broadband RF transformers

Add fractional turns ratio techniques to your impedance matching arsenal

Despite conventional wisdom, which holds that a transmission line transformer can be built only with integral turns ratios, it's entirely possible to build a practical 2:1 impedance change transformer — that is, a 1.5:1 turns ratio transformer. Many other fractions are also possible. But first let's review the evolution of RF transformers, keeping an eye out for some of the possible pitfalls along the way.

basic transformer

Consider a basic autotransformer, which has one winding, with a tap. If there are five turns from start to tap, and two more from tap to finish, then the input impedance from start to finish, assuming 25 ohms between start and tap, is (25 x 7 x 7)/(5 x 5), or 49 ohms. This is within 2 percent of 50 ohms, so it could serve as a 2:1 transformer.

leakage inductance

Leakage inductance occurs when the flux from any part of a turn doesn't cut all of another turn. Leakage inductance is always present — it's just a question of *how much*. One might think that any flux that cuts the cores couldn't possibly contribute to leakage inductance, because it would then couple to the other turns. Thus many early transformer designs stressed placing the windings close to the cores. Note that by definition, both the primary and secondary have separate, and therefore probably unequal, leakage inductances. These leakage inductances limit the high frequency response because they are very real inductors in series with the transformer's leads.

twisted and braided windings

One might think that lowest leakage inductance is achieved when all the wires are wound tightly together. Imagine a rope consisting of five parallel strands of insulated wire twisted together. This rope is wound through a core for five turns only. Then a group of three of the strands are unwound one turn and then cut off, leaving two strands with five turns and three strands with four turns. The three four-turn strands are then connected in parallel to one another. These are in turn connected in series, aiding with both of the remaining five-turn windings. To summarize: from the bottom up, there are five turns in series with five turns to the tap, and then four turns to the top-end, producing a 14:10 ratio.

Another idea is to use seven strands twisted together as a rope with only one turn of this rope around the core. Connect five of these turns in series out to a tap, then add the remaining two in series. In theory this method might offer the lowest leakage inductance of any construction, but I can't handle the rat-nest of splices and still keep the leads short! And both of these techniques ignore capacitive effects that limit high frequency response.

transmission line

As the primary and secondary wires are brought closer to each other, rather than closer to the core, their mutual inductance and capacitance increases. It then becomes easier to envision the pair of wires as a transmission line. At first one might think the extra capacitance would limit the high frequency response, but it doesn't. The capacitance and leakage inductance combine to make a transmission line. The closer the wires are, the lower the transmission line's impedance. Considering the windings as transmission lines is a useful conceptual aid. It is now the standard method for making RF transformers, because it leads to wider-bandwidth performance. The high frequency end is helped without affecting the low frequencies.

bandwidth limitations

A transformer's low frequency response is a function of the type of core, its cross-sectional area, and the number of turns. The high frequency response depends on the inductance and the turn-to-turn capacitance as well as the length of the winding. The limiting length occurs when the induced voltage of a single turn adds to the next turns' (voltage) at a significantly *later* angle. This equates to a transmission line whose delay angle is determined by its length and velocity of propagation. The phase delay of the transformer limits its high frequency usefulness.

balanced transmission lines

Consider a pair of parallel conductors arranged so closely that when the current in one conductor flows in one direction, the current in the other flows in the

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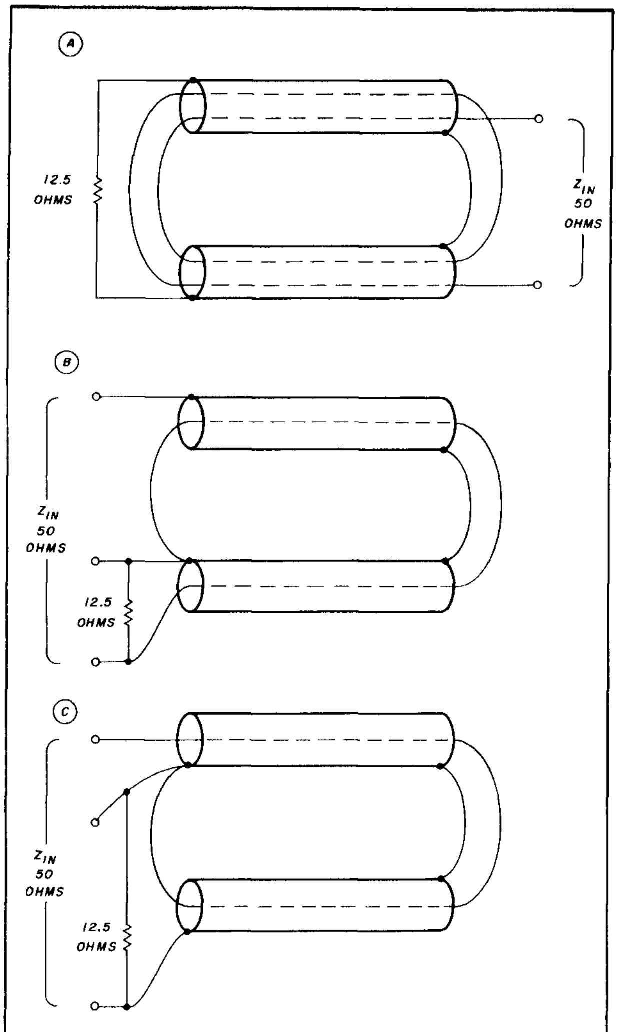

