ENGINEERING TRAINING SUPPLEMENT

No. 5

AN INTRODUCTION TO SLOT AERIALS

BRITISH BROADCASTING CORPORATION

ENGINEERING TRAINING SUPPLEMENT

No. 5

AN INTRODUCTION TO SLOT AERIALS

ISSUED BY ENGINEERING TRAINING DEPARTMENT
B B C
1950

CONTENTS

AN INTRODUCTION TO SLOT AERIALS

Slot aerials have certain advantages for v.h.f. transmission purposes and the Wrotham f.m. transmitter will employ such a system. Some information on the characteristics and performance of slot aerials will be of interest to the staff of the BBC Engineering Division and this Supplement aims to provide this information with the aid of physical rather than mathematical arguments.

In order to obtain a clear picture of the characteristics and properties of slot aerials it is necessary first to consider (a) the distribution of voltage and current (and hence the distribution of electric and magnetic fields) on short lengths of transmission line, (b) the impedances presented by these lengths of line, and (c) the conditions necessary to obtain effective radiation from a radiating system. It is easier to approach the subject of slot aerials through the folded dipole and we shall follow this procedure.

Transmission Lines

The simplest transmission line consists of two round wires separated by a uniform distance which is small compared with the wavelength in use. If the separating distance is not small in comparison with the wavelength, the line will act as an aerial and power will be lost in radiation. When the wires are close, mutual cancellation of the radiation field takes place because the effect on one wire of a change of current in the other wire is instantaneous.

In a balanced two-wire line, each wire being of exactly the same length, the currents will be in push-pull, that is to say, at any given distance from the generator connected to the sending end of the line, the instantaneous current in one wire will be equal in magnitude but opposite in direction to the instantaneous current in the other. The voltages to earth from each wire will also be equal in value but of opposite polarity.

Consider a two-wire balanced line of variable length connected to a resistance load, R_r, variable in value from zero to infinity, and assume that the line losses due to radiation, resistance and leakage are negligible. Imagine that the line is connected to a r.f. generator of fixed frequency. We wish to know the order of the impedance presented to the generator by the line and load, and also the distribution of voltage and current along the line when the length is varied. With a line of zero length, the impedance presented to the generator will obviously be that of the load itself.

Let us now make the length of the line finite but small (less than a quarter-wavelength). See Fig. 1(a). With R_r set to infinity, the only path for current to flow in the circuit is through the capacitance between the two wires, and the magnitude of the current will decrease towards the load;

at the load terminals no current will flow but there will be a voltage across the wires.

Although the inductance and capacitance of the line are distributed along its length, it is easier and, within the limits of this simple explanation, justifiable to consider the inductance as lumped and acting where there is maximum magnetic flux (i.e., maximum current) and also the capacitance where there is maximum electric stress (i.e., maximum voltage). Referring to Fig. 1(a), since R_r is infinite the current through it is zero and magnetic

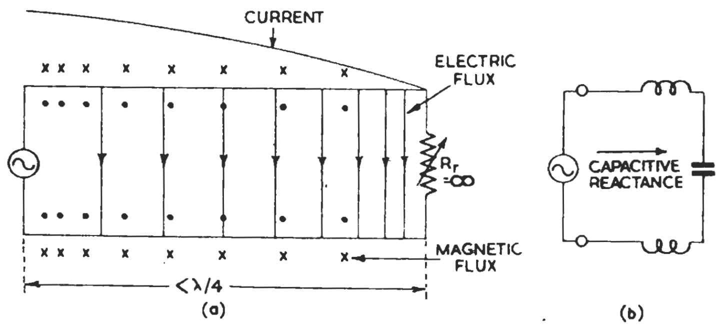

Fig. 1. (a) Open-circuited Two-wire Balanced Transmission Line of Length less than a Quarter-wavelength, (b) Impedance-equivalent Circuit

flux is also zero. On the other hand voltage and electric stress are maximum. We must, therefore, place our equivalent capacitance at the load and our equivalent inductance between load and generator as shown in Fig. 1(b). A length of line less than a quarter-wavelength will present a capacitance in the same manner as a series-tuned circuit below resonance.

If the line is extended still further, the inductance and capacitance will both increase and at some point the inductive reactance will equal the capacitive reactance and series resonance will occur. This takes place when the length of the line from the load terminals is equal to a quarter-wavelength at the applied frequency. See Fig. 2. The impedance presented to the generator by an open-circuited quarter-wavelength line is therefore zero, which is the same as a short circuit.

Again let us connect the original length of line to the load but this time set R_r to zero. See Fig. 3(a). There can obviously be no electric stress across the load terminals but current will flow setting up lines of magnetic force ; inductance may, therefore, be lumped at this point. As

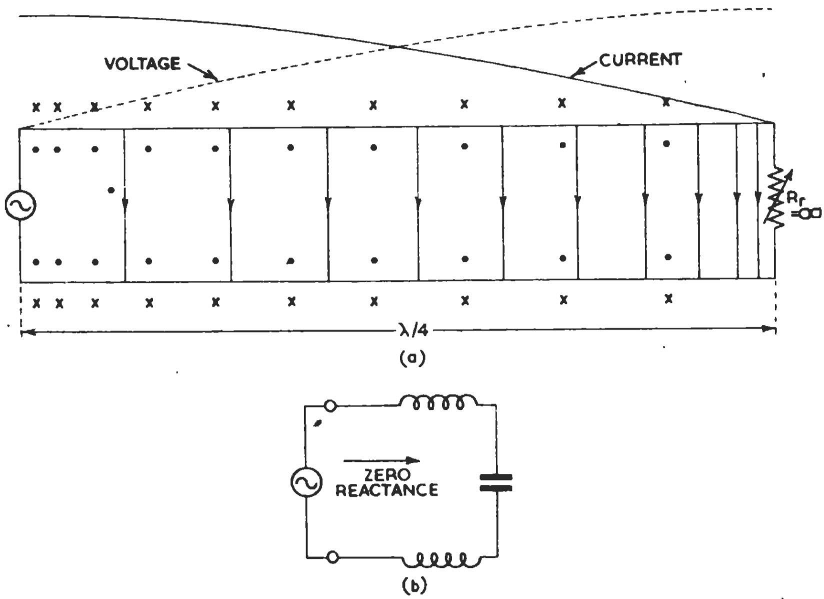

Fig. 2. (a) Open-circuited Two-wire Balanced Transmission Line of Length equal to a Quarter-wavelength, (b) Impedance-equivalent Circuit

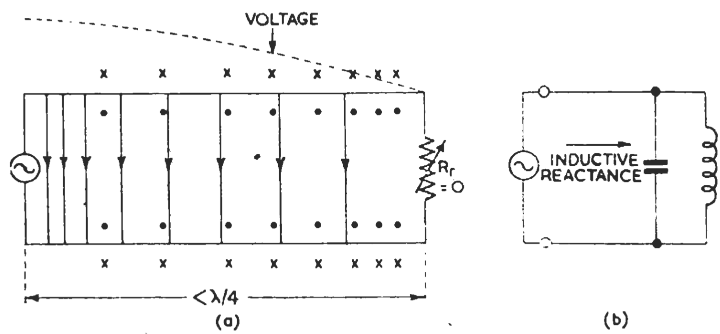

Fig. 3. (a) Short-circuited Two-wire Balanced Transmission Line of Length less than a Quarter-wavelength, (b) Impedance-equivalent Circuit

we proceed from the load (a short circuit) to the generator, a voltage will build up across the inductive reactance and electric lines of stress will appear.; we may, therefore, lump the capacitance at the generator terminals. See Fig. 3(b). A length of short-circuited line less than a quarter-wavelength will present to the generator a pure inductive reactance in the same manner as a parallel-tuned circuit below resonance.

If the line length be increased to a quarter-wavelength, Fig. 4, parallel resonance will take place and the impedance presented to the generator will be very high indeed ; in fact, practically an open circuit.

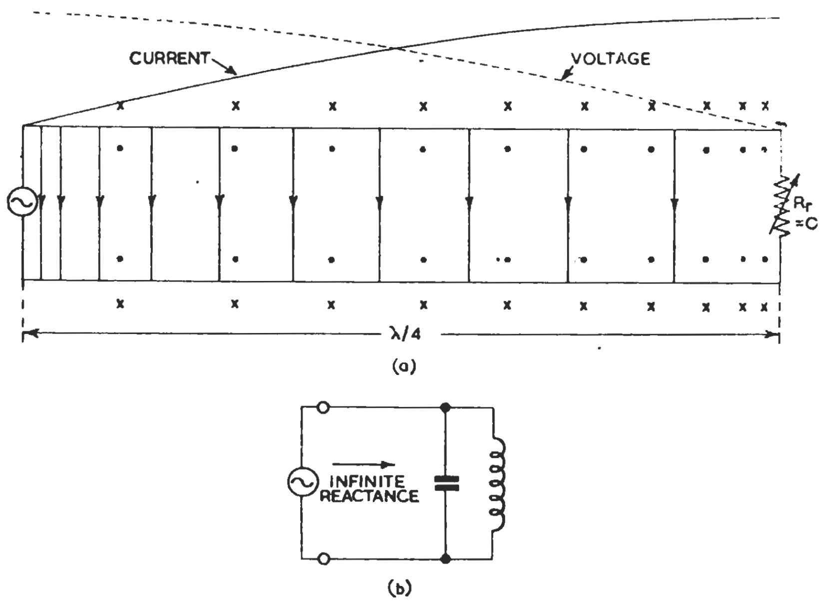

Fig. 4. (a) Short-circuited Two-wire Balanced Transmission Line of Length equal to a Quarter-wavelength, (b) Impedance-equivalent Circuit

It will now be seen that by changing the value of R_r from infinity to zero on a quarter-wavelength line, the load impedance presented to the generator changes from zero to infinity. With a line less than a quarter-wavelength and R_r set at infinity a capacitance is presented, and with R_r set at zero an inductance is presented.

