Sensor and Simulation Notes

Note XXIII
27 July 1966

A Technique for the Distribution of Signal Inputs to Loops

1/Lt Carl E. Baum

Air Force Weapons Laboratory

Abstract

Using multiax cable (coaxial cable with additional coaxial shields, insulated from each other), techniques are discussed which allow azimuthal distribution of the signal input positions around a loop structure. Also discussed are uses of this kind of multiax cable structure for multi-turn loops. In some cases there are improvements in the performance of loops (for measuring the magnetic field or its time derivative) by using these techniques.

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I. Introduction

For certain applications it may be desirable to distribute the signal inputs to loops for measuring the magnetic field and/or the time derivative of the magnetic field. One method of doing this involves the use of multiple signal inputs (or loop gaps) which take the signal from several positions on the loop structure and then add these signals together for the net signal. This accomplishes an averaging effect of the signal over the loop structure as well as distributing the admittance associated with the signal cables as several discrete admittances. Likewise the admittances associated with the loop structure may be changed, affecting the frequency response characteristics of the loop.

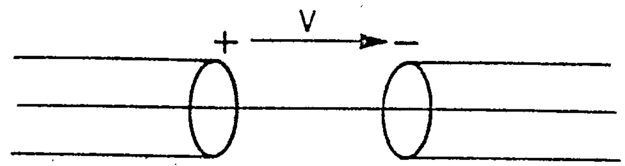
Distributing the loop signal inputs can affect the loop response in various ways. For example, a single-gap toroidal loop has an appreciable error in measuring the magnetic field for loop dimensions of even a small fraction of a wavelength unless the loop gap is optimally oriented with respect to the incident wave. However, a symmetrical two-gap toroidal loop significantly reduces this error.[1] Thus, to reduce this error (which is sometimes called the electric field sensitivity of the loop) we may wish to distribute the loop signal inputs azimuthally around the loop structure. As discussed in another note, using a cylindrical, rather than a toroidal, loop structure improves the frequency response for measuring the time rate of change of the magnetic field.[2] In this case there is an advantage to distributing the loop inputs axially (along the length of the cylinder). These considerations have been developed mostly for the case in which the air conducitivity is unimportant.

In this note there is discussed a technique based on the use of multiax cable (coaxial cable with additional coaxial shields, insulated from each other). This will allow us to distribute several signal inputs azimuthally around loops to reduce error signals and perhaps improve the frequency response characteristics. It will also allow us to make a multi-turn cylindrical loop with axial distribution of the signal inputs.

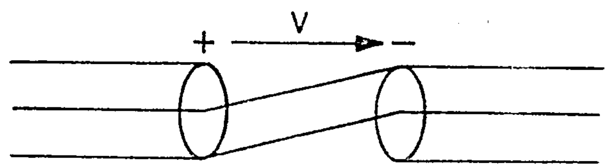
II. Multiax Cable for Signal Input Distribution

Consider then the special cable structure, beginning first with the gaps, illustrated in figure 1, for introducing the signal into the coaxial cable structure. Figures 1A and 1B illustrate the split-shield gap and moebius strip gap discussed in a previous note.[3] The split-shield gap divides the gap voltage into two equal voltages, each of half the gap voltage (for equal cable impedances), the signals propagating in opposite directions inside the two signal cables. The moebius strip gap has the characteristic that the two voltages are each the same size as the gap voltage. However, in figure 1C, there is what might be called an unsymmetrical gap in which the gap voltage produces a voltage which propagates down only one cable (arbitrarily to the left in the figure) and is of amplitude equal to the gap voltage. The center

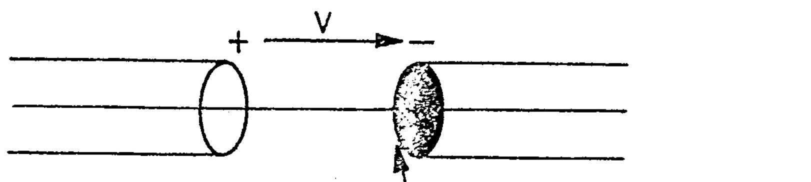
1. H. Whiteside and R.W.P. King, The Loop Antenna as a Probe, IEEE Trans. on Antennas and Propagation, May 1964.
2. Lt Carl E. Baum, Sensor and Simulation Note VIII, Maximizing Frequency Response of a $\dot{B}$ Loop, Dec. 1964.
3. Lt Carl E. Baum, Sensor and Simulation Note VII, Characteristics of the Moebius Strip Loop, Dec. 1964.



A. SPLIT-SHIELD GAP



B. MOEBIUS STRIP GAP



C. UNSYMMETRICAL GAP

FIGURE 1 SIGNAL INTRODUCTION GAPS

conductor in the right cable is not used so that it could be replaced by a single wire. However, it may be advantageous to use a coaxial cable to make the external conductors (on both sides of the gap) of the same size. It is this last case, the unsymmetrical gap, which we shall combine with the multiax cable for a technique for distributing signal inputs and combining the signals from these inputs together as a single signal.

