THE WEST RAND AMATEUR RADIO CLUB

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ANODE

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Special points of interest:

- Contact details on back page (corrected & updated)
- Ham-Comp Latest on web site.

Editor's Comments

Volume 10, Issue 6
December 2009

Broadband Matching Transformers

Watching the guys at the club a couple of months back, made me look up the original article that caused such a stir in the late 70's.

So I scanned and OCR'ed the original photo-copied Electronics Article. I present it here for you to study. I expect from now on, you will be able to match any antenna to any transmitter over the entire H.F. Band…

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Tis the season to be jolly! Jolly grateful that you aren't a Robot pole, Lamppost, road sign or Armco in Gauteng....

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Broadband matching transformers can handle many kilowatts

The discovery that transformers with transmission-line windings have 98% efficiencies opens up new uses for them in high-power applications

by Jerry Sevick, Bell Labotatories, Murray Hill, N.J.

The big, news about broadband matching transmission-line transformers is their ability, to deal with many kilowatts of power. On investigation, their efficiency turns out to be much higher than anyone had suspected an astonishing 98% over most of a frequency range spanning several hundred kilohertz to 100 megahertz. Also news is the fact that they can be built with fractional impedance transformation ratios.

The small rugged devices, made of a short length of transmission line coiled around a single magnetic core, are in wide use because of their inherently large band width. Now their applications should be extended in particular to matching high-power amplifiers to an antenna, as well as matching small-signal amplifiers.

Experience long ago showed that other broadband matching devices whether networks of capacitors and inductors or conventional transformers had smaller bandwidths and lower efficiencies. High ohmic loss characterizes inductors of the size needed at low frequencies. High core loss in conventional transformers drastically reduces their efficiency and with it their power-handling

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capability.

But only recently (1976) have careful experiments been done to determine just why a broadband transmission-line transformer is so superior. The new data explodes several assumptions about its mode of operation and about the function of the core.

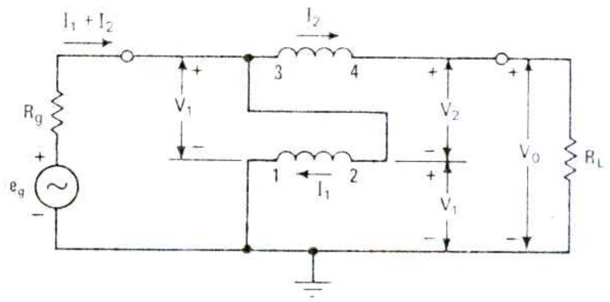
In particular, the device was always thought to behave quite differently at the low and high ends of its frequency range. It was supposed to act like a conventional, three-terminal auto transformer at lower frequencies, coupling energy magnetically through the core, but like a transmission line at high frequencies, with the core having little effect.

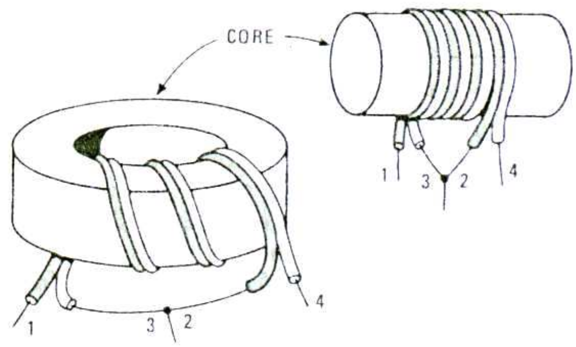
What really happens...

Accurate measurements suggest another explanation. The transmission-line mode seems to be in effect throughout the frequency range, except at the very lowest end. The core's role is to prevent shunting currents at all frequencies and never to couple energy, except at the very lowest end of the range.

The equal and opposite currents that flow in the transmission-line windings essentially cancel core flux and so minimize core loss. The shortness of the transmission line (in relation to the wavelength of the highest operating frequency) minimizes ohmic losses, keeping output voltage nearly equal to input voltage over a wide frequency range so that a constant transformation ratio is maintained. Coilling the line around a magnetic core provides the inductance needed to prevent unwanted currents from flowing, except at very low frequencies.

Three transformers with 4:1 impedance ratios were constructed, and their performance was measured under similar conditions (Fig. 1). One was a conventional autotransformer of 10 turns on a toroidal core. The other two were transmission line transformers of 10 turns with and without the core. The toroidal cores had an outer diameter of 1.25 inches, an inner diameter of 0.75 in., and a thickness of 0.375 in., and they both used high bulk-resistivity ferrite material (Indiana General Q1).





