DIELECTRIC WAVEGUIDES FOR UNDERWATER TRANSMISSION OF HIGH MICROWAVE POWER

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Abstract

For certain applications it is advantageous to transmit high power levels by microwaves underwater via a dielectric layered tube structure with outer metal braiding which is, for example, simultaneously used for the passage of breathing gas for divers. Details of launching waves into this structure, the transmission properties, and suitable absorbers for such applications as heating are described. The system under study operates with a power level of 3-4kW at 8GHz when the dielectric line can be conveniently slim.

Introduction

The exploration of energy and mineral resources in relatively shallow sea waters requires new technological approaches. It is, for example, essential to supply divers reliably with breathing gas and heat. The latter becomes essential when He/O_2 mixtures are employed which cause a heat loss of up to 2kW to the diver by breathing alone. This heat can be provided by high-voltage low-frequency supplies because of the danger of electrocution of divers in conducting sea waters. Therefore a low-voltage high-current dc supply is used at present which however results in heavy umbilical connections due to the need for a thick copper wire as conductor, and divers are severely handicapped in their activities with such a heavy life line trailing behind them. Similarly various types of tools and other subsea facilities have to be supplied with power.

The other possibility of power transfer is based on microwave propagation along a dielectric layered tube structure with outer metal braiding which can simultaneously be used for the transport of gas. In principle, a normal diver's hose pipe consists of an outer protective metal braid and a dielectric tube of a relatively low dielectric constant. In order to remove any negative effects of the braiding on microwave propagation, such as increased losses, small mechanical accidental surface damage due to rough handling etc., this tube is coated along the inside with a dielectric film of a high dielectric constant at microwave frequencies.

The breathing gas is then heated a few feet away from the diver (at a sufficient distance so that any stray microwave field is well reduced below any danger level) by a porous matched load which is heated by the microwaves and which permits the passage of the breathing gas while this is heated to the required temperature.

The Transmission Line

With an operating frequency of 8GHz in view of a minimised diameter of the line for the power and the gas flow required, the diameters of the tube are chosen to support only the HE_{11} surface mode along the inner dielectric lining. It is well known that dielectric hollow tubular waveguides have smaller losses than the equivalent metallic tube, provided that the loss constant of this dielectric material is low. [1] In fact, from this point of view, there is no advantage in solid dielectric guides, and the useful feature of gas transport by a tubular guide causes no principle disadvantage regarding transmission losses. However, the braiding, commonly employed as a protective measure of these underwater pipes, introduces some losses, although they are important to enable the operators to use reasonably sharp bends, where otherwise purely dielectric lines would not contain the electromagnetic wave which would be strongly emitted at such a bend. To reduce such losses the dielectric tube is provided along the inside surface with a highly dielectric coating which concentrates the electromagnetic power into the inner space of the guide. This produces an important further advantage in that any perturbation of the outer parts of the pipe due to rough handling, as commonly occurring under marine conditions, does not substantially affect the propagation characteristics as otherwise local changes in characteristic impedance would produce reflections and resonances leading to an intolerable modification of the microwave power received by the load. Similarly, a highly dielectric inner coating on an insulating tube of low dielectric constant has the advantage that the metal braiding does not have to satisfy the close tolerances that circular metal waveguides impose.

It was suggested previously that metal shields are unsatisfactory for dielectric waveguides because they can easily result in mode cross couplings.[2] For limited bandwidth applications it is, however, felt that this is not a serious disadvantage as long as the correct mode of operation can be selected for the operating frequency range of interest.

Shielded dielectric rod waveguides have already been investigated in the past.[3] No information is, however, given in the literature on the properties of hollow dielectric waveguides, where part of the inner core of the dielectric rod is replaced by some other dielectric material, usually air. Since both metal waveguide and dielectric waveguide modes are likely to exist in a shielded dielectric tube, it has been decided to develop a theoretical model for such structures. This can be used for the correct design of such guides and their evaluation by providing information on their cut-off frequencies and mode spectra.

