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A Review of Common Line-Section Directional Couplers

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Here is a short review of directional coupler principles and construction, plus a note on a new digital interface for a product using a "classic" design

An ideal directional coupler will sample (for measurement) the forward- and reverse-moving waves in a transmission line, keeping the two directions separated, without disturbing the direct signal path through the coupler. Of course, such an ideal device is impossible, thus we have specifications that describe a coupler's performance in each of these areas:

Directivity—The degree of rejection (in dB) for the unwanted signal direction. Typical couplers may have directivities from 20 to 40 dB.

Coupling—The ratio (in dB) of the incident power to the coupled power output. Higher operating power levels require higher coupling values to avoid overload of external circuitry. A higher coupling ratio typically has less effect on the through path.

VSWR—The VSWR of the coupler alone, terminated with an ideal load. This is a measure of the effect on the through path. As noted above, this is related to the coupling value, but is also affected by the physical design of the coupler.

Frequency response—All couplers have frequency-dependent performance resulting from fixed-size structures. Different physical designs have varying performance, and electrical design may include frequency compensation circuitry.

Directional Coupler Operation

First, we assume that a directional coupler operates *in an operational signal path*. This is in contrast to a VSWR bridge, which may include lossy elements and is intended as a temporarily installed measuring device. I make this clarification because both devices may be used to obtain the same data (VSWR).

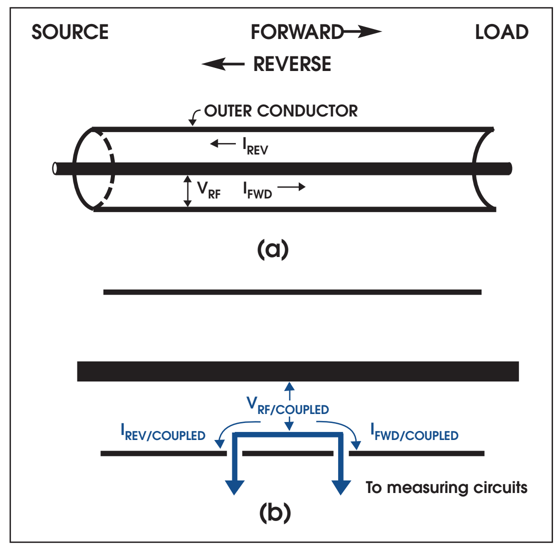

Figure 1 · A simple coaxial line section (a), and a line section with directional coupler sampling probe (b).

Figure 1a shows a coaxial transmission line segment (the line may also be stripline or microstrip), showing the voltage between the center and outer conductors, and the direction of current flow of the forward and reverse RF energy. The conventional notations of source, load and direction of power flow are also shown. Figure 1b shows how a typical directional coupler samples voltage and current. In various references, the probe may be referred to as a "loop" or a "short line section" depending on the author's perspective. A combination of both is probably most accurate.

In a coupled-line sampler, there are two coupling mechanisms. The first is simple capacitive coupling between the sampling probe conductor and the center conductor. This creates a voltage divider made up of this capacitive coupling and the impedance of the sampling circuit to the reference plane ("ground"). Thus a sample of voltage is obtained.

The second mechanism is inductive coupling between the current traveling on the through line, and the inductor represented by the "loop" of the sampling line. Because magnetic forces have a direction (remember the "right hand rule), I_{FWD} and I_{REV} will be exactly opposite when the sampling line is exactly orthogonal to the magnetic lines of force resulting from those currents. This property enables the directivity in this type of coupler.

To see this directivity on a measuring instrument (e.g., a voltmeter), the sampling line is first terminated on one end by a resistor, typically 50 ohms to establish a standard "source" impedance for the measuring circuit. The sampling line is initially oriented so $V_{RF/COUPLED}$ and $I_{FWD/COUPLED}$ are in-phase, and therefore, summed.

The "forward power" sample is the sum of the coupled RF voltage, and a second voltage across the terminating resistor, which results from the coupled forward current. Actually, the net current induced will be reduced by $I_{REV/COUPLED}$.

