A Shunt Fixture for Low Impedance Measurements
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Introduction

Measurements of impedances in the 0.01-10 ohm range are useful for measuring the resistance of capacitors, inductors and crystals, or even the resistance of wires. Standard 50-ohm reflection bridges are optimized for impedances in a broad range around 50 ohms, ideally in the 5-500 ohm range. They generally do not do well with very low impedances such as 0.5 ohms. A very simple fixture can be built that does well at measuring low impedances.

Standard reflection-mode measurements of impedance typically require OSL calibration. Such calibration is capable of correcting many errors, but the requirement to run scans on three separate standards (Open, Short and Load) is sometimes a bit of a pain, especially if the DUT connection is made by directly soldering it to the fixture. Also, it requires a full VNA, and is not susceptible of calculation with simpler equipment, such as a spectrum analyzer with tracking generator. Some of the methods described here can even be applied with a signal generator and power measuring device.

An additional issue is that whatever measurement fixture we use, getting an accurate measurement of low impedances may require the device-under-test (DUT) to be located very close to the fixture. This is easier to do if the fixture is very simple.

The purpose of this document is to present an extremely simple fixture for measurement of low impedances with a VNA that can be used with equipment as simple as a signal generator and power measuring device, or with more elaborate equipment such as a spectrum analyzer with tracking generator, a VNA with Reference (Response) Calibration, or a VNA with full OSL calibration. In the discussion that follows, we will generally discuss in terms of using VNA transmission measurements with this fixture.

We also demonstrate the use of this fixture to measure wire resistance. Use of the fixture as a “dip meter” is described elsewhere.

The Fixture

Several variations are possible, but here is the basic fixture:

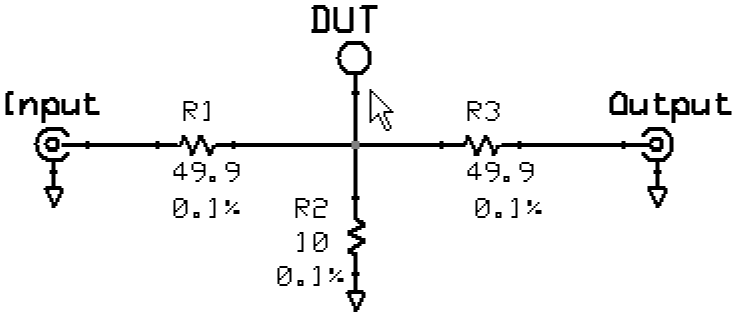


Figure 1—Shunt Fixture
DUT is connected to DUT port and ground.
The resistors can have any tolerance 1% or better.

This is so simple I hesitate to call it a "fixture", but in practice it is handy to assemble the three resistors on a tiny board that can connect directly to the DUT, with coax cables leading to the signal source and the measuring device, so it in fact ends up as a fixture.

To analyze this circuit, we use the following equivalent circuit.

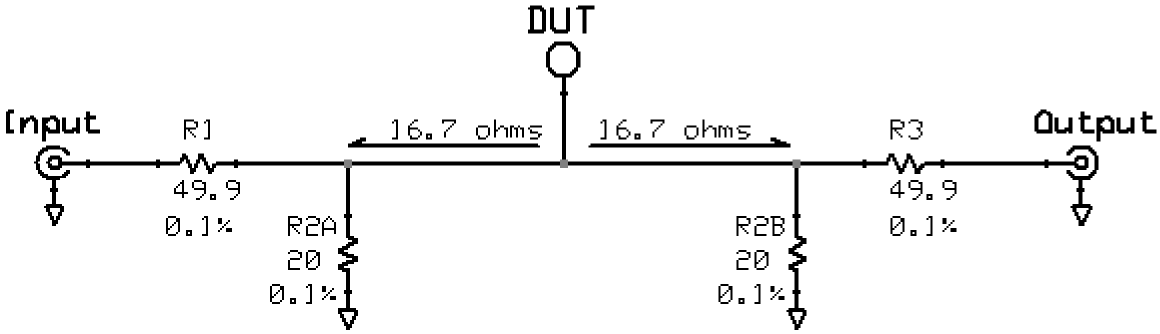


Figure 2—Equivalent Circuit to Figure 1

The idea is simply to buffer the DUT on each side with an attenuator, so that it sees close to the desired impedance (here, a net 8.35 ohms) despite deviations of the source and load from their ideal of 50 ohms. The fixture is called a "shunt" fixture because the DUT is placed shunt to ground between the two attenuators. Note that we omitted the usual "outside" shunt resistors on the attenuators. They are not necessary because the source and load will each see impedances in the 50-60 ohm range no matter what the impedance of the DUT. It is not important that they see exactly 50 ohms, only that they be stable with the impedances presented to them.

