Surface-wave transmission lines for microwave frequencies

I. The various types of transmission line
II. Applications of the dielectric line

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In microwave techniques, the millimetre and submillimetre wavebands are coming to acquire a practical importance comparable to that at present occupied by the centimetre waveband. Components and measuring techniques for these extremely high frequencies are often a result of the marriage of known principles from transmission lines and optics.

A special problem is the low-loss transmission of millimetre and submillimetre waves. There are various surface-wave transmission lines that can be used for this purpose. Since the transmission of the electromagnetic energy chiefly takes place in the space surrounding the line, not only the attenuation of these lines but also the radial extent of the field has to be taken into account.

The dielectric line, on the basis of theoretical and practical results so far obtained, seems to be the most appropriate surface-wave line for transmitting electromagnetic energy in the 1 mm wavelength range.

I. The various types of transmission line

H. Severin

In comparing various forms of transmission line for electromagnetic waves with their practical applicability in mind, two classes of problem must be taken into account. The first relates to the transmission properties of the straight infinitely long line. Maxwell's equations have to be solved for the special boundary-values, giving the field configuration, the phase velocity and the attenuation of the wave as a function of guide dimensions and frequency.

The second class of problem is of a more practical nature. It concerns, for example, the possibilities of exciting a certain mode, of matching various lines, of constructing components and measuring devices, such as attenuators, directional couplers, slotted lines, etc.; and also, for surface-wave lines, the method of mounting and the avoidance of radiation losses at bends. The theoretical and the practical problems are certainly of equal importance in deciding which type of transmission line is the most favourable for a particular application. Nevertheless the theoretical problem can be said to be of primary interest, because one cannot attempt to treat the more practical questions until the transmission properties are known. Part I of this paper deals exclusively with the first class of problem, giving a survey of the various types of transmission line for surface waves. Part II follows with a survey of the more practical questions for the dielectric line, which the theoretical work showed to be the most promising.

By way of introduction a short summary is given of the properties of the conventional transmission lines for high frequencies. For decimetre and centimetre waves coaxial cables and waveguides of rectangular cross-section are chiefly employed at present [1]. The attenuation of these transmission lines increases with the square root of the frequency because the skin depth decreases with frequency [2], so that there are already considerable losses at centimetre wavelengths. Since, on the other hand, the attenuation decreases with increasing surface it can — to a certain extent — be reduced by enlarging the cross-section of the transmission line. This is one of the reasons for the preferred application of waveguides for centimetre waves. At a frequency of 10 Gc/s — corresponding to a wavelength of 3 cm — the attenuation of a standard copper coaxial line without dielectric (outer conductor diameter 9.53 mm, inner conductor diameter 2.65 mm) is 226 dB/km, whereas the attenuation of the standard copper rectangular waveguide for the 10 Gc/s frequency-band (inside dimensions 22.9 mm × 10.2 mm) is 96 dB/km. At a wavelength of 5 mm, the waveguide for the 60 Gc/s frequency-band (inside dimensions 3.76 mm × 1.88 mm) has an attenuation of 1300 dB/km.

In view of these attenuation values, the coaxial line and conventional waveguides are not suitable for longer distance transmission, because, with the present state of amplifier technique, the attenuation for sline transmission must be no greater than 3.5 dB/km.

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Even for short connections, e.g. antenna feeders, the attenuation is considerable, especially at high frequencies.

The idea of increasing the conducting surface takes us from the coaxial cable to the "Clogston-type" or "laminated cable" in which the inner and outer conductors consist of many concentric metal layers insulated from each other [3]. If the thickness of the individual layers is small compared with the skin depth at the highest frequency to be transmitted, such a cable has a constant attenuation over a wide frequency range. In addition, the attenuation is much smaller than that of a coaxial line of the same size. The laminated cable will perhaps find application as a broad-band cable in the frequency range from 0.1 to 10 Mc/s, for example in carrier-frequency telephony or for television programme transmission, as soon as the difficulties of economic production are overcome.

For waveguides, increasing the conducting surface to reduce the losses leads to larger waveguide cross-sections. Apart from being expensive, this gives rise to difficulties because of the simultaneous excitation of unwanted higher-order modes, whose number grows with increasing cross-section. The H_{01}-mode in circular waveguide proves to be superior to all other waveguide modes because for equal attenuation it requires the smallest guide cross-section, and is thus accompanied by the smallest possible number of unwanted modes. While for waveguide modes at high frequencies the attenuation due to ohmic losses usually increases with the square root of the frequency, the H_{01}-mode shows a completely different behaviour: for this mode the attenuation approaches zero with increasing frequency. The ohmic losses arise exclusively from circular wall currents due to the axial component of the magnetic field. Since the magnitude of the axial field component decreases with increasing frequency for all waveguide modes, the wall currents for the H_{01}-mode and hence the ohmic losses decrease with frequency.

An immediate consequence of this behaviour is the fact that in principle the attenuation at any frequency can be made as small as desired if the diameter of the waveguide is chosen large enough [4]. For example, at a carrier frequency of 50 Gc/s, corresponding to a wavelength of 6 mm, an attenuation of about 1.25 dB/km (13% reduction in amplitude), which is typical for microwave links, is obtained by using a copper waveguide of 5 cm diameter.

The following example illustrates the superiority of the H_{01}-mode for circular waveguide compared with the dominant H_{11}-mode. For the required attenuation of 1.25 dB/km the diameters required for the two modes at a frequency of 10 Gc/s are 11.2 cm and 43 cm respectively, and the number of possible modes is 40 for the H_{01} mode and more than 300 for the H_{11}-mode.

The low attenuation of the surface wave transmission lines treated below is due to the fact that the electro-magnetic field extends appreciably into the surrounding space. In order to judge the applicability of these lines it is therefore not sufficient to know their attenuation: the extent of the electro-magnetic field around the line must also be known. A line supporting a wave whose field extends considerably into the surrounding space is unsuitable for practical purposes, even if its attenuation is extremely low.

