The Matched, Lossless, Reciprocal Coupler

We desire a coupler that is **matched** and **lossless**. In addition, the coupler will likely be **reciprocal**.

Q: *What do these three terms mean??*

A: Let's explain each of them **one at a time**!

Matched

A matched device is another way of saying that the **input impedance** at each port is **equal to Z_0**, provided that all other ports are matched. As a result, the **reflection coefficient** of each port is **zero**—no signal will be come out of a port if a signal is incident on that port (and only that port).

In other words, we want:

$$V_m^- = S_{mm} V_m^+ = 0 \quad \text{for all } m$$

a result that occurs when:

$$S_{mm} = 0 \quad \text{for all } m$$

We find therefore that a matched device will exhibit a scattering matrix where all **diagonal elements** are **zero**.

Therefore:

$$\bar{\bar{\mathbf{S}}} = \begin{bmatrix} 0 & 0.1 & j0.2 \\ 0.1 & 0 & 0.3 \\ j0.2 & 0.3 & 0 \end{bmatrix}$$

is an example of a scattering matrix for a **matched,** three port device.

Lossless

A matched coupler will insure that all the power incident on a coupler will be delivered **into** the coupler. However, we also want to make sure that power eventually finds its way **out**!

In other words, we do **not** want this power to be **absorbed** by the coupler—we do **not** want this power to be **converted to heat**!

Such a device is said to be **lossless**.

Consider, for example, a **four-port** device. Say a signal is incident on port 1, and that **all** other ports are **terminated**. The power **incident** on port 1 is therefore:

$$P_1^+ = \frac{\left|V_1^+\right|^2}{2Z_0}$$

while the power **leaving** the device at each port is:

$$P_m^- = \frac{|V_m^-|^2}{2Z_0} = \frac{|S_{m1}V_1^-|^2}{2Z_0} = |S_{m1}|^2 P_1^+$$

The **total** power leaving the device is therefore:

$$\begin{aligned} P_{out} &= P_1^- + P_2^- + P_3^- + P_4^- \\ &= |S_{11}|^2 P_1^+ + |S_{21}|^2 P_1^+ + |S_{31}|^2 P_1^+ + |S_{41}|^2 P_1^+ \\ &= \left(|S_{11}|^2 + |S_{21}|^2 + |S_{31}|^2 + |S_{41}|^2\right) P_1^+ \end{aligned}$$

Note therefore that if the device is **lossless**, the output power will be **equal** to the input power, i.e., $P_{out} = P_1^+$. This is true **only** if:

$$|S_{11}|^2 + |S_{21}|^2 + |S_{31}|^2 + |S_{41}|^2 = 1$$

If the device is lossless, this will likewise be true for each of the **other** ports:

$$\begin{aligned} |S_{12}|^2 + |S_{22}|^2 + |S_{32}|^2 + |S_{42}|^2 &= 1 \\ |S_{13}|^2 + |S_{23}|^2 + |S_{33}|^2 + |S_{43}|^2 &= 1 \\ |S_{14}|^2 + |S_{24}|^2 + |S_{34}|^2 + |S_{44}|^2 &= 1 \end{aligned}$$

In fact, it can be shown that a lossless device will have a **unitary** scattering matrix, i.e.:

$$\bar{\bar{\mathbf{S}}}^H \bar{\bar{\mathbf{S}}} = \bar{\bar{\mathbf{I}}}$$

where H indicates **conjugate transpose** and $\bar{\bar{\mathbf{I}}}$ is the **identity** matrix. The columns of a unitary matrix form an **orthonormal set**—that is, the **magnitude** of each column is 1 (as shown above) and dissimilar column vector are mutually **orthogonal**.

Reciprocal

This is not necessarily a desirable trait, but rather is the result when building a **passive** (i.e., unpowered) device with **simple** materials.

For a reciprocal device, we find that the elements of the scattering matrix are **related** as:

$$S_{mn} = S_{nm}$$

For example, a reciprocal device will have $S_{21} = S_{12}$ or $S_{32} = S_{23}$. We can write reciprocity in matrix form as:

$$\bar{\bar{\mathbf{S}}}^T = \bar{\bar{\mathbf{S}}}$$

where T indicates (non-conjugate) transpose.