ATTENUATORS

Attenuators allow a known source of power to be reduced by a predetermined factor usually expressed as decibels. Attenuators are linear, passive or active networks or devices that attenuate electrical or microwave signals, such as voltages or currents, and hence power in a system by a predetermined ratio. The most commonly used method in attenuators is placing resistors at the center of an electric field, which induces a current resulting in ohmic loss. A great advantage of attenuators is that since it is made from non-inductive resistors, they are able to change a source or load, which might be reactive, into one which is precisely known and resistive. This power reduction is achieved by the attenuator without introducing distortion. Attenuators are used in a wide variety of applications and can satisfy almost any requirement where a reduction in power is needed. Attenuators are used to extend the dynamic range of devices such as power meters and amplifiers, reduce signal levels to detectors, match circuits and are used daily in lab applications to aid in product design. Attenuators are also used to balance out transmission lines that otherwise would have unequal signal levels. Attenuation is usually expressed as the ratio of input power (P_{in}) to output power (P_{out}), in decibels (dB), as

$$\text{Attenuation}\,(A) = 10\log_{10}\frac{P_{\text{in}}}{P_{\text{out}}} = 20\log\frac{E_{\text{in}}}{E_{\text{out}}} = 20\log\frac{E_1}{E_2} \quad (1)$$

This is derived from the standard definition of attenuation in Nepers (Np), as

$$\text{Attenuation}\,(A) = \alpha\Delta x = -\ln\frac{|E_2|}{|E_1|} \quad (2)$$

where α is attenuation constant, Np/m, and Δx is the distance between the voltages of interest, E_1 and E_2.

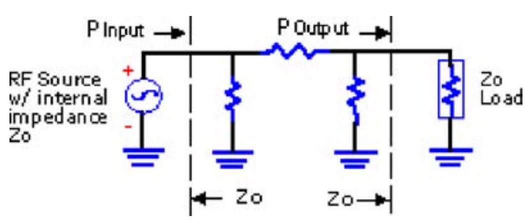

Figure 1a Concept and definition of attenuation.

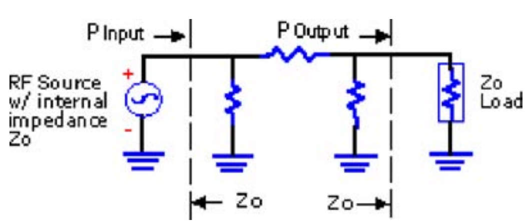

Figure 1b Alternative representation.

Figure 1 illustrates this concept. The relation between Np and dB is,

$$1Np = 8.686\,\text{dB} \quad (3)$$

Here the load and source are matched to the characteristic impedance. The decibels are converted to the attenuation ratio as follows: $P_{\text{in}}/P_{\text{out}} = \log^{-1}{}_{10}$ dB/10 or $V_{\text{in}}/V_{\text{out}} = \log^{-1}{}_{10}$ dB/20.

APPLICATION

There are many instances when it is necessary to reduce the value or level of electrical or microwave signals, such as voltages and currents by a fixed or variable amount to allow for the rest of the system to work properly. Attenuators are used for this purpose. For example, in turning down the volume on a radio, stereo CD player or IPod, we make use of a variable attenuator to reduce the signal. Almost all electronic instruments use attenuators to allow for the measurement of a wide range of voltage and current values, such as voltmeters, oscilloscopes, and other electronic instruments. Thus, the various applications in which attenuators are used include the following:

- To reduce signal levels to prevent overloading
- To match source and load impedances to reduce their interaction
- To measure loss or gain of two-port devices
- To provide isolation between circuit components, or circuits or instruments so as to reduce interaction among them
- To extend the dynamic range of equipment and prevent burn-out or overloading equipment

TYPES

There are various types of attenuators based on the nature of circuit elements used, type of configuration, and kind of adjustment. They are as follows:

- Passive and active attenuators
- Absorptive and reflective attenuators
- Fixed and variable attenuators

A fixed attenuator is used when the attenuation is constant. Variable attenuators have varying attenuation, using varying resistances for instance. The variability can be in steps or continuous, obtained either manually or programmably. There are also electronically variable attenuators. They are reversible, except in special cases, such as a high-power attenuator. They are linear, resistive, or reactive, and are normally symmetrical in impedance. They include waveguide, coaxial, and strip lines, as well as calibrated and uncalibrated versions. Figures 2, 3, and 4 show fixed, manual step, and continuously variable commercial attenuators.

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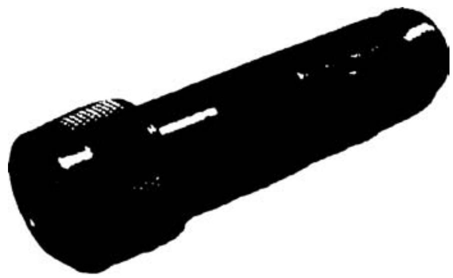


Figure 2. Fixed coaxial attenuator. (Courtesy of Weinschel Associates.)

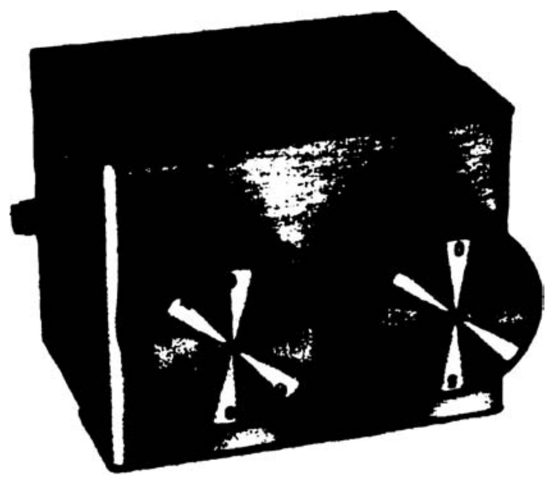


Figure 3. Manual step attenuator. (Courtesy of Weinschel Associates.)

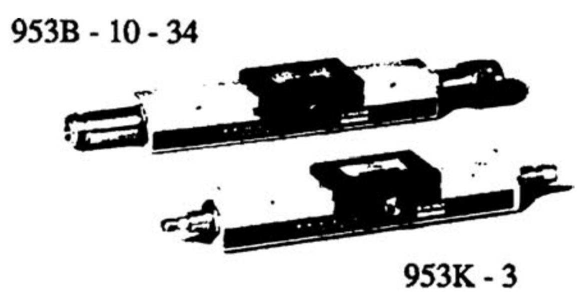


Figure 4. Continuously variable attenuator. (Courtesy of Weinschel Associates.)

Based on their usage, IEEE Std 474 classifies them as

Class I	Standard
Class II	Precision
Class III	General purpose
Class VI	Utility

Typical commercial attenuators are listed below:

WA 1 (0 GHz to 12.4 GHz), WA 2 (0 GHz to 3 GHz), coaxial, fixed attenuators: 1 dB to 60 dB; 5 W av./1 kW PK

WA 115A manual step attenuators: 0 GHz to 18 GHz, 0 dB to 9 dB, 1 dB steps

VA/02/100 continuously variable attenuators, resistive, 0 GHz to 2 GHz, 5 W av./0.5 kW PK

HP 84904L programmable step attenuator, direct current (dc) to 40 GHz, 0 dB to 11 dB, 1 dB steps

HP 84906K programmable step attenuator, dc to 26.5 GHz, 0 dB to 90 dB, 10 dB steps

HP 84904L programmable step attenuator, dc to 40 GHz, 0 dB to 70 dB, 10 dB steps

HP 8495B manual step attenuator, dc to 18 GHz, 0 dB to 70 dB, 10 dB steps

HP 355F programmable step attenuator, dc to 1 GHz, 0 dB to 120 dB, 10 dB steps

HP 8493A Coaxial fixed attenuator, dc to 12.4 GHz

Based on their utility, military attenuators are classified as:

Class I	For use as a primary standard
Class II	For use as a secondary standard, and in lab and precision test equipment A—with lumped-constant or distributed shunt and series elements B—with lossy-line pads
Class III	For use in general field equipment
Class VI	For use in equipment where precision and stability are secondary considerations

Typical mil specifications for fixed coaxial attenuators are as follows:

Mil-A-3933/1: Attenuators, fixed, coaxial line, dc to 3 GHz, class IIA, low power

Mil-A-3933/2: Attenuators, fixed, coaxial line, 1 GHz to 4 GHz, class IIB, medium power

Mil-A-3933/10: Attenuators, fixed, coaxial line, dc to 18 GHz, class III, medium power

Mil-A-3933/26: Attenuators, fixed, coaxial line, 0.4 GHz to 18 GHz, class IV low power

SPECIFICATIONS

To specify an attenuator, the purpose of the attenuator should be known. Attenuators are used to provide protection, reduce power, and extend the dynamic range of the test equipment. In choosing an attenuator, the frequency range of operation should be considered since the accuracy depends on the frequency. Attenuation involves placing resistive material to absorb the signal's electric field. This means, there will always be some reflection. So, attenuators must be designed to minimize reflection. This is quantified in terms of voltage standing wave ratio (*VSWR*). Another factor to be considered is the insertion loss, which is the ratio of power levels with and without the component insertion. If it is a variable step attenuator, the step size is to be known. Thus, the parameters available in the specs are as follows:

dB rating
VSWR
Accuracy
Power rating

Step size (if variable)

Frequency band

Degree of stability (measured by the change in attenuation due to temperature, humidity, frequency, and power level variations)

Characteristic impedance of attenuator

Repeatability

Life

Degree of resolution (difference between actual attenuation and measured value)

The definitions of various parameters used in selecting attenuators are given below.

Electrical Parameters and Definitions (From MIL-HDBK-216)

Attenuation A general transmission term used to indicate a decrease in signal magnitude. This decrease in power is commonly expressed in decibels (dB) as:

$$\text{Attenuation}\,(A) = 10\log_{10}\frac{P_{\text{in}}}{P_{\text{out}}}$$

Deviation of Attenuation from Normal Difference in actual attenuation from the nominal value at 23°C and an input power of 10 mW at a specified reference frequency or frequency range. When used in a frequency range, it involves the frequency sensitivity.

Frequency Sensitivity This is the peak-to-peak variation in the loss of the attenuator through the specified frequency range.

Frequency Range Range of frequency over which the accuracy of attenuator is specified.

Insertion Loss Amount of power loss due to the insertion of the attenuator in the transmission system. It is expressed as a ratio of the power delivered to that part of the system following the attenuator, before and after the insertion.

Characteristic Insertion Loss This is the insertion loss in a transmission line or waveguide that is reflectionless in both directions from the inserted attenuator.

Power-Handling Capabilities Maximum power that can be applied to the attenuator under specified conditions and durations without producing a permanent change in the performance characteristics that would be outside of specification limits.

Power Sensitivity This is the temporary variation in attenuation (dB/W) under steady-state conditions when the input power is varied from 10 mW to maximum input power.

Stability of Attenuation Capability of attenuator to retain its parameters when subjected to various environmental conditions.

Operating Temperature Range Temperature range the attenuator can be operated with maximum input power.

Temperature Sensitivity Temperature variation in attenuation [dB/(dB × °C)] over the operating range.

Input VSWR This is the level of reflected signal created at the attenuator input when the output is terminated with a load with the same characteristic impedance as the source.

Output VSWR This is the level of reflected signal created at the attenuator output when the input is terminated with a load with the same characteristic impedance as the source.

PASSIVE ATTENUATORS

Resistance Networks for Attenuators

Typically T, Pi, or L designs are used for attenuators. Figure 5 shows four commonly used symmetrical (input and output resistors of equal value) configurations. The formulas for the resistance values in ohms for these pads when the characteristic resistance $R_0 = 1\ \Omega$ are given below. If R_0 is other than 1 Ω, multiply each of the resistance

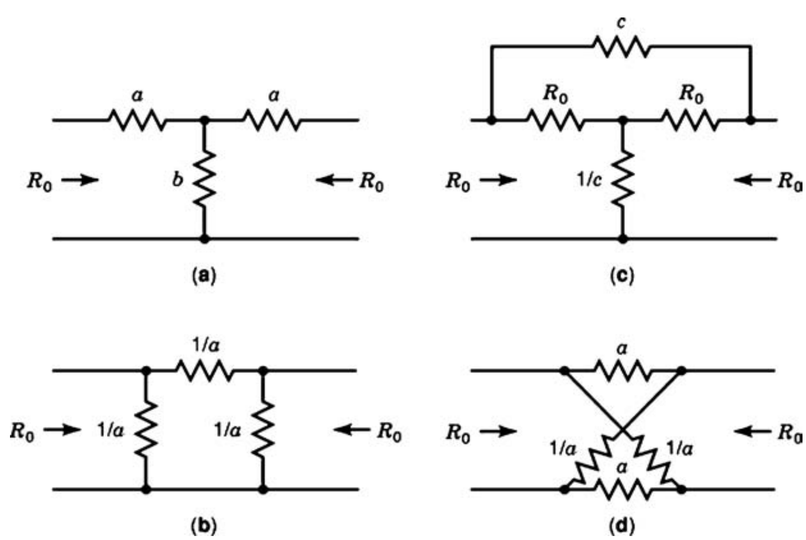


Figure 5. Symmetrical pads with matched impedances. (a) T pad. (b) Pi pad. (c) Bridged T pad. (d) Balanced pad.

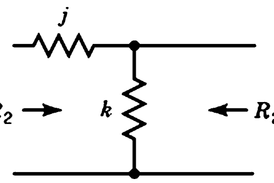


Figure 6. Unsymmetrical matching L attenuator.

values (a, b, c, $1/a$, $1/b$, and $1/c$) by R_0, where

$$a = (10^{\mathrm{dB}/20} - 1)/(10^{\mathrm{dB}/20} + 1) \quad (4)$$

$$b = 2 \times 10^{\mathrm{dB}/20}/(10^{\mathrm{dB}/10} - 1) \quad (5)$$

$$c = (10^{\mathrm{dB}/20} - 1) \quad (6)$$

Simple wirewound resistors are used in audio applications. Nonreactive wirewound resistors, such as mica card, Aryton-Perry winding, woven resistors are used for high frequencies. For coaxial applications (over 26.5 GHz), thin-film resistors are used. For higher frequencies, distributive resistive films, such as nichrome alloy film, on a high quality ceramic substrate, such as alumina or sapphire, is used. An unsymmetrical pad is shown in Figure 6, and the formulas for this pad are

$$j = R_1 - kR_2/(k + R_2) \quad (7)$$

$$k = [R_1 R_2^2/(R_1 - R_2)]^{1/2} \text{ where } R_1 > R_2 \quad (8)$$

$$\text{Minimum loss (dB)} = 20 \log \left\{ \left[\frac{(R_1 - R_2)}{R_2} \right]^{1/2} + \left(\frac{R_1}{R_2} \right)^{1/2} \right\} \quad (9)$$

Typical values for the pads in Figure 5 are shown in Table 1, and those of Figure 6 are shown in Table 2.

For a broad-band match between impedances R_1 and R_2, use the minimum loss L pad (Figure 6).

Power Dissipation within a T Pad

Table 3 lists values of power dissipation within a T pad. The values are for an input of 1 W; for other input powers, multiply the values by the input power.

INSERTION LOSS

An attenuator is used to introduce attenuation between a source and a load. Due to the introduction of the attenuator, there is change in the current. This loss is designated as insertion loss, which depends on the configuration. Usually, the load and source impedances are matched. Figure 7 illustrates this concept. If I_{L0} is the load current without the attenuator pad, and I_L is the current with the attenuator pad, then the ratio I_L/I_{L0} is called the insertion loss, one of the parameters of the attenuates. Figure 7(a) shows the source and load connected without an attenuator, and Figure 7(b) shows the same system with an attenuator. (The quantities, I_L, R_{in}, and R_{out} depend on the attenuator configuration.) The quantities insertion loss (I_L), input resistance (R_{in}), and output resistance (R_{out}) depend on the

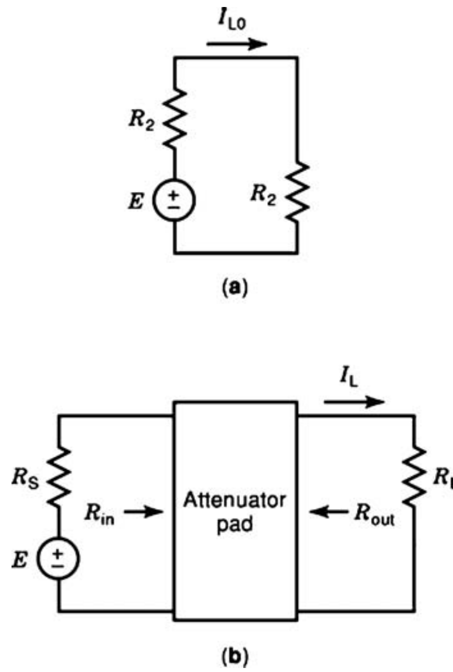


Figure 7. Definition of characteristic insertion loss. (a) Original setup without attenuator. (b) Original setup with attenuator between source and load.

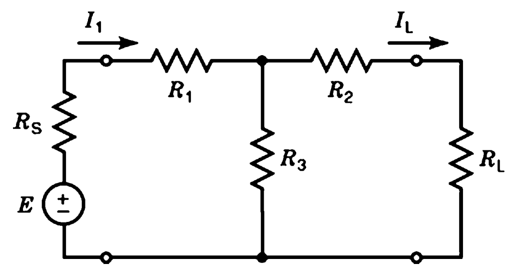


Figure 8. T attenuator configuration.

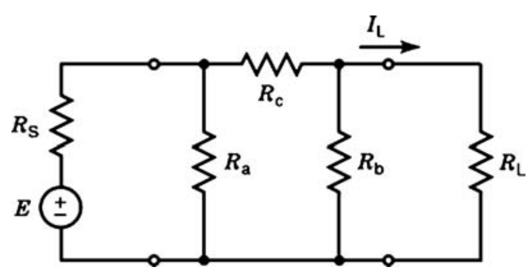
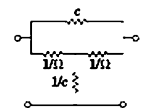


Figure 9. Pi attenuator configuration.

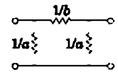
attenuator configuration. The value of each of the three resistors of the T (Figure 8) and Pi (Figure 9) attenuators can be chosen independently of others. This enables the three-design criteria of input resistance, output resistance, and insertion loss to be met. In many situations, the only function of the pad is to provide matching between source and load; and although attenuation will be introduced, this may not be a critical design parameter. This allows a simpler type of pad to be designed, requiring only two resistors; it is known as an L pad.

