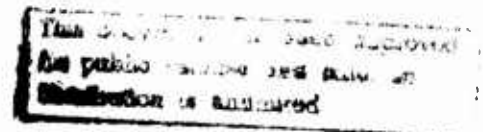
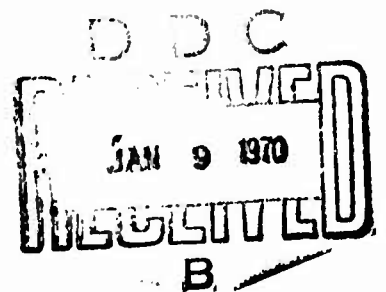



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SURFACE TRANSFER IMPEDANCE MEASUREMENTS - A
PRACTICAL AID TO COMMUNICATION CABLE SHIELDING DESIGN

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21

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"SURFACE TRANSFER IMPEDANCE MEASUREMENTS - A
PRACTICAL AID TO COMMUNICATION CABLE SHIELDING DESIGN"

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R.J. OAKLEY

ABSTRACT:

An expository overview of cable shields and shielding quality is given, up to and including the V.H.F. band, leading to the problem of evaluating different shields whilst still at the design stage. The changes in shielding effectiveness brought about by small design changes can be adequately gauged by the measurement of surface transfer impedance on short sample lengths.

The frequency range for the measurements presented in this paper on all types of shield is up to 300 MHz.

Some experimental results are presented and discussed, including a section on copolymer bonded aluminum sheaths. Here a study was made of the effects of overlap width and bonding copolymer thickness.

1.0 INTRODUCTION:

Distortions which occur to transmitted signals inside a cable can be attributed in general to variations in the physical characteristics of the cable, or to its transmission parameters that are frequency dependent. Some of these variations can be avoided by good engineering and manufacturing, and others are inherent in all cables and are largely incorrigible.

Those distortions which result from external disturbances can be controlled by appropriate shielding. Appropriate shielding, however, does vary in style and cost. Experimental verification of shielding effectiveness has long been a debated question, and is the subject of this paper.

Very little work on surface transfer impedance has been reported previously on anything but braided shields, and even that only at relatively low frequencies. The system of measurement and equipment described in this paper have enabled results to be obtained that are valid up to 300 MHz on all types of shield. The results of surface transfer impedance measurements, as presented, cover both the general and particular cases, in order to demonstrate how such results may be valuable to the shielding engineer.

A particular study was made of the type of shield constructed from an aluminum tape with a copolymer coating. This copolymer will fuse with a polyethylene jacket as it is extruded over the shield, thus hermetically sealing the cable. This shield type is referred to in this paper as "bonded".

The measurement embraces the hand-made prototype because only a short sample is required, not an expensive trial production length.

1.1 DEFINITION OF SURFACE TRANSFER IMPEDANCE:

The definition as used in this paper is as follows:

If a current is caused to flow along the shield* of a coaxial cable, with its return path outside that coaxial cable, then the longitudinal voltage along an incremental length which results on the inside surface of the shield is related to that current by the surface transfer impedance, and has units of impedance per unit length.

The concept of surface transfer impedance was first introduced by S.A. Schelkunoff in 1934 (ref. 12) but practical limitations have restricted the majority of the work done using it to below a few megahertz. The results presented here are valid for the most part to 300 MHz.

*The word "shield" as used in the definition includes all conducting layers where more than one exist.

2.0 SHIELDING PROTECTION IN GENERAL:

Because shielding of any sort would not be necessary if there existed no disturbances, it is convenient to classify different methods of protection by the type of disturbance they are intended to minimize. There are three basic mechanisms of undesired induction into a cable.

- (a) Electrostatic induction, or coupling via a capacitive circuit, is caused by the presence of a changing electric field, as in the proximity of high voltages. "Electrostatic" is a misnomer which has become accepted to have this connotation through long usage.
- (b) Magnetic induction, which results when the magnetic flux linked into the disturbed circuit changes, sometimes called near-field induction. This situation often arises near lines carrying high currents.
- (c) Electromagnetic induction. This mode is a far-field effect and is usually associated with higher frequencies than (a) or (b), which are commonly power frequency or harmonics. The electromagnetic waves stimulate the disturbed cable to act rather like an antenna.

Another means whereby one circuit is influenced by another is a physical, conducting, joint between them, obvious enough at low frequencies, but not quite so obvious at high frequencies when the skin effect has come into play.

In order to reduce interference in a communication cable it may be placed remote from any disturbance, which is frequently difficult to achieve, or induction is partially balanced as in the case of twisted pairs, or it is shielded, or a combination of these ways.

Because the tolerable noise arriving at the end of a cable is often specified, different incident field intensities require different minimum shielding efficiencies. This point immediately raises the question of economics. Industry in an attempt to market cables for every use has already introduced several shield designs, but the necessary emphasis on economic production of long lengths of cable is placing limitations on the choice of materials and constructions of the shields. Besides these manufacturing limitations restrictions are also imposed by installation and splicing requirements and the necessary avoidance of possible corrosion conditions. It is evident that the shield designer is severely restrained in his choice of materials.

The most serious interference at high frequencies is caused by electromagnetic waves penetrating shields, whereas at power frequencies, magnetic induction is the main problem. Unfortunately for cable designers, these two induction mechanisms are countered in different ways.

2.01 MAGNETIC FIELDS

Shielding against power frequency magnetic fields can be achieved by two basic means, namely,

- (i) circulating ground currents,
- (ii) magnetic field deflection.

In the first case the disturbing field sets up an e.m.f. in the metallic shield, which, when the shield circuit is completed to ground, allows a current to flow such that its magnetic field opposes that producing it. In some cases this field cancellation can be extremely efficient, but it is immediately obvious that the impedance of this ground circuit will have a critical effect on the effectiveness of such protection. More often than not, such shielding is inadequate on its own.

The second means, changing the path of the magnetic field, requires a magnetic material to surround the communication circuit in order to create a low reluctance path around it for the incident field. Providing the magnetic covering remains unsaturated, the disturbing field still inside it has only a very low intensity. Magnetic materials, however, are susceptible to eddy currents in the thicknesses used for cable protection, and the associated magnetic fields will be deleterious to the shielding properties. Steel tapes applied spirally are a common form of flexible magnetic shield, but any circulating ground currents are constrained to flow along the helix, and, like eddy currents, these have in their own magnetic field components which tend to reduce shielding efficiency.

