ABSTRACT

Various methods for waveguide power measurement were developed in the 1930's that have changed little over the years and are still in common use today. However, more recent improvements and advances in measurement signal processing technologies offer significant enhancements to the practical utilization of traditional power sensing methods. Before choosing a power sensing method for a particular application, the importance of coupling factor and directivity as performance parameters should be well understood. Measurement accuracy depends on a) the accuracy of calibration of the stated coupling factor, and b) the error introduced by the effects of reverse power as a result of finite directivity.

Three waveguide power sensing methods stand out as the most commonly used in laboratory and industrial heating systems, each having characteristics preferred for different applications.

Aperture Array Coupler – The two basic types of aperture array couplers are a) *Broadwall* couplers in which two parallel waveguide sections are coupled to each other along the broad wall by an array of apertures spaced ¼-guide wavelength apart, and b) *Cross-guide* couplers in which two perpendicular waveguide sections are coupled to each other by a single aperture.

Resistive Loop Coupler – Waveguide power is coupled magnetically and electrically to a sensor element consisting of a resistor-terminated loop and a probe.

Multi-probe Reflectometer – Three or four non-directional antenna probes detect voltages in the waveguide and enable the determination of standing wave reflection coefficient and relative phase angle as well as forward and reverse power.

The detected power signal must be converted to any of several forms as may be preferred for utilization in the application. The most popular signal conversion methods are diode detectors and thermocouple devices. Recent advances in detector circuitry offer significant improvements by combining a variety of useful features in cost-effective packages. Methods of calibration, an important factor in the accuracy of any measurement, are briefly reviewed.

INTRODUCTION

Measurements of microwave power became necessary simultaneously with the advent and use of high power microwave energy as early as the 1930's.[1] Several methods for power measurements were devised then and in the decades to follow, most of which are quite obsolete by today's standards. Of these methods, only a few are suitable for high power measurements (i.e. a few hundred Watts and above). For applications in microwave heating, the selection is further narrowed to methods suitable for operation within the ISM (Industrial, Scientific and Medical) frequency bands centered at 915 MHz (896 MHz in the UK) and 2450 MHz.

The methods of choice for most microwave heating applications are mainly those utilizing waveguide components for power coupling, along with various types of sensors for power signal processing. More recently, the integration of microprocessors and sophisticated electronic circuitry have greatly simplified the power measurement task and reduced costs while maintaining or improving accuracy and reliability. Fundamental differences in performance, reliability, size and cost necessitate careful consideration when selecting the measurement method best suited for a particular heating application.

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High Power Coupling Methods

Water loads were devised very early and quickly became the most widely used method for high power calibration.[2] The primary advantage is that power is absorbed directly into the water itself, thus acting as both a load and a means for reasonably accurate power measurement by calorimetry. However, water load calorimeters are mostly unsuitable for industrial heating applications due to their bulkiness and the complexity of ancillary equipment.

An interesting yet mostly impractical method is that of force-operated power indicators. Such instruments operate by interaction of the electromagnetic field with a moving object, such as a rotating vane. Several designs and methods have been devised, although most are highly sensitive to external effects of mechanical vibration making them unsuitable for general use.[3]

Various types of waveguide power couplers were devised as a means to divide the power between the main waveguide line and a branch line, ideally with no losses or reflections. A sensing device is then used to convert the microwave field in the branch line to a dc signal having a known mathematical relationship to microwave power. Waveguide couplers generally are either directional, meaning preferential to power flowing in one direction, or non-directional.

Another common waveguide power measurement device is the multi-port reflectometer. Detailed discussions of multi-port reflectometers can be found in early literature, but they did not gain popularity as waveguide power measurement devices until the 1970's with the advent of inexpensive desk-top computers.[3] Designs having three or four non-directional probes to sense the voltage at different points in the waveguide, along with appropriate signal processing, deliver information relating to the standing wave reflection coefficient and relative phase angle in addition to forward and reverse power.

WAVEGUIDE COUPLERS

Non-directional couplers typically employ a simple probe that protrudes into the waveguide to sense the e-field voltage at a single point in the waveguide. The voltage detected is the vector sum of voltages due to both forward and reverse power, thus the non-directionality of such devices. One can then see the inherent sensitivity to the relative phase of the standing wave resulting from the presence of both forward and reverse power. Consequently, non-directional couplers are best used in the absence of reverse power or where the relative phase of an anticipated standing wave is constant.