The single-wire transmission line (Sommerfeld line)

The problem of propagating electromagnetic waves along a *single* wire ("single-wire transmission line") was solved by Sommerfeld in 1899. Heinrich Hertz had previously treated this problem without success. We know today that his experimental investigation failed because of the large extent of the electro-magnetic field around the wire. Because of the large field extent the surroundings, such as the laboratory walls, disturbed the field configuration. Theoretically Hertz idealized the problem too much: he took the wire to be infinitely thin and to have an infinite conductivity σ. Sommerfeld's solution shows that in the limiting case $\sigma \rightarrow \infty$ a surface wave along the wire cannot exist.

For single-wire transmission line one can make the same distinction as for waveguides between H- and E-modes, in which either the magnetic field H or the electric field E respectively has a component along the direction of the wire. Sommerfeld's solution refers to the axially symmetrical E-mode, whose field is independent of φ and consists of the components E_r, E_z and H_φ if the wire coincides with the z-axis of a system of cylindrical coordinates r, φ, z (*fig. 1*). For all other E- and H-modes the major part of the field is inside the wire, as Hondros later showed. The attenuation of these

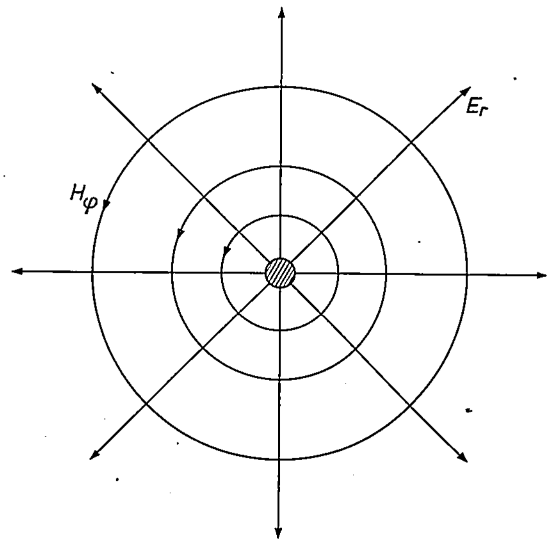


Fig. 1. Configuration of the transverse components E_r and H_φ of the electromagnetic field of the Sommerfeld wave. The third component E_z of this axially symmetrical E-mode is perpendicular to the plane of the figure (r, φ and z are cylindrical coordinates).

[1] W. Opechowski, Electromagnetic waves in waveguides, I and II, Philips tech. Rev. **10**, 13-25 and 46-54, 1948/49.
[2] The "skin depth" or "thickness of the equivalent conducting layer" is proportional to $1/\sqrt{f}$ (f = frequency). For copper the skin depth at f = 1000 Mc/s is 2×10^{-3} mm.
[3] A. M. Clogston, Reduction of skin effect losses by the use of laminated conductors, Bell Syst. tech. J. **30**, 491-529, 1951. E. F. Vaage, Transmission properties of laminated Clogston type conductors, Bell Syst. tech. J. **32**, 695-713, 1953.
[4] S. E. Miller and A. C. Beck, Low-loss waveguide transmission, Proc. IRE **41**, 348-358, 1953.

modes is extremely large and therefore they cannot be observed. Thus in practice the Sommerfeld wave is the only surface wave which can be excited on the single-wire transmission line.

Because of the cylindrical symmetry E_r, E_z and H_φ represent solutions of Bessel's differential equation. Without going into details of the theory, we shall briefly review a few essentials to give a better understanding of the following. The Bessel differential equation is linear and of second order, and thus has two independent linear solutions. The parameter p appearing in the differential equation and determining the order of the corresponding Bessel function can here for physical reasons be only zero or an integer. The two independent linear solutions are called Bessel functions of the first and the second kind, $J_p(u)$ and $N_p(u)$. ($N_p(u)$ is also known as a Neumann function.) For real argument u these functions are rather similar to damped sine or cosine oscillations; for $u = 0$ the Bessel functions of the second kind become infinite.

In order to describe the electromagnetic field of the cylindrical transmission line, non-oscillatory functions are required which fall off sufficiently quickly in a certain distance from the wire. These requirements are satisfied by the Bessel functions of the third kind $H_p^{(1)}(u)$ and $H_p^{(2)}(u)$ ($H_p(u)$ is also known as a Hankel function), which result from a linear combination of $J_p(u)$ and $jN_p(u)$. For imaginary argument u the asymptotic behaviour of these functions

$$H_p^{(1,2)}(u) = \rightarrow \sqrt{\frac{2}{\pi u}}\, e^{\pm j\left(u - p\frac{\pi}{2} - \frac{\pi}{4}\right)} \quad . . \quad (1)$$

shows the resemblance to the decreasing exponential function.

A direct measure of the field concentration around a cylindrical surface-wave transmission line is that radius of the cylindrical cross-section within which a certain fraction of the total energy is transmitted. For the Sommerfeld line the power N_z transmitted across a cross-section of radius R is:

$$N_z(R) = \pi \,\mathrm{Re}\left(\int_a^R E_r H_\varphi^* r \,\mathrm{d}r\right), \quad . . \quad (2)$$

where a is the radius of the wire. The radial distribution of E_r and H_φ (and therefore of course also of the conjugate complex quantity H_φ^*) is described by the first Hankel function. In order to express the argument u by the radial coordinate r we put $u = hr$, the coefficient h resulting from the solution of the wave equation for the boundary-value problem in question. Because of the asymptotic behaviour of $H_1(hr)$ it is clear that finite conductivity of the wire material is essential for the existence of the Sommerfeld wave (see eq. 1): this wave cannot exist for an ideal conductor, as when h is real the integral in eq. (2) does not converge for $R \rightarrow \infty$, which means that an infinitely large energy flow would be necessary for the propagation of the wave. For finite conductivity, on the other hand, h has an imaginary part which, for large values of r, causes an exponential decrease of the electromagnetic field, so that finite total energy is ensured.

Fig. 2 shows how, for a copper wire, field concentration and attenuation of the Sommerfeld wave depend on the frequency f and the radius a of the wire [5]. For a given frequency the losses decrease with increasing wire radius whereas the field extent increases. For a wavelength of 3 cm the attenuation α of a copper wire of 5 mm radius amounts to 12 dB/km, and the half-power radius $r_{3\mathrm{dB}}$ is 7 cm.

