DESIGN OF TRANSMISSION-LINE TRANSFORMERS

How coreless transformers can be made from coaxial transmission line

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Although transmission-line transformers are widely used in front ends of television receivers, there is not much information available about what they are and how they work. It is often assumed that they are just another ordinary transformer that uses a fancy high-frequency ferrite to obtain the desired results. In reality, the only thing in common between transmission-line and conventional transformers is the name. Their operating principles are totally different. In this article, we will explore what a transmission-line transformer is and how it works. But first let us see how it differs from conventional transformers.

How It Differs. In a conventional transformer, an alternating current in the primary continuously changes the amount of flux in the core, which, in turn, sets up a voltage in the secondary. Disregarding losses, since the amount of flux cuts every turn of both the primary and the secondary, the voltage ratio is directly proportional to the ratio of the turns in the windings. Also, since the action of the conventional transformer depends on the flux generated in the core, the bandwidth and efficiency depend entirely on the core material.

Normal iron cores are useful at frequencies up to a few hundred hertz. Although there are ferrite cores used in the megahertz range, their permeability and efficiency drop off fairly rapidly with increasing frequency. Another factor that comes into play at high frequencies is that the capacitance between the turns of the windings also limits the usefulness of the conventional transformer at megahertz frequencies.

It is useful at this point to examine a few conventional transformers to compare them to the transmission-line transformer we are talking about here.

A simple step-up transformer with a center-tapped secondary is shown in Fig. 1A. Three things are obtained with such a transformer: a step up in voltage at its output, isolation between its primary and secondary, and a secondary that is symmetrical about its center tap. Here we are mainly concerned with the voltage ratio. Another parameter that should be mentioned because it is very important in transmission-line transformers is the impedance ratio.

Another transformer that is very similar to that shown in Fig. 1A, except that the primary and part of the secondary are a common winding, is shown in Fig. 1B. This autotransformer does the same job as the previous transformer, except that there is no isolation between the primary and secondary windings.

Finally, in Fig. 1C is a very simple 1:1 isolation transformer. In this case, the impedance, turns and voltage ratios are all 1:1. The only purpose of such a transformer is to provide isolation between the primary and secondary windings.

Suppose that the primary of the transformer shown in Fig. 1A is rated 6 volts and 1 ampere (6 watts). Since we cannot obtain something for nothing, the output, even at 100% efficiency, can never be more than 6 watts. Hence, if the secondary potential is 12 volts, the secondary current can be no greater than 0.5 ampere.

By Ohm's Law, impedance is equal to the voltage divided by the current ($Z = E/I$), where E and I can be ac terms. Therefore, the impedance of the primary in our example is 6 volts/1 ampere, or 6 ohms, while the impedance of the secondary is 12 volts/0.5 ampere, or 24 ohms. Hence, even though the turns and voltage ratios are 1:2, the impedance ratio in our example is 1:4. (The impedance ratio is actually the *square* of the turns ratio.)

Although the schematic symbols shown in Fig. 1B and Fig. 1C can be and often are used for transmission-line transformers, this is where the resemblance between the conventional and transmission-line transformers ends. The first and perhaps most striking difference between the two is that with the transmission-line transformer, the core material is relatively unimportant. Instead of limiting the high-frequency response, the only effect it has is to extend the low-frequency response.

As far as high-frequency response is concerned, the core just does not matter. It could be made out of hard candy and the transformer would still work. A second very important difference is concerned with the number of turns. With the transmission-line transformer, the number of turns has nothing to do with

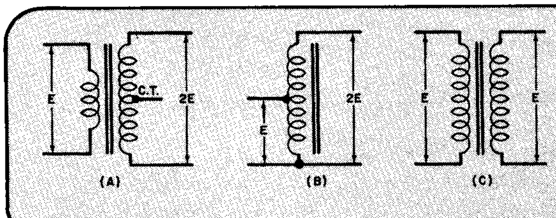

Fig. 1. Three basic transformers: (A) step-up; (B) autotransformer; (C) isolation.

the impedance. Finally, the pains taken to minimize capacitance in a conventional transformer are unnecessary in the transmission-line transformer. The transmission-line transformer uses the capacitance between its windings. In fact, this capacitance is often made as large as possible by twisting together the wires that make up the transmission-line transformer.

Technical Details. The transmission-line transformer is simply a length of transmission line. It is a pair of conductors that are either parallel to each other, twisted together, or arranged coaxially. Of importance is the spacing between the conductors, which must be constant throughout the line's length.

Each conductor in the transmission-line transformer has an inherent inductance. Also, between the wires of a conductor pair, there is an inherent capacitance. It is this combination of continuous inductance and capacitance that gives the transmission line its characteristic impedance. Any type of line can be used for a transmission-line transformer, but if a line is wound on a toroid, parallel or twisted lines are most often used because they are easy to handle and do not get pulled out of shape.

Examples of the characteristic impedances one can expect from various types of lines are as follows: No. 23 PVC-insulated hookup wire twisted at about one turn/inch yields about 150 ohms; 0.040" enamelled wire with about eight twists/inch yields about 25 ohms; and 0.040" enamelled wires wound side by side, with the turns kept as close together as possible, works out to between 50 and 70 ohms.

The essential condition for the proper operation of a transmission line is that the currents flowing in the two conductors be equal and opposite. Anything that causes an unbalanced current flow will prevent the line from operating properly. Suppose, for example, that a coaxial transmission line is very short and has one leg grounded at each end, as shown in Fig. 2. It is quite possible that there could be a ground current, I_g, flowing through the ground leg in addition to transmission-line current. There are, in fact, many ways in which a short transmission line can have unbalanced currents flowing through its conductors, all of which defeat the effect of the line.