The multiax cable consists of several concentric cylindrical conductors which form several transmission lines. Each transmission line consists of an adjacent pair of concentric conductors and has a characteristic impedance. A cross section of such a multiax cable is illustrated in figure 2A for the case of three concentric transmission lines or four concentric conductors (which we might call quadrax). For our application let us choose the impedances to be related to one another as

$$Z_m = \frac{Z_{m-1}}{2} \qquad (1)$$

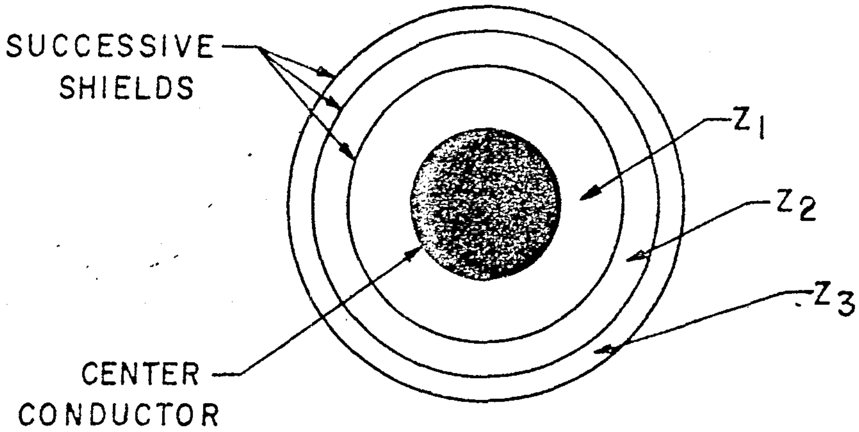
or

$$Z_m = 2^{-m+1} Z_1 \qquad (2)$$

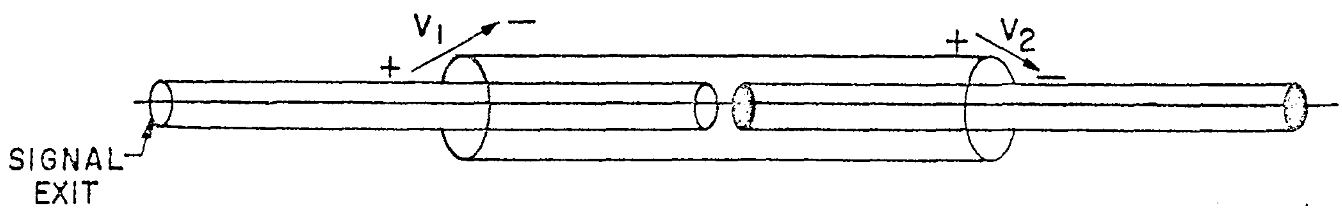
where m is a positive, non-zero integer. The first three impedances are labeled in figure 2A, starting in the center with Z_1 for the transmission line consisting of the center conductor and the first shield. We can take arbitrary (but convenient) choices for the various impedances based on a Z_1 such as 50 Ω or 100 Ω.

The purpose of constraining the relation among the impedances as in equations (1) and (2) is illustrated in figures 2B and 2C. Consider the use of triax as in figure 2B in which V_1 and V_2 propagate down equal length transmission lines (between the first and second shields), each of impedance, Z_2. These two signals simultaneously arrive at an unsymmetrical gap which takes V_1+V_2 into another transmission line (between the center conductor and first shield) of impedance Z_1. Since Z_2 is half Z_1 the sum of V_1 and V_2 is impedance matched from the two outer transmission lines to the inner transmission line with no reflection. Thus, at our signal exit (on the left in the figure) we have V_1+V_2 delayed by the transit time from any of the external gaps to the signal exit. (All such transit times are designed to be identical.) If V_1 and V_2 are not identical we can treat each one as the sum or difference of two signals, $0.5(V_1+V_2)$ and $0.5(V_1-V_2)$. The latter part of the signals, the differential part, will not appear in the inner transmission line as it will be cancelled out at the entrance to the inner transmission line. The common part of the two signals will add, matching into the inner transmission line, giving a total signal, V_1+V_2, driving an impedance, Z_1, (if the inner transmission is terminated in its characteristic impedance).

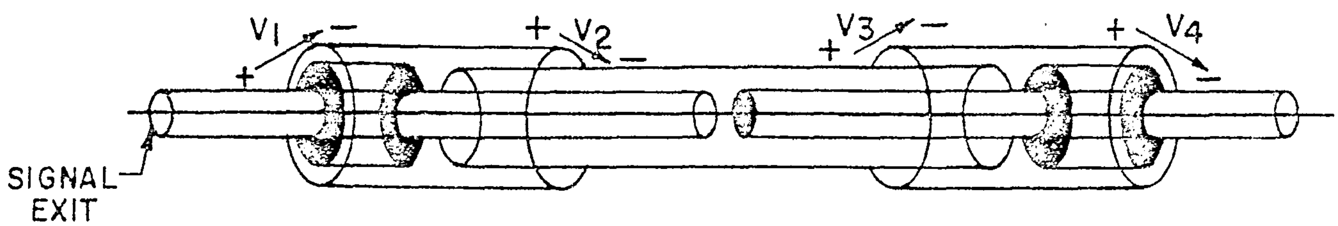
Similarly, as in figure 2C, we can further distribute the signal introduction gaps by the use of quadrax. The sums, V_1+V_2 and V_3+V_4, match from the outer transmission line of impedance, Z_3, into the middle transmission line of impedance, Z_2. The two sums then match into the inner transmission line giving a total signal, $V_1+V_2+V_3+V_4$, driving an impedance, Z_1. (The darkened areas in the figure indicate electrical shorts between adjacent concentric conductors.)



