Designing Precision Attenuation In a Microwave PIN Diode Switch

Avoid the Problem of Attenuation Accuracy *vs.* Supply Current

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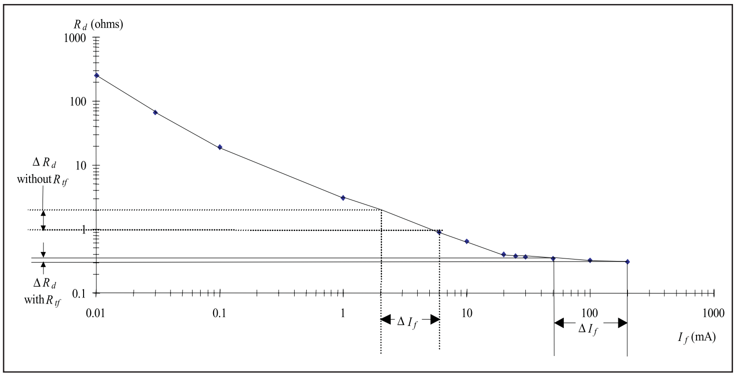
This paper presents a novel design method for delivering fixed RF attenuation over a wide supply current range I_f. Placing a small-value resistor R_{tf} in series with a current-controlled device such as a PIN diode creates an equivalent resistance R_{eq} that is less sensitive to current fluctuations. The sum of R_{tf} and the forward-bias resistance of a PIN diode R_d lessens the change in R_{eq} over I_f, thereby providing precise attenuation. Based upon this method, a mathematical expression for the total attenuation including R_{tf} is derived. Measurements of an SPDT absorptive switchable attenuator prove the technique.



■ **Figure 1. Series resistance R_d *vs.* forward-bias current I_f for a typical PIN diode.**

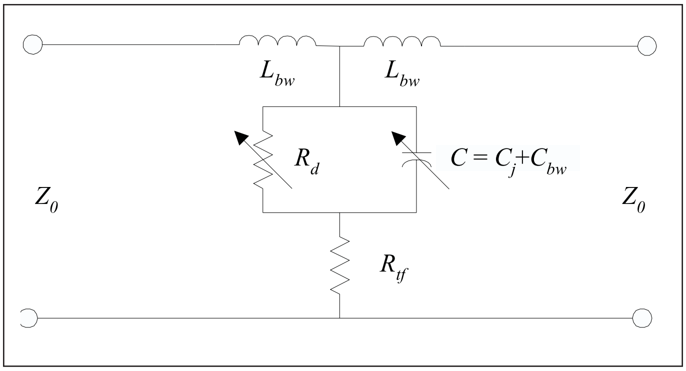
In space applications, the current and voltage from a power supply can drift due to temperature changes in the environment. This current drift can drastically alter the response of current-sensitive semiconductor devices. PIN diodes are used in circuits to switch between a low- and a high-RF attenuation simply by applying bias. In attenuator circuits, the exponential nature of a diode's current-voltage (I-V) curve can be a drawback. Changes in the supply current will result in a large change in the diode's resistance R_d.

When designing for fixed attenuation, a diode resistance R_d less affected by I_f is desirable. Figure 1 shows a typical series resistance curve R_d versus forward-bias current I_f. The challenge in designing precision attenuation with a fluctuating current is to find a region of the R_d *vs.* I_f curve where R_d is nearly constant. For example, if a particular amount of attenuation calls for 1.2 ohms of PIN diode resistance, then we would forward-bias the diode with I_f = 4 mA. However, temperature instabilities in the bias supply may cause this 4 mA to drift by +50 percent, resulting in R_d changing by +0.7 ohm. If we choose R_d = 0.2 ohm, then a +50 percent current drift results in an R_d variation of +0.01 ohm. Placing a 1 ohm thin-film resistor in series with R_d gets the 1.2 ohms needed for the attenuation. By choosing a region of the curve where R_d is more nearly constant, the attenuation will be less sensitive to current fluctuations.

This paper details a method for precision attenuation that withstands large variations of the diode's forward current. The next section provides the reader with a theoretical treatment of the technique, then that information is used to derive equations for the complete circuit. Finally, experimental results demonstrate the validity of the method.