Now, with R_r set at a certain critical value the inductance and capacitance of the line cannot be regarded as lumped at any particular point (even for the purpose of this simple explanation), for the current and voltage on the line are such that the magnetic flux and electric stress are evenly distributed along the line, and each increment of inductance, however small, is cancelled out by an equivalent increment of capacitance. This means that mutual cancellation takes place when the energy stored in the magnetic field over this small increment is equal to the energy stored in the electric field over the same increment, that is to say, when

$$\tfrac{1}{2}LI^2 \text{ joules} = \tfrac{1}{2}CV^2 \text{ joules}$$

where L = inductance in henrys per unit length of line
and C = capacitance in farads per unit length of line.

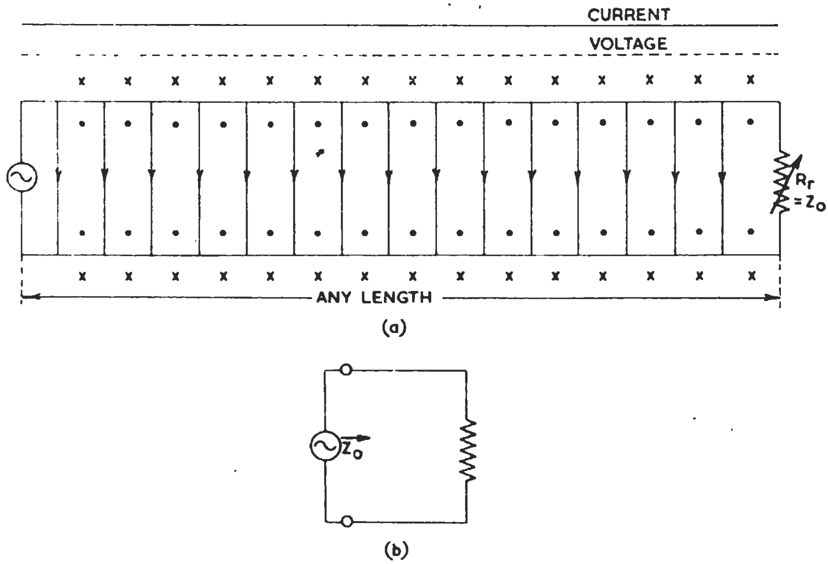

Fig. 5. (a) Two-wire Balanced Transmission Line Terminated by a Resistance equal to Z_o, (b) Impedance-equivalent Circuit

From the above equation it follows that

$$V/I = \sqrt{(L/C)}$$

It follows that if a particular line is terminated by a resistance R_r equal in value to $\sqrt{(L/C)}$ the ratio of voltage to current will be such that energies stored in the electric and magnetic fields all along the line will be equal and cancellation of reactance takes place. The impedance presented to the generator will be a resistance equal in value to $\sqrt{(L/C)}$ whatever the length of line and the line in this condition is said to be matched. The value $\sqrt{(L/C)}$ is known as the *characteristic impedance*, Z_o, of the line and the maximum values of current and voltage will be the same at any point on the matched line between the generator and the load. See Fig. 5.

Provided that the constants of the line and the terminating resistance R_r (equal to Z_o) do not change with frequency then the impedance presented to the generator will not change with frequency. The characteristic impedance of a two-wire line is dependent upon the thickness and spacing of the conductors. A thick conductor has less inductance and more capacitance for a given length than a thin one, and a reduction in the spacing of the separate conductors gives less inductance and more capacitance. Thus an increase in wire diameter and a reduction of the spacing both reduce Z_o.

If a line is terminated by an impedance other than a resistance equal to Z_o, the impedance presented to the generator will vary with the length of feeder and also with the frequency. This characteristic impedance Z_o can be considered as a reference impedance between zero and infinity and when the load resistance is greater than Z_o we can consider the line as tending towards an open circuit. Hence, the series-equivalent circuit of Fig. 8(b) will apply. Conversely when the load resistance is less than Z_o we can say that the line tends towards a short-circuit condition and the parallel-equivalent circuit of Fig. 6(b) applies.

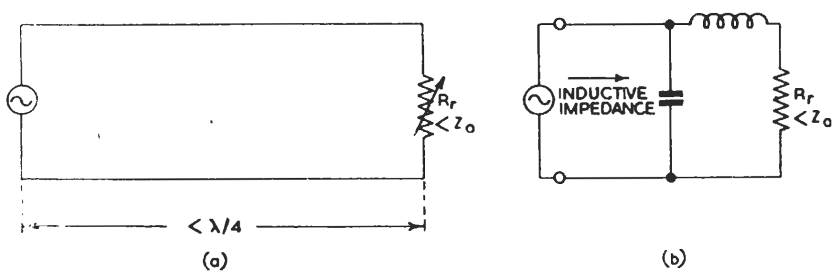

Fig. 6. (a) Two-wire Balanced Transmission Line of Length less than a Quarter-wavelength and Terminated by a Resistance less than Z_0, (b) Impedance-equivalent Circuit

Returning to our original generator, feeder and variable resistance R_r, when R_r is less than Z_o, thus tending to short-circuit the line, the section of the line will present an inductive impedance until its length again reaches a quarter-wave when it will present a pure resistance greater in value than Z_o. See Figs. 6 and 7.

The quarter-wave section with R_r less than Z_o may be drawn as a parallel-tuned circuit with the resistance R_r in series with the inductance. See Fig. 7(b). Such a circuit would present a resistance of value L/CR_r and since $L/C = Z_o^2$ the quarter-wave section will convert the load resistance into a resistance of value Z_o^2/R_r.

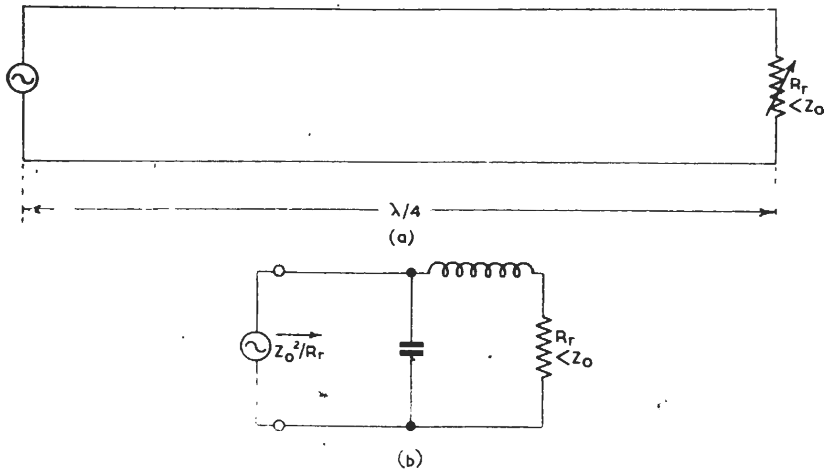

Fig. 7. (a) Two-wire Balanced Transmission Line of Length equal to a Quarter-wavelength and Terminated by a Resistance less than Z_o, (b) Impedance-equivalent Circuit

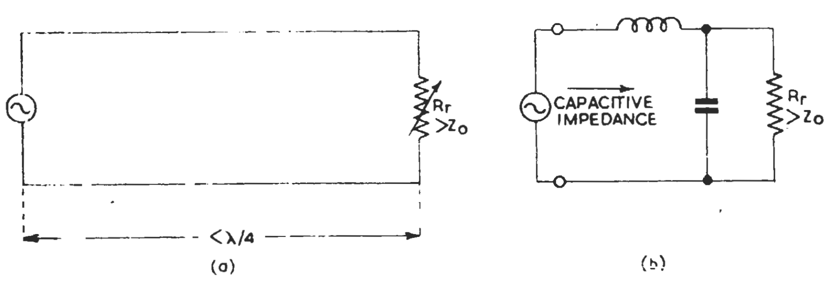

Fig. 8. (a) Two-wire Balanced Transmission Line of Length less than a Quarter-wavelength and Terminated by a Resistance greater than Z_o, (b) Impedance-equivalent Circuit

If R_r is greater than Z_o, it tends to open-circuit the line and the section of the line will present a capacitive impedance (see Fig. 8), until its length reaches a quarter-wave when it will again present a resistance but this time less in value than Z_o and again equal to Z_o^2/R_r. The equivalent circuit is that of Fig. 9(b) and it is clearly Fig. 7(b) with the generator and load positions reversed. Since the resistance looking in at the generator terminals of Fig. 7(b) is $R = Z_o^2/R_r$ we could equally well write $R_r = Z_o^2/R$ and this would then give us the circuit of Fig. 9(b). Thus we can say that the impedance looking in to line in Fig. 9(b) is Z_o^2/R_r where R_r is the load resistance. The resistance will tend to short circuit the line and we have a repetition of the condition outlined in the first example when $R_r < Z_o$.

