Methods of Producing High Levels of RF Power for Test Purposes

From 1988 NAB Engineering Conference Proceedings

by Peter S. Hayes and Robert A. Surette

Introduction

At some time early in the life of every passive RF component, the designer must seclude himself away in a dimly lit room and consult the spirits of electromagnetic phenomena, seeking guidance in assigning a power rating to his new creation. Sometimes, the guidance received is good and the new product begins a life of trouble-free operation. At other times, the guidance is not so good, and troubles with failure plague the new component until its true limitations are discovered.

Because of the many "unpredictables" involved with a component that is to be used in uncontrolled environments, establishing a safe power handling capability for the component requires some degree of mysticism as well as a healthy dose of science. The scientific portion of the procedure involves determining a realistic breakdown point under known conditions such as temperature, pressure and humidity. The mystical portion comes into play when the breakdown under known conditions must be adjusted in order to account for the unknown conditions under which a customer will actually use the product. This paper is a short discussion of three techniques used at Shively Labs to perform the scientific portion of the procedure - determining where breakdown occurs under known conditions.

A Division of Howell Laboratories, Inc., P. O. Box 389, Bridgton, Maine 04009 USA www.shively.com
(207) 647-3327 1-888-SHIVELY Fax: (207)647-8273 sales@shively.com
An Employee-Owned Company *Certified to ISO-9001:2000*

Failure Modes and Breakdown Levels

When we test a new component, two of the first questions that come to mind are, "How is it going to fail?" and, "How much power should it take?"

RF components can fail in two ways: high current failure or high voltage failure. High current failure occurs when the heat produced by I^2R losses in the component exceeds the heat that can be removed from the component while the component remains at a reasonable temperature. As power is dissipated in the component, its temperature rises, and the component rejects heat to its environment. If the dissipated power is too great, the component's temperature may rise high enough to cause detuning or even meltdown of the component. On the other hand, high voltage breakdown occurs when the voltage gradient or electric field (measured in volts per meter) between two points exceeds the breakdown strength of the insulating material separating the two points. The material ionizes, and an arc occurs.

Both of the above breakdown modes are very difficult to evaluate without experimentation. The ability of some arbitrary shape to reject heat to its surroundings is almost impossible to accurately predict. Add to this uncertainties in actual conductance, the effects of oxides on conductor surfaces and other unknowns, and it is easily seen that the high current breakdown point of a component is not an easily determined parameter. Similarly, the high-voltage breakdown point is no easier to predict. Although the voltage between two points may be calculated, the voltage gradient depends not only on the voltage, but also on the spacing and shape. So, in both cases, experimentation is the only sure way of answering "How is it going to fail?"

The second question, "How much power should it take?" is sometimes a bit easier to answer. If we are designing a component intended to be used with a particular size transmission line, for example, it should be capable of handling at least as much power as the transmission line. However, in some cases (depending on the component's use) the component's capabilities must be several times those of the transmission line.

Once we determine what power capability the component should have, we need to determine the power level up to which we want to test the component. This is the mystical part mentioned earlier. In the laboratory, we can create some conditions rain, high temperature, etc., but we can't create all the possible conditions under which the component might be operated. Therefore, we need to include a safety factor that will account for the degradation occurring in the field. Since we cannot predict everything that might happen, we try to select a safety factor large enough to ensure safe operation under any foreseeable conditions and hope that we've created a component that also works even under some unthinkable ones.

This brings us to the meat of this paper - once we've determined that some component should be tested to 100 kW, for example, how do we create this rather considerable amount of power?

What's in a Watt

I think that it's safe to assume that we all know the most basic definition of power:

(1a) $P \text{ (in watts)} = V \text{ (in volts)} \times I \text{ (in amps)}.$

Using Ohm's law, we can substitute for V and I above to get some of the other forms of expressions for power:

(1b) $P = VI = (IR) \times I = I^2R$

or

(1c) $P = VI = V(V/R) = V^2/R$

(The same expressions hold true if we use complex power and impedance, Z.)