The DUT sees 16.7 ohms in each direction. We call this the reference impedance, Z_0. As far as the DUT is concerned, it is attached to a voltage V_S through a resistance of $Z_0/2$ ohms. (V_S is not the input voltage; it is the voltage of the Thevenin equivalent source.) We can indirectly determine the V_S at each frequency by doing a transmission scan with an open-circuit DUT. That becomes the reference for subsequent scans with the actual DUT. In a VNA this is equivalent to doing Through or Line calibration and then performing normal transmission measurements. The same thing can be done with a spectrum analyzer with tracking generator, by storing the trace from the Open DUT and subtracting it (in dB) from subsequent DUT scans. Or we can manually do the same thing with a signal generator and power measuring device. The result is that we obtain a measurement in dB for the DUT transmission relative to the Open transmission. This is known as S_{21}. If we convert S_{21} in dB to a ratio (between -1 and +1), we can calculate the impedance, Z, of the DUT with the following formula:

$$Z = (Z_0 / 2) * S_{21} / (1 - S_{21})$$

Or, $Z = (Z_0 / 2) / (1 / S_{21} - 1)$

S_{21} is normally measured in dB (a negative number). To utilize it in that form our equation becomes

$$Z = (Z_0 / 2) / (10^{\frac{-dB}{20}} - 1) \qquad \text{(Eq. 1)}$$

The negative of S_{21} in dB is actually the Insertion Loss, so we could replace "-dB" with "IL". This calculation of impedance can be done manually, or by using the calculation abilities of a VNA. A VNA would also measure the phase of S_{21}, and would convert it to a complex number to apply the above equations.

Note again that Z_0 is the impedance presented on each side of the DUT in Figure 2; it is not the 50-ohm impedance of our signal source or measuring device.

Dynamic Range

The fixture of Figure 1 will produce an output of -26.6 dBm with an open-circuit DUT, with an input of -5 dBm. A 0.05 ohm DUT will produce -71.1 dBm. That range of signals, can easily be handled by a VNA or spectrum analyzer with tracking generator. It is possible that some amplification would be required to measure the output with a power meter, depending on its range. If the amplification is in place for both the Reference calibration and the DUT measurements, the exact amount of amplification does not need to be known.

Sources of Error

The primary source of error with this fixture is that the source and load may deviate from 50 ohms. If the source and load both have return losses better than 20 dB, the error in impedance measurement will not be worse than about 2%. If either has a worse return loss, the problem can be improved with additional attenuation. In fact, the primary purpose of the fixture being designed for Z_0=16.7 ohms rather than 50 ohms is that it makes the measurements less sensitive to source and load impedances.

Another source of error is separation between the test fixture and the DUT. At frequencies below 10 MHz, a few inches of separation likely creates little error. At higher frequencies, however, such separation may introduce inductance, capacitance or resistance that gets included in the measurement of the DUT's impedance. One advantage of the fixture of Figure 1 is that it is simple and compact, and can easily be located adjacent to the DUT. **Note that the most important factor is to be sure the 10 ohm resistor is located close to the DUT**. It is not nearly as important for the 49.9 ohm resistors to be close to the DUT. For certain types of DUTs, the 10 ohm resistor might even be located off the fixture board, soldered directly to the DUT.

The fixture can also be used with a VNA in reflection mode with full OSL calibration. This likely is necessary only above some threshold frequency, perhaps in the 10-30 MHz range, depending on required accuracy. When so used, the fixture would provide better accuracy than a standard reflection bridge for low impedances.