Then, the sampling line can be physically reversed (as in some directional wattmeters), or the termination can be switched to the opposite end of the sampling line. Now, the output is the difference of $V_{RF/COUPLED}$ and $I_{FWD/COUPLED}$, which is nearly zero, and the contribution of $I_{REV/COUPLED}$ is at its maximum. This results in the "reverse power" sample from the coupler.

The above conditions depend on either precise mechanical construction or an adjustable means of balancing the amplitudes of $V_{RF/COUPLED}$ and $I_{FWD/COUPLED}$ (with a "perfect" impedance match so that $I_{REV/COUPLED} = 0$.

Finally, these types of couplers are often used in instruments that calibrate a rectified voltage output so that it corresponds to power into the design load impedance (e.g., 50 ohms.). In this case, the indicated forward power will become inaccurate as the VSWR increases. The actual power will be the difference between the indicated forward and reverse power.

With careful mechanical design and application of relatively simple compensating circuitry, this type of coupler can achieve useful performance over a two octave bandwidth or more, or it can be calibrated for repeatable high accuracy over a narrower bandwidth.

The Legacy RF Wattmeter Meets the Computer Age

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The venerable in-line portable RF power meter, or wattmeter, has been a staple in the broadcast, military, scientific and two-way radio markets since the 1950s. Some newer manufacturers have offered a less expensive, less robust mechanical design, with broader bandwidth but tend to have lower accuracy. In contrast, some of the legacy wattmeters, though initially more expensive, are still in use after many decades and many owners. However, most of these earlier designs had failed to join the computer age until recently.

Some of the manufacturers of these legacy wattmeters are still producing their designs that incorporate a taut band meter movement similar to a watch spring. This is essentially a "frictionless" suspension of the needle and armature via a ribbon of metal. Full-scale meter indications are achieved with very low current and the movement or deflection of the needle is exceptionally smooth across the full deflection range. Taut band meters are highly resistant to particulate (dust, moisture, salt spray, aerosol, smoke, etc,) contamination in the environment.

RF power detection on most all analog style wattmeters typically uses germanium diodes dielectrically coupled to a feed-through transmission line. These classic wattmeters couple or detect the RF via "elements" or "slugs" placed with tight mechanical tolerances near a solid center conductor (Figure A). The center conductor is suspended with air as the dielectric within a solid metal cast or machined 7/8-inch line section. This design features precise impedance matching to 50Ω and is well suited for power levels approaching 10 kW due to its low insertion loss, ability to dissipate heat and lower risk of arcing compared to stripline designs using PC boards as the dielectric with thin, flat copper transmission lines. In addition, it uses no ferrite or toroidal cores that could become saturated at higher power levels.

Figure A · Plug-in elements are optimized for various frequency and power bands.

While the analog meter display has continued to perform admirably for decades, the real secret to its success is in the RF power detection. The mechanical configuration of the 7/8-inch line section is very broadband and is capable of a broad dynamic range thanks to the use of plug-in elements. RF power measurements from 100 mW to 10 kW translates into a +20 dBm to +70 dBm, or a 50

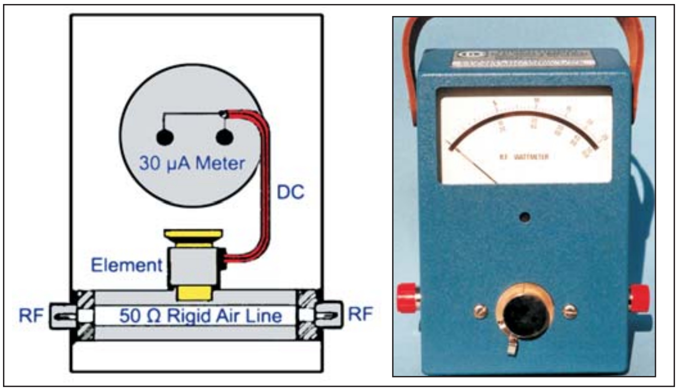

Figure B · A simplified diagram and photo of a legacy analog wattmeter, which Coaxial Dynamics now markets with PC connectivity.

