# Applying and Measuring Ferrite Beads

Whitham D. Reeve and Tom Hagen

**Part I ~ Ferrite Bead Properties and Test Fixtures**

## I-1. Introduction

This article describes in Part I ferrite beads and their applications and simple test fixtures that can be used to measure ferrite bead electrical properties. In Part II we describe the measurement results for a number of different ferrite beads. Part II will be published in the next issue of *Radio Astronomy*. Our test fixtures are a compromise to accommodate a range of clamshell beads but they are adequate for our purposes, which are to obtain reasonably good measurements comparable to manufacturer's data and to measure unidentified beads that have unknown characteristics.

Ferrite beads are used to reduce conducted noise on cables and wires. One or more beads are slipped or clamped over a cable, which forms an RF choke with low impedance at lower frequencies and high impedance at higher frequencies. Ferrite is a ceramic material made from powdered iron oxide plus other metal oxides such as manganese, zinc, copper and nickel in various combinations. For ferrite beads, the material is formed into a hollow cylindrical core and cooked (figure 1). The resulting core material is easily magnetized and demagnetized and is called a *soft ferrite* for this reason. However, ferrite material is mechanically rigid and brittle and can chip and break if mishandled. Many ferrites are electrically non-conductive. In these ferrites eddy currents do not flow in the material thus making them suitable for use at radio frequencies in transformers, inductors, baluns and loopstick antennas.



Figure 1 ~ Ferrite beads used for noise suppression. A solid bead (upper-middle) is shown surrounded by clamshell beads. The clamshell bead is split into two identical pieces and held together by a plastic housing with clasps. The mating surfaces of the clamshell bead are very smooth so that when they are clamped together there is negligible air gap. Ferrite beads are available in many lengths and inside and outside dimensions and different material mixes. Beads with a rectangular slot are available for flat cables.

When a ferrite core is placed around a wire or cable, the ferrite introduces impedance that varies with frequency. Some writers say ferrite beads are non-resonant. In fact, they are resonant to some degree (as

shown later) but they have low Q. Depending on the frequency the impedance may be primarily resistive, inductive or capacitive. The core has little effect at lower frequencies including powerline frequencies of 50 and 60 Hz and all reasonable harmonics. However, depending on the material beads can be quite inductive and lossy above 1 MHz and can be used to reject or absorb RF noise.

Although ferrites are available in many shapes, this article is concerned with only two very common types, the solid bead and clamshell bead. The solid bead generally is placed before the cable is terminated whereas the clamshell bead can be placed before or after. The clamshell bead, also called snap-on bead, clamp bead and split bead, is longitudinally split into two identical pieces that, when placed on the cable, are closely aligned with each other and tightly clamped. A plastic housing, or clamshell, designed for this purpose is provided with the bead. The performance of both solid and clamshell beads of the same materials and dimensions is the same unless the housing of the clamshell bead is damaged and allows physical misalignment.

### I-2. Ferrite Bead Applications

Ferrite beads are found on all cable types including USB cables, serial port cables and ac adapter power supply cables (figure 3). They also are placed on coaxial cables to form so-called *choke* baluns (figure 4). A choke balun can be used to reduce noise currents on the cable and, if placed at the point where the cable connects to a balanced antenna such as a dipole, the beads transform the balanced antenna currents to unbalanced coaxial cable currents.
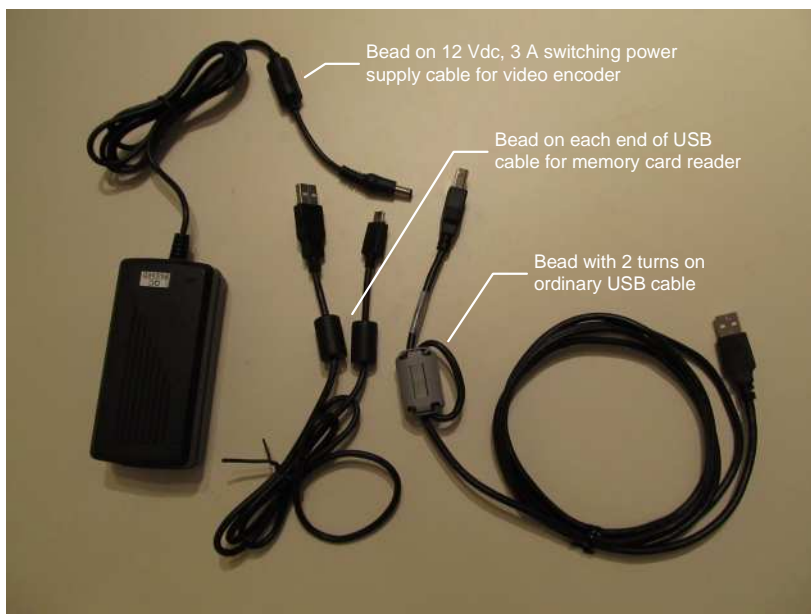


Figure 3 (above) ~ Common applications for ferrite beads include all types of power and signal interface cables.

