VOLTAGE ADJUSTABLE ATTENUATION WITH LOW 1/f NOISE

E.S. Ferre-Pikal and F.L. Walls

National Institute of Standards and Technology
Boulder, Colorado

Abstract

In this paper we describe voltage-controlled attenuator circuits using silicon p-n diodes as the variable resistor. We report the amplitude modulation (AM) and phase modulation (PM) noise sensitivities to power supply noise and to current noise. We also report the PM noise of these circuits as a function of dc control voltage.

Introduction

In this paper we describe voltage-controlled variable attenuators using silicon p-n diodes as a voltage-controlled variable resistor. The purpose of this work is to investigate the up-conversion of 1/f baseband current noise into amplitude modulation (AM) noise and phase modulation (PM) noise in these attenuators and to compare the PM noise in different configurations. Figure 1 shows the small-signal equivalent circuit of a forward-biased p-n diode. The small-signal resistance r_d is given by

$$r_d = \frac{nV_T}{I_d}, \qquad (1)$$

where n is a constant, $V_T \approx 0.026$ V, and I_d is the dc current through the diode. When the capacitance C_d is negligible, diodes can be used as voltage-controlled variable resistors.
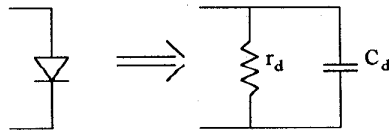

Figure 1. Small-signal model of a diode.

The dc current through the diode exhibits 1/f noise, a result of intrinsic noise in the diode [1] and power supply noise [2]. The dc current can thus be described by

$$I'_D = I_D\left[1 + \frac{\Delta I(f)}{I_D}\right], \qquad (3)$$

where $\Delta I(f)$ represent the 1/f noise component and f is the frequency of the noise. The transfer function of a diode attenuator circuit is

$$H(j\omega) = G(j\omega) \quad \angle \theta(j\omega), \qquad (4)$$

where G is the magnitude and θ is the phase. The AM and PM noise are given by [3]

$$S_a(f) = \left(\frac{\Delta G(f)}{G}\right)^2 \frac{1}{BW}, \qquad (6)$$

$$S_\phi(f) = (\Delta\theta(f))^2 \frac{1}{BW}. \qquad (7)$$

where BW is the bandwidth of the measurement system.

The transfer function of a diode attenuator is a function of dc current, therefore low frequency 1/f noise in the dc current will up-convert to AM and PM noise about the carrier. AM and PM noise resulting from baseband current noise are given by

$$S_a(f) = K_a^2\left(\frac{\Delta I(f)}{I}\right)^2 \frac{1}{BW}, \qquad (8)$$

$$S_\phi(f) = K_\phi^2\left(\frac{\Delta I(f)}{I}\right)^2 \frac{1}{BW}, \qquad (9)$$

where K_a and K_ϕ are the AM and PM sensitivities to current noise given by

$$K_a = \frac{I}{G}\frac{dG}{dI}\bigg|_I, \qquad (10)$$

$$K_\phi = I\frac{d\theta}{dI}\bigg|_I. \qquad (11)$$

186

Attenuator Circuits

Figure 2 shows the basic configuration of attenuators used in our study. Forward-biased silicon diodes were used as the voltage-controlled elements.
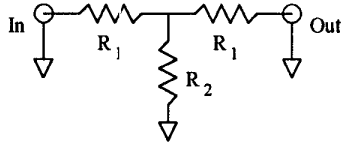

Figure 2. Basic configuration of attenuators used.

Figure 3 shows the block diagram of attenuator 1. In this circuit diodes are used as the resistors R_1 in Fig. 2. Figure 4 shows the magnitude and phase of the transmission of this circuit for two power levels at input frequencies of 5 MHz and 10 MHz. P_{in} refers to the input power in dB relative to 1 mW (dBm). While the magnitude of the transmission does not change much with power or frequency, the phase varies considerably at low dc control voltages. The change in phase with dc control voltage (and thus current) is smaller for lower input powers. In addition, the phase change is smaller at 10 MHz than at 5 MHz, indicating that the up-conversion of low frequency voltage and current noise to PM noise is smaller at 10 MHz.
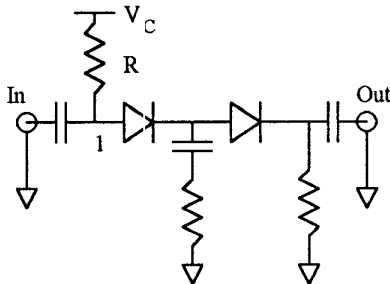

Figure 3. Voltage-controlled attenuator 1.