At high frequencies, magnetic fields will set up eddy currents on the surface of copper and the fields of these currents are effective in cancelling the disturbing field. In general non-propagating magnetic fields are little problem at high frequencies.

2.02 ELECTRIC FIELDS:

At all frequencies electrostatic shielding is achieved by surrounding the circuit by a metallic surface. The criterion for effectiveness here is the proportion of the circuit covered. An incomplete shield, like a braid, would afford less protection than a copper tube, which gives 100% electrostatic protection when grounded. The path to ground must have low impedance, otherwise much of the benefit is lost.

2.03 ELECTROMAGNETIC FIELDS:

The main source of interference at high frequencies is electromagnetic radiation, and for best protection the circuit to be shielded should be completely enclosed in a metallic sheath having no openings in it. Radiation can still be coupled into a shielded circuit by the fact that currents are induced into the shield by the incident radiation. To be more accurate, because no material is perfectly conducting, the highest induced current density is on the outside surface of the shield and diminishes through its thickness. A

longitudinal emf. proportional to the current density on the inside surface appears on the inside of the shield, so disturbing the protected circuit. Recalling that the skin effect is more pronounced at high frequencies, low frequency electromagnetic radiation is more likely to stimulate higher current densities on the inside surface, and correspondingly higher noise signals, than high frequency radiation.

In general then the attributes of a good shield could be listed as follows:

- a. Low resistance.
- b. High permeability.
- c. Complete coverage.
- d. Light weight.
- e. Strong and crush resistant.
- f. Electrically connectable.
- g. Flexible.
- h. Corrosion resistant.

This list is necessarily not complete, but long enough to indicate the diversity of materials and combinations which may be made. Each combination has its limitations and different shielding properties. What are they? How are they determined? Under very specific conditions, and with full knowledge of all the parameters, it is possible to calculate the "shielding factor" which is defined as:

$$\text{shielding factor} = \frac{\text{Voltage induced with shielding}}{\text{Voltage induced without shielding}}$$

If it were possible to calculate this factor for each shield alternative, the most suitable one for a given situation would soon be found. Because such calculations are rare possibilities, the choice is based on estimation, experience or experiment. Contemporary shield engineering is not in favour of educated guessing, and experience will often lead to overdesigning, so experiment remains the obvious way of proving a shield.

2.1 MEASUREMENT METHODS:

The measurement of surface transfer impedance has been made according to two basic fashions whose schemes correspond to figure 1.

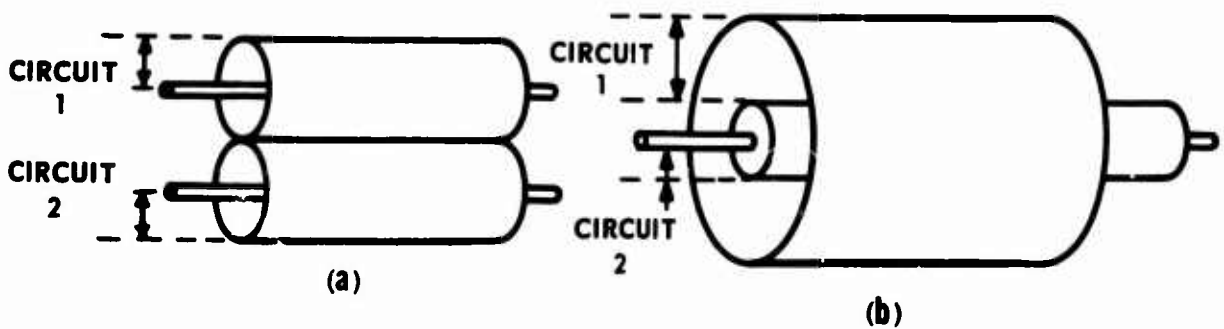


FIG. 1

The principles are the same in each, a current is made to flow in circuit 1, say, and a voltage measured emerging from circuit 2. (1 and 2 may be interchanged).

The various papers that have been written on this measurement have all been based on variations of the ancillary equipment and circuitry. It would require excessive space to review all the differences, but a fairly complete bibliography is appended.

The majority of earlier work produced results up to about 500 KHz (refs. 1,2), and later up to about 5 MHz (ref. 3). The story on braided shields is slightly different in that the measured signal eventually rises with frequency so measurements become comparatively easier to make. Results on braided shields have been published to 7.5 GHz (refs. 4,5,16).

The circuitry used for results published in this report is based on figure 1(b), being basically that set-up prescribed by the I.E.C. (ref. 5). A circuit lay-out is shown in figure 2, and a more detailed diagram of the sample holder is shown in figure 3.

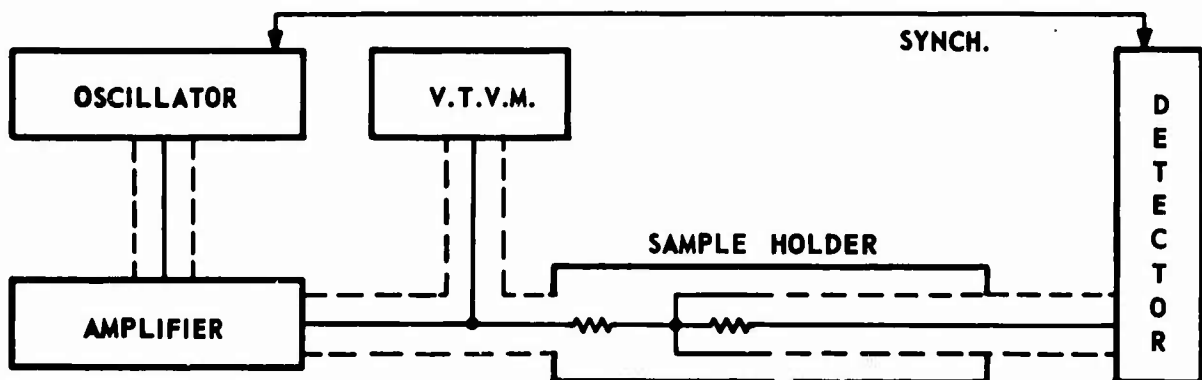


FIG. 2 LAY-OUT OF EQUIPMENT

The measurement requires a known current to pass along the shield under test, but because the disturbing system is short-circuited, the current at any point along the length of the sample depends on the frequency and location of that point.

