Fixed Impedance Ratio Lower Leakage Inductance End-Fed Half-Wave Transformer
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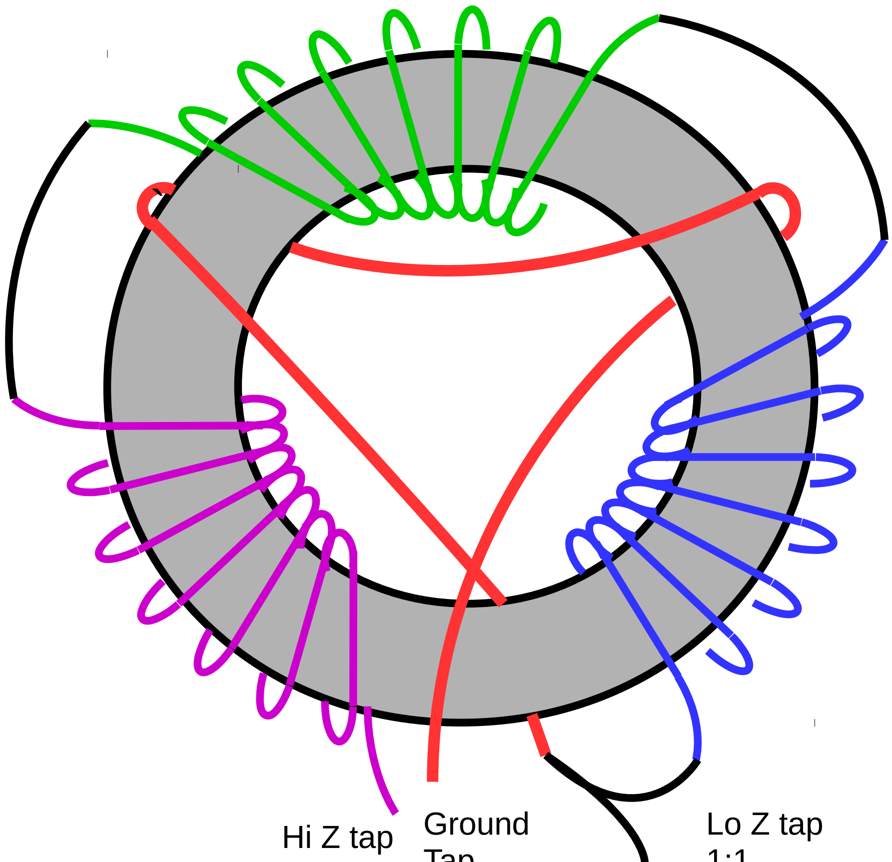
This document describes and characterizes a winding pattern for an autotransformer suitable for an end-fed half-wave antenna. These transformers must match loads of 2000-4000 ohms which is a challenging for a transformer to achieve properly. Both the leakage inductance and the winding capacitance of the transformer must be low for an end-fed half-wave antenna to be matched. However, leakage inductance causes losses in the ferrite core because ferrite material is lossy in the HF band, especially those with a permeability high enough to be effective for matching a high impedance load. Winding capacitance causes a reactive mismatch that may prevent power from being effectively delivered to the antenna, but as the dielectrics are generally far less lossy than ferrites, winding capacitance does not result in significant dissipated power in the transformer. If the winding capacitance can be compensated by an inductive reactance in the antenna, the winding capacitance does not prevent the antenna from being matched. A half-wave antenna may be made inductive by cutting is slightly shorter than a half-wave. However, if the antenna is cut too short, the impedance of the antenna drops and can no longer be matched by a transformer intended to match high impedances. If there is too much winding capacitance, the antenna would have to be cut too short to be an effective high impedance load and therefore can not be effectively matched.

A method of winding a transformer is presented here to reduce the leakage inductance and winding capacitance to low enough levels so that the transformer may be effectively used to match an end-fed half-wave antenna. To reduce the leakage inductance, the primary and secondary windings should be as close as possible. However, closer windings increase the winding capacitance so that there is a trade between the two parasitic effects. Winding a standard autotransformer with a high turns ratio only overlaps the primary and secondary windings for a small length of the entire coil, so that the side of the coil distant from the primary windings has less coupled flux. Because the windings are also typically spread out to reduce winding capacitance, this results in significant leakage inductance.

Instead of this approach, the winding shown here is a 3 primary:24 secondary windings, with the primary and secondary sharing three windings. The three primary windings are located 120º apart on the toroid. The secondary windings consist of three seven-turn coils placed between the three primary windings also 120º apart. This way each of the seven-turn secondary coils is between two primary windings. The three primary windings and the three seven-turn coil secondary windings are wired in series. Because the primary windings are in between the secondary windings, when the secondary winding coils are soldered together, the wires must be bridged over the primary windings. Because of the high voltages expected to be present in these high impedance ratio RF autotransformers, significant space between the wires should be left, at least a millimeter or two. It is best to use stiff magnetic wire that holds it shape so that it may be bent into shape in a pattern that keeps the windings from approaching each other.

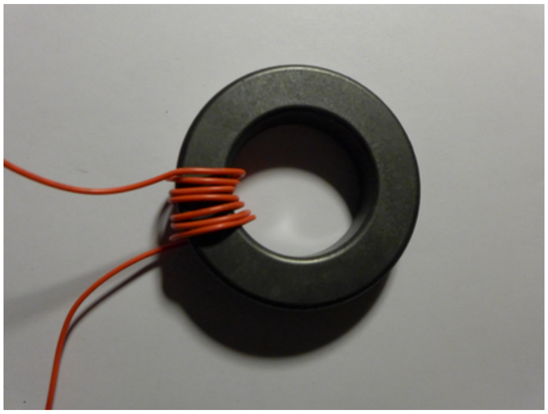
The winding pattern of the transformer is shown in the following figure. The windings are separated for clarity, but they should be spaced more equally around the toroid, except for the ground and the Hi Z tap wire, which should be separated by a centimeter or more.



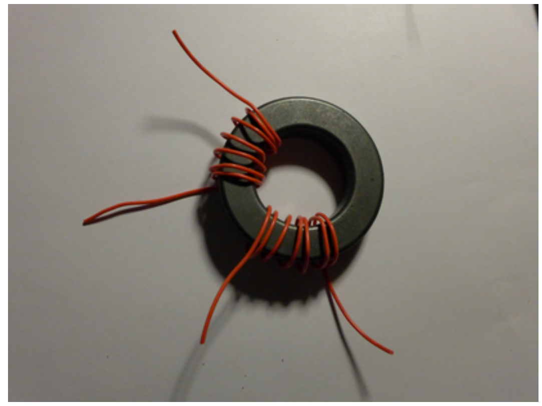
Winding pattern of the 3:24 turn end-fed half-wave transformer.

The red wire is the primary coil, and is wound three times around the core in an equilateral triangle pattern as shown. The three seven-turn secondary coils are blue, green, and magenta, and are located in between the windings of the red primary coil turns. The black wires show the connections between the four coils. The end of the primary coil is the Lo-Z 1:1 tap and is connected to the beginning of the first coil (blue). The end of the first coil is connected to the beginning of the second coil (green), jumping the wire over the primary coil wire so it does not come into contact. The end of the second coil is connected to the beginning of the third coil (magenta), again jumping it over the primary wire without touching the primary wire. Finally, the Hi Z tap is the end of the third coil.