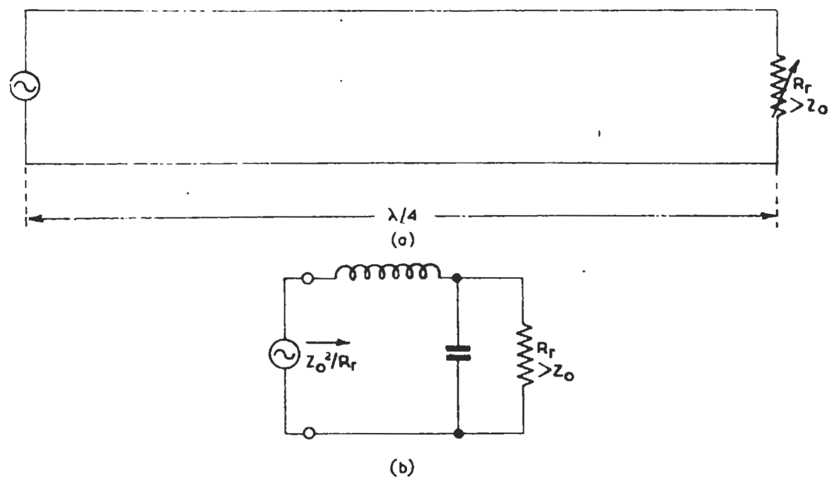

Fig. 9. (a) Two-wire Balanced Transmission Line of Length equal to a Quarter-wavelength and Terminated by a Resistance greater than Z_o, (b) Impedance-equivalent Circuit.

It can now be seen that all along the line between R_r and the generator, impedance transformations will occur if the line is terminated by an impedance not equal to Z_o. Impedance values will be repeated every half wavelength as shown in Fig. 10, which illustrates an example of a line terminated by $R_r < Z_o$. When power is supplied from the generator, maximum current will flow with minimum voltage at the low-resistance points, and minimum current at maximum voltage will occur at high-resistance points. The ratio between the maximum and minimum currents (or voltages) is called the standing-wave ratio.

It is convenient to express the length of a line in degrees or radians and this may be done in the following manner :—

$$\frac{\text{length} \times 360°}{\text{wavelength}} = \text{electrical length in degrees}$$

$$\frac{\text{length} \times 2\pi}{\text{wavelength}} = \text{electrical length in radians.}$$

The general formula for finding the impedance presented by a line of

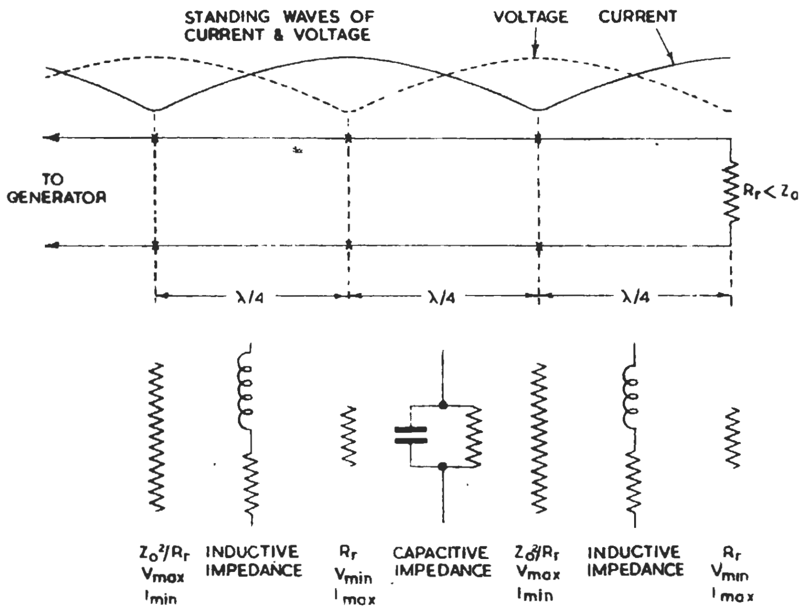

Fig. 10. Current and Voltage Distribution and Impedance Transformation along a Transmission Line of Length greater than a Quarter-wavelength and Terminated by a Resistance less than Z_o

characteristic impedance Z_o, whose electrical length is θ, terminated by any impedance Z_r, is as follows :—

$$Z_g = Z_o\left(\frac{Z_r + jZ_o \tan\theta}{Z_o + jZ_r \tan\theta}\right) \quad \dots \quad \dots \quad \dots \quad (1)$$

where Z_g = impedance presented. If Z_r is complex it must be expressed in the form $R_r + jX_r$.

When $Z_r = 0$ (i.e., the line is short circuited)

$$Z_g = +jZ_o \tan\theta \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

To determine the value of Z_g when Z_r is infinite it is best to divide the numerator and denominator of the right-hand expression of equation (1) by Z_r; we then have

$$Z_g = Z_o\left[\frac{1 + (jZ_o/Z_r)\tan\theta}{Z_o/Z_r + j\tan\theta}\right] \quad \ldots \quad \ldots \quad \ldots \quad (3)$$

When Z_r = infinity (i.e., the line is open-circuited),

$$Z_g = -jZ_o \cot\theta \quad \ldots \quad \ldots \quad \ldots \quad (4)$$

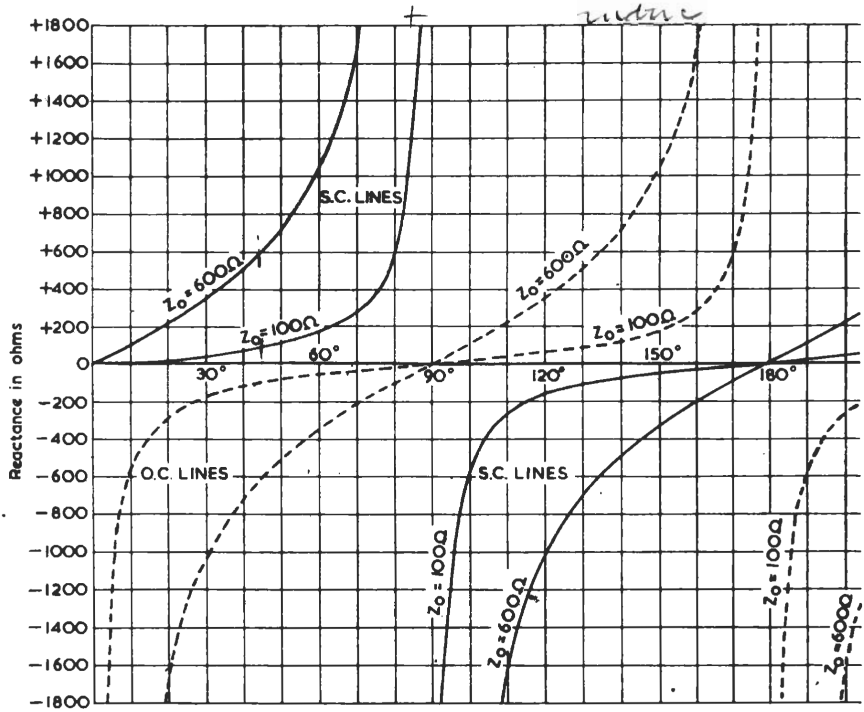

Fig. 11. Reactance of Short-circuited and Open-circuited Transmission Lines plotted against Electrical Length. Curves drawn for Lines of 600-ohms and 100-ohms Characteristic Impedance

Curves showing change of reactance with electrical length are given in Fig. 11, for short- and open-circuited lines of Z_o equal to 600 ohms and also 100 ohms. It will be noticed that the slope of the reactance curves depends

when θ = 90°

at λ/4 $Z_g = \frac{Z_o^2}{Z_r}$ $Z_r = R_r \pm jX_r$

must be series

on Z_0. We shall see later that this has important bearing on the design of wideband aerial systems.