Now, recall that the two breakdown modes are not strictly dependent on power; they occur either due to a high voltage or due to a high current. Furthermore, most of the components we design are built for use in 50-ohm transmission line systems; using the above expressions for power, we can write:

(2a) $P = VI = 1^2(50) = V^2/50$

where R = 50 has been used in order to specialize the expressions to 50-ohm transmission systems. Therefore, when we speak of testing a component to 100 kW, we are implying that the 100 kW is being applied to a 50-ohm system. This means that

(2b) $100 \times 10^3 \text{ watts} = I^2(50)$

or $I = \sqrt{100 \times 10^3/50} = 44.72$ amps,

and

(2c) 100 x 103 watts = V2/50

or $V = \sqrt{(50)(100 \times 10^{3)}} = 2{,}236.1$ volts.

In short, the above expressions state that 100,000 watts will produce 44.72 amps and 2,236.1 volts on 50 ohms. The realization of this fact reveals a means of testing high power components without the high power; simply impress on the test component the same current or voltage as is produced by the desired power level on 50 ohms.

As an example, suppose we have a coupler in 4-1/16" coax transmission line that we'd like to test to 100 kW. The coupler consists of a very small loop inserted through the outer conductor of the line. First, we can determine which breakdown mode is more likely. Because the coupler carries only an insignificant amount of current, there is essentially no chance of high-current breakdown, but, because of its sharp edges and position between the inner and outer coaxial conductors, there is some chance of high-voltage breakdown. In order to completely test the coupler for high-voltage breakdown at 100 kW, we need simply to apply 2,236.1 volts between the inner and outer conductors. The amperage and, hence, the power that we apply is unimportant as long as the voltage is 2,236.1 volts from inner to outer (and, to keep things exact, the frequency is in the range of the coupler's intended use). In a sense, we are causing a small amount of power to look like a large amount of power.

The Standing Wave Resonator

(making a mountain out of a molehill)

I can just hear some people cynically saying, "So what? So now we only need some source of 2,000-plus volts!" Let's take a look at equation 2c for a minute. This equation states that the square root of power, P, (100 x 103 in equation 2c) times line impedance, Z, (50 ohms in equation 2c) gives the voltage across the line's conductor. Generalizing this using P, Z and V leads to

(3a) $V = \sqrt{ZP}$.

If we can come up with any combination of Z and P that will yield 2,236.1 volts at the coupler, we can perform our test.

Now, let's switch tracks for a moment. Look at the Smith chart shown in Figure 1. Using the Smith chart as an impedance plot, the left edge of the chart indicates an ideal short circuit, zero ohms; the right edge of the chart is an ideal open circuit, infinite ohms. If we put a real short circuit on the end of a piece of coax line and measure the impedance, we will find a small real impedance, which can be plotted on the Smith chart as a (3a) point on the horizontal axis just inside the circle; the distance inside the circle's edge is proportional to the resistance of the short circuit (an ideal short would have zero ohms and would be on the edge of the circle).

Let's move along the coax line away from the short circuit; the impedance will travel along the Smith chart at a constant radius in a clockwise direction. At a quarter of a wavelength, $\lambda/4$, from the short circuit, the resulting impedance will be found on the right hand side of the Smith chart. The real short circuit will still be slightly inside of the circle, and the ideal short circuit will still be on the circle's edge. As just mentioned a bit ago, the right side of the Smith Chart is a near open circuit in the real case; the ideal short circuit would result in an ideal open circuit. This shows us that, by starting with a real-world short circuit, we can rotate through a quarter wavelength of line and produce an open circuit.

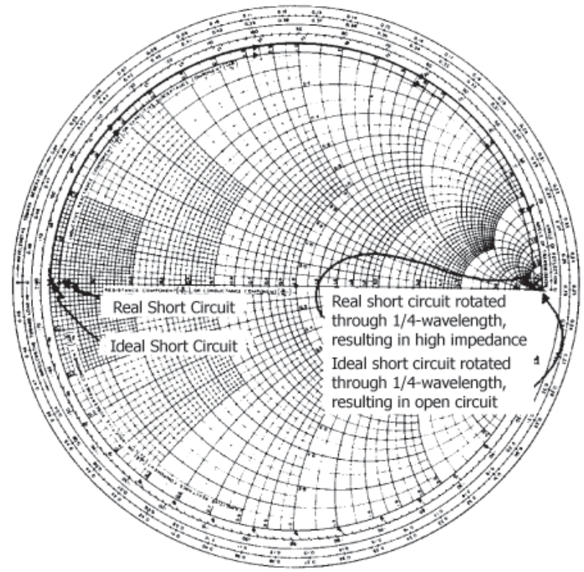


Figure 1. Smith Chart

How does this help us test our coupler? Let's place our coupler in this coax line a quarter wave from the short circuit. The coaxial impedance at the coupler location will not be a true open circuit because of losses in the short circuit and the coax line, however, it will be very high; for simplicity, let's assume that the impedance at the coupler is 1500 ohms. We now have 1500 ohms, and we know that we need 2,236.1 volts. Equation 3a gives us a way of relating the voltage we want, the impedance we have, and the power we need to produce the required voltage:

$$V = \sqrt{ZP}$$

or $P = V^2/Z$

so that, using 1500 ohms and 2,236.1 volts,

$$P = (2,236.1)2/1500 = 3.33 \text{ kW}$$

In other words, we can produce 100 kilowatts' worth of voltage effects on our coupler while using only slightly over 3 kilowatts of true power!

The next question some people I'm sure are asking is, "How do you get a transmitter to put 3 kW into a load like the one presented by the short circuited transmission line?" Elementary, my dear Watson! True, the impedance of the transmission line is far from 50 ohms, but nothing stops us from using a variable transformer to match our test circuit to a transmitter's 50 ohm (or any other impedance) output. Figure 2 shows a picture and schematic of the test arrangement.

The transmitter input consists of a rotatable loop inserted through the coax outer conductor near the short circuit. Because the short circuit creates a very low impedance at this point, high currents and high magnetic fields will exist here, allowing a very strong coupling between the input loop and

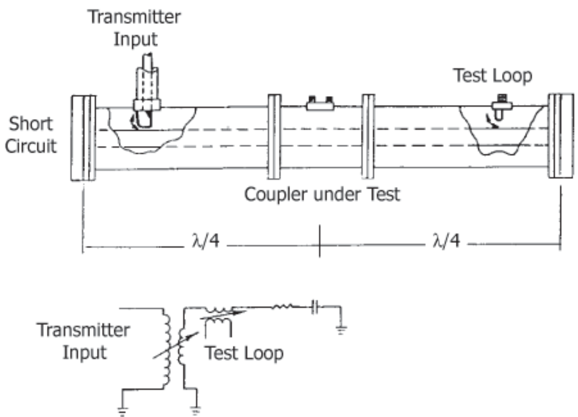


Figure 2. Coaxial Standing Wave Resonator

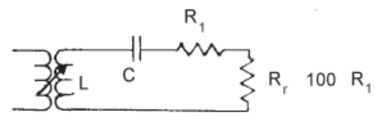
the fields in the coax. At the resonant frequency - that frequency at which the test circuit is a 1/2 wavelength long - the rotatable input loop acts as an impedance transformer, matching the small loss resistance of the short circuit and coax line (shown as R in the equivalent circuit) to the 50-ohm transmitter output. The test loop, located at the second short circuit, allows monitoring of the equivalent power level. It indicates the magnitude of the power that would produce the existing magnetic fields if the line were actually 50 ohms. In our example, if we were putting in the 3.33 kW, our test loop would indicate a power of 100 kW, because the currents at the short circuited ends of our test circuit (and the voltage at the coupler in the middle of our test circuit) are equivalent to those produced on a matched 50-ohm line by 100 kW. We therefore have a means of producing either a voltage or current equivalent to 100 kW while requiring only 3 kW of true power. The secret to this technique is that we produce the voltage or the current equivalent of 100 kW, but not both at the same time and place.

This is only the first of three resonant test circuits commonly used for high power testing. The two other circuits are described in the following sections.

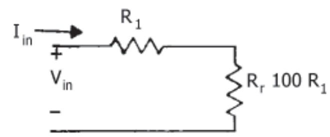
Antenna Testing

The standing wave resonator described above works well for almost any component that can be incorporated into a piece of transmission line. Antennas, however, cannot be tested using this arrangement. So, how do we test an antenna? Let's take a look at how an antenna works and see.

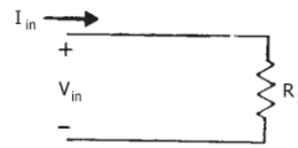
An antenna, to a very close degree, can be modeled as a series resonant circuit consisting of an inductor, a capacitor and two resistors; this circuit is shown in Figure 3A. The illustration shows two resistors (rather than just a single resistor equal to the sum of the two) in order to emphasize the two very different sources of resistance.