The radius $r_{10\mathrm{dB}}$ or $r_{20\mathrm{dB}}$ of the circular cross-section, i.e. the radius within which 90% or 99% of the power is transmitted, is of more practical interest. However the calculation of these radii for the range of a and f values in fig. 2 requires the tedious numerical evaluation of Hankel functions with complex argument, for which no appropriate tables are available. This difficulty can be avoided by introducing another parameter characterizing the field extension. Putting

$$h = h' + jh'' = h' + j\frac{1}{l}, \quad . . . \quad (3)$$

the real quantity l, which has the dimension of length, can serve as a measure of the field extent, For, since

$$e^{jhr} = e^{jh'r}\, e^{-r/l}, \quad . . . . . \quad (4)$$

the field amplitude decreases to $1/e = 0.37$ of its value

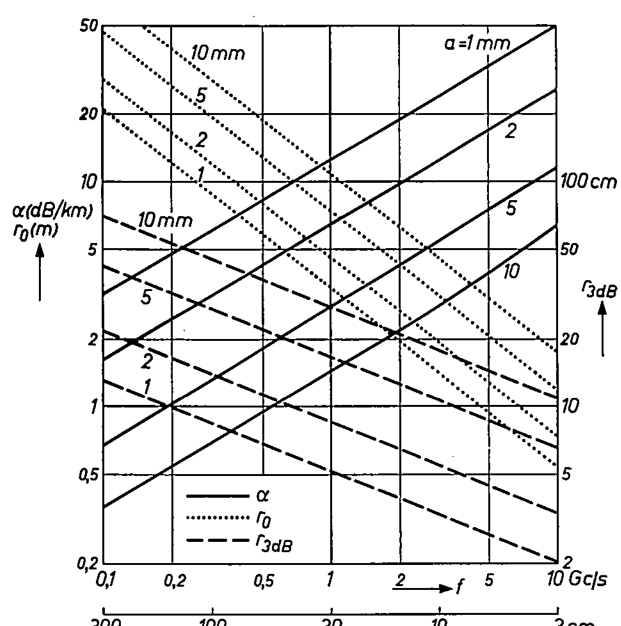


Fig. 2. Characteristic radius r_0, half-power radius r_{3dB} and attenuation α of the Sommerfeld wave for copper wires of various radii a (1 mm, 2 mm, 5 mm and 10 mm) as a function of the frequency f.

if radial distance increases by l, as long as r is such that eq. (1) is valid. Over the range of values of wire radius and frequency used in fig. 2, $|ha| < 0.1$, and as calculation shows, more than 90% of the energy is transmitted across the circular cross-section of radius $r_0 = l$. r_0 is called the "characteristic radius". The comparison of the curves in fig. 2 shows that for the chosen wire radii the characteristic radius, which gives a more realistic indication of the field concentration, is 20 to 150 times larger than the half-power radius $r_{3\text{dB}}$.

The characteristic radius has significance only if it is greater than the wire radius a. If one is interested in the properties of the Sommerfeld line for the millimetre waveband [6] and values of a greater than the wavelength are permitted, the range of values of ha cannot be restricted, as now we may have $h''a = a/l > 1$. Here one can introduce another distance characterizing the field extent, this distance being measured not from the axis but from the surface of the wire. The calculation shows that at least 87% of the energy is transmitted across the circular cross-section of radius $a + l = a + x_0$. The distance x_0 measured from the surface of the line is called the "characteristic distance". As long as $a \ll r_0$, x_0 is nearly equal to r_0. In the limiting case $a/\lambda \rightarrow \infty$, i.e. for the plane surface-wave transmission line, x_0 is that distance from the surface of the transmission line for which the field strength has fallen to 1/e of the value at the surface [7]. The curves of characteristic distance x_0 and attenuation α as functions of the frequency f and the wire radius a are, for large values of a/x_0, completely analogous to the curves of fig. 2 for small values of a/x_0. Again, for a given frequency, the losses can be reduced by using larger wire radii. This, however, increases the extent of the electromagnetic field. If a maximum attenuation of 3.5 dB/km is allowed, the Sommerfeld line is not very practical for use at wavelengths below 5 cm because the wire diameter becomes too large (see *fig. 3*). The upper frequency limit is determined by the field extent. At a wavelength of 15 cm the characteristic distance has reached a value of 5 m.

This type of transmission line does not seem particularly attractive as a stronger field concentration around the wire can only be achieved by reducing the conductivity. This is an unsatisfactory solution as the ohmic losses then increase. The basic difficulty with the Sommerfeld line is due to the fact that a finite conductivity is necessary for the existence of the surface wave. For conventional transmission lines, on the contrary, ohmic losses in the conductor are completely undesirable and superfluous. Attempts have therefore been made to modify the single-wire line in such a way that the conductivity is no longer a determining factor for the existence of surface waves.

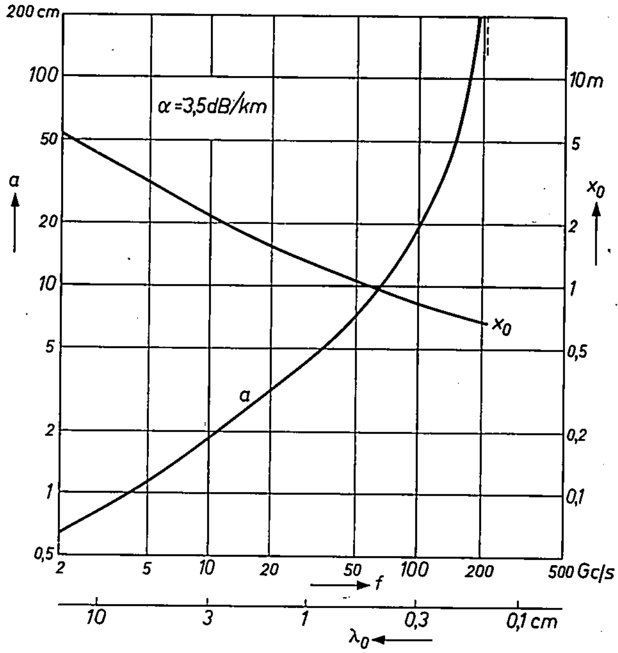


Fig. 3. Radius a of a Sommerfeld line, of copper, with attenuation of 3.5 dB/km and characteristic distance x_0, as a function of frequency f. For $a \rightarrow \infty$, x_0 approaches the value for the *plane* surface-wave transmission line with an attenuation of 3.5 dB/km. The corresponding frequency f is 202.2 Gc/s.