A. MULTIAX CABLE



B. TWO SIGNAL INTRODUCTION GAPS USING TRIAX



C. FOUR SIGNAL INTRODUCTION GAPS USING QUADRAX

FIGURE 2 MULTIAX CABLE CONFIGURATION

This procedure can be generalized. If Z_M is the impedance of the outermost transmission line, then the number of signal introduction gaps, n, is

$$n = 2^{M-1} \tag{3}$$

The net signal, V, appearing on the inner transmission line (terminated in its characteristic impedance, Z_1) is just

$$V = \sum_{j=1}^{n} V_j \tag{4}$$

if we preserve the impedance relationships of equations (1) and (2) and match the signal transit times from all the signal introduction gaps to the innermost transmission line.

There are practical limitations to how large we can make M. In coaxial geometry we have

$$Z_m = \frac{Z}{2\pi} \ln \left(\frac{r_{m+1}}{r_m} \right) \tag{5}$$

where r_m is the radius of the mth conductor starting with m=1 for the center conductor and ignoring the conductor thickness for m > 1 and where Z is the wave impedance of the cable dielectric used. Inverting equation (5) we have

$$\frac{r_{m+1}}{r_m} = e^{2\pi \frac{Z_m}{Z}} \tag{6}$$

showing that for large m (making Z_m small) r_{m+1} approaches r_m. In fact, ignoring the conductor thickness, we have for very large m the limiting case

$$\frac{r_\infty}{r_1} = \lim_{m \to \infty} \frac{r_{m+1}}{r_1} = e^{\frac{2\pi}{Z} \sum_{m=1}^{\infty} Z_m} \tag{7}$$

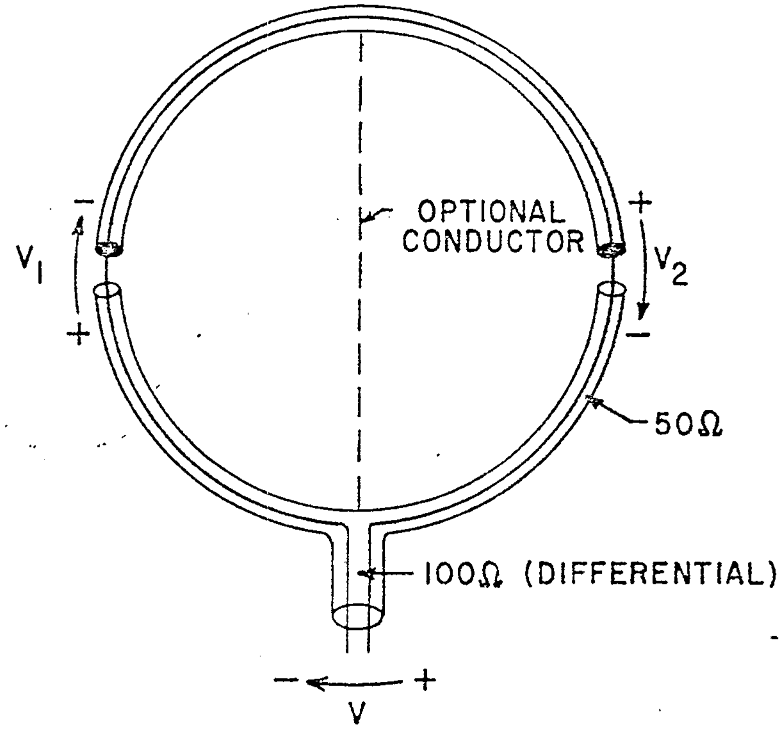
or using equation (2)

$$\frac{r_\infty}{r_1} = e^{2\pi \frac{Z_1}{Z} \sum_{m=1}^{\infty} 2^{-m+1}} = e^{4\pi \frac{Z_1}{Z}} = \left(\frac{r_2}{r_1} \right)^2 \tag{8}$$