In concept, this fixture is similar to 4-wire Kelvin measurements of DC resistance. Stray impedances in the lines leading to or from the fixture can have some impact on accuracy, but it tends to be a proportional error rather than an additive error. For example, if the line leading to the fixture presents an effective 51 ohm resistance, rather than 50 ohms, that creates a tiny percentage error (tiny because the impedance seen by the DUT is dominated by the 10 ohm resistor) in the measurement rather than directly adding or subtracting one ohm. On the other hand, a one-ohm impedance in the line from the 10 ohm resistor to the DUT would directly add one ohm of impedance to the measurement, a serious problem if you are trying to measure 0.2 ohms. That is why the critical connection is the one between the 10 ohm resistor and the DUT.

Physical Implementation

Figure 3 shows two possible implementations of the fixture of Figure 1.

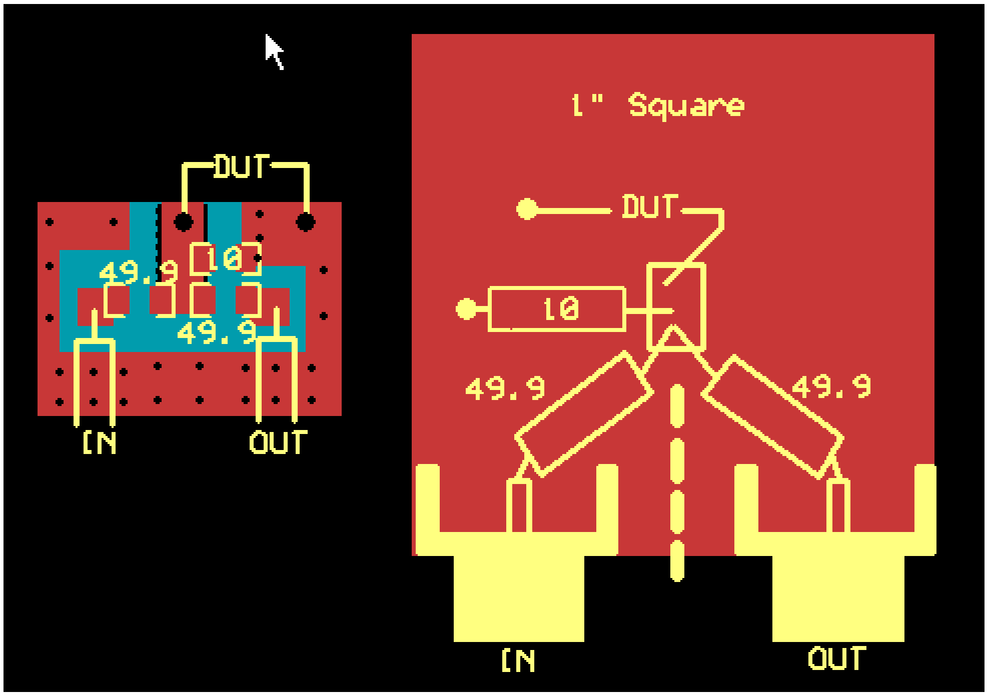


Figure 3—PCB implementations

Red is top layer; blue is bottom

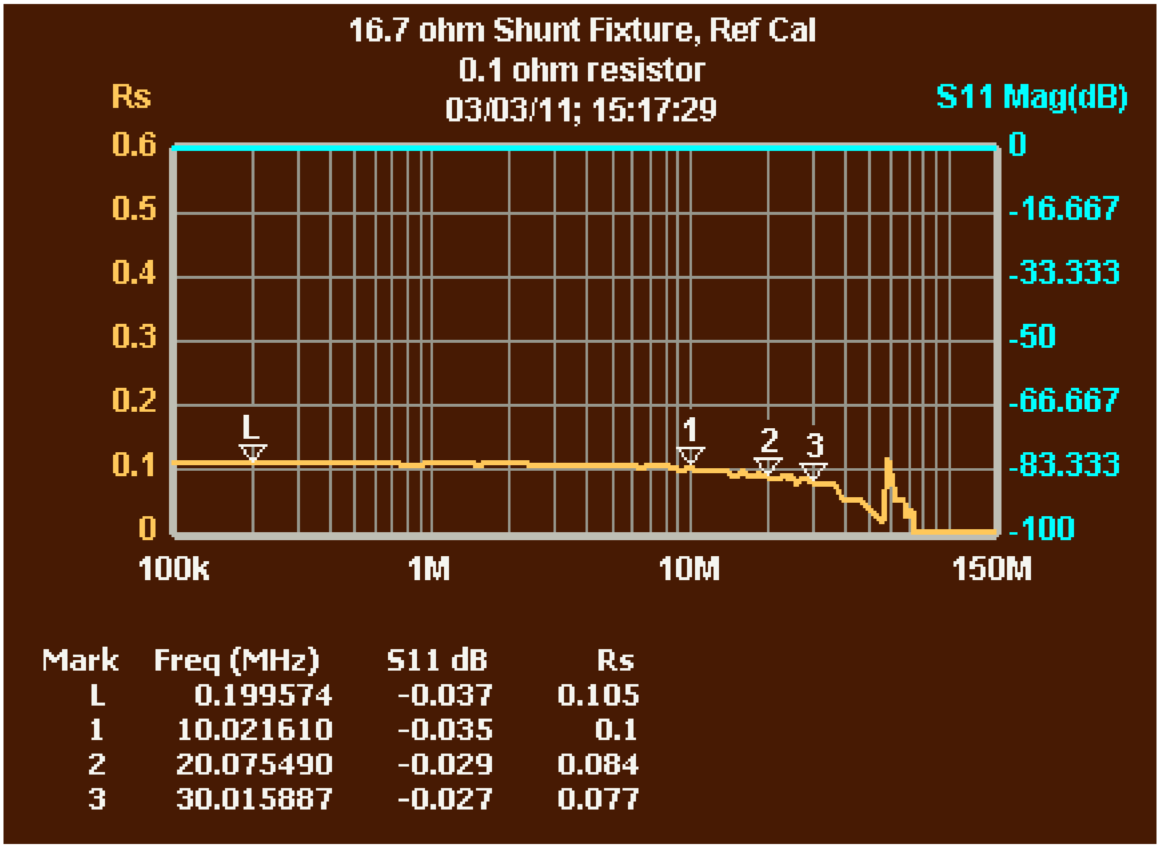
The left fixture of Figure 3 holds two coax cables (with shields soldered to top ground plane) and contains the three resistors (SMT) and a connection for the DUT. The right fixture uses leaded resistors on a single-sided PCB with SMA connectors. The rectangle in the center of the right fixture is a "Manhattan" pad made of PCB glued or soldered to the main PCB, to provide a soldering surface isolated from the ground plane. The dashed line in the right fixture is a line-of-sight shield wall which is likely necessary because the connectors and resistors are large and are raised above the board. The SMA connectors sit sideways on top of the board, though they could slide onto the edge of the board if some ground plane is removed around the center pin.

The fixtures are simple enough that they can be built as necessary to suit a particular DUT style, and replaced if they get worn out. DUTs can be connected by direct soldering, SMA connectors, socket connectors, or whatever works. If the DUT is attached by direct soldering and the fixture ultimately gets worn out by repeated soldering, it would be a simple matter to transfer the components to a new board.

The length of the coax cables is almost irrelevant as long as they are decent 50-ohm cables. It is convenient to use thin, flexible cable such as RG-174, which is not the highest quality but is perfectly OK for this purpose up to at least several feet. However, the shielding of RG-174 is not optimal, so the two cables should not be run directly adjacent to each other.

Tests with an Actual Fixture

I built a fixture with leaded resistors that looks much like the right side of Figure 3. It is not very compact, so we should expect a limited frequency range of operation. Figure 4 shows the results of measurement of a 0.1 ohm resistor (1% tolerance), using only Reference calibration (against an Open) with the MSA.