It will also be seen from Fig. 11 that for short-circuited lines of length $\theta = 90°$, and open-circuited lines of length $\theta = 180°$ (and, of course, $\theta = 0°$), the reactance is infinity, and that the slope in terms of reactance is unmanageable in these regions; curves have therefore been drawn in Fig. 12

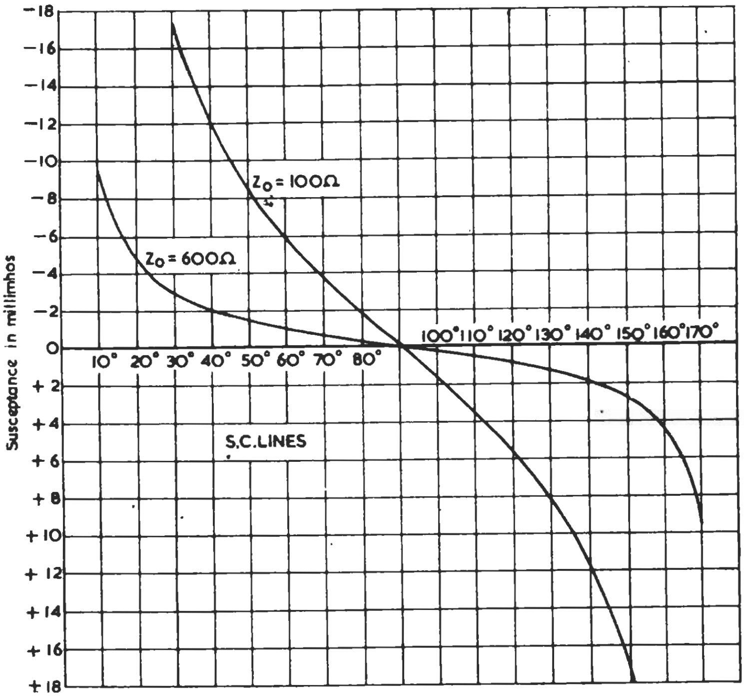

Fig. 12. Susceptance of Short-circuited Transmission Lines plotted against Electrical Length. Curves drawn for Lines of 600-ohms and 100-ohms Characteristic Impedance

showing susceptance changes in millimhos for short-circuited lines. It will be appreciated that although reactance and susceptance values have been plotted with respect to electrical length, curves of similar shape would be obtained if reactance and susceptance were plotted with respect to frequency, for changes in frequency necessarily involve proportional changes of electrical length.

As yet, only two-wire lines have been mentioned but most of the effects described occur with all types of r.f. lines including unbalanced concentric

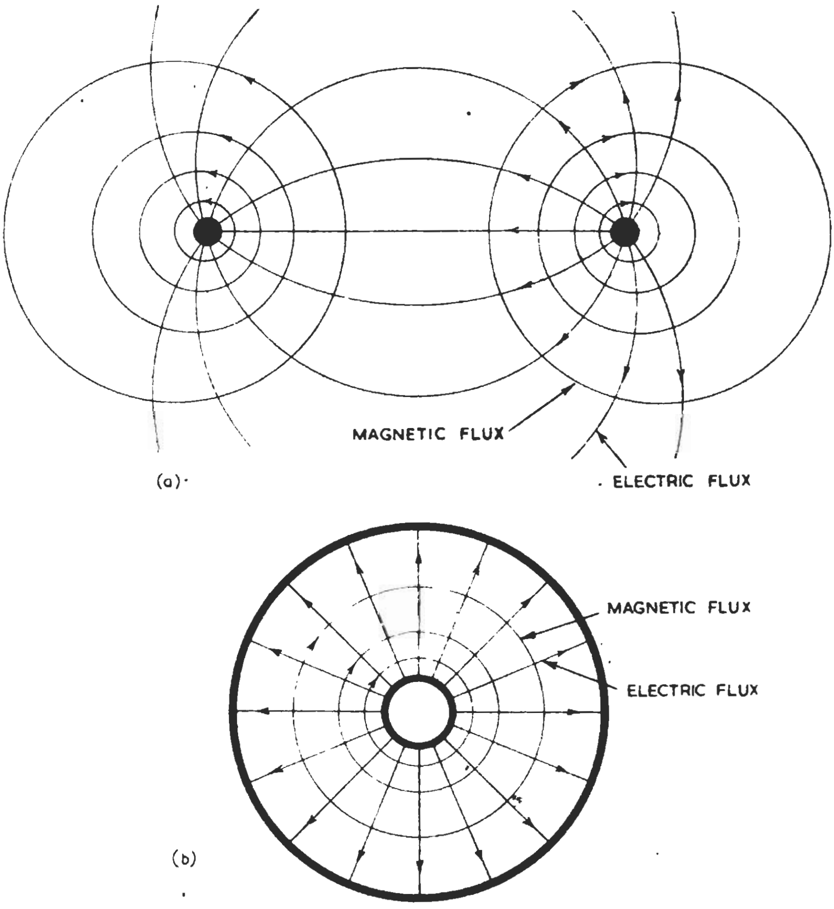

Fig. 13. *Approximate Field Patterns for (a) Two-wire Balanced Transmission Line, (b) Concentric-tube Unbalanced Transmission Line*

tubes. The main differences are the configurations of the magnetic and electrical lines of force. The approximate field patterns for two-wire and concentric-tube lines are shown in Fig. 13. An alternating magnetic field can only exist tangentially to a perfectly conducting surface and lines of electrical force must impinge at right angles on any such surface ; also all lines of force must be terminated, and magnetic and electrical lines cross at right angles. The magnetic fields of a two-wire line surround each conductor, but with concentric tubes the magnetic field surrounds the centre conductor only, provided the line acts purely as a feeder and that the outer conductor has zero potential to ground at all points.

Radiation

In circuits where element spacing is small in comparison with wavelength the effect of current and voltage changes may be regarded as instantaneous. For instance, lines of electric force between the plates of a capacitor are considered to reverse their direction instantaneously with reversal of polarity of voltage across the plates. Similarly, lines of magnetic force linking an inductance are assumed to reverse instantaneously with current reversal. These assumptions are justified for concentrated electric and magnetic fields when distances and time delays involved are small fractions of wavelength and period.

Imagine that a low-loss tuned circuit, Fig. 14(a), is connected to a r.f. source of power by means of a small coupling coil, and that the circuit is tuned to the same frequency as the source, then maximum voltage will be developed across the capacitor and maximum current will flow through it. Due to the concentration of the electric lines of force in the capacitor there will be no induced voltage in conductors, even a short distance from the capacitor. We also know that in order to couple inductively any circuit to the inductor, it is necessary to bring it quite close to the inductor ; this field of influence is termed the ***near zone***. Power lost in the circuit will be used mainly in heating the inductor and capacitor.

Now suppose that the plates of the capacitor are moved apart until the distance between them is approximately half a wavelength, Fig. 14(b), and that the turns of the inductor are pulled out so that the inductor is still connected to the capacitor. It is conceivable that the circuit may still be tuned to resonance, for if necessary the inductor could be adjusted to maintain resonance.

In a loss-free inductor or capacitor there is energy which is alternately stored and returned to the circuit. In order that the energy stored in the magnetic field may be returned to the circuit, all the lines of force created must collapse again into the inductor.

A similar argument applies to the electric lines of force between the plates of a capacitor. When electric and magnetic fields are concentrated by close element spacing there is little loss of energy, but when the element spacings are increased so that the distances involved introduce time delays, the lines of force do not return all their energy to the circuit. The lines of force cannot travel faster than the speed of light and by the time their reversal is accomplished the alternating source of power has created fresh lines of force in the same direction.

By the fundamental laws of like and unlike poles, the force lines are mutually repellant and the lines of force which have not time to return their

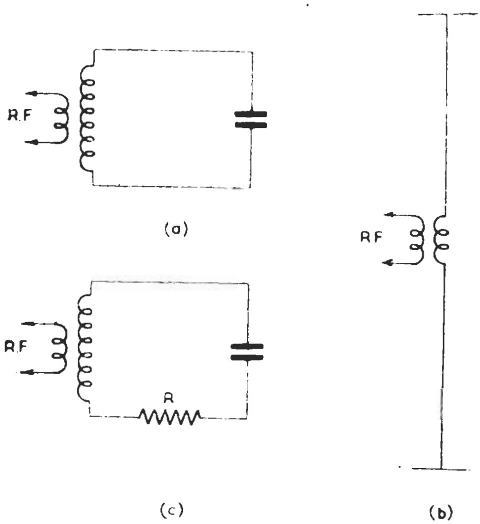

Fig. 14. (a) Concentrated Circuit, (b) Expanded Circuit, (c) Impedance-equivalent Circuit of Expanded Circuit

energy to the circuit are detached and travel outwards from the source with the speed of light. This applies to magnetic and electric lines equally and both are detached ; each exists by reason of the other, and the direction of their combined motion is at right angles to the electric and magnetic lines which are themselves perpendicular to each other. The displacement current in space is in time phase with the electric strain or potential ; therefore, the magnetic and electric fields are in time phase.

Thus is formed a train of electro-magnetic waves, flux lines existing in space, as though a potential existed and a current were flowing to create them. The wavefront presented by a train of electro-magnetic waves is generally considered to be *polarised* in the same direction as the electric lines of force. In other words, if the elements of the source are so placed that the lines of elecirıc force are vertical, the wavefront is said to be *vertically polarised* ; *horizontal polarisation* is similarly defined.