AM and PM noise sensitivities to power supply noise can be obtained from the slope of the transmission curves in Fig. 4. Table 1 shows the AM and PM noise sensitivities to power supply noise at 5 MHz obtained from the data in Fig. 4. The AM and PM sensitivities decrease as the dc control voltage increases (and the attenuation decreases). The sensitivities to current noise can be obtained by plotting the magnitude and phase of the transmission as a function of current and computing the slope of the curve at different current values.
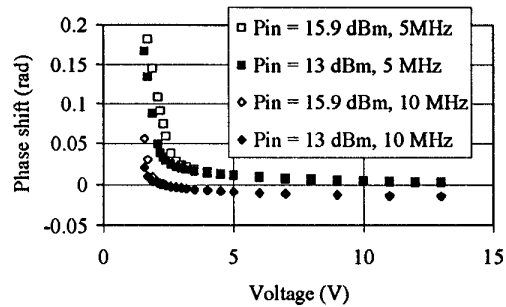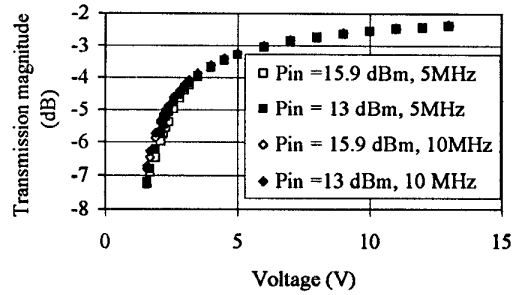

Figure 4. Magnitude and phase of transmission for attenuator 1. P_{in} is the input power to the attenuator.

Table 1. AM and PM noise sensitivities to power supply noise in attenuator 1. P_{in} is the input power to the attenuator.

| V_c (V) | Attenuation (dB) | P_{in} = 15.9 dBm | |
		AM sensitivity (dBc/Hz rel to $\Delta V = 1$ V)	PM sensitivity (dBc/Hz rel to $\Delta V = 1$ V)
2.35	5.5	-16.2	-19.3
3	4.4	-21	-38.3
5.5	3.2	-33.8	-55.9
12.5	2.4	-47.8	-68.6
		P_{in} = 13 dBm	
2.35	5.2	-16.7	-31.7
3	4.3	-22.3	-43.4
5.5	3.2	-33.8	-56.6
12.5	2.4	-47.8	-70.2

Table 2 shows the AM and PM sensitivities to fractional current noise in attenuator 1 at a carrier frequency of 5 MHz. The main difference between the two tables is that Table 2 shows sensitivities to a

normalized quantity (fractional current noise). The current through the diode was computed using

$$I_D = \frac{V_c - V_1}{R} \qquad (12)$$

where V_1 is the voltage at point 1 in Fig. 3. In general, the AM sensitivities were larger than the PM sensitivities, and the sensitivities decreased as the dc control voltage increased (and attenuation decreased).

Table 2. AM and PM sensitivities to fractional current noise in attenuator 1. P_{in} is the input power to the attenuator.

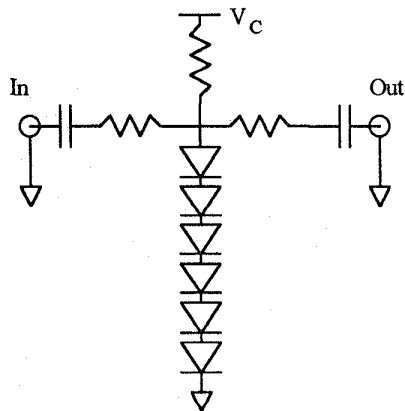| V_c (V)	Attenuation (dB)	AM sensitivity (dBc/Hz rel to $\Delta I/I = 1$)	PM sensitivity (dBc/Hz rel to $\Delta I/I = 1$)
		P_{in} = 15.9 dBm	
2.35	5.5	-13	-16
3	4.4	-14.9	-32.2
5.5	3.2	-20.9	-42.9
12.5	2.4	-26.7	-47.6
		P_{in} = 13 dBm	
2.35	5.2	-13.4	-28.5
3	4.3	-16.2	-37.3
5.5	3.2	-20.9	-43.6
12.5	2.4	-26.7	-47.6

Figure 5. Circuit diagram of attenuator 2.