[Fig 2. Transmission-line transformer. Both toroidal and rod type transformers provide broadband operation. Shown is the popular 4:1 unbalanced-to-unbalanced transformer that uses two wires of equal diameter closely wound around a magnetic core material.]

As the plot of transducer loss versus frequency shows, the transmission-line transformer with a core acts just like a conventional autotransformer at very low frequencies. At about 400 kHz transmission line operation starts contributing to its efficiency, and through 40 MHz it suffers much less than the autotransformer from transducer loss, suggesting reduced core loss. But without a magnetic core to choke off shunting currents,

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not only is its efficiency much less, but its frequency response also falls off rapidly below 1.5 MHz.

...and why

Figure 2 presents a model for the most widely used 4:1 unbalanced-to-unbalanced broadband transmission-line transformer. As can be seen from this model, if the line is half a wavelength long, V2 equals – V1 and the output power is zero.

But for much shorter transmission lines, V2 is very nearly equal to V1 because no standing waves exist. Then - provided that nothing much more than transmission-line current is flowing through the bottom winding - the output voltage is twice the input voltage, the output current is half the input current, and a 4:1 impedance transformation exists.

The relationship holds up quite well if the transmission line is shorter than 0.2 of the effective wavelength. At this length the mismatch corresponds to a voltage standing-wave ratio of 2:1 where the transducer loss increases by 0.4 decibel. Any longer, and the VSWR of the particular length will increase or decrease V2, and the transformer will become less useful.

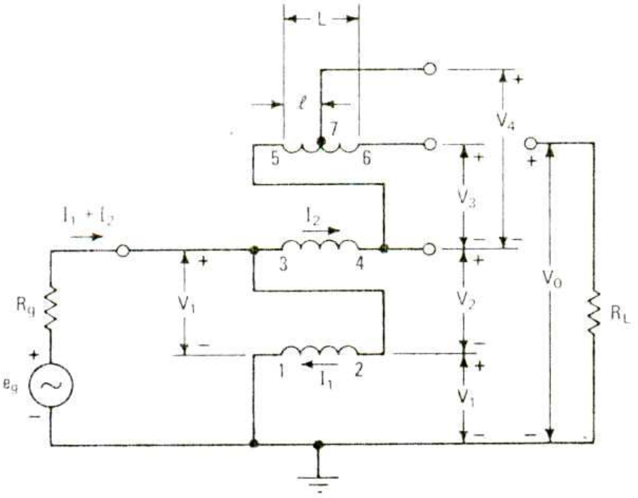
Two basic equations

The efficiency of such a transformer depends on different factors at high and low frequencies. The voltage standing-wave ratio is critical at the high end, and the reactance of the bottom winding to any shunting current present. though important throughout the range, becomes especially critical at the low end.

An equation for high-frequency transducer loss can be derived from the model in Fig. 2 if loop equations are applied to it, as Ruthroff has shown.(ref 1) When I1, is assumed equal to I2, the result is:

available power / output power =
(1 + 3 cos beta . l)^2 + 4 sin^2 beta . l
/
4 (l + cos beta . l)^2

where beta = 2 pi / lambda effective and l is the length of the transmission line.



[Fig 3. Other ratios. A 4:1 impedance ratio results when the transmission-line transformer's output is connected between ground and terminal 4, Rl when it is connected between ground and terminal 6. Tapping off the top winding (terminal 7) yields non-integer ratios.]

The equation is the reduction of a more general one, from which it is obtained by insertion of the optimum value for the characteristic impedance, Zo This value is the same as that of the quarter-wavelength matching transmission line, namely the geometric mean of the source and load resistance, (Rg Rl) ^ 0.5

Note that no reference to a core of magnetic material is contained in this analysis. In the

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transmission-line mode, the magnetic fields cancel at high frequencies, so that almost no flux threads the core.

However, the core's effect needs stating at low frequencies. At this end of the range, the transformer's response is determined mainly by the reactance of the bottom winding to the flow of a shunting current. If the reactance is made large enough, only transmission-line current will flow, and the impedance transformation ratio will be maintained.

One way to increase reactance would be to increase the number of turns of the transmission line, but that would lengthen it and so degrade its high-frequency performance. The preferred way is to use high-permiability core material, particularly in the case of a toroldal configuration.