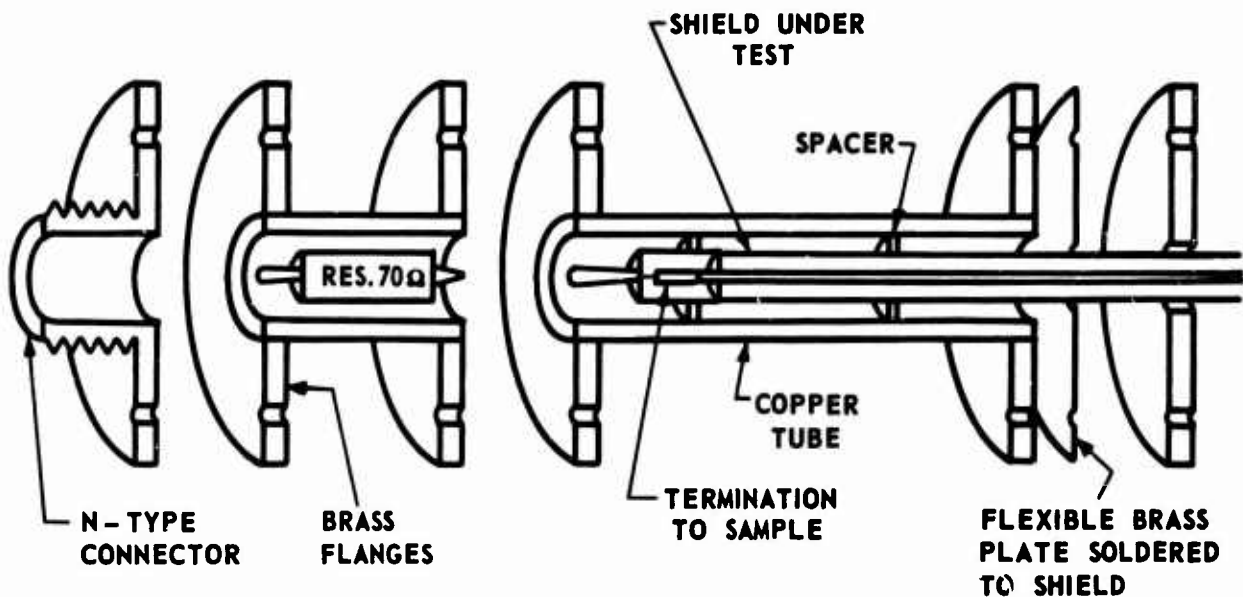


FIG. 3 SAMPLE HOLDER AND FEEDING RESISTOR

The voltage fed into the sample holder and the voltage appearing at the end of the sample are both measured. The quotient of these two voltages is needed in the evaluation of the transfer impedance. The mathematical analysis of the system given in appendix II shows how all the electrical parameters of the system modify the voltage quotient to give a value for the transfer impedance.

The analysis also shows that, provided the various parameters of the circuits are known, this system can be used at any frequency.

2.2 TRANSFER ADMITTANCE

There exists for poorly shielded cables, namely those with significant gaps in the shield, a capacitive path through the shield. The capacitance between the centre conductor of a coaxial cable and a surrounding conducting tube, with the coaxial shield grounded, is termed the "through capacity". If the characteristic impedance of the circuit formed by the tube and the coaxial shield is the same as that of the coaxial cable, then the admittance of the through capacity is called the "transfer admittance".

The measurement of this "transfer admittance" (ref. 5) is considered only when cables are to be used in very low field intensity regions, where the minimum of shielding is required. When this is not the case, then the shields used should have an unmeasurably small through capacity, preferably non-existent. Thus the index of shield efficiency may safely be taken as the surface transfer impedance for all but a small minority of cables when the two should be considered together.

3.0 EXPERIMENTAL RESULTS:

All quoted results are valid up to 300 MHz. Where curves terminate below that frequency, it is because the output voltage became too low to measure, and did not rise again to a measurable level.

3.1 ASSURANCE TESTS

In order to check the system and verify that surface transfer impedance was indeed being measured, a known standard was required. The formula developed by Schelkunoff which applies when the shield layer is isotropic (ref. 6),

$$\text{i.e. } Z_t = R_{dc} \cdot u / \sqrt{\cosh u - \cos u},$$

$$\text{where } u = t \sqrt{2g\omega\mu},$$

and g = conductivity of shield layer,

μ = permeability of shield layer,

t = thickness of shield layer,

ω = 2π x frequency,

R_{dc} = d.c. resistance of shield per unit length,

was used to calculate theoretical values for the surface transfer impedance of specially made coaxial cables, where the outer conductors were cupro-nickel tubes. The measured values on these tubes agreed very closely indeed with the predicted values, as can be seen from figure 4.

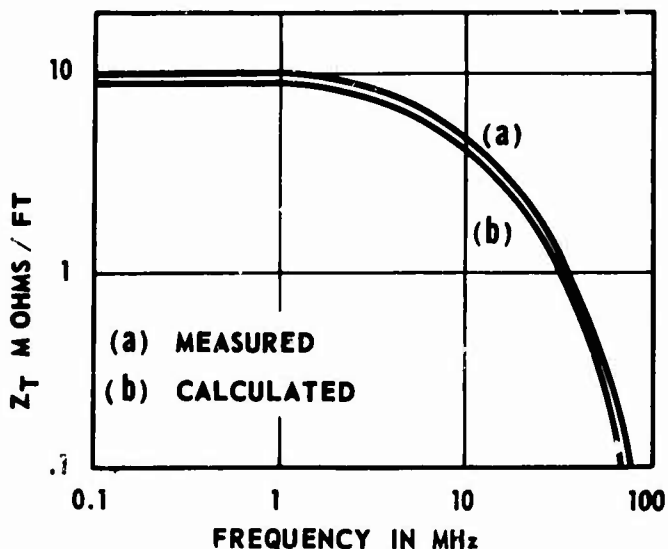


FIG. 4

TRANSFER IMPEDANCE FOR
CUPRO-NICKEL TUBES

3.2 FOLDED TAPE SHIELDS

Where a shield composed of a longitudinal overlapped tape was measured, values calculated for a hypothetical tube, with the same thickness and d.c. resistance as the shield, agreed very well with the experimental values when good contact along the overlap was maintained. See figure 7.

