WAVEGUIDE COMPONENTS AND CONFIGURATIONS FOR OPTIMAL PERFORMANCE IN MICROWAVE HEATING SYSTEMS

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ABSTRACT

Industrial microwave heating systems typically use a variety of standardized waveguide components for delivery of microwave energy, each having a specific and necessary function. The individual components are usually available in several different types and waveguide sizes offering different performance characteristics that are well suited for specific heating applications. They can also be arranged in any of several different configurations as required by the application. As a result, the system designer is presented with a wide variety of often difficult choices of components and configurations. This paper characterizes the most commonly used waveguide components, outlines several unique configurations for their use, and summarizes the advantages and disadvantages in each case.

INTRODUCTION

Most industrial microwave heating systems consist of three basic elements, a microwave power generator, a system of power delivery components, and a load to be heated. Output power and load volume (or throughput) are most often used to characterize the size of a system. Laboratory systems used for research and development purposes, as well as many production applications such as ceramic sintering and semiconductor plasma processing (CVD, etch, strip, etc.)[1], typically utilize a single generator ranging from a few hundred Watts output to several kilowatts. In such systems the load volume can range from a few tens of milliliters to hundreds of liters. Industrial processing systems can range from tens of kilowatts to megawatts of microwave power and have load volumes of hundreds of cubic meters.

Figure 1 illustrates a typical system configuration used for heating a column of fluid. Such a system might utilize 1 kW of microwave power to heat a continuous flow of fluid having a volume inside the applicator of only 1 ml. Large industrial batch processing systems are typically configured with similar but multiple sets of microwave generators and power delivery components.

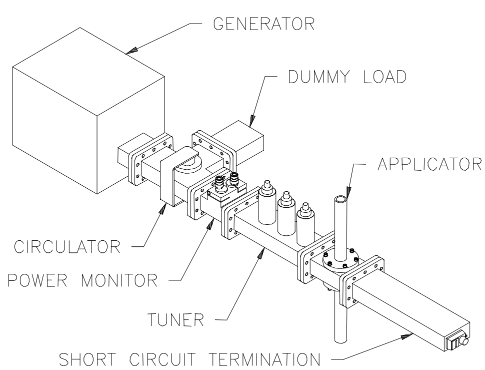

Figure 1. Typical laboratory system for fluid heating.

GENERATORS AND LOADS

Certain characteristics of microwave generators and loads affect the overall system performance and must be considered when configuring a system. Most important are output frequency stability and spectrum of the generator and frequency sensitivity of the load being heated.

Noting that most industrial microwave generators utilize magnetron oscillators, their output frequency spectrum is largely determined by output waveform [2]. Low ripple generators (also referred to as "cw" or continuous wave) produce a relatively narrow output frequency spectrum while high ripple and pulsed output generators produce a broad output spectrum. The importance of this characteristic becomes apparent when compared to the resonant frequency characteristics of the load. If the load is small and/or has a low dielectric loss factor then its "Q" (quality factor) will be relatively high, resulting in a narrow band of frequencies at which power can absorbed [3]. In Figure 2 it can be seen that operating a high ripple generator with a small or low loss load can result in large amounts of power that cannot be absorbed by the load and is reflected back.

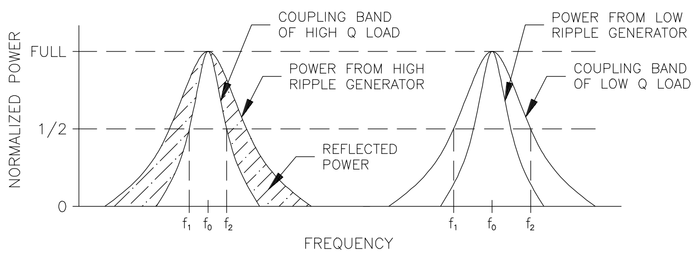

Figure 2. Generator output frequency spectrum compared to load coupling band.