It would be possible to couple a circuit inductively or capacitively to the expanded tuned circuit, but the effectiveness of such a coupling is proportional to the inverse square of the distance between the two circuits and consequently rapidly diminishes with distance. In this way the coupled circuit is influenced by those lines of force (electric or magnetic), which return energy to the expanded circuit, and if the coupled circuit is opened out in the same way as the original expanded circuit and is situated parallel with it, the coupled circuit will be influenced also by those lines of force which travel into space; this field of influence is termed the ***intermediate zone.*** If the coupled circuit is removed to such a distance that it is only influenced by the lines of force which travel outwards into space, it is then said to be in the ***far zone***; voltages will be induced and currents will flow in the expanded coupled circuit with an effectiveness which is proportional to the inverse distance and which consequently diminishes far less rapidly than in the inductively- or capacitively-coupled case. In fact any conductor whose length is parallel with the expanded length of the tuned circuit will receive energy from the radiated wave, though the voltage and current will only be a maximum when the receiving circuit is tuned to the same resonant frequency as the sending circuit.

The expenditure of energy from the sending circuit is equivalent to the dissipation of power in resistance. In its original state the tuned circuit was practically loss-free, but in its expanded state it radiates energy. This may be represented by inserting resistance in series with the equivalent tuned circuit, Fig. 14(c), of such a value, that with the same value of circulating current flowing, the same amount of power is dissipated as radiated in the expanded circuit. This equivalent resistance is referred to as the ***radiation resistance*** of the radiator, i.e., the expanded circuit, and it depends on the effectiveness of the circuit as a radiator. In actual fact when the circuit is expanded to nearly half a wavelength the circuit becomes just a straight conductor, the distributed inductance just tuning with the distributed capacitance. With the addition of supporting insulators (whose dielectric constant is always greater than that of air), forming lumped capacitance at each end of the conductor, the length for resonance is of the order of 0·465 wavelength, the exact value depending on the sectional area of the conductor and upon the frequency.

The circuit described is therefore a centre-driven dipole in free space, the presence of the earth having been disregarded.

The current distribution in this aerial obviously cannot be uniform for practically no current can flow at the ends of the conductor. Distribution of voltage and current is shown in Fig. 15.

In the equivalent tuned sending circuit, Fig. 14(c), the resistance R carries the full circulating current I, and the power will be I^2R. If, therefore, the radiation resistance is to be represented by R in the tuned circuit, the radiation resistance must be taken as the centre resistance of the dipole where maximum current flows. Although, in fact, radiation resistance is distributed over the length of the conductor it is always taken to be the value at the centre of a half-wave dipole, and the product of the square of the r.m.s. value of the current and the resistance at the centre gives the value of power radiated (losses being neglected).

Thus if the magnetic and electric fields are expanded so as to produce a time delay in the return of energy to the originating circuit, radiation will take place, and the radiation resistance is a measure of the degree of radiation. Radiation may be regarded as coupling to free space and any factor which changes that coupling will also change the radiation resistance. For instance, if the radiator is totally enclosed by an earthed loss-free conducting screen, the radiation resistance will drop to zero.

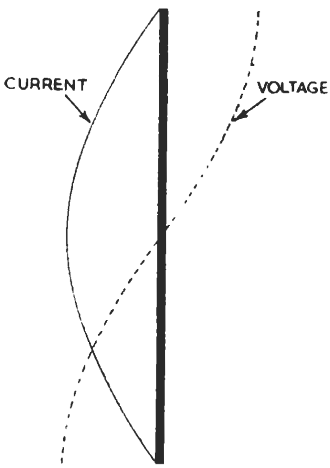

Fig. 15. Current and Voltage Distribution in Half-wave Dipole

The centre or radiation resistance of a half-wave dipole varies with height above ground and with distance from other conductors in the near or intermediate zones (it is unaffected by conductors in the far zone), but a normal working value is taken as approximately 70 ohms.

Now let us consider the gradual extension of a vertical conductor from the terminal of a r.f. generator, the other terminal being earthed. With no conductor attached to the terminal, the impedance presented to the generator is obviously infinite, for no current can flow. With a very short conductor connected, a high capacitive reactance is presented (in a similar way to the gradually extended feeder), but as the length of conductor is increased inductance will also be added, and radiation will take place, for there is no mutual cancellation as with the two-wire feeder. When the conductor is approximately a quarter-wavelength in length, the inductive and capacitive reactances cancel, the impedance is at a minimum and purely resistive, the circuit being similar to a series circuit at resonance. The resistance value is of the order of 35 ohms and approximately half the centre resistance of a half-wave dipole.

With a further extension of the conductor the impedance will become inductive and the resistance will increase. Parallel resonance will take place at half-wavelength and the resistance presented to the generator will be a maximum. With a still greater extension of the conductor, the impedance

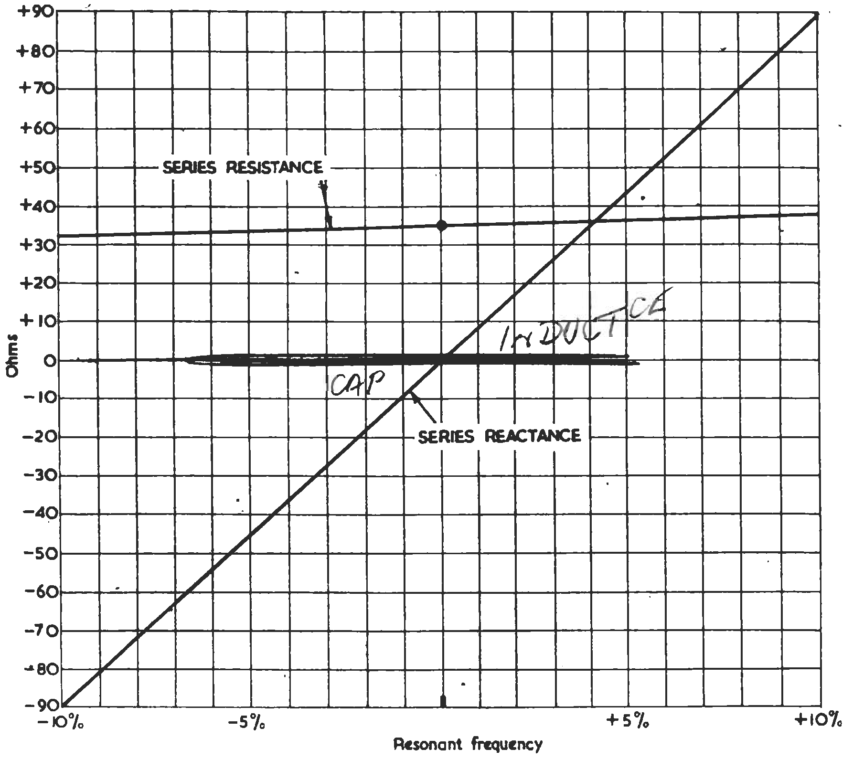

Fig. 16. Resistance and Reactance Curves for a Unipole

again becomes capacitive, series resonance again taking place at approximately three-quarters of a wavelength. Thus when the conductor length is an odd multiple of a quarter-wavelength series resonance will take place and the resistance will be low ; at even multiples, parallel resonance will occur and the resistance presented will be high. The reactance will change sign at each quarter-wave when the impedance is purely resistive. The reactance at these quarter-wave points may be regarded as either an infinite parallel value or a zero series value. If the length of conductor is fixed and the frequency is changed, the impedance will obviously vary in a similar manner, according to the fraction of a wavelength the conductor happens to be at the different applied frequencies.

The resistive component of the impedance presented to the generator includes radiation and loss resistance, and it is obviously desirable that the latter should be kept as low as possible. In addition to the provision of a low-resistance conductor, the earth connection of the r.f. generator is part of the radiator circuit and its impedance should be kept as low as possible.

The impedance/frequency characteristic of a radiator whose length is approximately a quarter-wavelength is similar to that of a series tuned circuit about the resonant frequency (see Fig. 16) but the resistive component of the aerial impedance (which is mainly radiation resistance) generally varies to a greater extent. It will be seen that the impedance varies considerably even with a slight change of frequency.

For television and f.m. transmission it is highly desirable that the impedance presented by the radiator (or aerial) should be constant over a wide frequency band, and particularly so if the aerial is to be used for different carrier frequencies in the same wave band.

To reduce the variation of impedance with change of frequency near the point of resonance, the aerial may be made less selective by increasing the diameter of the conductor or by paralleling several conductors in the form of a cage ; this has the effect of reducing the L/C ratio of the resonant circuit. A further increase of bandwidth may be obtained by folding the aerial in the form of a ' folded dipole.'

