6. Attenuators and Switches

The state of the switch is controlled by some **digital logic**, and there is a different scattering matrix for each state.

HO: Microwave Switches

HO: The Microwave Switch Spec Sheet

We can **combine** fixed attenuators with microwave switches to create very important and useful devices—the **variable** (digital) attenuator.

HO: Attenuators

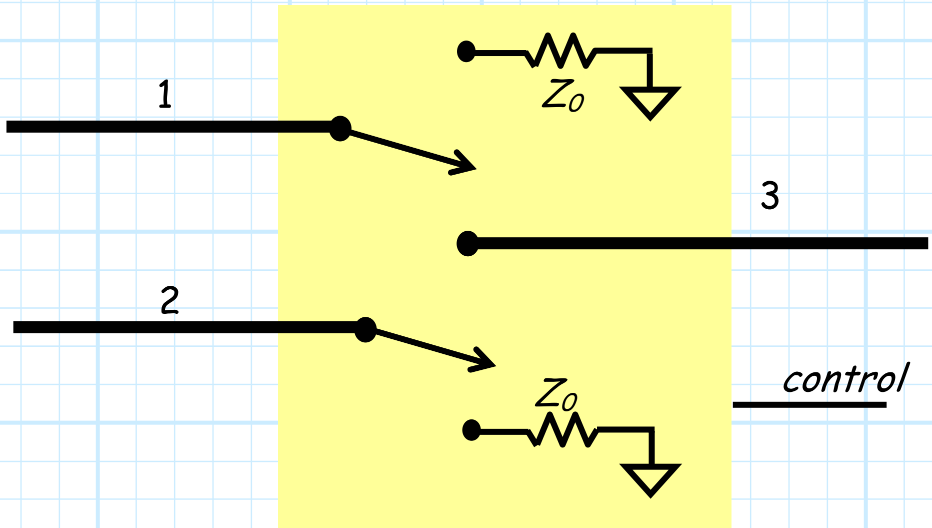
HO: The Digital Attenuator Spec Sheet

We typically make switches and voltage controlled attenuators with PIN diodes. **If** you are interested, you might check out the handout below (no, this handout below will **not** be on any exam!).

HO: PIN Diodes

Microwave Switches

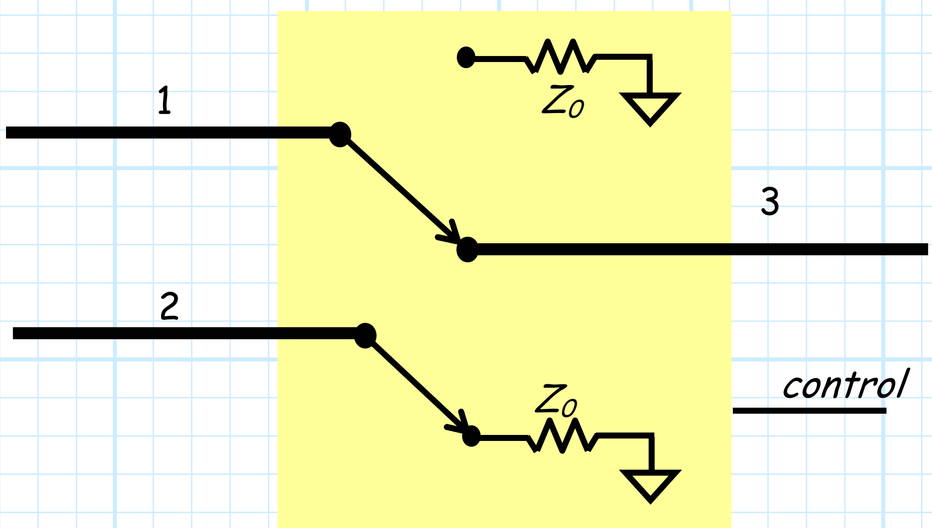
Consider an **ideal** microwave SPDT **switch**.



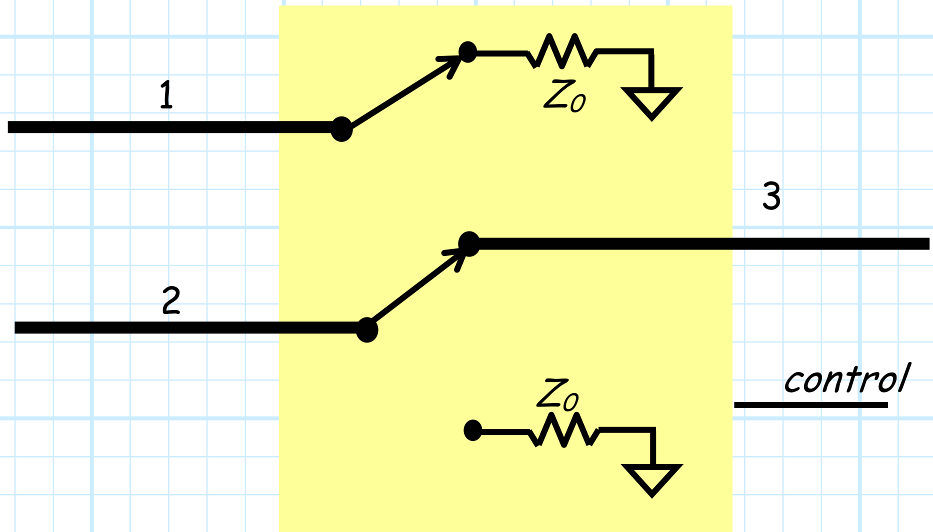
The **scattering matrix** will have one of two forms:

$$\bar{\bar{S}}_{13} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} \qquad \bar{\bar{S}}_{23} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

where $\bar{\bar{S}}_{13}$ describes the device when port 1 is **connected** to port 3:



and where $\bar{\bar{\mathbf{S}}}_{23}$ describes the device when port 2 is **connected** to port 3:

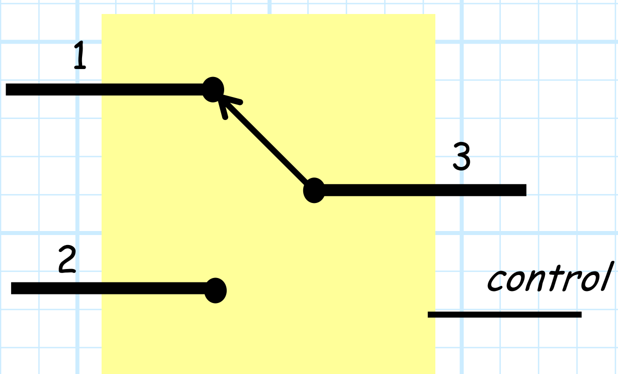


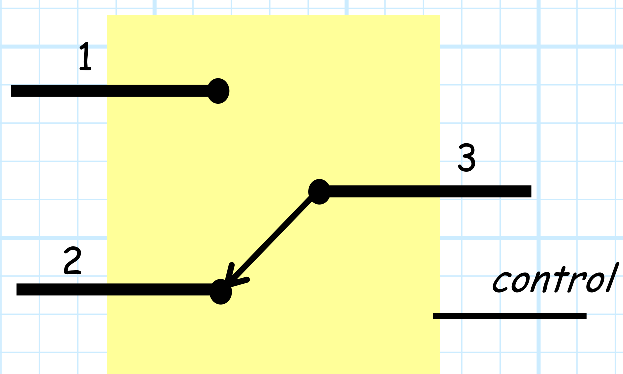
These ideal switches are called matched, or **absorptive switches**, as ports 1 and 2 remain matched, even when **not connected**.

This is in contrast to a **reflective switch**, where the disconnected port will be perfectly reflective, i.e.,

$$\bar{\bar{\mathbf{S}}}_{13} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & e^{j\phi} & 0 \\ 1 & 0 & 0 \end{bmatrix} \qquad \bar{\bar{\mathbf{S}}}_{23} = \begin{bmatrix} e^{j\phi} & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

where of course $\left|e^{j\phi}\right| = 1$.





Of course, just as with **all** ideal components, the ideal switch does **not** exist!

Using the fact that switches are **reciprocal** devices, we can write **for** $\bar{\bar{\mathbf{S}}}_{13}$ for a non-ideal switch:

$$\bar{\bar{\mathbf{S}}}_{13} = \begin{bmatrix} S_{11} & S_{21} & S_{31} \\ S_{21} & S_{22} & S_{32} \\ S_{31} & S_{32} & S_{33} \end{bmatrix}$$

We can therefore consider the following **parameters** for specifying switch performance.

Insertion Loss

$$IL = -10\log_{10}\left|S_{31}\right|^2$$

Insertion Loss indicates the loss encountered as a signal propagates **through** the switch. Ideally, this value is 0 dB. Typically, this value is around 1 dB.

Isolation

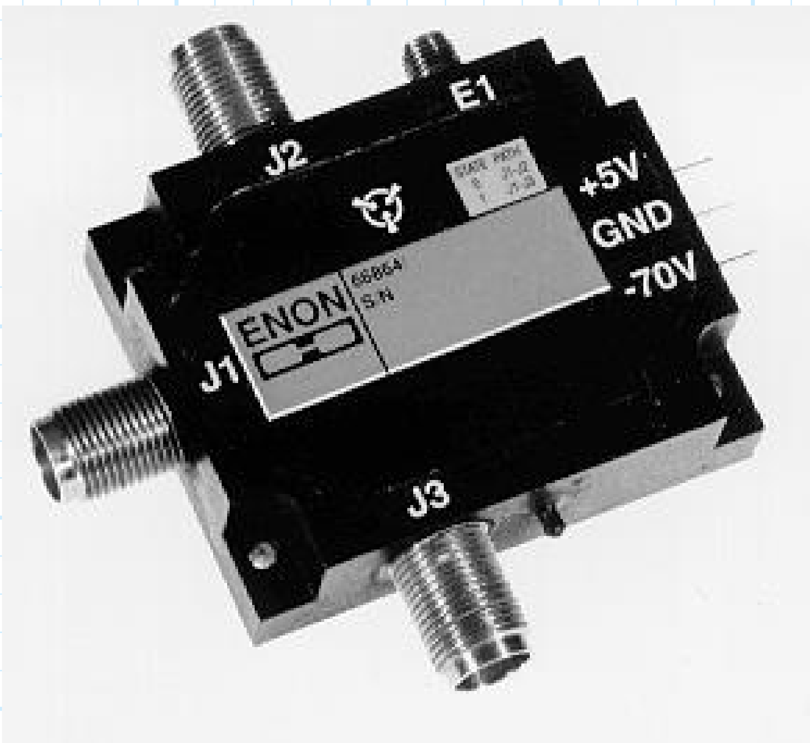
$$Isolation = -10\log_{10}\left|S_{32}\right|^2$$

