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Impedance Matching Transformers for Receiving Antennas at Medium and Lower Shortwave Frequencies

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INTRODUCTION by John Bryant

All three of the co-authors have been involved in designing, fabricating and testing impedance transformers for many years. In fact, I first met Nick Hall-Patch when I asked his assistance in designing a matching transformer soon after erecting my first Beverage antenna in 1985. Nick, then as now, the Technical Editor of the International Radio Club bulletin, had written and/or edited some of the early articles on this subject. Subsequently, Nick and I co-authored several articles on impedance matching devices and associated subjects throughout the 1990s. The most recent such article "Fabricating Impedance Transformers for Receiving Antennas" was written by me in May of 2001 and published in numerous club bulletins and on the Internet. Nick and Bill were unattributed advisors on that article. With each of those articles, we were intensely aware that we were relying on conventional wisdom and the general state of the art at the time of authoring. We were also aware that there were some assumptions inherent in the basic formula governing the design of impedance transformers that we had not seen tested. At the time, the only source for technical data and design formula were in the professional realm and from manufacturers of ferrite toroids.

In early 2003, DXer George Maroti, mentioned to Nick that although he had been very successful in following the article guidelines for impedance matching transformers with isolated windings, he had noticed that ferrite core types 43, 73 and 75 had all been suggested for use in these transformers by different people. He inquired “what parameter(s) are critical in determining what material to use for a given frequency range?” and Nick had to admit that, other than the following the recommendations offered by the core manufacturers, he did not have a clear answer to that question.

Happily, our total reliance on standard formula and data had begun to change as Bill Bowers became more active as a radio enthusiast. Bill, educated in physics and electrical engineering, spent his career focused on the transmission of low-level signals and the magnetic properties of the electro-mechanical cables used in logging oil wells. In recent years, Bill has been heavily involved in developing circuits and antennas for the Lowfer hobby (150 to 300 kHz.) and has slowly built his array of sophisticated test instruments to the level that many professional labs would look at with envy.

About two years ago, Bill began a cycle of design and testing that would lead to a series of articles on impedance transformers for receiving antennas *at low frequencies*. This work led to some basic changes in the design formula for impedance transformers, at low frequencies.

Bill and I had worked together in testing antennas in years past. When he learned of our interest in investigating the design of impedance transformers for signals on medium wave and "Tropical Band" frequencies, Bill was very interested in participating. Fortunately, these frequencies - from about 300kHz to 5MHz - cover some of the most popular frequency ranges of radio amateur operation, as well. It took no persuasion at all to have Nick join the team as an essential advisor to Bill. Beside having been Technical Editor for IRCA for many years, Nick is also an electronics professional, being involved in the design, fabrication and operation of electronic instrumentation used primarily in oceanography. Throughout the study, Nick worked with Bill on some of the finer technical points of transformer design while I took notes and acted as cheerleader and scribe.

The three authors wish to extend special thanks to Guy Atkins and Mika Makelainen. Guy worked his usual professional-level graphics wizardry to reduce the file size of this article from over 4 megabytes to its current svelte size. We would also like to thank Mika for being willing to publish such an extensive article on this subject. That is, we hope, a real service to several of the radio-related communities.

Despite the fact that our previous articles on this subject were based on the state-of-the-art at the time, Nick and I are surprised that this study shows that the state-of-the-art and "conventional wisdom" was far from the best. I will be rebuilding all of my transformers based on the findings of this study; I suspect that Nick and probably *you* will be doing some rebuilding, too.

IMPEDANCE

Before discussing the design of impedance transformers, it is useful to briefly discuss the nature of impedance and impedance in receiving antennas, since many radio enthusiasts find the concept somewhat slippery. Impedance is a force that inhibits the flow of *alternating* current through a transmission line, transformer, coil, etc. When dealing with DC current flow, the only inhibition to current flow is simple resistance, measured in ohms. With *alternating* current, two other inhibiting effects come into play: inductive reactance and capacitive reactance. These are each generated by the fact that the current is alternating and by the physical attributes of the device or conductor in question. The summation of all three of these inhibitions to AC current flow is impedance, also measured in ohms.

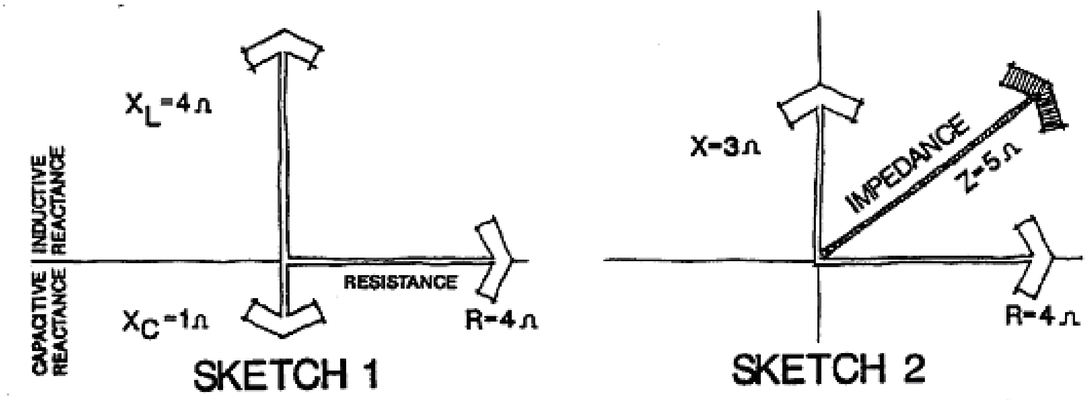
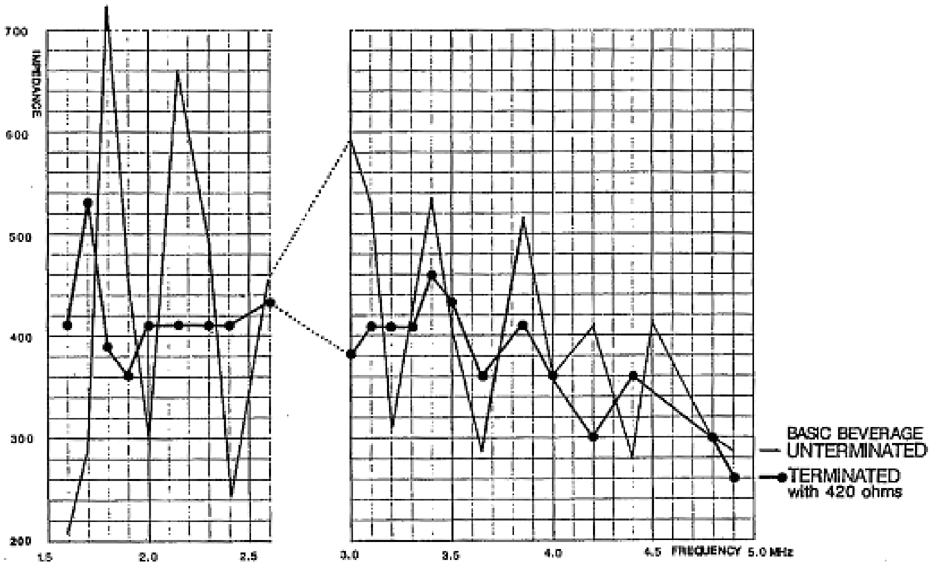


FIGURE 1

Why is all of this important? It is absolutely provable that the maximum signal power transfers from the antenna to the receiver when the resistive component of the antenna is equal to the resistive component of the receiver and the reactive component of the antenna and receiver are equal but opposite in sign. That is the ideal condition and the goal to which all antenna-matching devices aspire. Most modern communications receivers are designed for the 50-ohm impedance available from common RG-8 or RG-58 coaxial cable: theoretically, a perfect match. If 50-ohm coaxial cable is used to bring signals to a 50-ohm receiver, the primary impedance concern remaining is achieving a good impedance match between the antenna and the coaxial cable. That, of course, is the purpose of this study.

Although our work concentrated exclusively of the impedance device itself, it is important to remember that impedance of the antennas that we are attempting to match is a moving target. Impedance in antennas is dependant on their length, height above ground, configuration and often, on the frequency of the signals being received. Most Beverage antennas are said to have a characteristic impedance of about 450 ohms. For a cardioid (one direction) reception pattern, it is further recommended that the far end of the antenna be grounded through 450 ohms of non-inductive resistance. Figure 2 is from our 1989 article that illustrates the variation in impedance at various frequencies found by John in the 1200 foot "Okie" Beverage. Unfortunately, our instrumentation at the time only tuned down to 1 MHz. Note also how much more consistent the impedance becomes when the antenna is properly terminated at the far end. This is a real argument for always terminating Beverages unless reception off the backside is really desirable.

Given the widely varying (with frequency) impedance of Beverage and similar receiving antennas, we felt that it was most reasonable to attempt to maximize the efficiency of the impedance transformer about the approximate characteristic impedance of Beverages (450 ohms) and to also develop a design at 900 ohms to work with Deltas, Flags, Pennants, etc.



Beverage fabricated from 18 ga. wire, mounted at aprox. 8'-0"

IMPEDANCE CURVES • 1200' OKIE BEVERAGE • WITHOUT MATCHING

FIGURE 2

DESIGN CONSIDERATIONS

Initially, our general design goals were to determine the most appropriate ferrite type, winding pattern and turns count for several frequency bands within the 150 kHz. to 7 MHz range. We expected to recommend one design if you were for MW+LW, maybe a second for MW only and a third design for MW+ lower SW. We did not imagine that there would be a single design that would work fairly well at LF, and excellently at least up to 5 MHz, with some service above that, though this would be our ideal, since many Listener DXers are somewhat interested in DXing the few remaining LW broadcasting stations and are intensely interested in DXing either the MW band or the so-called Tropical Bands (up to about 5.2 MHz.) or possibly both. Fortunately, Bill's rather extensive preliminary design and testing phase at the beginning of this project indicated that an "ideal" broadband design was within reach, so developing the optimum selection of ferrite type, core size, winding pattern, and turns count for that single design became our final goal.

Core Size and Configuration

After a decent amount of discussion among the team, we decided to concentrate our design on the toroid (lifesaver-shaped) form of ferrite core. It is possible to construct impedance transformers from "binocular" and bobbin-shaped cores, but the toroid is the most common form available and, happily, it will accommodate a wide range of winding patterns and turns counts. We also decided to concentrate on medium-sized toroids of .82 and 1.14 inches outside diameter. It is possible to fabricate good impedance transformers from much smaller cores, but these demand much smaller wire and a high degree of dexterity. Further, both Bill and John have had multiple failures of very small transformers in the high static electricity environment of Oklahoma in the springtime. We also decided to use #30 wire with Kynar insulation, since it is commonly available from Radio Shack and electronic parts houses in small rolls of multiple colors.