Figure 4 (right) ~ A choke balun is made by slipping several ferrite beads over a coaxial cable. This image shows five solid beads on LMR-400 cable that have been covered with heatshrink tubing.

When a bead is placed on a cable, the combination is equivalent to a 1-turn or 1-winding coil. The inductive reactance of a coil is proportional to the square of the number of turns (doubling the turns quadruples the reactance).  Each pass of the cable through the core is counted as one turn. Beads used with larger sizes of coaxial cable have enough room for only one pass, but multiple turns of a small coaxial cable, such as RG-174/U, can be wrapped around the core (figure 4). However, increasing the number of turns also increases the winding capacitance, which shifts the point of maximum impedance to a lower frequency. Testing should be performed to verify that this is not detrimental to the application.



Figure 4 ~ Clamshell ferrite bead with four windings of RG-174/U coaxial cable. The bead is a very common TDK p/n ZCAT-2035-0930 and has a 9 mm inside diameter.

The most widely available clamshell beads have a 6, 7, 9, 10 or 12 mm inside diameters. A table is provided for quick reference showing common coaxial cable types that may be used with each bead size (table 1). The core inside diameter should never be smaller than the coaxial cable maximum outside diameter or else the cable will be crushed when the core is snapped closed.

Table 1 ~ Cross-reference for core inside diameters and common coaxial cable types with ordinary jackets. The combinations shown accommodate one winding. <u>Note</u>: Most manufacturers supply cables with different outer jackets and shielding options to meet various service requirements (for example, plenum rating or double-shielding), and the outside diameter of these cables may vary from that shown here. (ID: inside diameter). Cable groups are designations used by connector manufacturers to indicate similar dimensions.

| Cable types (basic designation) | Bead ID mm (inch) | Cable group | Remarks |
|---|---|---|---|
| RG-58, RG-142, RG-174, RG-316, LMR-100, LMR-195, LMR-200 | 6 (0.236) | B, C | RG-174, RG-316 and LMR-100 may be used with 3 mm ID |
| RG-59, RG-62, RG-8X, LMR-240 | 7 (0.275) | D, X | Includes some versions of RG-6 |
| RG-6 | 9 (0.354) | | Includes quad-shielded RG-6 |
| RG-6 | 10 (0.393) | | |
| RG-8, RG-213, RG-11, LMR-400 | 12 (0.472) | E, F, I | |

A single ferrite bead may not provide the necessary noise suppression of common-mode RFI currents. Bead inductance theoretically is proportional to its length, so impedance can be increased by using more beads on a given cable. It may be found that four or five, or more beads are needed. The beads should be placed as close together as possible. Spacing is limited by the plastic shells on clamshell types or bends in the cable but solid beads can be stacked in contact with each other on straight cable sections. A cable with many beads on it can become quite heavy and may need special mechanical support to prevent damage to the cable or its connectors.

Where noise is coupled to the cable by conduction, the ferrite bead should be located at the end of the cable closest to the noise source. For example, if beads are used to reduce conducted noise from a switch-mode power supply, they should be placed as close to the power supply as possible. However, if the noise is coupled by other means, the bead should be located as close as possible to the susceptible equipment. The inside diameter of the core should match as close as possible the outside diameter of the cable to provide a close fit. If more than one turn of cable is placed on a core, the windings should be wrapped tightly around the core. However, care needs to be taken with coaxial cable to prevent its deformation and with insulated or coated wire to prevent damage.

A ferrite bead's ability to suppress noise currents in a cable is related to the core temperature and net value of direct current (dc) flowing in the conductors. Significant temperature increases or decreases from normal room temperatures tend to reduce the impedance of a ferrite bead. However, for ordinary low-power indoor applications any changes in bead characteristics are small. Where a ferrite bead is used on a cable that carries dc, if both the feed and return conductors pass through the core, the net dc will be zero and it will not affect the characteristics of the bead; otherwise, the noise suppression capabilities could be reduced. It should be noted that if the return path of the dc circuit is bonded to ground at both ends, then not all of the return path current will flow through the ferrite core, leaving a possibly detrimental unbalanced dc current flow. Additional discussions of temperature and dc effects are beyond the scope of this article but may be found in **References and Further Reading**.