A. Circuit model of loop-coupled antenna



B. Circuit at resonance where ωL = 1/ωC



C. Circuit in metal room at resonance

Figure 3. Circuit Model of Antenna.

R_1 is a relatively small resistance caused by the actual conductor losses in the material of which the antenna is made. When power is put into an antenna, R_1 is responsible for the slight heating of the antenna. Therefore, any power dissipated in R_1 is not radiated into space, i.e., is lost power.

Rr is a much larger resistance (usually more than 100 times the resistance of R_1) and is called the radiation resistance of the antenna. The source of this resistance is the power radiated into space by the antenna, i.e., R_r is an imaginary resistance that represents the portion of input power that is transferred into electromagnetic waves in the air surrounding the antenna.

In Figure 3A, the transformer is shown to indicate that most of the antennas we build are loop coupled or externally fed. For the time being, we'll ignore the transformer and look at the series RLC circuit on the right side (i.e., from the transformer secondary to the right). At resonance, the impedances of the inductor and capacitor are equal in magnitude and opposite in polarity so that they cancel. We can therefore ignore L and C for the time being and look at the simple resistive circuit of Figure 3B.

This circuit is now a simple resistive divider. For the sake of simplicity, let's assume that $R_1 + R_r = 50$ ohms. This means that R_1 is approximately 0.5 ohm and Rr is approximately 49.5 ohms. It also means that we can feed the antenna directly with 50-ohm transmission line. Let's put 10 kW into the antenna at its resonant frequency and see where the power goes. Using our previous equations relating power, voltage, current, and impedance (resistance in this case), we can find V_{in}, and I_{in} as shown in Figure 3B to be:

$$V_{in} = \sqrt{(50)(10{,}000)} = 707.1 \text{ volts}$$

and

$$I_{in} = \sqrt{(50)(10{,}000)} = 707.1 \text{ volts}.$$

Let's look at the power dissipated in each of the two resistors:

$$P_{R1} = 1^2R_1 = (14.1)^2 \times (0.5) = 99.4 \text{ watts}$$

and

$$P_{Rr} = I^2R_r = (14.1)^2 \times (49.5) = 9.8411 \text{ kW},$$

where each was rounded to the nearest tenth of a watt. This shows that a vast majority of the input power (over 98%) is radiated by the radiation resistance into space, as it should be.

Now, let's take this antenna, still feeding it its diet of 10 kW, and put it inside a large, sealed, metal room. If our room were made well enough, none of the radiated power could escape from the room to the outside. But, we're still pumping 10 kW out of our transmitter into the antenna, which is inside the room. Where does the power go?

When the power radiated by the antenna encounters the metal walls of the room, it is reflected from the walls back to the antenna. A very small amount of the radiated power is turned into heat in the walls, but nearly all of the radiated power is returned to the antenna. Since there is almost no radiation, there is little or no radiation resistance in our antenna's equivalent circuit, so that, at resonance, the equivalent circuit of the antenna in the metal room is that shown in Figure 3C.

Now, we have 10 kW being dissipated by only the very small loss resistance of the antenna, R_1. Let's take a look at the currents needed to do this.

$$10{,}000 \text{ Watts} = I^2R_1 = I^2(0.5 \text{ ohm})$$

therefore

$$I = \sqrt{(10{,}000)/(0.5)} = 141.4 \text{ amps},$$

i.e., we've increased the current by 10 times. Remember that, even though we've ignored the impedance effects of L and C, they are still in the circuit, and we have increased the currents through and voltages across them also. These components represent the resonant elements of the actual antenna; hence, we have created voltages and currents on the antenna equivalent to much higher power levels than we could possibly achieve in real life. If the antenna were to have 141.4 amps flowing into it in free space, where the radiation resistance is not suppressed, the power input would be

$$P = I^2 (R_1 + R_r) = I^2(50) = (141.4)^2(50)$$
$$= 999.7 \text{ kW !}$$

Again, as in the coax resonant circuit, we need some way of matching the low impedance antenna in the metal room to the 50-ohm transmitter output. This is accomplished with the coupling loop, represented by the transformer of Figure 3A. The loop allows the antenna to be reasonably well matched both in free space and in the metal test room.

A little thought might lead to a question of measuring the currents and voltages existing on the antenna in the test room. Unlike the coax resonant circuit, we cannot actually make measurements under power. However, there is an accurate means of determining the relative equivalent power levels between free space and the test room.