Figure 5 shows the circuit diagram of the second attenuator studied. In this case six diodes in series were used as the resistor R_2 in Fig. 2. The magnitude and phase of the transmission for this circuit are shown in Fig. 6. The magnitude of the transmission (in dB) is approximately linear with dc control voltage and the

total phase change is less than 0.02 radians at 5 MHz. The small phase change indicates that the PM noise of the circuit should be small. Table 3 compares the AM noise sensitivity to fractional current and voltage noise for attenuators 1 and 2 at a carrier frequency of 5 MHz and an input power of 13 dBm. The AM sensitivity to voltage noise is approximately constant with voltage in attenuator 2. Nevertheless, the AM sensitivity to fractional current noise is similar for both attenuators, increasing with attenuation.
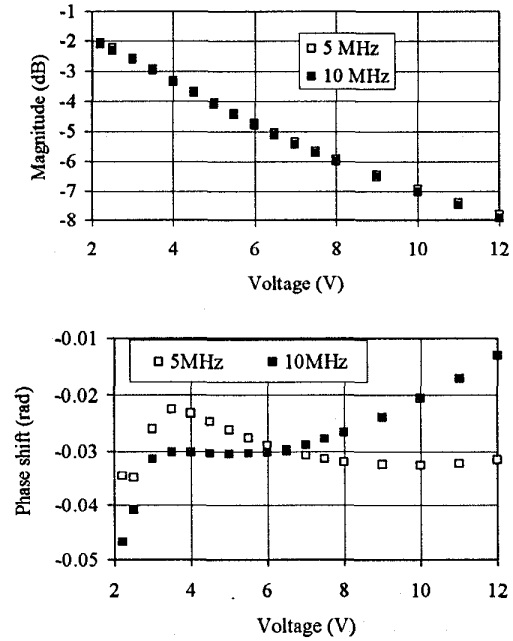

Figure 6. Magnitude and phase of the transmission for attenuator 2.

Table 3. AM sensitivities to power supply and fractional current noise for attenuators 1 and 2.

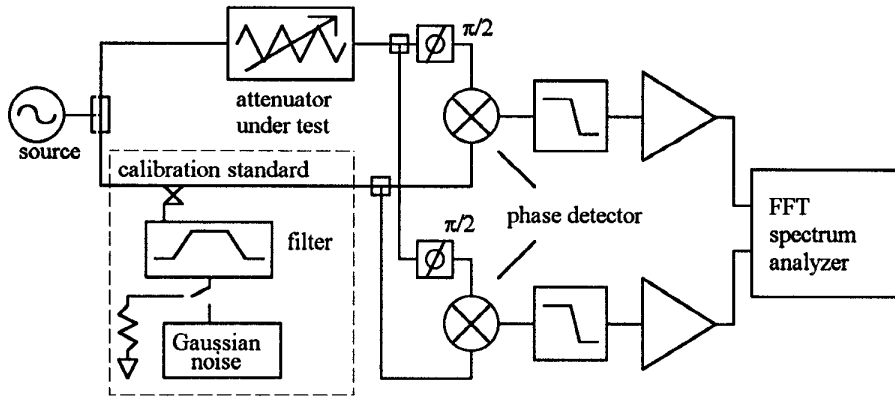| Attenuation (dB)	AM sensitivity to ΔV (dBc/Hz rel to $\Delta V = 1$)	AM sensitivity to $\Delta I/I$ (dBc/Hz rel to $\Delta I/I = 1$)
	Attenuator 1	
3.2	-33.8	-20.9
4.3	-22.3	-16.2
5.2	-16.7	-13.4
	Attenuator 2	
3.2	-24.3	-22.5
4.2	-24.6	-17.4
5.5	-26.2	-13.8
6.7	-28.2	-12.3

Figure 7. Block diagram of PM noise measurement system.