The Folded Dipole

In Fig. 17(a) a simple unipole quarter-wave radiator is shown, whose input resistance will be approximately 35 ohms. Fig. 17(b) shows a quarter-wave section of concentric-tube line with the outer conductor earthed at the base. This section obviously will not radiate because the electric and magnetic fields are confined inside the outer conductor, i.e., there is no external field ; the input impedance will be very high indeed, because the far end of the quarter-wave section is short circuited. The quarter-wave section shown in Fig. 17(c) will radiate, for the outer conductor is driven and there will be internal and external fields. The open-wire quarter-wave section shown in

Fig. 17(d) will radiate and is termed a *folded unipole*. The twin-wire unipole of Fig. 17(e) presents a resistance of approximately 35 ohms at resonance but with its reduced L/C ratio will cover effectively a wider frequency band than the unipole of Fig. 17(a).

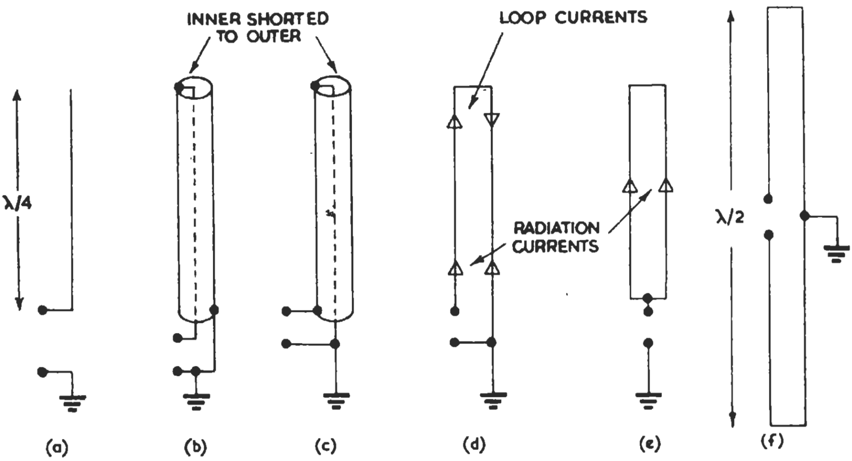

Fig. 17. (a) Simple Unipole Quarter-wave Radiator, (b) Quarter-wave Section of Concentric-tube Line earthed at the Base, Centre Conductor Driven, (c) Quarter-wave Section of Concentric-tube Line earthed at the Base, Outer Conductor Driven, (d) Folded Unipole Radiator, (e) Twin-wire Unipole Radiator, (f) Folded Dipole Radiator

The radiator in which we are particularly interested is the folded unipole shown in Fig. 17(d). Both conductors of the folded unipole will radiate, each possessing capacitance to ground and an external electric field. The driven conductor will raise and lower the potential of the extremity remote from earth of the other conductor, current will flow in the same direction in both conductors and an expanded magnetic field will surround both.

As far as radiation is concerned, for a given power, the conductors will carry currents approximately equal to each other and to the currents in each conductor of the twin-wire unipole of Fig. 17(e) provided the dimensions are identical. In addition to the currents which give rise to radiation, however, currents will flow in the closed loop because the section will also act as a short-circuited line presenting a high parallel impedance at resonance.

As far as the input current is concerned, at resonance, the short-circuited quarter-wave line current is negligible and the input current is proportional to radiation conductance. For a given power the input current at resonance will be half the total input current I of the twin-wire (or single-wire) unipole,

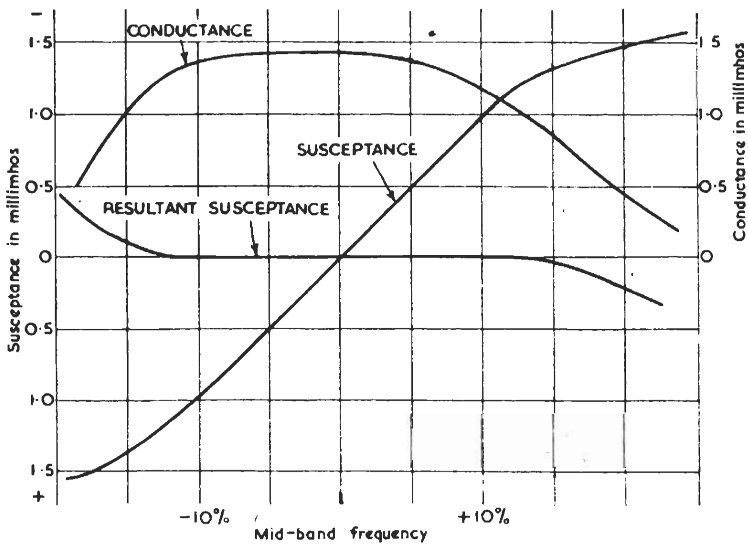

Fig. 18. Approximate Conductance and Susceptance Curves for a Folded Dipole

therefore

$$\left(\frac{I}{2}\right)^2 R = I^2 . 35$$

$$\frac{I^2R}{4} = I^2 . 35$$

$$R = 140 \text{ ohms}$$

where R is the input resistance of the folded unipole. The input resistance at resonance of a folded unipole is therefore four times that of a single or twin-wire unipole.

The impedance of the folded unipole as a radiator would be inductive with increase of frequency (and, of course, capacitive with decrease of frequency) but as a short-circuited line (note the loop currents in Fig. 17d) the parallel reactance change with frequency is of opposite sign. Thus, as far as the impedance presented is concerned, reactance compensation takes place and a wide impedance/frequency characteristic is obtained.

Due to the difficulty of illustrating the slope of reactance with frequency at infinite reactance, it is preferable to convert to susceptances. Fig. 18 shows conductance and susceptance curves and also the effect of the correcting parallel susceptance.

The folded dipole will have similar impedance/frequency characteristics to the folded unipole, but being equivalent to two unipoles in series will present twice the impedance, i.e., approximately 280 ohms at resonance.

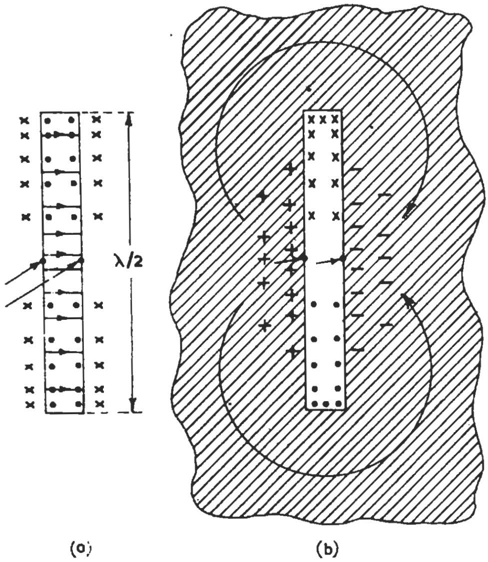

Fig. 19. (a) Half-wavelength Section of Two-wire Transmission Line, Short-circuited at Both Ends, (b) Half-wavelength Slot, showing Current Circulation, Magnetic Field and Electric Charges

See Fig. 17(f). The load presented by the folded dipole is balanced with respect to earth and the centre point of the dipole may be earthed or not as desired.

Slot Radiators

In Fig. 19(a) a half-wavelength section of two-wire line is shown, short circuited at both ends. This is equivalent to two quarter-wavelength short-circuited lines in parallel and the impedance presented at the centre tap is very high indeed. Provided the circuit is balanced with respect to earth, it will not radiate for the electric and magnetic fields will be concentrated between and around the conductors as shown.

Let us now consider the effect of extending indefinitely the width of the conductors, in one plane only, until the half-wavelength line becomes a half-wavelength slot in a very large conducting sheet, the width of the slot being small in comparison with its length. The current will flow around the ends of the slot. See Fig. 19(b). The magnetic field can no longer surround the current path, however, for this would necessitate the magnetic lines of force entering the surface of the conducting sheet, giving rise to opposing currents and cancelling the magnetic field in that direction. Lines of magnetic force, therefore, due to current flowing around the upper end of the slot will link up with the lines of force due to the current flowing around the lower end, and this results in an expanded magnetic field. See Fig. 20.

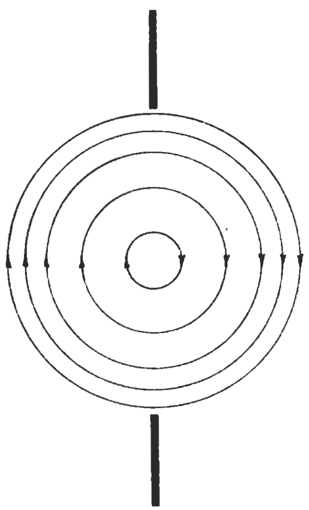

Fig. 20. Magnetic Field of Half-wavelength Slot, Viewed through Section of Sheet

The electric field, instead of being concentrated in the vicinity of the feed points will spread across the sheet of metal horizontally. Radiation will now take place. The polarisation as defined by the direction of the electric field will be at right angles to the length of the slot, and the resistance presented at the feed point will fall from some very high value to one of the order of 500 ohms. When the slot length is approximately half a wavelength the impedance presented is a pure resistance and the slot may be considered as resonant. Above resonance the impedance presented will be capacitive and below resonance it will be inductive, as would be expected from comparison with the half-wavelength line.