3.3 BRAID SHIELDS

The shielding afforded by metal braid shields has been fairly extensively studied and reported (refs. 3,5,7,16). The results shown in figure 5 are typical of the transfer impedance curves obtained. Those shown apply to single copper braids (one layer of braiding only) and indicate the measureable variation in shielding which is caused by changing the coverage given by the braid.

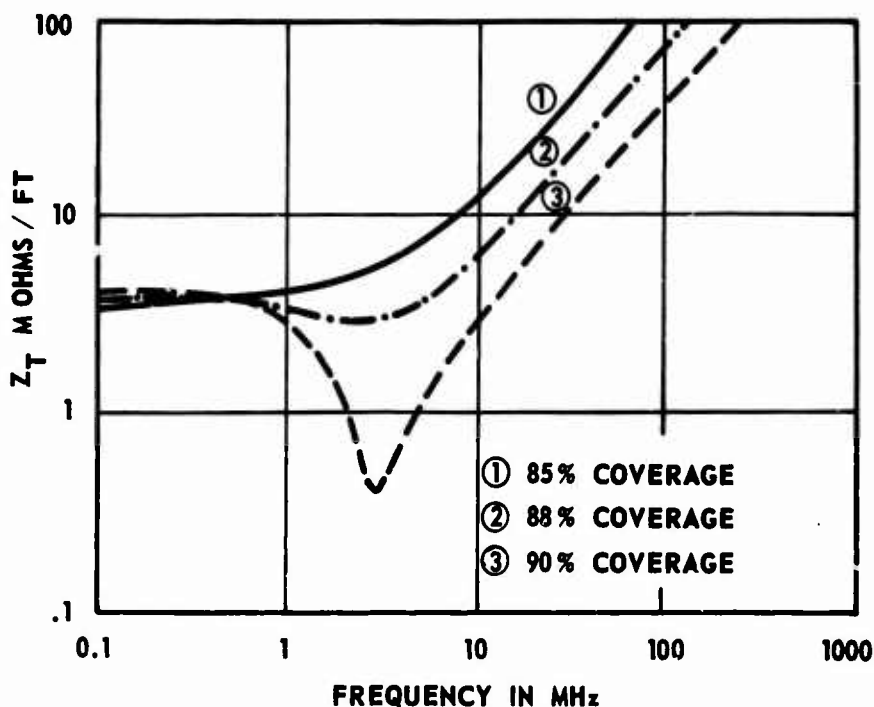


FIG. 5 TRANSFER IMPEDANCE OF SINGLE BRAIDED SHIELDS

It is not intended to dwell upon braided shields and at this point it should be noted that:

- (a) similar shields yield similar curves,
- (b) The lower the curve the better the shielding, and
- (c) in any one figure all curves refer to the same size cable, because shields on different sized cables cannot be compared directly.

In figures 4 and 5 the two basic shapes of surface transfer impedance vs. frequency curves are evident, one continually falling corresponding to an isotropic shield, and one which rises indicating an incomplete coverage by the shield.

3.4 AGING EFFECTS ON OVERLAPPED SHIELDS

In figure 6, curves for a coaxial television drop wire with a longitudinal overlapped copper tape as outer conductor and covered with a copper braid show what happens after aging of the cable takes place. The curves shown were measured on the same sample, one as a new product, the other after a few days in a hotmoist air oven. The layer of oxide which formed between the faces of the overlap was sufficient to change the shielding characteristics from the desirable dropping curve to the rising one of the incomplete shield. This effect had been previously noted in the field where a marked rise in radiation level had been found in the vicinity of a small length of cable whose outer protective jacket was damaged, so allowing this short length of shield to become oxidized.

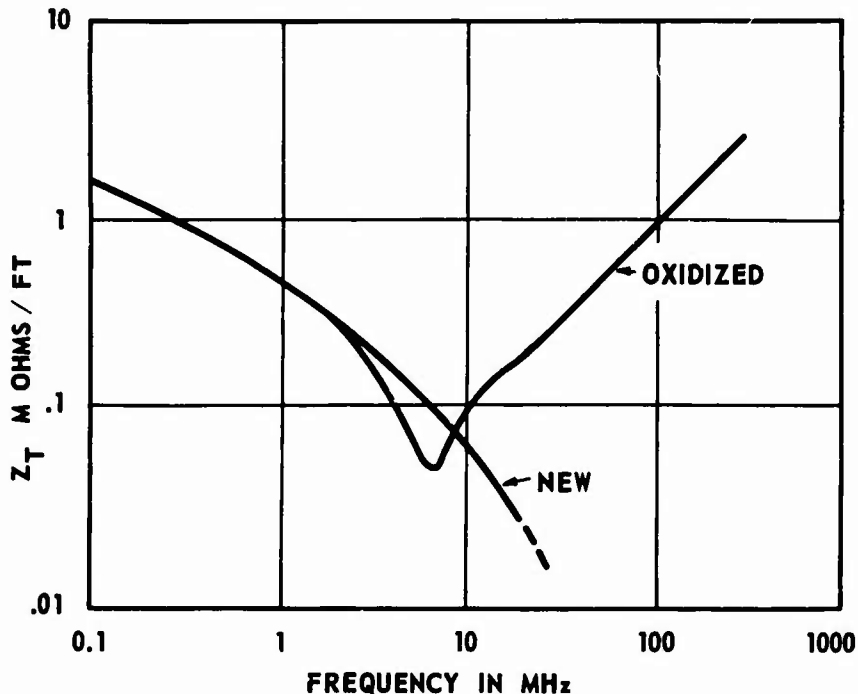


FIG. 6 TRANSFER IMPEDANCE OF 59 TYPE CABLE (Shield = overlapped copper tape and copper braid)

3.5 MULTIPLE LAYER SHIELDS

A single overlapped longitudinal copper tape formed into a tube acts very much like an ideal shield and will give a transfer impedance curve similar to curve (a) in figure 7. When a steel tape is spiralled over the top of this, and another copper tape overlapped longitudinally over the steel, then curve (b) is obtained. This curve (b) obviously does not have the usual dropping characteristic because of the effects of the shield being layered, and being a mixture of magnetic and non-magnetic metals. This curve emphasises the point that it is easier to measure the shielding effectiveness of composite shields than to try calculating it.

