Application Note
AN10174-01

A Low Impedance PIN Diode Driver Circuit with Temperature Compensation

Two Philips BAP50-05 PIN diodes are used in an RF attenuator with a low impedance driver circuit to significantly decrease the rise and fall times. A standard attenuator with an unspecified driver is shown in Figure 1. Each of the two PIN diodes operates as an RF resistor whose value is controlled by the DC current[1]. The signals reflect off of the diodes and through the 3 dB hybrid in a way to add in phase. The amount of signal that is reflected off the diodes depends on the resistance value. In this circuit, the diodes are operated from several hundred ohms down to a value approaching 50 ohms, where there is no reflection and thus maximum attenuation.

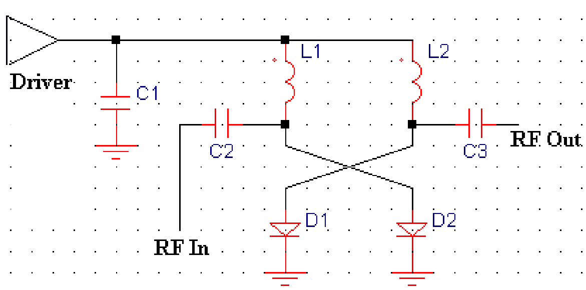

Figure 1. Commonly Used Attenuator. Diodes are BAP50-05.

C1 is required for RF bypass, and typically might be 10-100 pF when working in the GHz range. An application for this attenuator circuit is a fast gain controllers in predistorted and/or feedforward amplifiers, where the circuit is required to change attenuation in tens of nS, where C1, C2, and C3 can limit the speed. Insertion loss is generally not important in this application, and the dynamic range required may be only 8 to 10 dB. When this is true, it is possible to achieve a large improvement in speed.

In driving a PIN diode attenuator, conflicting requirements arise from speed, linearity, and temperature compensation. For the best speed, a low impedance source (<50 ohms) is required; for linearity and temperature compensation, a current source is by far the best, especially if it is desired to go to maximum resistance (lowest current) in the PIN diodes. Figures 2 and 3 show current, voltage, and attenuation for the circuit of Figure 1 in two different formats (linear and log *x* axis), with a current source for the driver.

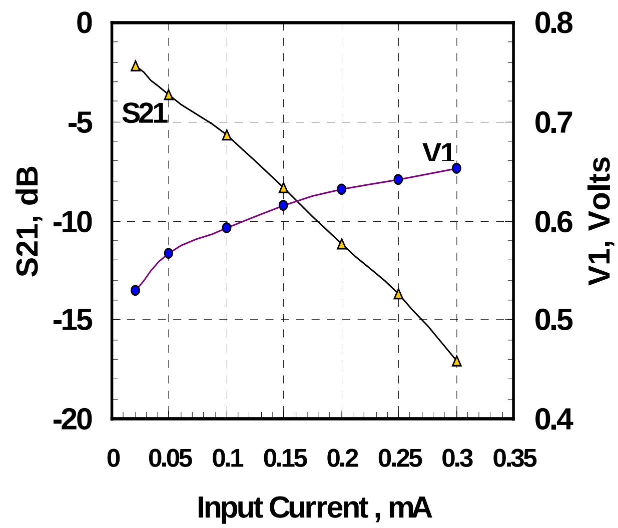

Figure 2.

[1] Although the BAP50-05 contains two diodes, only one per package is used for mechanical layout reasons.

At medium attenuation, the PIN diode[2] resistance is in the region of several hundred ohms, and current is in the region of 10-100 uA. The *control* impedance[3] (impedance of the diodes) is $Z = \frac{KT}{qI}$. If driven by a current source, such as a current output DAC, the source impedance is high and the total impedance is determined by the diodes. The risetime will be limited by the inevitable capacitances (illustrated by C5).