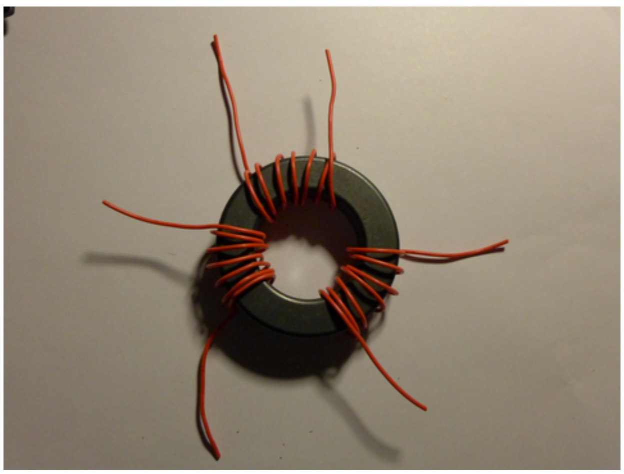
The following photographs show the progress of winding the coil. The toroid used is a FT240-43 toroid.



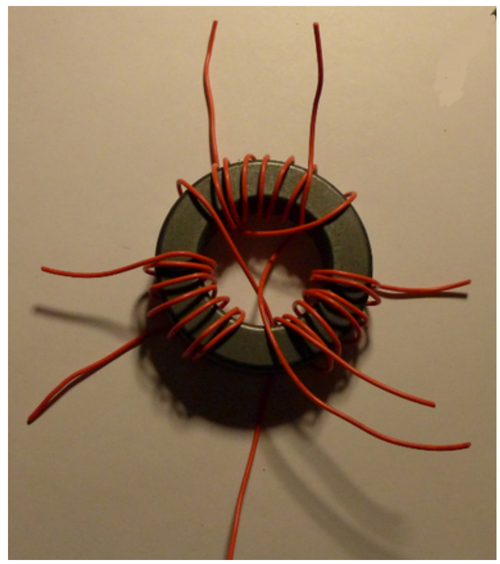
Wrap on first coil of 7 winds



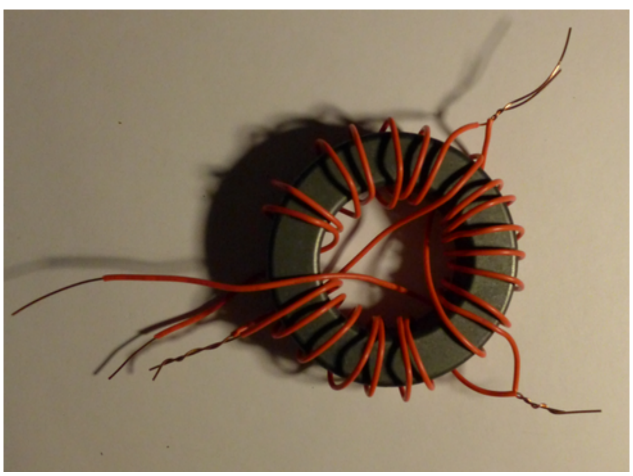
Wrap on second coil of 7 winds

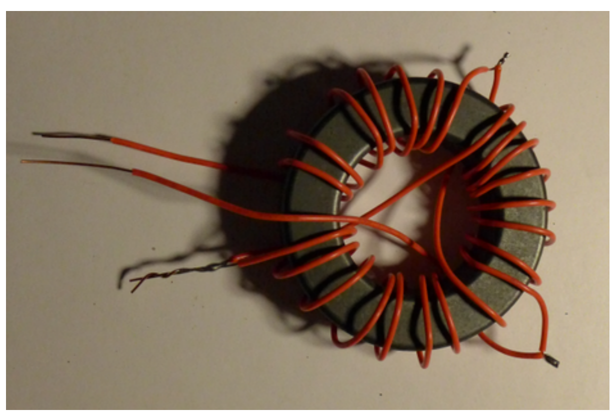


Wrap on third coil of seven winds



Wrap a fourth wire between the three coils in the same direction





Twist end of fourth wire on the beginning of the first coil, looping over the toroid. Twist the end of the first coil on the beginning of the second coil, looping over the fourth wire. Finally, twist the end of the second coil onto the third coil, looping over the fourth wire again. The four wires together make 24 loops over the core. When you are done, solder the twisted wires together. Keep the wires spaced apart, make sure they do not touch!

A test of the transformer with its secondary winding shorted to ground and an open circuit test was performed. The shorted to ground test allows one to determine the leakage inductance. For a frequency much lower than the self-resonant frequency of the primary winding, the reactance X is measured in ohms at a frequency f. Then the leakage inductance may be calculated as:

$$L_I = X/(2\pi f)$$

Secondly, the open circuit test may be used to determine the secondary winding capacitance. A series resonance occurs between the secondary winding capacitance and the primary and secondary windings in series (as referenced to the primary side). If f is the frequency of the series resonance, and N_p and N_s are the number of primary and secondary windings, respectively, the secondary winding capacitance can be estimated in the limit of small leakage inductance:

$$C_s = N_p^2/(8\pi^2 N_s^2 L_I f^2)$$

Finally, if a capacitor C_p is placed at the Lo Z tap and ground, the new series resonance frequency is given by