The metal braiding of dielectric waveguides acts as a conventional continuous metal shield if the pitch of the winding is practically equal to zero. For large pitch values, there is no direct electrical contact between successive windings and therefore every analysis is bound to be complicated since it requires the use of a special model for the braiding. In the following it will be assumed that the braidings of the dielectric waveguide tubes under consideration are very dense. The inner surface of the shield can therefore be treated as perfectly conducting, resulting in a longitudinal component of the electric field equal to zero (on the metal boundary), a condition which is not otherwise met in braided dielectric waveguides.

The model used in the analysis is given in Figure 1. Three different dielectric regions are considered, the one of the actual dielectric tube being defined as region 2. We assume an absolute dielectric constant and permeability ε_i and μ_i $(i = 1,2,3)$ for each of the above regions. The inner and outer radius of the dielectric tube are defined as a and b respectively, while the inner radius of the metal shield is equal to c. The following definitions are also used: $f = \frac{a}{b}$, $g = \frac{b}{c}$.

Let us analyse the dielectric waveguide system in cylindrical co-ordinates by denoting the electric and magnetic field components by E_{zi}, $E_{\theta i}$, E_{ri}, and H_{zi}, $H_{\theta i}$, H_{ri} respectively (i = 1,2,3 refers to the appropriate dielectric region). By assuming a field dependence of the form $e^{i(\omega t-\beta z)}$ one finds the E_z, H_z components in a circular cylindrical waveguide are solutions of the following equations:

$$\frac{\partial^2 E_z}{\partial r^2} + \frac{1}{r}\frac{\partial E_z}{\partial r} + \frac{1}{r^2}\frac{\partial^2 E_z}{\partial \theta^2} = -k^2 E_z \qquad (1)$$

$$\frac{\partial^2 H_z}{\partial r^2} + \frac{1}{r}\frac{\partial H_z}{\partial r} + \frac{1}{r^2}\frac{\partial^2 H_z}{\partial \theta^2} = -k^2 H_z \qquad (2)$$

where $k^2 = \omega^2\mu\varepsilon - \beta^2$ (3)

Equations (1) and (2) are typical Bessel differential equations. Their solutions can therefore be expressed as linear combinations of Bessel functions $J_n(kr)$ and $N_n(kr)$ of the first and second kind respectively. Expressions have in this way been obtained for the electromagnetic field components of each of the three dielectric regions. It is then possible to derive a characteristic equation, which gives the cut-off frequencies.

For the numerical evaluation of the dispersion characteristics numerical methods involving Bessel functions were used. In the following we will be concerned with the first order solutions, that is with modes such as TE_{01}, TM_{01}, HE_{11}. We assume that the dielectric materials have no magnetic properties:

$$\mu_1 = \mu_2 = \mu_3 = \mu_o \qquad (4)$$

One can now find that the dielectric tube diameter b normalised to the free space wavelength λ is given by

$$\left(\frac{b}{\lambda}\right)^2 = \frac{V^2 - Y^2}{(2n)^2(\varepsilon_{r2} - \varepsilon_{r3})} \qquad (5)$$

where V and $Y = \frac{\varepsilon_{r3}}{\varepsilon_{r2}} V$ are quantities which are given by the arguments of the relevant Bessel functions at the interfaces of the dielectric media at r = b for regions 2 and 3 respectively. Additionally, the guide wavelength λ_g reads as follows:

$$\left(\frac{\lambda_g}{\lambda}\right)^2 = \frac{V^2 - Y^2}{\varepsilon_{r3} V^2 - \varepsilon_{r2} Y^2} \qquad (6)$$

One can therefore evaluate the corresponding $\frac{b}{\lambda}$ and $\frac{\lambda_g}{\lambda}$ values and consequently determine the dispersion characteristics of the mode. The cut-off criteria are determined by the condition that λ/λ_g becomes equal to zero, since the guide wavelength tends in such a case to infinity.

The validity of the developed theory was tested by direct comparison with results already available in the literature on shielded dielectric rods.[3] The latter type of waveguide can be analysed with the help of the theory developed here, by assuming that the inner radius of the dielectric tube becomes equal to zero. It was indeed confirmed that our equations gave the same results as those previously published on such a simplified system.

