10.3 RF Diode Characteristics

Reading Assignment: ***pp. 514-521***

Another important microwave component is a microwave switch.

HO: MICROWAVE SWITCHES

Microwave switches are often constructed with PIN diodes.

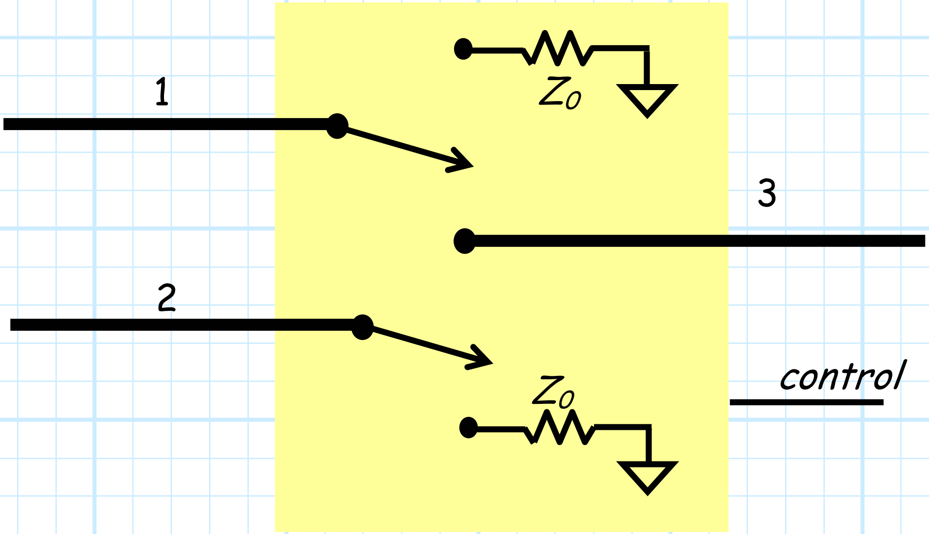
HO: PIN DIODES

Q: *Just how are PIN diodes used to construct switches?*

A: **HO: PIN DIODE MICROWAVE SWITCHES**

Microwave Switches

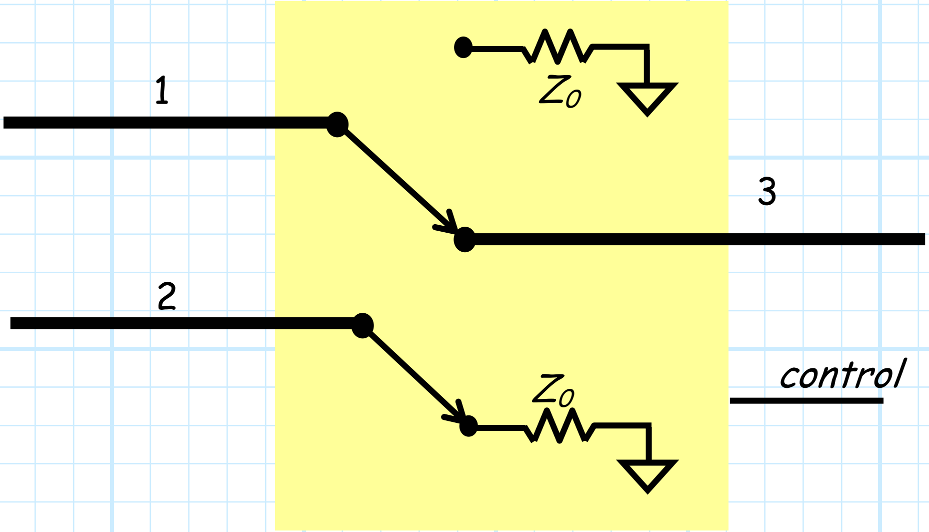
Consider an **ideal** microwave SPDT **switch**.