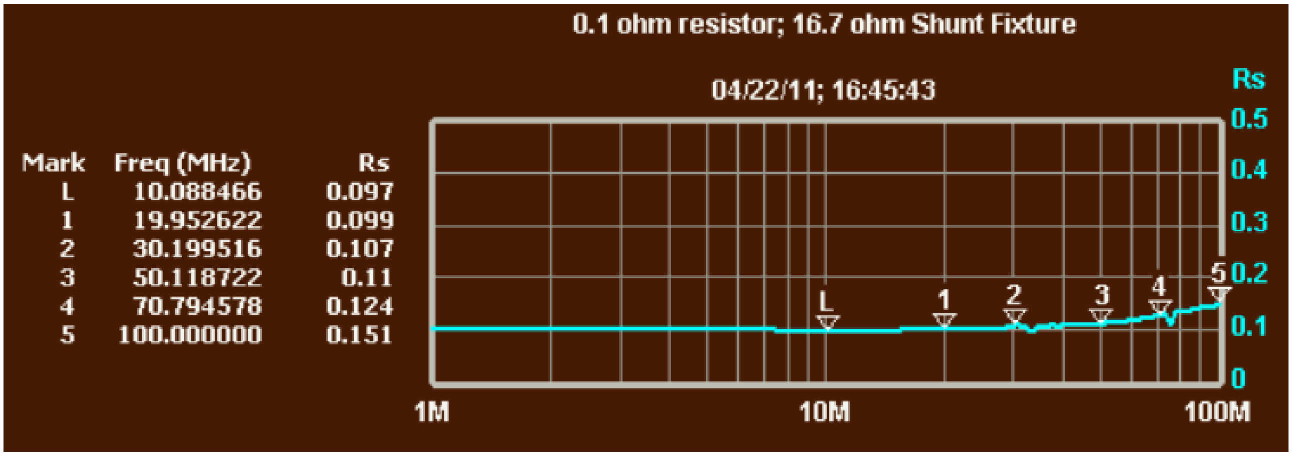


Mark	Freq (MHz)	S11 dB	Rs
L	0.199574	-0.037	0.105
1	10.021610	-0.035	0.1
2	20.075490	-0.029	0.084
3	30.015887	-0.027	0.077

Figure 4—Scan of 0.1 ohm resistor
(S11 is graphed re 50 ohms, even though fixture is 16.7 ohms)

The resistance was measured after calibrating against the Open, and was very accurate to 10 MHz. By 30 MHz the error is 23%. But such an error would often not be critical. At any rate it is clear that the frequency limit of this fixture with Reference calibration will be somewhere in the 10-30 MHz range, depending on required accuracy. The frequency range will be lower for smaller impedances, but higher for larger impedances.

The frequency limitation is likely due in large part to the use of leaded resistors with significant inductance. The SMT fixture on the left side of Figure 3 would likely have a much better frequency range due to its compactness. Since we made these measurements with a VNA in Reflection mode, it is possible to improve the results with OSL calibration. I was trying to avoid that, because it is a bit awkward when the Short and Load have to be soldered to the fixture. But I gave OSL a try. I used a wide brass strip as the Short and a 10-ohm resistor as the Load (the load does not have to match Z_0; we just have to tell the MSA what the value is.)



0.1 ohm resistor; 16.7 ohm Shunt Fixture

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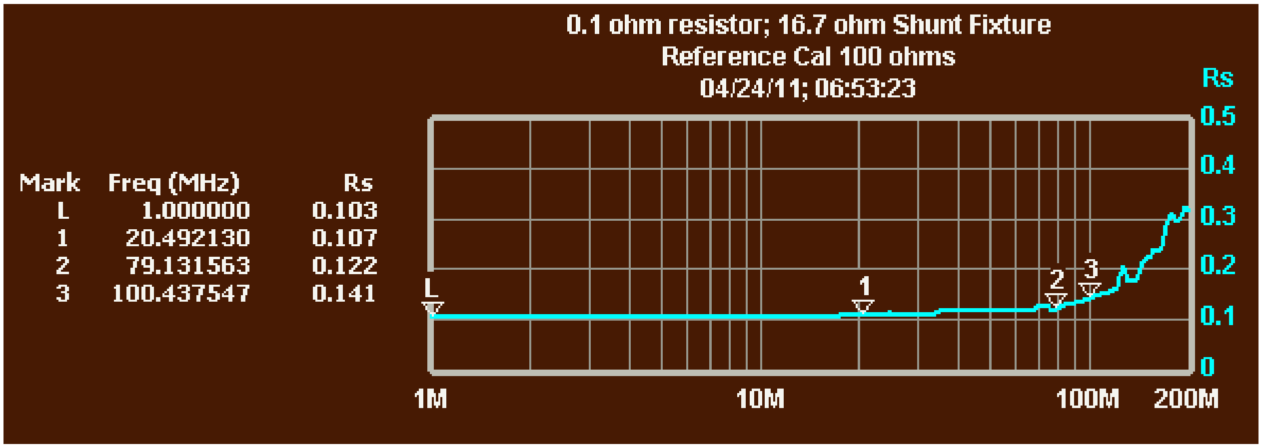
Mark	Freq (MHz)	Rs
L	10.088466	0.097
1	19.952622	0.099
2	30.199516	0.107
3	50.118722	0.11
4	70.794578	0.124
5	100.000000	0.151