fig. 1. 4:1 impedance change tubing transformers: (*A*), connected as a transformer; (*B*) and (*C*), connected as an auto-transformer.

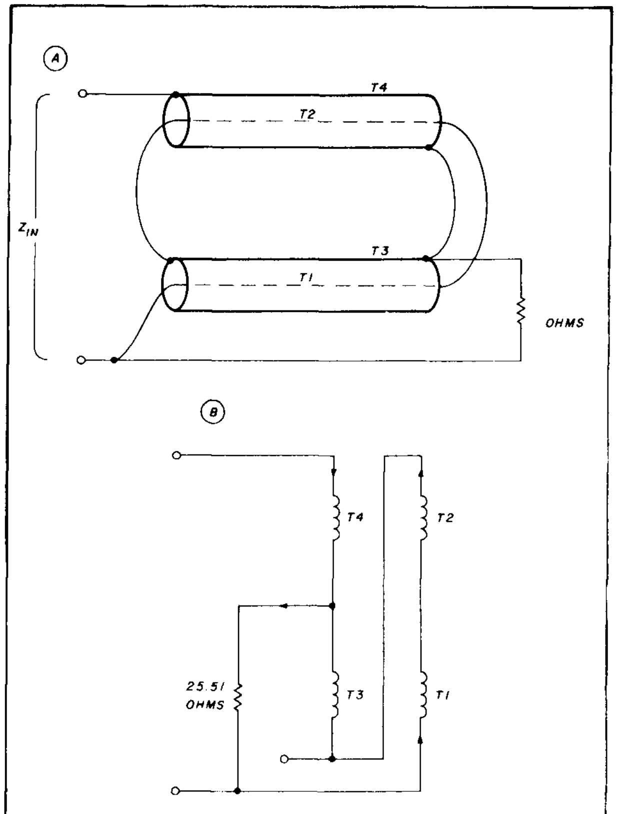

fig. 2. (*A*) Pictorial and (*B*) schematic representation of a tubing transformer connected to provide a 2:1 impedance change. (The reason it *won't* work is explained in the text.)

opposite direction. (Both are equal in magnitude.) This allows their magnetic fields to cancel out as soon as one is outside the space between the wires. As long as the currents are equal, the magnetic field does not need to intercept the cores. The inter-wire space also has an electric field due to the potential difference between the wires. The electric field diminishes as soon as one is away from the wires several times their spacing, especially if a material with a high dielectric constant is between the wires. Consequently, electromagnetic field propagates between the wires and transmission line theory applies. The uncoupled magnetic lines result in a leakage inductance, analogous to a transmission line unbalance which results in line radiation.

transmission line impedance

The impedance of a transmission line is sometimes defined as the square root of the ratio of inductance per unit length divided by the capacitance per unit length. If one has inductance and capacitance meters, this can be measured easily by shorting the output end of the transmission line and measuring the inductance at the other end. Capacitance is measured directly after the short is removed. Measurements are taken at a frequency in which the line length is less than 1/10 of a wavelength. Divide the Henries by the Farads and take the square-root of this ratio to get the impedance of the transmission line in ohms. A vector impedance meter can be used to measure the line impedance by varying the frequency at about the 1/8 wavelength point until the magnitude of impedance stays the same as the other end of the line is alternately shorted and left open. The phase swings from inductive to capacitive; its amount is ignored. The surge impedance can be read directly.