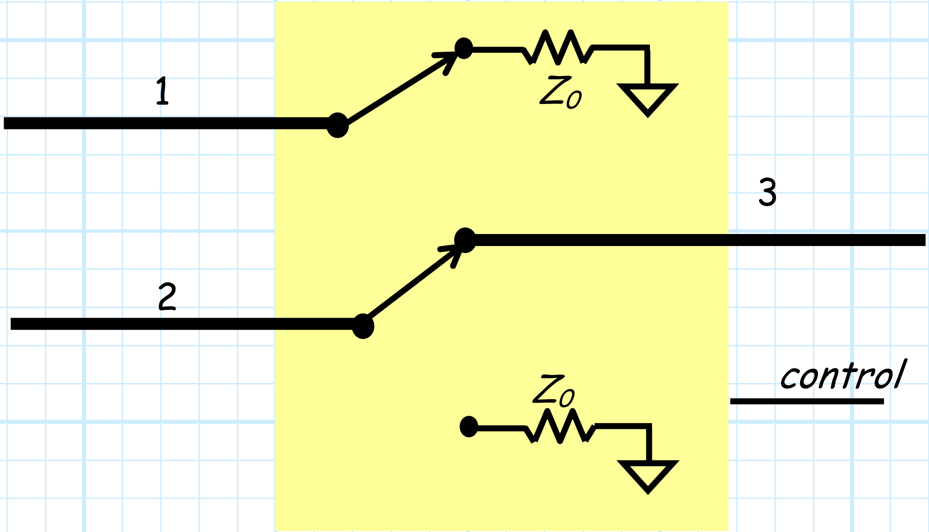
The **scattering matrix** will have one of two forms:

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

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



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

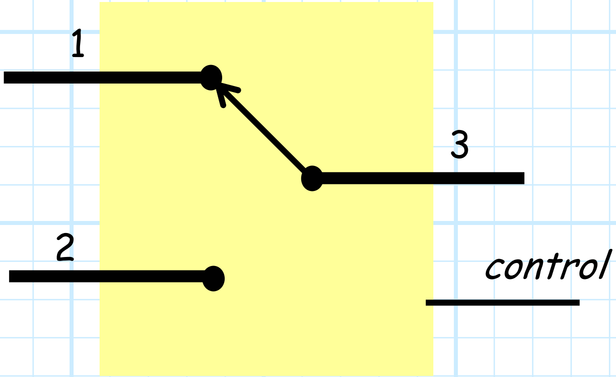


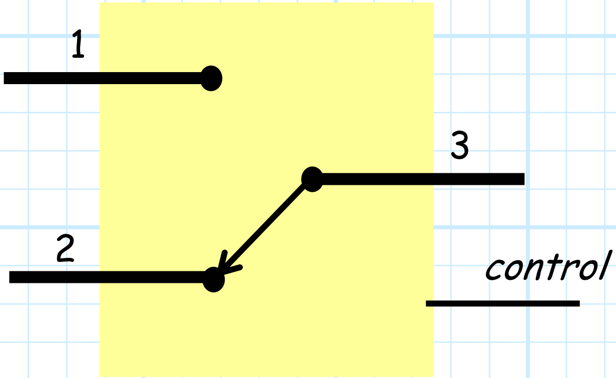
These ideal switches are called matched, or **absorptive switches**, as ports 1 and 2 remain matched, even when **not connected**.

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

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

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** $\mathcal{S}_{13}$ for a non-ideal switch:

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

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

Insertion Loss

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

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

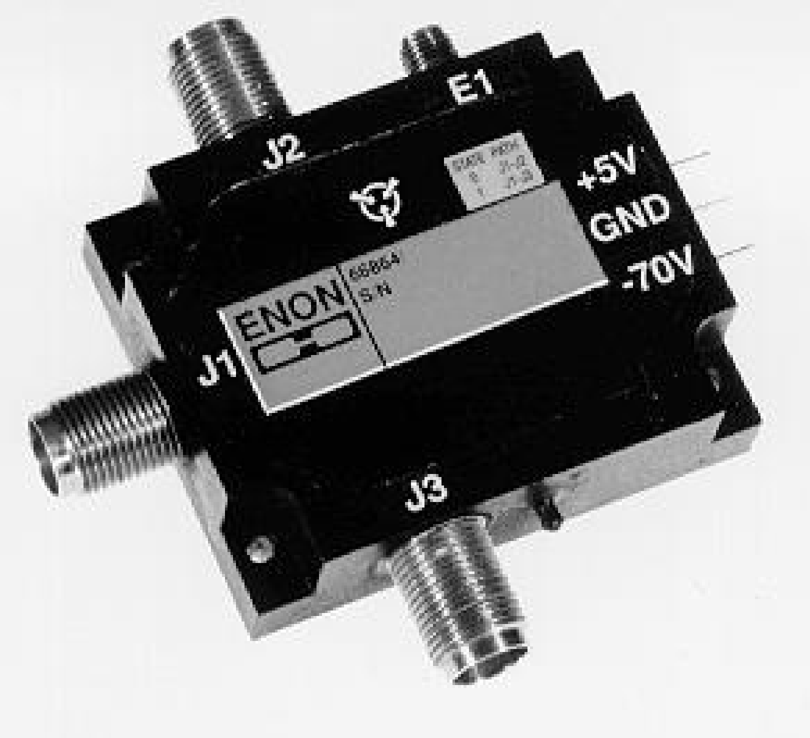
$$Isolation = -10\log_{10}|S_{32}|^2$$

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

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

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!



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_D) and a small, time-varying signal (v_d):

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

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

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

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

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

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

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

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

We recognize that:

$$I_S\left(e^{V_D/nV_T} - 1\right) = \text{D.C. Bias Current} \doteq \mathrm{I}_D$$

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

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

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

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

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

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_D, 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**.

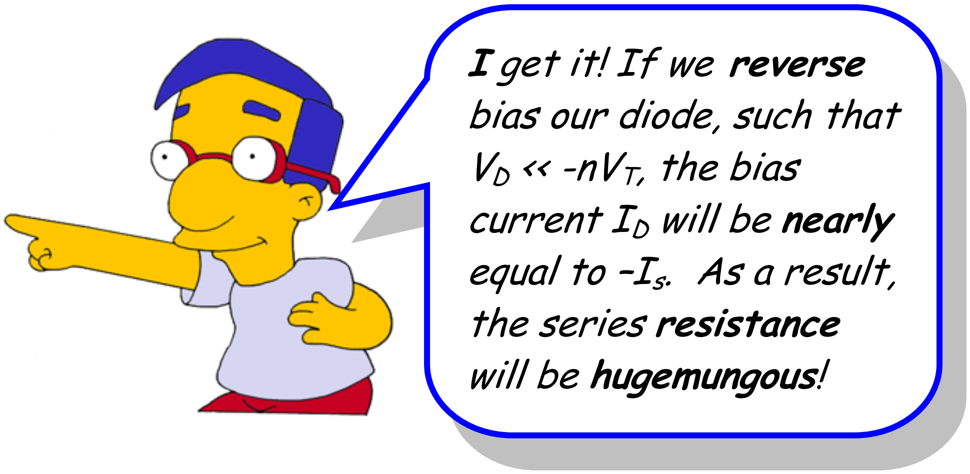
Moreover, we can **control** and **modify** the resistance of the diode by **changing** the D.C. **bias**.

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

For example, if we put the diode into **forward** bias ($V_D >> nV_T$), the bias current I_D 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**!

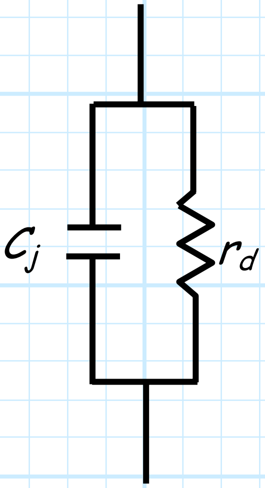
$$r_d = \frac{nV_T}{I_D + I_s}$$



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!

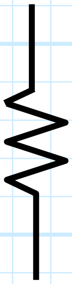
Recall that in **reverse** bias, the junction capacitance of a diode can be **significant**, and in fact generally **increases** as the bias voltage becomes more negative!

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



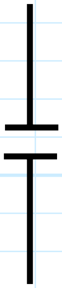
$$Z_D = \frac{r_d}{1 + j\omega\, r_d C_j}$$

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):



$$Z_D^{fb} \approx r_d \ll Z_0$$

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:



$$Z_D^{rb} = \frac{1}{j\omega C_j} \gg Z_0$$

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.

