in the reverse biased condition. \( R \) is the reverse parallel resistance of the diode. This resistance is much greater than the diode package capacitance, \( X_C \).

The circuit of Figure 1-4(a) can be converted into the equivalent series circuit of Figure 1-4(b). At the operating (resonant) frequency, \(-jX'_C = jX_L\), so that the equivalent circuit becomes a shunt impedance, \( R' \), across the waveguide, as Figure 1-4(b) shows. Since \( R' \) is much lower than \( Z_0 \), the attenuation provided by the diode is very high due to strong reflections produced at the diode.

![Figure 1-4. Equivalent RF circuit of the Lab-Volt PIN Diode in the reverse biased condition.](image)

Attenuation of a Reverse Biased PIN Diode as a Function of Frequency

The high attenuation provided by a PIN diode in the reverse biased condition varies with frequency. This occurs because the structure and packaging of the diode cause its equivalent circuit to have a frequency-sensitive response. Figure 1-5 shows an example of an attenuation-versus-frequency curve of a PIN diode in the reverse biased condition.
PIN Diodes

Applications of PIN Diodes

PIN diodes are used in numerous microwave and wireless applications, including those listed below.

- They are used for **microwave switching**.
- They are used as **variable attenuators**. PIN diode attenuators can be designed as **matched** or **reflective**.
- They are used for **amplitude modulation and leveling** of microwave signals.
- They are used as **microwave phase shifters**.

Figure 1-5. Example of an attenuation-versus-frequency curve of a PIN diode in the reverse biased condition.
PIN Diodes

Procedure Summary

In the first part of this exercise, you will characterize the Lab-Volt PIN Diode by plotting the following response curves at 10.525 GHz: the bias current-versus-bias voltage curve, and the attenuation-versus-bias current curve.

In the second part of the exercise, you will use the PIN Diode as a microwave switch. To do this, you will modulate the amplitude of the bias voltage applied to the diode with a 1-kHz square-wave signal.

In the third part of the exercise (optional), an additional curve is plotted to complete characterization of the PIN Diode: the attenuation-versus-frequency curve of the diode.

Note: The third part of the exercise section requires the use of the Lab-Volt Voltage Controlled RF Oscillator, Model 9511, available as an option, and a power meter able to provide stable power readings to -45 dBm or lower with the required probe adapter.

PROCEDURE

Characterization of the PIN Diode

1. Make sure that all power switches are set to the O (off) position. Set up the modules as shown in Figure 1-6.

![Figure 1-6. Module arrangement.](image)

DB-9 SUPPLY CABLE

DB-9 CONNECTOR

POWER METER

GUNN OSCILLATOR POWER SUPPLY

PIN DIODE/RF OSCILLATOR CONTROLLER

PIN DIODE ENG MONITORING OUTPUTS

TO RF OSCILLATOR

AMPLITUDE MODULATION

INPUT SELECT

OUTPUT SELECT

INPUT SELECT

OUTPUT SELECT

INPUT SELECT

OUTPUT SELECT
As the figure shows, connect the DB-9 supply cable of the PIN Diode/RF Oscillator Controller to the DB-9 connector at the top of the Power Meter. This will allow the controller to be powered via the internal power buses of the Gunn Oscillator Power Supply and Power Meter when these modules are turned on.

2. Assemble the setup of Figure 1-7.

- Before connecting the Thermistor Mount into the setup, withdraw the matching screws so that they do not penetrate into the waveguide.

- Connect the PIN DIODE BIAS AND MODULATION OUTPUT of the PIN Diode/RF Oscillator Controller to the BNC input of the PIN Diode.

**CAUTION!**

The PIN DIODE BIAS AND MODULATION OUTPUT of the PIN Diode/RF Oscillator Controller is intended to be connected to the PIN Diode input only. Connection of this output to other modules or components might result in damage to the equipment.

- On the PIN Diode/RF Oscillator Controller, connect a DC voltmeter across the "V" terminals of the PIN DIODE BIAS MONITORING OUTPUTS. Connect a DC ammeter in series with the "I" terminals of these outputs (see Figure 1-7).

Do not leave the "I" terminals unconnected, otherwise no bias voltage will be applied to the PIN Diode.

**Note:** If you want to use a single multimeter to perform the PIN Diode's bias voltage and bias current measurements required in this section, proceed as directed below.