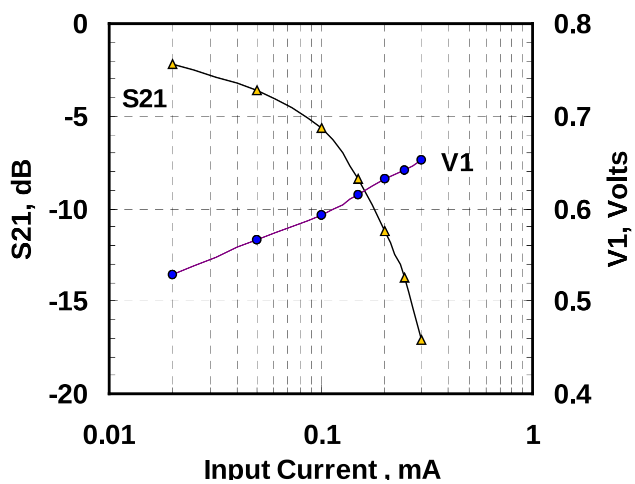

Figure 3.

If the diodes are driven from a voltage source (not shown), the speed is very fast, but the attenuation is highly nonlinear and is highly temperature dependent.

Shunting the PIN Diodes

Figure 4 shows a circuit which maintains a low impedance in the PIN circuit, to keep the rise and fall times short, but linearizes the circuit to some extent and is temperature compensated. Only one diode is shown for simplicity.

Operation is as follows: Q1 operates as a diode and absorbs most of the current from the current source. It is shown below that for two diodes in parallel (whether formed by PINs or transistors), the ratio of the two currents is fixed for all currents (over many decades), and is controlled by the voltage offsets applied to them (with respect to each other). This principle is used in *translinear* analog multipliers, of which the Gilbert cell multiplier is a type.

In this circuit, the offset is adjusted with V2, which is only some tens of millivolts. Operating the device like this is similar to circuits where the base and collector are tied together to form a diode. The collector to emitter voltage is *less* than the base to emitter voltage, in magnitude. V_{CE} is roughly 0.65 V. This is acceptable, without resorting to a negative supply for the collector, because there is still several hundred mV of margin from the standpoint of device saturation.

Q1 is thermally tied to the PIN diodes by virtue of their proximity, providing a first order temperature compensation. Q1 thus is operating as a log circuit converting current to voltage in a way that linearizes the attenuation.

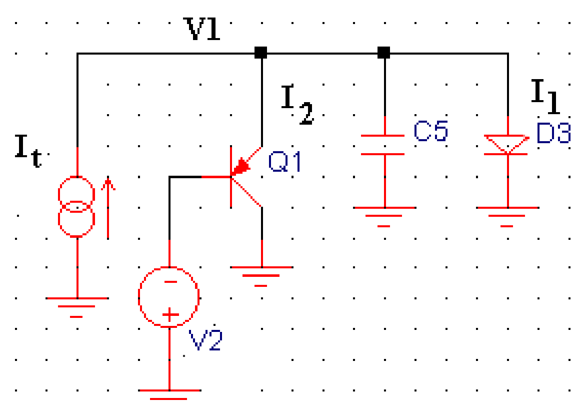

Figure 4. Transistor Shunt. V2 is < 200 mV.

The complete circuit is shown in Figure 5. The hybrid is a surface mount Anaren Xinger 1D1304-3. Figures 6 and 7 show the current, voltage, and attenuation characteristics. Note that the input current is much higher than with the original circuit (Figures 2 and 3). This reduces efficiency but it is desirable from a standpoint of keeping the total impedance low.

[2] Actually two diodes in parallel, but for analysis we will consider one.

[3] Not to be confused with RF impedance.

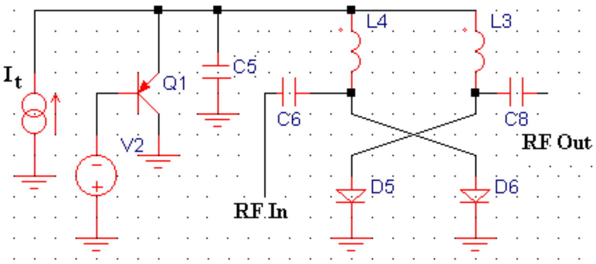

Figure 5 . Circuit with Two Diodes and Hybrid. D5 and D6 are Philips BAS50-04. Q1 is PMBT3906.