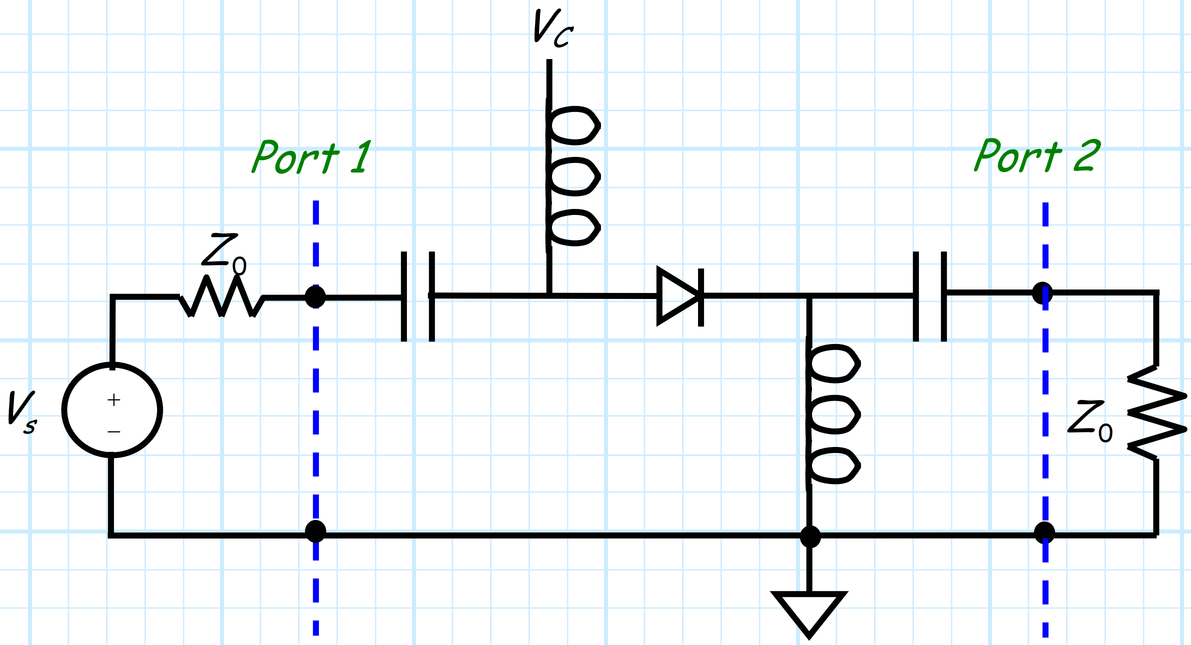
In order for the impedance $Z_D^{rb} = 1/j\omega C_j$ to be very **large** at **microwave** frequencies, the junction capacitance C_j must be **very**, **very** small.

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!

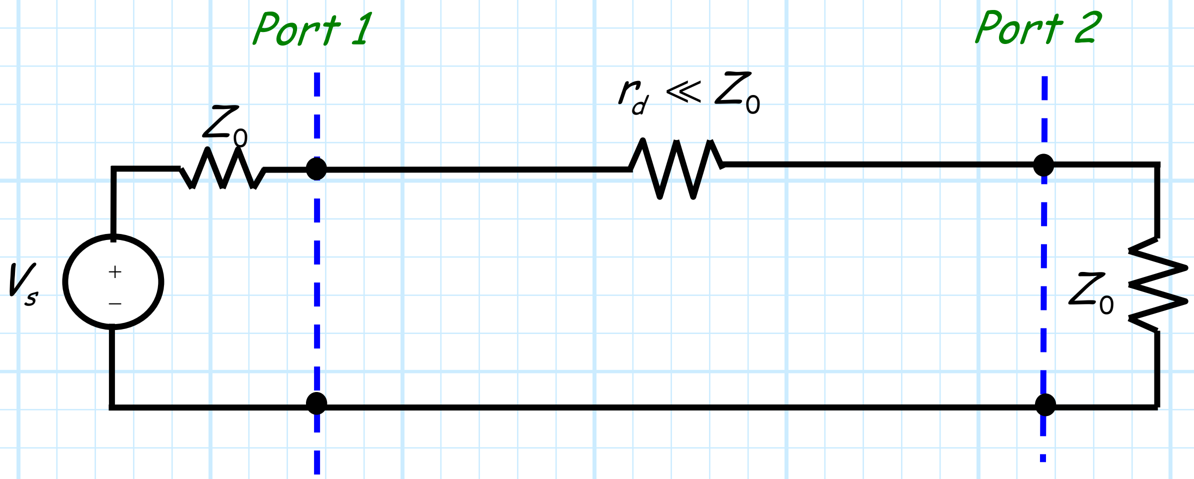
PIN Diode Microwave Switches

We can use PIN diodes to build microwave switches. There are two basic design configurations for a single pole switch. We first consider the **series** configuration.