3.6 "BONDED" SHIELDS

The desirability of hermetically sealed cables is obvious, and the last few years have seen considerable improvements with the use of "bonded" aluminum outer conductors. This sealing is achieved using an aluminum strip with a thin layer of copolymer bonded to one or both sides of it. Once it is formed into a tube and overlapped, the extrusion of the final polyethylene jacket over the tube fuses the adjacent polyethylene and copolymer layers together. This effectively puts an insulating layer between the surfaces of the overlap. This shield form was examined using copper tapes and "mylar"† as an overlap insulator. Copper was used to facilitate the experiment because it is easily soldered, and the transfer impedance characteristics reflect the constructional variations of the shield and not the metal in this case.

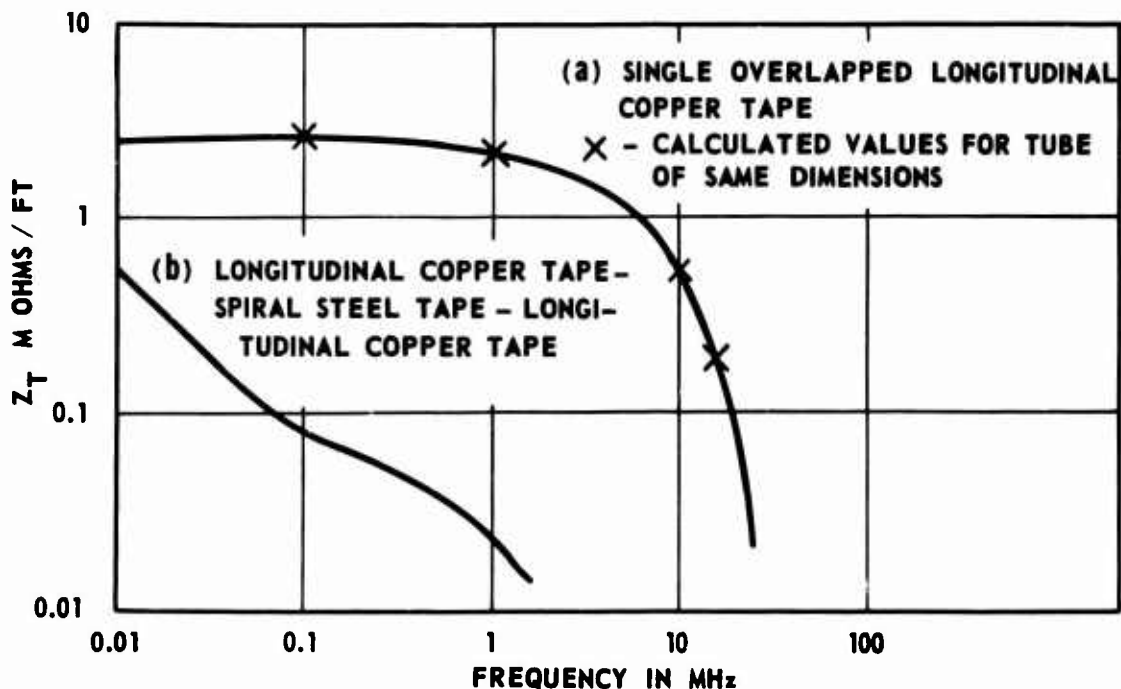


FIG. 7 TRANSFER IMPEDANCE OF A MULTIPLE LAYER SHIELD

† NOTE: In this paper the term "Mylar"† is the registered trade name for a polyester film made by E. I. Dupont de Nemours & Co..

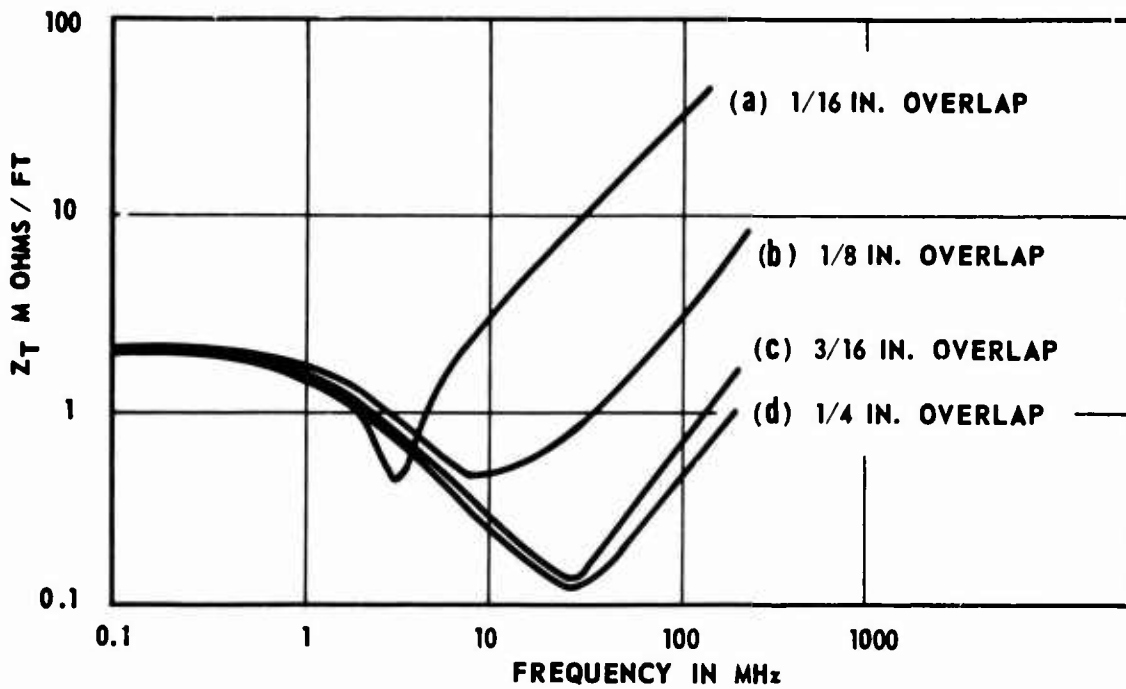


FIG. 8 TRANSFER IMPEDANCE OF 'BONDED' SHIELDS
(single copper tape & 3 mils 'mylar'† insulated overlap)

