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ELECTROMAGNETIC MODING IN LOSSY GEOLOGICAL STRATA

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Abstract—Recent research into very large, regularly shaped, geological structures has shown that in the 100 kHz to 10 MHz frequency range electromagnetic waveguide behaviour is observed when the material forming the structure is not too lossy (conductivity $\sigma < 0.0001$). While mode formation and modal behaviour in electromagnetic waveguides is very well understood, much of the literature describes high frequency structures for which it can generally be assumed that the loss tangent of the wave guiding medium ($\tan\delta$) is very much less than unity. In this case, wave attenuation is small and can generally be considered to be insignificant. This is not true for large low frequency waveguides, such as those formed by geological strata, and little seems to have been reported in the literature on the nature of modes in waveguides of this description. The paper takes the form of a parametric study aimed at ascertaining the limitations to modal formation in waveguides, for which $\tan\delta$ is greater than unity, by revisiting the basic equations describing electromagnetic wave propagation in lossy media. The theoretical predictions are supported by modelling studies on large waveguide strata formed from material layers with dimensions typical of a geological structure such as a coal seam or oil-wet, strata-bound, petroleum reservoir.

1. INTRODUCTION

The possibility that geological layers within the earth's crust could form waveguides for electromagnetic waves was first suggested by Wait ([1] on the basis of theoretical studies of propagation in a regularly-shaped medium with uniform electrical characteristics (e.g., a coal seam) sandwiched symmetrically between two geological layers of

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similar permittivity but higher conductivity. Practical demonstrations of wave guiding in a coal-seam were first reported in the 1970's [2, 3]. These papers claim to have demonstrated horizontal propagation distances through a coal-seam of several hundred metres, at frequencies in the range 300 kHz to 3 MHz . Improved theoretical predictions for an asymmetric seam geometry have been reported by Hill [4]. Quasi-TEM (TM_{00}) mode field patterns are presented for a dry coal seam (conductivity $\sigma = 0.0001\,\mathrm{S/m}$, relative permittivity $\varepsilon_r = 6$) trapped between rock layers with differing values of σ of the order of 0.1 S/m, and with $\varepsilon_r = 15$. Calculations were performed for a frequency of 500 kHz. This implies that the loss tangent ($\tan\delta = \frac{\sigma}{\omega\varepsilon}$) for the studied coal-seam was less than unity.

More recently several papers have been published [5] which describe the development of a radio imaging method (RIM) for geological structures. The RIM technique relies on seam waveguide propagation and electromagnetic wave scattering to build images of coal panel anomalies or discontinuities from electromagnetic wave sensors located strategically and regularly along the 'long wall' edges of the panel.

All of the reported investigations cited above appear to have been directed at a guiding stratum which is sufficiently low loss ($\sigma < 0.0001\,\mathrm{S/m}$) so that $\tan\delta$ for the propagating medium is less than unity in the frequency range of interest (typically 300 kHz to 3 MHz). However, in very many practical situations, the geological guiding layers of interest exhibit $\tan\delta$ values, which are significantly larger than unity, in the frequency range indicated above. This paper revisits the nature of wave guiding in geological layers when the loss tangent can no longer be considered to be small ($\ll 1$) by re-examining the basic equations describing electromagnetic wave propagation in lossy media. The theoretical predictions are supported by finite element simulations [6] which have been applied to large waveguide structures with material parameter values and dimensions typical of a geological layer such as a coal seam. New results, based on calculations on a range of coal seam scenarios, of injected power required to establish detectable modal fields, indicate that for a well coupled source, and provided seam losses are not too high, a 'power window' for mode formation exists.

2. PROPAGATION IN A LOSSY GEOLOGICAL STRATUM

Electromagnetic wave propagation in complex media is governed by the Maxwell's equations (Eqs. (1)–(4)). These encompass all of the electrical physics governing electromagnetic fields in any medium defined at the macroscopic level. Consequently in this fundamental form they are applicable to electromagnetic wave propagation in all media no matter how lossy.

$$\nabla \times \underline{\mathrm{E}} = -\mathrm{j}\omega\mu\underline{\mathrm{H}} \tag{1}$$
$$\nabla \times \underline{\mathrm{H}} = \mathrm{j}\omega\varepsilon\underline{\mathrm{E}} + \sigma\underline{\mathrm{E}} \tag{2}$$
$$\nabla \cdot \underline{\mathrm{D}} = 0 \tag{3}$$
$$\nabla \cdot \underline{\mathrm{B}} = 0 \tag{4}$$

The passive form of the equations given above, are usually converted into second order differential equations for E and/or H before solution, e.g.,

$$\nabla^2\underline{\mathrm{E}} + k^2\underline{\mathrm{E}} = 0 \tag{5}$$

and

$$\nabla^2\underline{\mathrm{H}} + k^2\underline{\mathrm{H}} = 0 \tag{6}$$

where

$$\gamma^2 = -\omega^2\mu_0\varepsilon_c \tag{7}$$
$$\varepsilon_c = \varepsilon\left(1 - j\tan\delta\right) \tag{8}$$
$$\tan\delta = \frac{\sigma}{\omega\varepsilon} \tag{9}$$

In these equations ε_c is the complex permittivity of the propagation medium, ε is its real permittivity, μ_0 is its permeability (assumed non-magnetic) and σ is its conductivity. ω is the radian frequency of the propagating wave. Also $\gamma = \alpha + j\beta$ is the complex propagation coefficient for the wave, while α (nep/m) is the attenuation constant and β is the phase constant (rad/m).