Early designs of directional couplers included relatively simple arrangements between adjacent waveguide sections connected by one or more apertures as well as resistive-loop type couplers. Three directional coupling types as shown in Figure 1 have proven to be quite popular for microwave heating applications.
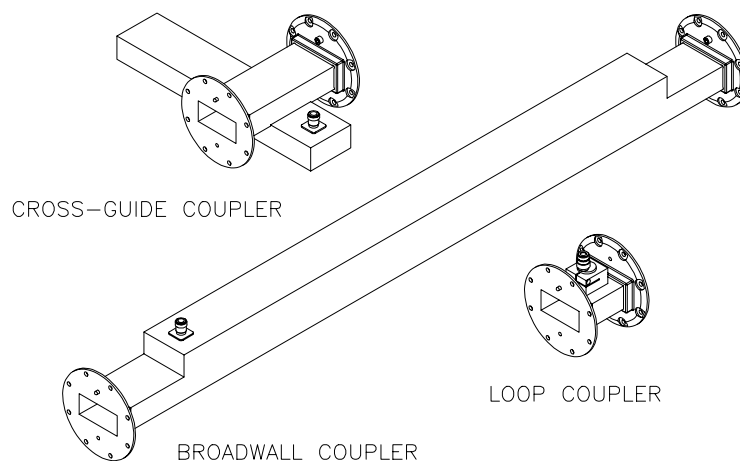

CROSS—GUIDE COUPLER

LOOP COUPLER

BROADWALL COUPLER

Figure 1, Common waveguide directional coupler types.

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Cross-guide Couplers

Cross-guide couplers consist of two perpendicular waveguide sections which are coupled to each other by a single aperture (two apertures for bi-directional couplers). The aperture is located such that a unidirectional circularly polarized H-field wave in the main waveguide couples a similar circularly polarized H-field in the branch waveguide which then excites unidirectional wave propagation.[4] Directivity is obtained by the fact that H-field polarization is opposite in direction between forward and reverse propagating waves, preventing a reverse wave from coupling through an aperture located for the forward wave and vise versa. Cross-guide couplers offer superior flatness of coupling factor over a broad band, although directivity is generally less than other coupler types.

Broadwall Coupler

In broadwall couplers, two parallel waveguide sections are coupled to each other along the broad wall by an array of apertures spaced ¼-guide wavelength apart. Energy propagating in one direction in the main waveguide section couples through each aperture and propagates initially in both directions in the branch waveguide. However, as a result of the aperture spacing, reverse propagating energy in the branch waveguide cancels while forward energy is additive.[2,3,4] Broadwall couplers offer superior directivity of 40 dB or more, but their large size is a significant disadvantage in most industrial applications.

Resistive Loop Coupler

A resistive loop type coupler is where the branch line is a sensor element consisting of a small strip of metal terminated at one end by a resistor and the other end by the output connector. Again taking advantage of the change in polarity between forward and reverse waves, the loop is oriented in such a manner as to couple only to the transverse magnetic field polarized in the preferred direction.[2,4] Loop couplers typically have the smallest size of all waveguide coupler types and offer reasonably good coupling factor and directivity performance.

DIRECTIONAL COUPLER PERFORMANCE

The operation and performance of a waveguide directional coupler are generally expressed in terms of a) accuracy and frequency sensitivity of its coupling factor, and b) directivity. It is important to understand the potential error in coupling factor that can be introduced due to finite directivity.

Performance Parameters

Coupling factor is defined as the ratio between the measured (forward) wave in the main waveguide and the coupled output wave.[2,4] When connected as shown in Figure 2(a) to a source and perfect loads, coupling factor is expressed in decibels (dB) as

$$CF = 10\log(\frac{P_F}{P_{3F}}) = 20\log(\frac{V_F}{V_{3F}}) = 20\log(\frac{1}{S_{31}}) \tag{1}$$

where P, V, and S represent power, voltage and s-parameter measurements, respectively. This equation represents a positive value for coupling factor, although it is often given as a negative value by inverting the logarithm function.