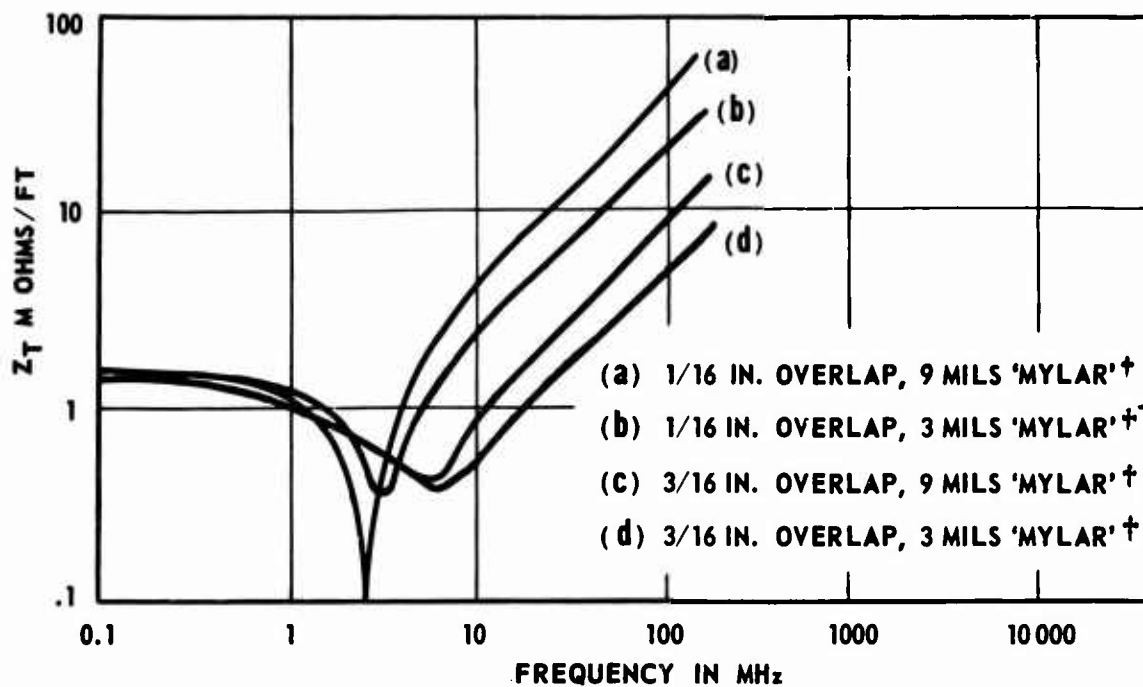


FIG. 9 TRANSFER IMPEDANCE OF 'BONDED' SHIELDS

The results shown in figures 8 and 9 for bonded shields indicate the variations in shielding brought about by variations in overlap width and thickness of insulation in the overlap.

3.7 "BONDED" SHIELDS - INDETERMINATE CONTACTS

In many cases the film of insulation in the overlap is very thin and the final fusing and extrusion pressure may cause the soft copolymer to flow and so make irregular contacts between the faces. This situation was simulated by making definite contacts along the length of the samples.

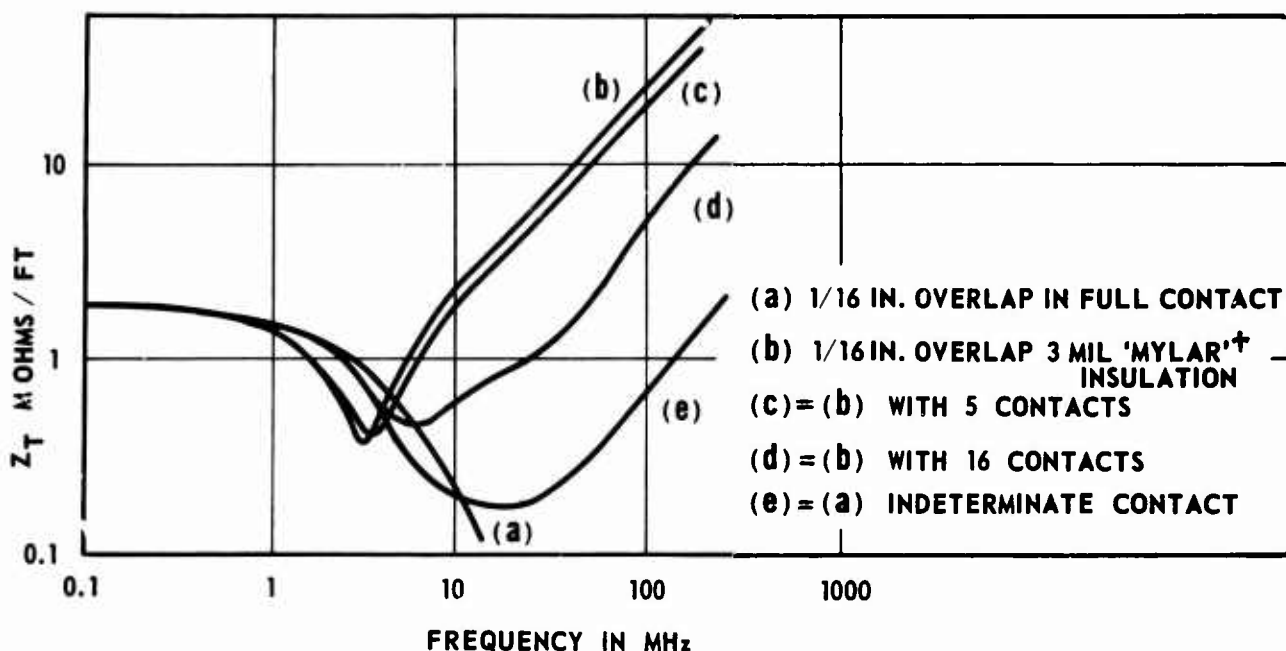


FIG. 10 TRANSFER IMPEDANCE OF 'BONDED' SHIELDS

The curves shown in figure 10 demonstrate how a few contact points along the length of a bonded overlap improve the shielding above 5 MHz. All the samples (except for curve (e),) had an adhesive plastic tape wound around them to maintain rigidity and contact between the overlap faces where possible. (This comment applies to all the specially hand-made samples.) The effect of this restraining tape is seen by comparing curves (a) and (e), in the one case, (a), there is continuous contact along the length, and in the other (e), the number of contacts is indeterminate. Flexing the sample produced a slightly different curve caused by a different set of contact points.

