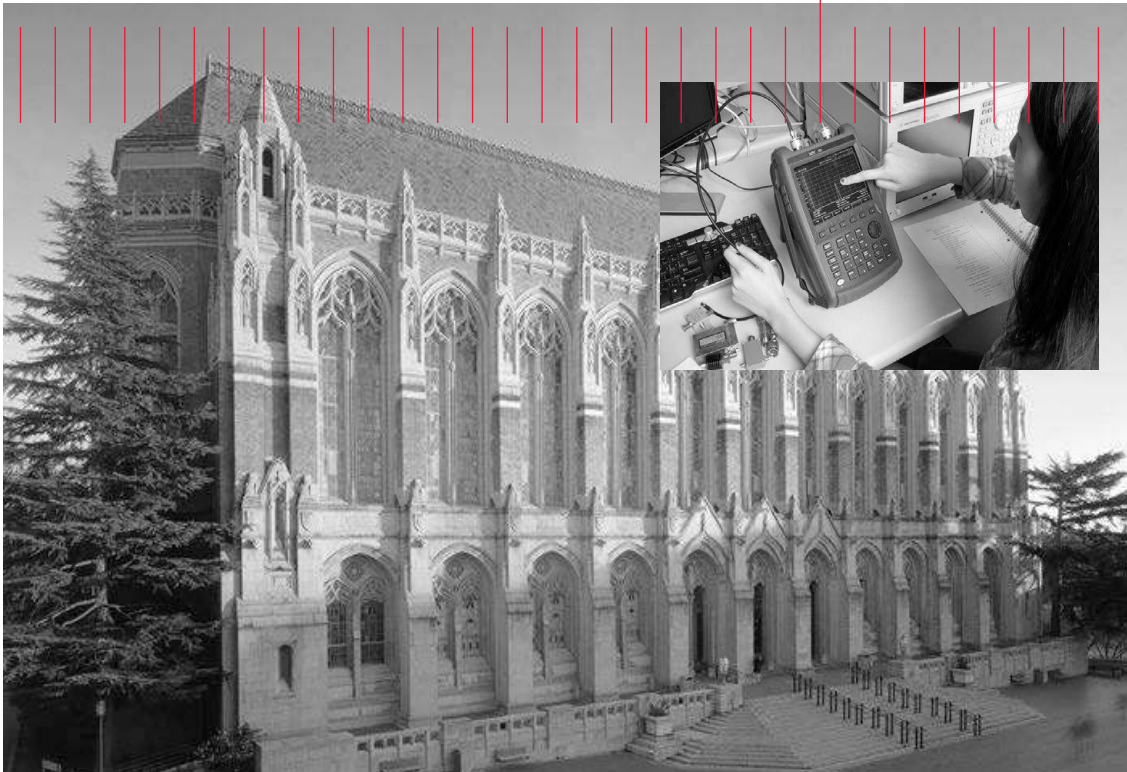


Keysight Technologies

Introduction to the FieldFox RF Analyzer

University Engineering Lab Series - Lab 1

Application Note





Introduction

The Keysight Technologies, Inc. FieldFox RF analyzers are a new generation of portable, handheld instruments which provide a variety of powerful functions all within the same unit. They combine a precision microwave/RF swept frequency source with a tuned phase-sensitive receiver which can be configured by embedded software to create the traditional microwave/RF instruments such as a spectrum analyzer (SA), a network analyzer (NA), or a cable-antenna test (CAT) system. Other functions which use the same microwave/RF platform can also be installed as software packages, such as an RF power meter (PM), and vector voltmeter (VVM). The FieldFox also features very high accuracy measurements with greatly simplified calibration and a wide variety of connectivity options that allow the instrument to be controlled and monitored remotely.

A quick overview

The Keysight N9914A is the 6.5 GHz version of the FieldFox, and its operating range is from 30 kHz to 6.5 GHz for the CAT and VNA modes, and 9 kHz to 6.5 GHz for the SA mode. Other models are available with frequency ranges up to 26.5 GHz. The embedded computer and controller runs a version of Windows CE, so its boot up and shut down bears some resemblance to these systems. When the FieldFox is first turned on, the Windows CE operating system is the first thing that initializes. The microwave/RF source and receiver are controlled by applications that run under this Windows CE operating system. The N9914A referenced in this lab includes three main software applications: a cable-antenna test (CAT), a network analyzer (NA), and a spectrum analyzer (SA). When FieldFox is first turned on, the CAT application is normally loaded and launched first, so this is the starting application that the user will first see upon a cold-start power up.