Isolation is a measure of how much power "**leaks**" into the **disconnected** port. Ideally, this value would be very **large**—typical switch isolation is 30 – 50 dB.

Return Loss

$$\text{Return Loss} = -10\log_{10}|S_{11}|^2$$

Just as we have **always** defined it ! We of course want this value to very high (typical values are 20 to 40 dB). However, we find for **reflective** switches, this value can be nearly 0 dB for the **disconnected** port!



The Microwave Switch Specification Sheet

Switch Type

A microwave switch is **either** absorptive or reflective, which refers to the input impedance of the disconnected port.

A microwave switch can have **multiple** ports (e.g., SPDT , SP4T)

Bandwidth (Hz)

A switch, like all other devices, can effectively operate only within a finite **bandwidth** (e.g., 2-5 GHz or 300-400 MHz).

Input Impedance (Γ, return loss, VSWR)

This of course is dependent on the **state** of the switch (i.e., whether a port is connected or disconnected).

Insertion Loss (dB)

Typically this is 2 dB or less for good switches, but is somewhat dependent on frequency (insertion loss **increases** with frequency).

Maximum Input power (dBm)

Switches have a **maximum** input power. Typical values range from 10 to 25 dBm.

Switching Speed (seconds)

The state of a microwave switch **cannot** change instantaneously. It takes some small but non-zero amount of time to change from one state to another. Typical values range from 0.1 to 10.0 μ–seconds.

Isolation (dB)

Typical values range from 20 to 50 dB.

Switch Logic

Describes the control line values required to switch the port switch state. Typically **TTL** logic values are used—0 volts for one state and 5V for the other.

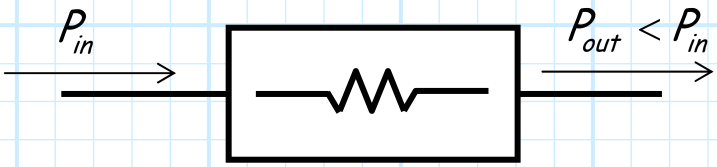
DC Power

Switches are **not** passive devices! They require a D.C. voltage (5 or 15 V typical) and will draw some amount of D.C current. The product of the two of course is equal to the D.C. **power** delivered to the switch (typically << 1W)

Attenuators

Under certain situations, we may actually want to **reduce** signal power!

Thus, we need an inverse amplifier—an **attenuator**.



An **ideal** attenuator has a scattering matrix of the form:

$$\bar{\bar{\mathbf{S}}} = \begin{bmatrix} 0 & \alpha \\ \alpha & 0 \end{bmatrix}$$

where $|\alpha| < 1$.

Thus, an attenuator is **matched** and **reciprocal**, but it is certainly **not** lossless.

The **attenuation** of an attenuator is defined as:

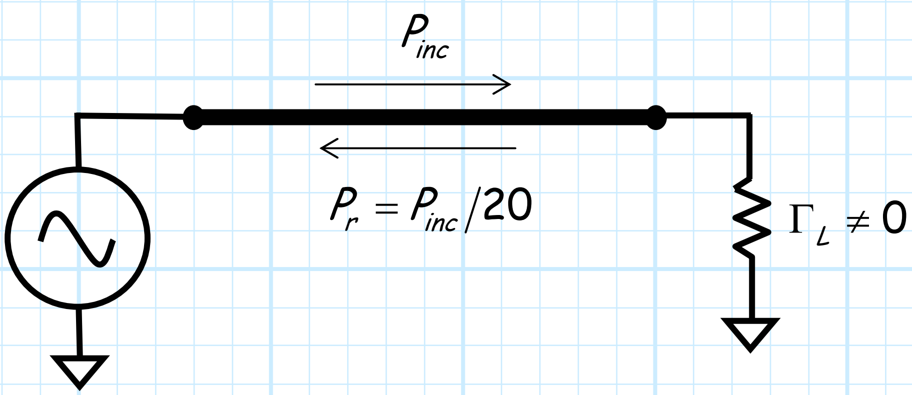
$$Attenuation = -10\log_{10}|\alpha|^2$$

Typical values of **fixed** attenuators (sometimes called "pads") are 3 dB, 6 dB, 10 dB, 20 dB and 30 dB.