**I-3. Noise Suppression**

Ferrite beads suppress higher frequency common-mode currents in a cable. Common-mode currents are currents on the separate cable conductors that flow in the same direction in contrast to signal currents that are differential-mode (also called transverse-mode or normal-mode) and flow in the opposite direction (figure 5). Common-mode currents can be coupled by conduction into the cable from connected equipment but often are coupled by inductive and capacitive means or by electromagnetic radiation into the cable from the surrounding environment. Ferrite beads are very lossy to common-mode currents but in principle are not lossy to the differential-mode signal currents; differential currents are discussed later. It should be remembered that ferrite beads are not designed to reduce noise that is received by an antenna and coupled along with the desired signals into the coaxial cable transmission line as differential-mode currents.
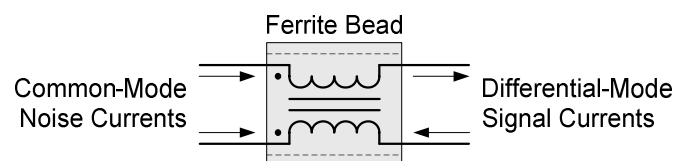


Figure 5 ~ Conceptual diagram of common-mode and differential-mode currents. The magnetic fields setup by the common-mode currents reinforce each other leading to high losses, whereas the fields setup by the differential-mode currents cancel each other out and the currents are not affected.

At lower frequencies in the usable range, the ferrite bead is mostly inductive and rejects (or blocks) common-mode currents because of its inductive reactance. As frequency is increased the impedance is more resistive and the bead absorbs the currents, dissipating them as heat. A ferrite bead can be represented by a simple

equivalent circuit consisting of inductance, resistance and capacitance (figure 6). Referring to the circuit, $R_{bead}$ and $L_{bead}$ are the dc series resistance and effective inductance and $C_{par}$ and $R_{par}$ are the parallel parasitic capacitance and resistance of the bead. At low frequencies, the parasitic capacitance $C_{par}$ acts as an open circuit and $L_{bead}$ as a short circuit, leaving only $R_{bead}$ in the circuit. As the frequency increases, the impedance of $L_{bead}$ initially increases linearly while the impedance of $C_{par}$ decreases. The rising slope at the lower frequencies is mostly determined by the inductance of $L_{bead}$, but eventually the impedance of $C_{par}$ begins to dominate and the bead's impedance starts to decrease. The falling slope is determined by $C_{par}$. $R_{par}$ works to reduce the Q of the bead. These characteristics result in an impedance plot that has inductive, resistive and capacitive regions (figure 7). For more detailed technical explanations and circuit theory, see **References and Further Reading** at the end of this article.
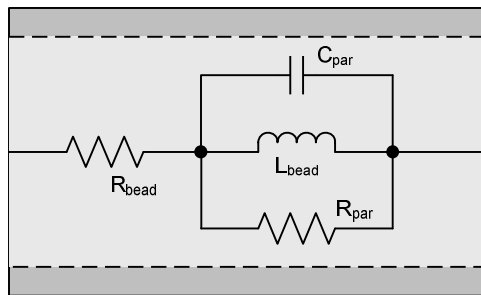


Figure 6 ~ Simplified ferrite bead equivalent circuit. This circuit fairly represents a ferrite bead in isolation. In practical applications, the bead's environment may introduce additional components in complicated arrangements.
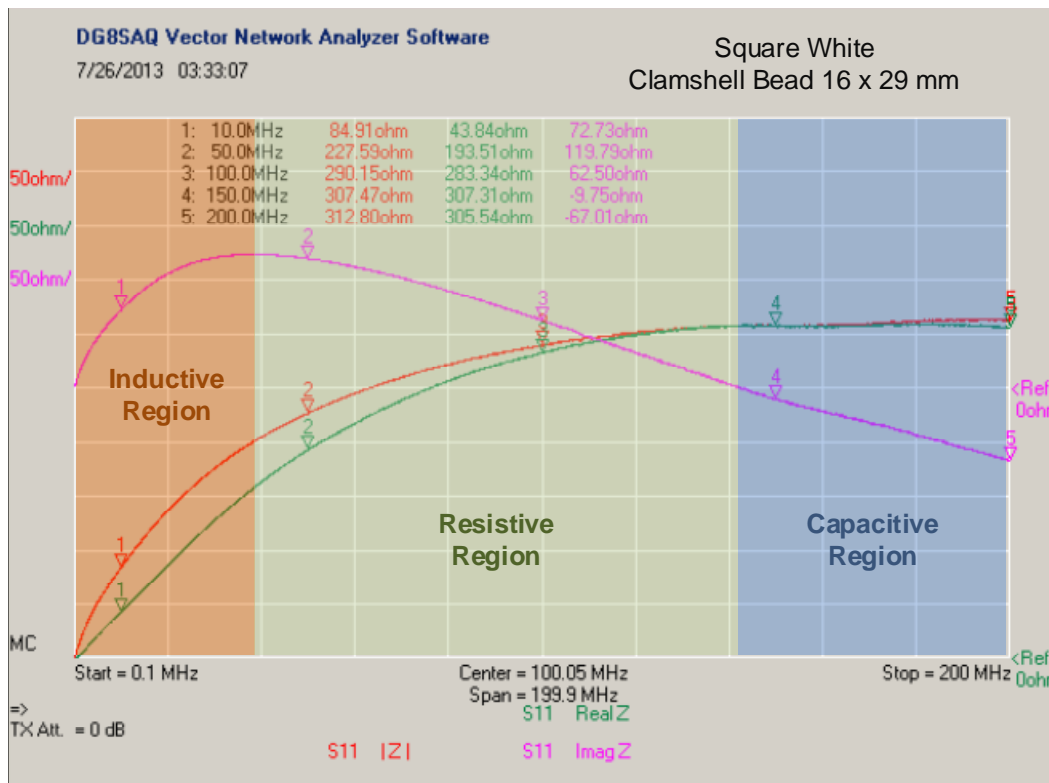