- To perform DC bias voltage measurements: connect the multimeter (set to measure DC voltage) across the "V" terminals of the PIN DIODE BIAS MONITORING OUTPUTS. The "I" terminals of the PIN DIODE BIAS MONITORING OUTPUTS must be interconnected with the provided bypass jumper (shown in Figure 1-7), otherwise no bias voltage will be applied to the PIN Diode.

- To perform DC bias current measurements: remove the bypass jumper from the "I" terminals of the PIN DIODE BIAS MONITORING OUTPUTS, then connect the multimeter (set to measure DC current) in series with these terminals. The "V" terminals must be left unconnected. If these terminals are interconnected, no bias voltage will be applied to the PIN Diode.
3. Make the following settings:

On the Gunn Oscillator Power Supply:

VOLTAGE ......................................................... MIN.
MODE ........................................................... DC
METER RANGE ........................................... 10 V
4. Turn on the Gunn Oscillator Power Supply and the Power Meter. Wait for about 5 minutes to allow the modules to warm up. On the Power Meter, use the ZERO ADJUST knobs to align this meter’s needle with the 0-mW mark.

5. Set the Gunn Oscillator’s supply voltage to the maximum.

6. On the Thermistor Mount, adjust the moveable short circuit and the matching screws to maximize the power reading on the Power Meter.

Note: If the Power Meter reading is less than 3 mW, select the 3-mW RANGE on the Power Meter. Readjust the zero of the Power Meter: disconnect the cable at the OUTPUT of the Gunn Oscillator Power Supply, then realign the Power Meter needle with the 0-mW mark by using the ZERO ADJUST knobs. Reconnect the Gunn Oscillator to the Gunn Oscillator Power Supply and then perform step 6.

7. When the PIN DIODE BIAS knob of the PIN Diode/RF Oscillator Controller is set to the fully clockwise (CW) position, the maximum forward bias voltage is currently applied to the PIN Diode.

In this case, the current flowing through the PIN Diode is maximum. This causes the resistance of the diode to the passing of the Gunn Oscillator’s output signal to be minimum, so that the Power Meter reads the maximum power. In the first row of Table 1-1,

- record the DC voltage present across the "V" terminals of the controller’s PIN DIODE BIAS MONITORING OUTPUTS, \( \Delta V_{(\text{MAX})} \), as indicated by the DC voltmeter.
- record the DC current flowing through the "I" terminals of the controller’s PIN DIODE BIAS MONITORING OUTPUTS, \( I_{\text{BIAS(MAX)}} \), as indicated by the DC ammeter.
- record the power absorbed by the thermistor, \( P_{\text{READ(MAX)}} \), as indicated by the Power Meter.
## PIN Diodes

<table>
<thead>
<tr>
<th>Voltage Across the &quot;V&quot; Terminals, $\Delta V$ (V)</th>
<th>Pin Diode Bias Current, $I_{bias}$ (mA)</th>
<th>Pin Diode Bias Voltage, $V_{bias}$ (V)</th>
<th>Power Meter Reading, $P_{read}$ (mW)</th>
<th>Attenuation, $A$ (dB)</th>
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<tr>
<td>BIAS KNOB FULLY CW: $\Delta V_{(max.)} =$ ______</td>
<td>$I_{bias_{(max.)}} =$ ______</td>
<td>$P_{read_{(max.)}} =$ ______</td>
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<td>BIAS KNOB FULLY CCW: $\Delta V_{(min.)} =$ ______</td>
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Table 1-1. Determining the characteristics of the PIN Diode at 10.525 GHz.
8. Fill in the columns "PIN DIODE BIAS CURRENT" and "POWER METER READING" of Table 1-1. Adjust the DC voltage across the "V" terminals of the controller's PIN DIODE BIAS MONITORING OUTPUTS to each of the ΔV settings listed in the leftmost column of the table, using the controller's PIN DIODE BIAS knob.

- For each ΔV setting, measure the DC current flowing through the "I" terminals of the controller's PIN DIODE BIAS MONITORING OUTPUTS, I_{BIAS}, and record it in the column "PIN DIODE BIAS CURRENT".

- For each ΔV setting, measure the power absorbed by the thermistor, P_{READ}, as indicated by the Power Meter, and record it in the column "POWER METER READING".

   **Note:** To ensure accuracy of power measurements: each time the Power Meter reading becomes lower than the maximum value of the next lower RANGE, select that RANGE and readjust the zero of the Power Meter (that is, disconnect the cable at the OUTPUT of the Gunn Oscillator Power Supply, select the next lower range on the Power Meter, and then realign the Power Meter needle with the 0-mW mark by using the ZERO ADJUST knobs. Reconnect the Gunn Oscillator to the Gunn Oscillator Power Supply and then perform the power measurement.