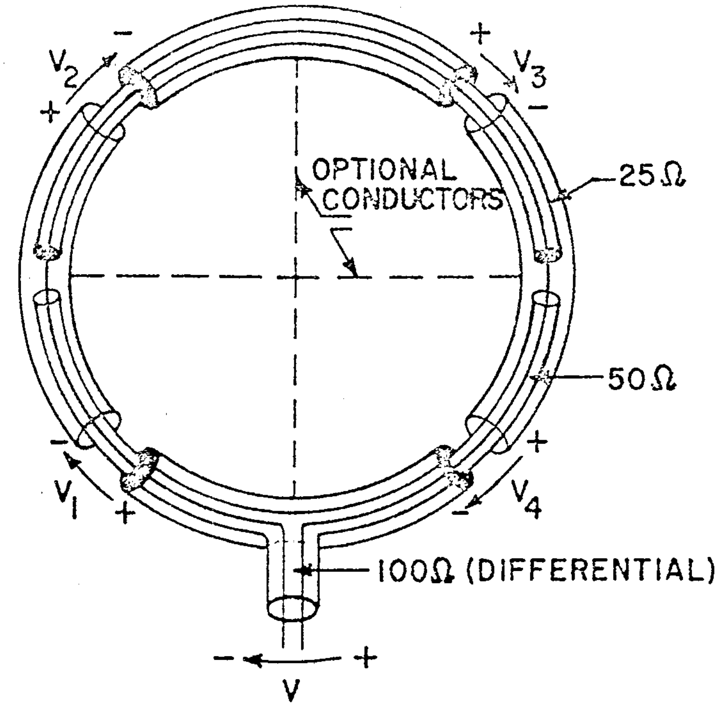
Thus, for large m the dielectric thickness can be impractically thin, limiting the practical M (or number of concentric transmission lines) we can have.

III. Azimuthal Distribution of Signal Inputs to Loops

Now apply this technique for signal input distribution to magnetic field loops. Consider first the two one turn toroidal loops in figure 3 with convenient cable impedances as illustrated. The model in figure 3A, with two



A. TWO LOOP GAPS



B. FOUR LOOP GAPS

FIGURE 3 ONE TURN TOROIDAL LOOPS

symmetrically located signal introduction gaps (or simply loop gaps), requires two cable structures as in figure 1C to form the loop, and a twinax cable to transmit the signal. The model in figure 3B, with four symmetrically located loop gaps, takes two cable structures as in figure 2B to form the loop. In both cases, the twinax cable is symmetrically located with respect to the loop gaps to minimize the coupling of the fields scattered from the twinax into the loop. Also the cable structure forming the loop is kept at a constant outer diameter for symmetry purposes. If desired we can also place conductors along loop diameters, as indicated in the figure, without disturbing the operation of the loop as a magnetic field measuring device. Such conductors may help reduce signals from undesired excitation modes of the loop which could inadvertently appear in the signal output due to geometrical inaccuracies in the loop construction, and/or inadequate common mode rejection in the recording system looking at the differential signal on the twinax. Ideally, the differential signal, V, on the twinax is just the sum of the signals on the loop gaps, delayed by the transit time (equal from all loop gaps) through the cable system.

If we modify the relationship among the impedances of the multiax cable we can azimuthally distribute the signal inputs to other than one turn toroidal loops. Consider, for example, the moebius strip loop, as in figure 4, with two loop gaps. Since the effective impedance at the moebius strip gap is half the inner coax impedance or 25 Ω , the second (or outer) transmission line should have an impedance of 12.5 Ω or one fourth the inner coax impedance. This is a two-turn toroidal loop with two azimuthally distributed loop gaps and a signal voltage, V, given by

$$V = 2\ [V_1 + V_2] \qquad (9)$$

with a time delay due to the transit time in the cables.[4] The number of loop gaps can be increased to four or more by adding more concentric transmission lines of the proper impedances in a manner similar to that used in figure 3 in going from two to four loop gaps.

Another variation on the distribution of signal inputs is shown in figure 5. By a series-parallel combination of the signals from the four loop gaps we have an effective half turn loop, i.e.,

$$V = \frac{1}{2}\ [V_1 + V_2 + V_3 + V_4] \qquad (10)$$

where again V is delayed by the transit time in the cables. In this case, as before, we can increase the number of loop gaps to eight or more by adding more concentric transmission lines of the proper impedances. For this half turn loop the impedance at each loop gap is 100 Ω (for signals common to all four gaps) giving a signal cable impedance around the loop circumference of 400 Ω. For the one turn loop of figure 3B the impedance at each loop gap is 25 Ω giving a signal cable impedance around the loop circumference of 100 Ω and the two turn loop of figure 4 has an impedance at each of the two loop gaps of 12.5 Ω, giving a signal cable impedance around the loop circumference of 25 Ω. Since, in all of these cases, the loops are driving the same impedance