Figure 7 ~ Ferrite bead measurements indicate inductive, resistive and capacitive regions as frequency increases. Many beads show a linear increase in impedance at low frequencies, but this particular bead does not. These measurements were made on the test fixtures described later. Resonance is indicated where the impedance imaginary component is zero, just

above 140 MHz for this bead. The colors corresponding to the traces are indicated at the bottom of the plot for impedance magnitude |Z|, RealZ (resistive component) and ImagZ (reactive component). The reference values for each trace are indicated on the right vertical scale and the ohms per division are on the left vertical scale. The markers tabulated at the top indicate the impedances at various frequencies.

A ferrite bead's effectiveness in suppressing noise currents depends on the relative magnitudes of the source, ferrite bead and load impedances at the frequencies of interest. These are shown in a further simplified equivalent circuit (figure 8). If the source and load impedances are known, the insertion loss in dB of a bead may be determined from

$$IL(dB) = 20 \cdot \log\left( \frac{Z_{source} + Z_{load}}{Z_{source} + Z_{load} + Z_{bead}} \right) \tag{1}$$

where $Z_{source}$, $Z_{load}$ and $Z_{bead}$ are the respective impedances. It can be seen that, for given source and load impedances, increasing the bead impedance will increase the insertion loss. It is important to remember that the impedances are complex and must be known at the interfering noise frequencies.
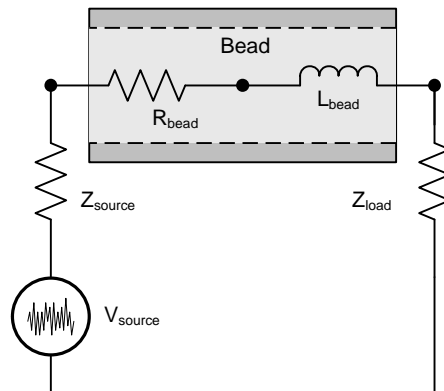


Figure 8 ~ Simplified equivalent circuit of a ferrite bead with the noise source (marked $V_{source}$) and load. When the impedances are known, the insertion loss of the bead may be calculated. To be effective, the bead impedance at the noise frequencies must be much larger than the total source and load impedances.

Unfortunately, the source and load impedances usually are unknown and difficult to accurately measure at higher frequencies. There are two ways to approach this problem: 1) Figure out how to measure the source and load impedances and make the necessary calculations. An insertion loss of 3 to 6 dB would be a reasonable starting point although higher values may be necessary; or 2) Experiment with different cores, number of windings and number of cores, tempered by measurements described later, until the noise is reduced to an acceptable level. Approach 2) probably is the method undertaken by most readers of this article. A starting point is to strive for ferrite bead impedance on the order of 500 to 1000 ohms throughout the frequency range of interest. These loss and impedance values are somewhat arbitrary – the necessary values depend on the details of the noise environment – but it is often helpful to have a starting point.