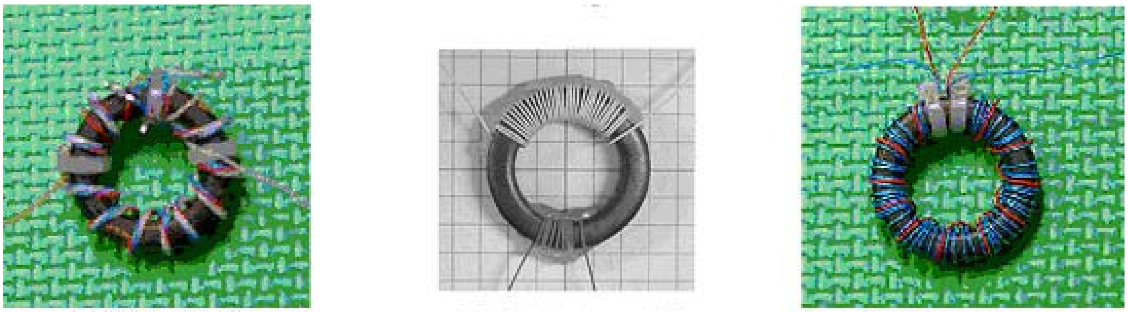
Material Type

Initially, we selected three core materials: Amidon's types 43, 61 and 75. These were selected based on Amidon's technical data and, to a degree on our own experience. Nick and most people who concentrate on MWDX have long favored Type 43 material, while John has been recommending Type 75 in recent years. After the preliminary round of testing, we eliminated the Type 61 material from further consideration because its magnetic characteristics generated a very high number of turns at the lower frequencies. The main series of tests were then conducted on cores of Types 43 and 75. *Please note that Type 75 and Type J may be interchanged at will, based on availability: refer to the 450 Ohm Recommendations and Final Tests, pp. 13-14.*

Winding Pattern

Certainly the most controversial issue surrounding the design of these and similar transformers is the winding pattern. There are really three choices: A) close-wound primary and secondary windings carefully placed as far apart as possible on opposite sides of the toroid [called "SS" windings in this study]; B) an overlapped pattern where the primary winding was carefully spread around the entire toroid and then the much smaller secondary winding was carefully wound atop the primary winding, but also equally spaced around the toroid ["OL" here]; C) the primary and secondary created simultaneously by winding what might be called a "quadra-filar" cable of wire around the core. Four wires of different color were twisted together in a cable (one turn per .75 inch), wound around the core the proper turns count for the secondary and then three of the four wires were connected in series to form the primary while the fourth wire was connected by itself as the secondary. This pattern was called "TW" winding here.

Preliminary testing determined that the TW and OL winding patterns were almost indistinguishable from each other, electrically. Since the TW winding was MUCH easier to accomplish and since Bill had many transformers to wind during this study, we agreed to eliminate the labor-intensive OL winding pattern from the tests until the very end. At that point, Bill would test the optimum design with all three winding patterns.



TW (twisted) winding

SS (side-by-side) winding

OL (overlapped) winding

FIGURE 3

The controversy between proponents of the close-wound but spread-apart SS winding pattern and that of the more closely meshed OL and TW patterns is somewhat difficult to visualize. The advocates of the traditional overlapped design (OL) tend to claim that such close intermeshing generates the most efficient signal transfer. Advocates of the quadra-filar TW design tend to believe that their pattern is "just as efficient, electrically, and a whole lot easier." Advocates of the spread apart SS windings (see Fig.3 center) are generally concerned about one of two things. First, it is well known that there is capacitive coupling between the primary and secondary windings of transformers (Cp-s in Diagram A in the Technical Discussion at the end of this article). This capacitive coupling essentially allows signal energy to bypass the transformer altogether and not gain the benefit of the impedance transformation process. A second concern expressed by SS pattern advocates also relates to that capacitive coupling. One of the secondary reasons to use a transformer between an antenna and a lead-in is to break the ground loop between the listening post's earth ground, and household and other power line grounds that are connected to the radio. This concern is that the more turns you have on a transformer core, especially twisted turns, the higher the capacity between those windings, therefore the more likely a ground loop path via that capacitance from power line (coax) ground to the isolated ground at the matching transformer. It is only fair to note that both Nick Hall-Patch and John Bryant have been advocating the SS winding pattern in the past few years.

Turns Count

Standard references and manufacturers data give two general equations that, together may be used to determine the turns count for the winding of an impedance transformer:

The desired inductance (**L**) of the primary winding **$L = X_L/2\pi f$**

where **L=** Inductance in millihenries **X_L=**Reactance in ohms **f=**Lowest frequency of operation in kHz

X_L may be found by multiplying the impedance of the antenna to be matched by a factor of 4.

After finding the inductance (**L**) needed for the primary winding, we can apply the following formula to determine the number of turns needed for the primary winding.

$N = 1000 \sqrt{}L/A_L$

In narrative, this formula should be read: Number of turns required (**N**) is equal to 1000 times the **square root** (√) of the Inductance (**L**) divided by the constant **A_L**. A_L = Core Constant (from Amidon in mH/1000 turns.) Note that other manufacturers of ferrite toroids may use a different Core Constant; refer to their technical data for proper values.

Note the X_L factor in the first equation. All sources give that factor as "four times the impedance of the antenna to be matched. The multiplier of "four" is dubbed hereafter as the "K" factor and is never explained in the standard references. The authors are unaware of any empirical data that has been published to support the value of this particular multiplier being equal to 4. During Bill Bower's study of impedance transformer design for LF use, his data support a K value much more nearly 6. We have no means of determining, except through this study, whether the conventional value of K= 4 is appropriate for these design frequencies or whether some other value will be more appropriate.

Temperature Effects

During Bill's low frequency studies, he discovered that the ambient temperature had significant effect on the properties of ferrite toroids. In the recommendations section of this study, we present his findings for temperature-related changes to transformers at these design frequencies.

TEST PARAMETERS

During the preliminary round of testing, there was considerable discussion as to what factors to consider as we began the winnowing process. The main test equipment, the Hewlett-Packard 4192A Impedance Analyzer, could accurately measure far more factors of transformer performance than would be necessary to develop the "ideal" impedance transformer. The 4192A covers variable testing frequencies from 5 Hz to 13 MHz and is a very accurate high-end laboratory device which may be used to perform both network analysis and impedance analysis on complex electronic devices and basic components. Both floating and grounded devices may be tested. We finally settled on four factors to test at sixteen different frequencies from 100 kHz. to 7MHz.: Impedance, Angle, SWR and Loss.

Impedance

The ideal transformer should accurately transform the 50ohm receiver or coax impedance up to match the 450ohm impedance of the antenna throughout our primary frequencies of interest. Given the physics of transformers, however, one winding turn more or less might add or subtract ten to 30 ohms. The practical goal, therefore, became designing a transformer that would produce a smooth impedance curve vs frequency "at or near" 450 ohms. The same smooth performance was also sought with the 900 ohm design.

Angle
The angle recorded in the impedance tests is the angle between Impedance and pure Resistance as seen in Sketch 2 of Figure 1. An angle of 0 degrees would be ideal and would describe a transformer impedance of pure resistance. A positive angle represents the presence of an amount of Inductive Reactance while a negative angle represents the presence of Capacitive Reactance. *Essentially, the nearer to zero, the better. Capacitive Reactance (negative angles) represent capacitive coupling between the windings and is undesirable.* Refer to the Technical Appendix for further discussion.

SWR
Standing Wave Ratio is a primary concern in the design of *transmitting* antennas. Its use in the design of receiving antennas is much less common. In this case, SWR actually measures the efficiency of the transfer of signal energy from the antenna to the transformer. On page 7-17 of the Third Edition of his book *Low-Band DXing*, 160 meter guru John Devoldere states "A good transformer has an insertion loss of typically less that .5 dB and an SWR = 1.2 to 1." Essentially, in this case, *we hoped that our final design would maintain an SWR of* ***less than 1.2 to 1*** *throughout the frequencies of interest.* As it turns out, the actual insertion loss is rather small. At 1.6 to 1, the insertion loss is only .2 dB and it reaches 1 dB at just above SWR of 2.6 to 1. Refer to the Technical Appendix for further discussion.

Loss
The loss measurement recorded in this test series is the actual internal loss within the transformer from all sources. Naturally, *lower is better.*

TEST PROCEDURES

Two identical transformers were wound for each design tested. They were wound on carefully matched cores. The H-P 4192A, a highly automated instrument, was able to develop the first 3 data points (Impedance, Angle and SWR) for each frequency of the transformer tested in a single "Impedance Test." During that test, the transformer was attached to the test facility of the 4192A and terminated with 50 ohms. A second "Loss" test was performed to determine that final data point at each frequency. In this second test, the two identical transformers were connected in a "back-to-back" array so that a pure 50 ohms was presented to the test instrument from each end of the array. Signals of the 16 different frequencies were then passed through the array and the internal loss of a single transformer was determined by dividing the results of the test by two. A detailed discussion of the test procedures is found in the Technical Appendix.

TEST RESULTS - 450 OHMS

The results of the test runs for the 450 ohm transformer are presented on the following four pages. They are worthy of close scrutiny and they are presented in their entirety. In general, the desired results were the lowest loss, coupled with the least degradation of performances at the high and low frequency extremes of the test spectrum and smooth operation in the mid frequency range. Also, all other things being equal, fewer turns are preferred over more. These data fields are followed by discussions of the findings and design recommendations. If your frequency band of interest is not exactly that we have used (for instance, if you are *only* interested in medium wave frequencies), your choice of the "ideal" design might be slightly different than ours.

The first core tested is a .82 diameter ferrite toroid from type 43 material. We have used the Amidon nomenclature and refer to this toroid as "FT-82-43." "N" is the number of turns of the transformer.

FT-82-43

450 ohms

RFT-82-43-TW --Impedance , SWR & Insertion Loss

FT-	82-43				82-43				82-43				82-43			
N=	26/78-TW				20/60-TW				15/45-TW				11/33 -TW			
.freq	Z	angle	SWR	Loss	Z	angle	SWR	Loss	Z	angle	SWR	Loss	Z	angle	SWR	Loss
MHz	Ohms	deg.		-db	ohms	deg.		-db	ohms	deg.		-db	ohms	deg.		-db
0.1	426	12.2	1.24	0.285	400	19.3	1.43	0.509	357	29.4	1.80	1.076	275	43.8	2,75	2.048
0.3	443	4.9	1.09	0.124	435	8.0	1.15	0.182	420	12.8	1.26	0.349	384	22.2	1.53	0.667
0.5	447	3.3	1.06	0.096	442	5.3	1.09	0.130	433	8.6	1.16	0.218	412	15.3	1.32	0.400
0.7	449	2.5	1.04	0.089	445	4.1	1.07	0.108	438	6.7	1.12	0.168	423	11.9	1.24	0.299
0.9	450	2.1	1.03	0.088	447	3.4	1.06	0.100	441	5.6	1.10	0.148	430	10.0	1.19	0.245
1.1	451	1.8	1.03	0.090	448	3.0	1.05	0.097	443	4.9	1.09	0.129	433	8.6	1.16	0.208
1.3	452	1.6	1.02	0.094	449	2.7	1.04	0.096	444	4.4	1.08	0.122	436	7.7	1.14	0.188
1.5	453	1.5	1.02	0.100	450	2.4	1.04	0.093	446	4.0	1.07	0.119	438	7.1	1.13	0.176
1.7	454	1.4	1.02	0.106	451	2.3	1.04	0.100	447	3.8	1.06	0.118	440	6.6	1.12	0.168
1.9	454	1.3	1.02	0.112	451	2.1	1.03	0.104	447	3.6	1.06	0.119	441	6.3	1.11	0.163
2.1	455	1.2	1.02	0.119	452	2.0	1.03	0.108	448	3.5	1.06	0.120	442	6.0	1.11	0.160
3.0	459	1.0	1.02	0.151	455	1.9	1.03	0.122	450	3.2	1.05	0.133	445	5.5	1.10	0.154
4.0	465	0.9	1.03	0.186	459	1.8	1.03	0.150	453	3.3	1.06	0.149	448	5.5	1.10	0.165
5.0	472	0.8	1.05	0.222	464	1.8	1.04	0.173	457	3.5	1.06	0.166	451	5.7	1.10	0.173
6.0	481	0.5	1.06	0.260	470	1.8	1.05	0.191	461	3.7	1.07	0.188	455	6.1	1.11	0.181
7.0	491	0.1	1.09	0.299	478	1.7	1.07	0.219	466	4.0	1.08	0.201	459	6.6	1.12	0.190