Capacitors C6 and C8 are essentially in parallel with C5 from a standpoint of the drive circuitry.

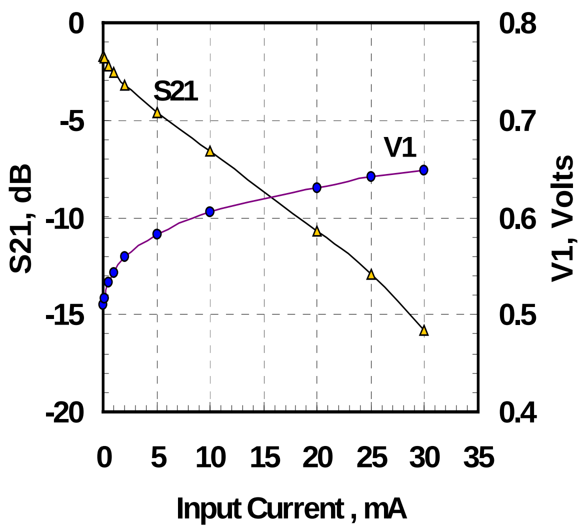

Figure 6. Circuit of Figure 5 (measured).

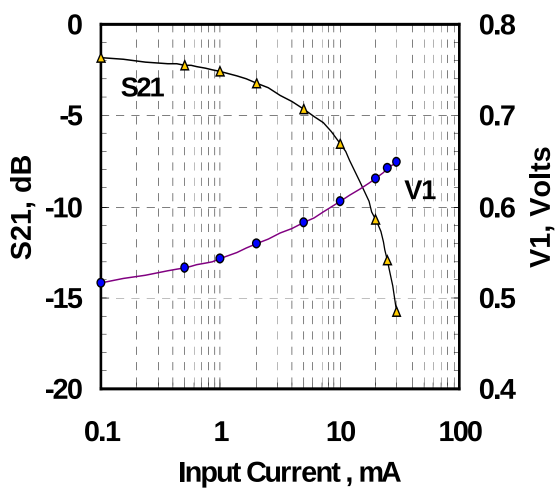

Figure 7. Same as Figure 6 with Log Scale.

Relationship of the Diode and Transistor Currents

Refer to Figure 4. From basic diode equations, the currents in the PIN diode and Q1 are:

$$I_1 = I_{S1}(e^{\frac{qV1}{KT}} - 1) \qquad (1)$$

$$I_2 = \beta I_{S2}(e^{\frac{q(V1-V2)}{KT}} - 1) \qquad (2)$$

where

q is the electron charge, 1.602E-19,
K = Bolzmann's constant, 1.381E-23
T = temperature in degrees K
I_{S1} = Saturation current for the PIN diode
I_{S2} = Saturation current for the base junction of the transistor
V_1 - V_2 = the base to emitter voltage of the transistor ($V_2 < 0$)
$\frac{q}{KT} \approx 40$ at room temperature

For voltages over a few millivolts, the exponential terms in (1) and (2) dominate the "1", and the equations can be simplified to

$$I_1 = I_{S1} e^{\frac{qV_1}{KT}} \qquad (3)$$

$$I_2 = \beta I_{S2} e^{\frac{q(V_1-V_2)}{KT}} \qquad (4)$$

Then, the ratio of the currents is:

$$\frac{I_1}{I_2} = \frac{I_{S1} e^{\frac{qV_1}{KT}}}{\beta I_{S2} e^{\frac{q(V_1-V_2)}{KT}}} = \frac{I_{S1}}{\beta I_{S2} e^{\frac{-qV_2}{KT}}} = \frac{I_{S1}}{\beta I_{S2} e^{-40V_2}} \qquad (5)$$

To the extent that β is constant with temperature[4], we see that the current ratio is

[4] β is certainly not constant with temperature, but this is a second order effect, not nearly as strong as the direct temperature relationship as with the base emitter

dependent only on V_2, which, stated another way, the current in the PIN diode is a fixed percentage of the total input current. There is first order temperature compensation, by virtue of the parallel tracking of the two diode junctions.