## I-4. Ferrite Bead Selection

Ferrite beads are readily available from electronic component distributors and sellers, surplus electronics sellers and auction websites. An internet search with keyword "ferrite bead" will reveal many companies. Some

manufacturers allow factory-direct ordering. The cost of clamshell beads varies from about US$0.50 to US$10.00 each depending on the source. Some well-known manufacturers of ferrite beads are:

| Manufacturers | |
|---|---|
| Fair-Rite Products Corp. | http://www.fair-rite.com/newfair/index.htm |
| Ferrishield | http://www.ferrishield.com/ |
| Ferroxcube | http://www.ferroxcube.com/ |
| Murata | http://www.murata.com/products/emc/index.html |
| NEC/Tokin | http://www.nec-tokin.com/english/product/dl_emc.html |
| Parker Chomerics | http://www.chomerics.com/products/emi/cableconnector.html |
| Laird (Steward) | http://www.lairdtech.com/Products/EMI-Solutions/Ferrite-Products/ |
| TDK | http://www.tdk.com/ferrites.php |
| Würth Electronik | http://www.we-online.com/web/en/passive_bauelemente_standard/willkommen_pbs/Welcome.php |

Ferrite beads may be used in ordinary inductors at lower frequencies (in their linear impedance region) but for noise suppression applications the bead must be highly inductive or lossy at the noise frequencies, usually above 1 MHz. All clamshell beads are specifically designed for noise suppression. Unfortunately, most ferrite beads have no identification except possibly a color mark. This color is meaningless unless the user also knows the manufacturer and the color code. Some clamshell beads are marked with a manufacturer and part number on the shell; for example, TDK usually marks their clamshell beads. Almost all beads obtained from surplus electronics vendors and online auction websites have no identification. For unmarked beads, it is necessary to perform some tests to determine their basic characteristics. Test fixtures are described in the next section.

One manufacturer, Fair-Rite, provides a chart that makes it relatively easy to select the proper bead from their product line (figure 9). In Part II we provide measurements for all Fair-Rite clamshell bead materials given in the chart. Some manufacturers claim to make parts that are equivalent to Fair-Rite, but it is impossible to verify equivalency without detailed tests or datasheets.
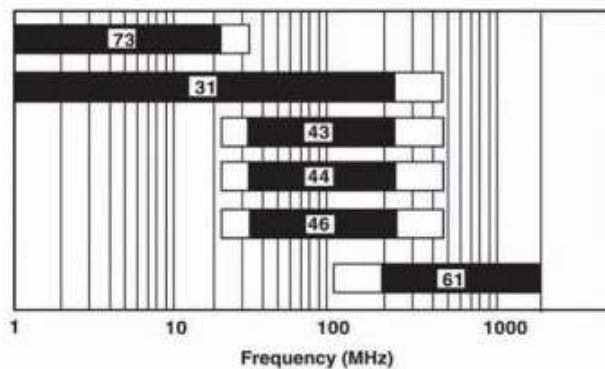


Figure 9 ~ Fair-Rite noise suppression materials. The categorization (73, 31, 43 and so on) is specific to Fair-Rite, although other manufacturers claim to make equivalent materials. According to this chart, for lower frequency noise suppression between 1 and 10 MHz, the 73 material would be a good choice and above 200 MHz, the 61 material would be a good choice. Illustration from fig. 26 of [Fair-Rite].

## I-5. Test Fixtures and Equipment

The preferred instrument for measuring ferrite bead impedance is an impedance analyzer that uses the *RF I-V* method. Another method, called *network analysis* or *reflection coefficient* method uses a vector network analyzer (VNA) (see references [HP], [Agilent1] and [Agilent2]). The RF I-V method is best because it measures applied voltage and induced current directly at the terminals of the device being measured. The VNA measures reflection coefficient (S11 scattering parameter) and converts the readings to complex impedances; however, as the measured impedance departs from the reference impedance (usually 50 ohms), the VNA measurement uncertainty increases. The rule-of-thumb best accuracy for inexpensive VNAs is when measurements fall in the 5 to 500 ohms range. The network/impedance analyzer with RF I-V fixture described below can have comparable accuracy over the 0.2 to 20k ohm range.