The front panel of the Keysight FieldFox is shown in figure 1. The power switch is the prominent bright white button located in the lower left of the front panel. Pressing this button once will turn on the instrument and start its boot up routine, ultimately ending up in the CAT application. When turned on in the run mode, the power LED below the power button will glow green. Turning the instrument off is a little more complicated. Pressing the power button once will not turn the instrument off, but instead move it into a standby mode in which the computer memory remains loaded with its current contents, but the RF systems, display, and user I/O are shut down to conserve power. The standby mode can be recognized by the blank display but the power LED will flash yellow. Pressing the power button again will move the instrument from standby to run mode, with the power LED glowing green. The power up from standby mode is considerably faster than that from a complete off state, since all of the operating system and applications are already loaded into memory. To turn the instrument completely off, from the run mode, the power button must be pressed and held down for about 5 seconds. The power LED below the power button will blink and then extinguish to indicate that FieldFox is completely off.

The FieldFox is a battery-powered device to make it portable. The run time depends upon how the unit is being used, but generally about three hours can be expected from a full charge. If the FieldFox is being used in a lab, it is generally a good idea to plug it into the DC charger just to insure that the batteries do not run out during a lab session. The battery pack is a four-cell Li-ion cartridge which slides into the FieldFox through a cover slot on the lower right hand side of the instrument. For normal use, there is no need to access the battery. The battery is charged using the 15 Volt DC external power supply which plugs into a standard 120 VAC receptacle. The external power supply plugs into the FieldFox through the third rubber-sealed port from the top on the left side of the instrument. This is located right underneath the nylon carrying strap. When the battery is being charged, the power LED below the power button will slowly pulse yellow. Complete recharging of a spent battery usually takes about two hours. When FieldFox is running, the display will show a battery icon at the top of the screen with a set of bars which indicate the battery's charge status. Be aware that the battery may need to be recharged with only half of the bars still showing.



Figure 1. Front view of the Keysight FieldFox N9914A

The FieldFox is a two-port instrument, which means that it has two primary connections to the device or system that it will make measurements on. These are denoted port 1 and port 2, and shown in figure 3. The two ports get used in different ways depending upon the application that is running. For the CAT, the cable is connected only to port 1. For the NA, both port 1 and port 2 are used together. For the SA, the signal to be analyzed is connected only to port 2.



Figure 2. The FieldFox connected to its DC power supply

The two ports on the FieldFox use Type-N RF connectors, the most commonly used connector on RF instrument front panels with frequencies of 18 GHz or less. These are rugged and precision RF coaxial connectors, but their physical size makes them somewhat awkward for use in the lab.

All of the laboratory experiments in this lab are designed to use the smaller and more easily handled SMA connectors.

Each of the laboratory kits for FieldFox contain coaxial adapters to convert the Type-N (female) connectors on the FieldFox to SMA (female) connectors. As much as these will be used, it is good practice to simply leave these adapters on the FieldFox ports, as shown in figure 3. Instances may arise in which BNC connectors are required to connect the FieldFox to an experiment or design project. The lab kits also include a pair of Type-N (female) to BNC (female) adapters which can be exchanged for the Type-N to SMA adapters when needed.

Beyond the power button, the second-most important button on the FieldFox front panel is the Mode button located in the upper left of the keypad area. The Mode button has a white rectangle on it to make it easier to find. The Mode button allows selection of which software measurement application is currently running. Pressing the Mode button assigns the installed applications to the FieldFox soft keys, the six buttons located just below the display. The current configuration of the FieldFox's Mode button will label the left three soft keys as CAT/ NA/SA. Pressing one of these soft keys will launch that application. If the application has not been loaded into memory yet, pressing one of these soft keys will load the application and then launch it. Once an application has been loaded into memory, launching it again from the Mode selection is quite fast.

Next in order of importance is the Measure button, also the number "1" key on the keypad. Pressing this button brings up a selection of pre-programmed measurement functions on the soft keys. In some cases the right most soft key provides a More/Back function for additional measurement functions. For example, for the CAT application, the Measure button will bring up the measurement functions of Distance-To-Fault (DTF) (dB), Return Loss & DTF, Return Loss (dB), VSWR, DTF (VSWR), Cable Loss (1-port), Insertion Loss (2-port), and DTF (Lin). One of the measurement options will always be selected, and that selection will appear in black background while the other choices remain in blue background. The default wake-up state for FieldFox is the CAT application with the Return Loss (dB) measurement function.