The dielectric properties of most load materials vary with changes in temperature (i.e. water heating), phase (i.e. plasma ignition) or chemical composition (i.e. polymer curing). This results in a gradual or sometimes rapid shift in resonant frequency as the load is heated. Similarly, the generator output frequency shifts due to changes in output power, magnetron operating temperature, reflected power, and a variety of other factors. When a low ripple generator is used to heat a high Q load, the consequence of a shift in output frequency can be a dramatic loss of coupled power as illustrated in Figure 3.

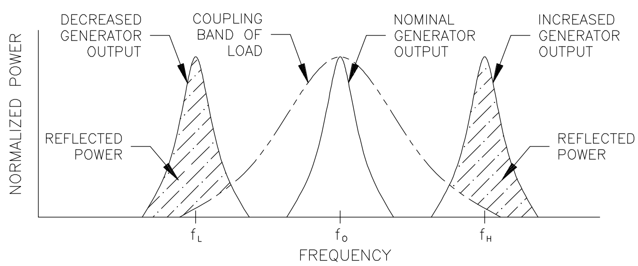

Figure 3. Generator output frequency shifting due to output power changes.

It should be noted that a variety of factors can influence the selection of generator for use with a particular load or process. However, for most cases the above discussion suggests that high ripple generators provide the best performance for large or high loss loads. Similarly, low ripple generators are usually preferred for small or low loss loads, although the inherent coupling instabilities require additional measures for stable heating performance.

POWER DELIVERY COMPONENTS

Most common high power waveguide configurations include a circulator, one or more loads, an impedance tuner, a means for power measurement, and some combination of basic waveguide elbows, twists and/or straight sections. However, some of these components are unnecessary in certain applications, while in others they might be deleted due to cost considerations outweighing the disadvantages presented by their absence. Waveguide sizes, flange types and the materials of component construction can impact performance and should also be considered. While components are available from several equipment manufacturers, most conform to established standards and may be used together without concern for compatibility or compromise in performance.

Waveguide Sizes and Flange Types

The choice of waveguide size depends mostly on operating frequency, power rating, component availability and cost. Table I lists various waveguide sizes commonly used for operation at the two ISM (industrial, scientific and medical) frequencies most commonly used for microwave heating, 2450 MHz (S band) and 915 MHz (L band).

Table I. Popular waveguide sizes used for industrial microwave heating.

Inside Dimensions (inches)	Frequency Band	Official Designations IEC	RCSC (UK)	EIA (US)
2.84 x 1.34	S	R32	WG10	WR284
3.40 x 1.70	S	R26	WG9A	WR340
4.30 x 2.15	S	R22	WG8	WR430
9.75 x 4.875	L		WG4	WR975

Although the established frequency range for WR284 waveguide is 2.60-3.95 GHz, this size is often the preferred choice for 2.45 GHz operation at average power levels up to 6kW. WR340 waveguide is used at power levels up to 20 kW while WR430 is recommended for higher power levels.

Standard flange types have been defined for each waveguide size, although alternate flange designs have become popular for certain applications. For most applications the standard flat face, or “contact,” flanges provide the most cost effective performance, as opposed to “choke” type flanges which are more common in military and communication applications. Some manufacturers offer components with flanges designed for quick-disconnect clamps which are popular where components are repeatedly assembled and disassembled.

Almost all waveguide components available commercially are constructed primarily of aluminum for its good performance and low cost. Copper is often used in cases where heat loss and dissipation are of concern, although its cost often outweighs this slight advantage. Stainless steel is used in pharmaceutical and food processing systems where sanitation requirements outweigh the disadvantages of higher power losses and costs.

Isolators and Circulators

Isolators are two-port devices that allow microwave power to pass through in the forward but not reverse direction. Perhaps the most common use of such a device is to protect the microwave generator, specifically its magnetron, from the damaging effects of reverse power. Another device often used for isolation purposes is a waveguide circulator, a three-port device ideally having no power attenuation capability. Because circulators are not designed to absorb power, a separate “dummy” waveguide load is connected to the circulator and used to absorb the reverse power. Using a circulator and dummy load in place of an isolator often allows greater flexibility by utilizing the component types that are best suited for a particular application. Circulators are also quite useful for other non-isolation purposes, an example of which is described in the next section.