The horizontal polar diagram of a vertical slot in an infinite sheet of metal is a complete circle; a sheet of finite width reduces the field along the surface as shown in Fig. 21. The vertical polar diagram is somewhat sharper than that of a vertical wire dipole.

There is a relation between a slot radiator and the dipole formed by the strip of metal cut out of the slot. The relation between their impedances is as follows:—

$$Z_{slot}\, Z_{strip} = \frac{377^2}{4}$$

The impedance of the strip dipole, Z_{strip}, will be approximately 70 ohms and will not vary appreciably with change of cross section. Therefore, the impedance of the equivalent slot, Z_{slot}

$$= \frac{377^2}{4 \times 70} = 500 \text{ ohms}$$

Thus, within limits, Z_{slot} does not vary appreciably with slot width.

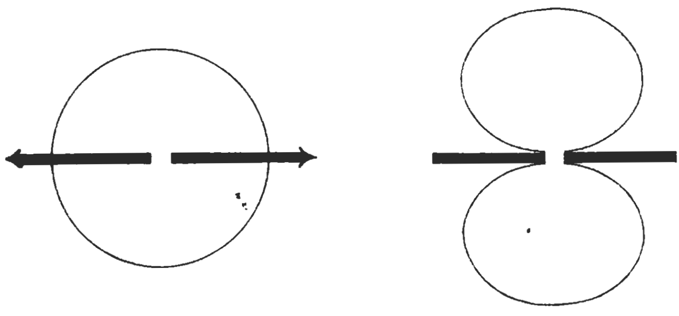

Fig. 21. (a) Horizontal Polar Diagram of a Vertical Slot in an Infinite Sheet of Metal, (b) Horizontal Polar Diagram of a Vertical Slot in a Finite Sheet of Metal

The impedance/frequency bandwidth of the slot is comparable with that of the equivalent strip dipole and, therefore, the bandwidth increases with slot width. If only the edge of the slot is thickened, the electric field is concentrated to some extent, with consequent reduction of radiation conductance, i.e., the radiation resistance and the impedance presented are increased.

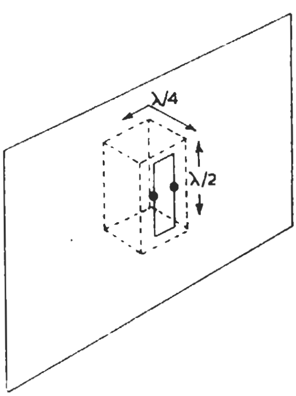

Fig. 22. Boxed Slot

Radiation may be confined to one side only of the metal sheet by enclosing the slot on one side with a metal box or cage, as shown in Fig. 22 (not drawn to scale). The radiation conductance will be decreased considerably and if the marked dimension of the box is a quarter-wavelength the resistance presented is of the order of 800 ohms. For box dimensions less than a quarter-wavelength, an increase of slot length is necessary to maintain resonance. This is because the box acts as an inductance loading the slot.

An extension of the principles of the boxed slot is found with a slot cut in the wall of a cylinder as shown in Fig. 23. If the diameter of the cylinder is a quarter-wavelength the horizontal polar diagram is more or less heart-shaped, but if the diameter is reduced to something approaching a tenth of a wavelength, horizontal radiation is substantially omni-directional.

Reduction of the diameter of the cylinder, however, must be accompanied by an increase in the length of the slot to maintain resonance and this is a limiting factor. For example, looking into a slot in a cylinder of small diameter, the slot, as a line, is loaded by the inductance of the cylinder (being less than a quarter-wavelength in diameter) behind it, the length of the slot, therefore, must be greater than a half-wavelength for resonance. See Fig. 24.

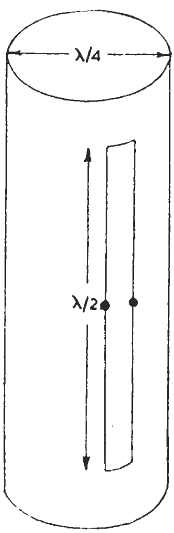

Fig. 23. Slot cut in the Wall of a Cylinder of Diameter equal to a Quarter wavelength

In order to sharpen the vertical polar diagram, stacks of slots may be used in the same way as stacked dipoles in an array, the distance between the centres of the slots being usually of the order of one wavelength.

If the cylinder diameter necessary to produce an omnidirectional horizontal polar diagram is inconveniently small (as it might well be with a stack of slots) an almost circular horizontal field pattern may be obtained by the use of a cylinder of larger diameter and an increased number of slots at each level, equally spaced.

Increase of diameter is limited by waveguide-resonance effects in the cylinder, which prevent the slot being driven in the required manner, resulting in a deterioration of the polar diagram in the appearance of minor lobes of radiation. In general, it will be necessary to 'box in' each slot to prevent the waveguide resonance effect mentioned above. The 'boxing in' may be skeletonised and may take the form of horizontal conducting bars behind each vertical slot. The slot length correction necessary for resonance is less with a skeletonised box than with a continuous metal box for a given distance (less than a quarter-wave) between slot and box ; this is to be expected considering the reduction of inductive loading. Fig. 25 shows a unit of four slots in a cylinder. If several of these units are stacked vertically, a high degree of vertical directivity may be achieved.

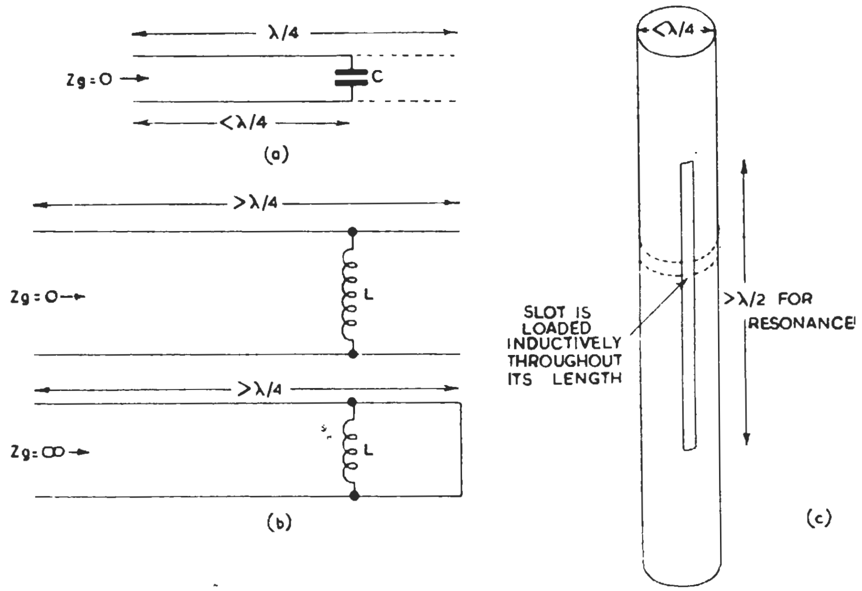

Fig. 24. (a) Lumped Capacitance is Equivalent to extra Line Length, (b) Lumped Inductance requires extra Line Length for Resonance, (c) Slot cut in the Wall of a Cylinder of Diameter less than a Quarter-wavelength

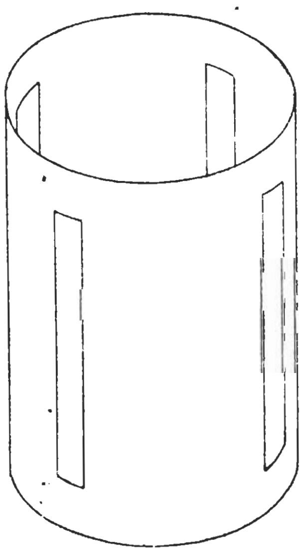

Fig. 25. Unit of Four Slots in a Cylinder

Folded Slot Radiators

In order to increase the impedance/frequency bandwidth, a slot may be folded, to provide reactance correction, in a manner similar to that of the folded dipole. See Fig. 26(a).

The folded slot is fed between one side of the slot and the central conducting strip. Consider the folded slot as a symmetrical arrangement with three terminals, 1 and 3, each side of the slot, and 2 on the central conductor. It is to be expected that the impedance between terminals 1 and 2 will be the same as between 2 and 3. The equivalent circuit is shown in Fig. 26(b) and consists of three impedances, x, y and z connected in the manner shown.