$$f = \left[8\pi^2 \left(C_s N_s^2/N_p^2 + C_p\right) L_I\right]^{-0.5}$$

And the new effective secondary winding capacitance is given by

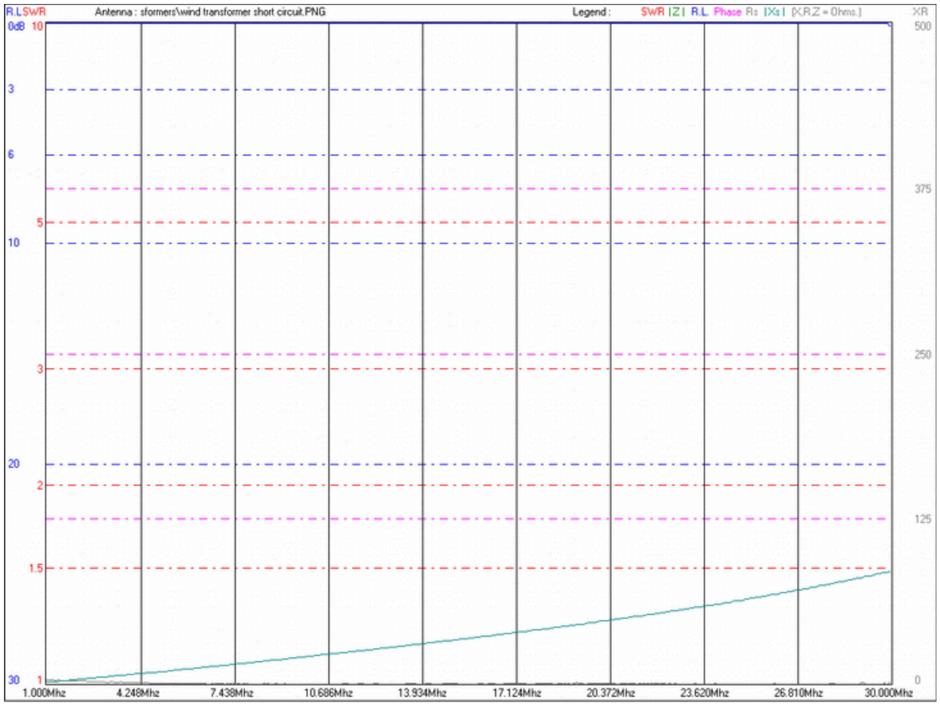
$$C_s' = C_p N_p^2/N_s^2 + C_s$$

The expected parallel resonance frequency with a shorted secondary is given by

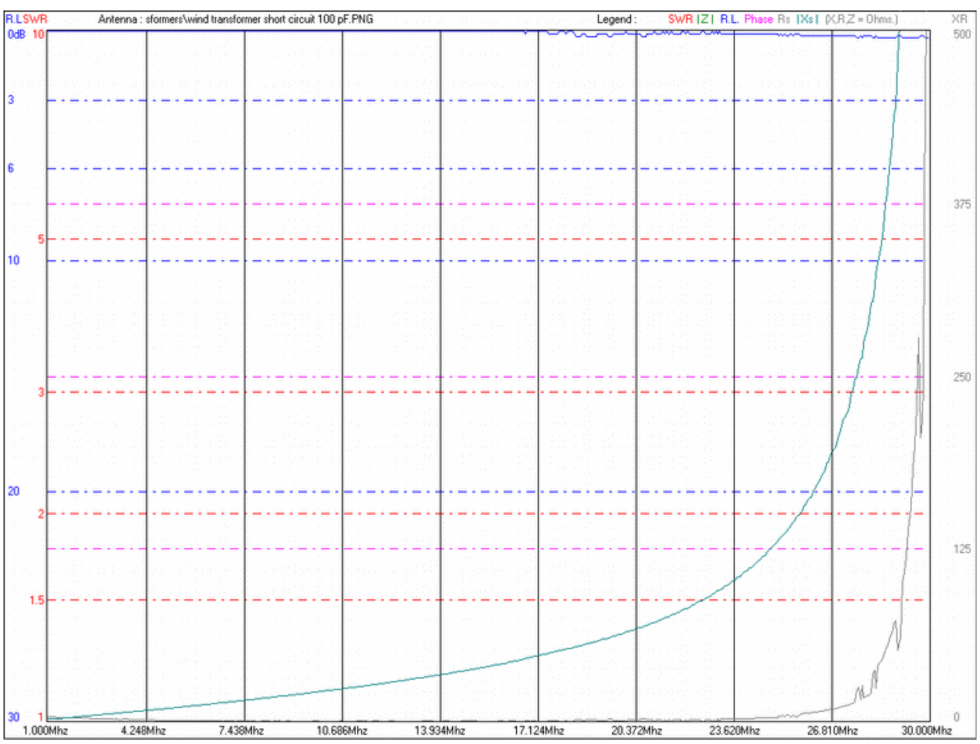
$$f = 1/(2\pi\sqrt{L_I C_p})$$

The measurements of the leakage inductance and winding capacitance are given below.

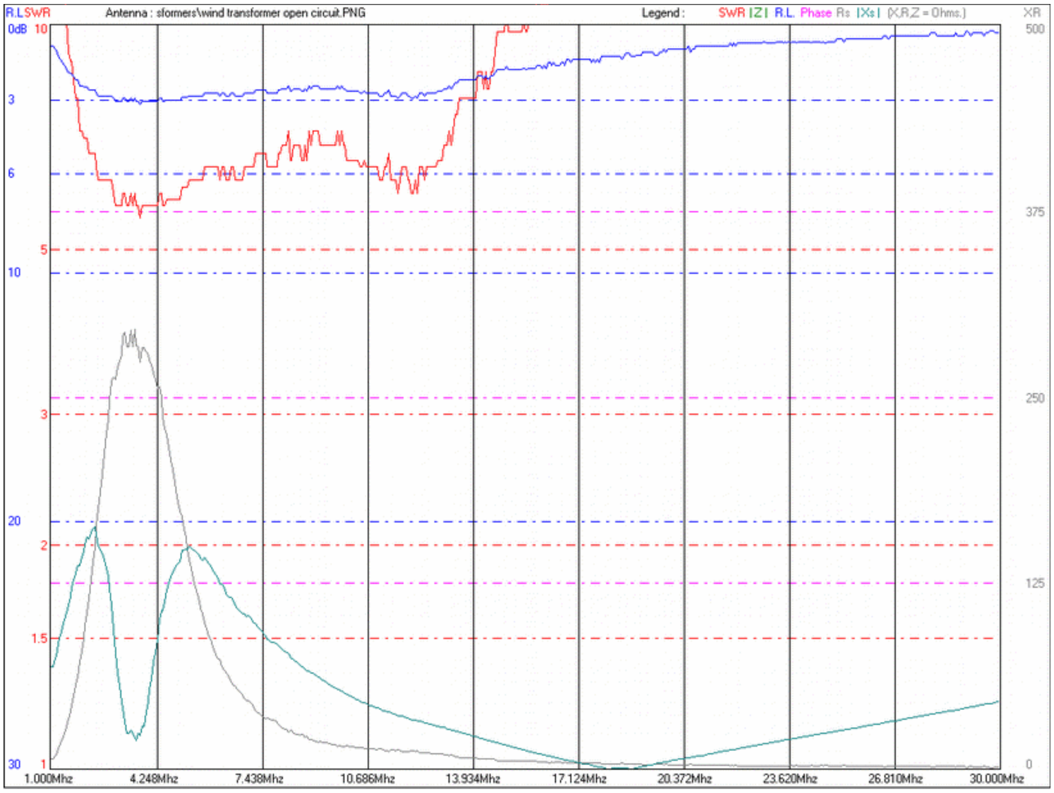
As the permeability changes with frequency, the leakage inductance also changes with frequency as well, so these formulas are approximate throughout a limited frequency range. Generally the permeability and therefore the inductance decreases with increasing frequency.