Figure 4 is a sketch of a ring-style antenna used for FM broadcasting. The two vertical (one up, one down) arms of the antenna are high-voltage points while the back side of the horizontal rings (where thev meet with the rectangular "block") are high-current points. Small probes (loops for current probes, electrically small monopoles for voltage probes) are inserted in these areas, as shown in the blow-up sketches. Cables from these probes are run through the tubing of the antenna (to provide shielding) and out of the back of the antenna through a shielded conduit. These probes allow current and voltage measurements to be made as described below.

A network analyzer (typically a HP 8505 or HP 8753A) is calibrated in reflection and transmission and connected to measure the return loss of the antenna on its feed line using one channel of the analyzer (as shown in Figure 5). The second analyzer channel is used to measure the transmission between the antenna and each of the small probes; these measurements are performed in free space and again in the test room. Although the measurements are not valid in an absolute sense (i.e., in reading the electric and magnetic fields in volts and amps per meter), because the probes are uncalibrated, they allow an accurate determination to be made of the relationship between the fields in the test room and the fields in free space. In other words, we can measure the difference in current and voltage between the antenna operating in the test room, where there is essentially no radiation resistance, and free space, where the radiation resistance is present. This allows us to determine an equivalence in power, such as we did in the example above. In that example, you'll remember, 10 kW into the antenna in the test room produced the same currents and voltages as nearly I MW would produce on the antenna in free space!

Armed with this knowledge, we place the antenna in the test room, which is actually constructed of wire mesh, and connect it to the transmitter. All probes are either removed or capped (to prevent their incineration!) and the power is turned on. Monitoring the transmitter output power tells us how much

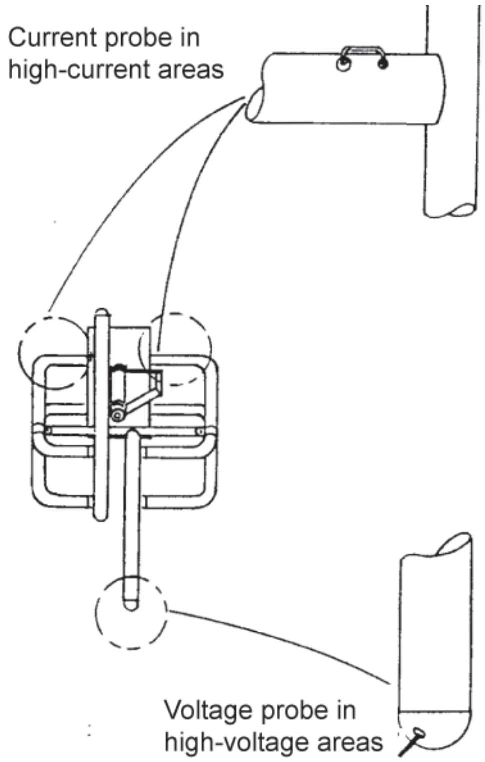


Figure 4. Antenna Test Probe Types and Locations

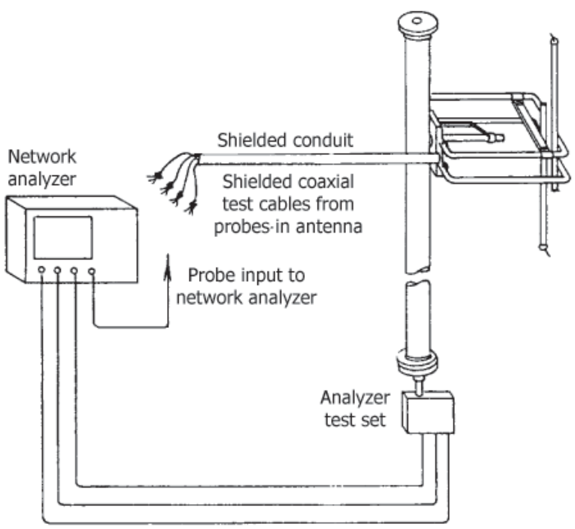


Figure 5. Antenna Test Configuration

power is actually being dissipated in the loss resistance while the knowledge of our free space to test room readings tells us what equivalent power would produce the same currents and voltages in free space that are produced by our transmitter power in the test room. Using this technique, we have produced equivalent power levels of over 1.5 MW.