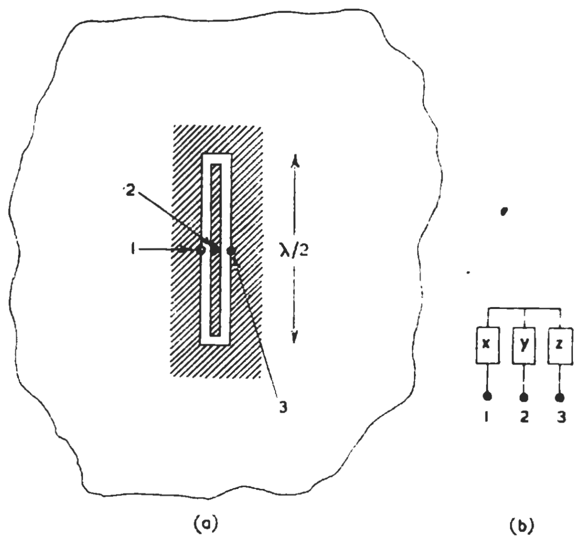

Fig. 26. (a) Folded Slot, (b) Equivalent Impedances

By reason of symmetry $x = z$.

Let $Z_a = x + z = 2x =$ the impedance between terminals 1 and 3.

Let $Z_b = y + \frac{x}{2} =$ the impedance between terminals 2 and terminals 1 and 3 shorted together.

and $Z = x + y =$ the impedance between terminals 1 and 2 or 2 and 3.

From the above, $x = \frac{Z_a}{2}$

$$y = Z_b - \frac{x}{2} = Z_b - \frac{Z_a}{4}$$

therefore $$Z = \frac{Z_a}{2} + Z_b - \frac{Z_a}{4} = \frac{Z_a}{4} + Z_b$$

From this it follows that the impedance between one side of the slot and the central conductor is equal to the sum of a quarter of the impedance across the whole slot and the impedance between the central conductor and the two sides when these are shorted tcgether. This latter impedance is a pure reactance and is due to the slot and the central conductor acting as an open-circuited feeder ; at resonance this series reactance will be zero. The

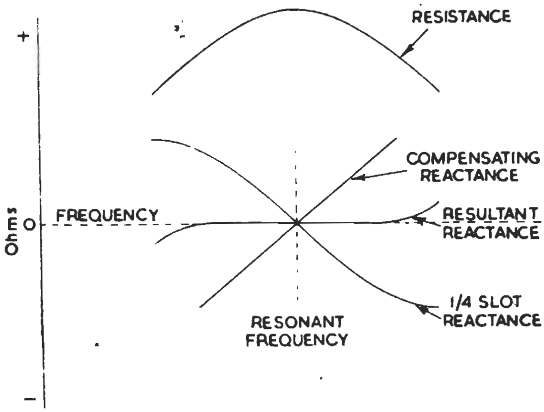

Fig. 27. Folded Slot, Reactance and Resistance, Plotted against Frequency

two halves of the central conductor are, therefore, in parallel and at resonance the removal of one half will have no effect ; off resonance the slope of the series reactance change will be increased and we shall see later that this is a desirable feature.

At resonance the impedance $Z = \frac{Z_a}{4} = 125$ ohms approximately.

The reactance change off resonance presented by a normally-fed slot will be similar to that of a parallel-tuned circuit, i.e., a negative slope with increase of frequency ; but due to feeding the slot by means of the central conductor (the series reactance Z_b having a positive slope), the reactance component of the impedance presented can be made zero over a considerable frequency band, resulting in a wideband aerial. See. Fig. 27. The slot and compensating reactances must be zero at the same frequency but this will not necessarily be the frequency at which maximum resistance occurs.

It is found in practice that the reactance slope of the feeder, formed by the central conductor and the slot, is insufficiently high to provide complete correction and the reduction of the cross-sectional area of the central conductor, in order to obtain a high characteristic impedance, and consequently a high reactance slope, leads to an impracticably thin conductor.

A method of obtaining the required high-reactance slope is to terminate the central conductor by a further quarter-wave short-circuited section of line of low characteristic impedance, as shown in Fig. 28. The reactance slope of a compound section of line is discussed in the Appendix.

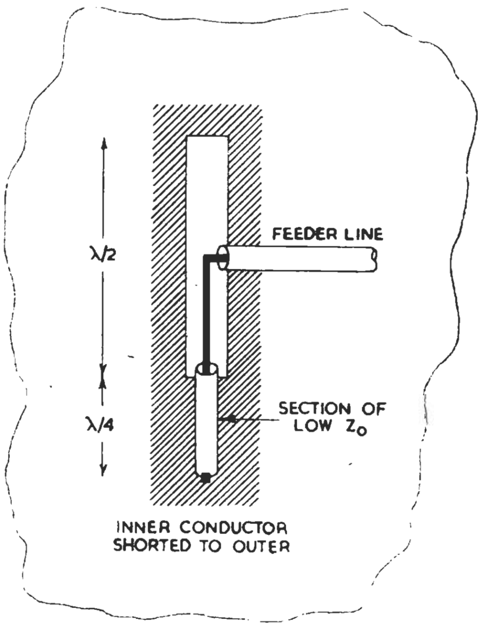

Fig. 28. Folded Slot, with Quarter-wave Short-circuited Stub

The folded slot may be driven by means of a concentric line of appropriate characteristic impedance, the inner conductor of the line being connected to the central conductor of the slot. The outer conductor must be connected to one edge of the slot at its centre and must run along the surface of the metal until a neutral point is reached. Alternatively, a single conductor may be connected to the central conductor of the slot and an unbalanced feeder may be formed by the single conductor and the metal sheet in which the slot is cut.

The removal of one half of the central conductor has the advantage of doubling the reactance-slope and obviates the necessity for symmetry between the two halves of the central conductor ; also only one terminating short-circuited line is required. There is a greater tendency for a small amount of power to be radiated by the central conductor when one half only is used but this effect is not considered to be very important.

The slot aerial is particularly useful when horizontal polarisation is required, for it may be built into the structure of a mast with no protruding elements. The actual slots may be filled in with a low-loss non-conductor to reduce windage effects and difficulties due to icing.

APPENDIX

The reactance slope of a compound short-circuited line comprising two quarter-wave sections of different Z_o in series.

The two lengths of line shown in Fig. 29 are equal ; let us call the length of each θ.

At the resonant frequency (i.e., when $\theta = 90°$) $X = 0$, for the line of characteristic impedance Z_o is terminated by an infinite impedance due to

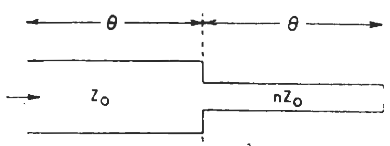

Fig. 29. Compound Short-circuited Line comprising two Quarter-wave Sections of different Z_o in Series

Increase freq still matched
or decr.

the line of characteristic impedance $n\,Z_o$, where n is less than unity. At any frequency

$$X = Z_o\left(\frac{jnZ_o \tan\theta + jZ_o \tan\theta}{Z_o - nZ_o \tan^2\theta}\right)$$

this is obtained from equation (1), page 9, by substituting $jnZ_o \tan\theta$ for Z_r. Simplifying,

$$X = \frac{jZ_o \tan\theta\,(n+1)}{1 - n\tan^2\theta}$$

$$= \frac{jZ_o\,(n+1)}{\cot\theta - n\tan\theta}$$

Differentiating to find the reactance change with change of electrical length,

$$\frac{dX}{d\theta} = \frac{jZ_o\,(n+1)\,(+\operatorname{cosec}^2\theta + n\sec^2\theta)}{(\cot\theta - n\tan\theta)^2}$$

Multiply the right-hand expression by

$$\frac{\cos^2\theta\ \sin^2\theta}{\cos^2\theta\ \sin^2\theta} \text{ to simplify}$$

and we have

$$\frac{dX}{d\theta} = \frac{jZ_o\,(n+1)\ (\cos^2\theta + n\sin^2\theta)}{(\cos^2\theta - n\sin^2\theta)^2}.$$

For small variations of θ from 90° (i.e. from quarter-wave resonance) $\cos^2\theta$ is very small in comparison with $\sin^2\theta$ and may be neglected, therefore

$$\frac{dX}{d\theta} \simeq \frac{jZ_o\,(n+1)}{n\sin^2\theta} \simeq \frac{jZ_o}{\sin^2\theta}\left(1+\frac{1}{n}\right)$$

from which it may be seen that if n is made small $\frac{dX}{d\theta}$ will be large.

Compare this result with the reactance slope of an open-circuited line unterminated. When $X = -jZ_o \cot\theta$

$$\frac{dX}{d\theta} = \frac{-jZ_o}{-\sin^2\theta} = \frac{jZ_o}{\sin^2\theta}$$

From this it follows that the reactance slope of the compound line will be increased by a factor $\left(1+\frac{1}{n}\right)$

$$\text{where } n = \frac{\text{characteristic impedance of s/c section}}{\text{characteristic impedance of o/c section}}$$

REFERENCES

Booker, H. G., " Slot Aerials and Their Relationship to Complementary Wire Aerials." *Journal of the Institution of Electrical Engineers*, Part IIIA, No. 4, p. 620.

Jordan, E. C. and Miller, W. E., " Slotted Cylinder Antenna." *Electronics*, February, 1947. pp. 90-93.

BBC Research Report No. E.034. Serial No. 1948/19.

Electrical Press Ltd., London and Maidenhead