PM Noise Measurements

Figure 7 shows the block diagram of the system used to measure the PM noise in the attenuator circuits. The power spectral density of the cross-spectrum of channels 1 and 2, measured with a two-channel FFT spectrum analyzer, yields the PM noise of the attenuator circuit. The noise in the phase detectors is averaged away as $1/\sqrt{N}$, where N is the number of averages [4]. A PM noise calibration standard was used to obtain the gain of the system [5].
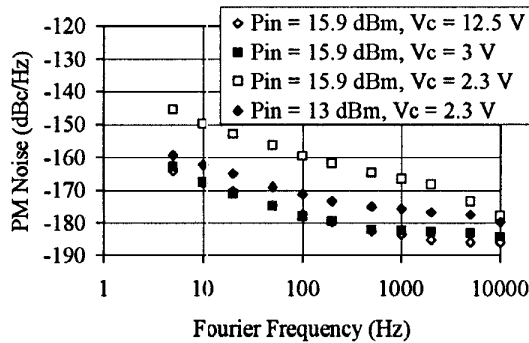

Figure 8. PM noise of attenuator 1 for various dc control voltages. P_{in} is the input power to the attenuator.

Figure 8 shows the PM noise of attenuator 1 for different operating points at a carrier frequency of 5 MHz. In this plot V_c = 12.5 V corresponds to an attenuation of approximately 2.3 dB, V_c = 3 V corresponds to an attenuation of approximately 4.3 dB, and V_c = 2.3 V corresponds to an attenuation of

approximately 5.3 dB. The PM noise is very low at supply voltages of 3 V and 12.5 V, probably limited by the noise floor of the measurement system. When the circuit was operated at 2.3 V, the PM noise increased approximately 17 dB, as expected from the phase data. Figure 8 also shows the PM noise at an input power of 13 dBm and V_c = 2.3 V. The flicker noise is 10 dB lower than the measured noise at an input power of 15.9 dBm. This agrees with the phase data in Fig. 4.

Figure 9 shows the PM noise of attenuator 1 at two different carrier frequencies (5 MHz and 10 MHz). The input power (P_{in}) was 15.9 dBm. The PM noise below 100 Hz is approximately 15 dB lower at 10 MHz when compared to the PM noise at 5 MHz.
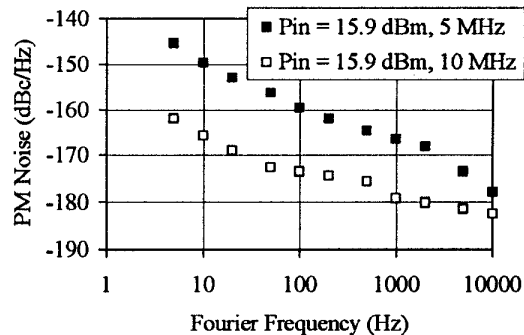

Figure 9. PM noise of attenuator 1.

Figure 10 shows the PM noise of attenuator 2 at 5 MHz for three different operating voltages. In all three cases the PM noise is very low, limited by the measurement system noise floor. This was expected

189

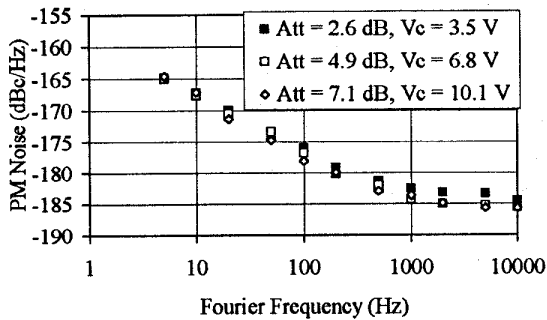since the total phase change with voltage for this circuit was very small (< 0.02 rad.).

Figure 10. PM noise of attenuator 2 at 5 MHz.

Reduction of 1/f current noise

If the 1/f intrinsic current noise limits the AM and/or PM noise of an attenuator circuit then a feedback circuit that reduces the current noise can be used to reduce the AM and PM noise [2,3]. An example of such a circuit is shown in Fig. 11. In this circuit the current through the diode is read, amplified and inverted, and fedback to point 2 (diode input).
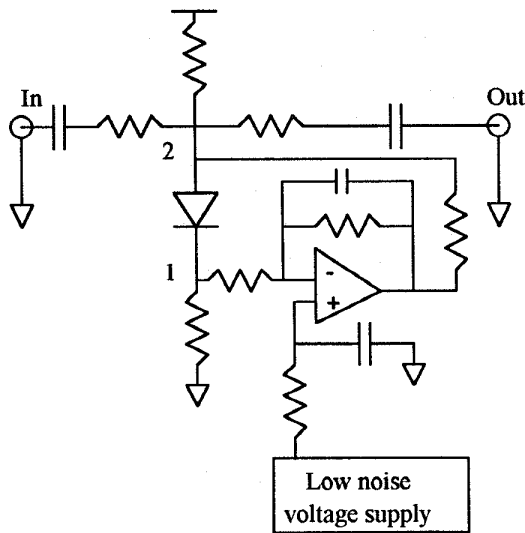

Figure 11. Diode attenuator with feedback circuit to reduce current noise.