Ideally, all of the forward power entering the input port will exit the output port and all reverse power entering the output port will all be absorbed by the isolator. In practice, however, a small amount of forward power is absorbed by the isolator and/or reflected back to the source, and a small amount of reverse power inevitably passes through. Thus, the following parameters are commonly used to measure the performance of an isolator:

Isolation – A measure of the <u>minimum</u> attenuation of reverse power as it passes through the device

Insertion Loss – A measure of the <u>maximum</u> attenuation of forward power as it passes through the device

Input VSWR – A measure of <u>maximum</u> VSWR at the input port due to forward power only (assumes no reverse power)

Note that these parameters are often measured and specified by the manufacturer at low power operation. Because of the thermal effects due to power absorption, the actual performance can vary from the manufacturer's specifications when the device is operated at high power or in the presence of high VSWR.

Terminations

A wide variety of waveguide terminations are available for various applications. Most commonly found in industrial microwave heating systems are those at the opposite ends of the power absorption range, dummy loads (maximum absorption) and short circuits (minimum absorption).

Dummy loads can be grouped into two main categories, wet loads and dry loads. By definition, wet loads are designed to absorb microwave power directly into a high loss fluid medium, usually water. Not surprisingly, dry loads absorb power directly into a high loss solid, usually silicon carbide. Each of these load types have very distinct advantages and disadvantages.

Perhaps the most significant advantage of wet loads is their small size and high power rating as compared to dry loads. Dry loads require a relatively large surface area to dissipate the absorbed heat energy and are limited in power rating due to the poor thermal conductivity of the absorption medium. As expected, wet loads also have a significant cost advantage over dry loads.

However, wet loads exhibit less consistent performance than dry loads and are more susceptible to damage from misuse. The variation in return loss performance of a wet load as shown in Figure 4 is primarily due to the varying dielectric properties of water. For similar reasons, the performance of wet loads changes as input power varies. Dry loads are far less affected by changes in power level or operating temperature. In the event of insufficient cooling, dry loads can sustain a much greater temperature rise without damage or significant loss of performance, whereas wet loads are more easily damaged if insufficient water flow causes boiling. Wet loads are quite adequate and often preferred in isolator configurations, while dry loads are preferred for applications where standing waves must be minimized such as with traveling wave applicators.

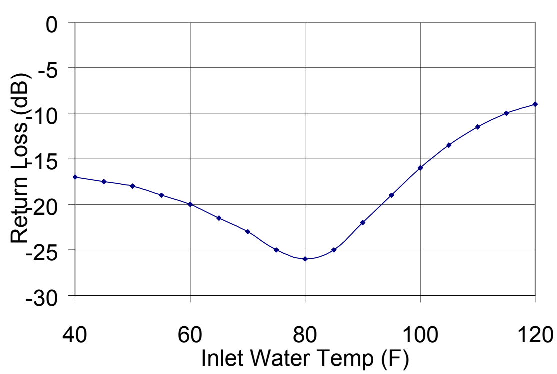

Figure 4. Return loss performance of a typical 3 kW wet dummy load.

Waveguide short circuits establish a standing wave within the waveguide configuration, typically for locating high electric fields at the load to be heated. Fixed position short circuits can be found with waveguide applicators designed for a specific process or material where the position of the short has been optimized for maximum power coupling. Applicators are often used for a variety of processes or materials, thus a movable short circuit is preferred so that the short position can be optimized for each case.

Power Couplers

Waveguide power couplers are used to obtain an accurate measure of the level of microwave power propagating in waveguide. These are multi-port devices which divide the power at the input port into desired fractions at the output ports such that the sum of all output power levels equals the input power [4].

The smaller of the output signals is then converted, typically to a d.c. voltage, for use by a meter or some other calibrated signal measuring device. Couplers generally fall into one of three categories: directional, non-directional and analytical.