Table 1. Resistance Values for Attenuator Pads When $R_0 = 1\,\Omega^a$

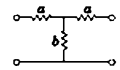
Bridged T Pad



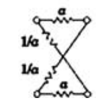
Pi Pad



T Pad



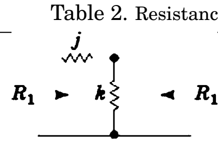
Balanced Pad



dB[b]	a	b	$1/b$	$1/a$	c	$1/c$	a	$1/a$
0.100	0.006	86.853	0.012	173.710	0.012	86.356	0.006	173.710
0.200	0.012	43.424	0.023	86.859	0.023	42.930	0.012	86.859
0.300	0.017	28.947	0.034	57.910	0.035	28.455	0.017	57.910
0.400	0.023	21.707	0.046	43.438	0.047	21.219	0.023	43.438
0.500	0.029	17.362	0.058	34.753	0.059	16.877	0.029	34.753
0.600	0.034	14.465	0.069	28.965	0.072	13.982	0.034	28.965
0.700	0.040	12.395	0.081	24.830	0.084	11.915	0.040	24.830
0.800	0.046	10.842	0.092	21.730	0.096	10.365	0.046	21.730
0.900	0.052	9.634	0.104	19.319	0.109	9.160	0.052	19.319
1.000	0.057	8.667	0.115	17.391	0.122	8.195	0.058	17.391
2.000	0.115	4.305	0.232	8.724	0.259	3.862	0.115	8.724
3.000	0.171	2.838	0.352	5.848	0.412	2.424	0.171	5.848
4.000	0.226	2.097	0.477	4.419	0.584	1.710	0.226	4.419
5.000	0.280	1.645	0.608	3.570	0.778	1.285	0.280	3.570
6.000	0.332	1.339	0.747	3.010	0.995	1.005	0.332	3.010
7.000	0.382	1.116	0.896	2.614	1.239	0.807	0.382	2.614
8.000	0.430	0.946	1.057	2.323	1.512	0.661	0.430	2.323
9.000	0.476	0.812	1.232	2.100	1.818	0.550	0.476	2.100
10.000	0.519	70.273[c]	1.423	1.925	2.162	46.248[c]	0.519	1.925
20.000	0.818	20.202[c]	4.950	1.222	9.000	11.111[c]	0.818	1.222
30.000	0.939	6330.900[c]	15.796	1.065	30.623	3265.500[c]	0.939	1.065
40.000	0.980	2000.200[c]	49.995	1.020	99.000	1010.100[c]	0.980	1.020
50.000	0.994	632.460[c]	158.110	1.006	315.230	317.230[c]	0.994	1.006
60.000	0.998	200.000[c]	500.000	1.002	999.000	100.100[c]	0.998	1.002
70.000	0.999	63.246[c]	1581.100	1.006	3161.300	31.633[c]	0.999	1.001
80.000	1.000	20.000[c]	5000.000	1.000	9999.000	10.001[c]	1.000	1.000
90.000	1.000	6.3246[c]	15.811	1.000	31.622	3.163[c]	1.000	1.000
100.000	1.000	2.000[c]	50.000	1.000	99.999	1.000[c]	1.000	1.000

[a] If $R_0 \neq 1\,\Omega$, multiply all values by R_0. (From Ref. data for *Radio Engineers, 1985*.)
[b]For other decibel values, use formulas in text.
[c]These values have been multiplied by 10^3.

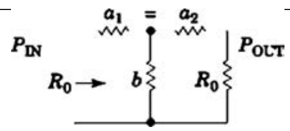
Table 2. Resistance Values and Attenuation for L Pad[a]



R_1/R_2	j	j	dB
20.00	19.49	1.03	18.92
16.00	15.49	1.03	17.92
12.00	11.49	1.04	16.63
10.00	9.49	1.05	15.79
8.00	7.48	1.07	14.77
6.00	5.48	1.10	13.42
5.00	4.47	1.12	12.54
4.00	3.47	1.16	11.44
3.00	2.45	1.22	9.96
2.40	1.83	1.31	8.73
2.00	1.41	1.41	7.66
1.60	0.98	1.63	6.19
1.20	0.49	2.45	3.77
1.00	0.00	∞	0.00

[a] For $R_2 = 1\,\Omega$ and $R_1 > R_2$. If $R_2 \neq 1\,\Omega$, multiply values by R_2. For ratios not in the table, use the formulas in the text. (From Ref. data for *Radio Engineers*, 1985.)
Examples of use of table:
If $R_1 = 50\,\Omega$ and $R_2 = 25\,\Omega$, then $R_1/R_2 = 2.0$, and $j = k = 1.414 \times 25\,\Omega = 35.35\,\Omega$.
If $R_1/R_2 = 1.0$, minimum loss = 0 dB.
For $R_1/R_2 = 2.0$, the insertion loss with the use of j and k for matching is 7.66 dB above that for $R_1/R_2 = 0$

Table 3. Power Dissipation in T Pad[a]



dB	Watts, Input Series Resistor	Watts, Shunt Resistor	Watts, Output Series Resistor
0.100	0.006	0.011	0.006
0.300	0.017	0.033	0.016
0.500	0.029	0.954	0.025
0.700	0.040	0.074	0.034
0.900	0.052	0.093	0.042
1.00	0.058	0.102	0.046
1.200	0.069	0.120	0.052
1.400	0.080	0.114	0.058
1.600	0.092	0.152	0.064
1.800	0.103	0.167	0.068
2.000	0.114	0.181	0.072
2.200	0.126	0.195	0.076
2.400	0.137	0.208	0.079
2.600	0.149	0.220	0.082
2.800	0.160	0.232	0.084
3.000	0.171	0.242	0.086
3.200	0.182	0.252	0.087
3.400	0.193	0.260	0.088
3.600	0.204	0.270	0.089
3.800	0.215	0.278	0.090
4.000	0.226	0.285	0.090
5.000	0.280	0.314	0.088
6.000	0.332	0.332	0.083
7.000	0.382	0.341	0.076
8.000	0.430	0.343	0.068
9.000	0.476	0.338	0.060
10.000	0.519	0.328	0.052
12.000	0.598	0.300	0.038
14.000	0.667	0.266	0.027
16.000	0.726	0.230	0.018
18.000	0.776	0.200	0.012
20.000	0.818	0.163	0.010
30.000	0.938	0.059	0.001
40.000	0.980	0.020	0.000

[a]For 1 W input and matched termination. If input $\neq$ 1 W, multiply values by P_{in}. (From Ref. data for *Radio Engineers*, 1985.)

Table 4. Resistors R_1 and R_2 values for various Attenuators (assuming $Z_0 = 50\,\Omega$)

	Tee		Pi		Bridged Tee		Reflection	
dB	R_1	R_2	R_1	R_2	R_1	R_2	R_1	R_2
0	0.0	open	open	0.0	0.0	open	0.0	open
1	2.9	433.3	869.5	5.8	6.1	409.8	2.9	869.5
2	5.7	215.2	436.2	11.6	12.9	193.1	5.7	436.2
3	8.5	141.9	292.4	17.6	20.6	121.2	8.5	292.4
5	14.0	82.2	178.5	30.4	38.9	64.2	14.0	178.5
7	19.1	55.8	130.7	44.8	61.9	40.4	19.1	130.7
8	21.5	47.3	116.1	52.8	75.6	33.1	21.5	116.1
10	26.0	35.1	96.2	71.2	108.1	23.1	26.0	96.2
15	34.9	18.4	71.6	136.1	231.2	10.8	34.9	71.6
20	40.9	10.1	61.1	247.5	450.0	5.6	40.9	61.1
30	46.9	3.2	53.3	789.8	1531.1	1.6	46.9	53.3
40	49.0	1.0	51.0	2499.8	4950.0	0.5	49.0	51.0
50	49.7	0.3	50.3	7905.6	15761.4	0.2	49.7	50.3
100	50.0	0.0	50.0	open	open	0.0	50.0	50.0

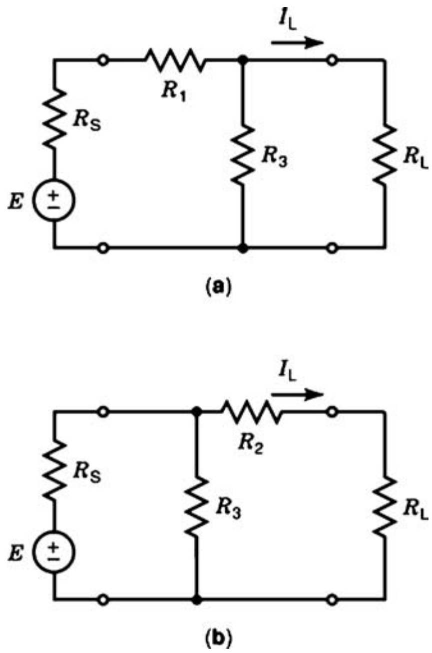


Figure 10. L attenuator configuration. (a) $R_s < R_I$. (b) $R_s > R_I$.

Figure 10 shows an L attenuator, which can be derived from either a T or a pi attenuator, simply by removing one of the resistors. As shown, different configurations are required depending on whether $R_S > R_L$ or $R_S < R_L$.

T Attenuator Insertion Loss

The T attenuator contains resistors R_1, R_2, and R_3; these form a T configuration, as shown in Figure 6. Insertion loss is usually measured in dB, defined as I_L (dB) $= -20$ log I_L or $|20 \log I_L|$, the amount of attenuation required. The insertion loss I_L is given as

$$I_L(\mathrm{dB}) = \frac{I_L}{I_{L0}} = \frac{R_3(R_S+R_L)}{(R_S+R_1+R_3)(R_2+R_3+R_L)-R_3^2} \tag{10}$$

The input and the output of resistances of the attenuator are given by

$$R_{in} = R_1 + \frac{R_3(R_2+R_L)}{(R_2+R_3+R_L)} \tag{11}$$

and

$$R_{out} = R_2 + \frac{R_3(R_1+R_S)}{(R_1+R_3+R_S)} \tag{12}$$

In many cases, the attenuator has also to match the load and the source impedance. In this case, $R_1 = R_2 = R$ and $R_{in} = \mathrm{R}_{out} = R_0$. Thus,

$$R_0 = R + \frac{R_3(R+R_0)}{(R_3+R+R_0)} \tag{13}$$

and the insertion loss is given by

$$I_L = \frac{R_3}{R_3+R+R_0} \tag{14}$$

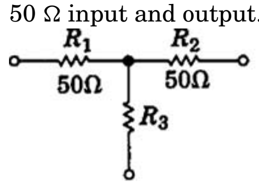
and

$$R = R_0\frac{1-I_L}{1+I_L} \tag{15}$$

and

$$R_3 = \frac{2R_0I_L}{1-(I_L)^2} \tag{16}$$

Example: (T Attenuator) A T-type attenuator is required to provide 3 × 0 dB insertion loss and to match 50 Ω input and output. Find the resistor values.



$$3\,\mathrm{dB} = -20 \log I_L$$
$$I_L = 10^{(-3/20)} = 0.708$$

using the following equation:

$$R = R_0\frac{1-I_L}{1+I_L} = 50\left(\frac{1-0.708}{1+0.708}\right) = 8.55\Omega$$

using the following equation:

$$R_3 = \frac{2R_0I_L}{1-(I_L)^2} = \frac{2\times 50\times 0.708}{1-(0.708)^2} = 141.6\Omega$$

Check:

$$I_L = \frac{R_3}{R_3+R+R_0} = \frac{141.6}{141.6+8.55+50} = 0.708$$

The Pi Attenuator Insertion Loss. Figure 9 shows a Pi attenuator formed by resistors R_a, R_b, and R_c. The insertion loss and conductances G_{in} and G_{out} are given by

$$I_L = G_c\frac{G_S+G_L}{(G_S+G_a+G_c(G_b+G_c+G_L)-G_c^2} \tag{17}$$

$$G_{in} = G_a + \frac{G_c(G_b+G_L)}{G_b+G_c+G_L} \tag{18}$$

$$G_{out} = G_b + \frac{G_c(G_a+G_S)}{G_a+G_c+G_S} \tag{19}$$

where $G = 1/R$; i.e., $G_L = 1/R_L$ and so on.

The same Pi attenuator can be realized using a T attenuator with R_1, R_2, and R_3 values using the Y–Δ transformation, as

$$R_a = \frac{R_1R_2+R_1R_3+R_2R_3}{R_2} \tag{20}$$

$$R_b = R_a\frac{R_2}{R_1} \tag{21}$$

$$R_c = R_a\frac{R_2}{R_3} \tag{22}$$

Table 5. Attenuator Input Power Reduction

% Input Power attenuated = $(1\text{-}10^{-\text{dB}/10}) \times 100\%$			
dB	%	dB	%
1	20.57	12	93.70
2	36.90	13	94.98
3	49.88	14	96.02
4	60.19	15	96.84
5	68.38	16	97.58
6	74.88	17	98.00
7	80.05	18	98.42
8	84.15	19	98.74
9	87.41	20	99.00
10	90.00	30	99.90
11	92.06	40	99.99

Table 6. HPND-4165 PIN Diode Specifications

Parameter	HPND-4165	Test Conditions
High-resistance limit, R_H	1100–1660 Ω	10 μA
Low-resistance limit R_L	16–24 Ω	1 mA
Maximum difference in resistance versus bias slope x	0.04	10 μA and 1 mA

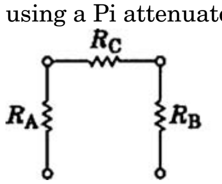
The selection between Pi and T is based on the value of resistors that can be used in practice. With matching source and load impedances, the values of the pi attenuator are

$$R_a = R_b = R_0 \frac{1 + I_L}{1 - I_L} \tag{23}$$

and

$$R_c = R_0 \frac{1 - (I_L)2}{2I_L} \tag{24}$$

Example: (Pi Attenuator) Repeat the above problem using a Pi attenuator:



$$R_L(\text{dB}) = 3 = -20 \log I_L$$
$$I_L = 10^{(-3/20)} = 0.708$$

Using the following equation:

$$R_A = R_B = R_0 \frac{1 + I_L}{1 - I_L} = 50 \left(\frac{1 + 0.708}{1 - 0.708} \right) = 292.46\Omega$$

Using the following equation:

$$R_C = R_0 \left(\frac{1 - (I_C)^2}{2I_L} \right) = 50 \left(\frac{1 - (0.708)^2}{2 \times 0.708} \right) = 17.61\Omega$$

The L Attenuator Insertion Loss. An L attenuator can be derived from a T or a Pi attenuator by removing one resistor. As shown in Figure 10, two configurations are obtained depending upon $R_S > R_L$ or $R_S < R_L$. Simple circuit theory shows that for $R_S > R_L$, we have

$$R_S = R_{in} = R_1 + \frac{R_3 R_L}{R_3 + R_L} \tag{25}$$

and

$$R_L = R_{out} = \frac{R_3(R_1 + R_S)}{R_3 + R_1 + R_S} \tag{26}$$

from which it can be shown that

$$R_1 = \sqrt{R_S(R_S - R_L)} \tag{27}$$

and

$$R_3 = \frac{R_s^2 - R_1^2}{R_1} \tag{28}$$

and when we put $R_2 = 0$, the insertion loss is calculated as

$$I_L = \frac{R_3(R_S + R_L)}{(R_S + R_1 + R_3)(R_3 + R_L) - R_3^2} \tag{29}$$

Example Design an L attenuator to match a 300Ω source to a 50Ω load and determine insertion loss. Here $R_S > R_L$ using the following equation:

$$R_1 = \sqrt{R_S(R_S - R_L)} = \sqrt{300(300 - 50)}$$
$$= \sqrt{300 \times 250} = 273.86\Omega$$

Using the following Equation:

$$R_3 = \frac{R_S^2 - R_1^2}{R_1} = \frac{300^2 - 273.86^2}{273.86} = 54.775\Omega$$

$$R_L = \frac{R_3(R_S + R_L)}{(R_S + R_1 + R_3)}(R_3 + R_L) - R_3^2$$
$$= \frac{54.775(300 + 50)}{(300 + 273.86 + 54.775)(54.775 + 50) - (54.775)^2}$$
$$= 0.305$$

$$R_L(\text{dB}) = -20 \log 0.305 = 10.3\,\text{dB}$$

For $R_s < R_l$, we have

$$R_{in} = \frac{R_3(R_2 + R_L)}{R_2 + R_3 + R_L} \tag{30}$$

and

$$R_{out} = R_2 + \frac{R_3 R_S}{R_3 + R_S} \tag{31}$$

and

$$R_2 = \sqrt{R_L(R_L - R_S)} \tag{32}$$

and

$$R_3 = \frac{R_L^2 - R_2^2}{R_2} \tag{33}$$

The corresponding insertion loss is

$$I_L = \frac{R_3(R_S + R_L)}{(R_S + R_3)(R_2 + R_3 - R_L) - R_3^2} \tag{34}$$

Table 7. Attenuator Resistor Values for Different Levels of Attenuation

Attenuation (dB)	R_1 (Ω)	R_2 (Ω)
2	5.73	215.24
4	11.31	104.83
6	16.61	66.93
8	21.53	47.31
10	25.97	35.14
12	29.92	26.81
14	33.37	20.78
22	42.64	7.99

Table 8. π-Attenuator Resistor Values for Different Levels of Attenuation

Attenuation (dB)	R_1 (Ω)	R_2 (Ω)
2	436	11.61
4	221	23.85
6	150.5	37.35
8	116.14	52.84
10	96.25	71.15
12	83.54	93.25
14	74.93	120.31
22	58.63	312.90

Example Design an L attenuator to match 50Ω source to 75Ω load and determine the insertion loss.

$R_S < R_L$, using the following equation:

$$R_2 = \sqrt{R_L(R_L - R_S)} = \sqrt{75(75-50)} = 43.3\Omega$$

using the following equation:

$$R_3 = \frac{R_L^2 - R_2^2}{R_2} = \frac{75^2 - 43.3^2}{43.3} = 86.6\Omega$$

using the following equation:

$$R_L = \frac{R_3(R_S + R_L)}{(R_S + R_3)(R_2 + R_3 + R_L) - R_3^2} = 0.0123$$
$$= 38.2\text{dB}$$

FIXED ATTENUATORS

Fixed attenuators, commonly known as pads, reduce the input signal power by a fixed amount, such as 3 dB, 10 dB, and 50 dB. For example, an input signal of 10 dBm (10 mW) passing through a 3 dB fixed attenuator will exit with a power of 10 dBm − 3 dB = 7 dBm (5 mW). Figure 2 shows a fixed coaxial commercial attenuator. A typical data sheet for a fixed coaxial attenuator is as follows (courtesy of Weinschel Associates).

Frequency:	0 GHz to 3 GHz
Attenuation:	50 dB
Accuracy:	±0.10 dB (dc)
	±0.15 dB (0 GHz to 2 GHz)
	±0.13 dB (0 GHz to 3 GHz)
VSWR:	1.15 (0 GHz to 1 GHz)
Input power:	1.20 (1 GHz to 3 GHz)
Connectors:	1 W av., 1 kW PK at −30° to 70°C
Length:	Type N; St. St.; m, f
Diameter:	68 mm (2.7 in.)
Weight:	210 mm (0.83 in.)
Power sensitivity:	100 g (3.6 oz)
Temperature stability	<0.005 dB/dB × W; bidirectional in power
<0.0004 dB/dB × °C	

Applications

Fixed attenuators are used in numerous applications. In general, they can be classified into two distinct categories:

1. Reduction in signal level
2. Impedance matching of a source and a load

Those in the first category are used in the following situations:

- Operation of a detector in its square-law range for most efficient operations.
- Testing of devices in their small signal range.
- Reduction of a high-power signal to a level compatible with sensitive power measuring equipment, such as power sensors and thermistor mounts.