Our measurements were made with custom-built bead test fixtures and professional and semi-professional analyzers, the HP 4396A Network/Spectrum/Impedance Analyzer with a 43961A Impedance Test Kit (Hagen) and the DG8SAQ VNWA vector network analyzer (Reeve). The 4396A/43961A originally cost about US$40000 (1995 catalog price) and the DG8SAQ VNWA about US$700 (2013). The size and weight of the two test sets are roughly in the same ratio as costs. It is expected that the more expensive professional equipment provides higher measurement accuracy and lower uncertainty. We will discuss this in our results in Part II.
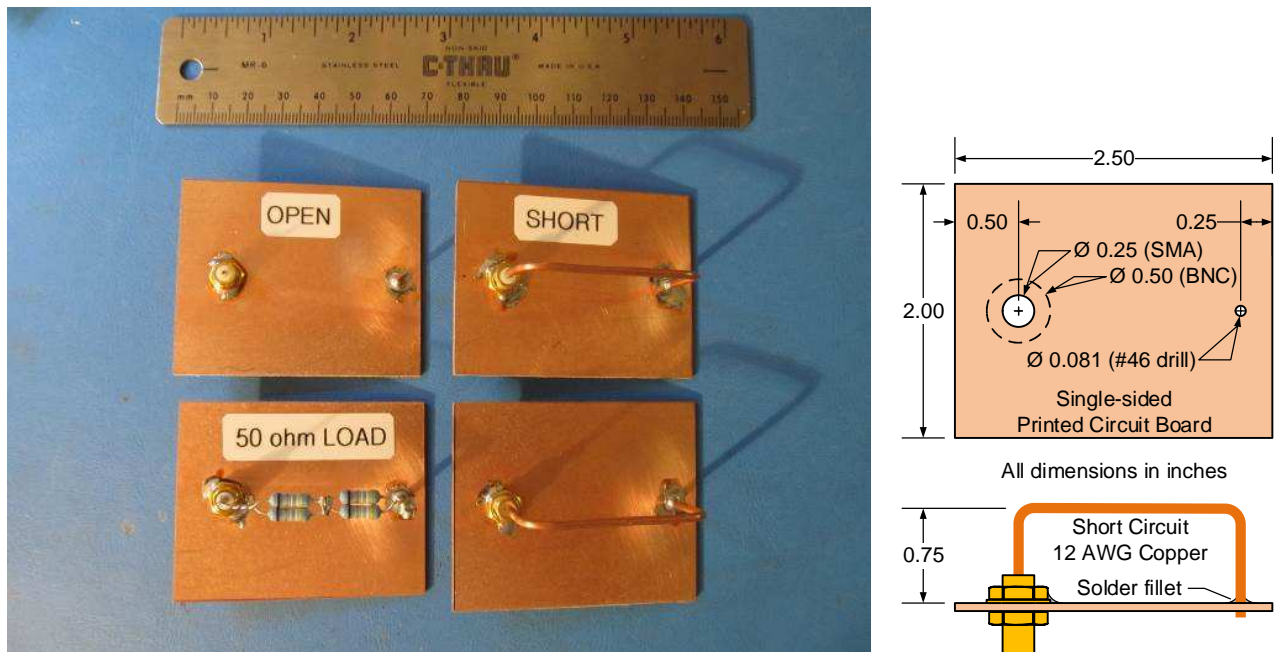


Figure 10 ~ Left: Test fixture calibrators for Short, Open and 50 ohm Load (two identical shorts are shown). The Short also holds the bead during measurement. Each fixture has a panel-mount SMA-F or BNC-F connector at one end (fixtures with SMA connectors are shown). Right: The dimensions shown are for the boards we built. The lower drawing shows the short circuit. The short circuit should be only long enough to hold the bead. The dimension shown will accommodate all but the largest clamshell beads.

The bead test fixtures were designed by one of us (Hagen) and were fabricated from sheets of single-sided copper printed circuit board (PCB) material. The fixtures use a connector that matches the analyzer – BNC connector for the HP 4396A/43961A impedance analyzer and SMA connector for the DG8SAQ VNWA. Three test boards are required for calibration and measurement, one each configured as a short circuit, open circuit and 50

ohm load (figure 10). These three serve as the Short, Open, Load (SOL) calibrators, and the Short fixture also is used to hold a bead during measurement. The shape and dimensions given are convenient for measuring a variety of clamshell beads. Solid beads also may be measured with this type of setup but require a little more work – the wire used for the short circuit and to hold the bead must be soldered and desoldered for each bead to be measured. We did not attempt to measure solid beads.
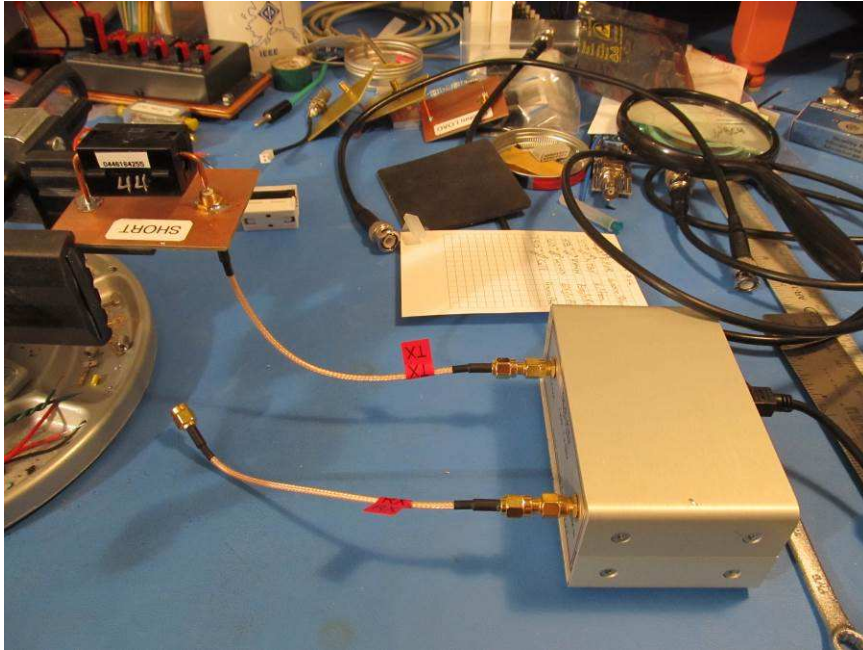