Figure 3. Top view of the FieldFox connection ports with the SMA adapters attached

A practice cable measurement

This exercise will give some practice in setting up the FieldFox for making a cable measurement and in the process provide some familiarization with the operation and menu structure of the instrument.

Return loss (RL) is one of the most fundamental of RF and microwave system measurements. Stated most simply, the instrument sends out a test signal and then measures how much of that test signal returns. The strength of the returned signal is expressed as a ratio relative to the strength of the original test signal which was sent out. This makes decibels the most natural unit for expressing return loss. If 1 mW of power were sent out as a test signal, and if 0.5 mW of that test signal was then returned, the return loss would be

Return Loss (RL) =

$$-10 \log \frac{P_{\text{return}}}{P_{\text{test}}} = -10 \log \frac{0.5 \text{ mW}}{1.0 \text{ mW}} = -10 \log \frac{1}{2} = 3.01 \text{ dB}$$

Because the strength of the returned signal depends upon the frequency of the test signal, return loss is usually measured as a function of frequency as the independent variable on the horizontal axis. The strength of the returned signal can also vary over an extremely wide range, which is why the vertical scale is usually made logarithmic. By using dB units on the vertical scale, one automatically gets a logarithmic scale. It is conventional to plot signal strength in dB going upwards on the vertical axis. This means that the reduction in signal strength caused by propagation losses is measured going downward on the same vertical scale from some reference point. The reference point is simply the strength of the test signal. If all of the test signal were returned, in other words, 100 percent perfect reflection, then the return loss would be 0.00 dB. Recall that 0 dB is equivalent to a ratio of unity: $P_{\text{return}} / P_{\text{test}} = 1$, or just $P_{\text{return}} = P_{\text{test}}$.

To perform a practice measurement of return loss, first, set up a FieldFox N9914A on a bench and connect its DC power supply to a 120 VAC wall receptacle, as shown in figure 2. Power up the instrument and wait for the operating system to boot, followed by loading and launching of the CAT application. After a few moments, the FieldFox should show a measurement display for the Return Loss (dB) measurement function, the instrument wake-up default. If they are not already present, attach a pair of Type-N to SMA coaxial adapters to the two ports of the FieldFox, as shown in figure 3.

Next, observe what the display is showing. The vertical axis is the return signal strength, measured in decibels (dB), which results from sending a signal out from the FieldFox port 1 and measuring what fraction of that signal bounces back into the same port 1. For a perfect open circuited port, this should be 100% return, or equivalently zero return loss. The yellow trace of the measurement should lie directly over top of the 0 dB reference level at the top of the displayed white grid. Notice that the loss in returned signal is measured downward from the reference level in dB. The horizontal axis is the test frequency, and the FieldFox wake-up default is for a full range sweep from 30 kHz to 6.5 GHz. These two frequency limits are shown at the bottom corners of the displayed grid.

Locate an 18-inch long section of RG58C/U coaxial cable which is terminated in two male SMA connectors from the lab kit. Connect one of the ends of the coaxial cable to port 1, as shown in figure 4 and observe what happens to the measurement trace. Notice that the FieldFox is continuously sweeping the frequency range, so any changes that are made to port 1 will be shown almost instantaneously. By connecting the short section of coaxial cable, the yellow measurement trace should be seen to slowly fall with increasing frequency.



Figure 4. Connection of the RG58C/U coaxial cable to the FieldFox

This arises physically from the dielectric material of the cable becoming increasingly lossy with higher frequencies, so that waves propagating through the cable become attenuated in strength as they travel. As the incident wave makes one round-trip transit through the cable, the cable loss reduces the amount of power that is reflected back into port 1. The ratio of the returned signal power relative to the power of the test signal is the return loss (RL) of the cable. Distances on a dB scale represent ratios. Thus, the distance that the returned signal power lies below the test signal power is the return loss. The further down on the vertical scale the returned signal lies, the greater the return loss. The next step is to zoom into a particular region of the measurement and extract a numerical value for this loss or attenuation.