4. For a discussion of the moebius strip loop see Sensor and Simulation Note VII (ref. 3).

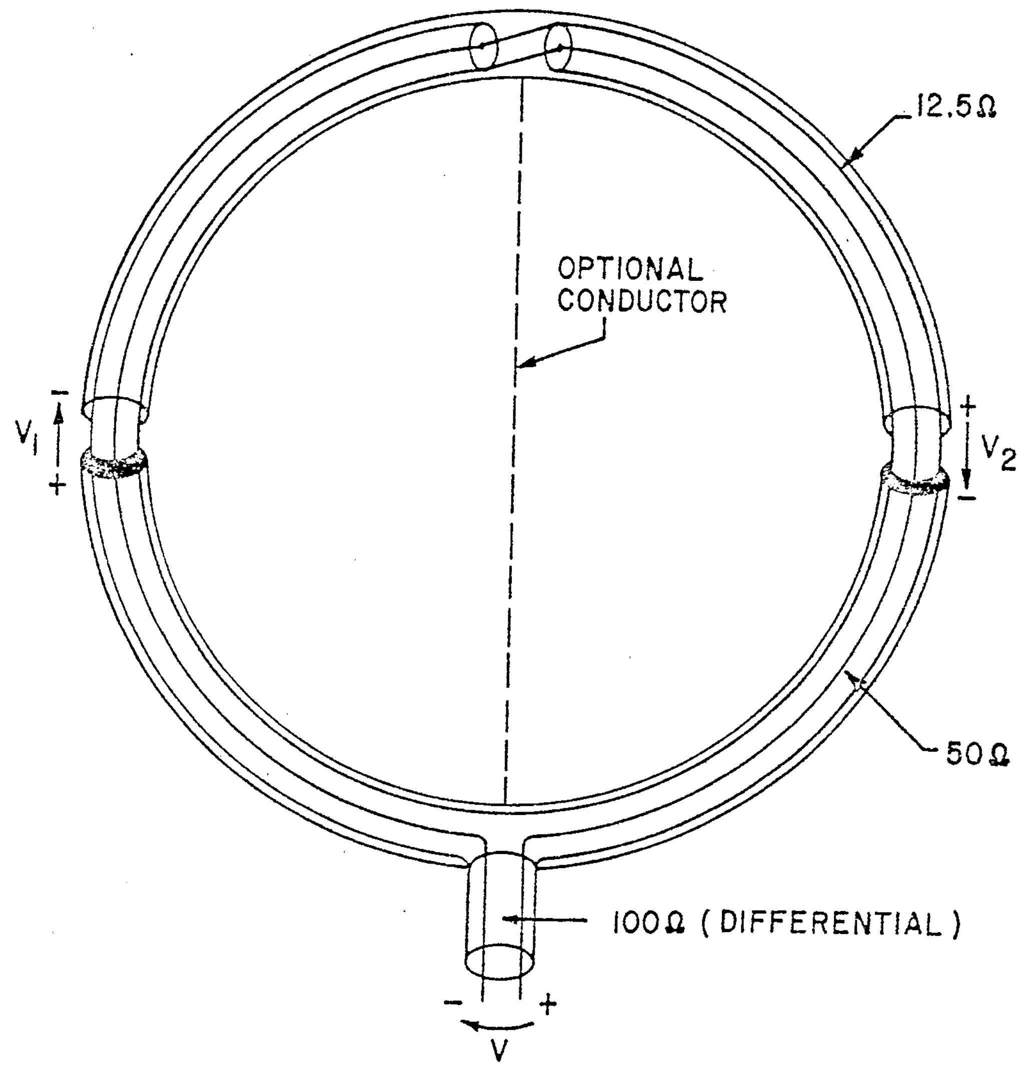


FIGURE 4 MOEBIUS STRIP LOOP WITH TWO LOOP GAPS

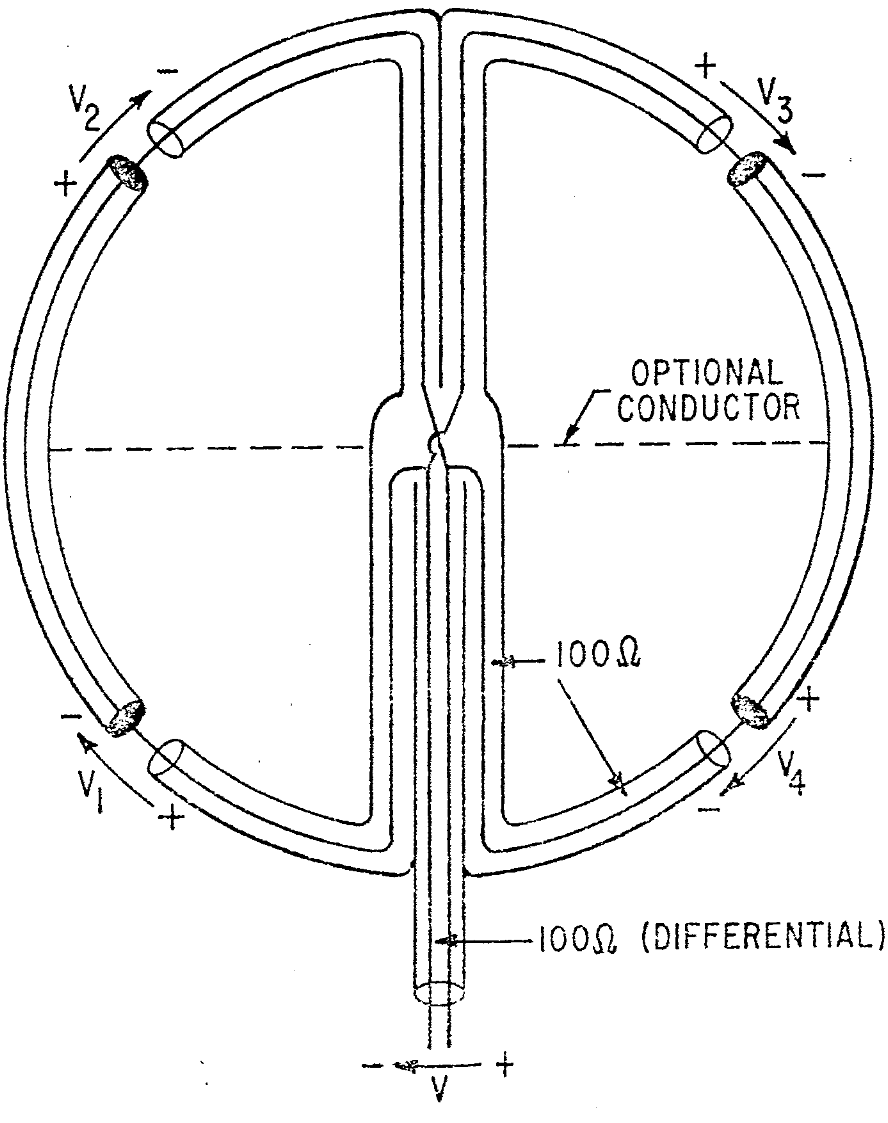


FIGURE 5 ONE HALF TURN TOROIDAL LOOP
WITH FOUR LOOP GAPS

twinax (100 Ω) we have a certain amount of flexibility in the signal cable impedance around the loop circumference.

We can also combine the azimuthal distribution of loop gaps with axial distribution of the signal inputs as in the case of the cylindrical loop. Illustrated in figure 6 we have an example with two axial input positions and four azimuthal input positions for a total of eight signal input points on the loop structure. This structure is formed by taking two one turn toroidal loops (figure 3B, except using different impedances), wiring them in parallel, placing them on a common geometric axis, and adding cylindrical conductors parallel to the axis. As in figure 3B we can also add radial conductors (in the same positions) without disturbing the loop operation. Of course, we can combine other toroidal loops (such as the ones in figures 3A, 4, and 5) in a similar manner to form a cylindrical structure.

These examples indicate a few of the possibilities for distributing signal inputs over loop structures. These techniques can be extended in various ways and combined with one another for various applications. We can vary the number of loop turns, the number of azimuthal signal input positions, and the number of axial signal input positions.

IV. Multi-Turn Cylindrical Loops Using Multiax Cable