The dielectric-coated wire (Harms-Goubau line)

The radial distribution and the asymptotic behaviour of the field of the single-wire line (eq. (1) with $u = hr$) indicate how an exponential decrease of the field can be achieved for large values of r : h must have an imaginary component. If the propagation in the positive z-direction is described in the usual way by $\exp(\mathrm{j}\omega t - \gamma z)$ (γ = propagation constant), it follows from the wave equation that

$$h = \sqrt{k^2 + \gamma^2}, \quad \ldots\ldots \quad (5)$$

where $k = \omega/c = 2\pi/\lambda_0$, $\omega = 2\pi f$ is the angular frequency of the signal, c is the velocity of light in free space, and λ_0 is the free-space wavelength. For the Sommerfeld line, because of the attenuation α, the propagation constant γ is complex: $\gamma = \alpha + \mathrm{j}\beta$. It would, however, be more desirable if γ were imaginary ($\alpha = 0$), so that

$$-\mathrm{j}\gamma = \beta = \frac{\omega}{v} = \frac{2\pi}{\lambda}, \quad \ldots\ldots \quad (6)$$

and if at the same time $\beta^2 > k^2$, i.e. the phase velocity

[5] G. Goubau, Surface waves and their application to transmission lines, J. appl. Phys. **21**, 1119-1128, 1950.
O. Zinke, Kabel- und Funkweg im Mikrowellenbereich, Nachrichtentechn. Z. **10**, 425-430, 1957.
H. Kaden, Fortschritte in der Theorie der Drahtwellen, Archiv elektr. Übertr. **5**, 399-414, 1951.

[6] H. Severin, Sommerfeld- und Harms-Goubau-Wellenleiter im Bereich der Zentimeter- und Millimeterwellen, Archiv elektr. Übertr. **14**, 155-162, 1960.

[7] H. Kaden, Dielektrische und metallische Wellenleiter, Archiv elektr. Übertr. **6**, 319-332, 1952.

$v < c$ (λ = wavelength on the line, $\lambda < \lambda_0$). h would then become imaginary and a surface wave can exist without the attenuation being a necessary condition.

One possibility of reducing the phase velocity and therefore the field extent of the wave is given by coating the wire with a thin dielectric layer. The theory of such a transmission line was developed by Harms in 1907 following Sommerfeld's paper. The possibility of an application in the microwave range was first discussed in 1950, by Goubau [5], who showed in particular how surface waves can be excited with good efficiency on single wires.

The mathematical treatment of this problem shows that the axially symmetrical E-mode is again the only mode with low attenuation as long as the greater part of the electro-magnetic field extends into the surrounding space. The thin dielectric coating brings about the desired concentration of the field around the transmission line by means of the retardation of the wave front in the dielectric, even if the conductivity of the wire is infinite. For the Harms-Goubau line ohmic losses are undesirable and not necessary for the existence of the surface wave .This physical fact permits an essential simplification of the calculation, that could not be made with the Sommerfeld line: the field extent can be given for the idealized assumption that there are no losses. The attenuation of the Harms-Goubau wave is then calculated separately, assuming as is usual for low-loss lines that the field distribution is to a first-order approximation the same as in the loss-free case.

For the problem thus idealized the field extent of the Harms-Goubau wave can be given as a function of the line data and frequency. Since Hankel functions with imaginary argument are tabulated, the radius of the cross-section transmitting a stated percentage of the energy may be calculated. Exactly as with the Sommerfeld line, for large $|h|a'$ (a' = radius of the Harms-Goubau line) at least 87% of the energy, and for small $|h|a'$ about 95% of the energy is transmitted within a distance x_0 from the surface of the line as fig. 4 shows. Even with the above simplifying assumptions it is again not possible to express $|h| = 1/x_0$ explicitly as a function of the transmission line data. A transcendental equation is obtained, and graphical evaluation shows that the field concentration round the line increases as the wire radius decreases, and increases as the dielectric constant of the coating, its thickness, and the frequency increase. *Figs. 5* and *6* show for example that at 10 Gc/s (λ = 3 cm) with a wire radius a of 1 mm, the field extent can be reduced by a factor of about 10 by applying a 0.05 mm dielectric coating, but that the attenuation due to ohmic losses is increased only by a factor of 1.6. The additional dielectric losses are only a small fraction of the ohmic losses (*fig. 7*). In practice by suitably choosing the transmission line data, any desired field concentration can be obtained. However, at the same time the attenuation increases so that a compromise between field extension and attenuation always has to be made. The result is that the Harms-Goubau line can be applied for metre and decimetre waves down to a smallest wavelength of about 8 cm. For longer wavelengths it is also possible to use a magnetic coating instead of a dielectric one (Kaden [5]).

In a first application the Harms-Goubau line has been used for feeding transmitting aerials [8].

Metallic conductors with periodic structure

For the existence of a surface wave, longitudinal field components are necessary. In the Sommerfeld line they are provided for by the finite conductivity of the wire; in the Harms-Goubau-type line by the retardation of the wave front in the dielectric layer.

Another way of obtaining longitudinal field components is to use a helical wire. Such helical lines have already become familiar through their application in travelling wave tubes. In this application its function is to reduce the phase velocity of the wave so that interaction can take place between the axial component of the electromagnetic field and the electron beam. For this application helices of small pitch (helix angle 5° — 8°) are used. For transmission lines however large pitch (helix angle 70° — 80°) should be chosen to keep ohmic losses low.