The model for the low-frequency region can then be represented by an inductance in parallel with an ideal transformer. In mathematical terms:

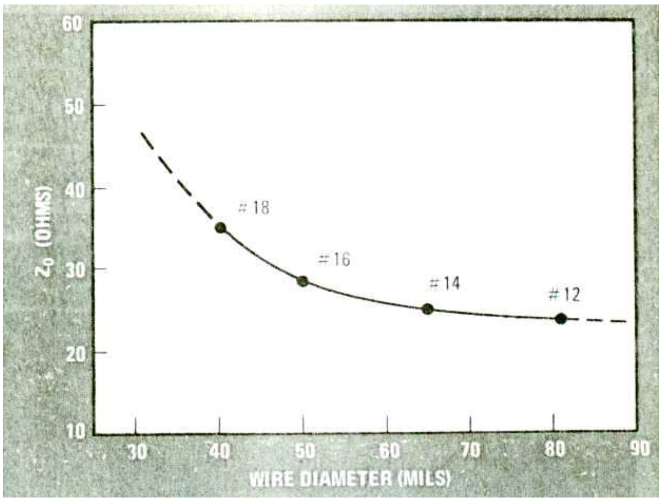
$$\text{available power} / \text{output power} = R_g^2 + 4X^2 / 4X^2$$

equation (2)

where X is the reactance of the bottom winding with the secondary open-circulted.

A different mechanism

Although this equation is identical to that for the low frequency response of the conventional transformer, the modes of operation are different. The transmission-line transformer, for as long as it is transferring considerable quantities of power at low frequencies, is still acting like a transmission line and not like a conventional transformer, which transfers power entirely by the common flux linkage. But it may start acting as an autotransformer at still lower frequencies if it experiences appreciable core flux and the choking action is inadequate to prevent the generation of excessive currents in the bottom winding.



[Fig 4. Experimental data. Characteristic impedance Zo is plotted for closely wound coils of the size of wire used in power applications. Twisting the wires together decreases Zo slightly; reducing the spacing between adjacent pairs lowers Zo as much as 40%.]

The analysis of the transimission-line transformer's operation need not stop here. If It is carried a step further. it is possible to show that single-core transimisslon-line transformers can be constructed with integer impedance ratios of other than 4:1 and even with non-integer impedance ratios-in other words, with fractional impedance ratios.

Figure 3 presents the model for the extended analysis, which employs the same sort of loop equations as before. In this case, three windings are used instead of two, and the associated voltages V1, V2 and V3 are summed across the load. Conventional fransmission-line

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equations determine V2 with respect to V1 as well as V3 with respect to V2. Output voltage Vo is determined from two transmission lines of equal lengths, not from one transmission line of- twice the length. The voltages simply add when transmission lines are short – Vo is three times larger than the input voltage V1 and I1 is twice as large as I2, complying with the principle of the conservation of energy. Also, the flux from the bottom winding tends to cancel the flux from the other two, minimizing core losses. The result is an impedance transformation ratio of 9:1.

Obtaining fractional ratios

Impedance ratios of other than 9 or 4 to 1 become possible if the top winding is tapped. Since all windings are tightly coupled electrically, a common voltage gradient of V1 exists from left to right along the windings, and the voltage at the tap, terminal 7, becomes Vo = V1 + V2 + V4. Now V1 = V2, and V4 = (l / L)V1, where L is the length of the transmission line and l the length to the tap.

Consequently:

Vo = V1 (2 + l/L)

To generalize this equation, let n = the number of windings below the top winding which is tapped so that:

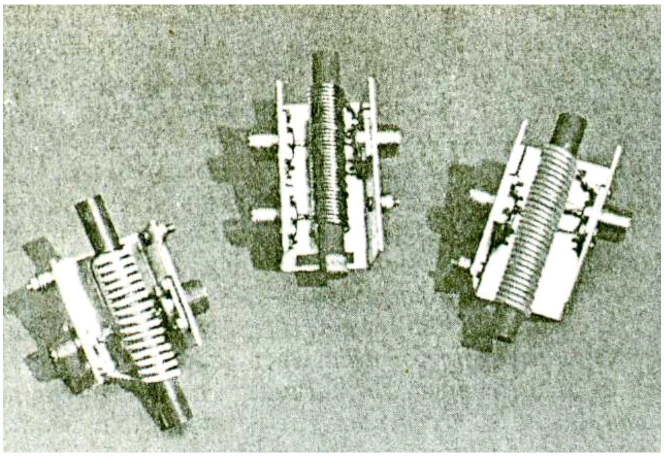
Vo = V1(n + l/L)

Rod-core transformers allow for fractional turns, so their 1 can have any value tip to L. But for toroidal-core transformers., which do not allow fractional turns, the equation becomes:

Vo = V1(n + n1 / N)

where n, equals the number of tapped integer turns and where N equals the total number of integer turns.