The numerical results of cut-off frequency ($= v_o/\lambda_{oc}$, with v_o the velocity of light in free space) as a function of appropriate dimensional ratios for our waveguiding system are shown in Figures 2 and 3 for the case of a practical delectric waveguide structure, composed of a metal-impregnated inner PTFE tube which is in its turn separated from the outer metal shielding through unloaded PTFE. The dielectric constants used in our computer simulations were obtained by experimental investigations of such types of composite dielectric specimens. A cross section of the considered model is given in the insert of Figure 2. As can be seen the cut-off frequencies of TM_{01} modes are smaller than for TE_{01} modes. The cut-off frequency of the TM_{01} mode is consequently determining the upper frequency limit to which the hybrid HE_{11} mode can safely be used.

For large shielding tubes (small g = b/c ratios) and constant outer dielectric tube diameters b, the HE_{11} mode operation becomes more broadband by increasing the wall thickness. The opposite occurs at large g - ratios, where the cut-off frequencies of TM_0 modes are found to increase with the parameter f. In the latter case the HE_{11} propagation is possible over a larger frequency range by reducing the wall thickness. This is in agreement with published results on unshielded dielectric waveguides which show a more broadband HE_{11} mode operation with dielectric tubes rather than rods. The different behaviour for small g ratios is most likely attributed to the presence of the unloaded PTFE layer which is in the latter case thicker and can consequently influence in a more drastic manner the waveguide properties.

If the dielectric tube parameters are fixed, then the operation at the HE_{11} mode is more broadband for larger separation distances between the metal shield and the dielectric tube outer surface (see constant f curves of Figures 2 and 3). This is in accordance with already published results[3] for dielectric rods having a dielectric constant higher than that of the material occupying the space between the dielectric waveguide and the metal shield.

In practice, the shielding diameter c is usually quite small due to size considerations of the waveguide structures. This results in small g ratios and is consequently suggesting that the only way to improve the broadband properties of the HE_{11} mode is by making the tube walls as thick as possible.

For TE_{01} modes the cut-off frequency changes with wall thickness in a manner which is not affected by the value of the parameter g. Thus the cut-off frequency is always larger the thinner the tube walls are.

Finally it is pointed out that the effect of the wall thickness on the waveguide cut-off frequency is more pronounced for TM_{01} rather than TE_{01} modes.

The Launcher

An important aspect of the microwave system for underwater power transfer is the availability of an efficient launcher of the relevant wave mode. As one wants to couple the power from a normal metal waveguide primarily into the highly dielectric inner coating of the insulating tube, it can be considered as a problem of exciting power principally into the inner-surface wave.

The same considerations apply of course to delaunchers which couple out power from the dielectric line. We are first discussing some miniature structures which however show a relatively small launching efficiency and are therefore possibly more suited for partial delaunching applications.

Possibilities such as an array of monopoles embedded in the dielectric material were attempted. Such a type of launcher is in principal the same as the one reported previously.[4,5] The results reported here concern the examination of the properties of a monopole launcher at higher frequencies and for lines of small diameters d (8GHz and d = 1.4cm). Because the HE_{11} mode is symmetrical about a plane passing through the axis of a dielectric tube it has been preferred to examine the properties of a monopole launcher for the case of a half P.T.F.E. tube cut along its axis and mounted on an aluminium 20cm wide sheet; the latter configuration permits an easy extrapolation of the launcher characteristics to the dielectric tube case while its construction is such that a co-axial microwave feeder can be easily mounted on the ground plane under the line (see Figure 4). In order to improve the characteristics an experimental optimization was carried out[6] by inserting into the dielectric, pins of various heights so that a miniature Yagi-Uda antenna could be formed. Three reflector and two director pins were used in the final launcher configuration. The examined monopole surface wave exciter although not possessing any exceptionally high efficiency has the advantage of small size and would therefore be useful as an extra delauncher for localised power extraction.

Improved efficiencies were found with a slot fed dipole launcher (S.F.D.L.)[8] as shown in Figure 6. Its operation is based on the superposition of the TEM mode (propagating inside the OSM-line) and all the higher order modes resulting from the presence of the short-circuiting post. It appears that the field configuration at the launcher end resembles very much that of an HE_{11} surface wave; this was confirmed by examining the electromagnetic field configuration of the launched surface wave with the aid of a set of magnetic and capacitive couplers. The efficiency figures obtained for the S.F.D.L. were somewhat better than the value achieved with a monopole image line launcher.