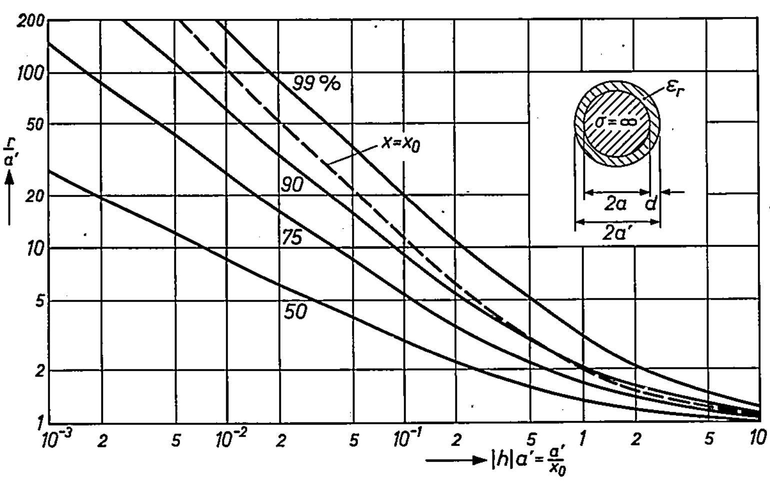


Fig. 4. Radii of the cross-sections across which 50%, 75%, 90% and 99% of the energy of the Harms-Goubau wave are transmitted, as a function of the frequency and the line data.

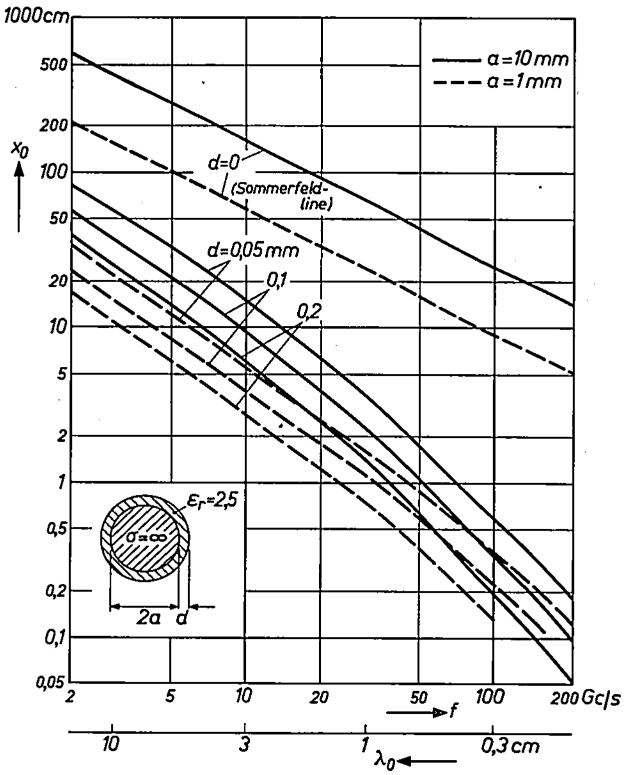


Fig. 5. Characteristic distances x_0 of the Harms-Goubau and the Sommerfeld lines as a function of the frequency and the line data.

Pitch D, helix angle ψ and radius ϱ of the helix are connected by the relation:

$$\cot\psi = \frac{2\pi\varrho}{D}. \quad \ldots\ldots\ldots \quad (7)$$

In a first approximation [9] useful in many cases, the helix is replaced in the calculation by an extremely thin cylindrical tube whose wall has very high conductivity in the direction determined by the pitch angle ψ and is non-conducting in the perpendicular direction $(\psi + \pi/2)$. The resulting electromagnetic field has all six components and can be interpreted as superposition of an H- and an E-mode with equal propagation constants. As with the Sommerfeld and the Harms-Goubau lines, the relationship between the propagation constant and the radius, the pitch angle of the helix, and the frequency is by no means simple. For a large pitch, which is of interest here, the helical line has the same transmission properties as the Harms-Goubau line if between the data for the two lines the relation

$$\left(1-\frac{1}{\varepsilon}\right)\frac{d}{a} = \frac{1}{2}\cot^2\psi. \quad \ldots \quad (8)$$

[8] F. R. Huber, Speisung von Sendeantennen mit Hilfe von Goubau-Leitungen, Nachrichtentechn. Fachber. 23, 114-125, 1961.

[9] H. Kaden, Eine allgemeine Theorie des Wendelleiters, Archiv elektr. Übertr. 5, 534-538, 1951.

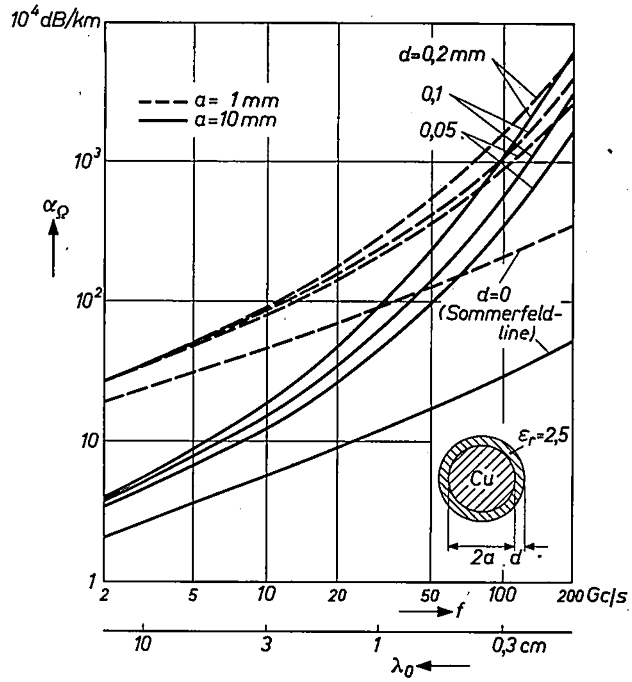


Fig. 6. Attenuation α_Ω due to ohmic losses for the Harms-Goubau and the Sommerfeld lines as a function of the frequency and the line data.