Simply tapping off the top winding of the two-winding 4:1 transformer shown in Fig. 2 makes n equal 1, so that ratios of less than 4:1 become possible.



[Fig 6. Varying the impedance ratio. Two-winding step-up transmissionline transformers provide a 1.55.1 ratio (left) and a 2.1 ratio (right), while a three-winding transformer (middle) can provide either a 9:1 or 4.1 ratio. All three devices were wound with 14-gauge enameled wire on 0.5 inch-diarneter, 4-inch-long ferrite rods. The frequency response of each of the transformers is plotted in Fig. 7.]

Since the output voltage depends on the length ratio or turns ratio, it is easy to design a matching transformer for a particular impedance. For example, to match a 50 Ohm coaxial cable to a 35-ohm self-resonant vertical antenna, the impedance ratio must be 50/35 or 1.43. Since the voltage ratio is proportional to the square root of the impedance ratio, Vo/Vi = (1.43)^ 0.5 = 1.2. Then the value of 1/L can be found from the general equation for a bifilar-wound rod-core transformer:

Vo/Vi = n + (l / L)
1.2 = 1 + (l / L)
l / L = 0.2

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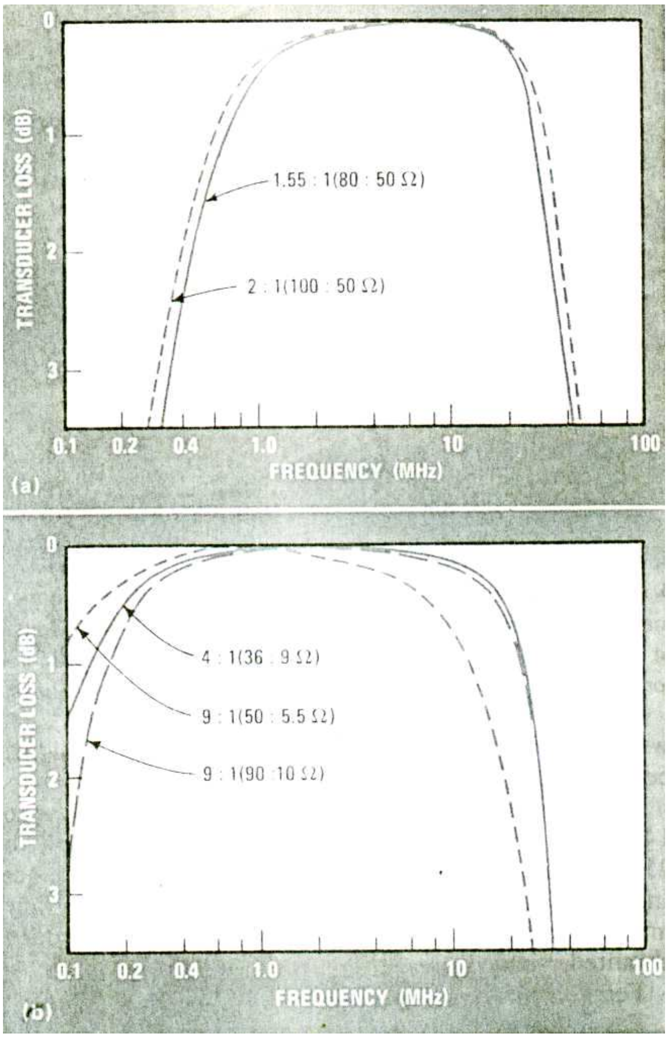
Thus, the two-winding network with a rod core will require a tap at 0.2 of its length from terminal 3 of Fig. 2. For a toroidal-core transformer, tapping 22 out of 5 turns, or 4 out of 10, would give.a similar result.

Besides the two basic equations (1) and (2), three parameters are needed to design broadband transformers. They are: characteristic impedance Z, which depends on the number of turns and the shape and spacing of the windings; the shunting inductance that affects low-frequency rolloff and itself depends on the size and type of core material; and the effective phase constant of the coiled transmission line, which determines the transformer's high frequency response and depends on the dielectric of the wire insulation and coupling between windings.