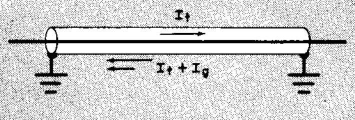

Fig. 2. Current flow in a short piece of coax line grounded at each end.

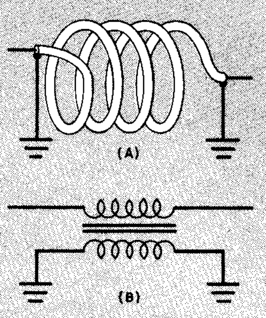

Fig. 3. Coax line wound to form an inductor (A) and its schematic (B).

Suppose the short transmission line shown in Fig. 2 were wound to form an inductor, as shown in Fig. 3A. (Its schematic representation is shown in Fig. 3B.) Even though one leg is still grounded at each end, the ground current will be impeded by inductive reactance. The transmission-line currents, however, would not be affected here because they are equal and opposite at every point along the line, thus neutralizing the inductive effect of the coil. The actual line length can be short as 1/50-wavelength so no significant phase shift takes place.

If the transmission line were now wound on a ferrite rod or, better yet, a toroid core, it would be even more effective and would produce a higher degree of isolation. As the frequency increases, less inductance would be required to obtain the same isolation effect. Even if the core material is useless at very high frequencies, the isolating effect would still remain.

The autotransformer shown in Fig. 1B has a voltage ratio of 2:1 and an impedance ratio of 4:1. Exactly the same ratios can be obtained with a transmission-line transformer. The principle involved can be readily seen with a coaxial transmission line, as shown in Fig. 4. This is the well-known 4:1 balun (balanced-to-unbalanced) transmission-line transformer. The schematic symbol for the balun transformer would be the same as for the autotransformer of Fig. 1B.

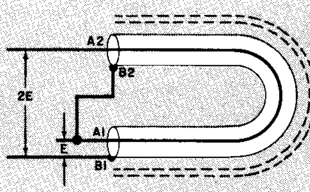

Fig. 4. The 4:1 balun is similar to autotransformer shown in Fig. 1B.

In Fig. 4, ignoring losses, if a voltage is supplied between points A1 and B1, it will appear at points A2 and B2. With point B2 connected to point A1, twice the input voltage would appear across output points B1 and A2. This means that the output impedance would be four times the input impedance and the output would be symmetrical about the A1/B2 junction. In practice, the A1/B2 junction would be connected to the shield of the main coaxial transmission line and would generally be grounded.

There must be a very high impedance to out-of-balance currents between A1 and A2, isolating the two ends from each other. As a rule-of-thumb, this could be at least 50 times the characteristic impedance of the line—2500 ohms for a 50-ohm line. Winding the cable around a toroid is an effective way of getting the required impedance. A special case is the ¼-wave balun, where isolation is provided by the ¼-wave effect. However, this is effective only at one frequency, and cannot provide a broadband transformer.

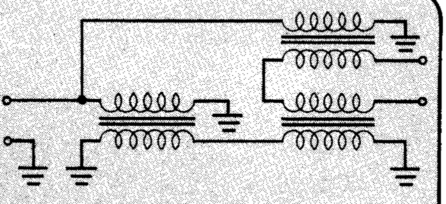

Fig. 5. A transmission-line transformer for interstage coupling with dc isolation.

Making a Transformer. Now that you know what a transmission-line transformer is and how it works, let us proceed to make a vhf power transformer using a core of audio-frequency material. Just about any type of toroid—ferrite or, better still, one made from flat strip iron rolled up in a coil, such as the type used in dc-to-dc converters—will do.

Wind two lengths of 0.040" enamelled wire onto the toroid. Keep the wires parallel to each other and make each turn touch the previous turn. Do not attempt to crowd too many turns on the toroid. The object is to wind only as many turns on the toroid in a single layer without having the conductors cross each other.

Bear in mind that many toroids have sharp edges and that even ferrite material is often conductive. If the edges cut into the insulation, the wire windings can be short-circuited. If the transformer does not operate as expected, short-circuiting will be the most probable cause since, practically speaking, there is nothing else that can really go wrong with the transformer. After winding your transformer, use an ohmmeter to test the insulation between each conductor and the core and between windings.

The basic transmission-line transformer just fabricated will yield a 1:1 impedance ratio and complete isolation so that it can be used as a balanced-to-unbalanced or, for that matter, any other type of configuration. If we need a 4:1 balun, it is necessary only to connect the ends of the conductors as shown in Fig. 4, without altering the winding.

When necessary, as when using a transmission-line transformer for interstage coupling, dc isolation can be obtained by using three transformers, as shown in Fig. 5. Remember that the core is there only to prevent out-of-balance currents. Therefore, if the wire size is small enough and the toroid core is large enough, it is possible to wind all three transformer windings on the same core.

In Conclusion. There is one basic limitation concerning transmission-line transformers. This is that the ratios obtainable are limited to 1:1 and 2:1, and multiples of 2:1 if two or more transformers are used. Also, it can be difficult to obtain the required impedance, particularly with a twisted-pair line.

If you want to build a wideband amplifier and must match, say, a 12-ohm transistor to a 50-ohm output, or make a balanced modulator, or provide really good isolation in a noise bridge, or make a balun transformer for a high-power transmitter, the transmission-line transformer is the way to go. The transmission-line transformer offers a great opportunity for experimenting. ◇