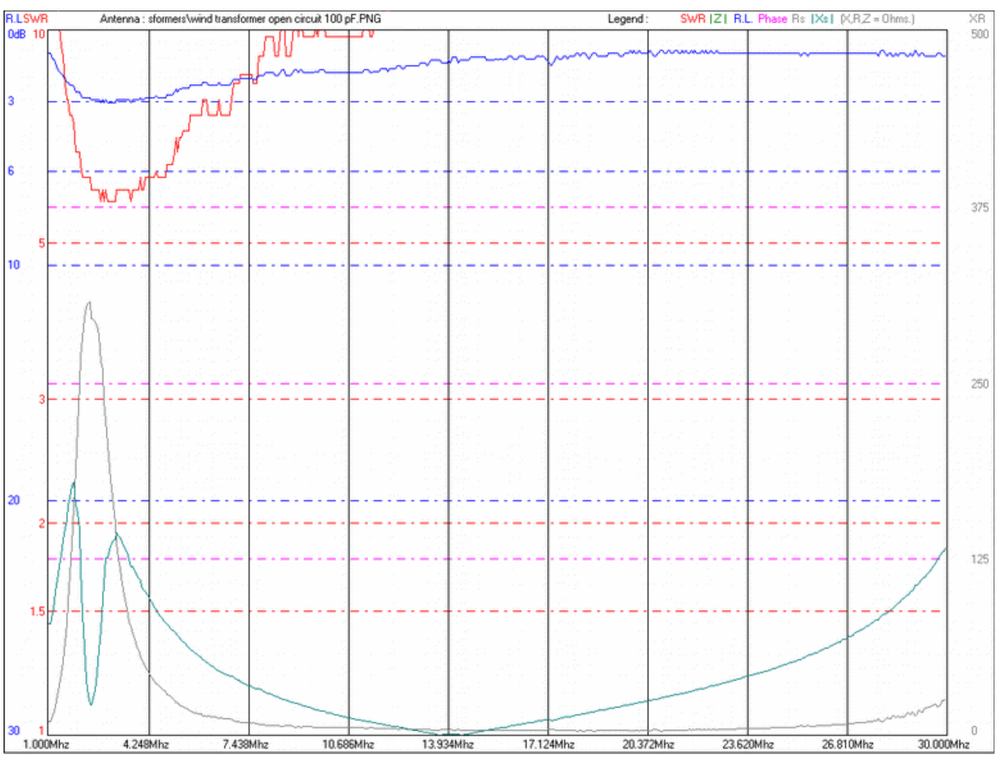
Short circuit reactance of the transformer. To calculate the leakage inductance, at a frequency well below the self-resonance frequency, such $f = 10$ MHz, observe the reactance, which in this case is approximately $X = 20\ \Omega$. Then the leakage inductance $L_I = X/(2\pi f)$ or approximately 0.3 µH.



Short circuit reactance of the transformer including a 100 pF capacitor across the primary.

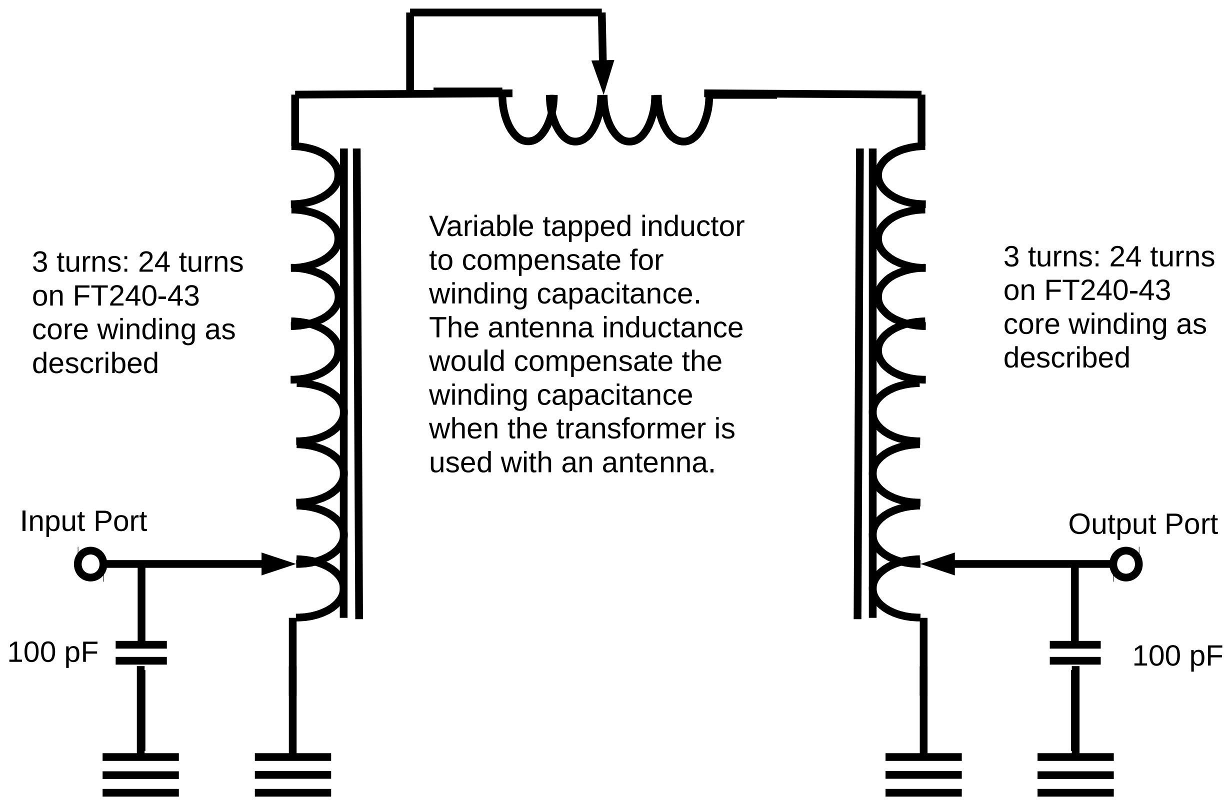


Open circuit reactance of the transformer. With $L_I = 0.3\ \mu\mathrm{H}$ leakage inductance, for series resonance to occur at $f_R = 18\ \mathrm{MHz}$, the secondary winding capacitance is $C_s \approx N_p^2/(8\pi^2 N_s^2 L_I f^2)$ or 2 pF.



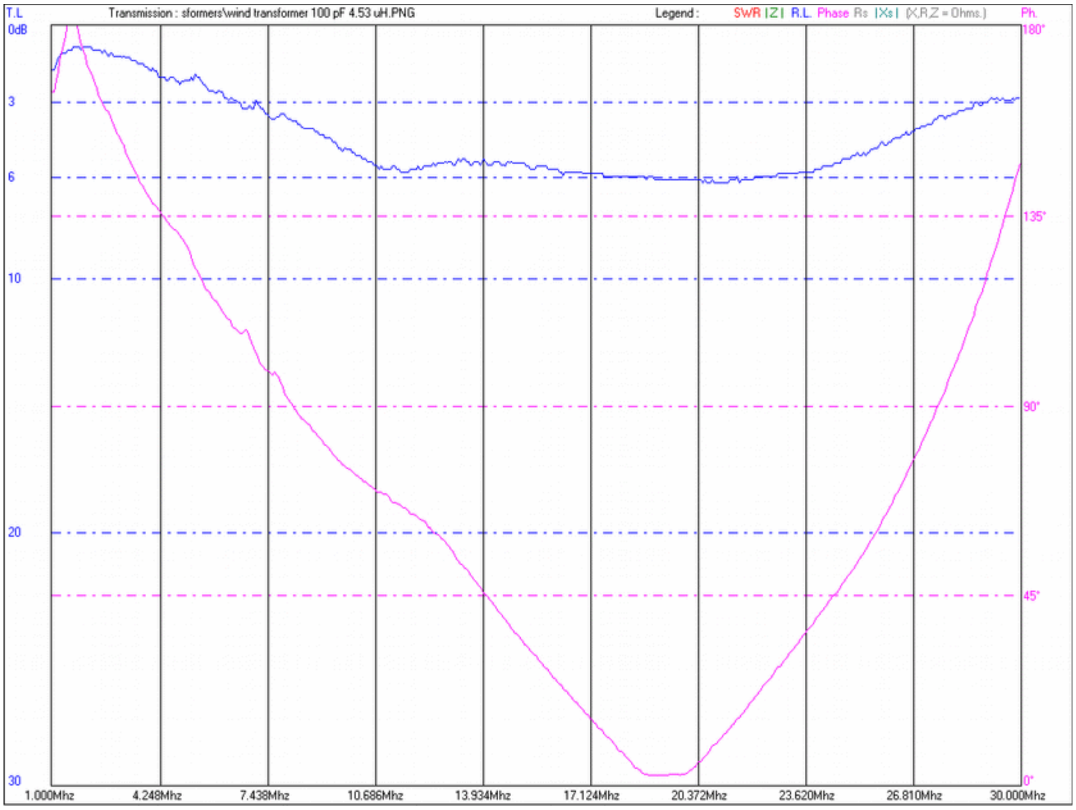
Open circuit reactance of the transformer with $C_p = 100\ \mathrm{pF}$ across the primary. The new resonant frequency is $f = \left[8\pi^2 \left(C_s N_s^2/N_p^2 + C_p\right) L_I\right]^{-0.5}$ or 13.6 MHz as predicted.