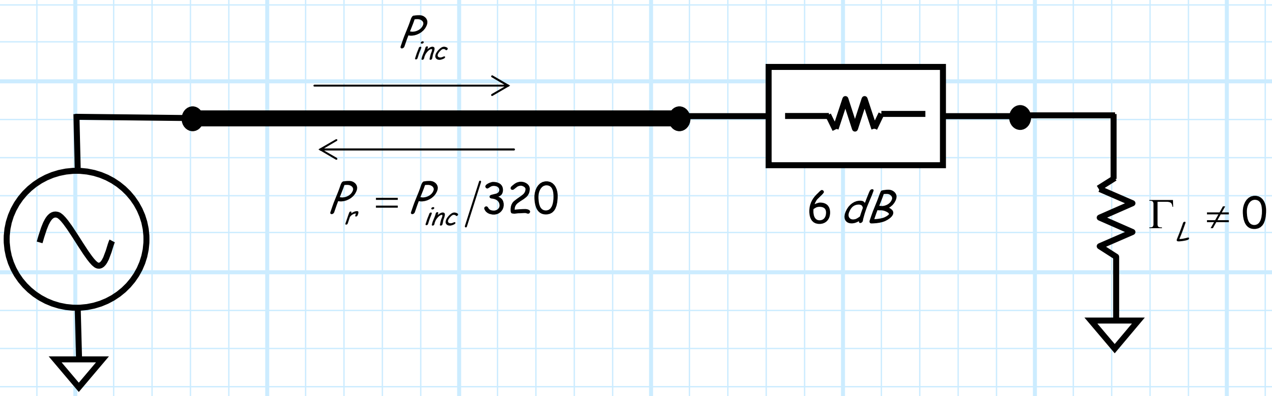
For example, a 6 dB pad will attenuate as signal by 6 dB—the output power will be **one forth** of the input power.

One **application** of **fixed** attenuators is to improve **return loss**.

For example, consider the case where the **return loss** of a mismatched load is 13 dB:



Say we now add a **6 dB pad** between the source and the load—we find that the return loss has **improved** to 25 dB!



The reason that the return loss improves by 12 dB (as opposed to 6 dB) is that reflected power is attenuated **twice**—once as it travels toward the load, and again after it is reflected from it.

Note from the standpoint of the source, the load is much **better matched**. As a result, the effect of **pulling** is reduced.

However, there is a definite downside to "matching" with a **fixed** attenuator—the power **delivered** to the load is also **reduced** by 6 dB !

Q: *Why do you keep referring to these devices as **fixed** attenuators? Do you really think we would use a **broken** one?*

A: In addition to fixed attenuators, engineers often used **variable** attenuators in radio system designs. A variable attenuator is a device whose attenuation can be **adjusted** (i.e., varied).

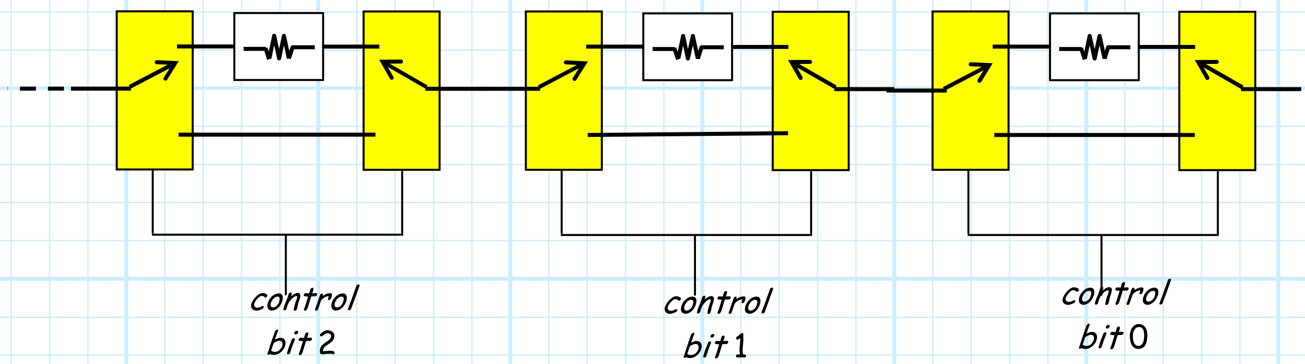
There are two types of (electronically) adjustable attenuators: **digital** and **voltage controlled**.

Digital Attenuators

As the name implies, digital attenuators are controlled with a set of **digital** (i.e., binary) **control lines**. As a result, the attenuator can be set to a specific number of **discrete** values.