   **Note:** For ΔV settings below 0.7 V approximately, the PIN Diode bias current will be approximately null, and the Power Meter reading will stay at some low, minimum level.

9. Fill in the column "PIN DIODE BIAS VOLTAGE" of Table 1-1. To do this, use the data recorded in the two leftmost columns of this table, and the formula below.

   **Note:** The formula below permits calculation of the bias voltage actually applied to the PIN Diode, V_{BIAS}, by accounting for the voltage drop caused by a 620-Ω resistor internally connected between the BNC input of the PIN Diode and the diode itself.

   \[ V_{BIAS} = \Delta V - \frac{620 \, \Omega \times I_{BIAS \, (mA)}}{10^3} \]

10. Fill in the column “ATTENUATION” of Table 1-1. To do this, use the data recorded in the column "POWER METER READING" of this table, and the formula below.

   \[ \text{Attenuation} = 10 \log \left( \frac{P_{READ \, (MAX.)}}{P_{READ}} \right) \]

   where

   \( P_{READ \, (MAX.)} \): Power Meter reading at ΔV \(_{MAX}\) (as recorded at the top of the table’s column "POWER METER READING").
11. From the results recorded in Table 1-1, plot in Figure 1-8 the bias current-versus-bias voltage curve of the PIN Diode at 10.525 GHz.

According to the obtained curve, describe how the bias current through the PIN Diode varies as a function of the bias voltage.

12. In the curve of Figure 1-8, is there a certain "dead zone" within which increasing the DC voltage results in no corresponding increase in the bias current? Explain.
13. From the results recorded in Table 1-1, plot the attenuation-versus-bias current curve of the PIN Diode at 10.525 GHz in Figure 1-9.

According to the curve obtained, describe how the attenuation provided by the PIN Diode varies as a function of the bias current and explain why this occurs.

![Figure 1-9. Attenuation-versus-bias current curve of the PIN Diode at 10.525 GHz.](image)

14. Disconnect the Gunn Oscillator's cable from the Gunn Oscillator Power Supply.

Set up the system as shown in Figure 1-10.

On the PIN Diode/RF Oscillator Controller, make sure the provided bypass jumper is connected between the "I" terminals of the PIN DIODE BIAS MONITORING OUTPUTS, as Figure 1-10 shows.
Reconnect the Gunn Oscillator's power supply cable to the Gunn Oscillator Power Supply. Wait for about 5 minutes to allow the modules to warm up.

15. On the PIN Diode/RF Oscillator Controller, make the following settings in order to modulate the amplitude of the bias voltage applied to the PIN Diode with a 1-kHz square-wave signal:

**AMPLITUDE MODULATION section:**

- "1-kHz/=" switch ........................................... 1 kHz
- PIN DIODE/RF OSCILLATOR switch ............ PIN DIODE

Figure 1-10. Setup used to perform microwave switching with a PIN Diode.
Note: When setting the controller to modulate the bias voltage applied to the PIN Diode with a 1-kHz square-wave signal, the setting of the PIN DIODE BIAS knob has no effect on the bias voltage to the diode. Refer to Appendix C of this manual for the detailed description of the PIN Diode/RF Oscillator Controller.

16. On the oscilloscope, make the following settings:

- Time base ......................... 0.2 ms/DIV
- Channel 1 .................................. 20 mV/DIV
- Input Coupling .............................. GND
- Vertical Mode ............................... Channel 1
- Trigger ..................................... Channel 1
- Trigger Coupling ......................... AC
- Trigger Mode ............................... Auto

17. Adjust the vertical position of the oscilloscope trace to the second line from the bottom of the graticule. Select DC Coupling for Channel 1.

18. Adjust the blade position of the Variable Attenuator so that the peak amplitude of the Crystal Detector’s output voltage (proportional to the Gunn Oscillator’s output signal power) is approximately 100 mV on the oscilloscope screen, as Figure 1-11 shows.

The Crystal Detector’s output voltage is very similar in shape to the 1-kHz square-wave signal produced by the PIN Diode/RF Oscillator Controller to modulate the bias voltage applied to the PIN Diode.