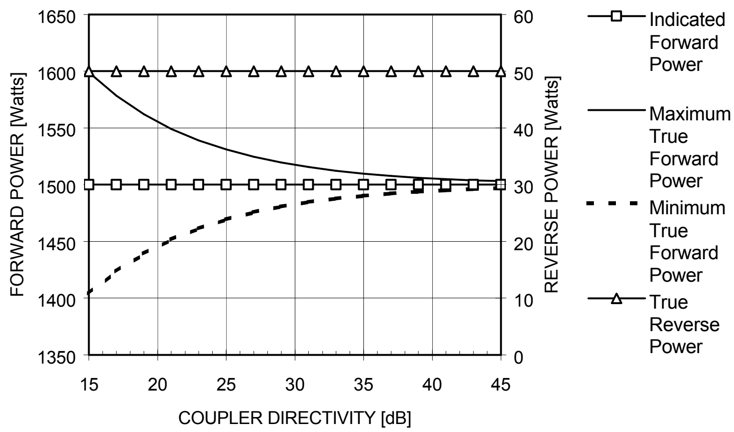

Figure 5. Error limits of true forward power for given indicated forward power and true reverse power.

Directional couplers, by definition, are designed to sample the power propagating in one direction only. The most important parameters relating to their performance are *coupling factor*, the attenuation between waveguide power and the output signal, and *directivity*, the attenuation between output signals derived from sampling the same waveguide power in opposite directions. Since all couplers lack perfect (infinite) directivity, power measurement errors result when power is propagating in both directions. An example of the potential measurement error is shown in Figure 5 for a case in which forward and reverse power are 1500 Watts and 50 Watts, respectively. While various coupler types are available, the two most commonly used for power measurement are loop and broadwall. Loop couplers are more compact than broadwall types, while broadwall couplers generally have higher directivity at the design frequency.

Non-directional couplers usually are simple voltage probes in the waveguide and are unable to distinguish between forward and reverse power. They are commonly found in dummy loads and isolators where only incident power is present. Their simplicity of design makes them quite economical for measuring reverse power at a circulator or isolator.

Analyzer couplers are used to detect the phase and amplitude of a standing wave in waveguide to derive both forward and reflected power. These couplers have multiple voltage probes which provide signals useful for calculating S-parameter coefficients. They are commonly used with automatic waveguide tuners for impedance matching or with accompanying software for high power network analysis.

Impedance Tuners

Coupling microwave power to a load requires the respective complex impedances between the load and the microwave power source to be matched. A common means to achieve a match capacitively is to insert a metallic element into the waveguide. However, since an impedance mismatch has phase and amplitude components, both position and depth of insertion of the matching element must be adjusted. Multi-stub tuners accomplish both position and insertion adjustments by inserting one or more metallic rods, or stubs, into the waveguide.

The design of the tuning stubs is critical for high power operation. A simple, economical design employs threaded stubs screwed directly through the broadwall of the waveguide along its centerline. In such designs the electrical currents flowing on the inside surface of the waveguide can cause burning and arcing at the screw threads, eventually overheating and/or seizing after repeated adjustments at high power. For more reliable high power operation a common design provides a ¼-wave choke around the stubs to effectively eliminate the electrical current at the interface between the stub and waveguide wall.

Manually adjusted tuners are by far the most common for industrial heating applications. However, without benefit of a polar display to monitor tuning progress, operating a manual tuner is mostly a practiced art that can only be learned by experience. Automatic tuners have gained popularity in applications where manual tuning is inconvenient or too slow to keep up with the dynamics of the heating process. Although quite costly by comparison, most available designs operate on a stand-alone basis and can achieve a superior impedance match within milliseconds.

Tuners should always be located as close to the load being matched as possible, especially when the load has a high Q. All components between the tuner and load become part of the resonant circuit when the impedance is matched. Having unnecessary components in the resonant circuit results in excessive power losses in cases where high power is coupled to a high Q load. Inserting an impedance discontinuity, such as a waveguide bend or vacuum window, between the tuner and the load can in some cases result in a falsely indicated match as the tuner is adjusted to the wrong impedance.

UNIQUE SYSTEM CONFIGURATIONS

Configuring a microwave power delivery system depends as much on the process as on the performance of available waveguide components. The following situations cover nearly the entire range of complexities that can be found.