4. CROSSTALK EVALUATION:

The transfer impedance results measured on coaxial tubes which are to be put together in multitube cables can be used to estimate the expected crosstalk levels in those cables. As an example of this, the results shown in figure 7(b) were used to find theoretical values for a cable which contained two similar coaxial pairs. The comparison between actual and calculated far-end crosstalk levels is shown in figure 11 for such a two tube cable. The formulae used are given in Appendix III.

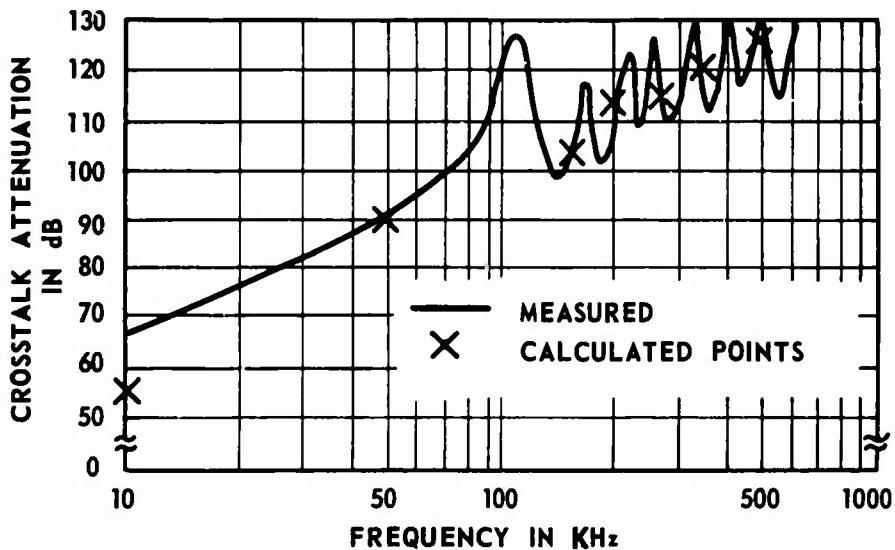


FIG. 11 FAR - END CROSSTALK

Detectable crosstalk is inherent between cabled coaxial pairs, but in most cases it is confined to a relatively low frequency band. However between cables whose transfer impedance characteristics turn up and rise with frequency, crosstalk is also likely to turn and become worse. In general, the type of coaxial pairs which are cabled together have adequate shielding (i.e. sufficiently low transfer impedance values) for crosstalk not to be a problem at the frequencies used, despite the fact that it is still present.

5. RADIATION:

Radiation levels, that is field strength, and transfer impedance were measured between 30 and 300 MHz on television drop wires, and the expected result appeared. A cable shield with a lower transfer impedance allowed less radiation to pass either into or out from the cable than did one with a higher transfer impedance.

It was known that shields with gaps in them allowed radiation to pass through them, and it has already been shown that bigger gaps, or less coverage, give higher surface transfer impedances, all else being equal.

From a cable with an extruded aluminum outer conductor no radiation could be detected. This cable also had a falling transfer impedance characteristic (similar in shape to figure 7(a)), so this was also expected.

The results of J. Quine (ref. 12) show that it was possible to relate magnetic field strength outside a cable to its transfer impedance between 0.15 and 2.4 MHz. The data gathered, up to the time of writing, between 30 and 300 MHz are not sufficient to warrant any more than the generalities preceding this paragraph. The study is continuing.

6. DIFFICULTIES ENCOUNTERED:

Various troubles were found during the early stages of experimenting, and care had to be taken to prevent their recurrence.

Most of the problems arose from two sources, either contacts which appeared good became intermittent at high frequencies, or radiation giving rise to unwanted coupling. In particular, if the short circuit connection did not completely close the end of the tube, radiation through the gaps tended to cause spurious signals to be measured. Similarly, if the sample being measured were a braided shield, radiation from the generator or amplifier could be picked up in the short length before the detector and so influence the results.

When a good contact was required to steel or aluminum shields a conducting epoxy cement was usually adequate, but high impedance contacts occasionally appeared, especially at the termination of the sample.

Errors are usually detected by a sharp change in the measured values. One of the more usual indicators is a very sharp change in the output voltage level when the sample or the tube length becomes an odd multiple of one quarter of a wavelength.

7. CONCLUSIONS:

Because shielding design is not a straightforward process, a practical technique is required to evaluate any new or modified design. The measurement of surface transfer impedance is considered ideal for this as it needs only a short sample, which in many cases can be made by hand.

The results shown in this paper are from actual laboratory measurements and have been commented on individually in section 3. They indicate the general sort of response to be expected for common shield types, and it is concluded that for frequencies up to 300 MHz.

- (i) The effects of shield design modifications may easily be evaluated,
- (ii) Crosstalk levels between two coaxial cables may be estimated,
- (iii) Further work needs to be done in order to relate radiation levels and surface transfer impedance.

APPENDIX I

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APPENDIX II

DERIVATION OF FORMULAE FOR TRANSFER IMPEDANCE:

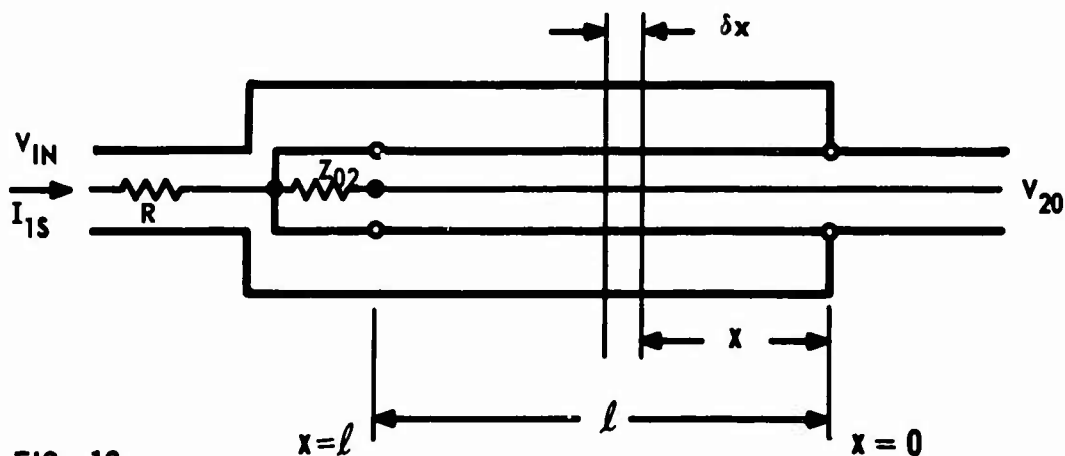


FIG. 12

Let subscript 1 represent outer circuit parameters,
and, subscript 2 represent inner circuit parameters.