This occurs because

- when the 1-kHz square-wave modulating signal is at logic level 1, a high forward bias current flows through the PIN Diode. In this condition, the impedance of the PIN Diode’s equivalent RF circuit (i.e. shunt resistor R') is much higher than the characteristic impedance of the waveguide, Z₀, causing the reflections produced at the diode, and therefore the attenuation of the diode, to be negligible. The Crystal Detector’s output voltage, therefore, is at some maximum level.

- when the 1-kHz square-wave modulating signal is at logic level 0, no current flows through the PIN Diode. In this condition, the impedance of the PIN Diode’s equivalent circuit (i.e. shunt resistor R') is much lower than Z₀, causing attenuation of the diode to be very high due to reflections produced at the diode.
Figure 1-11. Crystal Detector's output voltage on oscilloscope-channel 1.

- Observe that the voltage rises quite quickly, the rising edge becoming rounded at the top [Figure 1-12 (a)].

- Observe that the voltage falls rather slowly, the falling edge having the same shape as the voltage across a capacitor discharging through a series capacitor. [Figure 1-12 (b)].

Record below if this is what you observe, and explain why this occurs.
Figure 1-12. Rising edge (a) and falling edge (b) of the Crystal Detector’s output voltage.
PIN Diodes

20. On the oscilloscope, set the oscilloscope time base to 0.2 ms/DIV. Increase the channel-1 sensitivity in order to be able to measure the minimum level of the Crystal Detector’s output voltage, as Figure 1-13 shows. Record your result below. Explain why this voltage is not perfectly null (0 V).

Figure 1-13. Measuring the minimum level of the Crystal Detector’s output voltage.

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Attenuation-Versus-Frequency Curve of the PIN Diode (Optional Section)

Note: This section requires the use of the Lab-Volt Voltage Controlled RF Oscillator, Model 9511, offered as option, and a power meter able to provide stable power readings down to -45 dBm or lower, with the required probe adapter.

21. On the Gunn Oscillator Power Supply, set the VOLTAGE control knob to the MIN. position, then set the POWER switch to the O (off) position.
Assemble the components as shown in Figure 1-14.

Note: In the setup of Figure 1-14, an Anritsu™ Model 2437A power meter is used. It is connected to the microwave circuit via a Lab-Volt waveguide-to-coaxial transition, Model 28631.

22. On the PIN Diode/RF Oscillator Controller, set the AMPLITUDE MODULATION switches as follows:

- 1-kHz/Hz switch ...................................... "=" (DC)
- PIN DIODE/RF OSCILLATOR switch ............... RF OSCILLATOR
PIN Diodes

23. Turn on the Gunn Oscillator Power Supply and your power meter.

Wait for about 5 minutes to allow the modules to warm up.

24. Since the AMPLITUDE MODULATION switches of the PIN Diode/RF Oscillator Controller are set to "=" (DC) and to "RF OSCILLATOR",

- the controller applies an unmodulated DC voltage to the VCO of the Voltage Controlled RF Oscillator. Therefore, the RF oscillator's output signal is an unmodulated microwave signal whose frequency can be varied, over the nominal range of 9.6 to 10.6 GHz, using the controller's RF OSCILLATOR FREQUENCY knob;

- the controller is applying an unmodulated bias voltage to the PIN Diode; the magnitude of this voltage can be varied by using the controller's PIN DIODE BIAS knob.

Note: If required, refer to Appendix C of this manual for the detailed description of the PIN Diode/RF Oscillator Controller.

25. On the PIN Diode/RF Oscillator Controller, adjust the RF OSCILLATOR FREQUENCY knob until the frequency of the Voltage Controlled RF Oscillator's output signal is 9.6 GHz (by referring to the frequency counter reading multiplied by the prescaler factor of 64—that is, the counter must read 150.0 MHz approximately). 9.6 GHz is the nominal minimum frequency of the RF oscillator's output signal.

26. With the RF Oscillator's output signal frequency set to 9.6 GHz, measure the maximum attenuation that the PIN Diode can provide, using the steps below.

a. On the PIN Diode/RF Oscillator Controller, set the PIN DIODE BIAS knob to the fully counterclockwise position to apply the minimum bias voltage. This sets the attenuation provided by the PIN Diode to the maximum.

b. Note and record the RF power indicated by the power meter in the "9.6 GHz" row of Table 1-2, under the column "MINIMUM POWER".

c. On the PIN Diode/RF Oscillator Controller, set the PIN DIODE BIAS knob to the fully clockwise position. This sets the attenuation provided by the PIN Diode to the minimum.