We must be able to identify every conductor with a mate carrying current in the opposite direction, resulting in the absence of an external magnetic field and consequently small leakage inductance. However, even this procedure is difficult, since the capacity of each wire is not only to every adjacent wire(s), but also to ground; and the currents in parallel conductors still

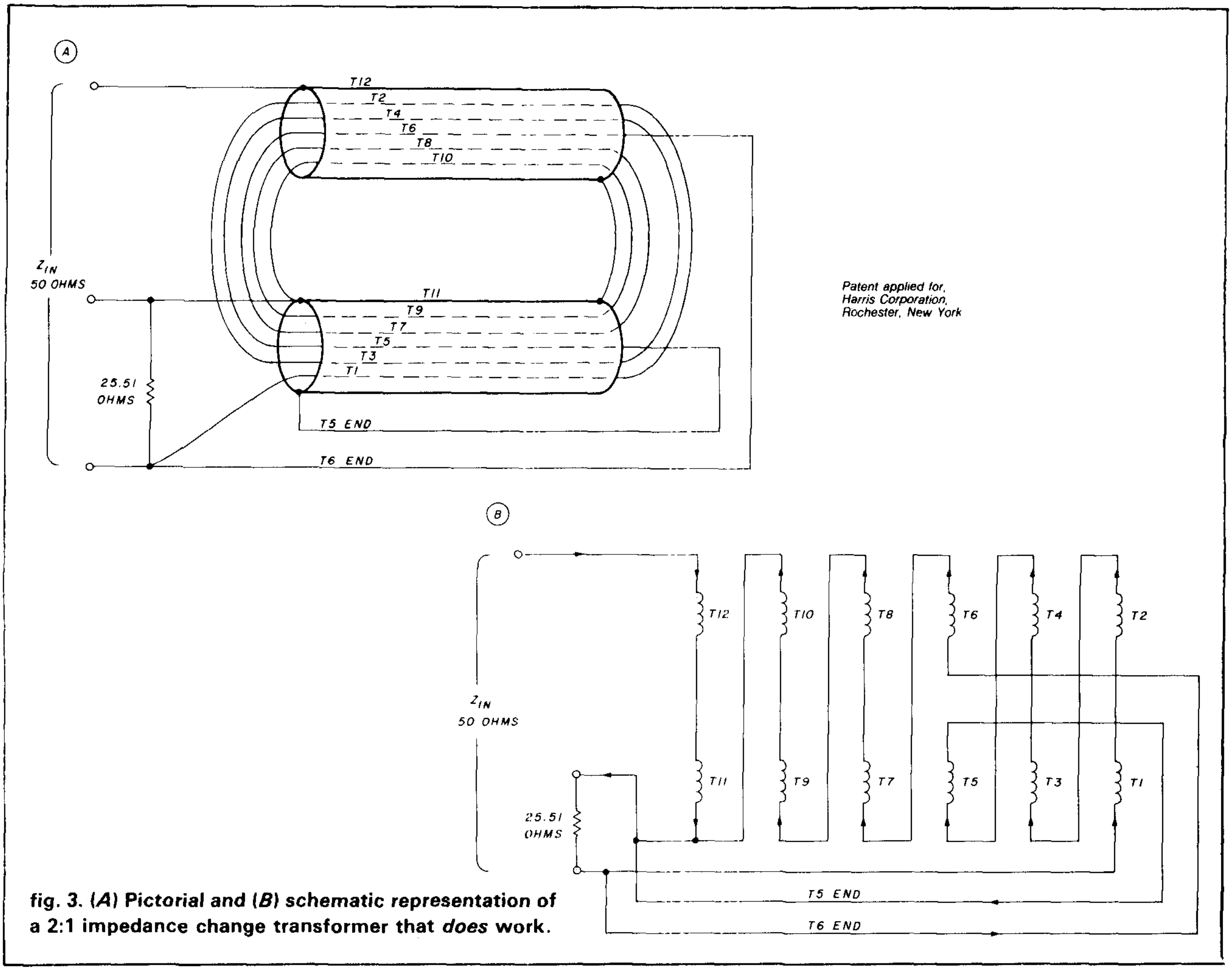

fig. 3. (*A*) Pictorial and (*B*) schematic representation of a 2:1 impedance change transformer that *does* work.

must be kept equal and opposite for each subgrouping of closely spaced conductors.

This means that every wire can have several individual characteristic impedances, each of which should be constructed to provide the same impedance as obtained by dividing voltage by current, or Z_ϕ. Z_ϕ is determined by wire size, spacing, insulation, and number of conductors. The ultimate limit in high frequency response is the physical length of all the turns, considered as a percentage of its electrical wave length. There's another paradox here: if one looks at it as a conventional transformer, the induced voltage of each turn must be the same because the flux is changing at the same time in each turn. However, with transmission line analysis, there isn't any external field, so it's much easier to see that it's the total length that counts.

tubing transformers

Tubing transformers, now very popular in transistor transmitters, use two parallel sections of metal tubing electrically connected at one end. The free ends of the tubing have terminals. The tubing itself can then be used as part or all of one of the windings, or the tubing may simply be grounded to serve as an electrostatic shield for the cores. Cores of ferrite or powdered iron are threaded onto the exterior of the tubes to increase the low frequency inductance. Wire is then run through the interior of the tubing to make the other winding(s). The wires can come out at either the terminal ends of the tubing or at the common connected end; it makes no difference. The wires must make a complete turn, so the turns ratio is again always an integer. **Figure 1A** shows a 12.5 to 50-ohm transformer. **Figures 1B** and **1C** show a similar construction, connected as an autotransformer to transform 12.5 to 50 ohms.