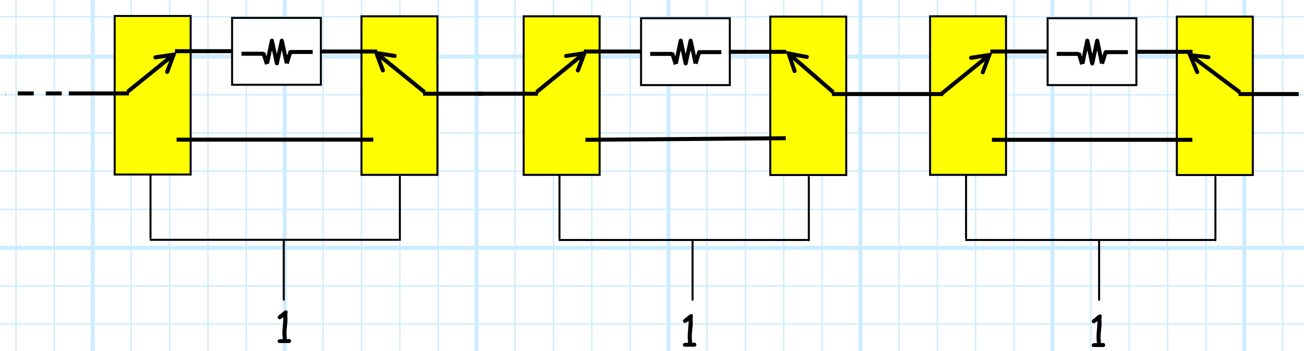
For example, a 6-bit attenuator can be set to one of $2^6 = 64$ **different** attenuation values!

Digital attenuators are typically made from **switches** and **fixed** attenuators, arranged in the following form:

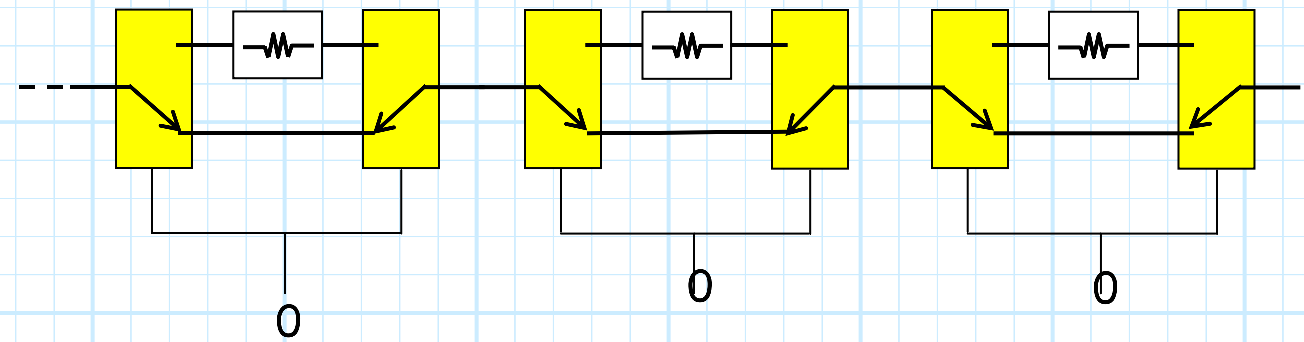


Theoretically, we can construct a digital attenuator with as **many** sections as we wish. However, because of switch **insertion loss**, digital attenuators typically use no more than 8 to 10 bits (i.e., 8 to 10 sections).

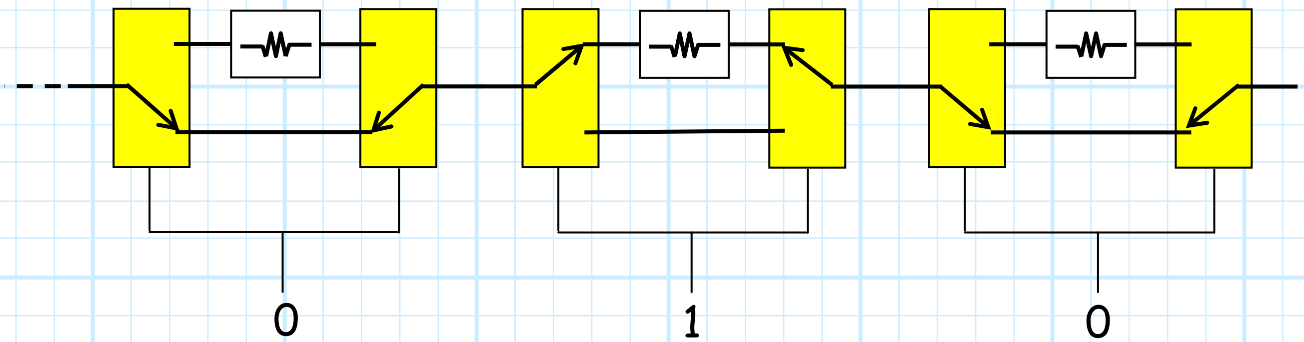
It is apparent from the schematic above that each section allows us to switch in its attenuator into the signal path (maximum attenuation):



Or we can **bypass** the attenuators, thus providing no attenuation (except for switch insertion loss!):



Or we can select **some** attenuators and bypass **others**, thus setting the attenuation to be somewhere in between max and min!



For most digital attenuators, the attenuation of each section has a **different** value, and almost always are selected such that the values in dB are **binary**.

For example, consider a 6-bit digital attenuator. A typical design might use **these** attenuator values:

	bit 5	bit 4	bit 3	bit 2	bit 1	bit 0
attenuator	32 dB	16 dB	8 dB	4 dB	2 dB	1 dB

We note therefore, that by selecting the proper switches, we can select **any** attenuation between 0 dB and 63 dB, in **steps** of 1 dB.