Further improvements in coupling efficiencies were obtained with a circular waveguide exciter (C.W.E.). Its design procedure starts with the specification of the size of the dielectric line to be used. A study of the possible modes of propagation in a circular waveguide shows that the TE_{11} mode resembles very much the HE_{11} surface wave mode. This indicates the possibility of an HE_{11} wave excitation by embedding the dielectric tube in a circular waveguide operating at the TE_{11} mode.

A good transition from the co-axial to the circular waveguide was designed as shown in Figure 7. The launching efficiency was easily controlled by the position of the moveable short. The distance between the OSM centre conductor and the back wall of the waveguide should be equal to one quarter of the guide wavelength λ_w. This is essential in order to provide open circuit conditions at the reference plane AA′ (see Figure 7). A launching efficiency of 75% was recorded at 10.95GHz.

High launching efficiencies can be expected from a rectangular-horn launcher. By inspecting the field configuration of the HE_{11} mode it can be seen that it resembles very much the dominant TE_{10} mode of rectangular waveguides. Experiments on a neoprene tube inserted in a rectangular horn have shown that the launching efficiency is greatly dependent on the geometry of the embedded part of the dielectric line. The upper and lower frequency limits for the practical existence of the HE_{11} mode in the tube were calculated to be 15.92 and 5.76GHz respectively. Various tapering angles and lengths have been tested and the optimum configuration is shown in Figure 5. It consists of two tapers, one for the electric and one for the magnetic field components. The launching efficiency was found to be in excess of 90% for the correct frequency.

The system reported here consists of a main horn-launcher placed together with the microwave source outside a submerged compression chamber; the dielectric guide is then passed into the chamber through a waterproof adapter and breathing gas is supplied to the pipe by an array of holes in the guide.

The Wave Absorber

Experiments were performed in order to absorb the microwave power carried by the surface wave by porous lossy material positioned at the end of the dielectric tube to heat for example the diver's breathing gas. The results reported here were obtained with the use of an absorber made by carbon impregnated Silicone rubber (Emerson and Cuming) and having a loss tangent ($\tan\delta$) of 1.3 at 8.6GHz. The relative dielectric constant of this material at the same frequency was 14.

An assessment of the absorber length required for 2.5kW of power at the diver's position with a breathing gas at a temperature of 47°C was made. Breathing gas mixtures flowing through the pipe at a rate of 160cm^3/min could be heated from 20°C up to 47°C when the Silicon rubber tube was at a temperature of 150°C. This experiment shows that a length of 29cm of absorbing material is required for 2.5kW power and the breathing gas at a temperature of 47°C.

Conclusions

It has been demonstrated that microwave power transfer concepts can be useful for some of the new technological approaches which have become necessary for an exploitation of sub-sea energy and mineral resources.

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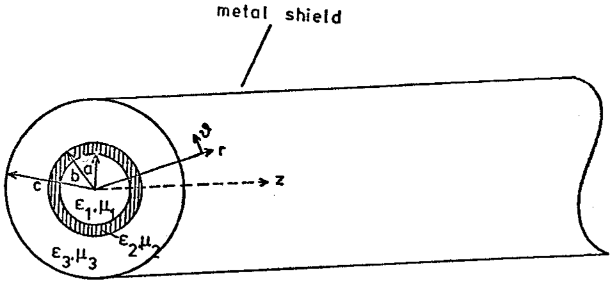