A transmitted through power test was performed with two identically wound transformers placed secondary-sides connected with an inductor in between to act as the inductance of the antenna to compensate the winding capacitance. If power is lost in the ferrite, it will be detected in the through power measurement. The setup is shown below.

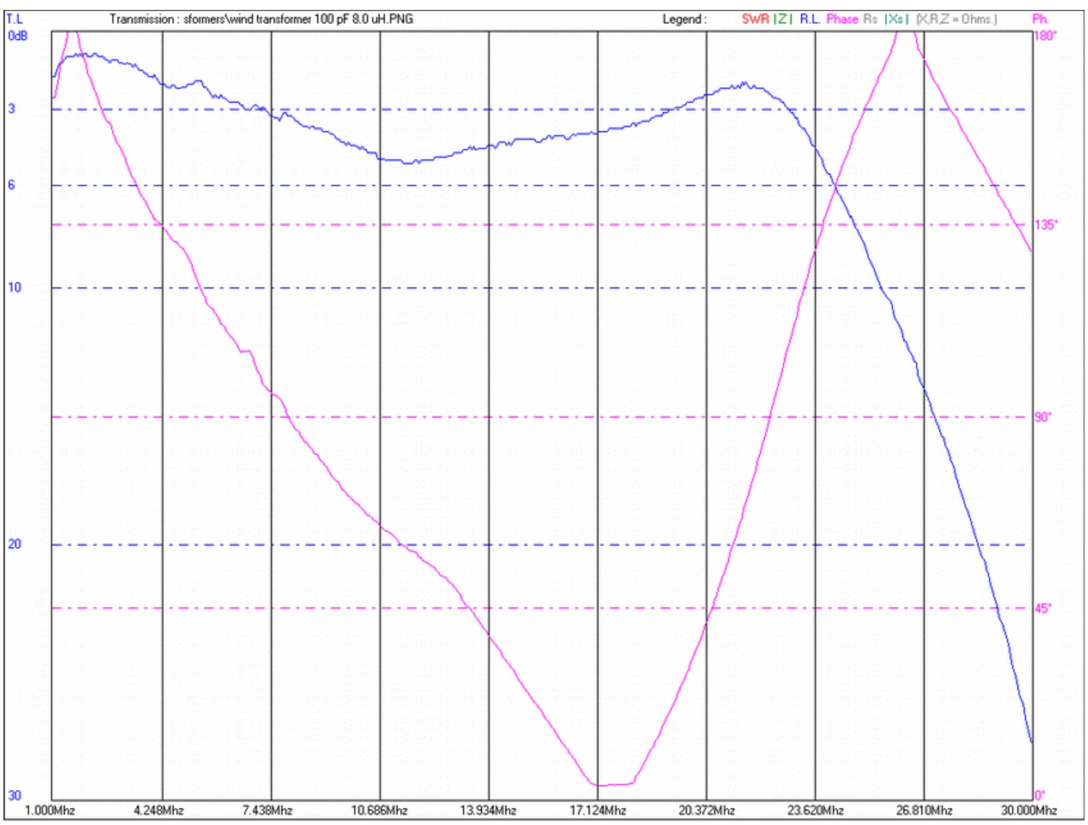


As the inductance between the two transformers is increased, the winding capacitance is resonated at a lower frequency. At the resonant frequency, the winding capacitance is an open circuit and therefore does not degrade the impedance transformation.

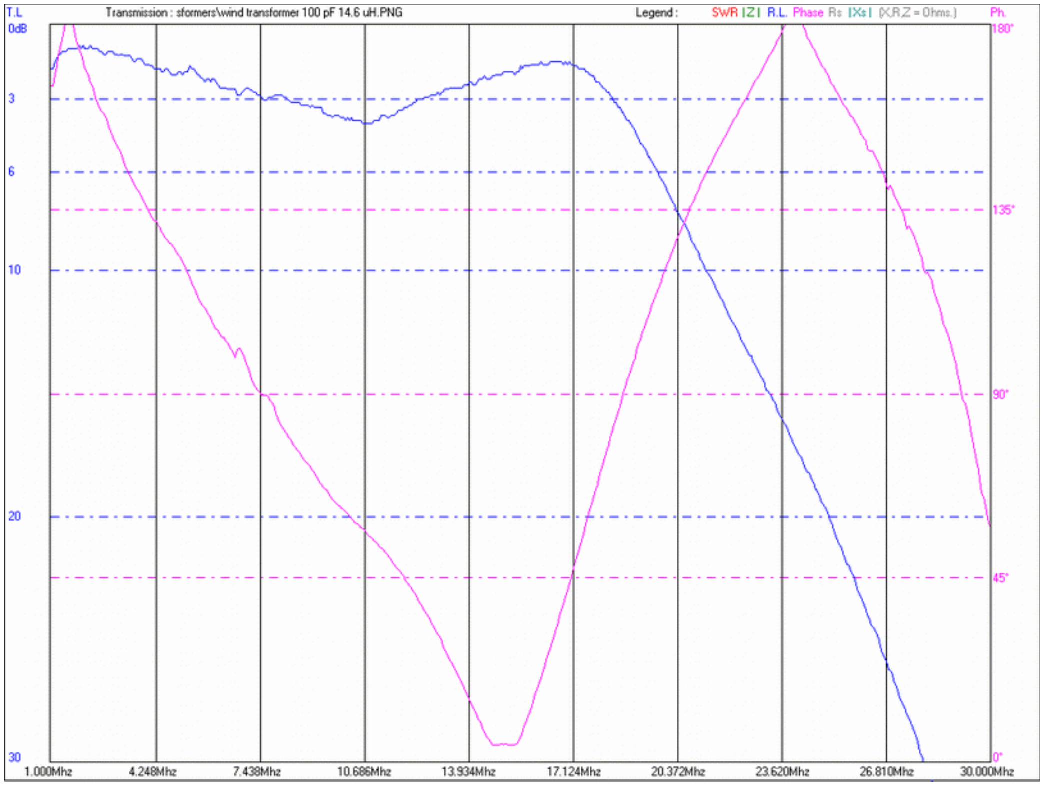
In practice, at each frequency for which the end-fed half-wave antenna is a half-wave, at a slightly higher frequency, the inductive reactance at that frequency resonates the winding capacitance. As long the winding capacitance is not excessively large, the shift in resonance frequency is small enough so that the impedance of the antenna is still high and can be effectively transformed. Even if the feedpoint resistance of the half-wave antenna drops, as it tends to do at the higher multiple of half-waves, the parallel resonance increases the effective resistance of the antenna so it can be efficiently fed.