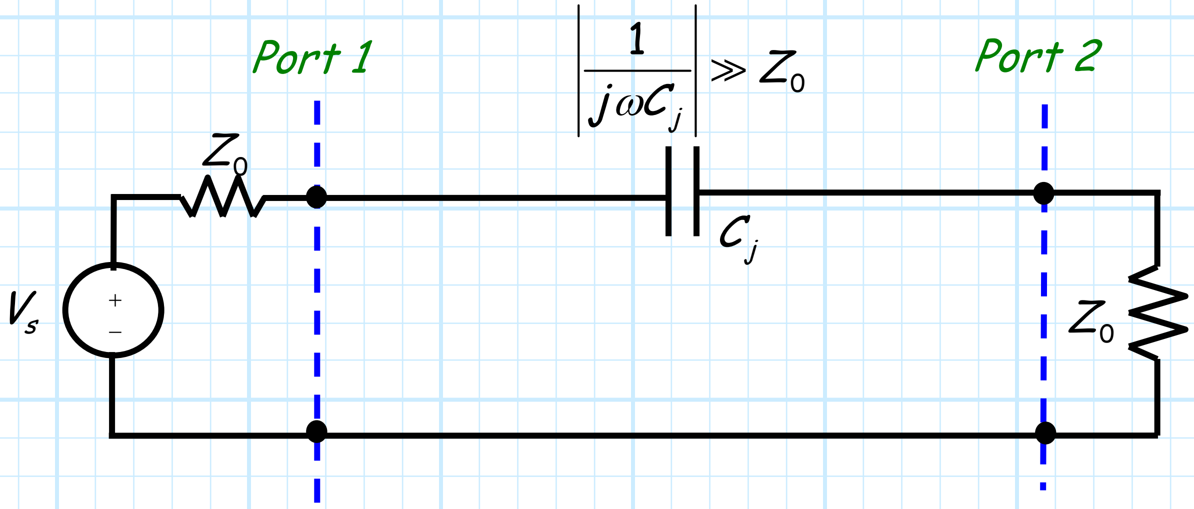
Here the inductors are **microwave chokes** and the capacitors are **DC blocking capacitors**.

If the DC control voltage V_C is set such that the PIN diode is **forward biased**, the equivalent microwave circuit becomes:



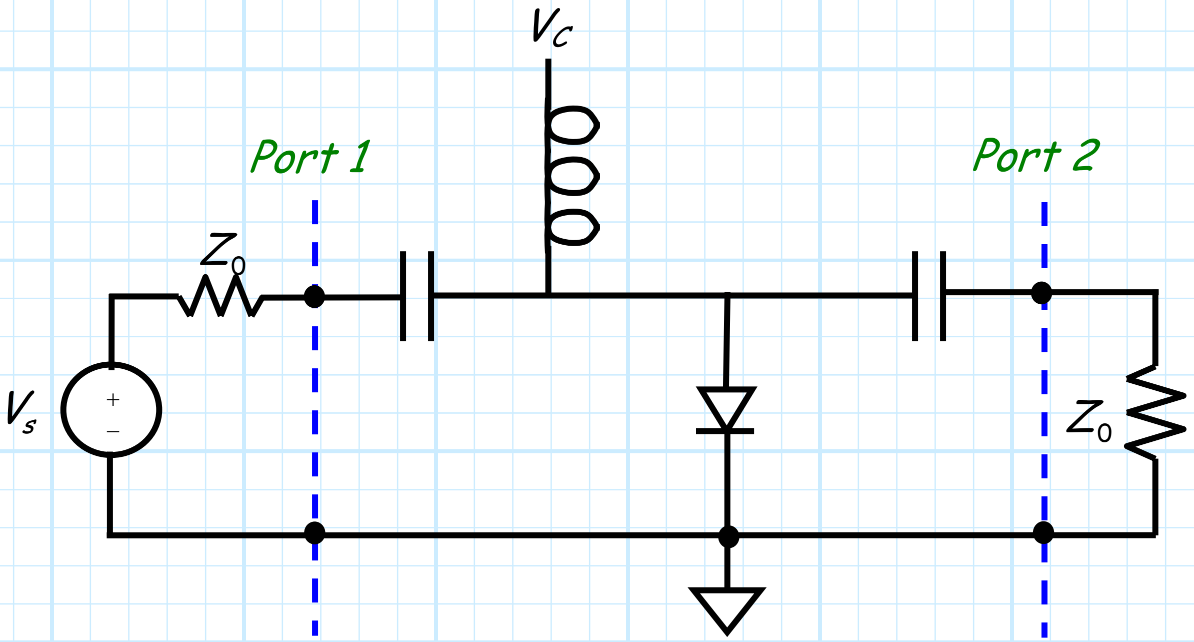
Note that $|S_{11}| \approx 0$ and $|S_{21}| \approx 1$ for this case, so that the switch has clearly **connected** the source to the load.