For **example**, the 6-bit binary word 101101 would result in attenuation of:

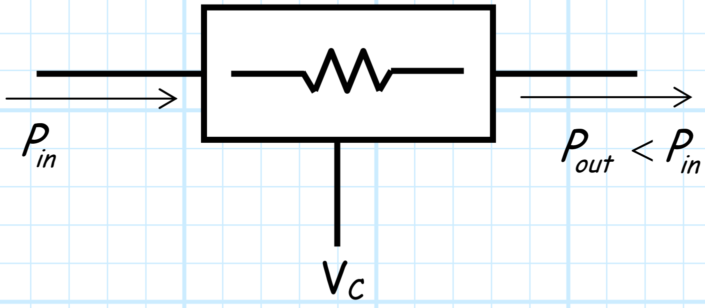
$$32 + 8 + 4 + 1 = 45 \text{ dB}$$

Note also that 101101 is the **binary** representation of the **decimal** number 45—the binary control word **equals** the attenuation in dB!!

Voltage Controlled Attenuators

Another adjustable attenuator is the **voltage-controlled attenuator**. This device uses a **single** control line, with the **voltage** at that control determining the attenuation of the device (an "analog" attenuator!):

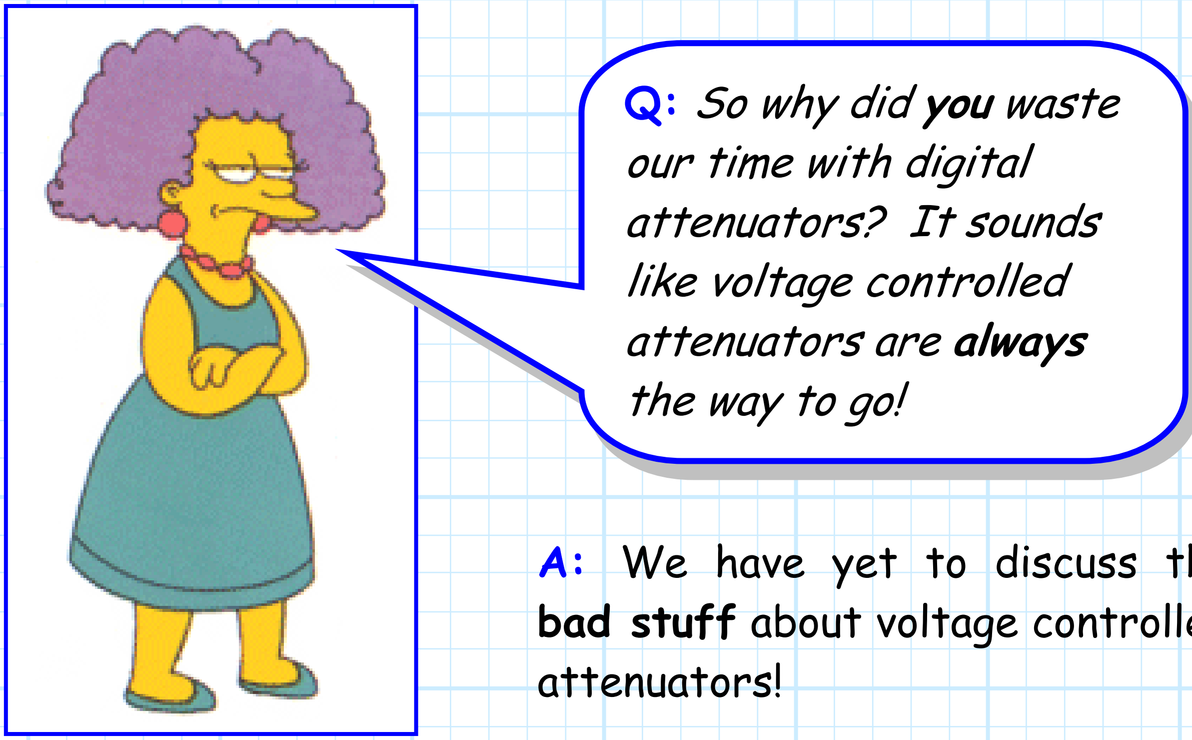
$$Attenuation = f\left(V_C\right)$$



Typical voltage control attenuators can provide attenuation from a **minimum** of a few dB to a **maximum** of as much as 50 dB.

Unlike the digital attenuator, this attenuation range is a **continuous** function of V_C, so that **any** and every attenuation between the minimum and maximum values can be selected.

Voltage controlled attenuators are typically **smaller**, simpler, and **cheaper** than their digital counterparts.



A: We have yet to discuss the **bad stuff** about voltage controlled attenuators!

* Voltage controlled attenuators are generally speaking **poorly matched**, with a return loss that varies with the control voltage V_C.

* Likewise, the phase delay, bandwidth, and just about every other device parameter also **changes** with V_C!

* Moreover, voltage controlled attenuators are notoriously **sensitive** to temperature, power supply variations, and load impedance.

Digital attenuators, on the other hand, generally exhibit **none** of the problems!

In addition, digital attenuators are ready made for integration with **digital controllers** or processors (i.e., computers).