RFT-82-43-SS--Impedance , SWR & Insertion Loss,

FT	82-43				82-43				82-43				82-43			
N=	22/66-SS				18/54-SS				14/42-SS				11/33-SS			
.freq	Z	angle	SWR	Loss	Z	angle	SWR	Loss	Z	angle	SWR	Loss	Z	angle	SWR	Loss
MHz	ohms	deg.		-db	ohms	deg.		-db	ohms	deg.		-db	ohms	deg.		-db
0.1	417	27.0	1.64	0.77	375	32.0	1.86	1.14	317	41.6	2.42	1.84	279	50.7	3.21	2.97
0.3	497	34.6	1.92	1.00	455	32.7	1.83	0.94	419	34.6	1.91	1.10	420	36.5	1.99	1.44
0.5	595	45.1	2.55	1.67	523	41.1	2.25	1.34	476	39.6	2.13	1.28	475	36.3	1.98	1.30
0.7	711	53.1	3.39	2.39	605	48.5	2.79	1.86	538	45.5	2.49	1.63	517	39.2	2.13	2.82
0.9	900	58.9	4.62	3.07	697	54.3	3.47	2.40	605	50.9	2.97	2.04	561	42.8	2.37	1.62
1.1	975	63.1	4.88	3.69	797	58.9	4.28	2.93	679	55.3	3.53	2.47	606	46.4	2.65	1.88
1.3	1117	66.4	7.06	4.25	900	62.5	5.22	3.42	758	58.9	4.17	2.89	655	49.7	2.97	2.16
1.5	1262	68.9	8.66	4.75	1008	65.3	6.26	3.88	840	62.0	4.91	3.29	706	52.8	3.35	2.45
1.7	1410	70.9	10.4	5.20	1119	67.6	7.44	4.30	924	64.5	5.72	3.68	761	55.5	3.76	2.70
1.9	1560	72.4	12.3	5.61	1231	69.5	8.74	4.69	1011	66.5	6.08	4.04	817	57.9	4.21	3.03
2.1	1710	73.7	14.4	5.98	1350	71.1	10.1	5.05	1099	68.3	7.58	4.38	875	60.0	4.70	3.31
3.0	2420	77.2	25.0	7.30	1880	75.5	17.5	6.37	1510	73.5	12.7	5.68	1152	66.8	7.35	4.45
4.0	3260	79.0	38.6	8.31	2490	78.0	27.4	7.44	1980	76.5	19.7	6.86	1480	71.3	11.1	5.48
5.0	4150	79.7	52.1	9.00	3120	79.3	38.0	8.24	2470	78.2	27.6	8.61	1820	74.0	15,5	6.32
6.0	5120	80.0	66.0	9.46	3790	80.0	49.1	8.83	2970	79.3	36.3	8.28	2160	75.8	20.3	7.00
7.0	6180	79.8	77.9	9.46	4480	80.3	59.6	9.28	3480	79.8	44.3	8.81	2520	77.0	25.6	7.57

FT-82-75

450 ohms

RFT-82-75-TW --Impedance , SWR & Insertion Loss,

FT-	82-75				82-75				82-75				82-75			
N=	21 / 63-TW				16 / 48-TW				11 / 33-TW				6 / 18-TW			
.freq	Z	angle	SWR	Loss	Z	angle	SWR	Loss	Z	angle	SWR	Loss	Z	angle	SWR	Loss
MHz	ohms	deg.		-db	ohms	deg.		-db	ohms	deg.		-db	ohms	deg.		-db
0.1	450	3.2	1.05	0.045	447	5.4	1.09	0.064	438	10.4	1.21	0.141	370	31.1	1.83	0.717
0.3	449	0.9	1.01	0.055	447	1.6	1.02	0.072	441	3.3	1.06	0.120	413	10.0	1.21	0.349
0.5	449	0.5	1.00	0.064	446	1.0	1.02	0.081	440	2.0	1.04	0.131	413	6.10	1.14	0.347
0.7	449	0.3	1.00	0.071	446	0.8	1.01	0.087	440	1.6	1.03	0.137	414	4.61	1.12	0.349
0.9	449	0.2	1.00	0.077	446	0.7	1.01	0.092	440	1.4	1.03	0.140	415	3.81	1.11	0.348
1.1	449	0.1	1.00	0.084	447	0.6	1.01	0.095	440	1.3	1.02	0.142	415	3.30	1.10	0.344
1.3	450	0.0	1.00	0.089	447	0.5	1.01	0.099	441	1.2	1.02	0.143	416	2.92	1.09	0.340
1.5	450	0.0	1.00	0.095	447	0.5	1.01	0.103	441	1.2	1.02	0.145	417	2.60	1.09	0.336
1.7	450	-0.1	1.00	0.100	447	0.5	1.01	0.107	441	1.2	1.02	0.146	418	2.43	1.08	0.333
1.9	451	-0.1	1.00	0.107	448	0.5	1.01	0.111	441	1.2	1.02	0.148	418	2.21	1.08	0.332
2.1	451	-0.2	1.00	0.113	448	0.5	1.01	0.115	442	1.2	1.02	0.151	418	2.10	1.08	0.332
3.0	453	-0.3	1.00	0.141	450	0.5	1.00	0.136	442	1.3	1.01	0.165	419	1.63	1.08	0.343
4.0	456	-0.6	1.01	0.171	452	0.5	1.01	0.159	443	1.5	1.01	0.180	419	1.51	1.07	0.366
5.0	460	-0.7	1.02	0.201	454	0.5	1.01	0.182	444	1.8	1.01	0.205	419	1.60	1.08	0.340
6.0	465	-1.0	1.03	0.231	458	0.6	1.02	0.206	445	2.1	1.01	0.226	419	1.83	1.08	0.413
7.0	472	-1.4	1.05	0.261	462	0.6	1.02	0.228	447	2.4	1.00	0.244	418	2.13	1.08	0.434

RFT-82-75-SS--Impedance , SWR & Insertion Loss,

FT-	82-75				82-75				82-75				82-75			
N=	21 / 63-SS				16 / 48-SS				11 / 33-SS				6 / 18-SS			
.freq	Z	angle	SWR	Loss	Z	angle	SWR	Loss	Z	angle	SWR	Loss	Z	angle	SWR	Loss
MHz	ohms	deg.		-db	ohms	deg.		-db	ohms	deg.		-db	ohms	deg.		-db
0.1	417	14.8	1.31	0.19	415	14.9	1.31	0.19	392	16.3	1.38	0.60	330	40.4	2.31	1.32
0.3	483	32.2	1.82	0.78	454	26.5	1.61	0.56	410	19.7	1.44	0..57	398	17.8	1.40	0.615
0.5	592	45.3	2.56	1.59	523	38.1	2.09	1.17	440	28.0	1.68	0.69	403	15.5	1.34	0.630
0.7	726	54.0	3.51	2.41	612	46.9	2.69	1.82	481	35.6	1.95	0.86	408	16.5	1.36	0.680
0.9	876	59,8	4.67	3.13	714	53.3	3.41	2.45	515	42.0	2.28	1.08	415	18.4	1.40	0.742
1.1	1036	63.9	6.05	3.87	826	58.1	4.27	3.03	588	47.3	2.68	1.32	423	20.5	1.44	0.812
1.3	1207	66.8	7.62	4.31	946	61.6	5.22	3.55	650	51.6	3.12	1.58	432	22.8	1.50	0.892
1.5	1390	69.0	9.41	4.79	1072	64.4	6.32	4.02	716	55.1	3.60	1.84	443	25.0	1.57	0.982
1.7	1580	70.6	11.3	5.20	1205	66.5	7.51	4.44	786	58.0	4.14	2.11	454	27.2	1.63	1.07
1.9	1780	71.8	12.8	5.55	1340	68.1	8.77	4.81	858	60.5	4.73	2.37	466	29.3	1.71	1.18
2.1	2000	72.7	15.6	5.86	1490	69.4	10.1	5.14	933	62.5	5.35	2.62	479	31.3	1.78	1.29
3.0	3190	73.8	25.8	6.74	2240	72.3	16.9	6.24	1300	68.3	8.63	3.65	547	39.0	2.16	1.83
4.0	5250	70.8	33.0	6.91	3330	71.9	24.2	6.88	1760	71.1	12.8	4.52	637	45.5	2.65	2.45
5.0	9240	60.7	42.4	6.22	4910	68.4	29.1	7.05	2280	72.0	16.9	5.24	739	50.0	3.18	3.03
6.0	17K	-30.	45.3	5.25	7440	60.6	33.7	6.70	2880	71.6	20.7	5.86	851	53.2	3.77	3.56
7.0	18K	-30.	46.0	8.62	11K	53.6	43.7	6.02	3590	70.2	23.8	6.00	971	55.2	4.36	4.03

FT-114-43 450 ohms

RFT-114-43-TW—Impedance , SWR & Insertion Loss,

FT-	114-43				114-43				114-43				114-43			
N=	26/78-TW				20/60-TW				15/45-TW				11/33-TW			
.freq	Z	angle	SWR	Loss	Z	angle	SWR	Loss	Z	angle	SWR	Loss	Z	angle	SWR	Loss
MHz	ohms	deg.		-db	ohms	deg.		-db	ohms	deg.		-db	ohms	degree		-db
0.1	421	13.5	1.28	0.345	398	20.1	1.46	0.638	327	34.5	2.01	1.39	252	46.3	3.07	2.59
0.3	441	5.5	1.10	0.144	433	8.2	1.16	0.235	407	15.7	1.34	0.468	370	24.3	1.62	0.910
0.5	446	3.6	1.07	0.115	440	5.4	1.10	0.163	424	10.5	1.21	0.295	401	16.8	1.38	0.505
0.7	448	2.8	1.05	0.105	444	4.0	1.08	0.137	432	8.1	1.16	0.276	415	13.0	1.28	0.401
0.9	449	2.3	1.04	0.104	445	3.2	1.06	0.125	436	6.6	1.13	0.190	423	10.7	1.22	0.324
1.1	450	1.9	1.03	0.106	447	2.6	1.05	0.120	438	5.6	1.11	0.171	428	9.2	1.18	0.277
1.3	451	1.7	1.03	0.111	448	2.2	1.04	0.119	440	4.9	1.09	0.160	431	8.1	1.16	0.249
1.5	452	1.5	1.03	0.118	448	1.9	1.03	0.121	442	4.4	1.08	0.152	433	7.2	1.14	0.230
1.7	453	1.4	1.03	0.125	449	1.6	1.03	0.124	443	3.9	1.07	0.150	435	6.6	1.13	0.216
1.9	454	1.3	1.03	0.132	450	1.4	1.03	0.127	443	3.6	1.07	0.149	437	6.1	1.12	0.208
2.1	455	1.2	1.02	0.140	450	1.3	1.02	0.131	444	3.3	1.06	0.148	438	5.7	1.11	0.202
3.0	459	0.9	1.03	0.178	452	0.7	1.01	0.150	447	2.6	1.05	0.152	441	4.5	1.09	0.192
4.0	466	0.6	1.04	0.221	456	0.3	1.01	0.182	449	2.2	1.04	0.173	444	3.9	1.07	0.196
5.0	474	0.3	1.05	0.265	460	0.0	1.02	0.210	452	1.9	1.03	0.190	446	3.7	1.06	0.204
6.0	484	-0.2	1.08	0.311	465	-0.4	1.03	0.240	456	1.9	1.04	0.207	449	3.6	1.07	0.214
7.0	495	-0.8	1.10	0.359	471	-0.8	1.05	0.269	460	1.8	1.04	0.225	452	3.6	1.07	0.225