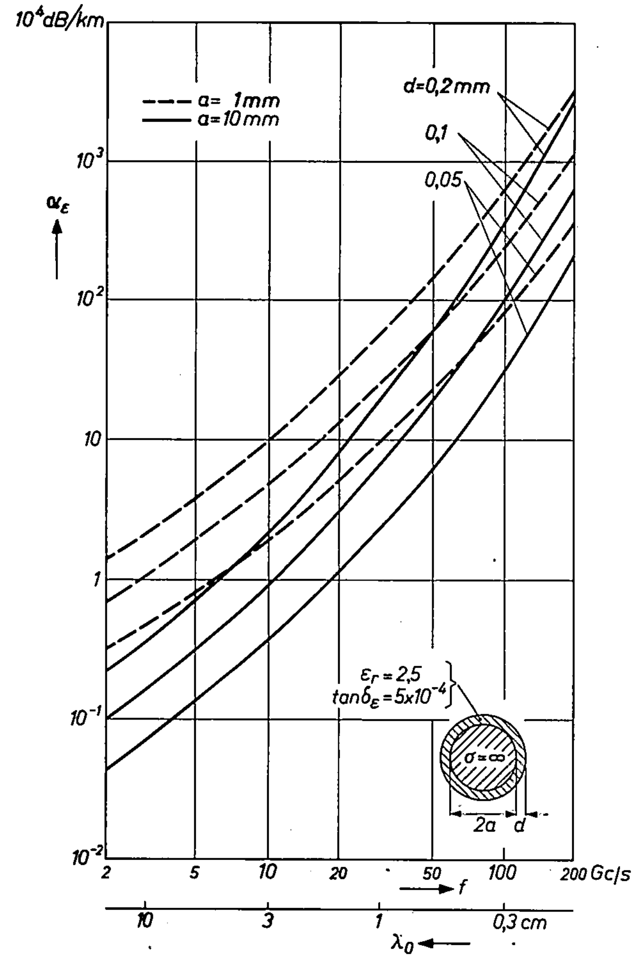


Fig. 7. Attenuation α_ε due to dielectric losses for the Harms-Goubau line as a function of the frequency and the line data.

holds. This means that the curves of figs. 4, 5 and 6 evaluated for the Harms-Goubau line apply also to the helical line.

Longitudinal field components and a reduction of phase velocity can also be obtained by a suitable "roughening" of the surface of the perfectly conducting wire. Goubau indicates in his paper [5] that instead of a dielectric coating, any periodic microstructure in the longitudinal direction, such as a screw thread, will also give rise to a greater field concentration. On deepening the grooves of the screw thread the structure eventually becomes that of a disc-loaded line. The periodic structure of the surface which to some extent may be interpreted as a kind of artificial dielectric shows, however, an essential difference when compared with the plain Harms-Goubau line: besides the dominant mode, the axially symmetrical E-mode already described, the periodic structure always has higher-order modes as well, the so-called "space harmonics" of the dominant mode [10]. Their relative amplitudes depend on depth, width and distance of the grooves. In order to keep the amplitudes of the space harmonics within the theoretical limits, a high degree of uniformity of the periodic structure is necessary. Moreover, surface-wave lines with periodic structure exhibit band-pass filter characteristics, i.e. they do not transmit over the whole frequency range but only in certain frequency-bands.

The dielectric line

In connection with Sommerfeld's paper dealing with waves on a metal wire Hondros and Debye, in 1910, investigated the propagation of electiromagnetic waves along circular cylinders of homogeneous dielectric. The experimental proof of the existence of such waves was given by Zahn in 1915. These basic studies, as well as more recent work [11], have shown that for the dielectric line as in the hollow metallic waveguide an infinite number of modes is possible.

All the modes, with the exception of the dominant mode, have a cut-off frequency, below which they cannot exist. Apart from the dominant mode, wave propagation is possible only if the diameter of the dielectric line is approximately equal to or larger than half the wavelength in the dielectric. The situation in which either the electric or the magnetic field has no components other than transverse ones only arises for waves of axially symmetric field. For such waves the field configurations over the cross-section will be similar to those of the corresponding modes in the metallic circular waveguide. For the H_{0n}-modes the electric field lines are concentric circles; however, the surface of the dielectric cylinder does not have to be a nodal surface of the electric field. For the E_{0n}-modes the transverse component of the electric field is radial.

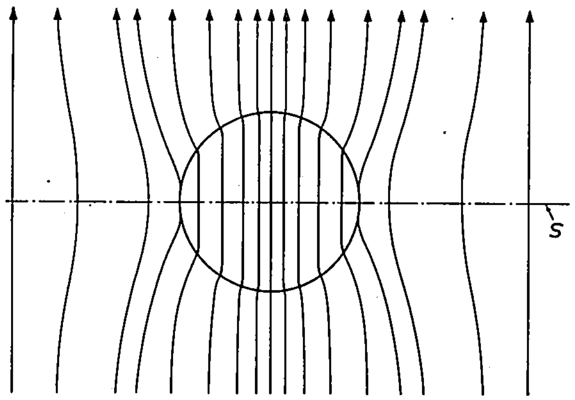


Fig. 8. Transverse component of the electric field E for the HE_{11}-mode (dominant mode) on a dielectric line.

For the non-axially symmetric waves the boundary conditions can no longer be satisfied by an H- or an E-mode alone. Modes with the first index $m \neq 1$, are, depending on their axial field components, called HE_{mn} modes if the field configuration is similar to that of an H-mode, and EH_{mn}-modes if it resembles an E-mode.