However, digital attenuators do have a downside—they **can** be relatively large and **expensive**.

The Digital Attenuator Specification Sheet

Number of Sections

Equal to the number of **bits**.

Bandwidth (Hz)

This device, like all other devices, can effectively operate only within a finite **bandwidth** (e.g., 2-5 GHz or 300-400 MHz).

Port Impedance (Γ, return loss, VSWR)

Insertion Loss (dB)

This is defined as the attenuation of the device in its **minimum** attenuation state (i.e., no attenuators are selected). Ideally, this would be 0 dB. However, the insertion loss of the **switches** makes this ideal value unachievable.

Typically, insertion loss will be equal to approximately 1 dB per bit. In other words a 6-bit attenuator will have an insertion loss of 6dB.

DC Power

See microwave switch spec sheet.

Maximum Attenuation (dB)

The attenuation of the device with **all** fixed attenuators selected. This value is therefore the sum (in dB) of every fixed attenuator, **plus** the insertion loss discussed above. Remember, the insertion loss of the switches is prevalent regardless of the attenuator state.

Attenuation Step Size (dB)

The vast majority of digital attenuators have attenuation states that are separated by a **fixed** value (e.g., 0.5, 1.0, or 2 dB).

Maximum Input power (dBm)

Digital attenuators have a **maximum** input power.

Switching Speed (seconds)

The state of a microwave switch **cannot** change instantaneously. It takes some small but non-zero amount of time to change from one attenuation state to another. Typical values range from 0.1 to 20.0 μseconds.

Switch Logic

See microwave switch spec sheet.

PIN Diodes

Q: *Just how do we **make** switches and voltage controlled attenuators?*

A: Typically, they are constructed with **PIN diodes**.

A PIN diode is simply a *p-n* junction diode that is designed to have a very **small junction capacitance** (0.01 to 0.1 pf).

→ Sort of the **opposite** of the **varactor** diode!

To see why this is important, recall diode **small signal analysis** from your first electronics course.

In small signal analysis, the **total** diode voltage consists of a D.C. bias voltage (V_0) and a small, time-varying signal (v_d):

$$v_D(t) = V_0 + v_d(t)$$

For radio engineering applications, the small signal is a **microwave** signal !!! I.E.,:

$$v_D(t) = V_0 + v_{RF}(t)$$

Thus, we know that the **diode current** i_D is:

$$i_D = I_s\left(\exp\left[\frac{V_0 + v_{RF}(t)}{nV_T}\right] - 1\right)$$

Since v_{RF} is very **small**, we can **approximate** this diode current $i_D(v_D)$ using a **Taylor Series** expansion around $v_D = V_0$:

$$i_D(v_D) \approx i_D(v_D)\Big|_{v_D=V_0} + \frac{\partial i_D(v_D)}{\partial v_D}\Bigg|_{v_D=V_0} v_{RF}(t)$$

$$= I_S\left(e^{V_0/nV_T} - 1\right) + \frac{I_S\, e^{V_0/nV_T}}{nV_T} v_{RF}(t)$$

We recognize that:

$$I_S\left(e^{V_0/nV_T} - 1\right) = \text{D.C. Bias Current} \doteq I_0$$

and thus we can write our **small-signal approximation** as:

$$i_D = I_0 + \frac{(I_0 + I_s)}{nV_T} v_{RF}(t)$$

$$= I_0 + \frac{v_{RF}(t)}{r_d}$$

where we have defined the diode **small-signal resistance** r_d as:

$$r_d = \frac{nV_T}{I_0 + I_s}$$

The diode small-signal resistance is also **often** referred to as the **junction** resistance R_j or the **series** resistance R_s.

We can further conclude that the total diode current i_D is the sum of the D.C. bias current I_0, and the **small-signal current** $i_{RF}(t)$, where:

$$i_{RF}(t) = \frac{v_{RF}(t)}{r_d}$$

→ Just like **Ohm's Law** !

To a small (i.e., low power) microwave signal, a diode "looks" like a **resistor**.

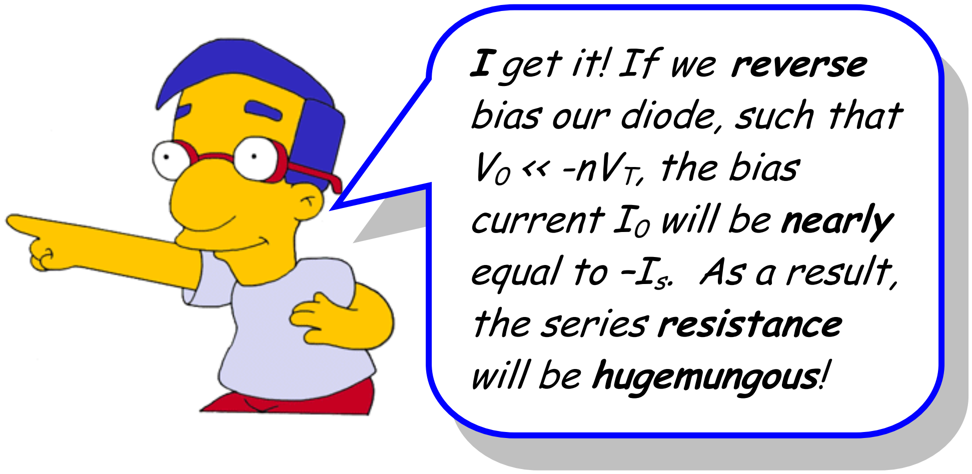
Moreover, we can **control** and **modify** the resistance of the diode by **changing** the D.C. **bias**.