Those in the second category are used in the following situations:

- Reduction of signal variations as a function of frequency. The variations here are caused by a high

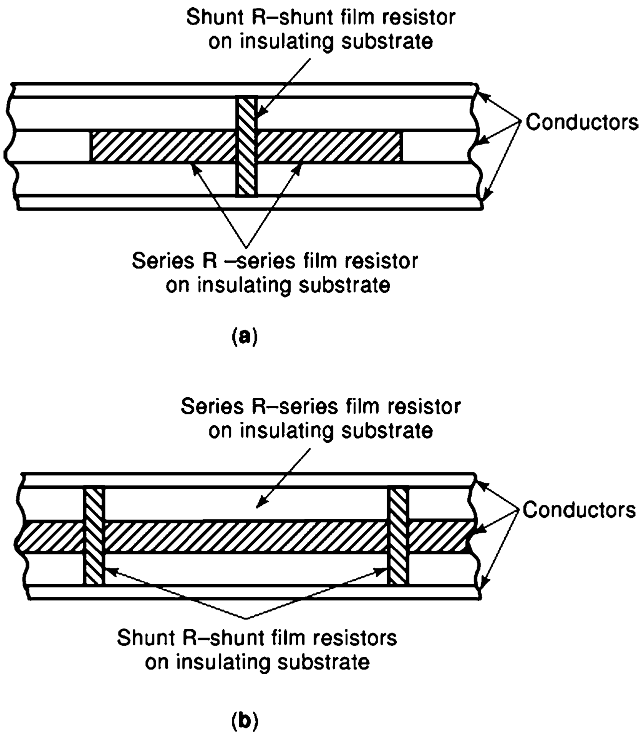


Figure 11. T/Pi fixed attenuator configuration. (a) T section. (b) Pi section.

VSWR. The attenuator provides a reduction in these variations and a better match.

- Reduction in frequency pulling (changing the source frequency by changing the load) of solid-state sources by high reflection loads.

Types

Based on construction, they are available in coaxial, waveguide, and strip line configurations. The various types are:

1. Waveguide vane
2. Rotary vane (fixed)
3. Directional coupler
4. T or Pi
5. Lossy line
6. Distributed resistive film

Coaxial Fixed Attenuators. T or Pi configurations are most commonly used both at low and high frequencies. At low frequencies, normal wirewound resistors are used. At high frequencies, thin film resistors are used. Figures 11 and 12 show T and Pi fixed attenuators. Thin-film resistors designed for microwave frequencies are used, in place of carbon resistors. These resistors employ a nichrome alloy film on a high-quality ceramic substrate to ensure a firmly bonded film with low-temperature coefficients. This type of construction makes the resistors extremely stable at high frequencies. The skin effect of these resistors is excellent, used extensively the microwave applications.

The T and Pi configuration is obtained by placing the resistors in series on the center conductor and in shunt, contacting both the center and outer conductor. Thus, the T configuration with one shunt flanked by two series resistors and the Pi configuration with one series flanked by two shunt resistors can be fabricated. The series resistors in the T and Pi configuration have less than 1 W capacity, thereby severely limiting the use at high-power applications, unless an elaborate heat sinking is provided. Power attenuators usually have huge sinks to handle high-power applications.

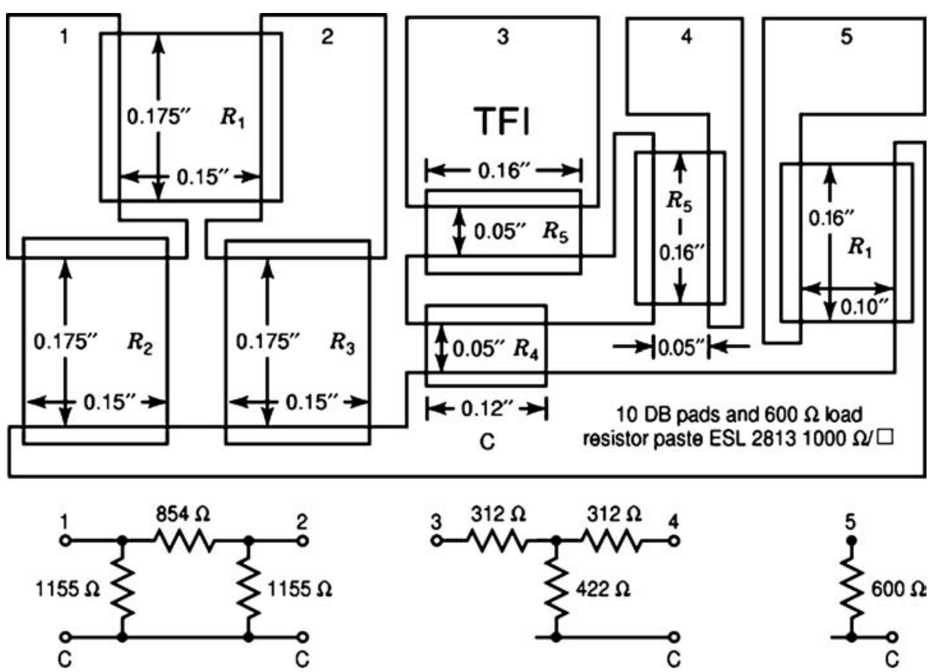


Figure 12. T/Pi fixed attenuator construction.

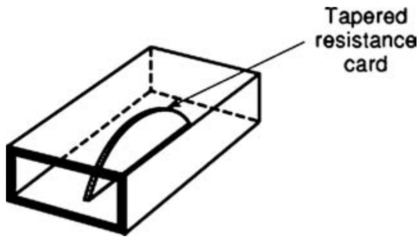


Figure 13. Fixed resistive card attenuator configuration.

Figure 14. Fixed RF attenuator.

Resistive Card Attenuator. In a fixed dissipative, waveguide-type resistive card attenuator, the card is bonded in place (Figure 13). It is tapered at both ends to maintain a low-input and low-output VSWR over the useful waveguide band. Maximum attenuation per length is obtained when the card is parallel to the E field and at the center, where the TE_{10} mode is maximum. The conductivity and the dimensions of the card are adjusted, by trial and error, to obtain the desired attenuation, which is a function of frequency. The attenuation increases with increase in frequency. In power applications, ceramic-type absorbing materials are used instead of a resistive card.

RF Fixed Attenuators

Figure 14 shows a commercial RF fixed attenuator whose specifications are shown below:

Average Power, W	5
Peak Power, W	125
Attenuation, dB	1, 6, 10, 20, 30
Frequency, GHz	DC-4, 4-6
VSWR	1.15:1, 1.20:1
Tolerance, dB	±0.30, ±0.50, ±0.75

Fixed Fiber optic Attenuators

Fiber optic attenuators are engineered and manufactured with continuous light absorbing metal-ion doped fiber. Metal-ion fiber optic attenuators offer better feed-back reflection and noise performance than other attenuators based on spliced fiber, air-gap or offset-fiber designs. The salient features of these attenuators are:

Figure 15. Fixed single-mode, fiber optic attenuator.

Environmentally stable over temperature, humidity, and vibration

High performance and low polarization dependent loss (PDL)

Simple plug-in style enables rapid deployment

Wavelength independent: 1310/1550nm

The specifications of a commercial, fiber-optic, fixed, single-mode attenuator is given below. Figure 15 shows a typical sample.

Technology Type	Doped Fiber
Attenuation, dB	1–10, 15, 20
Return Loss, dB	>50, typically 55
Attenuation accuracy	±0.5 for 1-5 dB; ±10% for $>$ 6 dB
Operating Temperature, °C	−40 to 75

VARIABLE ATTENUATORS

Variable attenuators have a range, such as 0 dB to 20 dB, 0 dB to 100 dB, and so on. The variation can be continuous or in steps, obtained manually or programmably.

Step Attenuators

A series of fixed attenuators are mechanically arranged to offer discrete step variation. The fixed attenuators are arranged in a rotatable drum or in a slab for switching between contacts. This arrangement provides discrete values of attenuation in each position and a high reliability factor. The step size can be 0.1 dB, 1 dB, or 10 dB. Stationary coaxial contacts provide the input and output of the device. These are used in applications requiring broadband flatness with low VSWR and satisfactory resettability over ranges from 0 to 120 dB. Their application range is dc to 18 GHz.

Figure 3 shows a commercial manual step attenuator. A typical data sheet looks as follows:

Manual Step Attenuators

Figure 3 shows manual step attenuator. A typical data sheet looks as follows:

Frequency:	0 to 4, 0 to 8, 0 to 12.4, 0 to 18 GHz
Attenuation:	0 to 9, 0 to 60, 0 to 69
Step size:	1 dB, 10 dB, 1 dB, respectively, for the above range
VSWR:	1.20, 1.25, 1.40, 1.50 for the above frequency range 1.25, 1.30, 1.45, 1.60 for the above frequency range
Connectors:	N/SMA; St. St.
Height:	83 mm (3.3 in.)
Depth:	79 mm (3.1 in.) (excludes shaft and knob)
Width:	65, 65, 118 mm (2.6, 2.6, 4.7 in.) for the above three attenuation ranges

Continuously Variable Attenuators

Figure 4 shows a continuously variable attenuator. Typical specs are:

Frequency:	1 GHz to 18 GHz, 1 W av./1 kW PK
Connectors:	St. St., M, F; type N, SMA
Zero loss:	typically 0.5 dB to 1 dB
Attenuation:	0 to 9, 0 to 60, 0 to 69 dB

The various types of continuously variable attenuators are:

Lossy wall
Moveable vane (Flap)
Rotary vane
Variable coupler
Absorptive type
Coaxial resistive film
Variable T
Waveguide below cutoff (Piston)

Variable Fiber Optic attenuator

The specifications of a commercial, variable, fiber-optic, single- and multi-mode attenuator is given below.

Back-Reflection	> 30 dB, >50 dB, >60 dB
Attenuation Range	2 to 80 dB
Resolution	0.01 dB up to 10 dB, 0.1 dB up to 30 dB
Wavelength	400–1625 nm
Fiber type	Single mode, multimode
Temperature Range, °C	−35 to 70

Digital Attenuators

Digital attenuators provide more than one step in attenuation. It depends on number of bits, LSB, attenuation range and power rating. Fig. 16 shows the functional schematic of a commercial, 5-bit, 15.5 dB, DC-GHz, digital attenuator that can be used for broadband communication system applications which require accurate, fast and low power devices. This is made of patented silicon On Insulator (SIO) CMOS manufacturing technology, which provides the performance of GaAs with the economy and integration capabilities of conventional CMOS.

Digital Step Attenuator

50Ω, RF digital step attenuators are available with the following specifications. Fig. 17 shows a functional schematic diagram.

Number of Bits	6
Range, dB	0.5 dB steps to 31.5
Frequency, GHz	DC to 4.0 GHz
Programming Interfaces	Flexible, serial and parallel
Insertion Loss, dB	1.5
Return Loss (DC −2.2 GHz)	20 dB

Programmable Attenuators

These are rapid switching attenuators with high accuracy and repeatability, useful for remote and computerized applications. Switching speeds can be as low as 30 ns. Two varieties of the programmable attenuators are the step-controlled and voltage-controlled types. The attenuation is varied by controlling the electrical signal applied to the attenuator. These signals can be in the form of either a biasing current or binary digit. The biasing can be pulses, square waves, or sine waves. A typical data sheet for coaxial programmable step attenuator is as follows:

Frequency:	dc to 40 GHz
Attenuation:	0 dB to 11 dB, in steps of 1 dB
Maximum VSWR:	1.3 GHz to 12.4 GHz
	1.7 GHz to 34 GHz
	1.8 GHz to 40 GHz
Insertion loss:	0.8 dB + 0.04 GHz
	0 dB setting
Repeatability:	0.03 dB
Power rating average:	1 W
Peak:	50 W
Maximum pulse width:	10 μs
Life:	5 million cycles per section minimum
Solenoid	
Voltage:	20 V to 30 V
Speed:	<20 ms
Power:	2.7 W
RF connectors:	2.4 mm, F
Shipping weight:	291 g (10.3 oz)

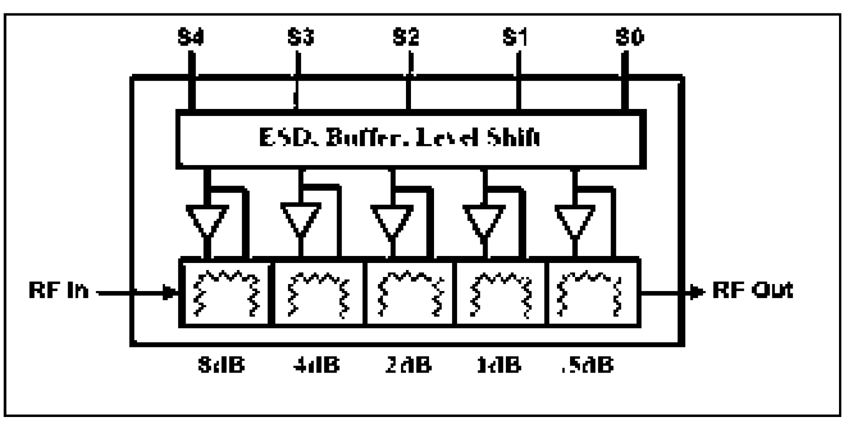


Figure 16. Bit digital attenuator.

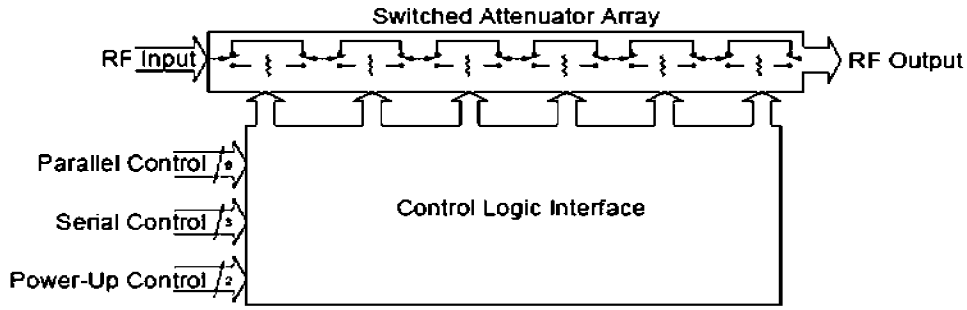


Figure 17. Digital step attenuator.

Solid State Programmable Attenuators

Solid state programmable attenuators operating from 30 MHz to 3 GHz are introduced in the market. They have low insertion loss and high switching speed. Specifications for two types are given below.

	Model 1	Model 2
Frequency Range	30 MHz to 3 GHz	400-2000 MHz
Impedance, Ω	50	50
Attenuation	0 to 127 in 1 dB steps	0 to 127 in 1 dB steps
Attenuation Steps, dB	1, 2, 4, 8, 16, 32 and 64	1, 2, 4, 8, 16, 32 and 64
VSWR	1.6:1 max	
Accuracy		
1, 2, 4, 8 dB	± 0.3 dB to 2 GHz	−0.25 dB for 1, 2, 4, 8 dB
1, 2, 4, 8 dB	± 0.4 dB to 2 GHz	−0.35 for 16 and 32 dB
16, 32, 64 dB	± 0.5 dB or 3% (whichever is higher)	−0.50 dB for 64 dB
		Max error ±0.5 dB or 2%
Insertion Loss	6 dB max to 2000 MHz	5 dB max t@ 1 GHz
	8 dB max to 3000 MHz	7 dB max t@ 2 GHz
RF Input power	±15 dBm operating	+10 dB
	±30 dBm no damage	
Switching Speed	20 μs max	2 μs
Operating Temperature	0 to 70°C	0 to 70°C
Programming	TTL low for thru path	TTL low for "0" setting
	TTL high for attenuation	TTL high for pad setting

Lossy Wall Attenuator

Figure 18 shows lossy wall variable attenuator. It consists of a glass vane coated with a lossy material, such as aquadag or carbon. For maximum attenuation the vane is placed in the center of the guide's wide dimension, where the electric field intensity is the maximum. A drive mechanism with a dial then shifts the vane away from the center so that the degree of attenuation is varied. This needs calibration by a precise attenuator. To match the attenuator to the waveguide, the vane can be tapered at each end; usually a taper of $\lambda g/2$ provides an adequate match. Thus, it is frequency sensitive and the glass dielectric introduces appreciable phase shift.

Attenuation may also be obtained by inserting a resistive element through a shutter. The plane of the element lies in the distribution of the electric field across the wide dimension of the waveguide and the result is a degree of attenuation, which increases with the depth of insertion. However, due to the discontinuity, there is reflection of energy.

Moveable Vane (Flap) Attenuator

Figure 19 shows a waveguide variable, dissipative attenuator. The card enters the waveguide through the slot in the broad wall, thereby intercepting and absorbing a portion of the TE_{10} wave. The card penetration, and hence the attenuation, is controlled by means of the hinge arrangement to obtain variable attenuation. The ratings are typically 30 dB and widely used in microwave equipment. However, the attenuation is frequency sensitive and the phase of the output signal is a function of card penetration and hence attenuation. This may result in nulling when the attenuator is part of a bridge network. Since it is not simple to calculate the loss in dB, this type of attenuator has to be calibrated against a superior standard. To overcome these drawbacks, a rotary vane attenuator is used.

Rotary Vane Attenuator

The rotary vane attenuator is a direct reading precision attenuator which obeys a simple mathematical law, $A = -20 \log \cos^2\theta = -40 \log \cos \theta$ dB. As such, it is frequency independent, which is very attractive criterion for an attenuator. A functional diagram illustrates the operating

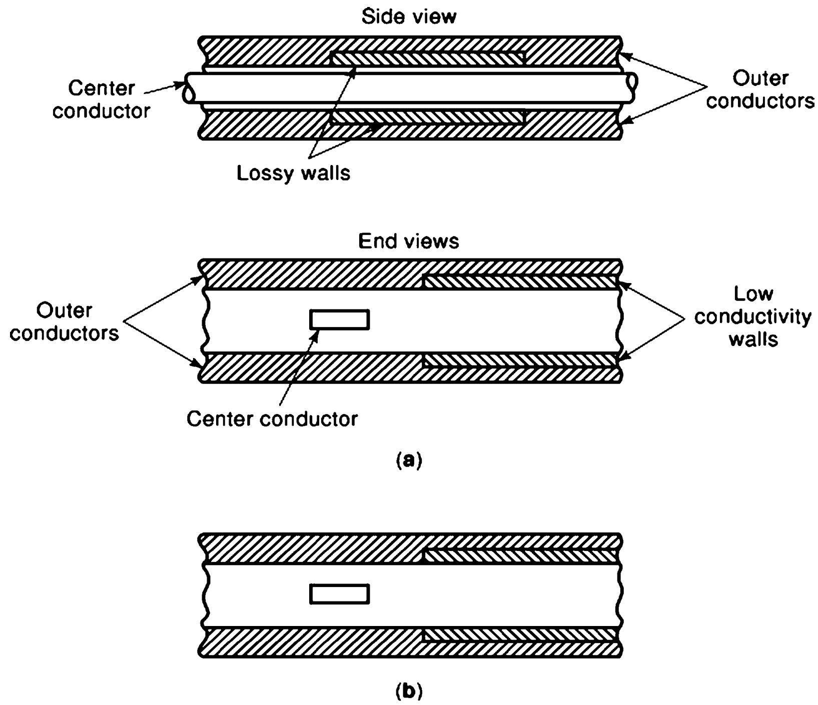


Figure 18. Lossy wall attenuator configuration. (a) Minimum attenuator. (b) Maximum attenuator.