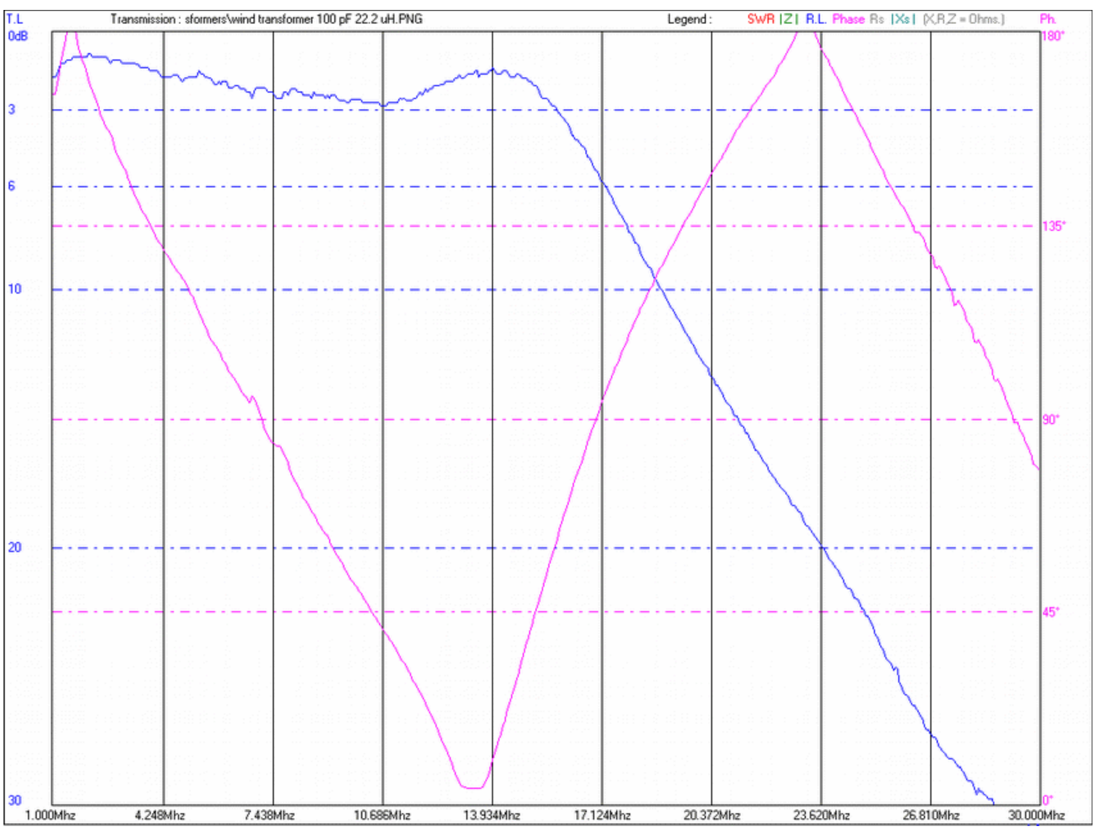
Back-to-back transformer test with 4.5 μH of inductance in series between the two secondaries of the transformers. Resonance occurs at about 30 MHz with about 1.5 dB loss per transformer.



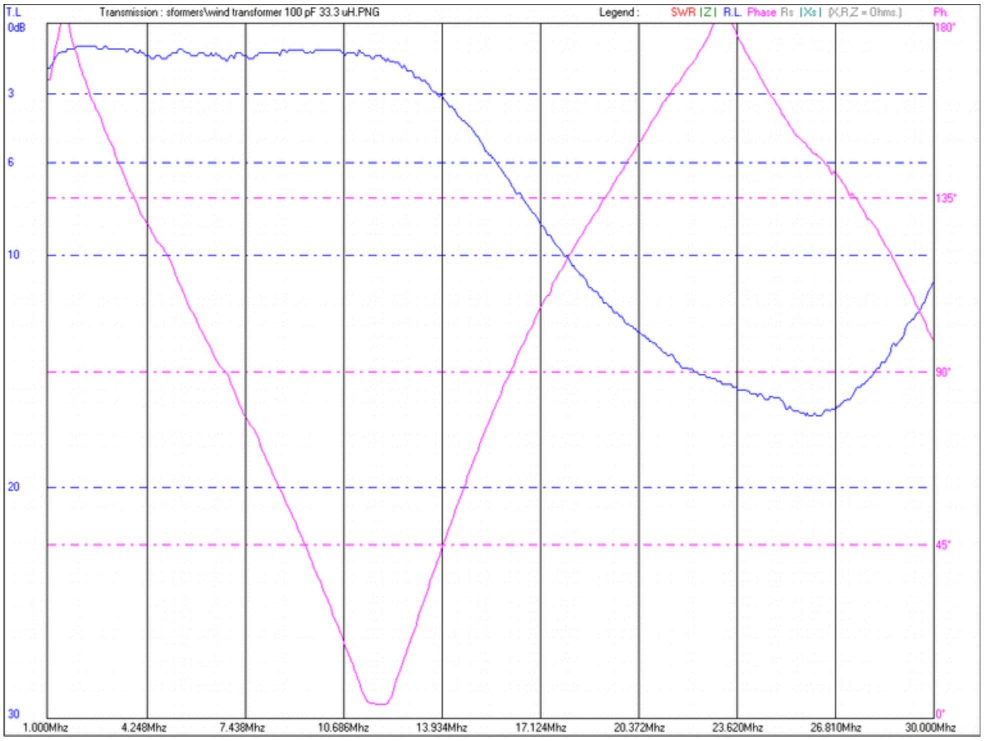
Back-to-back transformer test with 8.0 μH of inductance in series between the two secondaries of the transformers. Resonance occurs at about 22 MHz with about 1 dB loss per transformer.



Back-to-back transformer test with 14.6 µH of inductance in series between the two secondaries of the transformers. Resonance occurs at about 16 MHz with about 0.75 dB loss per transformer.