The HE_{11}-mode is the only mode with no cut-off frequency. This is the dominant mode of the dielectric line. *Fig. 8* shows the configuration of the transverse component of the electric field. Due to the fact that there

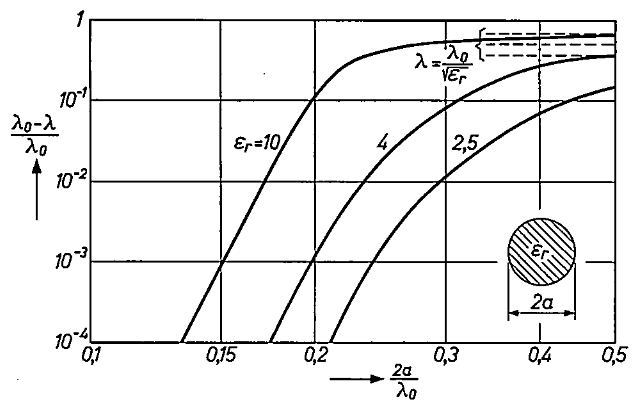


Fig. 9. Deviation of the wavelength λ for the HE_{11}-mode on a dielectric line from the wavelength in vacuo λ_0, given as a function of the ratio of the line diameter $2a$ to the wavelength in vacuo λ_0.

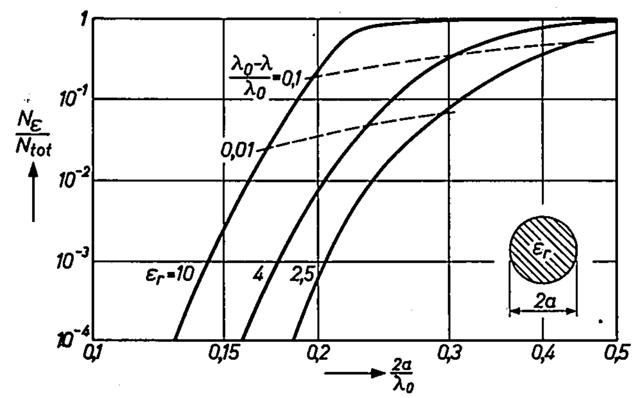
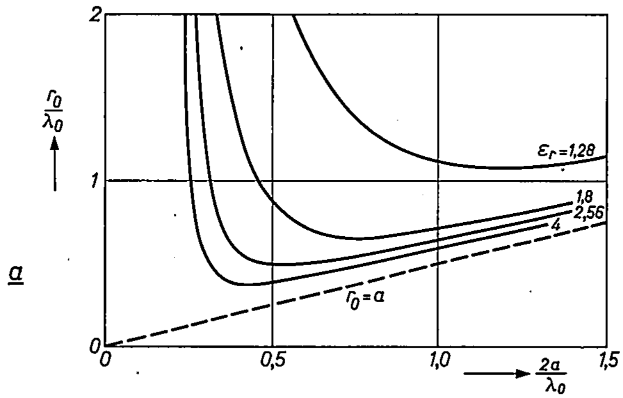


Fig. 10. Ratio of the energy N_ε transmitted in the dielectric to the total energy N_{tot} of the HE_{11}-mode on a dielectric line as a function of the ratio of the line diameter $2a$ to the wavelength in vacuo λ_0.

is no cut-off frequency, the line can be dimensioned in such a way that only a small percentage of energy is transmitted in the dielectric. This means that the attenuation can be kept very low, but the radial field extent is again large. An appreciable reduction of phase velocity and a corresponding concentration of the field is obtained only above a certain ratio of the diameter of the dielectric "string" to wavelength (*figs. 9* and *10*). For high values of the dielectric constant ε_r there is only a narrow band of frequencies in which the velocity remains substantially the same as that of light in vacuo. Only then is the field moderately concentrated. Therefore, the field of the HE_{11}-mode is either almost completely inside or almost completely outside the dielectric string. For transmission line application the strong frequency dependence of phase velocity, field extent and attenuation is undesirable. A small value of the dielectric constant should therefore be chosen in order to remain within the range of low dispersion. For ε_r values of 2.5 and 10, line wavelength and wavelength in vacuo differ from each other by 1% when $2a/\lambda_0 = 0.3$ and 0.17 respectively. When the deviation of the phase velocity from that of the velocity of light in vacuo is so small, only a small percentage of the energy is transmitted in the dielectric. According to fig. 10 the percentages are 7% and 2.5% for $\varepsilon_r = 2.5$ and 10 respectively.

The weaker frequency dependence of field extent and attenuation for small values of ε_r is also confirmed by *fig. 11*, which shows these quantities as a function of the ratio of dielectric string diameter to wavelength in vacuo for several values of ε_r. For each dielectric constant there is a minimum field extent, which cannot be reduced by further increase of the string diameter. For low-loss transmission however, it is the range of small $2a/\lambda_0$ which is of interest, for which the greater part of the field lies outside the string. In this case, contrary to that with the Sommerfeld and the Harms-Goubau lines, the attenuation decreases as the ratio of the string diameter to the wavelength in vacuo is decreased. The fact that the transmission depends so strongly on diameter and frequency necessitates close tolerances for



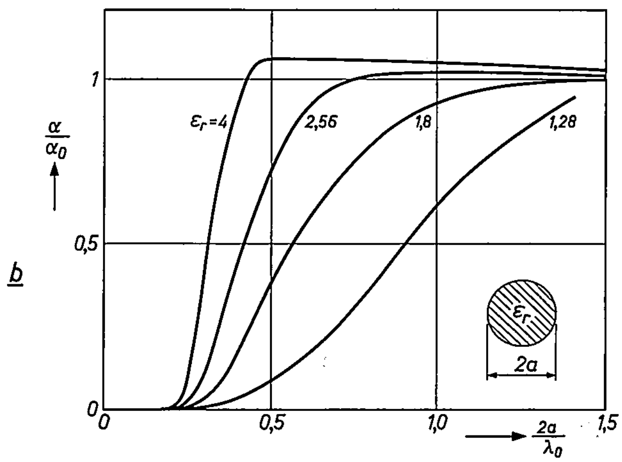


Fig. 11. *a*) Characteristic radius r_0 and *b*) attenuation α of the HE_{11}-mode of a dielectric line for various values of the dielectric constant ε_r, as a function of the ratio of the line diameter $2a$ to the wavelength in vacuo. $\alpha_0 = (\pi/\lambda_0)\sqrt{\varepsilon_r}\tan\delta_\varepsilon$ is the attenuation of a plane wave in the infinite dielectric.