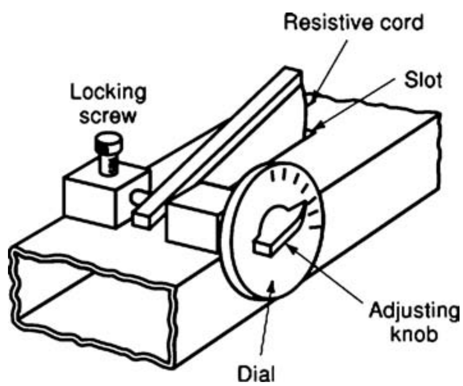


Figure 19. Movable vane (flap) variable attenuator configuration.

principle of this attenuator. It consists of three sections of waveguide in tandem as shown (Figure 20). A rectangular to circular waveguide transition containing a horizontal attenuator strip is connected to a rotatable circular waveguide containing an attenuator strip. This in turn is connected to a circular to rectangular waveguide transition containing a horizontal attenuator strip.

The incoming TE_{10} mode is transformed into the TE_{11} mode in the circular waveguide by the rectangular to circular waveguide transition with negligible reflections. The polarization of the TE_{11} mode is such that the e field is perpendicular to the thin resistive card in the transition section. As such, this resistive card has a negligible effect on the TE_{11} mode. Since the resistive card in the center can be rotated, its orientation relative to the electric field of the incoming TE_{11} mode can be varied so that the amount by which this mode is attenuated is adjustable.

When all the strips are aligned, the electric field of the applied wave is normal to the strips and hence no current flows in the attenuation strips and therefore no attenuation occurs. In a position where the central attenuation strip is rotated by an angle θ, the electric field of the applied wave can be resolved into two orthogonally polarized modes; one perpendicular and one parallel to the resistive card. That portion which is parallel to the resistive slab will be absorbed, whereas the portion, which is polarized perpendicular to the slab, will be transmitted.

Variable Coupler Attenuator

These are basically directional couplers where the attenuation is varied by mechanically changing the coupling between two sections. This is accomplished by varying the spacing between coupled lines. These attenuators have a large range, high power handling capability, and retain calibration over a range of ambient conditions. They have a higher insertion loss at lower frequencies (Figure 21).

Absorptive Attenuator

Figure 22 shows an absorptive variable attenuator. Attenuation is obtained by using a lossy dielectric material. The TEM electric field is concentrated in the vicinity of the center strip of the stripline. When the absorbing material is inserted in the high field region, a portion of the TEM wave is intercepted and absorbed by the lossy dielectric. Thus, the attenuation increases. Since the characteristic impedance of the stripline changes with the dielectric material insertion, the SWR tends to increase as the attenuation increases. To minimize this, the ends of the lossy material are tapered to provide a smooth impedance transformation into and out of the lossy section. SWR values of >1.5

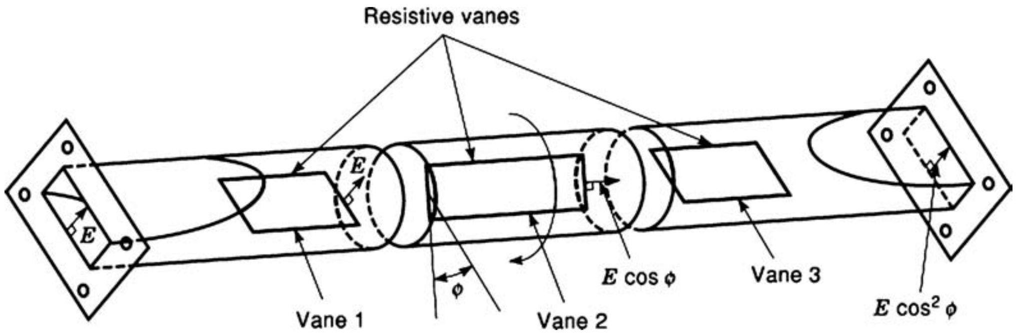


Figure 20. Rotary vane attenuator configuration.

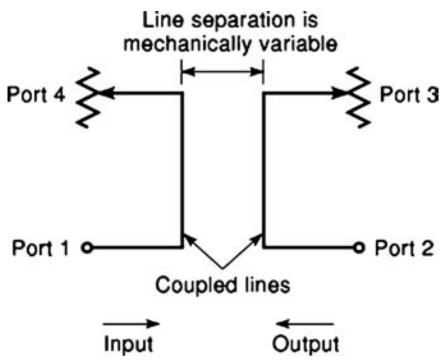


Figure 21. Variable coupler attenuator configuration.

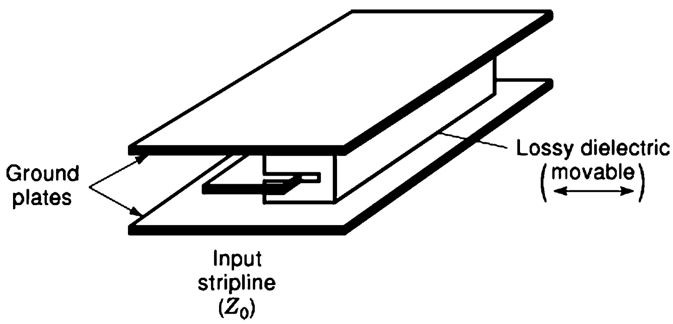


Figure 22. Absorptive-type variable attenuator configuration.

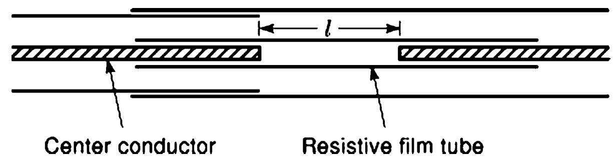


Figure 23. Coaxial resistive film attenuator configuration.

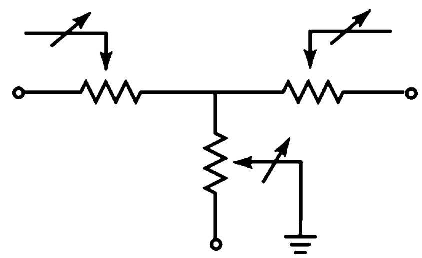


Figure 24. Variable T attenuator.

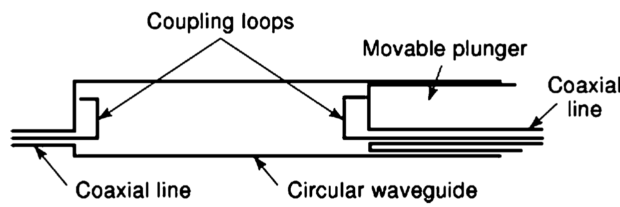


Figure 25. Coaxial variable cutoff attenuator configuration.

are possible over a limited frequency range. In general, the SWR deteriorates at low frequencies. The attenuation increases with increasing frequency for a fixed setting. This is another disadvantage, since this makes the calibration a cumbersome procedure. Compensation techniques are occasionally used to reduce this variation with frequency.

Coaxial Resistive Film Attenuator

Figure 23 shows a coaxial resistive film attenuator. In this configuration, if r is the RF resistance per unit length, by adjusting the length l, the series resistance $R = rl$ of the center conductor is changed; thus, the attenuation is variable. If I is the conduction current on the center conductor, the voltage drop is $V = RI = Irl$. If E_i is the input voltage, then the output voltage is $E_0 = E_i - rlI$ and the attenuation is

$$A = 20 \log \frac{E_i}{E_i - rlI} \text{ (dB)} \tag{35}$$

Variable T

The variable T attenuator is the same as the fixed attenuator except that the resistors are variable (Figure 24). All the three resistors are variable simultaneously to give good input/output VSWR.

Waveguide Below Cutoff or Piston Attenuator

The simple principle of cutoff below frequency is used in the piston or the cutoff attenuator. The cylindrical waveguide used is operating at a frequency below cutoff. For high power applications, a coaxial configuration is used. A simple waveguide cutoff attenuator is shown in Figure 25. A metal tube, acting as a waveguide, has loops arranged at each end to couple from the coaxial lines into and out of the waveguide. One of the loops is mounted on a movable plunger or hollow piston so that the distance between the

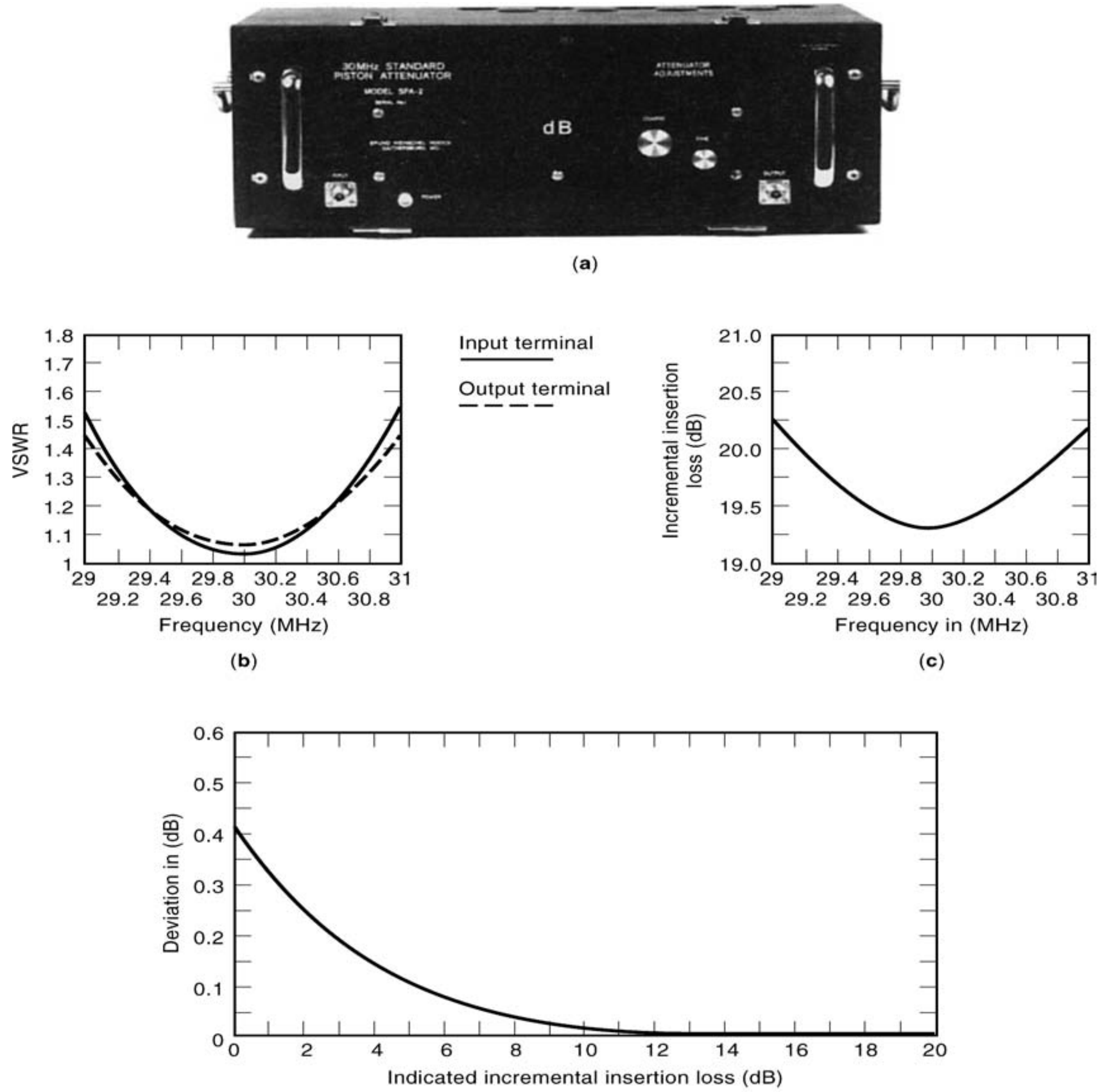


Figure 26. (a) Standard variable piston attenuator and (b–d) calibration curves. (b) Typical VSWR versus frequency of SPA-2 attenuator with frequency. (c) Typical variation of insertion loss of SPA-2 attenuator with frequency in a 50-Ω system. (d) Deviation versus indicated incremental insertion. Typical deviation from linearity for the model SPA-2 operating frequency is 30.0 MHz.

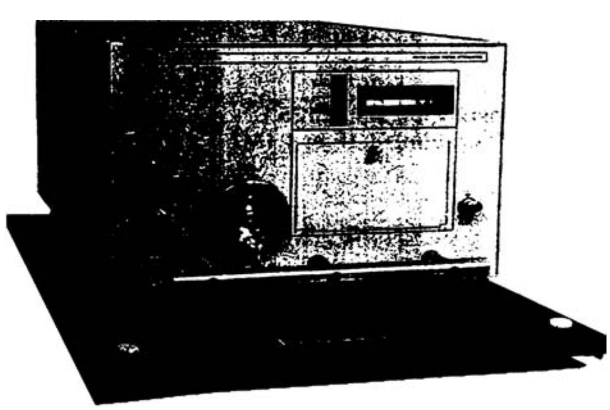


Figure 27. Laser piston attenuator. (Courtesy of Weinschel Associates.)

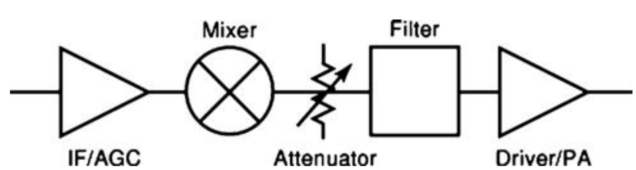


Figure 28. CDMA handset transmit application.

loops is variable. The input coupling loop converts the incoming TEM wave into the TE_{11} mode in the circular guide, while the output loop converts the attenuated TE_{11} mode back to TEM. The attenuator can be matched by adding Z_0 resistors. The attenuation is given as:

$$A\,(\mathrm{dB}) = 54.6\frac{l}{\lambda_c}\sqrt{1-\left(\frac{f}{f_c}\right)^2} \qquad (36)$$

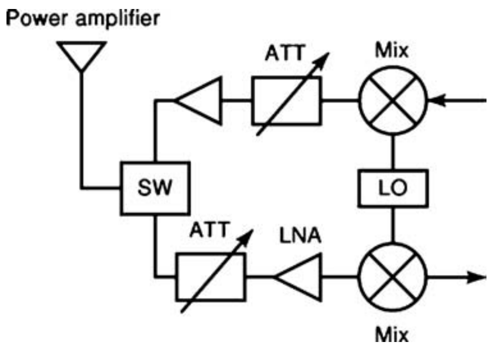


Figure 29. Functional block diagram of a digital cellular phone, using variable attenuators.

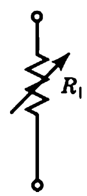


Figure 30. *Pin* diode high-frequency equivalent circuit.

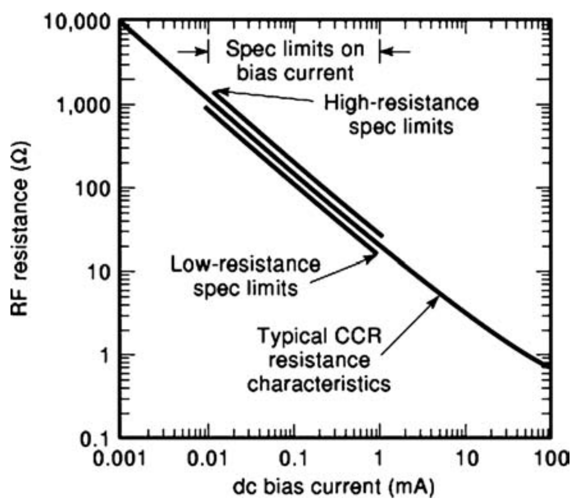


Figure 31. Typical RF resistance versus dc bias current for HPND-4165.

By choosing the diameter such that $\lambda_c < \lambda_o$, and hence $f/fc < 1$, the above equation reduces to

$$A\,(\mathrm{dB}) = 54.6\frac{1}{\lambda_c} \tag{37}$$

This was obtained from

$$\alpha = \frac{2\pi}{\lambda_{oc}} Np/m \quad \text{or} \quad \alpha = \frac{54.6}{\lambda_{oc}}\,\mathrm{dB}/m \text{ where } 1\,\mathrm{Np} = 8.686\mathrm{dB} \tag{38}$$

(If $\lambda_{oc} = 10$ cm, and λ_o is much greater (10 times or more (in this case, 1 m or more)), the attenuation increases 5.45 dB per cm of outward movement of the plunger.)

The sliding cylindrical conductors allow length l to be varied, which varies the attenuation, since attenuation $A = \alpha l$, where α is the attenuation constant due to the cutoff effect, and l is the length of the circular guide. The cutoff wavelength is, $\lambda_c = 1.706D$, where D is the diameter of the waveguide. Thus the attenuation is:

$$A(\mathrm{dB}) = 54.6\,\frac{l}{\lambda_c} = 32\,\frac{l}{D} \tag{39}$$

or

$$\Delta A(\mathrm{dB}) = \frac{32}{D}\,\Delta l \tag{40}$$

The attenuation is independent of frequency; it depends only on the physical dimensions and hence can be accurately controlled by maintaining tight tolerances on the length and diameter of the circular guide. With ΔA linearly proportional to Δl, the cutoff attenuator is easily calibrated and hence particularly useful as a precision variable attenuator.

The cutoff attenuator is one of the most widely used precision variable attenuators in coaxial measurement equipment. This is a reflective-type attenuator, since the waveguide is essentially dissipationless. The signal is reflected rather than absorbed. For higher attenuation (>10 dB), the SWR at both ports is very high (>30). This can cause problems in certain applications.