If a transformer similar to the one shown in **fig. 1C** were used to transform a 25-ohm resistor to 50 ohms by tapping up on the winding or tubing to get a fractional turn, the results would be poor (see **fig. 2A**.) In **fig. 2B** arrows indicate the direction of the currents. Note that T2's and T4's currents are in opposite directions canceling the magnetic fields. But T1's and T3's currents are in the same direction! This means that the fields can't cancel, so instead of a transmission

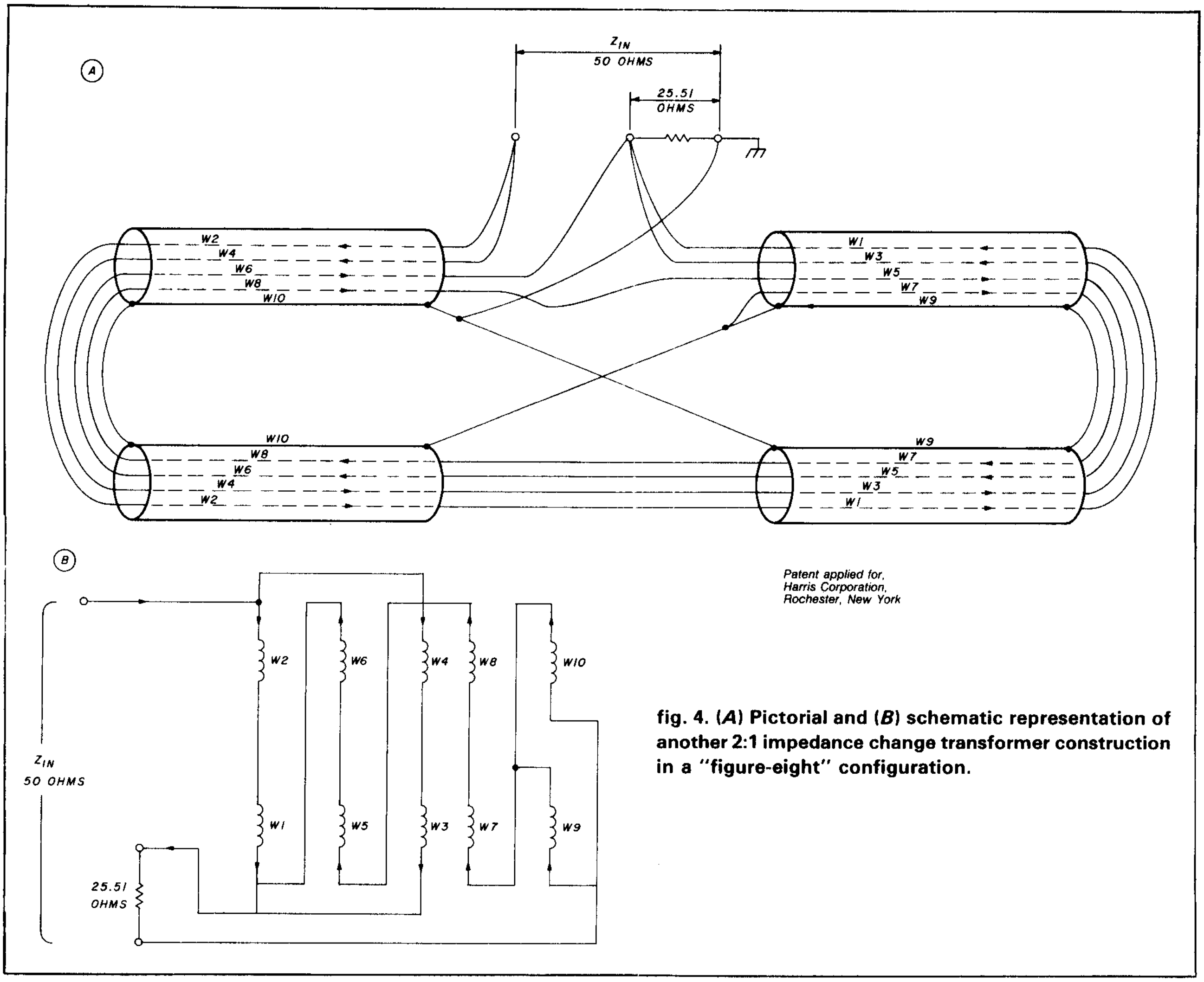

fig. 4. (*A*) **Pictorial and** (*B*) **schematic representation of another 2:1 impedance change transformer construction in a "figure-eight" configuration.**

line, we have a very good inductor — just what we *don't* need because it limits the high frequency response.