While power is being applied to the antenna, water can be sprayed through the screen of the test room in order to simulate rain collecting on the antenna. The power level at which the wet antenna arcs is considered the breakdown power level. This level is then derated by a safety factor to compensate for the effects of weathering, corrosion, exposure and other degradations that will occur when the antenna is used in the "real world."

The two techniques described so far for creating currents and voltages equivalent to high power levels are both standing wave resonator devices. Essentially, the impedance at various points is manipulated in order to produce high voltages or high currents, but not both at the same place at the same time (and, therefore, not high power). The third and last technique, the resonant ring, differs from the previous two in that an actual high power level is produced, rather than just an equivalent voltage or current.

The Resonant Ring

Figure 6 shows a schematic of a simple resonant ring. It consists of an input coupler, a monitoring coupler, two sliding short circuits, the device under test (D. U. T.), and enough transmission line to connect these components together in a closed loop that is an integral number of wavelengths long at the frequency of operation.

Power is provided from the transmitter to the input coupler. Some of this input power is coupled into the ring and creates a wave traveling in a counter clockwise direction around the ring. If the ring is an integral number of wavelengths long at the frequency being used, the wave in the ring arrives back at the input coupler in phase with the transmitter input to the coupler and attenuated by the ring losses. Because the two waves (the one in the ring and the other, from the transmitter, in the coupler) are in phase, the voltages will add and will strengthen the wave in the ring. This buildup of ring power and energy continues until, in a perfectly adjusted ring, nearly all of the transmitter's power is coupled into the ring and is dissipated in the ring losses. This is somewhat analogous to one child pushing another on a playground swing. Initially, the child pushing cannot transfer enough energy to the swing to raise the riding child very far off the ground. Each time the standing child pushes the swing, more energy is added, and the swing rises higher; each time the swing falls, some energy is lost to friction due to air resistance. At some point, the energy lost due to friction is equal to the energy that the child can provide with each push, and the swing rises to the same height each time - or goes over the top of the bar! In the same way, the transmitter keeps adding energy to the ring until, at some point, the energy added by the transmitter equals the energy lost in the ring.

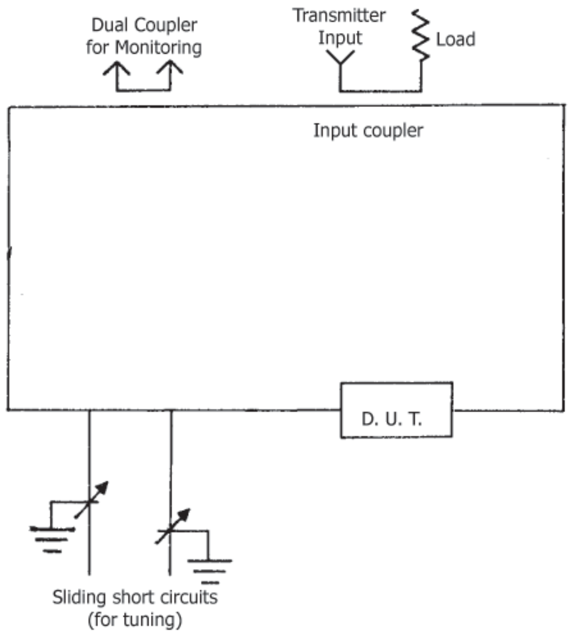


Figure 6. Resonant Ring

The exact expression for ring gain can be found in "Microwave Filters, Impedance Matching Networks, and Coupling Structures," authored by G. L. Matthaei, L. Young and E. M. T. Jones, and published by Artech House Books. This expression is

$$G = C^2/[1-10^{-(a/20)}(1-C^2)^{1/2}]^2$$

where G is the power gain in the ring, C is the voltage coupling ratio of the input coupler ($C = 10^{-g/20}$), where g is the coupling in dB) and a is the one trip attenuation in the ring. Knowing the ring gain is not absolutely necessary as long as the monitor coupler is included in the ring. Once calibrated for forward and reflected power readings, this coupler allows us to monitor the actual power in the ring during operation.

Using a 6-inch coaxial line resonant ring, we have produced actual ring power levels of nearly 200 kW, while using less than 10 kW of input power!

Conclusion

The preceding discussion has introduced three techni¬ques for creating or simulating power levels significantly higher than those obtainable from standard transmitters. The use of one or more of these techniques in testing a component to breakdown, combined with the use of a reasonable safety margin, provides a means of rating a component's power handling capabilities that ensures many years of failure free operation.