RFT-114-43-SS =-Impedance , SWR & Insertion Loss,

FT	114-43				114-43				114-43				114-43			
N=	26 / 78-SS				20 / 60-SS				15 / 45-SS				11/33-SS			
.freq	Z	angle	SWR	Loss	Z	angle	SWR	Loss	Z	angle	SWR	Loss	Z	angle	SWR	Loss
MHz	ohms	deg.		-db	ohms	deg.		-db	ohms	deg.		-db	ohms	deg.		-db
0.1	435	30.1	1.73	0.86	396	30.8	1.78	1.00	341	37.5	2.15	1.56	248	49.4	3.33	2.83
0.3	604	48.5	2.79	2.00	493	38.7	2.09	1.33	429	33.2	1.85	1.09	366	34.5	1.97	1.38
0.5	831	60.3	4.60	3.34	609	49.6	2.88	2.16	487	39.7	2.14	1.39	409	34.1	1.90	1.24
0.7	1082	66.9	7.04	4.46	745	57.3	3.92	3.01	554	46.3	2.56	1.85	442	36.8	1.99	1.35
0.9	1.35k	71.0	10.1	5.38	894	62.7	5.23	3.78	631	52.0	3.11	2.34	475	40.2	2.15	1.55
1.1	1.61k	73.7	13.6	6.24	1.05k	66.5	6.77	4.46	713	56.4	3.73	2.84	510	43.7	2.36	1.81
1.3	1.89k	75.5	17.6	6.78	1.21k	69.3	8.54	5.06	801	60.1	4.47	3.31	548	47.0	2.60	2.08
1.5	2.17k	76.8	21.9	7.34	1.38	71.5	10.5	5.60	891	63.0	5.28	3.85	589	50.1	2.88	2.37
1.7	2.45k	77.8	26.5	7.82	1.54k	73.1	12.6	6.07	985	65.4	6.19	4.16	631	52.8	3.18	2.65
1.9	2.74k	78.5	31.3	8.24	1.71k	74.4	15.0	6.48	1.08k	67.3	7.15	4.55	675	55.2	3.51	2.94
2.1	3.03k	79.0	36.0	8.62	1.88k	75.4	17.4	6.88	1.18k	68.9	8.22	4.90	721	57.3	3.86	3.21
3.0	4.38k	80.1	57.1	9.87	2.68k	78.0	31.2	8.23	1.63k	73.6	13.7	6.22	942	64.2	5.73	4.33
4.0	6.02k	79.8	75.9	10.6	3.62k	79.0	42.7	9.25	2.16k	76.1	20.8	7.29	1.20k	68.8	8.29	5.33
5.0	7.84k	78.9	90.7	11.0	4.61k	79.1	49.4	9.95	2.71k	77.3	28.3	8.08	1.48k	71.7	11.3	6.14
6.0	9.96	77.3	100	11.2	5.70	78.7	65.0	10.4	3.30k	77.8	35.3	8.69	1.76k	73.4	14.5	6.80
7.0	12k	75.3	105	10.8	6.88	78.0	73.8	10.6	3.90k	77.9	41.8	9.14	2.06k	74.5	17.8	7.34

FT-114-75 450 ohms

RFT-114-75-TW –Impedance, SWR & Insertion Loss

FT-	114-75				114-75				**114-75**				114-75			
N=	21 / 63-TW				16 / 48-TW				**11/33-TW**				6/18-TW			
.freq	Z	angle	SWR	Loss	Z	angle	SWR	Loss	**Z**	**angle**	**SWR**	**Loss**	Z	angle	SWR	Loss
MHz	ohms	deg.		-db	ohms	deg.		-db	**ohms**	**deg.**		**-db**	ohms	deg.		-db
0.1	450	3.4	1.06	0.040	448	5.8	1.11	0.054	**439**	**12.**	**1.24**	**0.137**	361	35	2.01	0.976
0.3	450	1.1	1.02	0.047	448	1.9	1.03	0.055	**443**	**3.7**	**1.07**	**0.090**	420	12	1.25	0.325
0.5	450	0.8	1.01	0.055	448	1.2	1.02	0.065	**443**	**2.3**	**1.04**	**0.103**	421	6.7	1.14	0.314
0.7	450	0.8	1.01	0.062	448	1.0	1.02	0.072	**443**	**1.7**	**1.04**	**0.110**	421	4.8	1.11	0.312
0.9	451	0.8	1.01	0.067	448	0.9	1.02	0.076	**443**	**1.4**	**1.03**	**0.113**	421	3.8	1.10	0.314
1.1	451	0.8	1.01	0.073	448	0.9	1.02	0.080	**443**	**1.3**	**1.03**	**0.116**	421	3.1	1.09	0.312
1.3	452	0.9	1.02	0.079	449	0.9	1.02	0.085	**443**	**1.2**	**1.03**	**0.119**	422	2.6	1.08	0.314
1.5	452	0.9	1.02	0.085	449	0.9	1.02	0.090	**443**	**1.0**	**1.02**	**0.122**	422	2.2	1.08	0.319
1.7	453	1.0	1.02	0.091	449	1.0	1.02	0.095	**443**	**1.0**	**1.02**	**0.127**	421	1.8	1.08	0.326
1.9	453	1.0	1.02	0.097	450	1.0	1.02	0.100	**443**	**1.0**	**1.02**	**0.132**	421	1.6	1.08	0.335
2.1	454	1.1	1.02	0.104	450	1.1	1.02	0.106	**443**	**1.1**	**1.02**	**0.138**	420	1.4	1.08	0.385
3.0	457	1.4	1.03	0.133	452	1.3	1.02	0.131	**443**	**1.3**	**1.03**	**0.163**	417	1.0	1.08	0.383
4.0	462	1.8	1.04	0.163	455	1.7	1.03	0.152	**443**	**1.6**	**1.03**	**0.188**	414	1.2	1.09	0.427
5.0	469	2.1	1.06	0.193	459	2.1	1.04	0.181	**445**	**2.0**	**1.04**	**0.210**	413	1.5	1.09	0.460
6.0	478	2.2	1.07	0.222	464	2.4	1.05	0.204	**447**	**2.4**	**1.04**	**0.224**	412	1.9	1.10	0.488
7.0	488	2.3	1.10	0.251	471	2.7	1.07	0.226	**450**	**2.9**	**1.05**	**0.248**	412	2.3	1.10	0.514

RFT-114-75-SS -Impedance , SWR & Insertion Loss,

FT	114-75				114-75				114-75				114-75			
N=	21/63-SS				16/48-SS				11/33-SS				6/18-SS			
.freq	Z	angle	SWR	Loss	Z	angle	SWR	Loss	Z	angle	SWR	Loss	Z	angle	SWR	Loss
MHz	ohms	deg.		-db	ohms	deg.		-db	ohms	deg.		-db	ohms	deg.		-db
0.1	391	21.0	1.49	0.31	456	17.1	1.35	0.23	439	16.5	1.34	0.22	361	36.4	2.06	1.03
0.3	423	44.9	2.45		536	32.9	1.88	0.84	456	17.1	1.35	0.28	421	15.7	1.33	0.34
0.5	720	58.1	3.95		645	45.8	2.68	1.68	479	23.9	1.54	0.50	425	13.4	1.27	0.40
0.7	947	65.4	6.03		792	54.5	3.74	2.54	512	30.6	1.78	0.78	428	14.2	1.29	0.44
0.9	1.12K	69.8	8.25		958	60.4	5.06	3.28	554	36.6	2.06	1.10	433	15.7	1.32	0.48
1.1	1.46K	72.7	11.8		1.1K	64.5	6.47	3.93	602	41.7	2.37	1.44	439	17.6	1.36	0.53
1.3	1.74K	74.5	15.3		1.3K	67.4	8.29	4.48	657	46.0	2.72	1.72	446	19.6	1.41	0.58
1.5	2.05K	75.7	19.2		1.5K	69.5	10.2	4.85	716	49.7	3.11	2.10	455	21.6	1.47	0.60
1.7	2.38K	76.5	23.4		1.7K	71.1	11.4	5.36	778	52.7	3.52	2.42	463	23.6	1.53	0.72
1.9	2.75K	77.0	27.8		1.9K	72.2	14.5	5.71	845	55.3	3.98	2.72	473	25.5	1.58	0.80
2.1	3.16K	77.1	32.0		2.2K	72.9	17.2	6.00	915	57.5	4.47	3.01	484	27.4	1.65	0.89
3.0	5.83K	74.3			3.6K	73.3	28.2	6.81	1.2K	63.9	6.76	4.09	541	35.1	1.98	1.34
4.0	13.3K	59.1			6.1K	68.6	37.3	6.85	1.7K	67.0	10.2	4.93	621	41.7	2.43	1.88
5.0	26.0K	-14.			11.K	54.3	41.9	5.89	2.2K	67.6	13.2	5.47	716	46.4	2.87	2.39
6.0	12.4K	-62.			20K	10.3	45.1	5.31	3.0K	66.5	17.0	5.74	823	49.7	3.37	2.85
7.0	7.65K	-72.			15K	-42.	44.7	8.63	3.9K	63.6	19.7	5.76	941	51.9	3.90	3.26

COMMENTARY AND RECOMMENDATIONS - 450 OHMS

Core Size

When comparing the test results only focusing on core size, there seemed to be no areas of performance that could distinguish one size from another. For instance, comparing an FT-82-43, 11/33-TW at the upper right of page one of the previous results with an FT-114-43, 11/33-TW (the only difference between these two being the diameter of the core), the performance data were nominally equal. This was the first of several reasons that we pursued an additional round of testing to fine tune the final recommendations.

Material Type

The same type of "apples to apples" comparison of performance was done between Type 43 and Type 75 material. Again, for instance, comparing the FT-82-43, 11/33-TW with the FT-114-43, 11/33-TW on the next page. It is clear that the Type 75 material gave consistently better performance, though the difference was not great except at the low end of the spectrum. The Type 75 material also seemed to produce "smoother" data throughout the mid-spectrum in many cases. From these tests, it would appear that the Type 75 is superior in this application. However, it is also clear that perfectly good impedance transformers can be constructed from Type 43 material.

Winding Pattern

It was evident from very early in the testing cycle that the SS windings were not producing results that were comparable to those of the TW windings. Performance of the SS wound transformers at the middle of the spectrum seemed to be adequate, but it fell off rapidly at both extremes. This was particularly unfortunate at the upper ends of the Tropical Bands where losses often reached 8 or 9 dB! These losses were largely generated through "Leakage Inductance" whereby much of the magnetic field of the primary winding would break out of the toroid toward the open center – thereby failing to transfer maximum signal to the secondary. The reader is cautioned, however, that the possibly superior noise rejection characteristics of the SS winding *might* make that winding pattern the design of choice in some high noise environments. The author team decided to concentrate on TW (and ultimately OL windings) for the "fine tuning" test runs, but to conduct several field tests to compare the TW or OL windings with the SS pattern.

Turns Pattern and Count

Distinguishing the "best" turns count turned out to be much more an art than a science. Once we had focused on exploring both the FT-82 and FT-114 size cores of Type 75 material and TW or OL windings, we could just look at the data with a concern for turns count. There are many arguments against high turns counts: High counts are more difficult to wind; they are more difficult to fit on small cores and by having more wire, they may be susceptible to more noise pick-up. On the other hand, lower turns counts produce poorer performance at the lower end of the spectrum. In the FT-82-75 size, we quickly focused on the 16/48 and 11/33 turns counts. It is evident that the 16/48 consistently had less Reactive Inductance (a lower "angle"), SWR and overall Loss. However all of these differences are very small… for instance loss differences on the order of .1 dB. On the other hand, the turns count difference between 16/48 and 11/33 is a total of 20 turns – rather large. So, the decision was made in favor of the 11/33 turns count at the FT-82 size. A similar reasoning pattern resulted in focusing on the 11/33 turns count at the FT-114 size, as well.

Therefore, at this point, we had obtained two "best" or "ideal" designs for a 450 to 50 ohm broadband impedance transformer at these frequencies: FT-82-75, 11/33-TW and FT-114-75, 11/33-TW. However, several questions remained.
First, we had committed to retesting the difference between the quadri-filar TW windings and the more traditional OL windings (refer to Figure 4 below).

In this series of Final Tests (below), It was found that the TW and OL windings perform equally well in this application. For several reasons we recommend the OL winding pattern:

1. Though it was easier for Bill to wind a lot of cores faster with the TW winding, when you are going to wind only one or two, ease of winding is just not important.
2. With the TW winding, inter-connecting the windings properly in series can be quite confusing.

3. The OL winding is just a much neater package and there are no stub windings. This especially important true with the 11/48, 900 Ohm design.
4. With the OL pattern, it is possible to wind the two coils so that the terminations for each are on opposite sides of the circumference of the toroid. This is very handy in some transformer applications.

Figure 4 below illustrates an 11/48 design with TW+4 and OL winding patterns.