This type of attenuator is very useful, but has the disadvantage of high insertion loss. Due to cutoff nature, the insertion loss is high, up to 15 dB to 20 dB. If this loss is overcome, piston attenuators are one of the most

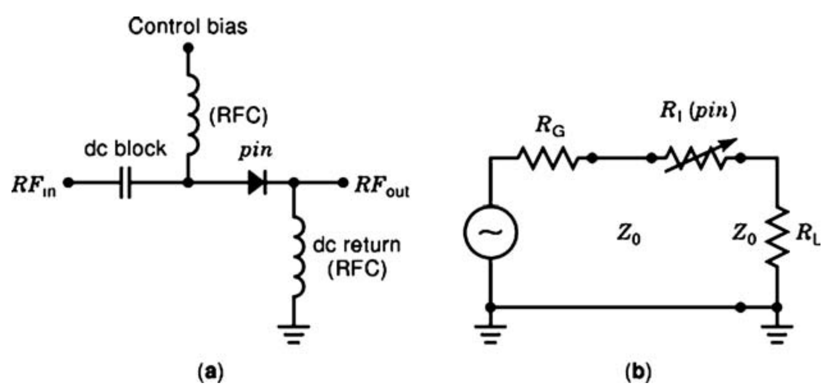


Figure 32. Series *pin* RF attenuator or switch. (a) Complete circuit. (b) Idealized RF equivalent circuit.

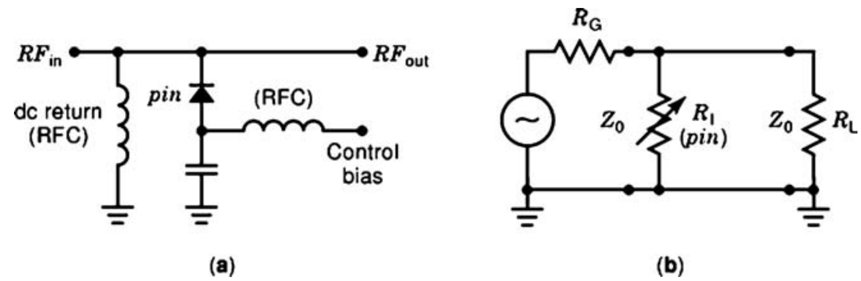


Figure 33. Shunt *pin* RF attenuator or switch. (a) Complete circuit. (b) Idealized RF equivalent circuit.

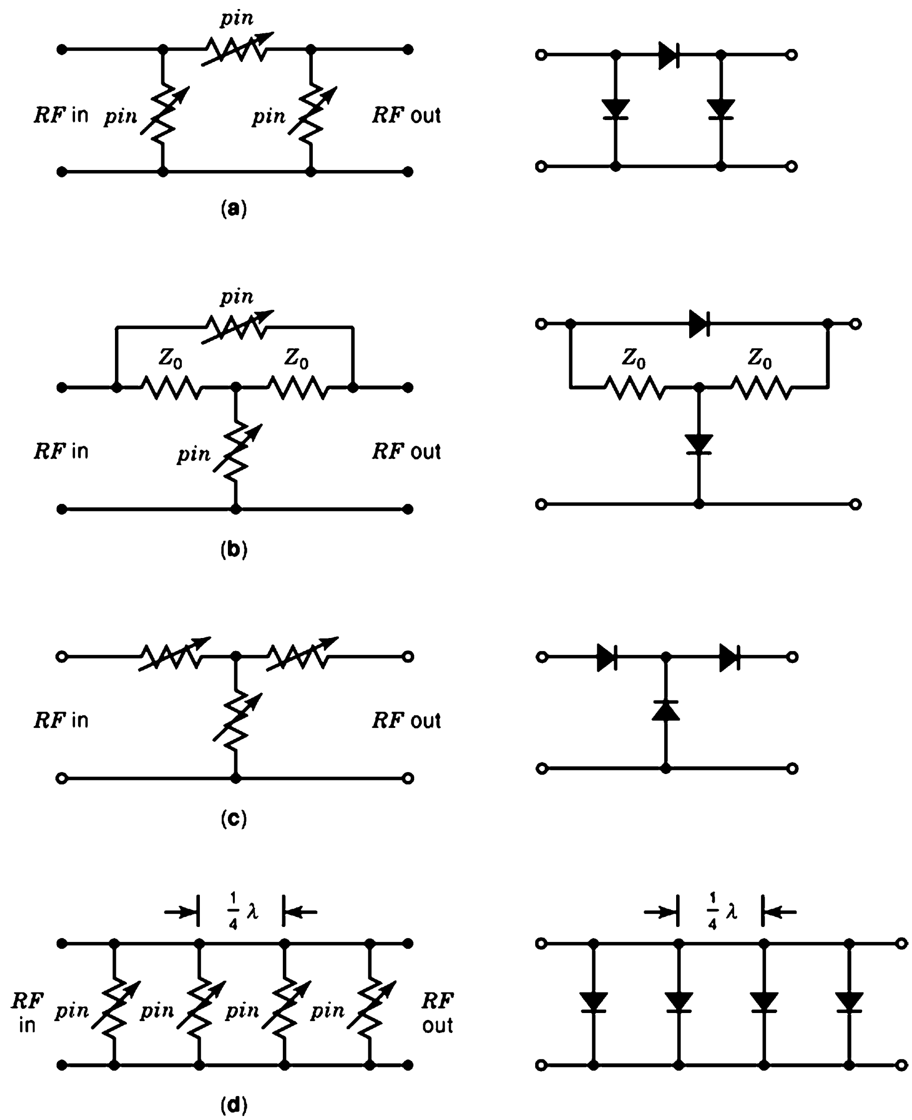
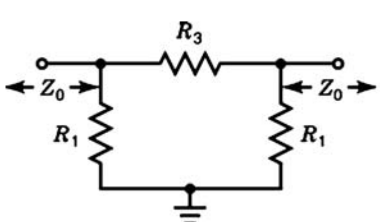


Figure 34. Constant impedance *pin* diode attenuators. (a) Pi attenuator. (b) Bridged T attenuator. (c) T attenuator. (d) Resistive line attenuator.



$$R_1 = Z_0\left[\frac{K+1}{K-1}\right]$$

$$R_3 = \frac{Z_0}{2}\left[K = \frac{1}{K}\right]$$

Figure 35. Fixed Pi attenuator.

accurate attenuators available. Values of 0.001 dB/10 dB of attenuation over a 60 dB range are common. A good input/output match is obtained using inductive loops within the waveguides. Excellent matching is obtained over the entire range of attenuation due to inductive loop coupling. Figure 26 shows a commercially available standard variable piston attenuator and the various calibration curves. It contains an accurately dimensioned tube acting as a circular waveguide, below cutoff TE_{11} mode. Typical specifications are (Courtesy of Weinschel Associates):

Frequency:	30 MHz
Mode:	TE_{11} cutoff
Range:	0 dB to 120 dB
	12.5 dB zero insertion loss
VSWR:	1.2 max in 50 Ω system
Connectors:	Type-N, panel mounted
Accuracy:	0.01 dB from 0 dB to 15 dB
	0.005 db/10 dB from 15 dB to 100 dB
	0.01 dB/10 dB from 100 dB to 120 dB
Resolution:	0.001 dB direct reading digital indicator

Laser Piston Attenuator. Figure 27 shows a laser piston attenuator. The heart of this instrument is a precise stainless steel circular waveguide, operated in the TE_{11} cutoff mode. Laser light, traveling between two antennas in the center of the circular waveguide, measures directly the changes in actual separation of the two antennas along the same path as the TE_{11} mode propagates. The laser signal is converted to attenuation in dB and corrected for skin effect, the refractive index of air, and changes due to temperature of the waveguide and pressure. The specifications are (Courtesy of Weinschel Associates):

Operating frequency:	Dual frequency 1.25 MHz + 0.05 MHz and 30.0 MHz + 0.1 MHz
Waveguide mode:	TE_{11}, below cut-off
Incremental attenuation range:	100 dB
Min insertion loss:	10 dB nominal
Resolution:	0.0001 dB for Δ dB, 0.002 dB for total loss
Attenuation readout:	Front panel 7 digit LED or remotely via IEEE bus
Connectors:	Type N jacks
VSWR (input and output):	1.2 max at 1.25 and 30 MHz in 50 Ω system
Accuracy:	0.001 dB/10 dB + 0.0005 dB between 15 and 115 dB total loss
Weight:	Net: 77 kg (170 lb); shipping: 145 kg (320 lb)
Accessories:	Power supply, controller, calibration tape, two power cables, one 22 wire power cable, Instruction and Maintenance manual

tor for leveling and amplitude modulating a RF signal.

These attenuators provide local oscillator, IF, and RF signal level control throughout communications, measurement, and control circuits. One example is the reduction in the output of a receive mixer in a Code-Division Multiple Access (*CDMA*) base station prior to the IF amplifier. Also, to provide one step of transmit level control with little degradation of the noise figure (*NF*), it could be used in a CDMA handset transmit chain between the mixer (upconverter) and the bandpass filter (Figure 28). Since the attenuator is purely passive, it produces no additive noise and the NF is essentially its insertion loss. Even in the attenuator mode, the effect on the noise figure would be minimal.

In Personal Communication Service (*PCS*) systems, the base stations may be fed from multiple picocells that are physically separated from it by up to 100 feet or more of coaxial cable. The signal levels coming into the base station will vary depending on the cable length and individual transponder power. It is desirable to keep the signals at uniform levels coming into the base station; to do so, it may be necessary to attenuate the stronger signals. An attenuator can be easily inserted for this purpose.

The upper end of a receiver's linear dynamic range is determined by the largest signal it can handle without being overdriven and producing unacceptable levels of distortion caused by device nonlinearities. Inserting an attenuator before a low noise amplifier (*LNA*) in the presence of strong, in-band signals produces better reception by preventing them from overdriving the receiver's front end. This effectively shifts the dynamic range upward by the amount of attenuation. It must be remembered that when inserted into the system, the attenuator will also present a load and a source impedance to the previous and succeeding stages, respectively, hence the importance of the attenuator impedance match.

RF variable attenuators are used to control the transmitting and receiving signal power levels to prevent strong–weak adjacent signals from seriously degrading the bit error rate (*BER*) of digital mobile communication systems, such as TDMA or CDMA. Figure 29 shows the basic RF functional block diagram of a typical digital cellular phone system, where variable attenuators are required.

ACTIVE ATTENUATORS

PIN Diode Attenuators

The normal diode junction consists of a *p*-type material brought together with an *n*-type material to form the familiar PN junction. The PIN diode is distinguished from the normal PN junction type by an area called an intrinsic region sandwiched between the $p+$ doped and $n+$ doped silicon layers. This intrinsic layer has almost no doping and thus has a very large resistance. When a variable dc control voltage forward biases the PIN diode, the dc bias or control current causes it to behave as almost a pure resistance at RF frequencies, with a resistance value that can be varied over a range of 1 Ω to 10 KΩ. As the bias current is increased, the diode resistance decreases. This relation makes the PIN diode ideally suited as a variable attenua-

Characteristics of the Pin Diode

The approximate high frequency equivalent circuit of a PIN diode is shown in Figure 30. Here, R_I is the effective resistance of the intrinsic (I) layer, given by

$$R_I = k/I_{\rm DC}^x \tag{41}$$

where $I_{\rm DC}$ is the dc bias current in mA, and k and x are device-dependent empirical constants. Although shown as a variable, this resistance is constant with respect to the RF signal. The high frequency resistance function is plotted in Figure 31 for the Hewlett Packard HPND-4165 diode. For a specific diode design, the exponent X is usually a constant. For the HPND-4165, X is typically 0.92. The constant k and therefore, R_I, however, are highly dependent on the fabrication and process control and its value can vary by as much as 3:1 from diode to diode. For analog applications, such as a variable attenuator, where repeatable attenuation with bias current is desired, the variation of R_I must be controlled. The HPND-4165 is precisely controlled in manufacturing, and resistance values at specific bias points are specified and the slope of resistance versus bias matched with narrow limits. The specification limits of these parameters are shown in Table 4.

Applications

The PIN diode is ideally suited to switch and attenuate RF signals. Since the PIN diode is a RF variable resistor, the logical application is that of a variable attenuator. This attenuator may be either a step or a continuously variable type. Two of the simplest circuits are the series and shunt attenuators shown in Figures 32 and 33.

Attenuation in the series PIN circuit is decreased (more power appears at the output) as the RF resistance of the diode is reduced. This resistance is reduced by increasing the forward bias control current on the diode. The opposite occurs for the shunt configuration. The attenuation in the shunt circuit is decreased when the RF resistance of the diode increases because less power is absorbed in the diode and more appears at the output. If the control bias is switched rapidly between high and low (zero) values, then the circuit acts simply as a switch. When used as a switch, the attenuation that exists when the switch is “on” is called insertion loss. The attenuation provided when the switch is “off” is called isolation. If the diode is a pure resistance, the attenuation for the series and shunt circuit can be calculated as

$$A\,(\text{series}) = 20\log\left(1+\frac{R_I}{Z_0}\right) \tag{42}$$

$$A\,(\text{shunt}) = 20\log\left(1+\frac{Z_0}{2R_I}\right) \tag{43}$$

where $Z_0 = R_{\rm G} = R_{\rm L}$ = circuit, generator, and load resistance, respectively. In reviewing these equations, it is seen that the attenuation is not a function of frequency but only a ratio of circuit and diode resistances, which is a great advantage. As the bias on the diode is varied, the load resistance experienced by the source also varies. These circuits are generally referred to as reflective attenuators because they operate on the principle of reflections.

Many RF systems require that the impedance at both RF ports remain essentially constant at the design value Z_0. Four such circuits and their PIN diode counterparts are shown in Figure 34. All four circuits operate on the principle of absorbing the undesired RF signal power in the PIN diodes. In circuits (a), (b), and (c), the control current variation through each diode is arranged in such a way that the impedance at both RF ports remain essentially constant at the characteristic impedance (Z_0) of the system while the attenuation can be varied over a range of less than 1 dB to greater than 20 dB. In circuit (d), the input impedance is kept constant by using a distributed structure with a large number of diodes. The impedance variation of each diode is also shaped so that the diodes in the center of the structure vary more than those near the ports. The resulting tapered impedance structure results in an essentially constant impedance at the ports, while the overall attenuation can be varied up to a range of 40 dB to 80 dB, depending on the length of the structure.

PIN diode Pi attenuator in Figure 30(a) is often selected when designing a variable attenuator. The basic Pi fixed attenuator is shown, along with its design equations, in Figure 35. Shunt resistors R_1 and the series resistor R_3 are set to achieve a desired value of attenuation, while simultaneously providing an input and output impedance which matches the characteristic impedance Z_0 of the system.

Three PIN diodes can be used as shown in Figure 36 to replace the fixed resistors of the Pi circuit to create a variable attenuator. The attenuator provides good performance over the frequency range of 10 MHz to over 500 MHz. However, the use of three diodes as the three variable resistors in a Pi attenuator results in a complex unsymmetrical bias network. If resistor R_3 is replaced by two diodes, as shown in Figure 37, the resulting attenuator is symmetrical and the bias network is significantly simplified. V_+ is a fixed voltage, and V_c is the variable control voltage, which controls the attenuation of the network. The only drawback to using two series diodes in place of one is the slight increase in insertion loss. Resistors R_1 and R_2 serve as bias returns for series diodes D_2 and D_3. Resistors R_3 and R_4 are chosen to match the specific characteristics of the PIN diodes used. Properly selected, they will provide the correct split of bias current between series and shunt diodes required to maintain a good impedance match over the entire dynamic range of attenuation.

The PIN diode variable attenuator is an excellent circuit used to set the power level of an RF signal from a voltage control; used widely in commercial applications, such as cellular telephones, *PCN* (personal communication networks), wireless *LAN*s (local area networks), and portable radios.

GaAs NMESFET Attenuator

The GaAs *N*-semiconductor metal semiconductor field effect transistor (*NMESFET*) is used in microwave attenuator designs. The metal–semiconductor FET (*MESFET*) is a field effect transistor that operates on the principle that the gate-to-source voltage controls the drain current. The MESFET is a device extension of a JFET, where the gate

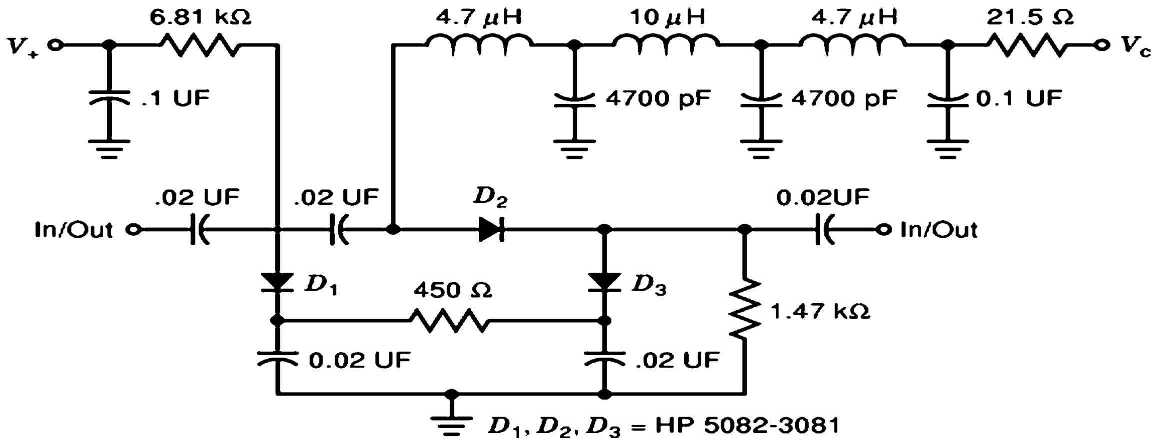
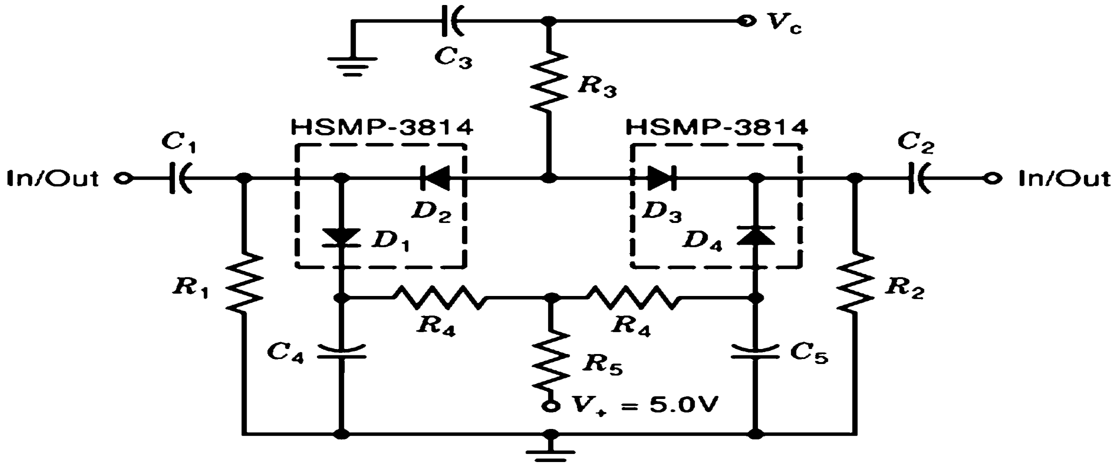


Figure 36. Three-diode Pi attenuator.