split the winding

Yes — you can use fractional turns and still have a transmission-line type device. The key is to add an extra winding that's mostly in parallel with the first so that two separate windings exist. The first winding has an extra half turn; the second winding skips that half turn and picks up the remaining half turn. Then the pair will function just like a single winding with a half-turn, but without a flux or current unbalance! Each of the two windings carries half as much current as the single winding did before it was split into two windings, so they can be made of smaller wire. (See **figs. 3A** and **3B**.)

The fractional turn transformer in **fig. 3** has a turns ratio of 7:5, which gives an impedance ratio of 49:25. The secondary has two windings in parallel: T1 through T5, in five sections; and T6 through T10, also in five sections. The primary has seven sections because it adds T11 and T12 to the secondary's five sections. Thus if one counts the complete turns, it's a three-and-a-half-turn to two-and-a-half-turn transformer! Note that the T5 end and T6 end are longer leads, but that their currents flow in opposite directions, and the voltage between them is the secondary voltage; thus they can be envisioned as a transmission line. The fields are balanced in one direction because the currents are equal/and opposite, so the net ampere-turns is zero. It works well.

ampere-turn and Z_0 analysis

To see this balancing action more clearly, consider that for the amp-turns to be zero, the current total of T2, T4, T6, T8, and T10 must equal T12's. Let's assume 25 volts across the secondary load resistor, so the output current is then 1 ampere. The power out is (25x25)/25.51 = 24.5 watts. From symmetry, the voltage across each of the "T" sections must be equal to each other, and since there are five in series across the secondary, each section has 5 volts. The total voltage input across the seven sections is then 35 volts. If we assume a lossless transformer, there must be 24.5 watts input. The input impedance is, then, equal to (35)(35)/24.51 = 50 ohms. The input current in T12 and T11 must therefore, from Ohms law, equal (35 volts)/(50 ohms) = 0.7 amperes. Likewise, the current out of the transformer is (25 volts)/(25.51 ohms) = 0.98 amperes. Since T5 and T6 are in parallel and symmetrical, the current flowing through each of them is equal and is: I = (I out − I in)/2 or (0.98 − 0.7) = 0.14 amperes.

Because we know all the currents, we can now calculate the amp-turn balance. Again, refer to the direction of the arrows in **fig. 3B**, noting that T2 plus T4, plus T6, plus T8 plus T10's currents must equal T12's. Five times the 0.14 ampere = 0.7 ampere, which was T12's current, verifying that the net external flux is zero.

The impedance of the T5-T6 lead transmission line should be 25 volts divided by 0.14 ampere or 178.6 ohms. Spacing the leads in the air can achieve this.

heat problems

Note that the tubing, which is the largest conductor, is used for the section of the transformer that carries the most current. This is good news. The bad news is that if high power operation is required, one finds that the hot spot is the ferrite cores, not the windings, which heat because of dielectric loss in the cores. The electric field is high on the cores because the tubing is at the highest RF voltage and the transformer is mounted near a chassis ground. Thus another novel technique, resulting in longer life at high power, evolved.

A tubular transformer, shaped as a figure-eight, was developed. This transformer allowed placing the leads closer together, eliminating the external line section, and permitting the tubing to work both as a better electrostatic shield and as the half-turn winding, thereby allowing the tubing to be placed near the chassis ground potential. The highest potential between the tubing and the cores is only a half-turn's worth, because it is now also used as the split turn. Note that in **fig. 4**, two labels are provided on each wire. These two quarter-turns are hereafter referred to as one half-turn. The turns of the secondary are W9 in parallel with W10, which serve as the half-turn, plus W7 and W8, W5 and W6. This makes a two-and-a-half-turn secondary. The primary totals three-and-a-half-turns because it adds to the secondary W3 plus W4 in parallel with W1 plus W2. The top primary turns are split into two paralleled sections because it carries the most current, and because physically W1-W2 and W5-W6 can be close-spaced to make one transmission line, and W3-W4 and W7-W8 are close-spaced to make a second transmission line.

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