Phase Shifters

Diode attenuators can be used to build voltage-controlled phase shifters in which the variable element is a resistor. Figure 12 is an example of such circuit (the dc paths have been omitted for simplicity). One problem with such circuit is that the attenuation is considerable, because of the use of resistors. In our circuit, we obtained a total phase change of 47° at 10 MHz for a dc control voltage range of 1-15 V. The attenuation varied from 4.7 dB to 6.1 dB. Another disadvantage of the circuit is the need of a transformer at the output. Transformers can be noisy, and thus possibly degrade the PM noise of the circuit.
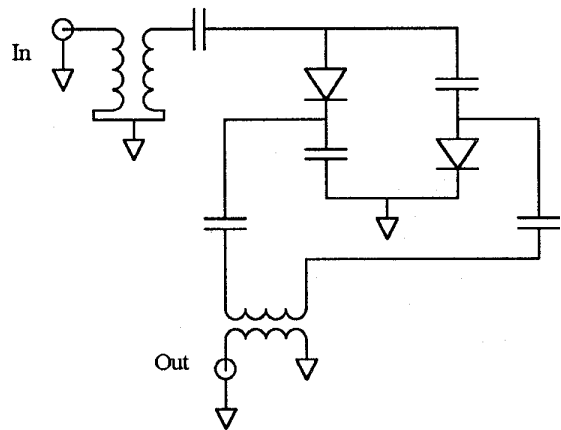

Figure 12. Phase shifter using diodes as variable resistors.

Summary and Conclusion

We have presented the transmission characteristics of voltage-controlled attenuators using silicon p-n diodes as the variable resistive elements. While the first configuration had a non-linear response (magnitude of attenuation versus dc control voltage), the second configuration showed relatively linear dependence of the magnitude (in dB) of the attenuation with dc control voltage. As expected, the AM noise sensitivities to low frequency noise were higher than the PM noise sensitivities. We found that in one configuration, at high input powers and high attenuation, the phase change with voltage change was large. This resulted in high PM sensitivity to current and voltage noise. Operation of this circuit under these conditions should be avoided. The PM noise of the two attenuator circuits studied agreed with the phase

shift measurements. For attenuator 1, the PM noise was low, $\mathcal{L}$(10 Hz) = -167 dB below the carrier in a 1 Hz bandwidth (dBc/Hz), when operated at dc control voltages of 3 V and 12.5 V and an input power of 15.9 dBm. The PM noise was high, $\mathcal{L}$(10 Hz) $\approx$ -150 dBc/Hz, when operated at a dc control voltage of 2.3 V and an input power of 15.9 dBm. For attenuator 2, the PM noise was $\mathcal{L}$(10 Hz) = -167 dBc/Hz at all operating points measured (V_c = 3.5 V (attenuation = 2.6 dB), 6.8 V (attenuation = 4.9 dB), 10.1 V (attenuation = 7.1 dB)). Attenuator 2 is therefore a better configuration because it provides linear attenuation with dc control voltage and its PM noise is independent of attenuation.

References

[1] A. van der Ziel, Noise in solid state devices and circuits, John Wiley & Sons, Inc., 1986, Chapter 8.

[2] E.S. Ferre-Pikal, F.L. Walls, and C.W. Nelson, "Guidelines for Designing BJT Amplifiers with Low 1/f AM and PM Noise," *IEEE Trans. Ultrason., Ferroelect., Freq. Control*, Vol. 44, No. 2, pp. 335 - 343, March 1997.

[3] F.L. Walls, E.S. Ferre-Pikal, and S.R. Jefferts, "Origin of 1/f PM and AM Noise in Bipolar Junction Transistor Amplifiers," *IEEE Trans. Ultrason., Ferroelect., Freq. Control*, Vol. 44, No. 2, pp. 326 - 334, March 1997.

[4] W.F. Walls, "Cross-correlation phase noise measurements," *Proc. 1992 IEEE Freq. Control Symp.*, pp. 257-261, 1992.

[5] F.L. Walls, "Secondary standard for PM and AM noise at 5, 10, and 100 MHz," *IEEE Trans. Instrum. Meas.*, Vol. 42, No. 2, pp. 136-143, April 1993.