The drop in the yellow measurement trace is fairly small as shown on the FieldFox screen. The first task is to expand the vertical scale to better view the result. Press the Scale/Amptd button on the left hand side of the keyboard. This will reassign the soft keys with functions to adjust the vertical axis reference level and scale factor. By default, the vertical scale is 10 dB/div, so press the second soft key, "Scale 10.0 dB/", then press the "2" key, and then the first soft key, "dB/". The vertical scale is now expanded to 2 dB/division. The vertical axis can also be autoscaled, although this gives division markings which are not usually convenient round numbers. It is usually better to manually set the vertical axis. This can be accomplished by entering values for the Scale, Ref Level, and Ref Pos, using the above entry method.

Alternatively, the Top and Bottom levels in dB can also be entered. Try out these different methods of adjusting the vertical axis to gain some proficiency. Setting the Top level to 0.0 dB and the Bottom level to 3.0 dB should produce a well centered display that now shows the detail of the return loss with good detail. Lastly, press Ref Pos, the "2" key, and "Enter." Notice how this drops the reference level at 0.0 dB down to the second division point on the display. The reference level represents the power or strength of the test signal. Press "Ref Pos", "0", and "Enter" to restore the reference level to the top of the display grid. Experiment with these functions to fully understand the difference in how these vertical axis functions work.

Next, the frequency sweep will be restricted to a much smaller range. To adjust the frequency sweep used in the horizontal axis, start by pressing the Freq/Dist button on the left hand side of the keyboard. The frequency range can be adjusted using two methods: start-stop and center-span. Start-stop should be obvious; center-span allows one to pick a center frequency and then the width of the frequency sweep that is centered about this value. Experiment with both methods to produce a frequency sweep that goes from 2.0 GHz to 4.0 GHz. This is equivalent to a center frequency of 3.0 GHz with a 2.0 GHz span.

To extract an accurate numerical value from the display without having to interpolate by eye, the Marker function can be used. Press the Marker button on the left hand side of the keyboard. This will reassign the soft keys to the marker functions, automatically turn on the yellow marker point, and show its position in a yellow font beneath the display. In the upper right hand corner of the display, in a smaller yellow font are shown the marker coordinates, both the value of the frequency at the marker point, and the value of the return loss in dB. For the 18-inch length of coaxial cable, the marker point coordinates should read: "M1: 3000.000 MHz 1.070 dB", or something fairly close. To move the marker point to a different frequency, simply rotate the dial on the FieldFox to drive the marker to the desired location. To move to a precise frequency, press the "Normal" soft key so that "Marker: 3.000000000 GHz" is shown in yellow below the display, and then enter the new frequency. Up to six markers can be added to the display by selecting them using successive presses of the first soft key "Marker 1 2 3 4 5 6". The currently selected marker will be underlined, its marker will be a solid color in the display, and its coordinates will be shown in the upper right corner of the display. Pressing the "OFF" soft key will remove that marker from the display.

Now an accurate number from the FieldFox has been obtained: At 3.0 GHz, the return loss of the 18-inch section of coaxial cable is about 1.0 dB.

Some further analysis

Now for some explanation of what has just been measured. For the return loss measurement, the FieldFox sends out a test signal through port 1 and sweeps it across the specified frequency range. It then measures the power that is reflected back into port 1 and displays the ratio of the returned power to the incident power at each point in frequency. The cable absorbs some of the signal power as it propagates, giving the cable an attenuation that grows with distance, i.e. the incident signal loses power as it propagates.

At the marker frequency of 3.00 GHz, the return loss on this 18-inch section of coaxial cable was found to be about 1.0 dB. This means that the power level returning to port 1 is $0.794 = 79.4\%$ of the power that was launched from port 1. For computation, $10^{-0.1} = 0.794$. The 20.6% of the power that did not return was "eaten" by the cable, presumably by the loss of its dielectric.

The attenuation of a cable is proportional to its length, so one way to characterize a cable is to specify its attenuation in dB/ft. For the present case, the launched signal propagated from port 1, down the length of the cable, then reflected by the open circuit at the end. The signal traveled back through the same cable to reach port 1 for an overall round trip distance of 36 inches or 3.0 feet. The measured attenuation of the cable at 3.0 GHz is therefore 0.333 dB/ft. If 100 feet of this same cable were used in an application to transmit a 3.0 GHz signal, one would predict that the cable transmission loss would be 33.3 dB. If 1.0 milliwatt were launched into one end, only 0.468 microwatts would emerge from the other end. That represents a power loss factor of more than 2000, and indicates some of the challenge involved in transmitting high frequency signals through long lengths of lossy cable.