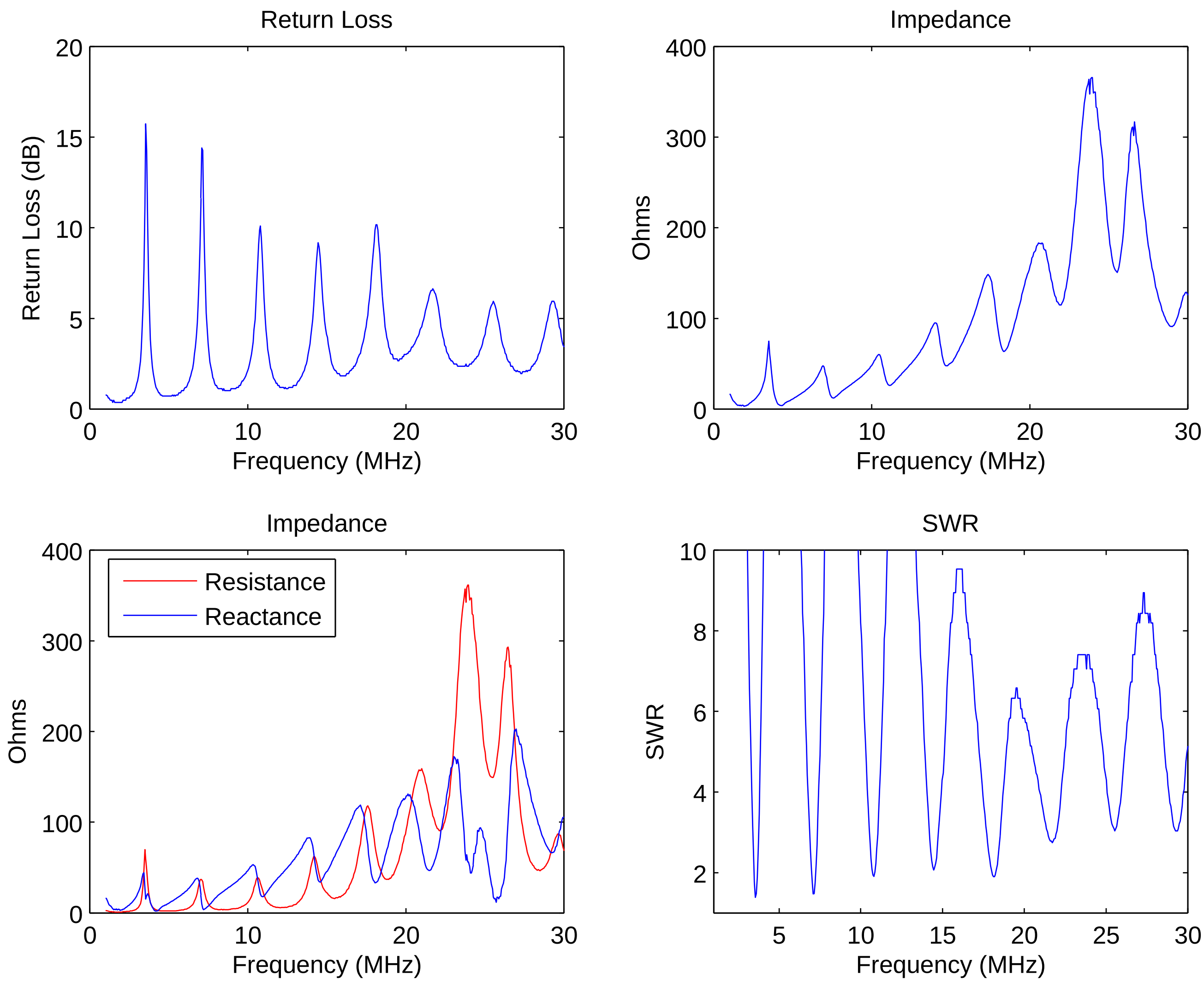


Back-to-back transformer test with 22.2 µH of inductance in series between the two secondaries of the transformers. Resonance occurs at about 14 MHz with about 0.75 dB loss per transformer.

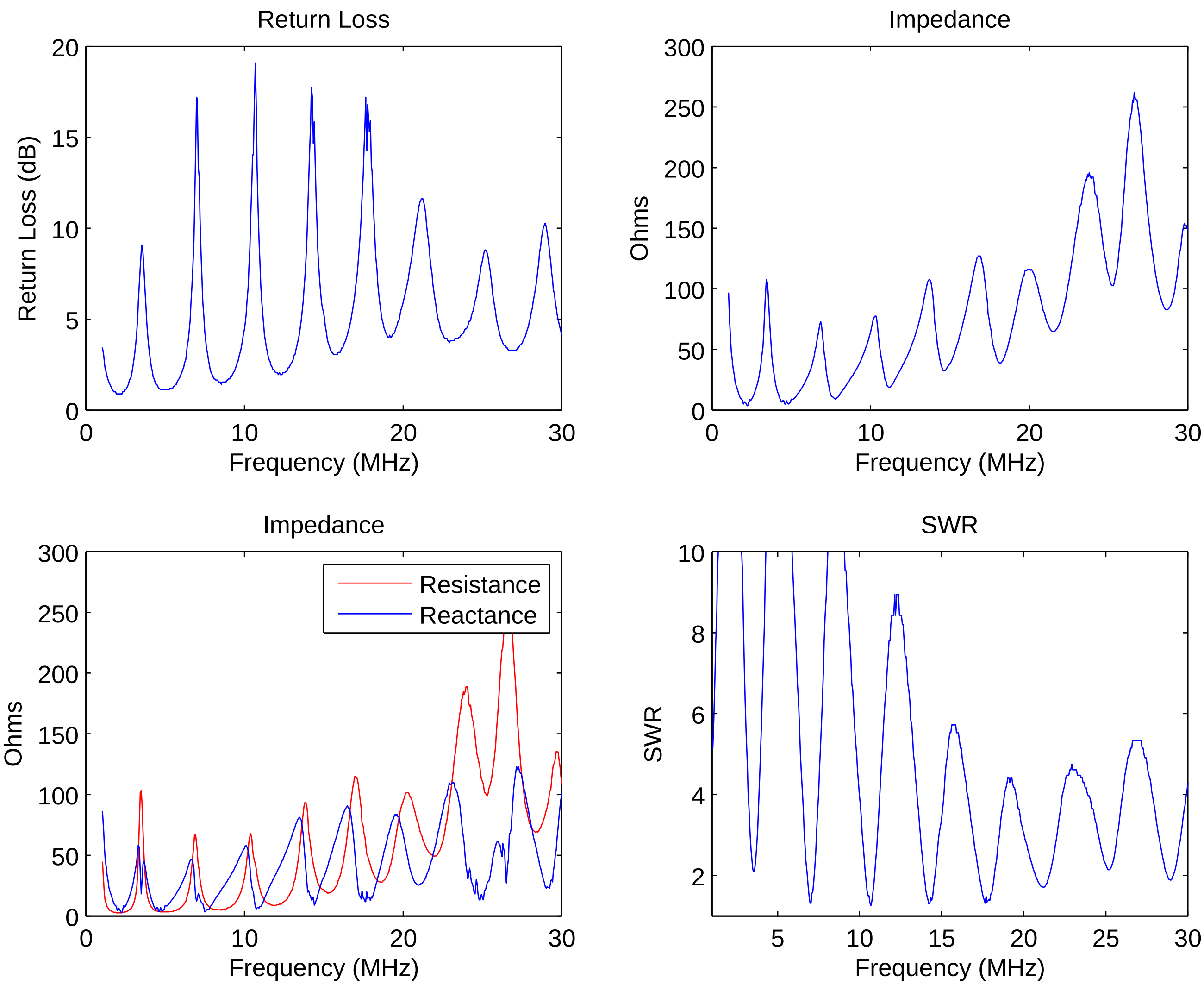


Back-to-back transformer test with 33.3 μH of inductance in series between the two secondaries of the transformers. Resonance occurs at about 10 MHz with about 0.5 dB loss per transformer.