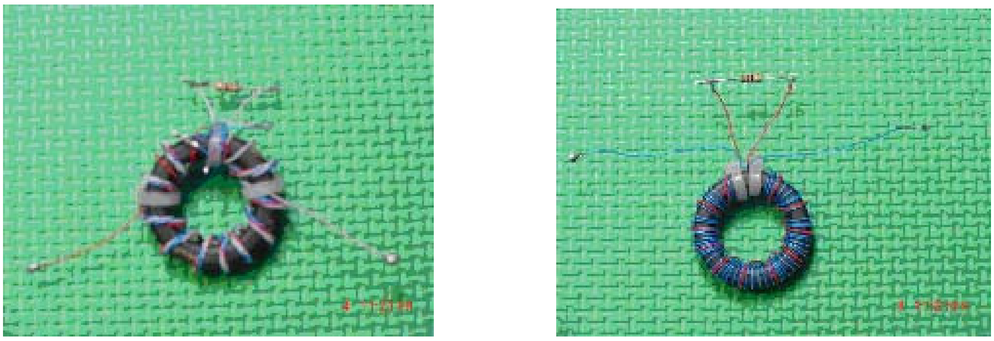


FIGURE 4

Important note: in fabricating a transformer with OL winding it is important to first wind the larger coil, (33, secondary), and then wind the smaller, (11, primary), winding the smaller coil over the larger in such a manner that there are 3 secondary turns between each primary turn. In winding the primary on the 11/48, skip 4 secondary turns 4 times and then 5 turns 4 times and finally 4 turns 4 times. Both windings MUST be evenly distributed around the full circumference of the toroid and all windings of each coil should be evenly spaced.

Once we focused on recommending the OL windings, we decided to make fine changes in turns count on either side of 11/33 to see if a 10/30 or 12/36 count would bring better results. They did not. Bill also explored winding an FT-114-75, 11/33 OL from 200/44 Litz wire, so highly regarded at low frequencies. There was no worthwhile improvement in our final design using this relatively difficult-to-obtain wire. The reason for this is that with high permeability cores only a few turns are required, so the resistance of the windings is not an important factor. The results of these tests are presented in the data fields that follow this section of narrative.

The "final" transformers, wound to compare TW and OL winding patterns, were made with connections to both the primary and secondary being at the same point on the circumference of the toroid. This occurs naturally with the TW pattern and arrangement. Bill used the same termination arrangement on the OL sample as he compared the two patterns. However, as we began to focus on the final placement of the toroid-based transformer in a box, with attachment fittings, etc., we realized that many of these arrangements would be more efficient if the attachment points of the primary and the secondary were on opposite sides of the circumference. An additional transformer with that arrangement was fabricated and tested. Those tests are documented at the lower left of the following data as "114-75, 11/33-OL-Reverse." Compare those data to the 114-75, 11/33-OL just above. It appears that both physical arrangements of the primary and secondary coils produce nominally equal results and may be used interchangeably.

Three final fields of results are presented below. First, the FT-82-75, 11/33-OL is presented as a very workable and less expensive alternative to its size 114 cousin. The windings of the secondary could terminate on the same or opposite side of the circumference.

At the present time, Amidon appears to no longer be producing FT-114 size toroids in Type 75 material. Happily, the electromagnetic differences between Type 75 and Type J materials are quite subtle and proved to be irrelevant to this application. FT-114-J, 11/33-OL test results are presented below, as well.

John Bryant prevailed on Bill to run the now standard series of tests on the transformer that John had recommended as the "ideal" transformer in his May 2001 article, an FT-114-75, SS-4/13. Happily, the results were not too embarrassing to John: probably around 2 dB of loss difference at the Longwave frequencies and 2 to 3 dB difference of loss at Tropical Band. Happily, there was less than 1 dB of difference across the MW spectrum. Those differences *might* be more than over come if the SS winding proved superior in a high-noise environment.

Finally, we had also been quite concerned that cold ambient temperatures, particularly the low temperatures in the northerly parts of North America would adversely affect transformer performance. Bill had found such to be the case at low frequencies. These effects are very difficult to derive mathematically, so Bill performed the similar laboratory tests on our transformer. As Bill had predicted, *there were no significant changes in transformer performance (at our frequencies of interest) with changes in outside temperature.* Results of these tests are presented in the Technical Appendices.

IMPORTANT NOTE ON LOSSES

One final point that we would like to bring up is that ‟ loss ‟ in our tables is only the *insertion loss* experienced by the signal as it passes through the transformer. When the SWR is greater than 1:1 then part of the signal from the antenna is reflected back to the antenna and never gets into the transformer. The total loss of the available signal from the antenna is therefore the sum of the ‟ insertion loss ‟ and the effective “loss due to the SWR”. As long as the SWR is in a reasonable range, (below 1:1.5, SWR loss = 0.17db), the insertion loss is really all that needs to be considered. At higher SWR values, the SWR loss can become significant.

SWR	1:1	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	7.0	8.0	9.0	10
-db	0	0.17	0.51	0.88	1.2	1.6	1.9	2.2	2.5	2.8	3.1	3.5	4.0	4.4	4.8

So, our recommendations for the “ideal” broadband 450 ohm impedance transformer for 150 kHz through 6 MHz is:

450 Ohm Design

Size: Either **FT-82** or **FT-114**
Material: Either **Type 75** or **Type J**
Winding Pattern: Either quadra-filar (TW) or traditional overlapped (OL) windings
Turns Count: **11/33**

Bill’s Final 450 Ohm Test results follow:

FINAL TESTS

450 ohms

RFT-114-75-OL —Impedance , SWR & Insertion Loss,

FT-	114-75				**114-75**				114-75				114-75-			
N=	10 / 30 - OL				**11/33- OL**				12/36 –OL				11/33-OL-LITZ-200/44			
.freq	Z	angle	SWR	Loss	**Z**	**angle**	**SWR**	**Loss**	Z	angle	SWR	Loss	Z	angle	SWR	Loss
MHz	ohms	deg.		-db	**ohms**	**deg.**		**-db**	ohms	deg.		-db	ohms	deg.		-db
0.1	434	13.6	1.27	0.18	439	12.0	1.24	0.14	442	9.7	1.18	0.10	440	11.3	1.22	0.12
0.3	439	4.5	1.08	0.13	444	4.0	1.07	0.09	443	3.4	1.06	0.09	443	3.3	1.06	0.09
0.5	439	3.0	1.06	0.13	444	2.7	1.05	0.10	443	2.4	1.04	0.10	443	1.8	1.03	0.09
0.7	439	2.5	1.05	0.13	444	2.3	1.04	0.11	443	2.2	1.04	0.10	443	1.0	1.02	0.09
0.9	439	2.4	1.05	0.13	444	2.2	1.04	0.11	443	2.2	1.04	0.10	443	0.6	1.02	0.09
1.1	439	2.3	1.05	0.13	444	2.2	1.04	0.11	444	2.2	1.04	0.10	443	0.3	1.02	0.10
1.3	440	2.3	1.05	0.14	444	2.3	1.04	0.11	444	2.2	1.04	0.10	443	0.0	1.02	0.10
1.5	440	2.3	1.05	0.14	444	2.4	1.05	0.11	444	2.5	1.04	0.11	443	-0.3	1.02	0.10
1.7	440	2.4	1.05	0.15	444	2.5	1.05	0.12	444	2.7	1.05	0.11	443	-0.5	1.02	0.11
1.9	440	2.5	1.05	0.15	444	2.7	1.05	0.12	444	2.9	1.05	0.12	443	-0.6	1.02	0.11
2.1	440	2.7	1.05	0.16	444	2.8	1.05	0.12	444	3.1	1.05	0.13	443	-0.8	1.02	0.12
3.0	440	3.5	1.06	0.19	445	3.7	1.07	0.15	445	4.2	1.07	0.15	443	-1.3	1.03	0.14
4.0	440	4.6	1.08	0.21	446	4.8	1.09	0.17	448	5.4	1.10	0.17	443	-1.8	1.03	0.16
5.0	443	5.7	1.10	0.24	448	5.9	1.11	0.19	451	6.7	1.12	0.19	445	-2.4	1.04	0.18
6.0	446	6.8	1.12	0.26	452	7.0	1.13	0.21	456	7.9	1.14	0.22	447	-2.9	1.05	0.20
7.0	450	7.8	1.14	0.28	456	8.1	1.15	0.23	462	9.1	1.17	0.24	450	-3.4	1.06	0.23

RFT-114-82-75-J-OL-OLR-Impedance , SWR & Insertion Loss,

FT	**114-75**				**82-75**				**114-J**				114-75			
N=	**11/33-OL-Reverse**				**11/33-OL**				**11/33-OL**				4 / 13			
.freq	**Z**	**angle**	**SWR**	**Loss**	Z	angle	SWR	Loss	**Z**	**angle**	**SWR**	**Loss**	Z	angle	SWR	Loss
MHz	**ohms**	**deg.**		**-db**	ohms	deg.		-db	**ohms**	**deg.**		**-db**	ohms	deg.		-db
0.1	439	12.3	1.24	0.14	425	15	1.31	0.24	439	11.4	1.22	0.13	278	57.5	3.90	2.9
0.3	443	4.2	1.08	0.09	435	4.9	1.09	0.16	442	3.9	1.07	0.10	436	26.6	1.62	1.00
0.5	443	3.0	1.06	0.10	434	3.1	1.06	0.17	443	2.7	1.05	0.11	452	18.9	1.39	0.85
0.7	443	2.7	1.05	0.11	434	2.6	1,06	0.17	443	2.3	1.04	0.11	458	17.1	1.35	0.84
0.9	443	2.5	1.05	0.11	434	2.4	1.06	0.18	443	2.2	1.04	0.11	463	17.0	1.35	0.85
1.1	443	2.5	1.05	0.11	434	2.3	1.06	0.18	443	2.3	1.04	0.11	469	17.6	1.37	0.86
1.3	443	2.5	1.05	0.11	434	2.4	1.06	0.18	443	2.3	1.04	0.11	475	18.5	1.39	0.86
1.5	443	2.6	1.05	0.12	434	2.4	1.06	0.18	443	2.4	1.04	0.12	482	19.6	1.42	0.93
1.7	444	2.8	1.05	0.12	434	2.5	1.06	0.18	443	2.5	1.05	0.12	489	20.8	1.46	0.98
1.9	444	2.9	1.05	0.13	435	2.6	1.06	0.18	443	2.7	1.05	0.12	495	22.0	1.50	1.04
2.1	444	3.0	1.05	0.13	435	2.7	1.06	0.18	443	2.9	1.05	0.13	503	23.3	1.54	1.11
3.0	445	4.0	1.07	0.16	436	3.3	1.07	0.19	444	3.8	1.07	0.14	542	29.2	1.76	1.47
4.0	447	5.3	1.09	0.18	437	4.1	1.08	0.20	446	5.0	1.09	0.18	600	35.0	2.05	1.97
5.0	450	6.8	1.12	0.20	439	5.0	1.10	0.21	449	6.2	1.11	0.20	671	39.5	2.38	2.36
6.0	455	8.3	1.16	0.22	441	5.8	1.11	0.22	453	7.3	1.13	0.22	752	42.7	2.72	2.79
7.0	458	9.7	1.19	0.24	444	6.7	1.13	0.22	457	8.5	1.16	0.24	840	44.8	3.06	3.18

RECOMMENDATIONS

900 OHMS

As we established the goals for this study, we committed to developing a recommended design for use with antennas that exhibit approximately 900 ohms characteristic impedance, such as flags, pennants, etc. There is a difficulty here, of course, of designing to an exact figure since the turns ratio is, in essence, the square root of the desired impedance ratio. The proper turns ratio of a 50 ohm to 800 ohm transformer (16 to 1 impedance ratio) would be four. An 11/48 turns count in OL pattern gets as close as physics will allow to a design for 900 ohm characteristic impedance. Transformers were tested with 3 and 4 turns added to the primary windings to 11/47 and 11/48 TW designs, but the results were slightly inferior to the FT-82 (or 114)-75 (or J), 11/48-OL design. The results of Bill's 900 ohm tests follow:

RFT-FT-114-82-75-OL-TW-900—Impedance , SWR & Insertion Loss,

FT-	**FT-82-75**				**FT-114-75**				FT-114-75				FT-114-75			
N=	**11/48-OL**				**11/48-OL**				11/48-TW+4				11/47-TW+3			
.freq	**Z**	**angle**	**SWR**	**Loss**	**Z**	**angle**	**SWR**	**Loss**	Z	angle	SWR	Loss	Z	angle	SWR	Loss
MHz	**ohms**	**deg.**		**-db**	**ohms**	**deg.**		**-db**	ohms	deg.		-db	ohms	deg.		-db
0.1	**919**	**14.2**	**1.28**	**0.19**	**927**	**12.1**	**1.24**	**0.14**	927	12.1	1.24	0.14	892	10.8	1.20	0.14
0.3	**926**	**4.5**	**1.08**	**0.14**	**937**	**3.6**	**1.07**	**0.10**	937	3.6	1.07	0.10	898	2.85	1.05	0.09
0.5	**924**	**2.8**	**1.06**	**0.15**	**935**	**2.0**	**1.05**	**0.11**	935	2.0	1.05	0.11	896	1.05	1.01	0.10
0.7	**924**	**2.1**	**1.05**	**0.16**	**935**	**1.4**	**1.04**	**0.11**	935	1.4	1.04	0.11	895	0.16	1.01	0.11
0.9	**924**	**1.7**	**1.04**	**0.16**	**935**	**0.9**	**1.04**	**0.12**	935	0.9	1.04	0.12	895	-0.47	1.01	0.12
1.1	**925**	**1.5**	**1.04**	**0.16**	**935**	**0.7**	**1.04**	**0.12**	935	0.7	1.04	0.12	895	-1.00	1.02	0.12
1.3	**926**	**1.4**	**1.04**	**0.16**	**936**	**0.5**	**1.04**	**0.13**	936	0.5	1.04	0.13	895	-1.48	1.03	0.13
1.5	**926**	**1.3**	**1.04**	**0.16**	**936**	**0.3**	**1.04**	**0.13**	936	0.3	1.04	0.13	894	-1.95	1.04	0.14
1.7	**927**	**1.2**	**1.04**	**0.16**	**936**	**0.2**	**1.04**	**0.14**	936	0.2	1.04	0.14	893	-2.37	1.04	0.15
1.9	**928**	**1.2**	**1.04**	**0.16**	**936**	**0.1**	**1.04**	**0.15**	936	0.1	1.04	0.15	892	-2.77	1.05	0.16
2.1	**929**	**1.1**	**1.04**	**0.16**	**936**	**-0.2**	**1.04**	**0.15**	936	-0.2	1.04	0.15	892	-3.14	1.06	0.17
3.0	**933**	**1.0**	**1.04**	**0.17**	**938**	**-0.4**	**1.04**	**0.18**	938	-0.4	1.04	0.18	887	-4.63	1.08	0.22
4.0	**937**	**1.1**	**1.05**	**0.19**	**943**	**-0.6**	**1.05**	**0.21**	943	-0.6	1.05	0.21	882	-6.08	1.11	0.26
5.0	**942**	**1.1**	**1.05**	**0.21**	**952**	**-0.9**	**1.06**	**0.28**	952	-0.9	1.06	0.28	878	-7.44	1.14	0.34
6.0	**949**	**1.2**	**1.06**	**0.23**	**964**	**-1.3**	**1.08**	**0.30**	964	-1.3	1.08	0.30	874	-8.75	1.17	0.40
7.0	**958**	**1.2**	**1.07**	**0.25**	**977**	**-1.8**	**1.09**	**0.35**	977	-1.8	1.09	0.35	871	-10.0	1.19	0.47

900 Ohm Design

Size: Either **FT-82** or **FT-114**
Material: Either **Type 75** or **Type J**
Winding Pattern: Either quadra-filar (TW) or traditional overlapped (OL) windings
Turns Count: **11/48**

TECHNICAL APPENDIX

PROCEDURES FOR MEASURING IMPEDANCE

To measure the impedance the transformer is connected directly to the test fixture of theHP-4192A. The test fixture was modified by adding alligator clips to allow quick, secure change. The effects of the test fixture and alligator clips are eliminated by the initial calibration procedure. Before measurements are started the ZERO offset adjustments are made. With no connection to the fixture the OPEN offset key is pressed and the HP-4192A measures the stray G+jB parameters and stores this data. With the test fixture is then shorted with a copper rod and the SHORTED offset key is pressed and the HP-4192A measure the residual R+jX and stores this data. During all subsequent measurements the stored OPEN & SHORTED dated is subtracted from the measurement being made. The stored offset data is automatically corrected for each frequency used in a measurement.

ASSURANCE THAT USE OF 50 OHM TRIM POT VALID

After performing the initial test phase using a 50 ohm carbon resistor to terminate the transformer under test, a screw type trim pot was chosen for the final tests only after measuring its characteristics over the test frequency range. It was found to be more accurate than the carbon resistors. In a test to determine the validity of using a trim pot rather than a carbon resistor, the trim pot was connected directly to the test fixture with alligator clips. When the trim pot was set at 50.00 ohms, its impedance measured from 49.99 ohms at .1 MHz to 50.1 ohms at 7 MHz. This was considerably more accurate for impedance testing than even hand-selected carbon resistors. The resistive element in a trim pot is a carbon film.

TEST VOLTAGE

Assuming that the initial permeability found in the core specification sheet is measured at 10 Gauss (Amidon catalog, January 1986), then the maximum correct test voltage at 100 kHz for these FT-114 cores would be,** using Faradays Law:

$B = [10^5(E)] / [4.44(a)(N)(f)]$ E- millivolts, $a = 0.375$ cm x cm ; $N = 33$; $f = 10^5$; $B = 10$ gauss

$E = [10][4.44(0.375)(33)(10^5)] / [10^5] = (10)(4.44)(0.375)(33) = 549$mv

The test voltage was set at 100 mv., well within the range of initial permeability .

PROCEDURES FOR MEASURING INSERTION LOSS

The procedure for measuring the insertion loss was as follows:

- Two cores are first picked that, with 20 turns on the core, have the same impedance - within +/- 2 Ohms, at 500KHz.
- Two transformers are then wound, each in exactly the same manner. They are checked for being a match by measuring the reflected impedance, terminated with 50 Ohms on the low side. In most cases, the match at 500KHz ** was within +/- 1ohm.
- These two transformers are connected, high side to high side, so that there is a 50 ohm ** in and out connection to the pair.
- The transformer pair is then mounted into a cast aluminum box with connections out through 2 chassis mount BNC connectors.

- The OSC. output of the HP-4192A is connected to a signal POWER SPLITTER, (Hp-#04912-61001). One side is then connected to Channel-A input and the other side is connected to Channel-B after passing through the transformers.
- The HP-4192A measures the difference between the signal levels of Channel –A & B and displays the attenuation resulting from the 2 transformers. Dividing this number by 2 gives the loss in each transformer.
- The above description is a simple explanation. To make the measurements accurate, the following steps were taken:
    1. All connecting cables were 50 ohm double shielded, HP-11170A
    2. Shielded inline 50 ohm terminators were used, HP-11048C
    3. The length of the cable from the power splitter to Channel-A input was exactly the same as the length of the cable from the power splitter through the transformers to Channel- B input.
    4. There were exactly the same numbers of BNC connectors in the coaxial cable going to Channels –A & B.
- The accuracy of the insertion loss setup was verified by replacing the transformers with a copper wire connecting the BNC connectors in the aluminum box. Over the test frequency range this shorted box showed an a measure insertion loss of 0.003db or less at each test frequency.

CALCULATING SWR

When the impedance of the antenna differs from the input impedance of the matching transformer, then a portion of the energy arriving from the antenna will be reflected back to the antenna. A ratio of the voltage of the reflected wave to the voltage of the incoming wave is the voltage reflection coefficient, (ρ). From this the

value of SWR can be calculated , as follows: (ARRL Handbook-1996, pp19.4)

$$\mathrm{SWR} := \frac{(1+\rho)}{(1-\rho)}$$

$$\rho := \frac{\left[(Z\cdot\cos(\theta) - \mathrm{Ro})^2 + (Z\cdot\sin(\theta))^2\right]^{\frac{1}{2}}}{\left[(Z\cdot\cos(\theta) + \mathrm{Ro})^2 + (Z\cdot\sin(\theta))^2\right]^{\frac{1}{2}}}$$

R_o = Antenna impedance = 450 Ohms

Z = reflected transformer Impedance (Z) & angle (Θ) tabulated in measured data

For example: RFT-82-75 with a turns ratio of 6/18 at a frequency of 1.3MHz.

RO = 450 Ω
Z = 432 Ω
θ = 22.8

ρ = [(432.Cos22.8 - 450)^2 + (432.Sin22.8)^2]^1/2
[(432.Cos22.8 +450)^2 + (432 Sin22.8)^2]^1/2

ρ = 175.2 / 864.5 = 0.2026

SWR = (1 + ρ) / (1 - ρ) = (1 + 0.2026) / (1 - 0.2026)

SWR = 1.50

CALCULATING LOSSES ENCOUNTERED DUE TO SWR

In this application, the calculated losses that result from mis-match of the antenna impedance to the transformer impedance were relatively small. These losses were calculated by:

Attn(SWR) = -4.34 ln $\{1-[(SWR-1) \div (SWR+1)]^2\}$] (ARRL Handbook, 1996 , pp30.36)

For instance, at SWR = 1.5

Attn (SWR) = -4.34 ln{ 1 – [(1.5-1) / (1.5 + 1)]^2 } = 0.177 db

SWR	1:1	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	7.0	8.0	9.0	10
-db	0	0.17	0.51	0.88	1.2	1.6	1.9	2.2	2.5	2.8	3.1	3.5	4.0	4.4	4.8

CALCULATING THE IMPEDANCE MULTIPLIER

Referring to the " Low Frequency Equivalent Circuit" the primary winding inductance, L, is shown as a load , (XL), on the signal The "K" factor is just a multiplier of the antenna impedance., (XL = K*R) at low frequencies XL gets smaller,(XL = 2Π*f*L) reducing the signal output. To improve low frequency response a higher value of K should be chosen, which will require more turns. The problem with increasing K (turns) is that it increases the losses due to leakage inductance and problems with capacity coupling at higher frequencies. Choosing the best value of K (turns) is a matter of compromise and all this test data is directed to provide a basis for making the best compromise.

CHANGING IMPEDANCE RATIOS

The findings in this report are primarily based on a 450-Ohm to 50-Ohm transformer. If you have a setup with a different impedance then you can use the following equation ** to determine the number of turns required.

N2 = N1 √R2 / R1

If you decide to use the 11 / 33 winding ratio but you have a 75-ohm receiver or cable connection, then adjust the 11 turns as follows:

N1 = 11 ; R2 = 75 ; R1 = 50

N2 = 11 √ 75 / 50 = 11* 1.22 = 13.47 = 14

If you have a 50-Ohm receiver input but a 600-Ohm antenna, then adjust the 33 winding in the same way.

N1 = 33 ; R2 = 600 ; R1 = 450

N2 = 33 √600 / 450 = 33 * 1.154 = 38.10 = 38

STUDIES OF TEMPERATURE EFFECTS

Amidon in their catalog show a graph of the initial permeability as a function temperature for type 75 and 43 ferrite materials. The AL factor, used in the design of the number of turns, is directly proportional to the initial permeability. AL = 4IIµ(ae / lm), where ae and lm are the effective core cross sectional area and mean path length around the core. The magnitude of the primary winding inductance is directly proportional to AL and therefore will primarily have an effect only on the low frequency response of a transformer.