In contrast, consider the equivalent microwave circuit if the DC control voltage V_c is set such that the PIN diode is **reverse biased:**



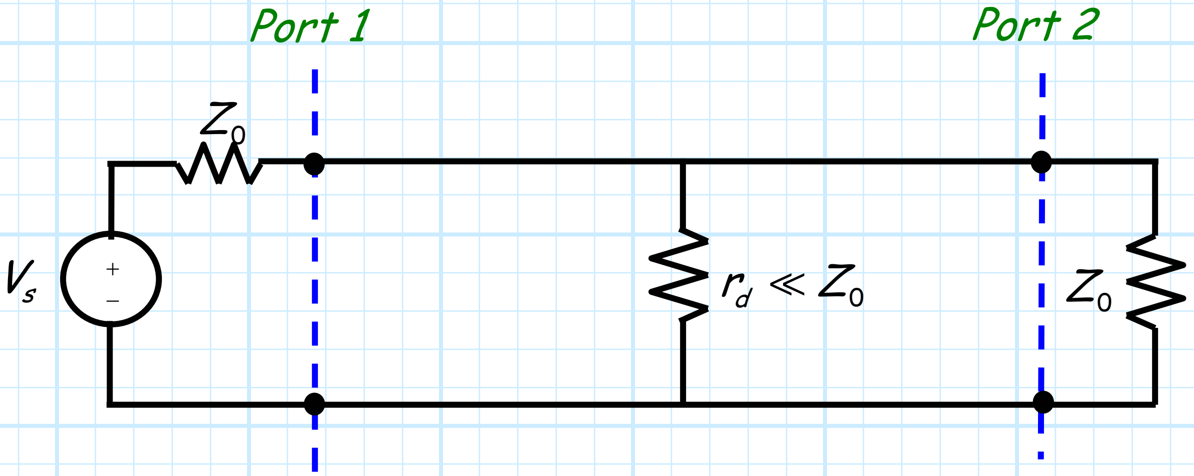
Note that $|S_{11}| \approx 1$ and $|S_{21}| \approx 0$ for this case, so that the switch has clearly **disconnected** the source from the load. Likewise, the input impedance of this switch has a very large magnitude—effectively an **open** circuit.

We now consider the **shunt** configuration:



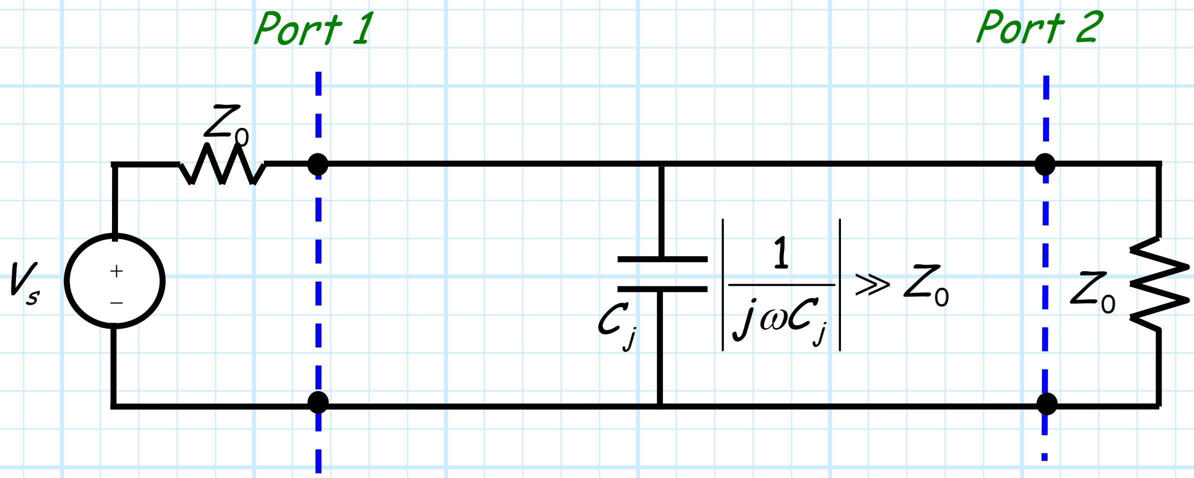
where the inductors are **microwave chokes** and the capacitors are **DC blocking capacitors**.