Using this multiax cable there is another way, besides using the moebius strip loop, of making a multi-turn loop in a cylindrical structure. In the one turn cylindrical loop (figure 6) we achieve our axial distribution of the signal inputs by connecting two or more toroidal loops in parallel. In the case illustrated in figure 7 the signals from the four axial inputs are combined in series to give an effective four turn loop.

To construct a loop of this type requires two identical (for symmetry) multiax cables configured similarly to the examples in figure 2 (B and C). The example in figure 7 takes two such multiax cables (figure 2B) with two signal introduction gaps each. Instead of connecting the two multiax cables to form a single turn toroidal loop as in figure 3, each multiax cable is coiled into a multi-turn loop such that all signal introduction gaps appear in the same azimuthal position. The number of turns in each multiax cable is then made the same as the number of signal introduction gaps, and the same applies to the combination of two such cables to form a balanced loop. Using the previous notation we have a number of turns, N, for the loop (from equation (3))

$$N = 2n = 2^M \qquad (11)$$

where M is the number of concentric transmission lines in the multiax cable.

If we now join the turns of the multiax cable by a cylindrical conductor, having the signal introduction gaps coincident with the cylindrical loop gap (as in figure 7), we obtain a multi-turn cylindrical loop. (In figure 7 the cylindrical structure has been split along one side and layed out flat to make the structure clearer.) As one way of thinking of this kind of loop, consider that some of the stray inductance and capacitance, associated with the turns of a standard multi-turn loop (say a simple solenoid), have been