As already noted, the optimum value for the characteristic impedance of the transmission line of a 4:1 matching transformer is the geometric mean of the input and output resistance, Zo = (Rg RL)^0.5. Initial results for fractional-ratio designs indicate that for them, too, the Optinium values of Zo are the geometric means of their input and output resistances. It has been found that generally, with characteristic impedances of twice or half the optimum value, the transducer loss is less than 0.2 db with short transmission lines of 0.09 lambda or less. The author found experimentally that little degradation is observed at the high-frequency cutoff with departures as large as10% from the optimum value of Zo. The characteristic impedance, however, does vary with freuuency because the permeability of the core material is frequency-sensitive. Usually the optimum value of Zo should be determined at the highest frequency of operation.

To lower the characteristic impedance, should that be necessary, transmission lines can be twisted together. Twisting them lowers Zo by increasing their distributed capacitance. A more significant change, however, can be



[Fig 7. **Plotting response.** The characteristic impedance is optimum for 1 the 4: 1 transformer but for the 9.. 1 transforr-ner only when matching 90 to 10 ohms, not 50 to 5.5 ohms. For the latter case this less-than-optimum impedance causes a more rapid falloff at high frequencies, but, since an inductive reactance of only 5.5 ohms, not 10 ohms, has to be exceeded, the low-frequency end is improved.]

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made by just tightly coiling the transmission lines and so minimizing spacing between windings.

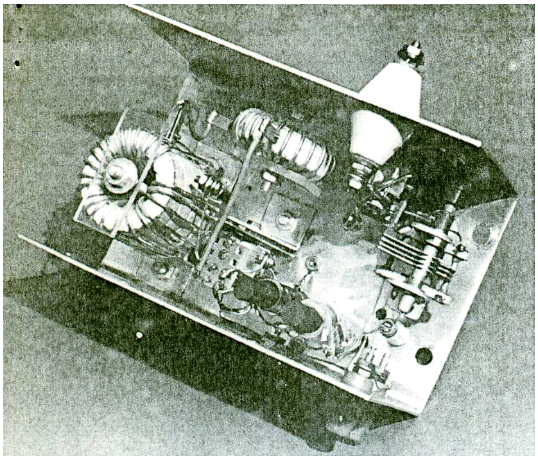
How to adjust Zo

Figure 4 shows experimental data for various tightly wound. bililar coils of' typical wire sizes used in power step-down applications. For instance, Zo can be lowered about 40% by, reducing the spacing between adjacent pairs of wires from three wire-diameters to that of the insulation of the wires.

For step-up transformers to maintain high-frequency performance, however, larger winding separations are necessary. This can be done by separating the turns with extra insulation, such as Teflon tubing, to increase the characteristic impedance. For example, tightly wound turns, separated by Teflon sleeving, approach a Zo of 70 ohms and are useful in step-up transformers that must match 50 ohms or more.

The core's role

Shunting inductance varies with the geometry and permeability of the transformer's core material. To define the core role more closely, three 4:1 matching transformers were tested (Fig. 5). Two used toroidal cores, and one used a solenoid. One torold was of Q1 ferrite material with an outer diameter of 2.4 in. and a thickness of 112 in. The other toroid was powdered iron (Carbonyl E, mu = 10 nominally) with an outer diameter of 2 in. and a thickness of a little less than 1/2 in. The solenoid was a rod of ferrite material, 1/8 in. in diameter and 4 in. long. (Various lengths of rod were tried, but with very similar results better low-frequency response.)



[Fig 8. **Antenna matching.** Two transmission line ferrite-rod transformers match the changing impedance of a 29-ft vertical antenna operating at 1.8, 4, and 7 MHz. The antenna is resonated by powdered-iron toroids at low frequencies, by a variable air capacitor at high ones.]

All transformers were tightly wound with 15 inches of 14-gauge wire to approximate an optimum Zo of 25 ohms and assure similar high-frequency performance. Inductance measurements at 1 MHz on the lowimpedance side of the network, with the output opencircuited, yielded:

Ferrite toroid, Loc = 11.08 uH
Powdered-iron torold, Loc = 1.67 uH
Ferrite rod, 7.5 in. long, Loc = 6.07 uH
Ferrite rod, 4 in. long, Loc = 4.67 uH
Ferrite rod, 2.5 in. long, Loc = 3.69 uH
Ferrite rod, rod removed. Loc = 0.413 uH

The low-frequency performance of a toroid is clearly superior to a rod's owing to the former's enclosed reluctance path and hence higher inductance. Because of the much higher value of reluctance in the airpath around the rod, little is gained at the low-frequincy end by increasing its permeability. But with a toroid, inductance is proportional to the material's permeability, so that the higher the permeability, the better the lowfrequency performance. Note the poor

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performance of the powdered-iron torold with its lower permeability.