If I_{1s} is the current at the input, the current at any point x in the outer system is

$$I_{1x} = I_{1s} \cdot \cosh \gamma_1 x / \cosh \gamma_2 \ell \quad \text{-----(1)}$$

Where γ represents the complex propagation constant and ℓ the sample length.

If Z_t is the surface transfer impedance per unit length, the voltage transferred to the inner system over a length δx at a distance x from the short-circuit at the end of the outer system is

$$\delta V_{2x} = I_{1x} \cdot Z_t \cdot \delta x \quad \text{-----(2)}$$

This in turn presents an incremental voltage to the matched voltmeter at the measuring end of the sample. To be in accord with the definition, the voltage measured should be an open circuit value, so the measured voltage is half the calculated δV_{2x} value, so

$$\delta V_{20} = \frac{1}{2} \cdot \delta V_{2x} \cdot e^{-\gamma_2 x} \quad \text{-----(3)}$$

This is summed over the length to give V_{20} ,

$$\text{i.e. } V_{20} = \frac{Z_t \cdot I_{1s}}{2 \cdot \cosh \gamma_1 \ell} \int_{\ell}^0 \cosh \gamma_1 x \cdot e^{-\gamma_2 x} \cdot dx \quad \text{-----(4)}$$

When the integration is performed, limits substituted, and the following substitutions made:

$$\begin{aligned} \gamma &= j\beta \\ n &= \lambda_1 / \lambda_2 \approx \beta_2 / \beta_1 \\ m &= Z_{01} / R \\ u &= 2\pi \ell / \lambda_1 = \beta_1 \ell. \end{aligned}$$

$$\begin{aligned} j &= \sqrt{-1} \\ \beta &= \text{phase constant} \\ \lambda &= \text{wavelength} \\ Z_0 &= \text{characteristic impedance} \\ R &= \text{feeding resistance} \end{aligned}$$

$$\text{and } I_{1s} = V_{in} / (R + Z_{01} \cdot \tanh \gamma_1 \ell) \quad V_{in} = \text{input voltage}$$

$$V_{20} = \frac{-Z_t \cdot V_{in} \cdot e^{-jnu} \cdot [(\sin u - n \cdot \sin nu) - j(n \cdot \cos u - n \cdot \cos nu)]}{2 \cdot R \cdot (\cos u - j m \cdot \sin u) \cdot \beta_1 \cdot (1 - n^2)} \quad \text{-----(5)}$$

so when rearranged for Z_t , and the modulus taken,

$$|Z_t| = 2 \left| \frac{V_{20}}{V_{in}} \right| \frac{R}{\ell} \cdot \frac{(1-n^2) \cdot u \cdot [\cos^2 u + m^2 \sin^2 u]^{1/2}}{[(\sin u - n \cdot \sin nu)^2 + n^2 (\cos u - \cos nu)^2]^{1/2}} \quad (6)$$

This can be rewritten as:

$$|Z_t| = 2 \cdot \left| \frac{V_{20}}{V_{in}} \right| \frac{R}{\ell} \cdot F(u) \quad \text{-----} (7)$$

In most cases $F(u)$ is close to unity and only becomes significantly different when ℓ is an appreciable part of a wavelength.

In the particular case where the wavelengths in the inner and outer systems are the same, then equation (6) cannot be used and an alternative is derived assuming.

$$\gamma_1 = \gamma_2 = j\beta$$

This leads to:

$$|Z_t| = 4 \left| \frac{V_{20}}{V_{in}} \right| \frac{R}{\ell} \cdot u \left[\frac{(\cos^2 u + m^2 \sin^2 u)}{(u^2 + u \cdot \sin 2u + \sin^2 u)} \right]^{1/2} \quad \text{-----} (8)$$

which can be rewritten as:

$$|Z_t| = 2 \left| \frac{V_{20}}{V_{in}} \right| \frac{R}{\ell} \cdot F'(u) \quad \text{-----} (9)$$

where again $F'(u)$ is close to unity in most cases.

APPENDIX III

CROSSTALK FORMULAE:

Formulae used in the calculation of crosstalk levels as derived in reference 8 between similar coaxial pairs. ($Z_{01} = Z_{02} = Z_0$; $\gamma_1 = \gamma_2 = \gamma$)

Where:

- system 1 is disturbing.
- system 2 is disturbed.
- system 3 is an intermediate circuit.
- E is source voltage on system 1.
- V_f is far-end voltage on system 2.
- V_n is near-end voltage on system 2.
- Z_t is surface transfer impedance.
- ℓ is exposure length.

(a) Direct near-end crosstalk

$$N = \frac{V_n}{E} = \frac{Z_t}{2 \cdot Z_0} \left[\frac{1 - e^{-2\gamma \ell}}{2\gamma} \right] \text{-----} (10)$$

(b) Direct far-end crosstalk

$$F = \frac{V_f}{E \cdot e^{-\gamma \ell}} = \frac{Z_t \cdot \ell}{2Z_0} \text{-----} (11)$$

(c) Indirect near-end crosstalk.

$$N' = \frac{(Z_t)^2}{4Z_0Z_{03}} \left[\frac{\gamma_3(1 - e^{-2\gamma \ell})}{\gamma(\gamma_3^2 - \gamma^2)} - \frac{(1 - 2e^{-(\gamma_3+\gamma)\ell} + e^{-2\gamma \ell})}{(\gamma_3^2 - \gamma^2)} \right] \text{-----} (12)$$

(d) Indirect far-end crosstalk

$$F' = \frac{(Z_t)^2}{4Z_0Z_{03}} \left[\frac{2\gamma_3 \ell}{(\gamma_3^2 - \gamma^2)} - \frac{[1 - e^{-(\gamma_3-\gamma)\ell}]}{(\gamma_3 - \gamma)^2} - \frac{[1 - e^{-(\gamma_3+\gamma)\ell}]}{(\gamma_3 + \gamma)^2} \right] \text{-----} (13)$$

Legitimate approximations are possible in equations (10) through (13) for very short lengths or long electrical lengths.

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