Directivity is then defined as the ratio between the forward coupled and reverse coupled waves.[2,4] When connected as shown in Figure 2(b) and assuming P_R is equal to P_F, directivity is expressed in decibels as

$$D = 10\log(\frac{P_{3F}}{P_{3R}}) = 20\log(\frac{V_{3F}}{V_{3R}}) = 20\log(\frac{S_{31}}{S_{32}}), \quad \text{or} \quad D = CF_R - CF_F \tag{2}$$
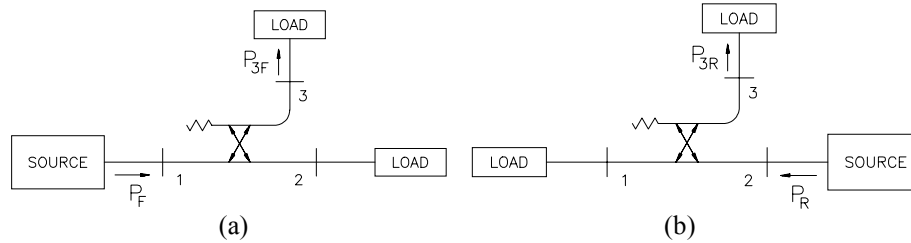
Figure 2, Directional coupler connections for measuring (a) coupling factor and (b) directivity.

Error Due to Directivity

As mentioned earlier, the finite directivity of a directional coupler gives rise to the potential for power measurement error due to interference from a reverse propagating wave. The *indicated* reading from the output of the branch line is derived from the *vector sum* of the forward coupled and reverse coupled wave. The vector diagram in Figure 3 shows that the reverse wave can be at any phase relative to the forward wave. Thus, the reading is sensitive to both relative phase of the reflection and coupler position along the waveguide.
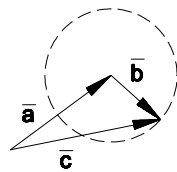
$\bar{a}$ = voltage at coupler probe output due to true forward power

$\bar{b}$ = interfering voltage from reverse power due to finite directivity

$\bar{c}$ = total actual voltage at coupler probe output

$\bar{c} = \bar{a} + \bar{b}$

Figure 3, Vector diagram of directional coupler output voltage.

From Figure 3 it is easy to see that the limits of the *true* reading can be found by adding and subtracting the absolute value of the interfering voltage from the actual output voltage. Thus,

$|\bar{c}|$ is calculated from the indicated power reading

$|\bar{b}|$ is calculated from known reverse power and coupler directivity

Limits of $|\bar{a}| = |\bar{c}| \pm |\bar{b}|$

Assuming waveguide impedance is constant, the actual voltage at the coupler probe output is calculated from the *indicated* forward power as

$$V_{Ind} = V_F \cdot 10^{\left(\frac{-CF}{20}\right)} = \sqrt{P_F} \cdot 10^{\left(\frac{-CF}{20}\right)} \tag{3}$$

If reverse power is present and known (and assumed correct), the *interfering* voltage is calculated as

$$V_{Int} = V_R \cdot 10^{\left(\frac{-(CF+D)}{20}\right)} = \sqrt{P_R} \cdot 10^{\left(\frac{-(CF+D)}{20}\right)} \tag{4}$$

The limits of actual forward power can then be found by adding and subtracting the interfering voltage from the indicated voltage,

$$P_{F\max} = V_{F\max}^2 = (V_{Ind} + V_{Int})^2 \cdot 10^{\left(\frac{CF}{10}\right)} \tag{5}$$

$$P_{F\min} = V_{F\min}^2 = (V_{Ind} - V_{Int})^2 \cdot 10^{\left(\frac{CF}{10}\right)} \tag{6}$$

A quick analysis of the exponents reveals that the term for coupling factor (CF) can be eliminated, implying that the error in power measurement due to finite directivity is entirely independent of coupling factor.

Figures 4 thru 6 illustrate the effects of the interference and magnitude of the resulting measurement error for typical cases encountered in microwave heating processes. Figure 4 represents a typical case where the load is reasonably well matched. The range of error is minimal when using a coupler with 40 dB directivity and within acceptable limits with a 25 dB directivity coupler.