Component	Value	Manufacturer and part number
R_1, R_2	560 Ω	Kyocera CR21-561JB1
R_3	330 Ω	Kyocera CR21-331JB1
R_4	1640 Ω	Kyocera CR21-162JB1
R_5	680 Ω	Kyocera CR21-6B1JB1
C_1–C_5	47,000 pF	Kyocera 08957473M2P03
D_1–D_4	–	Hewlett-Packard HSMP-3814

Figure 37. Wideband four-diode Π attenuator.

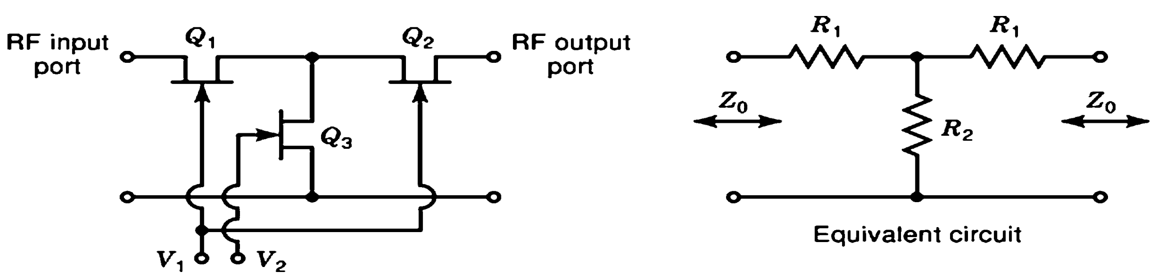


Figure 38. MESFET T attenuator.

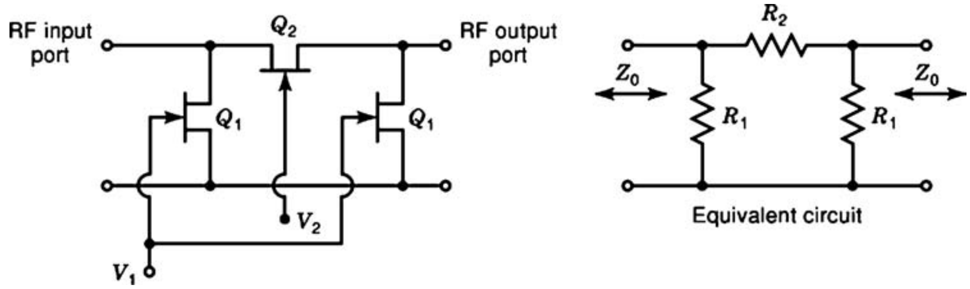


Figure 39. MESFET Pi attenuator.

structure is a Schottky MN (metal–*N* semiconductor) junction.

In GaAs NMESFET attenuator designs, the devices are operated either in the linear region where the device is modeled as a voltage variable resistor or they operate as an on/off switch in conjunction with thin-film nichrome resistors to provide appropriate levels of attenutation. The channel resistance of the GaAs NMESFET is known to follow the classical theory for a FET in the linear region of operation. With the FET biased in the linear region, the resistance varies inversely to the gate voltage as shown below:

$$R_{ds} = R_{dso}\left(\frac{1}{1-(V_g/V_p)}\right) \tag{44}$$

where V_g = gate bias voltage (V), V_p = pinch-off voltage (V), and R_{dso} = channel resistance (Ω) with V_g = 0 V.

As the gate voltage approaches the pinch-off voltage, the resistance becomes very high (relative to 50 Ω). Conversely, as the gate voltage approaches zero, so does the channel resistance. For each attenuator configuration, two independent gate bias voltages are used; one to control the series MESFETs and one to control the shunt MESFETs. The T attenuator configuration is shown in Figure 38, with one voltage controlling the series resistance arms, and another the shunt resistance arm. Table 5 gives the resistor values of the series and shunt resistances in a Z_0 = 50 Ω system. The channel resistances of the MESFETs are matched as closely as possible for these resistances. A matched condition at the input and output port to Z_0 occurs when,

$$Z_0^2 = R_1^2 + 2R_1R_2 \tag{45}$$

The resulting matched attenuation is

$$A = 20\log\left(\frac{R_1+R_2+Z_0}{R_2}\right) \tag{46}$$

The Pi attenuator configuration is shown in Figure 39, with one voltage controlling the shunt resistance arms, and another the series resistance arm. Table 6 gives the values of the series and shunt resistances for different levels of attenuation in a Z_0 = 50 Ω system. Shunt resistor R_1 and series resistor R_2 provide and input and output impedance which matches the characteristic impedance Z_0 = 50 Ω of the system, while setting the desired level of attenuation.

The design equations are:

$$R_1 = Z_0\left[\frac{K+1}{K-1}\right] \tag{47}$$

$$R_2 = \frac{Z_0}{2}\left[K-\frac{1}{K}\right] \tag{48}$$

$$A(\text{dB}) = 20\log K \tag{49}$$

where K is the input to output voltage ratio.

GaAs NMESFET digital attenuators allow a specific value of attenuation to be selected via a digital n bit programming word. In these designs, the NMESFET operates as an on/off switch and is used in conjunction with nichrome thin-film resistors to provide the desired level of attenuation. Figure 40 shows the circuit configurations used for individual attenuator bits. The switched bridged T attenuator consists of the classical bridged T attenuator with a shunt and series FET. These two FETs are switched on or off to switch between the two states. The attenuation in dB is given by

$$A(\text{dB}) = 20\log\left(\frac{Z_0+R_2}{R_2}\right) \tag{50}$$

where $Z^2{}_0 = R_1R_2$.

The performance is determined by the FET characteristics in the on and off states and the realizability limit on required resistance values and their associated parasitics. The switched T or Pi attenuators are similar in principle to the switched bridged T attenuator except for the circuit topology. These attenuators are normally used for high attenuation values. To obtain smaller values of attenuation, the thin-film resistors are replaced with appropriate channel resistances.

There are GaAs NMESFET digital RF attenuators on the market with excellent performance, in both step and continuously variable types. The variable or programmable class allows a specific value of attenuation to be selected from an overall range via an *N*-bit programming word. They are more flexible than step attenuators, as they allow any amount of attenuation to be set, but the cost is greater circuit complexity. Both types have a bypass state when no attenuation is selected, and the attenuation is just the insertion loss of the device. An example of each type is presented.

The RF Microdevices RF 2420 is a multistage monolithic variable or programmable attenuator which has as

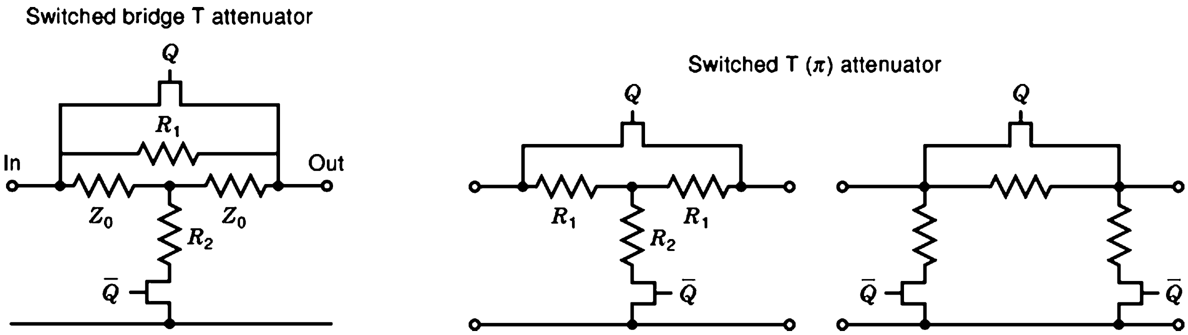


Figure 40. GaAs digital attenuator circuit configurations.

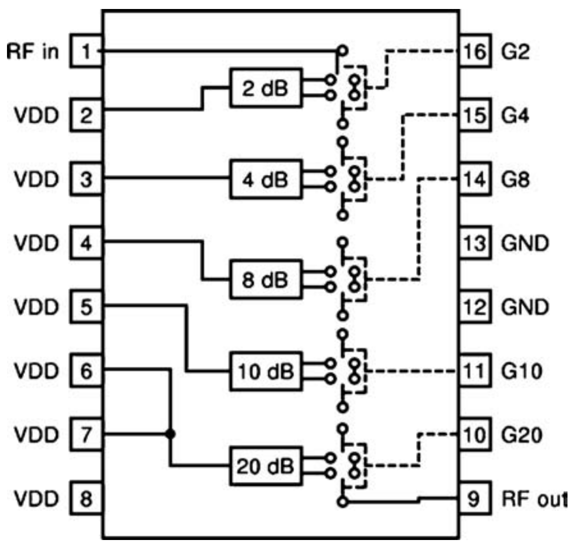


Figure 41. RF 2420 functional block diagram.

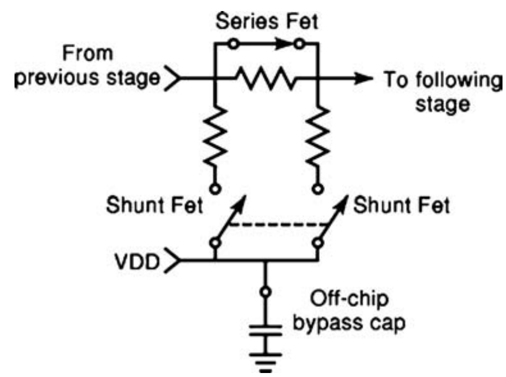


Figure 42. Functional schematic of RF 2420 (one attenuator section).

attenuation programmability over a 44 dB range in 2 dB steps. The attenuation is set by five bits of digital data. A functional block diagram of the RF 2420 is shown in Figure 41. It consists of five cascaded, dc-coupled attenuator sections, each with its own logic translator. The logic translator converts the one-bit control signal, which uses logic levels approximating standard TTL logic, to the voltage levels required to switch the attenuator stage FETS. The RF input and output signal lines are biased at approximately V_{DD}, and therefore external dc blocking capacitors are required. An external V_{DD} bypass capacitor is also required.

A functional schematic of the RF portion of one attenuator section is shown in Figure 42. A MESFET bridges the series resistor in a resistive Pi attenuator, and two more MESFETs are connected as a double-pole single-throw (*DPST*) RF switch connecting the shunt branches of the Pi attenuator to RF ground. In the bypass state, the bridge MESFET is in its high conductance state, and the DPST switch is open, so that the Pi-attenuator is effectively removed from the circuit. When the attenuator bit is selected, the bridge MESFET is put into its low conductance state or cutoff state and the shunt FETs are put into their on state, so that the Pi-attenuator is connected into the RF series path. This attenuator has only moderate variation across a broad band of operation from 100 MHz to 950 MHz, as illustrated in Figure 43.

Furthermore, the attenuation varies smoothly and consistently with attenuator switch settings. Other features of the device are single 3 V to 6 V supply operation, and 4 dB insertion loss, and the input and output have a low VSWR 50 Ω match. All these features make the RF 2420 an excellent component for communications systems that require RF transmit power control by digital means. Typical applications are in dual mode IS-54/55 compatible cellular transceivers and TETRA systems. Figure 44 shows the complete schematic details of the RF 2420 being employed in a typical RF/IF switching attenuator application.

The RF Microdevice RF 2421 is a GaAs MESFET switched step attenuator. It has a single-step digitally controlled attenuation of 10 dB. A functional block diagram of the device is shown in Figure 45. The supply voltage range required is 2.7 V to 6 V dc. The input and output of the device have a low voltage standing wave ratio (VSWR) 50 Ω match and the RF output can drive up to +16 dBm. It has 1.0 dB of insertion loss over the specified 500 MHz to 3 GHz operating frequency range. The resistors are nickel chromium (nichrome) and provide excellent temperature stability. The RF ports are reversible, which means the input signal can be applied to either port. The attenuation control pin has an internal pull-down resistor which causes the attenuator to be turned off when it is not connected. Figure 46 illustrates the RF 2421 being used to set the RF signal level in a communications system.

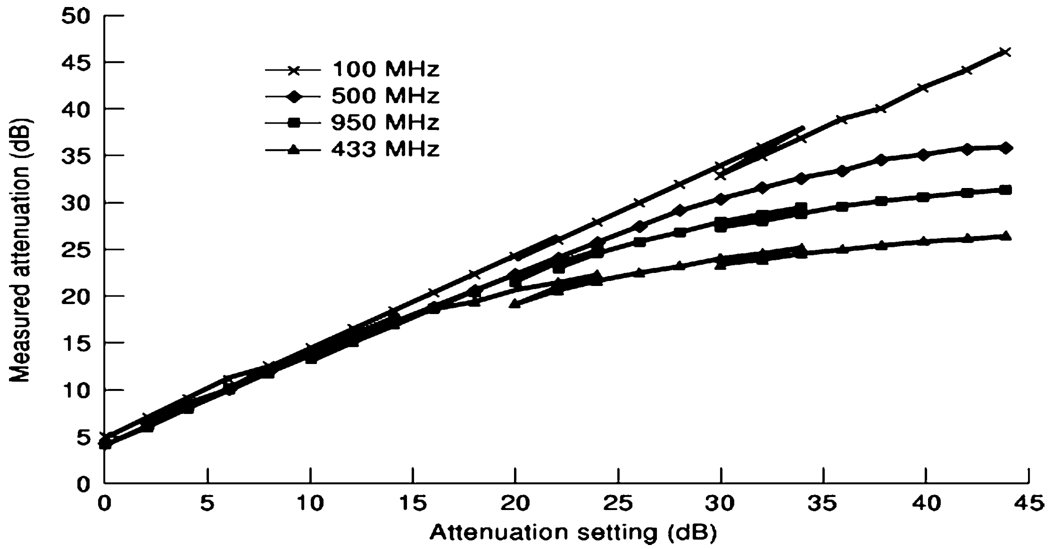


Figure 43. Attenuation and frequency response characteristics of RF 2420 5-bit digital RF attenuator.

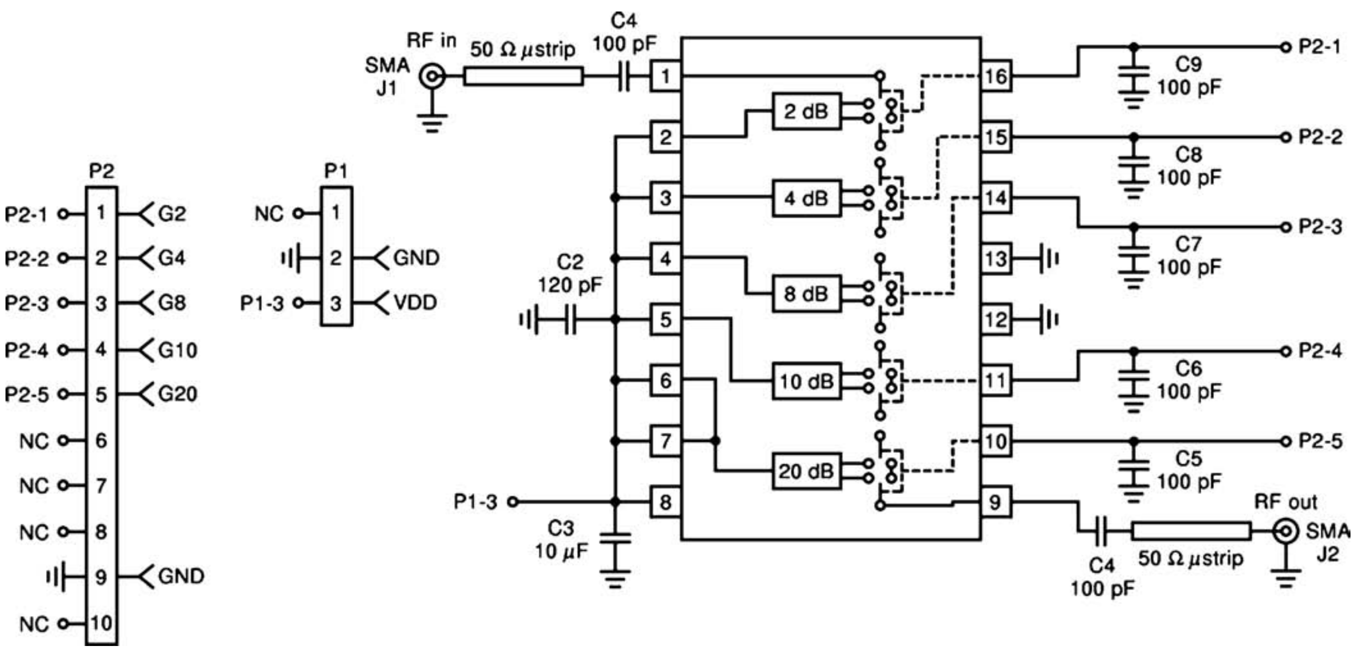


Figure 44. RF 2420 RF/IF switching attenuator schematic.

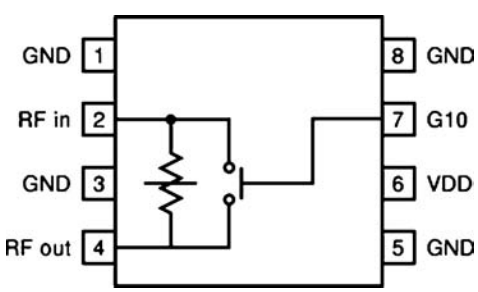


Figure 45. RF 2421 functional block diagram.

MOSFET Attenuators

Active voltage attenuators have many useful applications in analog integrated circuit design. Some of the applications are in the feedback loops of finite gain amplifiers and in the input stages of transconductance amplifiers. In discrete circuit design, the most popular way to design a finite gain amplifier with precisely controlled gain, high linearity, and low output noise is to use operational amplifier and a voltage attenuator in the feedback loop. Here the voltage attenuator consists of two resistors connected in series as shown in the classical noninverting and inverting op amp gain configurations of Figure 47. Resistor attenuators are

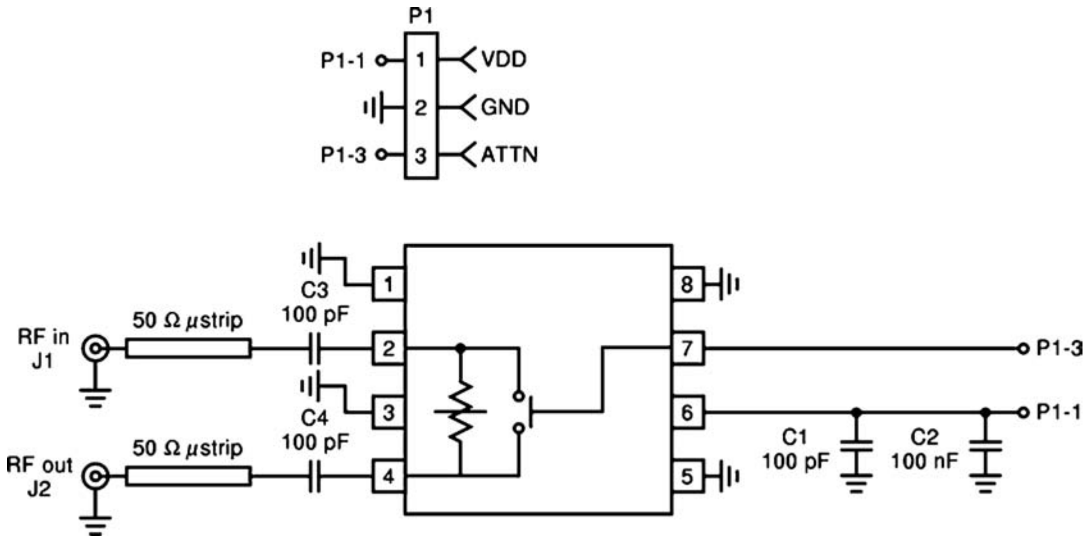


Figure 46. RF 2421 single-step 10 dB attenuator application.