The value of µ was calculated from measurements of inductance with 33 turns on a FT-114-75 & 43 cores. Inductance measurements were made from –20F to +60F and the calculated values of µ are tabulated below. At the top of each column is a value µa, which is the value of permeability taken from the Amidon charts.

The value of u is calculated as follows:
L = Inductance in mh
AL = mh / 1000 turns
u = calculated initial permeability at indicated temperature measured at different applied voltages
ua = initial permeability at temperature from Amidon Associates catalog.(Sept 1988, pages 67 & 74)
ae = effective cross sectional area of core, in cm x cm = 0.375
lm = mean path length around core, in cm = 7.42
N = 33 turns

AL = 4Πµ[a / lm]
AL = 10^6 [L / N^2] (from ferrite core data sheets)
Eliminating AL

u = 1446L

The measured values of µ for the type 43 material followed very closely to the values published by Amidon. In the case of the type 75 material, however, the value of µ did not change nearly as much as Amidon indicated. This was an unexpected benefit in the final use of the type 75 material.

FT-114-43 ; N = 33 ; f = 100kHz

T >	-20C ; ua=400		-10C; ua=480		0C; ua=560		+20C; ua=720		+40C; ua=960		+60C; ua=1200	
	L	u	L	u	L	u	L	u	L	u	L	u
Emv	mh				mh		mh		mh		mh	
100	0.234	338	0.238	389	0.321	464	0.517	747	0.674	974	0.800	1156
300	0.235	340	0.270	390	0.323	467	0.521	753	0.678	980	0.805	1164
550	0.237	343	0.273	395	0.326	471	0.528	763	0.687	993	0.818	1182
1000	0.239	346	0.277	400	0.333	482	0.543	785	0.703	1016	0.838	1211

FT-114-75 ; N= 33 ; f = 100kHz

	-20C;ua=3200		-10C;ua=3600		0C; ua=4000		+20;ua=4800		+40;ua=5600		+60C;ua=6400	
	L	u	L	u	L	u	L	u	L	u	L	u
Emv	mh		mh		mh		mh		mh		mh	
100	2.81	4063	3.00	4338	3.22	4656	3.36	4858	3.190	4612	3.180	4600
300	2.814	4069	3.02	4366	3.232	4673	3.364	4864	3.195	4620	3.185	4606
550	2.824	4083	3.038	4393	3.255	4707	3.376	4881	3.203	4632	3.192	4616
1000	2.844	4112	3.068	4436	3.281	4744	3.385	4895	3.215	4649	3..205	4634

For the final test on the effects of temperature*, measurements were made of the reflect impedance, using the " best" design, the FT-114-75-11/33-OL. As theory would indicate there was only a small change with temperature and only then at the low frequencies. This was partly due to the lower than expected temperature coefficient for the type 75 material.

FT-114-75-OL-R—Impedance vs TEMPERATURE

***** Even though the measured value of u for type 75 material only changed from 4063 to 4600 over the temperature range, it was decided to actually measure the change in the transformer reflected impedance over this temperature range. The results show only a small effect and as expected only on the lowest frequencies.

FT-	**FT-114-75**								
N=	11 / 33 – OL- R								
T >	-20C	-10C	0C	+10C	+20C	+30C	+40C	+50C	+60
.freq	Z	Z	Z	Z	Z	Z	Z	Z	Z
MHz	ohms	ohms	ohms	ohms	ohms	ohms	ohms	ohms	ohms
0.1	432	434	436	438	439	439	438	437	437
0.3	440	442	443	443	443	442	442	441	441
0.5	443	443	443	443	443	442	443	441	441
0.7	443	443	443	443	443	442	443	441	441
0.9	443	443	443	443	443	442	443	441	441
1.1	443	443	443	443	443	443	443	442	442
1.3	443	443	443	443	443	443	443	443	442
1.5	443	443	443	443	443	443	443	443	443
1.7	444	444	444	444	444	443	444	444	443
1.9	444	444	444	444	444	443	444	444	444
2.1	445	444	444	444	444	444	444	444	444
3.0	446	445	445	445	445	445	445	445	445
4.0	448	447	447	447	447	447	447	447	447
5.0	450	450	450	450	450	450	450	450	450
6.0	455	455	455	455	455	455	455	455	455
7.0	458	458	458	458	458	458	458	458	458

LEAKAGE INDUCTANCE & CAPACITY BETWEEN WINDINGS

The leakage inductance can be calculated approximately by taking the reactive component of the reflected impedance and dividing that quantity by 2Π***f***. At one MHz the values of leakage inductance for the FT-114-75-11/33 were, for the different winding methods: TW =1uH ; OL = 5uH ; SS = 58uH.

The capacity between the primary and secondary windings was measured at 500kHz for the different winding methods. SS = 8.7pf; OL = 19.2pf; TW = 36.4pf

TECHNICAL DISCUSSION

The main body of our article and the Technical Appendix above will likely answer all but the most technically oriented questions for readers. However, throughout our work on the article, Bill and Nick undertook a lively discussion of some of the finer points of impedance transformer design. While most of this discussion went beyond the bounds of my own technical understanding, I felt that many of the points made would be of interest to those with the understanding to appreciate these issues. Nick edited their e-mail discussion into a more comprehensible form, focusing on three topics as presented below: (BB – Bill Bowers; NHP -- Nick Hall-Patch)

Topic #1: Input voltage level effects on transformers:

BB: The value of permeability, in ferrite cores, varies significantly with temperature, frequency and signal strength, or more correctly, with flux density. All of these variations of permeability (and therefore A_L), have only secondary effects on transformers, primarily at low frequencies. They have drastic effects when trying to use ferrite inductors in tuned circuits.

***NHP: Although my tiddly random wire seems to have less than a few hundred millivolts pk-pk on it, when loaded down. Some people use serious antennas, so what sort of effect would larger antenna voltages have on the core? These cores will be faced with a large range of strong signals in some situations. For example, my calculations say that, for example, a 1 volt peak (2V peak to peak or 0.707 V RMS) delivered by an antenna to a FT114 size core with a 47 turn primary at 1 MHz would develop a flux density of 1.3 Gauss which doesn't seem enough to cause problems, especially as this is a transformer, not an inductor. Flux density would increase with lower number of turns and lower frequency, of course. At 100 kHz, the flux density would be 13 Gauss for example, but that's still a value that is way down on the B-H curve, which shows us where permeability starts to change due to excessive flux density.

The equation used to derive flux density is:

$$Bac = \frac{(Erms * 10^8)}{4.44 * Ae * N * f}$$

Bac *is flux density in Gauss*, Erms *is the applied AC voltage RMS (use peak AC voltage to find worst case* Bac*)*, Ae is *the effective cross sectional area of the core in square centimeters*, N *is the number of turns in the winding*, f *is frequency in Hertz. Core material does not enter into the equation.*

BB: Nick, you are correct, as long as the flux densities are below, something like 10 gauss, the permeability is fairly constant. It is only when signal strength (Erms) results in a flux density, (Bac), greater than 10 gauss, according to your formula. My initial concern about the effect of signal strength was based on the work done with audio filters. At 100Hz, the flux density is 10,000 times greater than at 1MHz , at the same applied signal level. The permeability of type 75 material at flux densities below 10 Gauss is a fairly constant 5000, but for example, at flux density of 4200 gauss the permeability is only 860. (This is found from the Hysteresis Loop, or B-H curve, in the Amidon catalog. Permeability = B/H.) At the RF frequencies, variation of permeability with antenna signal strengths should not be a problem. In the case of transformers, this change in permeability only affects the low frequency response, and then only at higher flux densities..

NHP: But for a B of 4200 Gauss, the applied voltage at 100 kHz with 33 turns on a 114 core would need to be 236 volts! Not from my antenna anytime soon, I hope. ***Looking again at the B-H curve, at 1000 Gauss, the permeability (B/H) is equal to 5000, much like the initial permeability. Voltage applied to a 33 turn winding in that case would have to be 55 volts, so it rather looks like we don't have to be concerned about input levels from a receiving antenna. Of course, the situation could be quite different with a much smaller core. For example, both Earl Cunningham, K6SE (http://lists.contesting.com/_topband/2002-March/014677.html) and Tom Rauch, W8JI (http://lists.contesting.com/_topband/1999-

February/004597.html) caution that the Mini-Circuits broadband transformers may saturate and cause intermodulation problems when used with antennas delivering a strong set of signals.

BB: I agree with your conclusions that for any " reasonable" size core there would never be an input level problem with antenna matching transformers. The Mini-Circuit are a different problem as their cores are so very small that they are easily overloaded.. I actually "burned out" 2 of the Mini-Circuit transformers when I tried to use them on a 2,000 foot Beverage.

NHP: Conclusion: Signal strength delivered by an antenna should not be a problem with 82 and 114 size cores, with flux densities below 10 Gauss. Flux density is greater with fewer turns, smaller cores and lower frequencies. Worst case would be if the entire signal delivered by the antenna was at the lowest frequency tested (100 kHz). Although the strongest individual signals delivered by an antenna are likely to be in the 540 to 1700 kHz range, one should be aware that if LF transmitters such as LORAN are nearby, their transmissions could cause saturation of these cores. It is quite likely, however, that the receiver itself would overload as well.

Topic #2: The effects of leakage flux in SS wound transformers

NHP: Looking at your observations until now, the ones on the side by side windings are ground breaking, because many, myself included, have suggested this method as a reasonable way to winding matching cores, especially as we felt it should minimize capacitive coupling of noise from one winding to the other. Why are SS wound cores apparently so unsuited for broadband matching? In your data, the reflected impedance from the 50 ohm resistor are all below 500 ohms up to about 1 MHz, though increasing in value as frequency increases; beyond 1 MHz, type 43 impedance mismatch increases about linearly with frequency, type 75/J mismatch increases more exponentially beyond 2 MHz. Losses, though "only a few dB" are just ghastly compared with the minimal losses found in the TW windings, and also increase with frequency right from 100kHz. In addition, losses and mismatch become worse yet with SS windings as the number of turns is increased on the transformers.

Core losses do not seem to be a possible explanation for what we are observing. Losses in magnetic materials are due to hysteresis loss, eddy current loss and "residual losses" (i.e. all the rest of the stuff that it's not as easy to explain, but is there. This is from the Philips/Ferroxcube publication: "Introduction soft ferrites"). Hysteresis losses are assumed not to be a concern when flux density is less than 1 Gauss as has been the case for your tests (see flux density equation above). The remaining two are included in the "loss factor" empirical specification found in the core specification sheets, and I'm not sure that even eddy current losses should be much of an issue in our case, as ferrite has quite a high electrical resistance at these frequencies and power levels. Core losses and permeability start to change for the worse in type 75/J material at frequencies in excess of 300 kHz, but type 43 core losses and permeability are consistent up to 20 MHz or so, yet the two core types seem to act nearly the same up to 2 MHz when SS windings are used.

There is obviously some sort of loss mechanism at work here that is common to both kinds of cores in spite of the differences in permeability and loss factor between them.

From my battles with the textbooks, it would appear that leakage flux (which causes the leakage inductance in your transformer diagrams; see below) is not nearly as heavily influenced by core material as permeability and loss factor are. In fact, one text I have at work, called "Transformer Design Handbook" (McLyman), advises that to minimize flux leakage one should minimize turns and use bifilar windings, among other pointers such as reducing the "build" of coils. Rather coincides with your observations of what makes a "better" transformer, doesn't it, Bill?

One of my first thoughts was that leakage flux becomes larger with frequency, primarily due to permeability becoming lower, and more flux escaping from the confines of the core (question #1: does that possibility make sense to you, Bill?). The SS windings on type 75/J cores give even poorer results at greater than 2MHz than the type 43 ones do, and interestingly, extrapolating on the permeability vs. frequency graph that you provided, at 2MHz the permeability of 75 is approximately equal to that of 43 (and then presumably becomes lower still at higher frequencies than 2 MHz).