Fig. 1. Schematic drawing of braided dielectric guiding structure

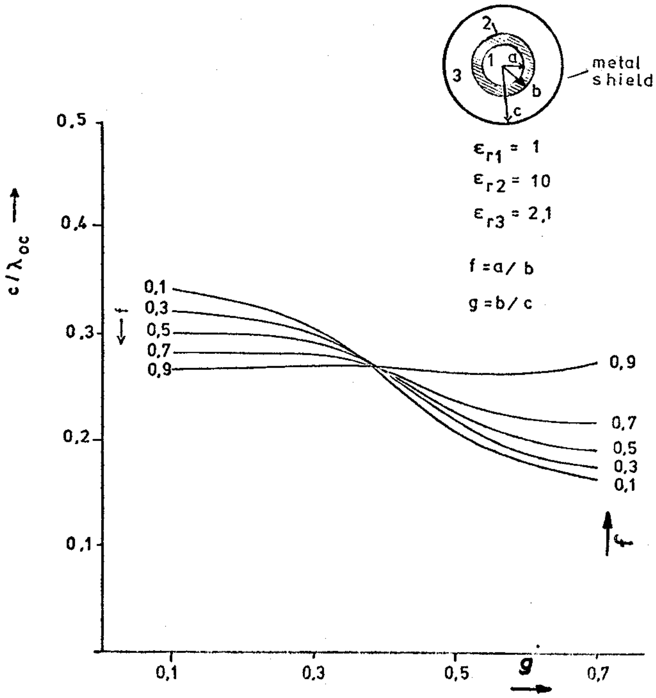

Fig.2 The cut-off frequency given by its wavelength λ_{oc} for the TM_{01} modes

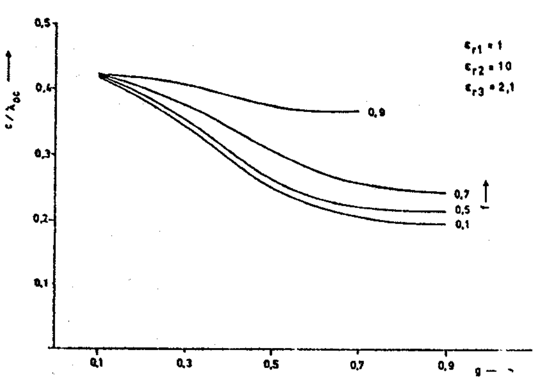

Fig. 3 The cut-off frequency given by its wavelength λ_{oc} for TE_{01} modes

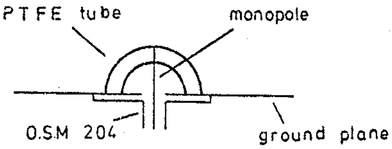

Fig. 4. The monopole launcher

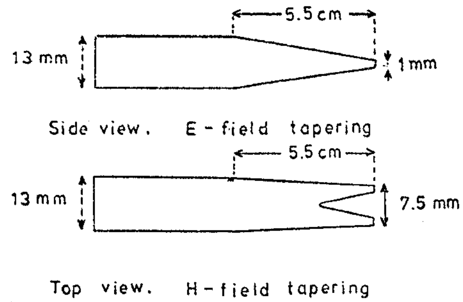

Fig. 5. The optimum taper of the dielectric tube for maximum efficiency of launching from a rectangular horn

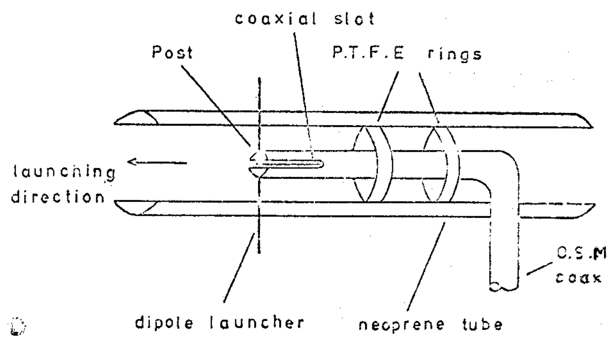

Fig. 6. The slot-fed dipole surface wave launcher

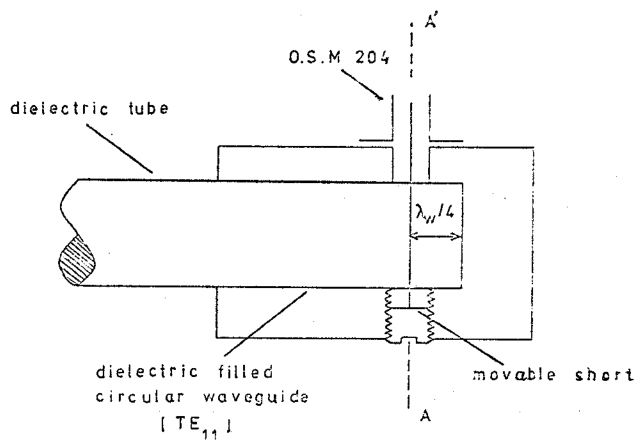

Fig. 7. The circular waveguide surface wave launcher