PIN diode theory — Single PIN diode in shunt

In this section, an expression for a single PIN diode in shunt with a thin-film resistor R_{tf} is derived (see Figure 2). Using basic circuit theo-



■ **Figure 2. Shunt PIN diode equivalent circuit. Schematic includes resistor R_{tf} in series with the diode's cathode.**

Equivalent Circuit Values	
Circuit Capacitance	$C = C_j + C_{bw}$
Junction Capacitance	C_j
Bondwire Capacitance to Ground	C_{bw}
Bondwire Phase Velocity	$V_{bw} = l_{bw}/\sqrt{(L_{bw}C_{bw})}$
Circuit Cutoff Frequency	$f_c = 1/2\pi\sqrt{L_{bw}C}$
Bondwire Length, l_{bw}	0.006 in.
Bondwire Inductance, L_{bw}	0.12 nH
Diode Resistance, R_d (with R_{tf})	0.35 Ω (mean)
(without R_{tf})	2.2 Ω (mean)
Thin-film Resistance, R_{tf}	2.0 Ω

■ **Table 1. Equivalent circuit values for the PIN diode represented in Figure 2.**

ry [1, 2], we can show that S_{21} of Figure 2 is as shown in Equation (1), below:

$$S_{21} = \frac{R_d + R_{tf}(1 + j\omega CR_d)}{R_d\left[1 + j\omega\left(L_{bw} + \frac{C}{2}\right)\right] + \frac{1}{2} + \left[R_{tf} + j\omega L_{bw}\left(1 + R_{tf} - \frac{\omega^2 L}{2}\right)\right](1 + j\omega CR_d)} e^{\frac{-2j\omega l_{bw}}{V_{bw}}}$$

■ **Equation (1).**

The exponential term of (1) adjusts the phase so that the reference plane of all measurements is moved to the diode's anode bond pad. For a linear circuit, the magnitude of S_{21} can be found by equivalent circuit reduction [3] or by the ABCD matrix method [4]. The ABCD matrix approach is valid since the diode is approximated by either its forward-bias or reverse-bias equivalent circuit [5, 6]. Table 1 gives the experimental values for the circuit in Figure 2.

Two shunt PIN diodes spaced l/4 wavelength apart

The basis of the attenuator is two or more shunt diodes separated by λ/4. The ABCD matrix for the circuit of Figure 2 is:

$$A_D = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1+\dfrac{j\omega L_{bw}}{R_d+R_{tf}} & 2j\omega L_{bw} - \dfrac{\omega^2 L_{bw}}{R_d+R_{tf}} \\ \dfrac{1}{R_d+R_{tf}} & 1+\dfrac{j\omega L_{bw}}{R_d+R_{tf}} \end{bmatrix} \qquad (2)$$

where we have assumed $R_d \omega C \ll 1$ in the diode's forward-bias case. The ABCD matrix for a section of lossless transmission line of length λ/4 is [7]:

$$A_L = \begin{bmatrix} 0 & jZ_0 \\ jZ_0^{-1} & 0 \end{bmatrix} \qquad (3)$$

where Z_0 is the characteristic impedance of the transmission line. For two diodes separated by a λ/4 transmission line, the ABCD matrix is:

$$A_T = A_D A_L A_D = \begin{bmatrix} A & B \\ C & D \end{bmatrix}_T \qquad (4)$$

where

$$A = D = -Z_0^{-1}\omega L_{bw} Y_{eq}\left(1+Y_{eq}\right) + j\frac{Z_0 Y_{eq}}{R_d+R_{tf}}$$

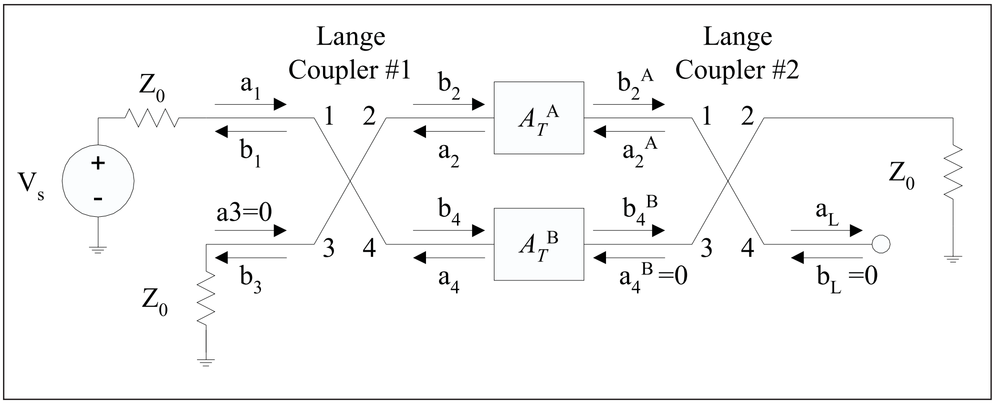
$$B = -j\omega^2 L^2{}_{bw} Z_0^{-1}\left(Y_{eq}+1\right)^2 + jZ_0 Y_{eq}^2$$