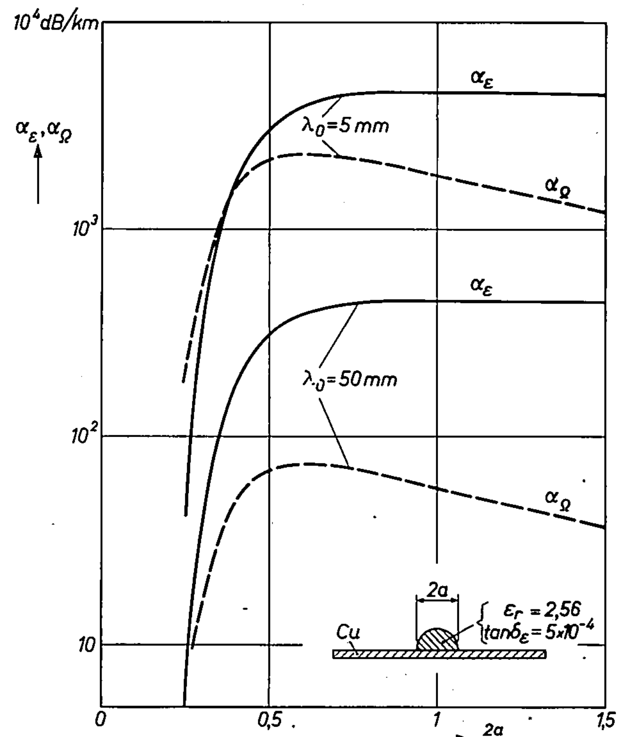


Fig. 12. Attenuation α_ε due to dielectric losses and attenuation α_Ω due to ohmic losses for the dielectric image line, for two wavelengths, as a function of the diameter.

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the dimensions and homogeneity of the dielectric line, and permits the transmission of only narrow frequency bands.

The problem of supporting surface-wave guides leads to another type of dielectric line, the so-called dielectric image line [12]. Since the electric field of the HE_{11}-mode at a plane of symmetry S is everywhere perpendicular to this plane (fig. 8), a perfectly conducting sheet in this plane would not disturb the field distribution. In practicy of course the finite conductivity of the reflector will add ohmic losses to the dielectric losses. *Fig. 12* shows that the attenuation due to the metal sheet is smaller than that due to the dielectric down to wavelengths of a few millimetres. However, this no longer holds if for small values of $2a/\lambda_0$ only a small percentage of the energy is transmitted inside the dielectric so that the dielectric losses are very small.

Experience has shown that the dielectric image line is applicable down to a wavelength of about 3 mm. For even shorter wavelengths the dielectric line is to be preferred.

Summary. Surface-wave transmission lines may be advantageous for the transmission of high-frequency signals. The most important types of line are the single metal wire (the Sommerfeld line), the metal wire with dielectric coating (the Harms-Goubau line) and the dielectric line. Their applicability depends on the attenuation and the radial extent of the electromagnetic field. The properties of the various types of lines treated in this paper lead to the conclusion that for wavelengths down to about 8 cm the Harms-Goubau line is the most suitable. For longer wavelengths a magnetic instead of dielectric coating can also be used. Between 15 and 5 cm wavelength the Sommerfeld line, whose attenuation decreases with increasing field extent is also applicable. For still shorter wavelengths the dielectric line and the dielectric image line are more suitable, the latter down to about 3 mm wavelength. Below this wavelength the dielectric line is up to now the only suitable surface-wave transmission line.

II. Applications of the dielectric line

G. Schulten

Further considerations for the dielectric line

Part I of this article explained the circumstances in which electromagnetic surface waves of cylindrical form can exist. It was shown that a cylindrical filament is always necessary for this purpose, but that it need not be of metal. The longitudinal component E_z of the electric field, without which a cylindrical surface wave is not possible, can be obtained just as well with a filament or "string" made from a dielectric material. It was also shown in part I that in this case it is possible to have a mode of the electromagnetic field which has no cut-off frequency, and which can therefore appear at arbitrarily low frequencies. The possible applications of the dielectric line are to be found, however, where it is difficult to employ coaxial conductors and waveguides, i.e. in the millimetre-wave range. The reason for this is that, on a line propagating surface waves, low attenuation is only possible if the field extent in the radial direction is fairly large — a distance of at least several wavelengths. Dielectric lines are therefore ruled out for lower frequency applications.

The thickness of the dielectric "string" can be suitably chosen so that only the dominant mode, known as the HE_{11} mode, may be set up, and not the other modes, i.e. the modes with cut-off frequencies. Let d be the diameter of the dielectric string, λ_0 the free space wavelength and ε_r the relative dielectric constant of the material, then the HE_{11} mode alone is possible if:

$$\frac{d}{\lambda_0}\sqrt{\varepsilon_r - 1} \leqq 0.7655 \,. \quad . \quad . \quad (1)$$

At a wavelength of 4 mm the diameter of the polyethylene dielectric ($\varepsilon_r = 2.4$) must be smaller than 2.59 mm in order to satisfy this condition. In general, however, the string will have to be very much thinner than this, say about 1 mm, to achieve lower attenuation. The best dielectric materials at present available (polyethylene, polytetrafluorethylene, polystyrene) have a loss angle of the order of $\tan\delta = 10^{-4}$. This means that a wave propagating completely inside the material would, at a wavelength of 4 mm, be attenuated at the rate of about 1 dB per metre. This still fairly considerable attenuation can be appreciable diminished if the electromagnetic energy is transmitted largely outside the material. This is accomplished by using a small diameter for the string.

If the power transmitted inside the dielectric is N_ε and the total power is N, the attenuation is given by:

$$\alpha = \frac{\pi}{\lambda_0}\sqrt{\varepsilon_r}\tan\delta\,\frac{N_\varepsilon}{N}\ \text{(nepers/metre)}\,, \quad . \quad (2)$$

where λ_0 is again the free space wavelength.

Fig. 1 shows in graphical form the dependence of N_ε/N on the ratio of the string diameter to the wavelength in air (d/λ_0), assuming $\varepsilon_r = 2.5$. It is clearly

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