Figure 5 represents a case where the load is poorly matched, as may be the case during initial startup and tuner adjustment. Again, the error limits are minimal for a 40 dB directivity coupler, but the limits for a 25 dB directivity coupler are significantly greater. The system operator should not be surprised to see large changes in the forward power reading during tuner adjustment.
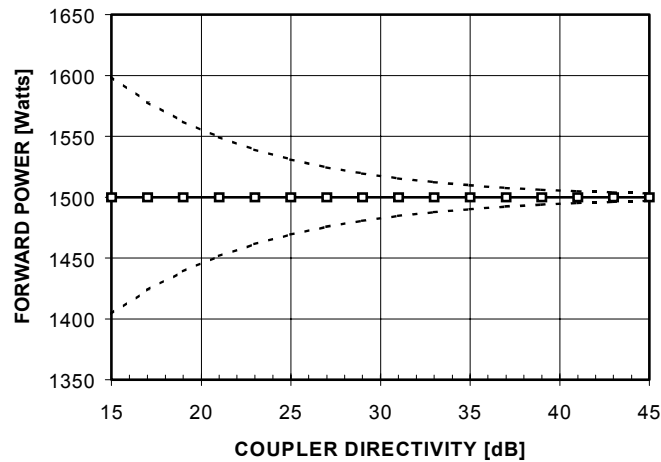

Figure 4, Minimum and maximum *true forward* power limits for a typical case with a matched load (1500 Watts *indicated forward* power, 50 Watts *true reverse* power)
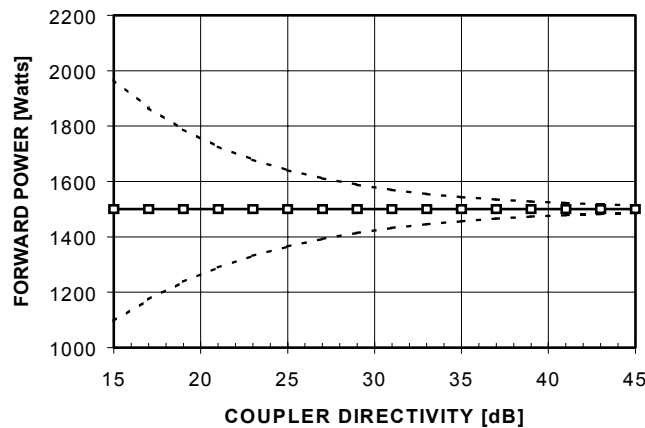

Figure 5, Minimum and maximum *true forward* power limits for a typical case with a poorly matched load (1500 Watts *indicated forward* power, 1000 Watts *true reverse* power)

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Power reflected from the process load is often measured on a continuous basis. If the load is well-matched and reflected power is minimal, the error caused by interference form the forward wave can be many times the indicated reading as illustrated in Figure 6. A common mistake especially in research applications is to infer a process effect based solely on a change in the reflected power reading without considering the potential magnitude of the interference.
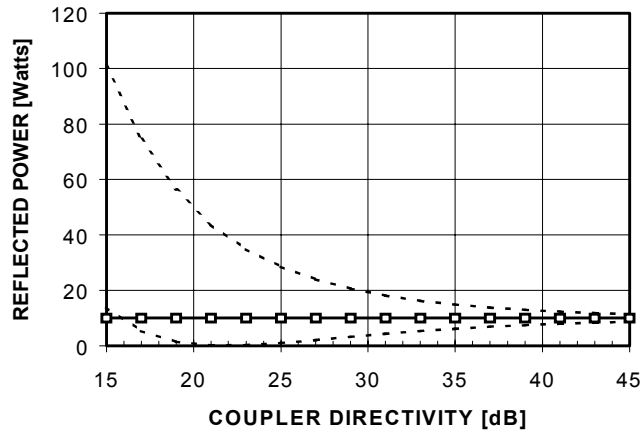

Figure 6, Minimum and maximum *true reflected* power limits for a typical case with a well matched load (10 Watts *indicated reflected* power, 1500 Watts *true forward* power)

Table 1 provides a comparison of performance characteristics between the three common coupler types. Note that the frequency response of the cross-guide coupler is much better than that of the loop coupler, but directivity is not as good. As such, the cross-guide coupler is preferred for well matched, broad band applications such as telecommunications whereas the loop coupler is preferred for heating applications. The broadwall coupler offers superior performance in both coupling factor and directivity compared to the other coupler types, but size and cost limit its usefulness and desirability.