$$C = jZ_0^{-1} Y_{eq}^2 + j\frac{Z_0}{\left(R_d+R_{tf}\right)^2}$$

and

$$Y_{eq} = 1+\frac{j\omega L_{bw}}{R_d+R_{tf}} \qquad (5)$$

For greater isolation, we simply add more diodes λ/4 apart [8] and multiply Equation (4) by the ABCD matrix of the additional elements.



■ **Figure 3. Balanced attenuator schematic. A_T^A and A_T^B each represent two PIN diodes separated by a λ/4 line.**

$$S_{21}^{A,B} = \frac{2}{-2Z_0^{-1}\omega L_{bw} Y_{eq}\left(1+Y_{eq}\right) + j\left[\frac{Z_0}{R_d+R_{tf}}\left(2Y_{eq}+\frac{1}{R_d+R_{tf}}\right) + Y_{eq}^2\left(Z_0+Z_0^{-1}\right) - \omega^2 L^2 Z_0^{-1}\left(1+Y_{eq}\right)^2\right]}$$

■ **Equation (6).**

Attenuator circuit calculations

The complete circuit performance (Figure 3) can be calculated by finding the response of each of the circuit blocks and then combining them [9]. For any balanced design, it is desirable for both RF paths (A and B) to have identical electrical performance, so that reflecting signals cancel one another out when an input coupler is used. Referring to Equation (4), we convert the ABCD matrix to S-parameters to get Equation (6), shown above. That equation shows that the frequency of operation ω and bondwire inductance L_{bw} can significantly affect the attenuation. The S-parameters for a Lange coupler are well-known [10]. Having defined the S-parameters of the constituent elements, we can now use Figure 3 to derive the S-parameter response of the complete SPDT switch circuit.

S_{21} of the circuit is found by:

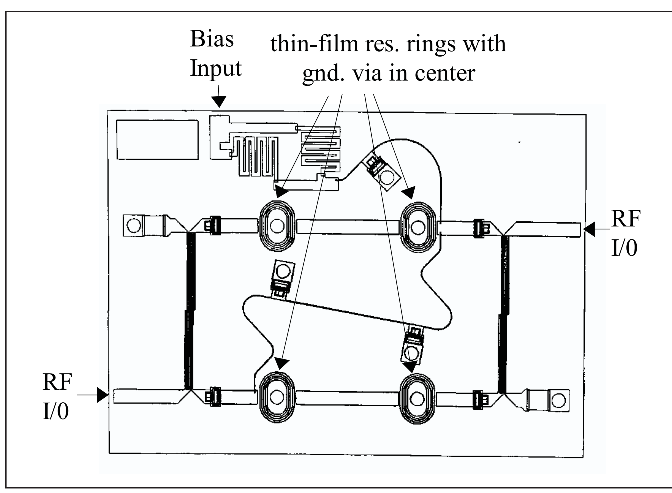
$$S_{21}^{ckt} = \left(\frac{a_L}{a_l}\right)^{ckt} = S_{41}^{L,C,\#2} S_{21}^{A} S_{21}^{L,C,\#1} + S_{43}^{L,C,\#2} S_{21}^{B} S_{41}^{L,C,\#1} \qquad (7)$$