This is an experiment showing the SWR and impedance of the transformer connected to a 40 m long wire antenna and a 4 m counterpoise. There were two taps on the transformer. The following shows the SWR for 64:1 impedance ratio (24:3 turns ratio) with a 100 pF capacitor across the primary:



This is the SWR for a 32.1:1 or 17:3 turns ratio



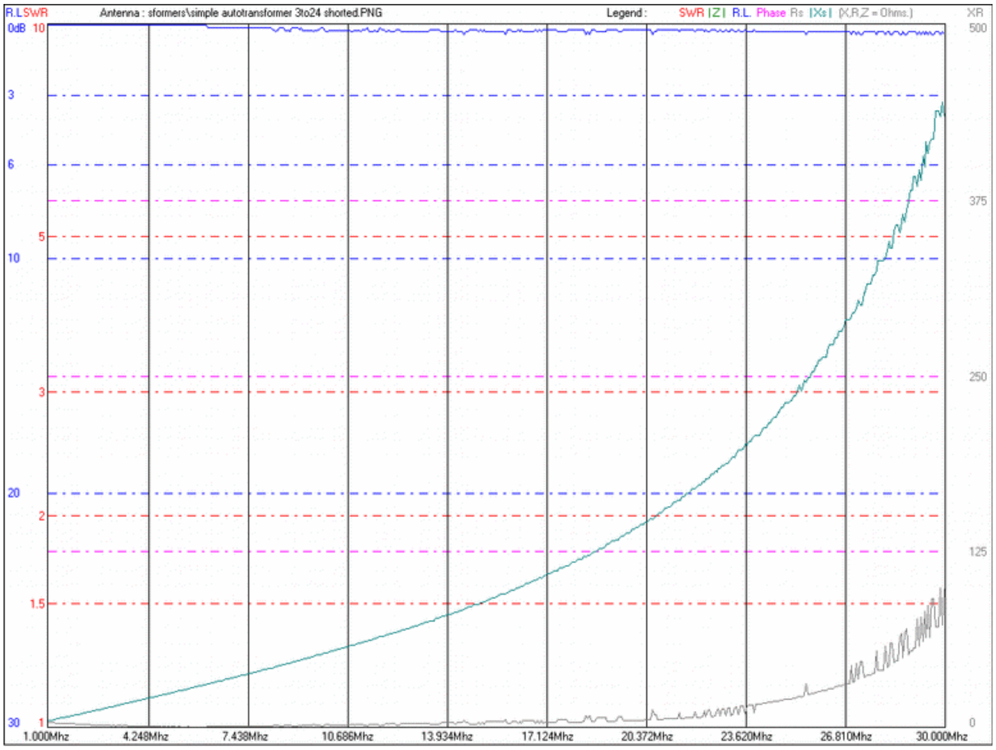
The SWR minimum is very narrow as the half-wave resonances. Between the resonances, the SWR remains above 6:1-8:1 (400 Ω to 600 Ω antenna impedance). At the higher bands, the impedance of the wire increases even in between the resonances, resulting in better matching at the half-wave resonances and in between the resonances. However, there still is probably some decrease in the SWR due to loss in the ferrite.

Using the antenna away from these resonances even using an antenna tuner would result in poorer performance as the impedance of the antenna drops greatly and much more current would flow through the counterpoise, reducing efficiency. For an antenna that can achieve a lower than 2:1 SWR on the 80 to 15 m bands, it is likely that a 49:1 impedance ratio would be a better choice than the 32:1 or 64:1 ratios.

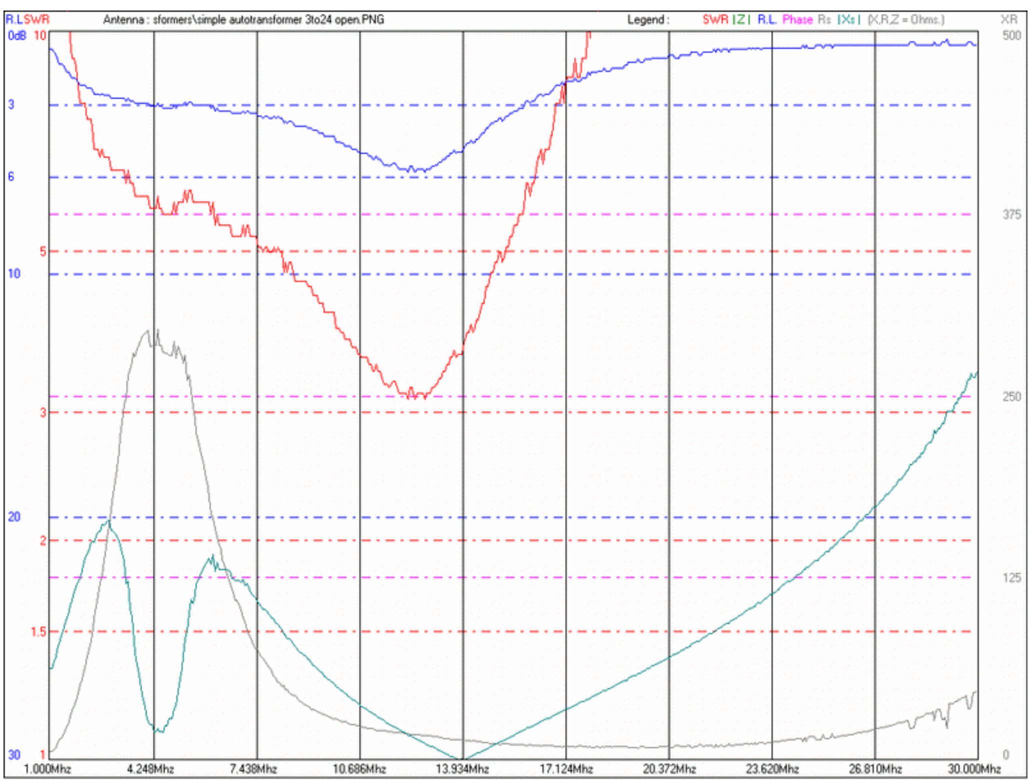
Comparison with a standard autotransformer.

A standard autotransformer was also wound with a 3:24 transformation ratio

This uses a more conventional winding technique with 3 turns of primary and secondary that are twisted together, and 21 more turns of separated secondary winding.



The short circuit test indicates 57 Ω ohms of impedance at 10.68 MHz which corresponds to 0.85 μH leakage inductance.



The open circuit test indicates a series self resonance frequency of 13.6 MHz which corresponds to a secondary winding capacitance of 1.26 pF.