Configuration 1 – No Power Delivery Components

Many microwave ovens and some industrial bulk processing systems are designed with magnetrons mounted directly to the oven cavity. Careless design can result in high VSWR at the magnetron, causing excessive back-heating and unstable operation. This configuration should be used only for processes with high loss, static loads that are well behaved and predictable.

Configuration 2 – Impedance Matching Only

In this configuration the magnetron is mounted to a short section of waveguide (often called a launch section) which in turn is mounted to the applicator cavity. The cavity interface is designed usually with a fixed impedance matching geometry for optimal power coupling into the cavity. This design is more robust and less susceptible to unstable magnetron operation, but it should still be limited to processes with high loss, static loads.

Configuration 3 – No Isolator

The isolator can be eliminated as a means to reduce equipment costs in cases where the load is predictable and remains well matched during the heating process. A tuner and power coupler might still be needed to adjust for impedance differences between load materials and for process monitoring. Figure 6 illustrates a system in which a variety of different fluids can be heated, each requiring slight impedance adjustments for optimal matching. To avoid magnetron damage, caution should be exercised to ensure the impedance match is attained prior to application of high power.

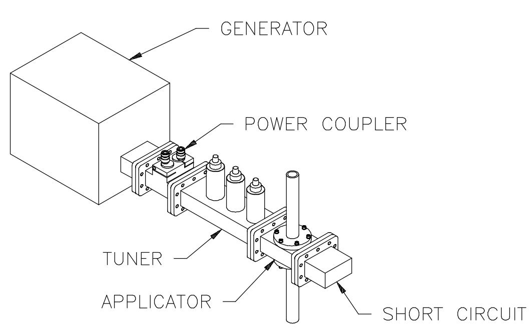

Figure 6. Basic heating system without isolator.

Configuration 4 – Directional Coupler Before Isolator

In applications where the control of forward power is critical, the measurement accuracy of forward power using directional couplers can be improved by locating the coupler ahead of the isolator as shown in Figure 7. Thus, the coupler is isolated from reverse power and the resulting errors due to its imperfect directivity. The consequence is that an additional power coupler is required at the isolator to monitor reverse power for tuning purposes. Also, the insertion loss of the isolator must remain constant, otherwise the resulting error between measured and net delivered power could offset improvements gained in power measurement accuracy.

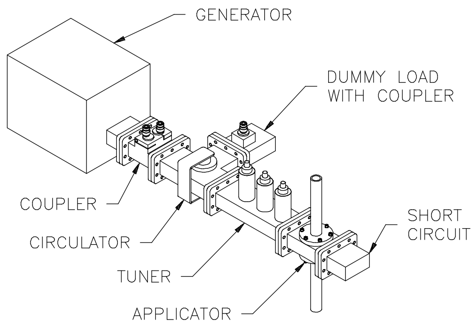

Figure 7. Basic heating system with coupler before isolator.

Configuration 5 – Constant Frequency Operation

As explained earlier, magnetron output frequency shifting at varying power levels can result in unstable operation when heating a high Q load. The configuration in Figure 8 overcomes this problem by providing a means to vary delivered power without varying magnetron output power. The microwave generator is operated at a fixed power level while all of its output power is initially delivered to the dummy load and reflecting stub connected to circulator 2. Adjusting the reflecting stub varies the amount of power reflected back to circulator 2 which then delivers the power to the applicator load. Once the load impedance is matched using the tuner, power coupling remains stable while delivered power is varied. However, power coupling can still become unstable if the load impedance varies significantly with temperature.