→ Sort of a **voltage-controlled** resistor!

For example, if we put the diode into **forward** bias ($V_0 >> nV_T$), the bias current I_0 will be positive and **big**, thus the junction resistance will be very **small** (e.g., r_d= a few ohms).

→ A **forward** biased diode is very nearly a microwave **short circuit**!

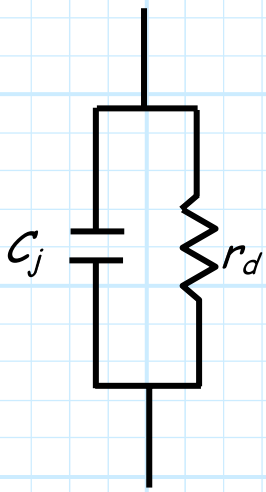
$$r_d = \frac{nV_T}{I_0 + I_s}$$



Not so fast! The small-signal **resistance** of a **reverse** biased diode is in fact **very large**. BUT, we must also consider the junction **capacitance** C_j!

Recall that in **reverse** bias, the junction capacitance of a diode can be **significant**, and in fact generally **increases** as the bias voltage becomes more negative!

As a result, a good microwave circuit **model** of a diode includes both the series resistance and junction capacitance:

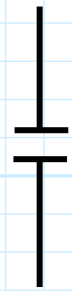


$$Z_D = \frac{r_d}{1 + j\omega\, r_d C_j}$$

For **forward** bias, where r_d is **very small**, we find that diode impedance Z_D is approximately equal to this **small** series **resistance** ($Z_D \approx r_d$)—a **short** circuit (approximately):

$$Z_D^{fb} \approx r_d$$

For reverse bias, where r_d is **very large**, we find that diode impedance Z_D is approximately equal to that of the junction **capacitance** C_j:

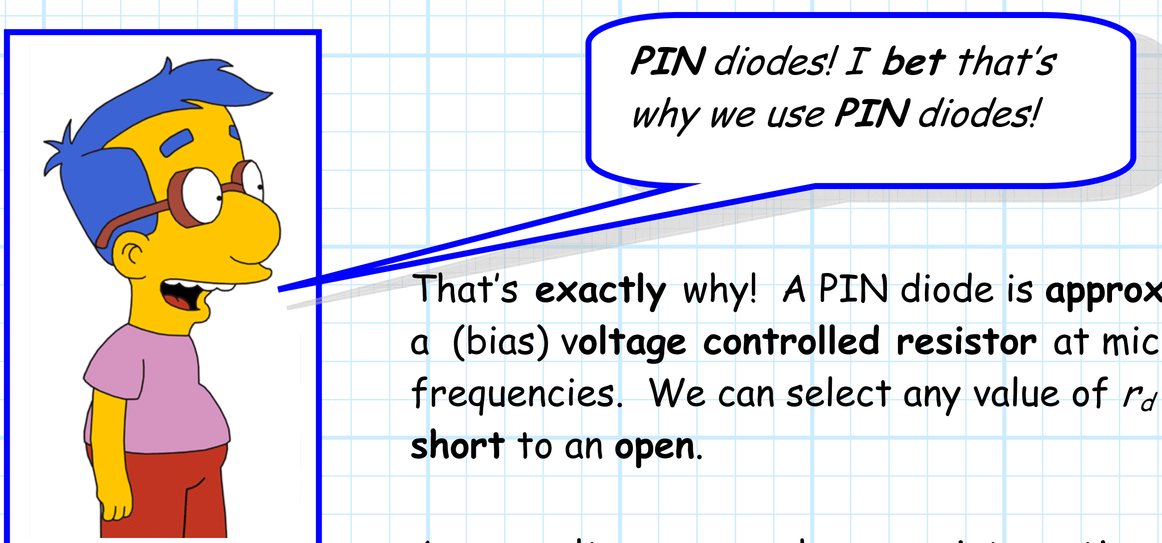


$$Z_D^{rb} = \frac{1}{j\omega C_j}$$

For low-frequencies (e.g., kHz), this impedance will be typically be **very** large and thus the diode can be approximate as an **open** circuit.

However, at microwave frequencies (where ω is very large) the reverse bias impedance Z_D^{rb} may **not** be particularly large, and thus the reverse biased diode **cannot** be considered an open circuit.

In order for the impedance $Z_D^{rb} = 1/j\omega C_j$ to be very **large** at **microwave** frequencies, the junction capacitance C_j must be **very, very** small.



That's **exactly** why! A PIN diode is **approximately** a (bias) **voltage controlled resistor** at microwave frequencies. We can select any value of r_d from a **short** to an **open**.

As a result, we can make **many** interesting devices!