d. Note and record the RF power indicated by the power meter in the row "9.6 GHz" of Table 1-2, under the column "MAXIMUM POWER".
e. From the data recorded in Table 1-2, calculate the maximum attenuation provided by the PIN Diode at 9.6 GHz, using the formula below. Record your result under the column "PIN DIODE MAXIMUM ATTENUATION" of the table.

$$\text{Maximum attenuation (dB)} = P_{\text{MIN, (dBm)}} - P_{\text{MAX, (dBm)}}$$

<table>
<thead>
<tr>
<th>RF OSCILLATOR OUTPUT SIGNAL'S FREQUENCY (GHz)</th>
<th>MINIMUM POWER, $P_{\text{MIN, (dBm)}}$</th>
<th>MAXIMUM POWER, $P_{\text{MAX, (dBm)}}$</th>
<th>PIN DIODE MAXIMUM ATTENUATION, A (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.6</td>
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<td>10.6</td>
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</tbody>
</table>

Table 1-2. Maximum PIN Diode attenuation at different frequencies.

☐ 27. On the PIN Diode/RF Oscillator Controller, adjust the RF OSCILLATOR FREQUENCY knob until the frequency of the Voltage Controlled RF Oscillator’s output signal is 9.7 GHz (by referring to the frequency counter reading multiplied by 64).

Then, repeat step 26 in order to fill the "9.7 GHz" row of Table 1-2.

☐ 28. Fill in the remainder of Table 1-2 by repeating step 27 for each of the other RF OSCILLATOR OUTPUT SIGNAL’s frequencies listed in Table 1-2.

☐ 29. From the results you obtained in Table 1-2, plot the maximum attenuation of the PIN Diode as a function of the frequency in Figure 1-15.
According to the curve obtained, does the maximum attenuation provided by the PIN Diode vary over the frequency range of 9.6 to 10.6 GHz? Explain.

Figure 1-15. Maximum attenuation-versus-frequency curve of the PIN Diode.

30. Turn off the Gunn Oscillator Power Supply by setting its POWER switch to the O (OFF) position. Disassemble the setup and return all components to their storage location.

CONCLUSION

In this exercise, you were introduced to PIN diodes. You learned that a PIN diode is a semiconductor device that acts like a variable resistor at microwave frequencies. The resistance of the diode is controlled by varying the DC current used to forward bias the diode.

You learned that when a PIN diode is forward biased, the diode allows RF signals having a period shorter than a certain time constant (τ, or minority carrier lifetime) to
PIN Diodes

pass through it, because it lacks sufficient time to pass from the "on" (conducting) state to the "off" (blocked) state.

You saw that as the bias current is increased, the resistance of the diode decreases rapidly, following a 1/x function. Beyond a certain bias current, the diode resistance becomes quite constant: the PIN diode can be considered as fully "on" (conducting).

Conversely, you learned that when a PIN diode is reverse biased, it acts as a capacitance, providing a high resistance independently of the reverse voltage across it. You saw that the high attenuation provided by a reverse biased PIN diode varies with frequency, as the structure and packaging of the diode cause its equivalent circuit to be frequency sensitive.

Finally, you learned that PIN diodes are used in numerous microwave applications, including microwave switching, variable attenuation, amplitude modulation and leveling, and wireless communication systems.

REVIEW QUESTIONS

1. What is a PIN diode? What does the acronym "PIN" stand for?

2. Briefly describe the typical resistance-versus-bias current response of a forward biased PIN diode at microwave frequencies.

3. How does a PIN diode behave when it is reverse biased?
PIN Diodes

4. What is meant by the "transition frequency" of a PIN diode? Explain.

5. List microwave applications in which PIN diodes are used.
Instructor Guide
Sample Exercise
Extracted from
PIN Diodes, Microwave Tees,
and Applications
## EXERCISE 1  PIN DIODES

### ANSWERS TO PROCEDURE STEP QUESTIONS

1.  

<table>
<thead>
<tr>
<th>VOLTAGE ACROSS THE &quot;V&quot; TERMINALS, ( \Delta V ) (V)</th>
<th>PIN DIODE BIAS CURRENT, ( I_{BIAS} ) (mA)</th>
<th>PIN DIODE BIAS VOLTAGE, ( V_{BIAS} ) (V)</th>
<th>POWER METER READING, ( P_{READ} ) (mW)</th>
<th>ATTENUATION, A (dB)</th>
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<td>-0.25</td>
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<td>0.0</td>
<td>-0.615</td>
<td>0.02</td>
<td>22.17</td>
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Table 1-1. Determining the characteristics of the PIN Diode at 10.525 GHz.
The curve shows that, when the bias voltage is negative, or below a minimum positive level of about 0.7 V DC, no bias current flows through the PIN Diode. When the minimum positive level is reached, the bias current increases rapidly with increasing bias voltage, quickly tending towards a quite constant level.