Figure 5—Measurement with OSL Calibration.

The measured resistor and the Load were both 1% tolerance. These measurements are quite respectable. There is still deterioration at high frequency. I believe that deterioration is due to the resistors (both the DUT and the calibration Load) having inductance. If only the DUT had inductance, the MSA should properly measure that inductance without affecting the resistance measurement. But inductance in the calibration Load complicates the matter, unless the MSA is told the amount of inductance in the Load, which is an unknown.

Note that at high frequency, the graph in Figure 4 falls and that of Figure 5 rises. The difference is that Figure 4 has error due to the capacitance of the Open reference, and Figure 5 has error due to the inductance of the 10-ohm Load, neither of which is accounted for. (Figure 5 also has capacitance in the Open, but with OSL calibration the Open has little effect on measurement of small impedances, whose error is dominated by the Short and Load.) The solution may be to use a 100-ohm resistor, an intermediate value which might cause the parasitic inductances and capacitances to cancel out. We could use that resistor as the reference in Reference calibration or as the Load in OSL calibration. Figure 6 shows the result with Reference calibration.



0.1 ohm resistor; 16.7 ohm Shunt Fixture
Reference Cal 100 ohms
04/24/11; 06:53:23

Mark	Freq (MHz)	Rs
L	1.000000	0.103
1	20.492130	0.107
2	79.131563	0.122
3	100.437547	0.141

Figure 6—Measurement with Reference Calibration, 100 ohms.
Note this runs to 200 MHz, so it initially looks worse than previous scans.

The results of Figure 6, with Reference using 100 ohms, are slightly better than those of Figure 5, which used OSL calibration, and far better than those of Figure 4, which used Reference calibration with an Open. While I did not try it, OSL calibration with a 100-ohm Load would likely produce even better results. The response of Figure 6 is usable to 80 or even 100 MHz.

It is interesting to consider why the measured resistance in Figure 6 rises sharply above 100 MHz. I tried calibrating with a reference of 1 ohm, and the rise became even more dramatic. Then I tried a reference of 0.2 ohms, and got a very interesting result. The resistance measured 0.1 ohms up to about 20 MHz, then rose gradually to 0.2 ohms, where it leveled off. What happens is that during calibration, there is inductance present but the MSA is told that the reference is a pure resistance. The smaller the reference resistance, the more the measured impedance is dominated by the inductance at high frequency. The measurement of the 0.1 ohm resistor is dominated by that same inductance. Therefore, at high frequency, the 0.1 ohm resistor and the calibration have very similar responses. This leads the MSA to conclude that the 0.1 ohm resistor is similar to the reference resistor, and the resistance measurement of the 0.1 ohm resistor gets exaggerated. In the extreme case, with large inductive reactance, the MSA cannot distinguish the two resistances and concludes that the 0.1 ohm resistor is equal to the reference resistor.

In Figure 4, the measurement had the opposite problem: there was a net capacitance present during calibration, probably due to the capacitance of the landing pad. That capacitance becomes less significant as the calibration reference (which is in parallel with the capacitance) becomes lower. There is probably some value of reference resistance that would optimally balance the parasitic capacitance and inductance, which would extend the frequency range of accurate measurement. That resistance could be found by experimenting with several different reference values, looking for the value that would best flatten the response of Figure 6.