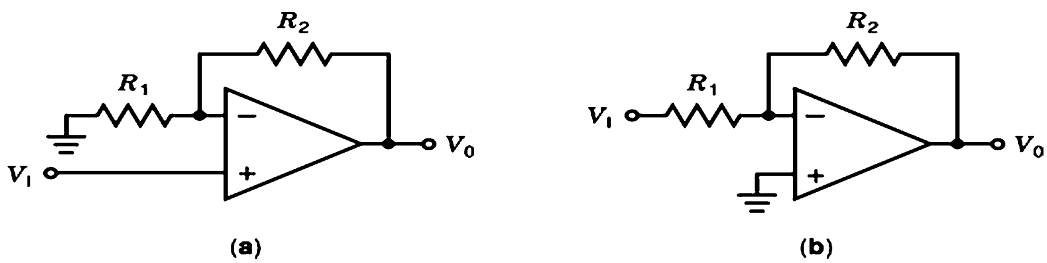


Figure 47. Op-amp noninverting (a) and inverting (b) gain configurations.

not useful in integrated circuit design because of their large areas, low input impedance, large power dissipation, and parasitic capacitances, and precise resistance values cannot be realized.

Three MOS active voltage attenuator configurations useful for the realization of finite gain amplifiers in monolithic circuits are presented. The attenuators are two single-input attenuators and a summing attenuator that has two inputs. These attenuators are simple in structure, consisting only of MOSFETs. Therefore, they are easy to fabricate in standard CMOS semiconductor processes. The attenuation factor is precisely controlled over a wide range of gains because it ideally depends only on the ratios of the dimensions of the MOSFETs.

Attenuator I, shown in Figure 48 is an active linear voltage attenuator consisting of two n-channel MOSFETs fabricated in a common substrate. The capability to fabricate the MOSFETs in a common substrate has several advantages. First, both n-channel and p-channel attenuators can be monolithically fabricated in a standard CMOS process. Second, the required area of the attenuator is much smaller. As seen in Figure 48, the substrate is common for both MOSFETs and is connected to the source of the bottom transistor M1. The circuit operates as a linear voltage attenuator when M1 is in the ohmic region and M2 is in the saturation region.

The operating conditions of the *MOS* attenuators in this section are derived as follows: The list of symbols used are:

V_I	Input voltage
V_o	Output voltage
V_{DD}	Drain supply voltage
V_B	Bias supply voltage 1
V_{BB}	Bias supply voltage 2
$V_{TON} = V_{TON1} = V_{TON2}$	Zero bias threshold voltage of M1 and M2
V_{T2}	Threshold voltage of M2 due to body bias effect
V_1	Input voltage 1
V_2	Input voltage 2
γ	Body effect parameter
ϕ	Barrier potential
I_D	Drain current
W	Width of channel
L	Length of channel
W_1, W_2	Width of channels 1, 2
L_1, L_2	Length of channels 1, 2
K'	Device constant, μ_n CoX
μ_n	Mobility of electron
CoX	Gate oxide capacitance per unit area

The zero bias threshold voltage of both MOSFETs is $V_{TON1} = V_{TON2} = V_{TON}$. The proper operating conditions will be met, provided

$$V_{TON} < V_I < V_{DD} + V_{T2} \tag{51}$$

where

$$V_{T2} = V_{TON} + \gamma(\sqrt{\phi + V_o} - \sqrt{\phi}) \tag{52}$$

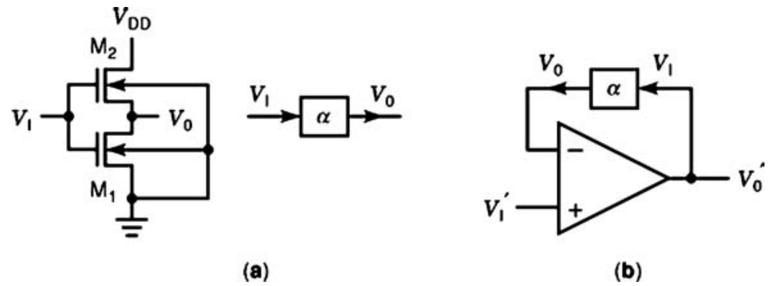


Figure 48. (a) Circuit and block diagram of attenuator I consisting of two n-channel MOSFETs, and (b) block diagram of amplifier consisting of an op-amp and attenuator.

Since M1 is operating in the ohmic region and M2 is in the saturation region, the drain current of each MOSFET is given by

$$I_{D1} = K'\frac{W_1}{L_1}\left(V_I - V_{TON} - \frac{V_o}{2}\right)V_o \qquad (53)$$

and

$$I_{D2} = K'\frac{W_2}{2L_2}(V_I - V_{T2} - V_o)^2 \qquad (54)$$

Equating the two drain currents, the relationship between V_1 and V_o is obtained as

$$2R\left(V_I - V_{TON} - \frac{V_o}{2}\right)V_o = \{V_I - V_{TON} - V_0 - \gamma(\sqrt{\phi + V_o} - \sqrt{\phi})\}^2 \qquad (55)$$

where

$$R = \frac{W_1/L_1}{W_2/L_2} \qquad (56)$$

If each MOSFET in the attenuator is fabricated in a separate substrate and the substrate of each MOSFET is connected to its source ($\gamma = 0$), the dc transfer characteristic relating V_I and V_o becomes a linear equation:

$$V_o = \alpha(V_I - V_{TON}) \qquad (57)$$

where α is the small signal attenuation factor.

In this case, α is

$$\alpha = 1 - \sqrt{\frac{R}{R+1}} = 1 - \sqrt{\frac{W_1/L_1}{W_1/L_1 + W_2/L_2}} \qquad (58)$$

Eq. (70) is a special case of Eq. (68), when the bulk effect term due to γ is ignored. When the substrate is separate, the small signal attenuation factor from Eq. (71) is precisely determined by width/length ratios. If the substrate is common, the relationship between the input and output is still very linear as given by Eq. (68) even though the equation appears to be a nonlinear quadratic.

Figure 49 shows the typical dc transfer characteristic of the attenuator consisting of M1 ($12 \times 10\ \mu m^2$) and M2 ($3 \times 10\ \mu m^2$) when the substrate is common ($\gamma \neq 0$) and $V_{DD} = 5$ V. The dc transfer characteristic exhibits a high degree of linearity for the input range 2 V to 5 V. The small signal attenuation factor (α) which is the slope of the dc transfer

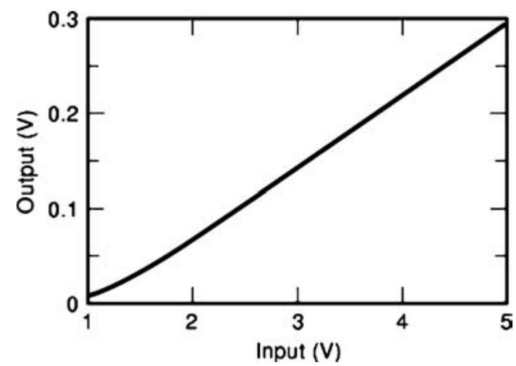


Figure 49. Dc transfer characteristic of attenuator I (α = 0.07824).

characteristic is 0.07824 at an input quiescent voltage of 3.5 V.

A finite gain amplifier consisting of an ideal op amp and attenuator I in the feedback loop is shown in Figure 48. Since the op amp is assumed ideal,

$$V_I' = V_o = \alpha V_I = \alpha V_o' \qquad (59)$$

or

$$V_0' = \frac{1}{\alpha}V_I' \qquad (60)$$

That is, the dc transfer function of the amplifier is the inverse function of the dc transfer function of the attenuator in the feedback loop. Thus, the transfer function between the input V'_I and the V'_o of the amplifier is given by Eq. (68) when V_o is replaced by V'_I and V_I by V'_o. The small signal voltage gain

$$\left(A_V = \frac{V_o'}{V_I'} = \frac{1}{\alpha}\right)$$

is the reciprocal of the attenuator's attenuation factor in the feedback loop. Figure 50 illustrates the dc transfer characteristic of the finite gain amplifier.

Two slightly different linear inverting voltage attenuator configurations consisting of two n-channel MOSFETs are shown in Figure 51. These circuits operate as a linear inverting voltage attenuator when both transistors are in the saturation region. Assuming the zero bias threshold of both of the MOSFETs is V_{TON}, the condition will be met,

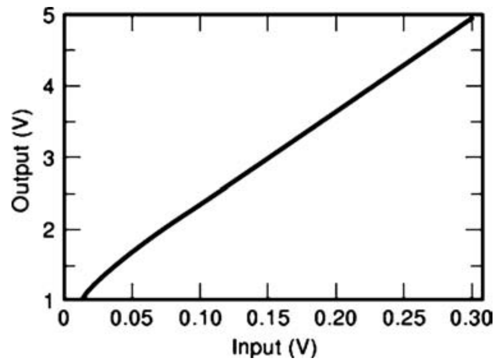


Figure 50. Dc transfer characteristic of amplifier ($A_V = 1/\alpha = 12.78$).

provided

$$V_o + V_{T2} < V_B < V_{DD} + V_{T2} \tag{61}$$

and

$$V_{TON} < V_I < V_o + V_{TON} \tag{62}$$

Under this condition, the drain currents of the transistors are given by:

$$I_{D1} = K'\frac{W_1}{2L_1}(V_I - V_{TON})^2 \tag{63}$$

$$I_{D2} = K'\frac{W_2}{2L_2}(V_B - V_o - V_{T2})^2 \tag{64}$$

where

$$V_{T2} = V_{TON} + \gamma(\sqrt{\phi + V_o} - \sqrt{\phi}) \tag{65}$$

Since the two drain currents are the same for the circuit, the dc transfer function relating V_I and V_o is found by equating Eqs. (77) and (64):

$$V_o + \gamma(\sqrt{\phi + V_o} - \sqrt{\phi}) = -R_1V_I + \{V_B + (R_1 - 1)V_{TON}\} \tag{66}$$

where

$$R_1 = \sqrt{\frac{W_1/L_1}{W_2/L_2}} \tag{67}$$

If $\gamma = 0$ in Eq. (80) which corresponds to the case of circuit (b) in Figure 51 where the substrate is separate, the dc transfer characteristic reduces to a linear equation,

$$V_o = \alpha V_I + \{V_B - (\alpha + 1)V_{TON}\} \tag{68}$$

In this case, the small signal attenuator factor is

$$\alpha = -R_1 \tag{69}$$

which is precisely determined by the width/length ratios of the MOSFETs. From Eqs. (80) and (68), it is noted that the output dc operating voltage is controlled by V_B, independent of the attenuation factor.

The dc transfer characteristic between V_I and V_o calculated from Eq. (80) for the common substrate case, $R_1 = 0.1149$ and $V_B = 3.993$, and the dc transfer characteristics calculated from Eq. (82) for the separate substrate case, $R_1 = 0.1$ and $V_B = 3.449$ are shown in Figure 48–52 for the

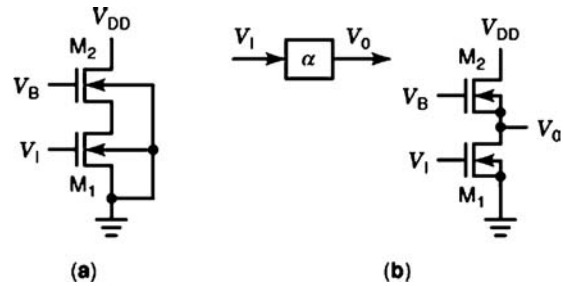


Figure 51. Circuit and block diagrams of linear inverting voltage attenuators consisting of two n-channel MOSFETs.

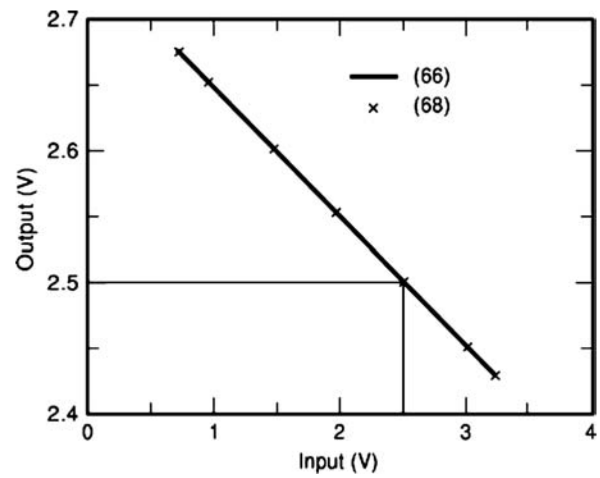


Figure 52. Dc transfer characteristics of attenuator II linear inverting voltage attenuators.

range restricted by Eq. (76). The parameter values ($\gamma = 0.525\ V^{1/2}$, $\phi = 0.6$ V, and $V_{TON1} = V_{TON2} = V_{TON} = 0.777$ V) were used in the calculation. The dc transfer function given by Eq. (80) for the common substrate case appears nonlinear, but the degradation from linearity due to practical values of γ is not significant. The small signal attenuation factor α, the slope of transfer characteristic in Figure 52, is -0.1. The high degree of linearity supports the usefulness of both configurations in precision attenuator or finite gain amplifier applications.

Figure 53 shows a finite gain amplifier with attenuator II in the feedback loop of an op amp. Assuming the op amp is ideal,

$$V_o' = \frac{1}{\alpha}V_I' \tag{70}$$

The transfer function of the amplifier is the inverse function of the transfer function of the attenuator in the feedback loop. The dc transfer function of the amplifier is given by Eq. (80) when V_I is replaced by V'_o and V_o is replaced by V'_I. If the substrate is separate, V_I replaces V'_o and V_o replaces V'_I in Eq. (82); then

$$V_o' = \frac{1}{\alpha}V_I' - \frac{1}{\alpha}\{V_B - (\alpha + 1)V_{TON}\} \tag{71}$$

where the small signal attenuator factor $\alpha = -R_1$.

A summing attenuator is necessary to realize versatile multiple input finite gain amplifiers in integrated circuits.

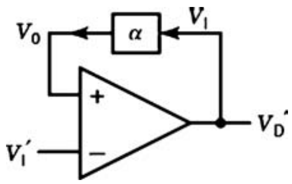


Figure 53. Amplifier consisting of op-amp and attenuator II in the feedback loop.

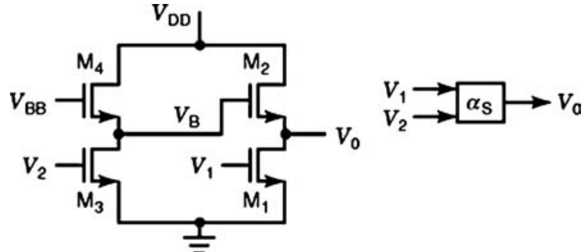


Figure 54. Circuit and block diagram of summing attenuator.

Figure 54 shows a two-input active linear inverting voltage summing attenuator which consists of two attenuators cascaded. For the summing attenuator, V_{BB} is used to control the output dc operating voltage and input signals are designated as V_1 and V_2.

As for the inverting attenuator, the summing attenuator works when all the MOSFETs M1–M4 are operating in the saturation region. The dc transfer characteristics are found by equating the drain currents in the saturation region for each transistor. Assuming the zero bias threshold voltages for the four MOSFETs are matched at V_{TON}, the four transistors are in the saturation region provided,

$$2(V_{TON} + \gamma(\sqrt{\phi + V_{TON}} - \sqrt{\phi})) + V_o < V_{BB} < V_{DD} + V_{T4} \quad (72)$$

$$V_{TON} < V_1 < V_0 + V_{TON} \quad (73)$$

$$V_{TON} < V_2 < V_B + V_{TON} \quad (74)$$

By equating the drain currents of M3 and M4 given by

$$I_{D3} = K' \frac{W_3}{2L_3}(V_2 - V_{TON})^2 \quad (75)$$

and

$$I_{D4} = K' \frac{W_4}{2L_4}(V_{BB} - V_B - V_{T4})^2 \quad (76)$$

where

$$V_{T4} = V_{TON} + \gamma(\sqrt{\phi + V_0} - \sqrt{\phi}) \quad (77)$$

The dc transfer function between V_2 and V_B is obtained as

$$V_B + \gamma(\sqrt{\phi + V_B} - \sqrt{\phi}) = -R_2V_2 + \{V_{BB} + (R_2 - 1)V_{TON}\} \quad (78)$$

where

$$R_2 = \sqrt{\frac{W_3L_4}{L_3W_4}} \quad (79)$$

Similarly, it can be shown, that the dc transfer function between V_1 and V_o is obtained as

$$V_o + \gamma(\sqrt{\phi + V_o} - \sqrt{\phi} = -R_1V_1 + \{V_B + (R_1 - 1)V_{TON}\} \quad (80)$$

where

$$R_1 = \sqrt{\frac{W_1L_2}{L_1W_2}} \quad (81)$$

If $\gamma = 0$ in Eqs. (92) and (80), the equations become linear. This is realized if each transistor is fabricated in a separate substrate and the substrate of each transistor is connected to its source. In this case, the attenuation factors are given by $\alpha_1 = -R_1$, and $\alpha_2 = -R_2$. Even when $\gamma \neq 0$, which is the case when the substrates are common, the transfer characteristics between V_1 and V_o and between V_2 and V_o are nearly linear as shown in Figure 57 for practical values of γ. In the calculation of Figure 55, $\gamma = 0.5255\ V^{1/2}$, $\phi = 0.6$ V, and $V_{TON} = 0.777$ V were used which are standard for a 2 μ CMOS process and $R_1 = 0.1149$ and $R_2 = 0.1290$ were set such that the small signal attenuation factors for V_1 and V_2 are both −0.1. The operating points were set by $V_{BB} = 5.712$ V such that $V_{oQ} = 2.5$ V ($V_{BQ} = 3.993$ V) when $V_{1Q} = V_{2Q} = 2.5$ V.