Figure 11 ~ Ferrite bead measurements.

Upper: The DG8SAQ VNWA (shown at lower-right) with the Short test fixture and a large clamshell bead (upper-left). The fixture is held in a work-holding vise. The VNWA was first calibrated with the extension cable and each of the Short, Open, Load fixtures. The red tag on the extension cable indicates its exclusive use with this particular VNWA.
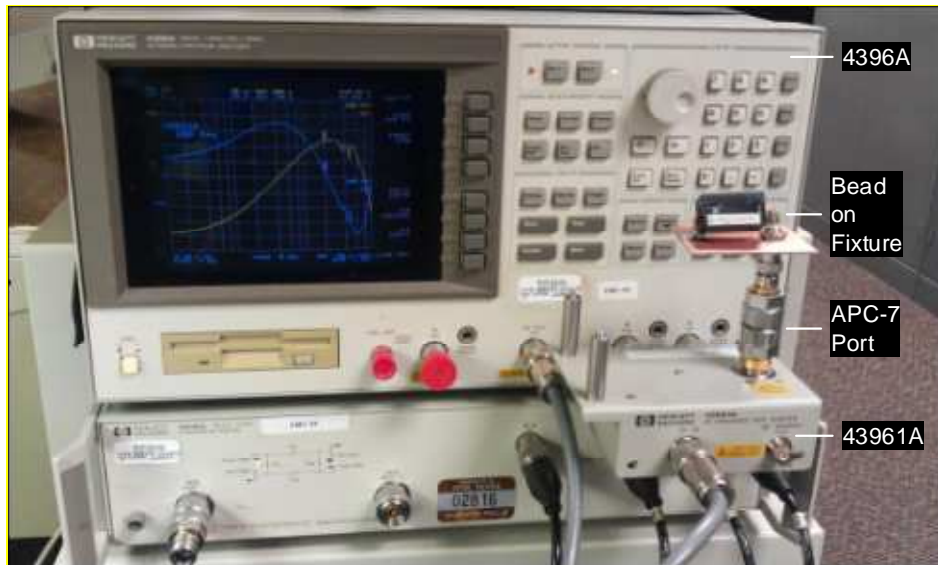
Lower: The H-P 4396A VNA with 43961A Impedance Test Kit shown with the Short test fixture and a clamshell bead. The 43961A is first calibrated using HP SOL calibrated references directly at the APC-7 port. Then an APC-7 to BNC adapter is connected at the port and is compensated with each of the custom Short, Open, Load fixtures.

Ideally, the test fixture itself does not affect the measurements at the frequencies of interest (usually < 100 or 200 MHz). As a practical matter, this is difficult to achieve. For example, the Short and Load fixtures have measurable inductance and capacitance that is impossible to eliminate. The reactance effects are most noticeable in mid-VHF range and above. The Short should be made as small as possible, but it can be made only so small and still hold a bead. For the 50 ohm load we used ordinary resistors, four 49.9 ohm resistors in series-parallel (Reeve) and two 100 ohm resistors in parallel (Hagen), and this configuration undoubtedly has some

inductive and capacitive reactance. As stated in the **Introduction**, the fixtures are adequate for our purposes (see next paragraph), which are to obtain reasonably good measurements comparable to manufacturer's data and to measure unidentified beads with unknown characteristics.

We each built our own SOL fixtures and calibrated the test sets as needed. We then placed a number of different clamshell beads on the Short fixture to measure their characteristics from 100 kHz to 200 MHz (figure 11). However, as we completed Part I of this article, we had not yet achieved an acceptable level of correlation between our measurements and recognize the calibration fixtures can be improved by, for example, reworking the connectors in the Open and Load fixtures and using surface mount device (SMD) load resistors to minimize reactance.  We will describe these changes in Part II. Meanwhile, Reeve's initial measurements with the fixtures described here corresponded quite well with published results of Fair-Rite and other manufacturers to within ±20%, but Hagen's reactance measurements especially did not correlate very well  to Reeve's or Fair-Rite's. Hagen's initial measurements, in which the correlation was not as good as expected, were made by calibrating the HP impedance test fixture with the three PCB SOL fixtures as described above. He was able to improve the measurements by calibrating with a discrete Short, nothing connected to the impedance analyzer for the Open and a discrete 50 ohm Load instead of the PCB SOL fixtures. We continue working on this issue and hope to resolve it up before publication of Part II.