Further, we can set the current ratio to an arbitrary amount by setting the base voltage V_2. If $\beta = 50$, and $I_{S1} = I_{S2}$ (by way of example only), and we want to set the PIN diode current to 1% of the total current, we have

$$.01 = \frac{1}{50e^{-40V_2}} \quad \text{so } V_2 = -.0173. \qquad (6)$$

By having a relatively large current in Q1, the dynamic impedance that the current source sees, defined by $\frac{dV_1}{dI_T}$ becomes much lower, dominated by the lower impedance of the Q1.

For a general *pn* junction this impedance is $Z = \frac{KT}{qI}$. Thus, in the circuit of Figure 1, with no shunt transistor, the PIN diodes operate at perhaps 10 to 100 uA (total for two diodes), and the impedance ranges from 2500 to 250 ohms.

In the circuit of Figures 4 and 5, the PIN diodes operate at the same 10 to 100 uA, but the impedance for the parallel combination of Q1 and the two diodes is 25 to 2.5 ohms[5].

Risetimes

In Figure 1, if all the capacitances C1, C2, and C3 add up to 100 pF, the worst case risetime, which occurs at the lowest current, will be RC = 2500*100E-12 = 250 nS. In contrast, the circuit of Figure 5, the worst case risetime is 25*100E-12 = 2.5 nS.

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voltage (Angelo, *"Electronics: BJTs, FETs and Microcircuits"*, McGraw Hill 1969.)

[5] Neglecting the series emitter resistance of the transistor which might be 1-2 ohms.

Adjustment

V_2 controls the amount of current that Q1 draws relative to the total current I_t. At low voltages (50 mV), Q1 does not draw much current relative to I_t, and the speed benefit will be minimal. However, the dynamic range is the highest, as shown in Figure 8. If lower dynamic range is acceptable, V_2 can be upwards of 150 mV, where the impedance is lower and the speed benefit will be the largest. Of course, using different types of devices for Q1 and the diodes may require different values of V_2.

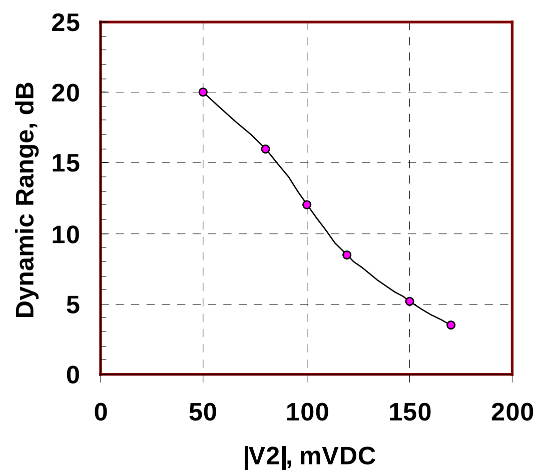

Figure 8. RF Dynamic Range.

Conclusion

A current controlled RF attenuator driver circuit has been shown which has the speed advantage of a low impedance (<50 ohm) driver, and the linearity advantage of a high impedance (current) driver. This is done by shunting the PIN diodes with a base-emitter junction of a transistor, which carries the bulk (e.g. 99%) of the driver current, lowering the impedance. The current divides itself between the transistor and the PIN diodes in a constant proportion. The current sharing percentage is settable with the base voltage. Temperature compensation on a first order basis is inherent from the tracking of the devices. The tradeoff is a lower efficiency, the circuit now requiring

10 to 20 mA of drive, as opposed to 100 uA for the simpler circuit. The current is in the range of many DACs (current output types) and this circuit lends itself well to that application. For application in an envelope restoration loop such as is found in predistorted amplifiers, the dynamic range of 8 to 10 dB is acceptable.