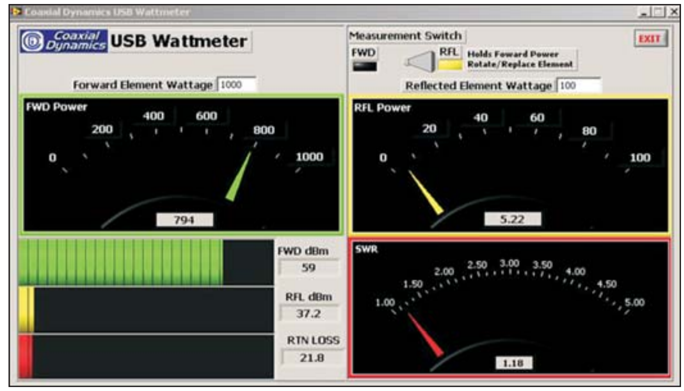

Figure C. The new USB-interfaced wattmeter's computer display, showing forward and reflected power, VSWR and units conversion features.

dB total dynamic range. The rigid line has a multi-octave bandwidth, permitting accurate power measurement from 450 kHz to 2.3 GHz.

Individual plug-in elements are specifically calibrated for high accuracy in specific power/frequency bands, and are less expensive than buying additional fixed coupler/detector assemblies or an entirely new wattmeter for different applications. The early wattmeters have sold in the hundreds of thousands. These products have never required a fundamental redesign for the basic functions of detecting and displaying forward and reflected RF power for over 50 years. However, nearly all of these wattmeters lack a function that prevents them from broadening their user-base today: a computer interface.

One of the manufacturers of these analog meters, Coaxial Dynamics, is introducing a USB Wattmeter for FM and CW average power measurements, with the same mechanical and electrical advantages as the legacy units (Figure B). Accuracy of ±5% of full scale is maintained, and the power display options have expanded greatly beyond the basic analog meter. The PC performs the number crunching to display the calculated SWR and Return Loss. Forward and reflected RF power are displayed in both watts and dBm.

The proprietary circuit technology introduced in the USB Wattmeter is a combination of two new microcontrollers with on-board e^2proms that sample and condition the element's DC output. Only using the USB bus means no additional power cabling is required. Other than the RF input and output cabling, the USB Wattmeter is a single cable system, drawing less than 100 mA total current when using the PC.

Limiting the cabling to and from power supplies or remote sensor/detectors reduces the potential of induced RF fields traveling along cables. Eliminating the maze of additional wires or cables is not only a cleaner installation, but reduces the possibility of loose or improperly grounded wires acting as antennae.

The microcontrollers and DC conditioning amplifiers of the USB Wattmeter are fully shielded within the metal enclosure of the wattmeter itself. This limits the potential of RF traveling along wires from remote sensors/detectors. This also means the wattmeter is just as portable as the original units. With the USB cable disconnected from the back of the wattmeter, it can be taken anywhere in the field without the need for any source of power, since the analog meter requires only the RF signal to indicate a forward or reflected power measurement.

The unique design blends the advantages of the original wattmeter with the functionality of modern computing. Figure C shows the USB Wattmeter computer display. It incorporates simulated needle movements for analog aficionados along with numeric and color-coded bar graph indicators. Forward power, reflected power and SWR are dynamically shown plus the conversion from watts to dBm and the automatic calculation of SWR and Return Loss. The software provides a "switch" that temporarily stores the forward power measurement while the plug-in element is replaced or rotated to the reflected power position.

Typically, the reflected element's full-scale power range is 1/10 that of the forward power element for best resolution. Since there have been hundreds of thousands of legacy wattmeters sold over the years, there are certainly more elements than that in use today. These same elements, built by several manufacturers over the years, will work with the new USB Wattmeter. Special elements or custom remote couplers are not required.

The original RF wattmeter has finally entered the computer age and has built upon, and maintained, its original advantages. The USB Wattmeter option is available with newly purchased units as the Coaxial Dynamics model 81040 or as a retrofit kit. The PC display software is included at no additional cost.