Table 1, Performance Comparison for WR284 Waveguide Directional Couplers

Coupler Type	Mfr	Operating Band (GHz)	Coupling Factor Frequency Response				CF Mean Accuracy (+/- dB)	Minimum Directivity (dB)
			Mfr Specification		Within ISM Band			
			+/- dB	% of Band	+/- dB	% Error		
Loop	A	2.60-3.95	0.75	25%	0.22	5.3%	0.5	25
	B	2.60-3.95	1.0	20%	0.37	8.9%	N/A	25
	C	2.4-2.5	0.2	100%	0.20	4.7%	0.2	28
Cross-guide	A	2.60-3.95	1.0	100%	0.07	1.7%	1.0	20
	B	2.60-3.95	1.5	100%	0.11	2.6%	0.5	20
Broadwall	A	2.60-3.95	0.5	100%	0.04	0.9%	1.0	40
	B	2.60-3.95	0.5	100%	0.04	0.9%	0.5	40

SENSORS

The microwave output signal from the branch line of a directional coupler is of little use for power measurement purposes until it has been converted to a form which can be easily displayed and/or recorded. Several types have been devised, each having characteristics preferred for specific applications.

Bolometric types, including thermistors, operate on the basis of the dc resistance temperature coefficient of a power absorbing element. Bolometers are favored for use as laboratory measurement standards

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due to their inherent accuracy and stability.[3] Thermistors have been commonly used commercially in conjunction with electronic power meters, but more recently they have been replaced by diode and thermocouple devices which offer greater sensitivity, dynamic range and power handling capability.[1]

Detector diodes operate by rectifying the microwave signal directly to provide a pulsed dc voltage signal. At the low end of the operating range, the output signal follows a "square-law" transfer function which is conveniently proportional to waveguide power. Diodes are quite popular in commercial and industrial applications for their simplicity and low cost. However, as semiconductor devices they have an inherently high temperature coefficient which limits their accuracy under varying ambient conditions.[1,3]

Thermocouple sensors are popular for high performance measurement requirements due to their higher sensitivity, ruggedness and accuracy. The principle of operation is based on the voltage generated due to the differential temperature between hot and cold junctions of dissimilar metals. The effect is inherently "square-law" in operation and truly averaging, making thermocouple sensors ideal for all types of signal waveforms. The only drawback to these sensors is high cost which limits their practicality in typical industrial heating applications.

REFLECTOMETERS

Multi-port reflectometers have gained popularity in industrial heating applications for their ability to provide information about the complex impedance of a load in addition to forward and reverse power. Commercially available types utilize three or four non-directional probes to detect the voltage at different positions along the waveguide. Various models with integrated electronics for signal detection and conditioning deliver the individual probe output signals, while others utilize microprocessors for signal analysis. Several mathematical methods are available for complex impedance analysis using three and four probe models with equal or random probe spacing.[5,6] The most sophisticated products are used in conjunction with automatic impedance tuners and predictive s-parameter algorithms for very high speed performance.

CALIBRATION

A critical factor in the usefulness of any directional coupler is its calibration accuracy. Reasonably accurate calibration at low power is possible using a standard network analyzer having suitably high dynamic range. However, high power calibration requires the use of a high power measurement standard. The National Institute of Standards and Technology (NIST) maintains standards up to 1 kW at up to 1 GHz, but in the 1 GHz to 98 GHz frequency range the available standards are limited to 10 mW.

Thus, alternate methods must be employed for high power calibration at 2.45 GHz using NIST-traceable standards. A simple method is by substituting a previously calibrated coupler with the coupler under test. A more cumbersome yet highly accurate method is the "cascaded-coupler" technique.[7] Commercially available calorimeters utilize the resistance substitution method which compares the electrical heat loss to microwave power absorption.

A calibration routine should be established depending on the type of coupler used and requirements for measurement accuracy in a particular application. Aperture array couplers have fixed geometries and thus require no periodic calibration. Resistive loop couplers are adjustable and therefore should be routinely calibrated at least once every 1-2 years. Devices employing electronic circuitry to derive the output signal are more subject to drift and should be calibrated a minimum of once every year.

SUMMARY

Several methods for high power measurements in waveguide are available, but only a few are recommended for industrial heating applications. Directional and non-directional couplers offer a range of performance characteristics for simple waveguide power measurements, while multi-port reflectometers add the capability to deliver information on the complex impedance of a load. Directivity and interference from reverse power should be well understood when interpreting the output reading from a directional coupler. Calibration must be routinely maintained to ensure measurement accuracy.

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