It was presumed that the measured cable loss arose from the lossy nature of its dielectric insulator. What other sources of RF power loss could possibly be responsible for the measured return loss of the cable? One possibility is the ohmic loss of the conductors, of both the center conductor and the shield. At 3.0 GHz, the skin effect is appreciable and conduction is confined to the surface of the metals to an average depth known as the skin depth δ . For copper with a resistivity of $1.72 \mu\Omega\text{-cm}$, the skin depth at 3.0 GHz is $1.21 \mu\text{m}$. Since the center conductor has the smallest surface area, it would contribute the most to the ohmic loss. The effective conducting cross section of the center conductor is its outer periphery times the skin depth, or approximately $1.76 \times 10^{-5} \text{ cm}^2$. This gives a resistance of $0.10 \Omega/\text{cm}$ or $3.0 \Omega/\text{ft.}$ at 3.0 GHz. Would the ohmic loss of the cable have a frequency dependence? The skin depth varies as $f^{-1/2}$, so the ohmic loss would vary as $f^{1/2}$.

Another source of loss is through radiation. Notice that the far end of the test cable was simply left open circuited. If the open circuited end were radiating power, it would show up as a return loss on the FieldFox. This would be a loss associated with just the open end of the cable, not the cable's dielectric or conductors, and it would not be indicative of the cable's loss per unit length. Radiation loss would also have a frequency dependence which increases with frequency because shorter wavelengths are more easily coupled into smaller radiating structures.

The return loss of a cable can therefore be caused by: (1) dielectric loss, (2) ohmic loss, or (3) radiation. The first two contribute to the cable's loss per unit length, while the third is a single point loss occurring at the end. The task now is to sort out which of these are contributing to the measured return loss of the cable.

The FieldFox has some additional measurement and display features which can be used to make such investigations much easier. First return the FieldFox to measure the return loss (RL) of the 18-inch length of coaxial cable, over a frequency range of 2.0 to 4.0 GHz, and with a vertical scale of 1.00 dB/ division.

The next feature to learn on the FieldFox is the Trace functions. Press the Trace button on the keyboard to bring up this menu. The FieldFox can display two traces simultaneously, either on the same or a different set of axes. This is a very handy function for observing the effects of two simultaneous measurements.

Next, press the green colored Math and Memory soft key. This brings up a menu of functions which allows an acquired sweep of data to be stored into and recalled from the FieldFox's display memory. It should be noted that display memory is different from the non-volatile flash memory built into the FieldFox, or which might be used with a removable USB flash drive. Display memory is volatile and is only used to display the previous data sweep on the same axes as a current one.

To illustrate the use of display memory, press the Data \rightarrow Mem soft key, after which a chime should be heard, indicating that the current displayed data sweep is now stored into the display memory. The display should still be showing the current return loss of the cable. Now press the Memory soft key to display what was stored into display memory. Displayed memory contents are shown as a slightly dimmed trace. Now press the Data & Memory soft key. Screw a short barrel connector into the free end of the 18-inch coaxial cable, which will have the effect of slightly lengthening the cable. The simultaneous Data & Memory display very conveniently shows the

differences between these two situations. This method of comparing an old and a new measurement sweep is an extremely useful one, so take some time to become proficient at using this feature. The display memory feature is best suited for comparing two different physical situations, but using the same measurement function. When finished, press the Data soft key to return the display to only show the current measurement sweep data. The current display should still be showing return loss (RL) over 2.0 to 4.0 GHz with a scale of 1.00 dB/ division.

Another measurement that can be made with FieldFox is 1-port cable loss. Press the Measure button to display the menu of measurement functions. Press the More soft key, and then press the Cable Loss (1-port) soft key. This changes Trace 1 to the Cable Loss (CL) measurement function. Next, the difference between return loss and cable loss will be examined. Observation of the RL and CL traces individually shows us that the return loss is exactly twice the cable loss. In fact, the cable loss is exactly the same measurement data as the return loss, but its dB reading is simply divided by two. By doing this, the cable loss function gives what would be the one-way trip loss through the cable, in contrast to the return loss function which represents a full round-trip loss.

Another measurement function within the CAT application is Insertion Loss (2-Port). This is similar to cable loss in that both give the loss associated with a one-way trip of the signal through the cable. The difference is that cable loss makes the measurement using only one end of the cable, a 1-port measurement, while insertion loss (IL) makes the measurement using both ends of the cable, a 2-port measurement. Cable loss and insertion loss measurements are made using different physical connections, and for IL measurements, the far end of the cable must be connected to port 2 of the FieldFox, whereas for CL and RL measurements, the far end is left unconnected. In general, the 2-port IL measurement method is more accurate than the 1-port CL measurement. However, in many cases such as in ships, submarines, or aircrafts, the RF communication cables are bolted down and it is not possible to bring the two ends of cables together. So to test the cables after installation, and during maintenance tests, the 1-port method is used.