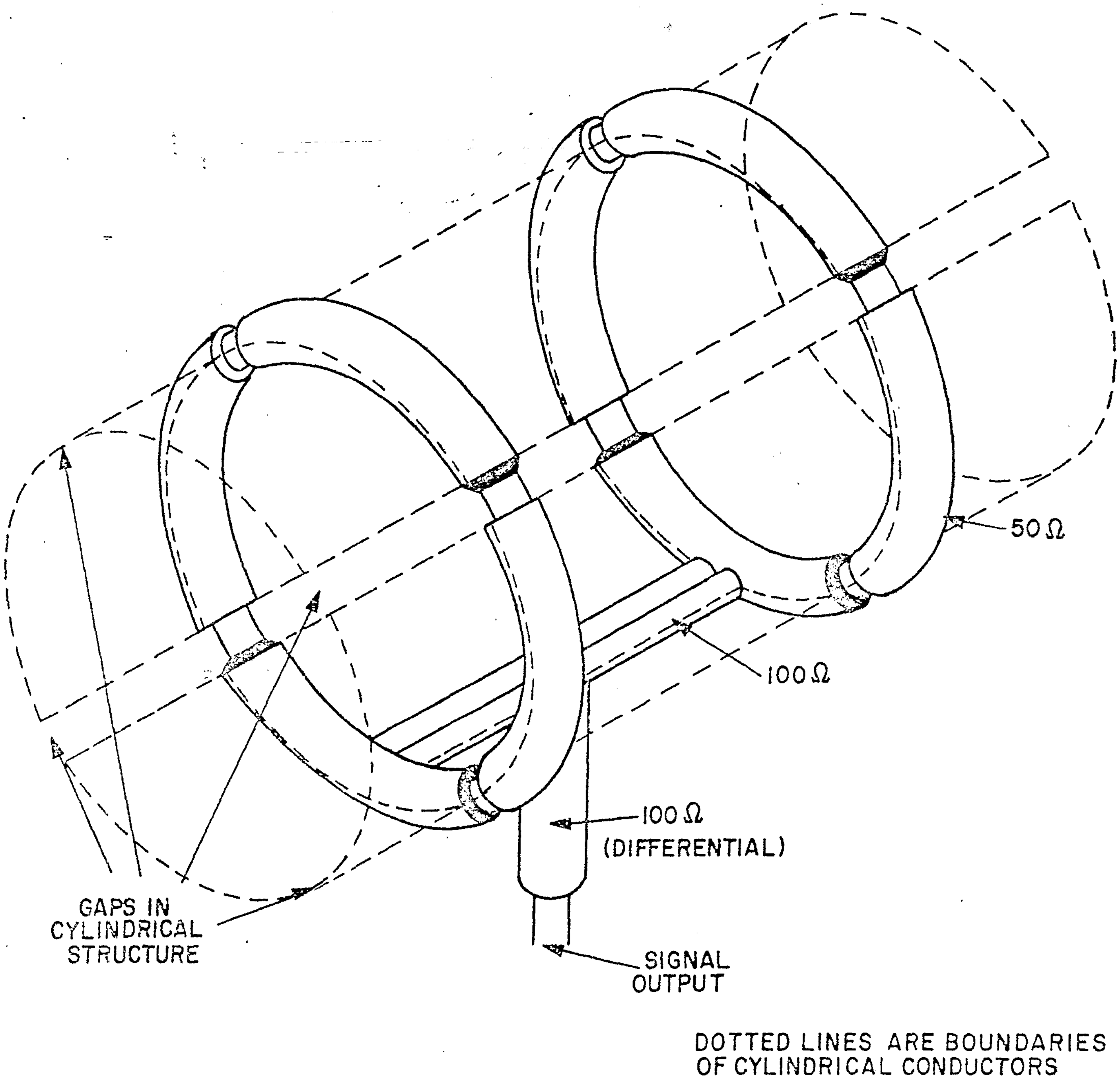


FIGURE 6 ONE TURN CYLINDRICAL LOOP WITH AXIAL AND AZIMUTHAL DISTRIBUTION OF SIGNAL INPUTS

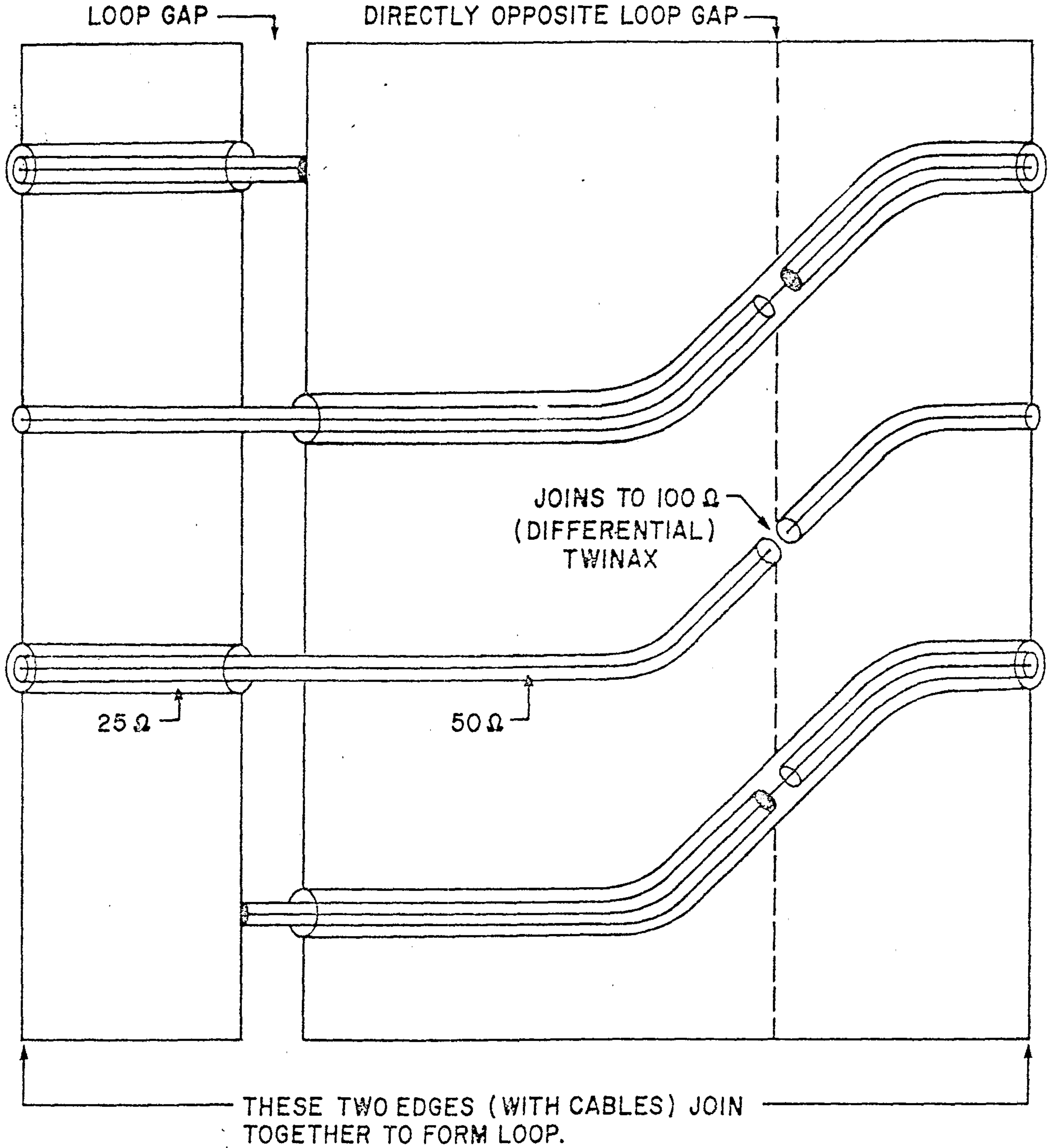


FIGURE 7 EXPANDED FOUR TURN CYLINDRICAL LOOP USING TRIAX CABLE

combined to form the impedance of the transmission lines (in the multiax cable). As with the moebius strip loop we can look at this loop in either (or both) of two ways: as an N turn loop driving a cable impedance, Z, (100 Ω twinax in figure 7), and as a one turn loop driving an impedance, Z/N^2, with a voltage multiplication factor of N. The results are the same in either case.

One advantage of this multi-turn cylindrical loop is the simple structure it presents to an incident electromagnetic wave. We can analyze it as a one turn cylindrical loop, i.e., as a slotted cylinder with resistive loading across the gap. Once the signal has entered the cable structure at the loop gap, the proper impedance and transit time matching in the multiax and twinax cables will add the voltages to give a multi-turn loop.

In this kind of a loop design the effective impedance at the gap, Z/N^2, can be low enough for large N that we have difficulty optimizing the frequency response for measuring $\dot{B}$ (in the sense discussed in Sensor and Simulation Note VIII). In such a case we can either use this type of loop for lower frequency response applications for measuring $\dot{B}$, or use it for measuring H, operating in the short circuit (instead of open circuit) mode. In the latter case, the simplicity of the structure (as presented to external fields) should make the upper frequency response (in the short circuit mode) be limited only by the size of the structure compared to the wavelength associated with that frequency.