In type 43 there is very little change in permeability as one approaches 7 MHz, unlike type 75/J, whose permeability actually starts to drop at only 300 kHz. So, if what we're observing is due to leakage flux due to decreased permeability, why does type 43 show increasing losses with frequency, when its permeability is not decreasing at all?

BB: First I appreciate your paraphrase of Philips, " stuff that is not easy to explain". I am afraid that some of the effects that have been observed fall into that category.

The SS windings, as we have called it, are transformers with the primary and secondary windings on opposite sides of the core. Any flux lines generated by the primary that do not link the secondary winding and visa-versa, are called leakage flux. In the case of the SS windings there is an area between the 2 windings where flux can leak across the core and link one winding and not the other. This leakage flux linking with the windings generates a series inductance with each of the windings. In the case of the primary and secondary windings being twisted together, any flux that cuts one winding must cut the other winding, so in principal there is no leakage flux. In the case of the OL windings, one winding wound on top of the other, there is little leakage, if both windings are evenly wound uniformly around the full circumference of the core.

Here I would like to correct a quote from McLyman that " to minimize the leakage flux one should minimize turns". What he should have said is that the effects of leakage flux are less with fewer turns, (very true), but it does not reduce the amount of leakage flux. A clear example of this is the comparison of 114-75-4/13 SS and the 114-75-11/33 SS transformers. Though both would have essentially the same leakage flux, the 4/13 SS with its fewer turns generated less leakage inductance and therefore lower losses at the higher frequencies. The 4/13 SS, however, did suffer at 100kHz with its lower primary inductance

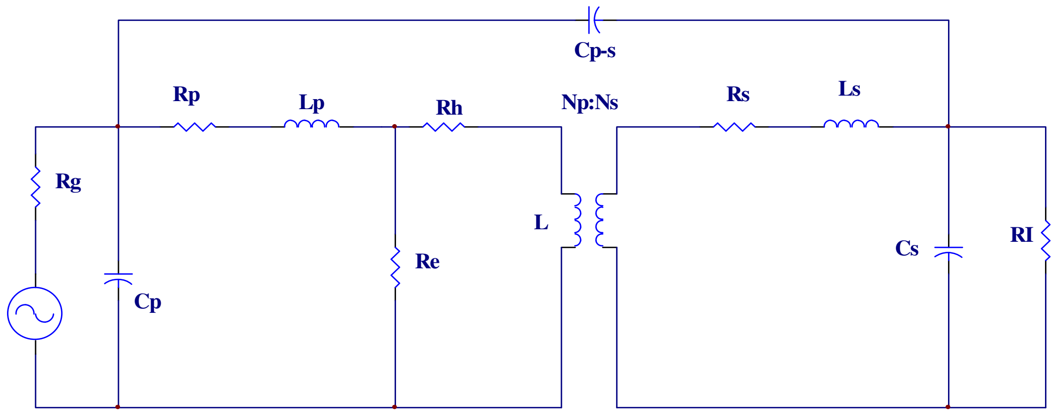
The series reactance, caused by the leakage flux, on both sides of the transformer reduces the output signal and therefore is measured as a signal loss. Looking at the data, (0.5 – 2.1MHz), from the SS-43 and SS-75, the reflected impedance changes significantly with frequency. This means that there is an inductive component caused by leakage flux, (leakage inductance), whose impedance increases with frequency. This is further indicated by the large angle (inductive), of the reflected impedance.

The simplistic model of a broadband transformer is that at the lower frequency range the dominant factor is the shunt impedance of the primary winding. That is why the low frequency response of a transformer improves as the number of turns increases. At the higher frequency end, the dominant factors are the "leakage inductance" in series with the output. The distributed capacity of the secondary is probably a factor at the higher frequencies but it does not seem to be a dominant factor. I would have thought that when turns were increased to improve the low frequency response, the capacitive effects would cause a much greater loss at the higher frequencies. The capacity losses may be in there but once the effects of leakage inductance are minimized, (TW & OL windings), the losses are remarkably low.

The reason that the reflected impedance (from the 50 ohm test resistor) increases with frequency is also that this leakage inductance is effectively in series with the secondary reflected impedance. Remember that even if the leakage inductance were constant as the frequency goes up, the ohmic value of the leakage reactance added to Z will go up directly with frequency. ($X_L = 2 * \pi * f * L$). The value of permeability for type 75 really goes to pot above 1.0Mhz and this, I speculate, is why I think Z for 75 material goes up faster than 43 with the same 11/33 SS windings. I am now in the area of "stuff that is not easily explained". I am, however, confident that the measurements and data reported are correct.

(*See diagram and explanations below for details about leakage inductance and reactance and its effects.)*

DIAGRAM A



Rg = Resistance of signal source; in this case, the antenna’s impedance of 450 ohms , as the antenna is the generator
Cp = Capacity between turns in the primary winding
Rp = Resistance of the primary winding
Lp = Leakage inductance of primary winding
L = Self inductance of primary winding
Re = Eddy current losses in the core
Rh = Hysteresis losses in the core
Np:Ns = 1 for this model
Rs = Resistance of secondary winding
Ls = Leakage inductance of secondary winding
Cs = Capacity between turns in the secondary winding
Cp-s = Capacity between primary and secondary windings
Rl = Resistance of load
(note that Re and Rh are likely insignificant in our tests)

DIAGRAM B

at low frequencies, the circuit acts like this

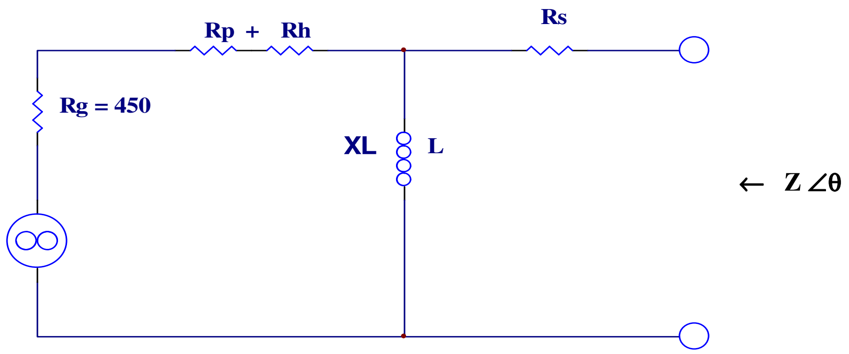


DIAGRAM C

at high frequencies, the circuit acts like this

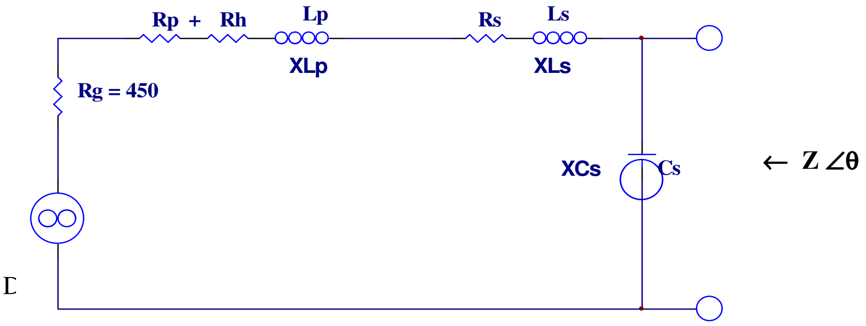
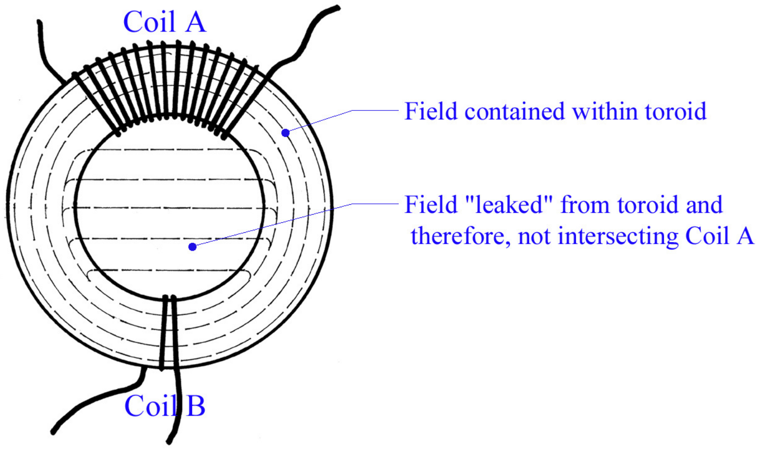


DIAGRAM D

leakage reactance related to Coil B



Referring to diagram " D ":

- The current in the primary , SS , winding will generate flux lines. Most of these lines go around the toroid and cut the secondary , SS, windings. A fraction of this flux will " leak" across the air space in the core center and back to the primary and not cut the secondary windings. This leakage flux results in a leakage inductance Lp.
- The same logic applies to current in the secondary resulting in Ls.
- Lp & Ls result in X_{Lp} & X_{Ls}. which increases directly with frequency and as the square of the number of turns.
- This leakage reactance, in the SS windings, is in series with the source resistance , so Z will increase with frequency and faster with the number of turns.
- With the TW windings, the primary and secondary windings are always together, so in principal there should be no leakage reactance, as any flux line that cuts the primary winding will cut the secondary winding. This why the value of Z in TW windings is much more constant with frequency than the SS windings.
- The small increase in Z with frequency seen in the TW windings, must be due to some secondary effects of hysteresis or winding capacitance ?

Topic #3: Can SS cores work in real life?

NHP: Some further "real-life" experiments were performed comparing SS with TW transformer windings using FT114-J cores, wound 48t to 12t on each for an 800:50 Ω Z ratio at 100 kHz and above..

I used a 12m sloping wire as an antenna (4m high at high end) to drive a Siemens D-2007 frequency selective voltmeter via the transformers. Initial tests were done on semi-local BCB stations, and on these signals the SS core always had as good signal strength (and up to 4 dB better strength in the middle of the BCB) as the TW core did. Longwave signals in the 200 kHz region had equal strength on both wires, but at 3MHz, signals on the SS core were at least 15 dB down from the TW core (I had to use a Drake R8 rather than the Siemens for the 3 MHz tests).

My major concern all along has been whether the SS core, useless though it may look in theses tests, would provide better isolation from local electrical noise than the TW cores would. At the lower frequencies such isolation wasn't noticeable, but there was a dB or so of S/N ratio gained on a signal at 1640 kHz. At 3.33 MHz, there was an instance where CHU gained an S-unit of S/N ratio on the SS core, in spite of its poorer signal strength overall. An OL core was similar in its S/N and signal strength to a TW core.

I'm not convinced the occasional isolation from electrical noise is worth the variability of the SS core's impedance matching that would be dependent on the receiver, and the type of random wire antenna being used. But the effect should be noted for the die-hard experimenter.

BB: The original objective was to find the most efficient transformer that would match 450+j0 to 50+j0 over the frequency range of 0.1 to 7MHz. I feel we have come pretty close to meeting that objective with the 114-75-11/33-OL being the "best" design. This "best" design may or may not be the best design for a given antenna at a particular frequency. It would only be best if the antenna had an impedance of 450+j0 (in the 9:1 case, or 800+j0 in the transformer used in the above experiments).

The SS design gives a significant inductive reactance component, and this, in some cases, will help to correct the capacitive reactance in the antenna. For example at 1.9 MHz the 114-75-11/33-SS the receiver impedance of 50+j0 presented an impedance of 481+j695 to the antenna. If the antenna had an impedance of 450 -j695 you would have a perfect match. The impedance of the " best" (OL) design at 1.9 MHz was 444+j21. With this low value of inductive reactive this transformer would not compensate for an antenna that had an impedance with a significant capacitive reactance component,

Quoting Terman, "The power delivered by the receiving antenna to a load impedance, (the receiver in this case), ... will be a maximum if the resistance of the antenna is equal to the load resistance and the reactance of the load is equal in magnitude but opposite in sign to the reactive component of the equivalent antenna impedance".

Tuned loop or terminated beverage antennas have a very low reactive component and the OL or TW winding would clearly provide the best design for these applications.

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