Summing and subtracting amplifier configurations using the inverting attenuator and the inverting summing attenuator are shown in Figure 56.

Circuit (a) in Figure 56 functions as a summing amplifier and the circuit (b) functions as a subtracting amplifier, with controllable weights. Assuming ideal op amps and attenuators, we obtain

$$V_- = \alpha_1V_1 + \alpha_2V_2 + \{V_{BB} - (\alpha_1 + \alpha_2 + 2)V_{TON}\} \quad (82)$$

$$V_+ = \alpha V_o + \{V_B - (\alpha + 1)V_{TON}\} \quad (83)$$

Equating V_- and V_+, the output is given by

$$V_o = \frac{\alpha_1}{\alpha}V_1 + \frac{\alpha_2}{\alpha}V_2 + \frac{1}{\alpha}\{V_{BB} - V_B - (\alpha_1 + \alpha_2 - \alpha + 1)V_{TON}\} \quad (84)$$

From Eq. (98), the circuit in Figure 56(a) is a summing amplifier with a wide range of available gain from each input. Similarly, for the circuit in Figure 56(b), we obtain

$$V_+ = \alpha_1V_o + \alpha_2V_2 + \{V_{BB} - (\alpha_1 + \alpha_2 + 2)V_{TON}\} \quad (85)$$

$$V_- = \alpha V_1 + \{V_B - (\alpha + 1)V_{TON}\} \quad (86)$$

Equating V_+ and V_-, the output is given by

$$V_o = \frac{\alpha}{\alpha_1}V_1 - \frac{\alpha_2}{\alpha_1}V_2 - \frac{1}{\alpha_1}\{V_{BB} - V_B - (\alpha_1 + \alpha_2 - \alpha + 1)V_{TON}\} \quad (87)$$

From Eq. (99), the circuit in Figure 56(b) is a subtracting amplifier with a wide range of available gain for each input.

The active attenuator and the active summing attenuator have many desirable characteristics such as small size, nearly infinite impedance, low power dissipation, and precisely controllable attenuation ratio with excellent linearity. These attenuators and the finite gain amplifiers

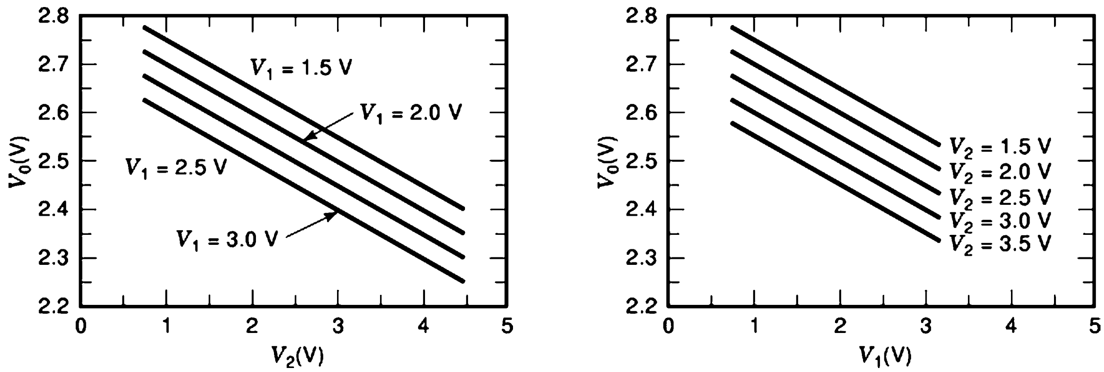


Figure 55. Dc transfer characteristics of summing attenuator.

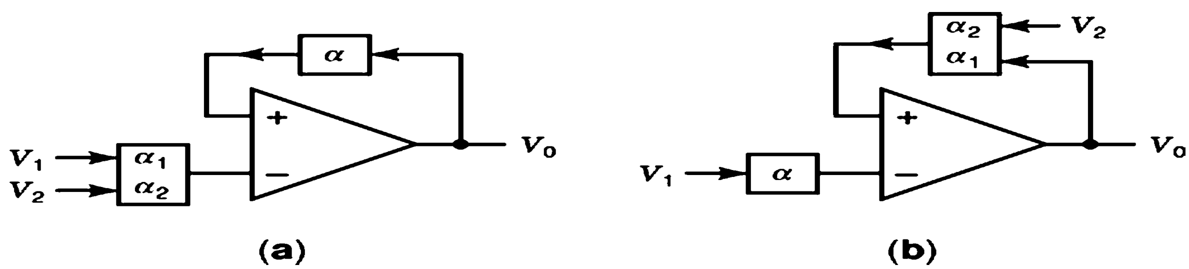


Figure 56. (a) Summing amplifier. (b) Subtracting amplifier.

obtained from these attenuators and op amps will find increased applications in analog integrated circuits.

Noise

Noise in a communication system can be classified in 2 broad categories, depending on its source. Noise generated by components within a communication system, such as resistive, extender, and solid-state active devices, comprise internal noise. The second category, external noise, results from sources outside a communication system, including atmospheric, man-made, and extraterrestrial sources.

External noise results from the random motion of a charge carrier in electronic components. The three types include:

1. Thermal noise: caused by random motion of free electrons in a conductor or semiconductor excited by thermal agitation;
2. Shot noise: caused by random amount of discrete charge carriers in such devices as thermionic tubes or semiconductors in devices
3. Flicker noise: produced by semiconductors by a mechanism not well understood and is more severe the lower the frequency.

Atmospheric noise results primarily from spurious radio waves generated by the natural discharges within the atmosphere associated with thunderstorms. Man-made noise sources include high voltage power line discharge and computer-generated noise in electric motors.

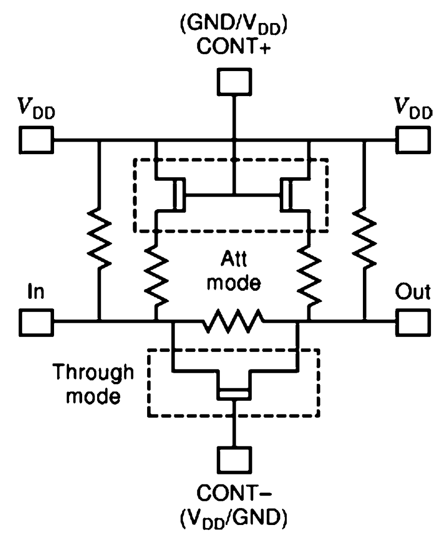


Figure 57. Variable attenuator using GaAs MESFET CONT+/CONT− = VDD/GND in attenuation mode and CONT+/CONT− = GND/VDD in through mode.

Other noises include:

- Generation–recombination noise: due to free carriers being generated and recombining in semiconductor material. They are random and can be treated as a shot noise process.
- Temperature-fluctuation noise: the result of the fluctuating heat exchange between a small body, such as a transistor, and its environment due to the fluctuations in the radiation and heat conduction processes.

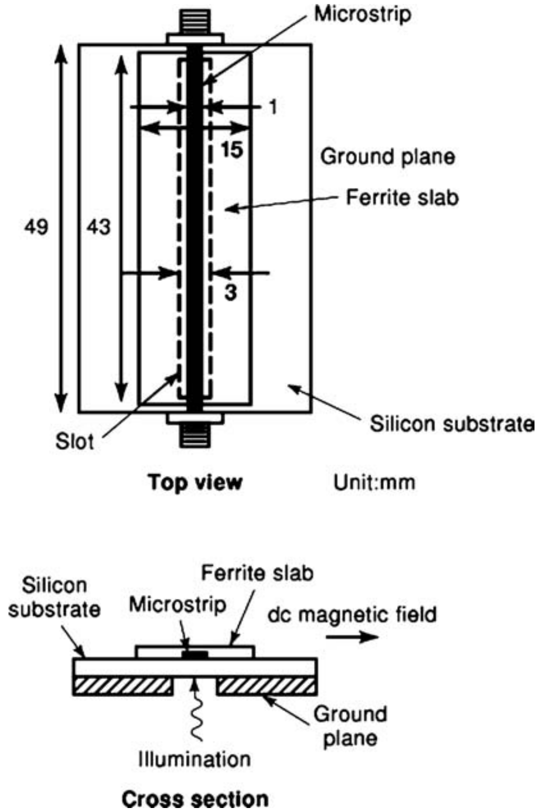


Figure 58. Microstrip–slot-line attenuator on a silicon substrate with an override ferrite slab.

ADDITIONAL TYPES

Figure 57 shows a 4 dB step, 28 dB variable attenuator for 1.9 GHz personal handy phone system transmitter fabricated using silicon bipolar technology with f_T of 15 GHz. The GaAs MESFET variable attenuator is configured with resistive Pi attenuators and GaAs switches as shown. Step accuracy within 1.2 dB and total vector modulation error of less than 4% were realized for −15 dBm output. The attenuator consumes 21 mA with 2.7 V power supply and occupies 1.1 mm × 0.5 mm. This unit is being developed. This shows the technology trend.

Figure 58 shows the top view and cross section of a prototype optical microwave attenuator that can be controlled by illuminating the silicon substrate. The maximum attenuation is 30 dB using laser diode illumination. It is a microstrip line whose substrate consists of silicon and ferrite slabs. The ferrite slab is overlaid on the microstrip. There is a slot on the ground plane under the strip. A white light from a xenon arc lamp with a parabolic mirror is focused by a lens to the silicon surface through the slot. The intensity of the light is not uniform along the slot direction. Due to the light, electron–hole pairs are induced and the permittivity and conductivity of the silicon are changed, which vary the phase and amplitude of the microwave. With 240 mW optical power illumination, an attenuation in the range of 17 dB to 26 dB was obtained in the frequency range from 8 GHz to 12 GHz.

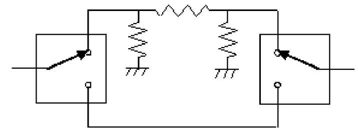


Figure 59. Switchable-network attenuator.

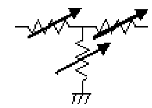


Figure 60. Switchable-element attenuator.

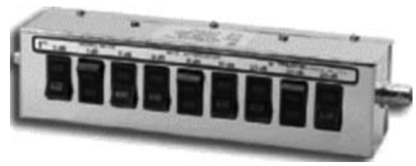


Figure 61. Switchable attenuator.

Switchable Attenuators

Switchable attenuators allow users to vary the attenuation for various applications, such as in production, field, and bench-top applications. They offer mechanically or electrically controllable attenuation levels. There are two types of switchable attenuators: (1) switched-network attenuators, and (2) switched element attenuators. In switched-network attenuators, PIN diode switches are used to develop two or more paths for changing attenuation values. Once developed, it can be used to obtain several attenuation values. In switched-element attenuator, the resistive elements have multiple values. Either a pi pad, a tee pad or a reflection attenuation configuration can be used as the initial network in which the resistive elements are variable. Typically FETs are used for switching and the set-up is implemented in MMIC format.

A typical data sheet for one model is shown in Table x

Frequency	DC-0.5 GHz
dB	0 to 102 by 1 dB
Impedance	50 Ω
VSWR	1.2:1 to 0.5 GHz
Accuracy	±0.5 dB to 0.03 GHz ±1 dB to 0.5 GHz
Insertion Loss	0.3 dB max to 0.1 GHz 1.5 dB max to 0.5 GHz
Average Power	0.5 W (25°C)
Peak Power	750 W, 3 μs pulse
Connectors	BNC

Audio Attenuators

Audio attenuators need compact design to reduce noise and give audio volume controls with accurate attenuation and tracking (0.05 dB). Resistor network using surface mount resistors for short signal path and very low inductance and stray capacitance seem to be successful in achieving the end results. Shown in Fig. 62 is a surface mount audio attenuator with 24 steps. The series resistor networks consist of 23 non-inductive, low noise surface mount film resistors. The layout of the PC boards and the surface mount resistors reduce the signal path compared to normal leaded resistors. The surface mount film resistors also have very low

Figure 62. Stereo attenuator.

Figure 63. High power attenuator—Model 1.

Figure 64. High power attenuator—Model 2.

series inductance and very low stray capacitance, allowing a wide bandwidth.

High Power Attenuators

Shown in Fig. 63 is the group of high power attenuator, a new addition to commercial, fixed attenuators. This model features a frequency range of DC-18 GHz with an input power rating of 50 W CW. Standard attenuation values are 3, 6, 10, 20, 30 and 40 dB and the VSWR is rated at 1.35:1 at 18 GHz. A robust mechanical package with stainless steel Type N connectors is designed to meet the requirements of MIL-A-3933. Applications include high power amplifier design and test environments as well as defense and radar requirements.

For applications including high power radar, amplifier test, telecommunication labs and MRI calibration another new type, high power, fixed attenuators were introduced in the market (Figure 64). This type features a frequency range of DC-8 GHz with an input power rating of 150 W CW. Standard attenuation values are 3, 6, 10, 20, 30 and 40 dB and the VSWR is rated at 1.20:1 @ 4 GHz and 1.30:1 @ 8 GHz. The specifications of the above two models are shown below.

	Model 1	Model 2
Power, W	50	150
Impedance, Ω	50	50
Frequency Range, GHz	DC to 18	DC to 8
Attenuation	3, 6, 10, 20, 30, 4	3, 6, 10, 20, 30, 4
Connection	N	N M/F
Max VSWR		
4 GHz		1.20:1
8 GHz		1.30:1
18 GHz	1.35:1	

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BIBLIOGRAPHY

Reading List

F. G. Ananasso "A Low Phase Shift Step Attenuator using PIN Diode Switches", *IEEE Trans. Microwave Theory Tech.*, **MTT-28** (7): July 1980.

P. S. Bochert *FET Attenuator*, 0-1 GHz Applied Microwave and Wireless, Spring 1996.

R. G. Brown *et al. Lines, Waves, Ana Antennas*, New York: The Ronald Press Co. 1973.

R. S. Elliot *An Introduction to Guided Waves and Microwave Circuits*, Englewood Cliffs, NJ: Prentice-Hall, 1993.

Engineering staff of the Microwave Division, *Microwave Theory and Measurements*, Hewlett-Packard Co., 1962.

S. C. Harsany *Principles of Microwave Technology*, Englewood Cliffs, NJ: Prentice Hall, 1997.

M. R. Haskard *Thick Film Hybrids—Manufacture and Design*, New York: Prentice-Hall, 1988.

Hewlett Packard Application Note 1048, A Low-Cost Surface Mount PIN Diode π Attenuator, Hewlett Packard Co., 1996.

Hewlett Packard Application Note 922, Applications of PIN Diodes, Hewlett Packard Co., 1997.

IEEE Std 474-1973, *Specifications and Test methods for Fixed and Variable Attenuators*, DC to 40 GHz.

T. Koryu Ishii *Microwave Engineering*, New York: Harcourt Brace Jovanovich, Publishers, 1989.

Joon-Yu Kim R. L. Geiger "MOS Active Attenuators for Analog ICS and Their Applications to Finite Gain Amplifiers", *Proceedings-IEEE International Symposium on Circuits and Systems, 1994.*

Joon-Yu Kim R. L. Geiger "Performance Characterization of an Active Attenuator Using Two Cascaded MOSFETS", *Proceedings of the 36th Midwest Symposium on Circuits and Systems*, 1993.

Joon-Yu Kim R. L. Geiger "Characterization of Linear MOS Active Attenuator and Amplifier" *Elec. Lett.*, **3** (7): March 30, 1995.

Joon-Yu Kim R. L. Geiger "An Inverting MOS Active Attenuator for Monolithic Applications", *Proceedings of the Midwest Electro-Technology Conference*, 1993.

T. S. Laverghetta *Practical Microwaves*, Englewood Cliffs, NJ: Prentice-Hall, 1996.

R. LaVerne Libbey *Video Attenuator using a Multiplier and FET*, A Publication of RCA, New Jersey: 1975.

RF Microdevices, RF 2420 Programmable Attenuator Data Sheet, 1997.

RF & Microwave Test Accessories Catalog, HP, 1997/98.

RF Microdevices Technical Application note TA 0027 Integrated, Single Step, 10 dB Attenuator for Power Control Applications, 1997.

RF Microdevices, RF 2421 10 dB Switched Attenuator Data Sheet, 1997.

MIL-HDBK-216, Military handbook, R. F. Transmission Lines and Fittings, Section 14, Attenuators, Nov. 1976.

MIL-A-3933E, Military specification, attenuators, fixed, general specification for 1985.

MIL-A-3933E, Suppl. 1, Military specification, Attenuators, Fixed, General Specification for 1985.

S. Otaka *et al.* "A 1.9 GHz Si-Bipolar variable Attenuator for PHS Transmitter", *IEEE J. Solid State Circuits*, **32** (9): 1424–1429, September, 1997

Reference Data for Radio Engineers, 1957, International Telephone and Telegraph Corp., New York.

P. A. Rizzi *Microwave Engineering—Passive Circuits*, Englewood Cliffs, NJ: Prentice-Hall, 1988.

D. Roddy *Microwave Technology*, Englewood Cliffs, NJ: Prentice-Hall, 1986.

S. E. Saddow C. H. Lee "Scattering Parameter Measurements on Optoelectronic Attenuator", *IEEE MIT-S Digest*, 1994.

H. W. Sams *Reference Data for Radio Engineers*, 7th ed., 1985, Indianapolis, IN.

G. E. Schafer A. Y. Rumfelt "Mismatch Errors in Cascade-Connected Variable Attenuators", *IRE Trans. Microwave Theory Tech.*, 1959.

H. Shimasaki S. Matsuda M. Tsutsumi "Phase compensation in an Optically Controlled Microwave attenuator", *IEEE MTT-S Digest*, 1703–1706, 1997.

V. A. Suprynowicz *Electrical and Electronics Fundamentals—An Applied Survey of Electrical Engineering*, New York: West Publishing Company, 1987.

A Vector Attenuator for Feedforward Amplifier and RF Predistortion Use, Product Feature, *Microwave J.*, Oct. 1997.

Weinschel Associates Catalogue, Attenuators and Terminations, 1998.

R. E. Ziemer W. H. Tranter *Principles of Communications—Systems, Modulation, and Noise*, New York: Wiley, 1988.

V. F. Valey *Modern Microwave Technology*, Englewood Cliffs, NJ: Prentice-Hall, 1987.

Additional Reading List

Attenuators, www.electronics-tutorials.com

www.microwaves101.com/encyclopedia/attenuators.cfm, Aug 28 2006

Rf Fixed attenuators, www.e-meca.com/rf-attenuators.htm, Aug 25 2006

Fiber optic attenuators, www.Telect.com, Aug 25 2006

Fiber optic fixed and variable attenuators, www.fiberdyne.com, sep 2006

High power attenuators, www.Trilithic.com, Aug 28 2006

Digital attenuator, www.psemi.com, Aug 2006

Audio attenuators, www.dact.com, Aug 25 2006

Parallel, digital attenuator, www.mysolservices.com, Sep 04 2006

Switchable attenuators, www.trilithic.com, Sep 04 2006

Solid state programmable attenuators, www.trilithic.com, Sep 04 2006

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