Finally, to ensure that these transformers were free of nonlinear or amplitude efrects, they were subjected to various power levels. Invariably no additional power loss was discernible at levels up to 1 kW.

The design potential

The transformers with ferrite cores covered a rather wide frequency range with losses of only about 0.05 dB. Since this loss is a combination of mismatch and transformer losses, efficiencies were greater than 98% over that range. Few networks can compete with such high efficiencies, which allow these transmission-line transformers to be cascaded to obtain higher impedance transformation ratios.

The major difficulty, however, is in getting the proper value of characteristic impedance for large step-down or step-up impedance ratios. For step-down a low value is needed. whereas step-up requires a higher value.

Generally, for very low values of characteristic impedance, stripline techniques are used. However, for higher values of Zo, the transmission lines must be separated. This is easily done. The use of Teflon or other insulating materials between windings provides known and controllable spacing.

These transmission-line transformers provide typically wideband performance even when tapped to provide a variety of impedance transformation ratios. This is not achievable with conventional transformers that use flux linkage as the energy-coupling method.

Figure 6 shows two transformers with other than 4:1 ratios, along with a transformer of three windings on a rod connected in a 4:1 and 9:1 fashion. The transformer on the left is tapped tor a 1.55:1 impedance transiormation, while the one on the right is a 2:1 step-up.

All were designed for operation with 50 Ohm coaxial cable, and their loss versus frequency is plotted in Fig. 7. Even using rod-type cores, these transformers exhibited rather wide frequency response. Of course, the bandwidth could be further increased if a toroidal core were used. But unless the extrd bandwidth is necessary, it does not pay to use the more expensive torold.

One difference is worth noting. The 1.55:1 and 2:1 transformers performed similarly whether matching 50 to 5.5 ohms or 90 to 10 ohms. But in the 9:1 transformer, matching between 50 and 5.5 Ohms produced better low frequency performance. The reason is that the inductive reactance of the transformer, although the same in either case. needs only to be greater than 5.5 Ohms of inductive reactance instead of 10 ohms. However, when matching to the higher impedance, the upper frequency cut off was greater since the characteristic impedance of the transformer was equal to the optimum value.

Cool operation

All transformers were tested at 1-kilowatt operation. As was also the case with the 4:1 transformer, they suffered no discernible power loss or heating.

Consequently, these fractional-ratio transformers can be cascaded to provide all sorts of impedance ratios. One instance is the network shown in Fig. 8, which can handle 1 kw of power and uses two transmission-line transformers wound on ferrite rods to match a

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Editor's Comments

(Continued from page 1)

The 52 pairs of socks delivered to you as a Christmas Present, are as a result of an SQL query deciding that you should get the present that you deserve this year.

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DARPA balloon-hunt compo

http://www.theregister.co.uk/2009/12/01/darpa_balloon_caper_precursor/

Pitchfork-wielding mobs encircle smart meters

http://www.theregister.co.uk/2009/11/27/smart_meter_backlash/

{—}

A New Direct Conversion Receiver (for SA Hams)

I am looking into sourcing of economic components for the 10 MHz direct conversion receiver. Check out the Ham-Comp pages on the web-site for more details.

http://www.jbcs.co.za/ham_radio.php

Have a great Christmas and prosperous New Year.

JB 2009-12-13

Broadband matching transformers can handle many kilowatts

50-ohm cable to a 29-foot vertical antenna having a 13 foot top hat at 1.8, 4 and 7 MHz.

The ferrite toroid was not fully looked into and now bears further investigation. The only comparison made was with a single value of permeability, that of Q1 material, which was the hrst nickel-zinc ferrite used tor amplitude-modulated radio antennas, i-f and rf transformers. Toroids with greater permeability look very promising for transmission 1ine transformers requiring even larger bandwidths at rather high power levels.

Roferoncos

1 C. L.. Ruthroff, “Some Broadband Transformers." Proc. IRE, vol. 47. August 1959, pp 1,337 - 1,342.

2. 0. Pitzalis and T. P. Couse, "Practical Design Information for Broadband Transmission Line Transformers.” Proc IEEE, April 1968, pp 738 – 739,

Scanned and copied from Electronics/ November 25, 1976, pages 123 - 128

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West Rand members - we need your input!

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In July 2003, we re-published an Anode Compendium on CD. It has the issues from July 2000 until June 2005. This included the new Adobe reader. It has been updated, check with the chairman for details.

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