Experimental results

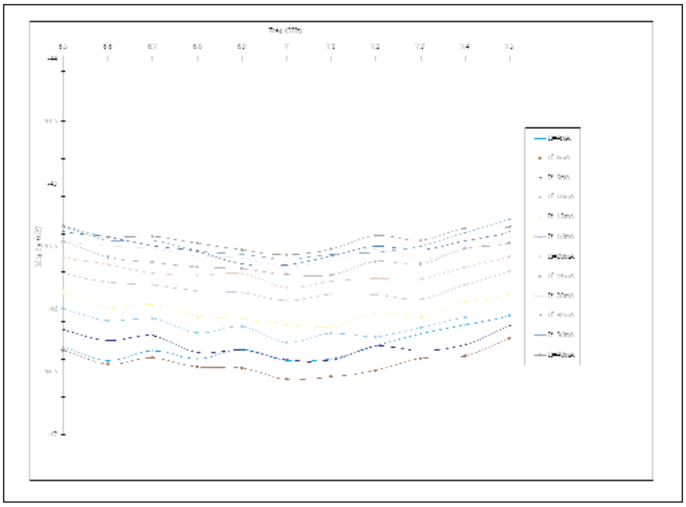
Figure 4 shows the experimental circuit designed for 45 dB of attenuation. It includes two 6.5-7.5 GHz, 3 dB Lange couplers with DC blocking capacitors at the through/coupled ports and a 50 ohm, 500 mW termination resistor at the isolated port. Each of the four oval pads is a 2.0 ohm resistor contacting a filled via at its center, resulting in a small resistance shunted to ground. A Narda Microwave GC4711 PIN diode was conductive-epoxied on top of each pad. Regarding the bias circuitry, three RF bypass capacitors were deposited λ/4 apart and two parallel 400 ohm serpentine resistors limit the input current. Care should be taken that the bias circuitry does not limit the response of the diodes. Except for the diodes, the entire circuit was thin-film deposited for ease of manufacturability.

Figure 5 shows the performance of the circuit without the shunt resistors. With the current varying over a 40 mA range, a 1.2 dB maximum attenuation variance was measured. The same circuit with the small resistor R_{tf} in series with the diode to ground showed a 0.2 dB maximum variance over an 800 mA range (Figure 6). The value of R_{tf} was chosen based on the value of R_{eq} needed to meet 45 dB attenuation specification and R_d (see Figure 1). In Table 1, note that the sum $R_{eq} = R_{tf} + R_d = 2.35$ ohm is not equivalent to R_d without the thin-film resistor. The diode's impedance was measured at 1 MHz instead of near the 7 GHz operating frequency, resulting in a slight difference in R_d.

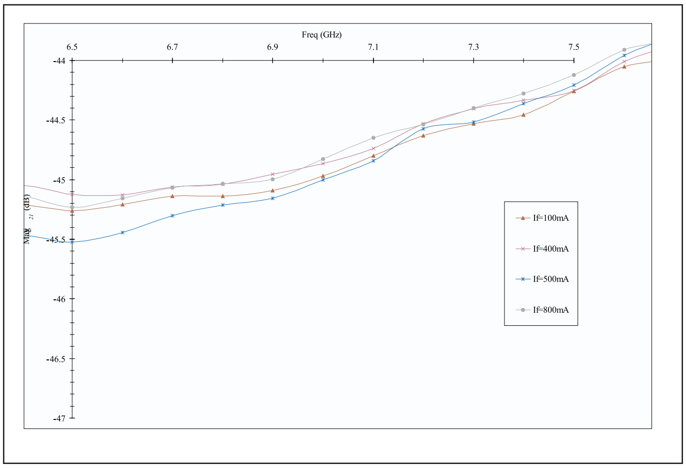
The measured response disagrees slightly with the expected results. The change in $|S_{21}|$ over frequency is worse in Figure 6, but this is believed to be due to the couplers. The narrowband Lange couplers are fine line structures and are sensitive to linewidth fabrication tolerances [11]. Also, if A and B paths are not perfectly balanced then the in-phase component of one path will not completely cancel with the out-of-phase component of



■ **Figure 4. Experimental thin-film switch circuit layout. Discrete PIN diodes are attached over the oval resistive pads using conductive epoxy.**



■ **Figure 5. Attenuation performance without R_{tf}.**



■ **Figure 6. Attenuation performance with R_{tf}.**

the other path. An imbalance between A_T^A and A_T^B may exist for several reasons. The PIN diodes might not have been created from the same wafer or the bond wire lengths may not be identical. The bias line going from A_T^A and A_T^B is separated by a high RF resistance 3l/4 line, which has a small DC voltage drop across it. This results in a slightly higher voltage being applied to A_T^A, causing slightly more current to flow in A_T^A and hence R_d to be slightly lower.

Summary

This paper presents a novel method of designing a circuit for a precise, fixed value of attenuation. Using a thin-film resistor R_{tf} mounted in shunt with a PIN diode cushions the effects of current variations through the PIN diode.

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