Simplifying Reference Calibration

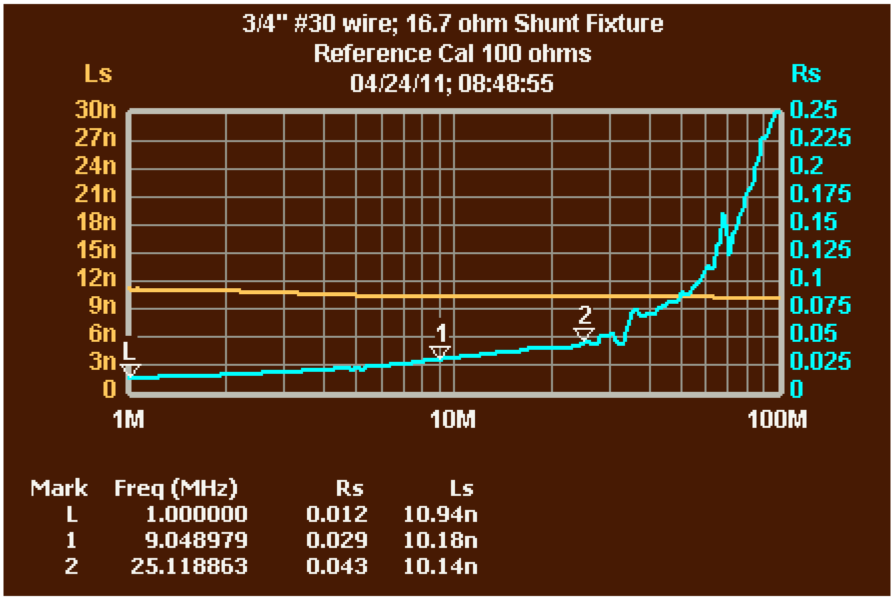
We have shown that it is best to do Reference calibration with a resistor—such as 100 ohms —rather than with an open circuit. That makes calibration a little more trouble, because we have to solder the resistor in place to calibrate and then remove it to measure the DUT. But if you are measuring impedances below a few ohms, we could actually just leave the 100 ohm calibration resistor in place, creating an error of at most a few percent in the measurement.

There is an interesting mathematical way to do the same thing without the 100 ohm resistor. Our 10 ohm resistor is the equivalent of an 11.1 ohm resistor in parallel with 100 ohms. So we could "pretend" (i.e. tell the MSA) that we are calibrating with a 100 ohm resistor but that our fixture has Z_0=18.2 ohms. (The DUT would see 18.2 ohms in each direction if R2 in Figure 1 were 11.1 ohms, which would make R2A and R2B equal to 22.2 ohms in Figure 2.) Then we never even have to add the 100 ohm resistor! I did not actually try this, because I felt that having to "lie" about the fixture Z_0 might get confusing.

Below 10 MHz, none of this is necessary, as calibration with an Open is satisfactory.

Measuring Wire Resistance

The fixture was used to measure the inductance and resistance of a piece of #30 wire that was approximately $\frac{3}{4}$" long.



3/4" #30 wire; 16.7 ohm Shunt Fixture
Reference Cal 100 ohms
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Mark   Freq (MHz)      Rs       Ls
  L      1.000000     0.012    10.94n
  1      9.048979     0.029    10.18n
  2     25.118863     0.043    10.14n
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Figure 7—Measurement with Reference Calibration at 100 ohms.

If the DC resistance of the wire is 0.005 ohms (the wire chart says #30 copper wire should be 0.006 ohms, but this is silver plated), then the AC resistances at the three markers would be 0.007, 0.0024 and 0.038 ohms. The AC impedances at markers 2 and 3, relative to marker 1, would then 3.4 and 5.4. Based on the fact that AC resistance is the result of skin effect, which is proportional to the square root of frequency, we would expect ratios of 3 and 5. This seems to indicate that our measurements are accurate to within a few milli-ohms, up to 25

MHz. Above that, the error increases due to two factors. One is that the inductive reactance swamps the resistance and makes the resistance difficult to measure accurately. The other is that the inductive reactance present during calibration becomes larger, and distorts the measurements. The latter factor could be mitigated with OSL calibration if we wanted to bother.