### I-6. Prior Work

The fixtures described above were inspired by a previous design one of us (Reeve) developed for testing multiple beads in series. This earlier design used a wood platform holding a 50 mm wide copper strip (figure 12). A section of coaxial cable was connected to each end of the strip and used to hold the beads. The fixture had a very sharp resonance at 100 MHz, which interfered with the bead measurements. It gave reasonable results below about 30 MHz but was wildly inaccurate at higher frequencies.
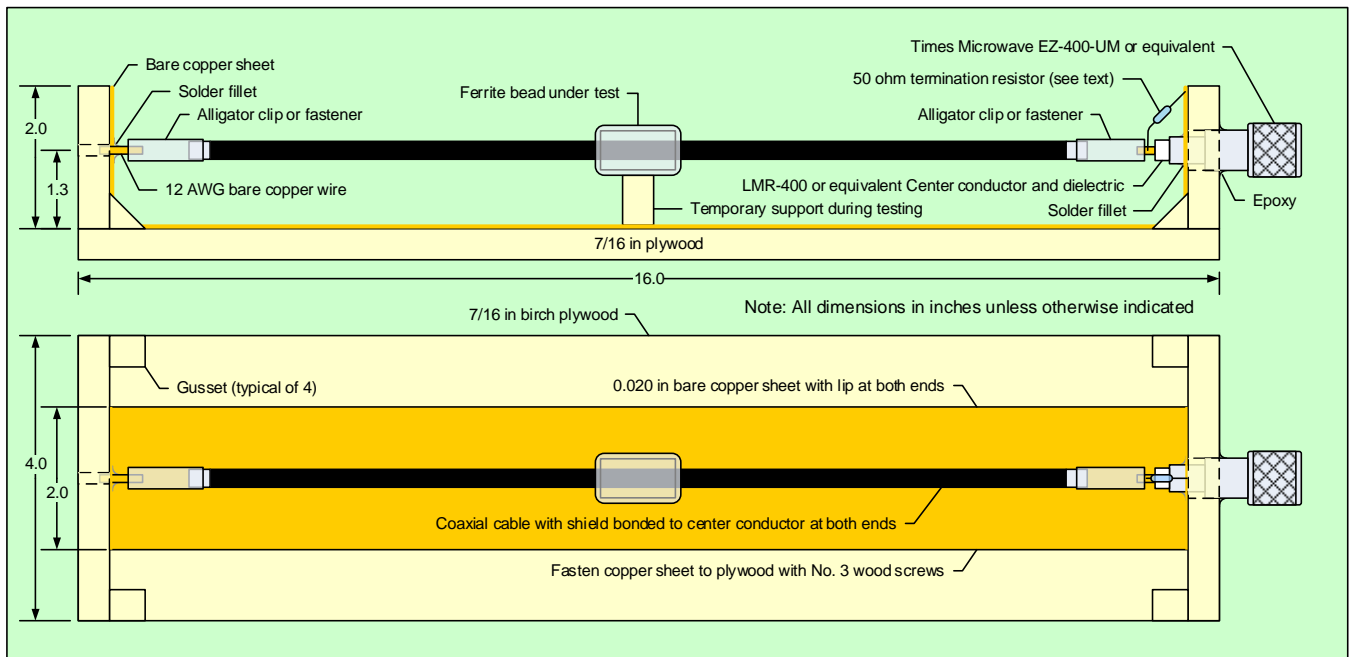
Figure 12 ~ Original ferrite bead test fixture. The fixture allowed at least five ferrite beads to be placed on the coaxial cable for testing. This fixture proved to be a failure for measuring ferrite beads above around 30 MHz.


## I-7. Conclusions

We discussed ferrites and their applications and described the test methods and fixtures that we use to measure ferrite bead impedance – the RF I-V method and reflection method. We each built three inexpensive printed circuit board test fixtures to provide Short, Open and Load for calibration and measurements. In Part II, we hope to resolve outstanding calibration issues and will provide comparative measurements of several clamshell beads using our fixtures and test equipment.


## I-8. References and Further Reading

References:
[Agilent1]  Agilent Impedance Measurement Handbook, 4$^{th}$ ed., June 17, 2009
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