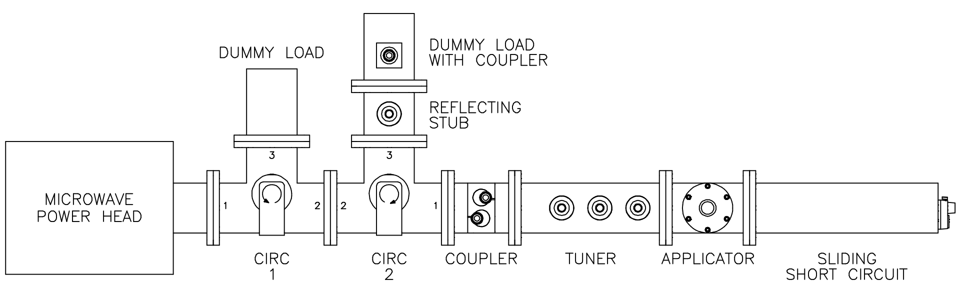

Figure 8. Waveguide configuration for delivering variable power at constant frequency.

Configuration 6 – Reciprocating Standing Wave

A common means to achieve heating uniformity in multi-mode applicators is to “stir” the electric field by rotating a multitude of metallic reflecting surfaces (called “mode stirrers”) inside the applicator. In single-mode applicators, however, such a technique is seldom feasible as it would dynamically alter the internal geometry that is necessary to achieve the desired mode pattern. The configuration illustrated in Figure 9 achieves enhanced heating uniformity in a single-mode applicator by reciprocating a standing wave inside the applicator [5].

The system operates by first splitting the generated microwave power into two equal and coherent wave fronts. Isolators are necessary at both output ports of the power splitter to prevent reverse power from disturbing the forward power symmetry. Both forward power wave fronts are then diverted through rotating phase shifters and then reflect back through the phase shifters before being routed to opposite ends of the applicator. The two coherent wave fronts converge inside the applicator to generate a pattern of standing waves having nearly infinite VSWR.

The phase shifters operate by rotating a thin dielectric slab inside the waveguide with its rotational axis in the plane of the electric field. When the slab, having low dielectric loss and high dielectric constant characteristics, rotates between positions perpendicular to and parallel with the waveguide centerline the phase shift alternates sinusoidally from near zero to maximum. Adjusting the slab geometry varies the phase shift amplitude. Rotating both phase shifters synchronously and exactly 90 degrees out of phase with each other will then cause a sinusoidal reciprocation of the standing wave pattern inside the applicator at constant amplitude.

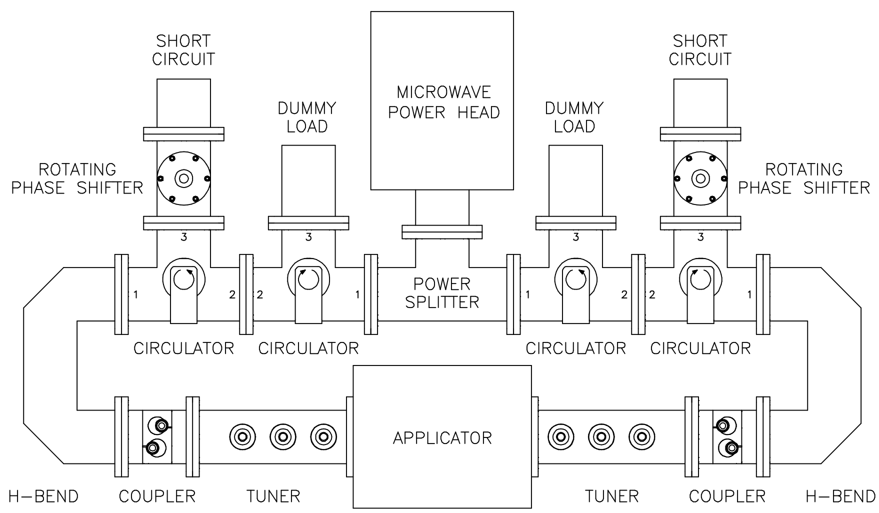

Figure 9. Waveguide configuration for reciprocating a standing wave in the applicator.

CONCLUSION

The intent of this paper was to provide the reader with a greater understanding of waveguide components and an appreciation for the many considerations to be made when configuring a microwave power delivery system. However, the scope of coverage was necessarily limited to a summary of the most basic components, leaving a number of other components, certain technical details and various design adaptations unmentioned. The possibilities for unique system configurations are limitless, but those leading to stable operation and optimal performance are far fewer.

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