Yes. When the DC voltage across the PIN Diode is negative, the diode is reverse biased. Then, for the first tenths of positive volts, the I-layer resistance of the PIN Diode remains very high, so that no bias current flows through the diode.
13. Figure 1-9. Attenuation-versus-bias current curve of the PIN Diode at 10.525 GHz.

The curve shows that, as the bias current is increased, the attenuation decreases rapidly, following a $1/x$ function, quickly tending towards a quite constant level.

This occurs because, as the bias current is increased, the impedance of the PIN Diode's equivalent RF circuit [see Figure 1-3 (d)] becomes increasingly higher than the characteristic impedance of the waveguide, $Z_0$, causing the reflections produced at the diode, and therefore the attenuation of the diode, to become negligible.

19. First, one must remember the simplified microwave circuit of the Lab-Volt Crystal Detector, which can be represented as a diode rectifier in series with a low-pass (RC) filter. This was explained in the Lab-Volt Student Manual "Microwave Fundamentals" (part number 28113).

Therefore, while the Crystal Detector's output voltage is rising to the maximum level (the PIN Diode being fully conducting), the Crystal Detector's diode is forward biased. In this condition, the detected voltage can flow through the low resistance of the low-pass filter. The capacitance of the low-pass filter has little impact on the time constant of the rise in detected voltage, so the voltage can rise quickly.

When the PIN Diode is switched off, the Crystal Detector's output voltage, which is at the maximum level, must discharge through the capacitor of the
detector's low-pass filter, because the detector's diode is in the blocked condition. This increases the time constant of the decreasing voltage. (One way of reducing this time constant would be to connect a 50-\( \Omega \) resistor in parallel with the capacitance of the low-pass filter).

20. The minimum level of the Crystal Detector's output voltage should be around 1 mV, as shown in Figure 1-13. This voltage is not perfectly null because, as was seen when plotting the attenuation-versus-bias current curve, the attenuation provided by the diode at a bias voltage of 0.0 V is not infinite.

26.

<table>
<thead>
<tr>
<th>RF OSCILLATOR OUTPUT SIGNAL'S FREQUENCY, ( f ) (GHz)</th>
<th>MINIMUM POWER, ( P_{\text{MIN}} ) (dBm)</th>
<th>MAXIMUM POWER, ( P_{\text{MAX}} ) (dBm)</th>
<th>PIN DIODE MAXIMUM ATTENUATION, ( A ) (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.6</td>
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<td>10.6</td>
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Table 1-2. Maximum PIN Diode attenuation at different frequencies.
The curve shown in Figure 1-15 is an example of what you might obtain. The curve shows that the maximum attenuation varies over the frequency range of 9.6 to 10.6 GHz. Thus, as the frequency is increased, the maximum attenuation increases, reaching a maximum at around 10.5 GHz.

ANSWERS TO REVIEW QUESTIONS

1. A PIN diode is a semiconductor device that acts like a variable resistor at microwave frequencies. The resistance of the diode is controlled by varying the DC current used to forward bias the diode.

The acronym "PIN" indicates the three types of materials that form the diode:

- A P layer of highly-doped P-type material.
- An I (intrinsic) layer of undoped semiconductor material.
- An N layer of highly doped N-type material.
2. As the bias current is increased, the resistance of the diode decreases rapidly, following a 1/x function. Beyond a certain bias current, the diode resistance becomes quite constant: the PIN diode can be considered as fully “on” (conducting).

3. When a PIN diode is reverse biased, it acts like a capacitance, providing a high resistance independently of the reverse voltage across it. The high attenuation provided by a reverse biased PIN diode varies with frequency, due to the structure and packaging of the diode.

4. The frequency at which a PIN diode stops acting like a PN diode and starts acting like a linear variable resistor is called the transition frequency. The transition frequency is a function of the thickness of the I layer.

5. PIN diodes are used in the following microwave applications:
   - for microwave switching;
   - as variable attenuators, which can be designed to be absorptive or reflective.
   - for amplitude modulation and leveling of microwave signals.
   - as microwave phase shifters.
   - in wireless communication systems.