Finally, this multi-turn loop structure can be combined with other techniques to obtain other performance features. For example, in the process of bending the multiax cable into a multi-turn loop, instead placing all the signal introduction gaps in one azimuthal position, place the gaps in two opposite azimuthal positions. Then we can add a cylinder with two full-length slots, coincident with the two azimuthal positions of the signal introduction gaps. In this manner we have halved the number of loop turns but at the same time have azimuthally distributed the loop gaps. Clearly we can extend this to different combinations of the number of loop turns and the number of azimuthal gap positions. Thus, we have combined the multi-turn loop of this section with the azimuthal loop-gap distribution of Section III. Perhaps there are many more variations on these techniques.

V. Summary

Thus, using multiax cable, with the proper impedances for the various transmission lines in the cable, we can distribute several signal introduction gaps along the cable. With appropriate electrical construction inside the cable the transit times from all the signal introduction gaps to the signal exit can be matched, thus adding the signals together (with a delay introduced by the cable).

This kind of cable structure can be used for several applications in the design of loops for measuring the magnetic field and/or the time derivative of the magnetic field. By azimuthally distributing the signal inputs the loop response becomes less dependent on the azimuthal direction of incidence of an electromagnetic wave (or, as it is sometimes termed, reduces the electric field sensitivity), and, in the process, we might vary the frequency response characteristics of the loop. Also, this type of cable structure can be used to form a multi-turn loop which presents a somewhat simpler cylindrical structure to an incident electromagnetic wave. Finally, different response characteristics for loops can be achieved by combining various techniques in several different ways.