If the DC control voltage V_c is set such that the PIN diode is **forward biased**, the equivalent microwave circuit becomes:



Note that $|S_{11}| \approx 1$ and $|S_{21}| \approx 0$ for this case, so that the switch has clearly **disconnected** the source from the load. Likewise, the input impedance of this switch has a very small magnitude—effectively a **short** circuit.

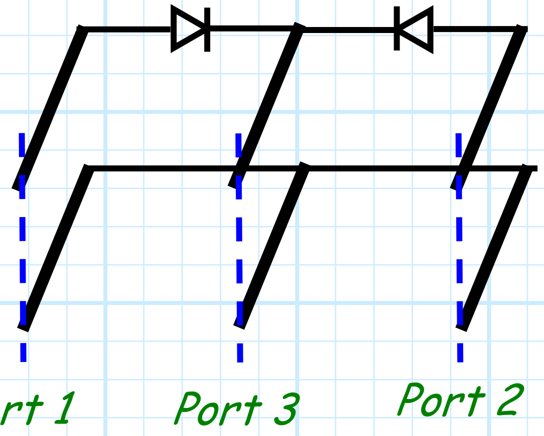
In contrast, consider the equivalent microwave circuit if the DC control voltage V_C is set such that the PIN diode is **reverse biased:**



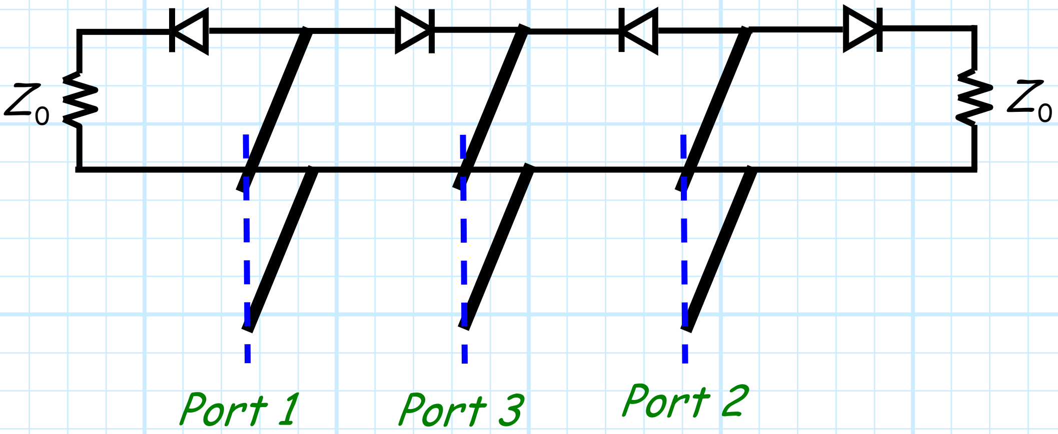
Note that $|S_{11}| \approx 0$ and $|S_{21}| \approx 1$ for this case, so that the switch has clearly **connected** the source to the load.

Q: *But these are both SPST microwave switches. What about a (**three-port**) SPDT switch?*

A: We can easily construct such a switch using the basic elements shown above. For example, a **reflective switch** would be (where DC bias elements have been ignored):



While an **absorptive switch** could be constructed as (where again the DC bias elements have been ignored):



In this case, the port (1 or 2) **disconnected** from port 3 is connected to a **matched load**.