Measurement assignment

Using the components in the supplied lab parts kit, devise some experiments and measurements which will help resolve the source of the measured return loss from the cable. Below are a few suggested approaches to start with, but they should not be considered as the only possibilities.

First consider the possibility of radiation coming off of the open circuited end of the cable. Screw a $50\ \Omega$ terminator load into the end of the test cable and notice that the return loss increases dramatically. If the system were ideal, the $50\ \Omega$ terminating load would absorb all of the incident power and the return signal back to the FieldFox would be zero. This would be equivalent to 100% radiation from the end. Next try a less perfect power absorber. Place a fingertip on the end of the cable so that it touches both the center pin of the SMA connector and the outer nut. This should also be observed to increase the return loss, indicating what happens when power is lost out of the end of the cable.

To illustrate increased radiation loss, insert a barrel connector (SMA (f) to SMA (f) adapter) onto the end of the test cable and then insert a short 2-3 inch straight piece of wire into the center socket of the barrel connector. This will create a crude antenna, and the return loss observed should increase. One way to eliminate radiation loss is to change the end termination of the cable from an open circuit to a short circuit. Add a shorting cap to the barrel connector and observe what happens to the return loss. While radiation might be escaping from the open circuit end of the test cable, the shorting cap will clearly not allow any radiation to escape. Likewise, a 2-port measurement of insertion loss would also create a system in which radiation should not be able to escape, and this could also be used to rule out radiation losses.

Another method of distinguishing between dielectric and ohmic losses which are proportional to length and radiation losses which occur only at the open end of the cable is to simply change the length of the cable. Use a barrel connector to connect two 18-inch long sections of test cable to the FieldFox. Observe what effect doubling the test cable length has on the measured return loss. From these simple tests and measurements, the effect of radiation on the measured return loss should now be established.

Next, the significance of ohmic losses can be examined. It was previously mentioned that the series resistance of the test cable at 3.0 GHz was about $R' = 3.0\ \Omega/\text{ft}$. A distributed loss such as series resistance will cause the amplitude of the propagating wave to decay exponentially along the line, following an $\exp(-\alpha z)$ dependence. For lines with small resistive losses, the decay constant can be approximated by $\alpha = R' / 2Z_0$, where R' is the series resistance per unit length and Z_0 is known as the characteristic impedance of the line. The characteristic impedance of the line will be discussed elsewhere, but for the present case, both the FieldFox and the test cable use a characteristic impedance of $Z_0 = 50\ \Omega$. If the amplitude of the propagating wave decays as $\exp(-\alpha z)$, then the power of the wave will decay as $\exp(-2\alpha z)$, since power is proportional to the square of the amplitude. For a propagation distance of ℓ , the power level will therefore

have fallen by a factor of $\exp(-R'l/Z_0)$. Compute this factor for a round trip path length of 36 inches = 3.0 ft., and from that factor compute the return loss that this series resistance loss might be expected to contribute. How does this value compare to the measured return loss at 3.0 GHz?

Dielectric loss in a cable increases linearly with frequency, whereas ohmic loss increases as the square root of frequency because of the skin effect. Run the return loss measurement again, but now using the full span of the FieldFox from 30 kHz to 6.5 GHz. Adjust the vertical scale as needed to best display the measurement data. What trends are observed? Is the loss proportional to frequency or the square root of frequency? Keep in mind that the vertical scale is already logarithmic since it displays the loss in units of dB. From these measurements and data analysis, it should now be possible to determine the physical source of the return loss of the test cable. At 3.0 GHz, give estimates of what percent of the overall return loss comes from radiation loss, ohmic loss, and dielectric loss.

If you were asked to send some RF power down 1000 feet of this type of cable, what would be the efficiency of that power transmission at 300 MHz, 1 GHz, and 3 GHz, based on the measured loss per unit length of the test cable at these frequencies?

This application note was created by Professor Bruce Darling, from University of Washington's Electrical Engineering Department, in collaboration with Keysight Technologies' handheld team within the Component Test Division. The content is designed to complement an introductory course in undergraduate electromagnetics.

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