Equations (1) and (9) can be applied quite generally to electromagnetic (EM) wave propagation in any medium provided macroscopic values for permittivity (ε) permeability (μ) and conductivity (σ) are available at the operating frequency. However to aid understanding of these complicated relationships certain approximations are commonly introduced in EM textbooks. For example when the displacement term $j\omega\varepsilon E$ is much larger than the conduction term σE in Eq. (2), the dissipation factor ($\tan\delta$) is much less than unity and hence $\varepsilon_c \approx \varepsilon$. This assumption leads to $\gamma \approx j\beta = j\omega\sqrt{\mu_0\varepsilon}$ and the second order differential equation to be solved is now referred to as the wave equation, i.e.,

$$\nabla^2\underline{\mathrm{E}} + \beta^2\underline{\mathrm{E}} = 0 \tag{10}$$

and

$$\nabla^2\underline{\mathrm{H}} + \beta^2\underline{\mathrm{H}} = 0 \tag{11}$$

In an unbounded region the solution to these equations is a plane transverse electromagnetic wave (TEM wave) exhibiting no attenuation.

The second approximation commonly made, particularly at low frequencies, takes advantage of the displacement term in Eq. (2) being much smaller than the conduction term, since ω is very small. The dissipation factor ($\tan\delta$) is now greater than unity and $\gamma \approx \sqrt{-j\omega\mu_0\sigma}$. The second order differential equation to be solved is now the diffusion equation, namely:

$$\nabla^2\underline{\mathrm{E}} - \mu_0\sigma\frac{\partial\underline{\mathrm{E}}}{\partial t} = 0 \tag{12}$$

and

$$\nabla^2\underline{\mathrm{H}} - \mu_0\sigma\frac{\partial\underline{\mathrm{H}}}{\partial t} = 0 \tag{13}$$

This equation exhibits an exponentially decaying solution with no phase shift per unit length.

These approximations can be misleading, because in practice attenuation is not absent at high frequency if σ is finite (it always is), and phase shift occurs at low frequency if ω is finite (again it always is). In fact the precise values for the attenuation coefficient and phase shift constant for a TEM wave propagating in any lossy medium are, using Eqs. (7), (8) and (9), as follows:

$$\alpha = \omega\sqrt{\frac{1}{2}\mu_0\varepsilon_r\varepsilon_0\left\{\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon_r\varepsilon_0}\right)^2}-1\right\}} \quad \text{(nep/m)} \tag{14}$$

$$\beta = \omega\sqrt{\frac{1}{2}\mu_0\varepsilon_r\varepsilon_0\left\{\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon_r\varepsilon_0}\right)^2}+1\right\}} \quad \text{(rad/m)} \tag{15}$$

Using Eqs. (14) and (15), α and β have been plotted as functions of frequency in Figs. 1 and 2. Fig. 1 represents propagation in a typical coal medium using σ and ε values taken from the literature while Fig. 2 uses measured values for a UK coal mine. Measurements indicate that for coal the electrical parameters (σ, ε, μ) are not particularly frequency dependent over the range of frequencies cited in the introduction. At the frequencies of interest, it is assumed that modal wavelengths will be too long for the modes to be influenced by any natural inhomogeneity and anisotropy of a coherent coal layer. Also shown is the low frequency estimate for the attenuation coefficient ($\alpha \approx \sqrt{\frac{\omega\mu_0\sigma}{2}}$ — dotted curve), which is clearly good for frequencies

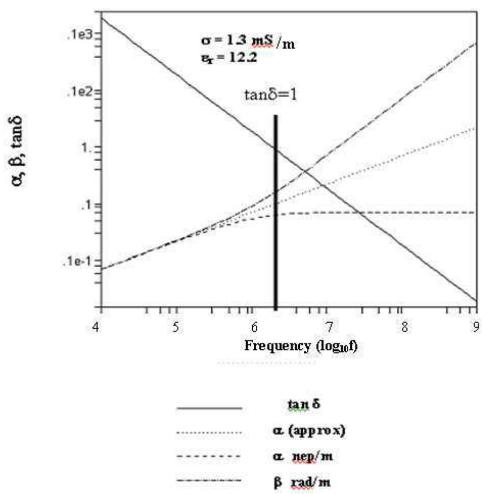


Figure 1. Propagation constants plus loss tangent versus frequency for a typical coal medium having $\sigma = 1.3\,\mathrm{mS/m}$, $\varepsilon_r = 12.2$, $\mu_r = 1$.

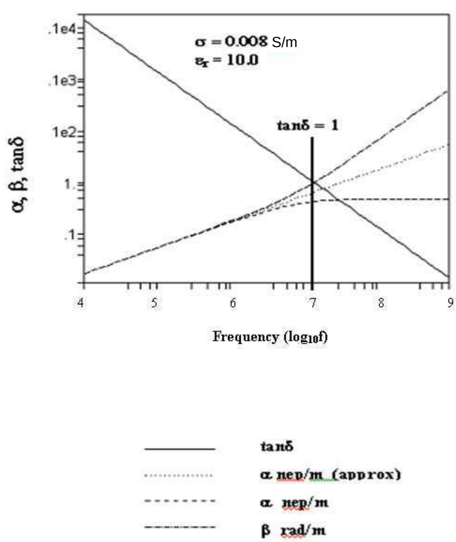


Figure 2. Propagation constants and loss tangent versus frequency for a UK coal medium having $\sigma = 8.0\,\mathrm{mS/m}$, $\varepsilon_r = 10$, $\mu_r = 1$.

below the $\tan\delta = 2$ value. It is important to note that below the frequency at which $\tan\delta = 1$, propagation in coal is by no means phase shiftless ($\beta \neq 0$) (i.e., wave behaviour does not strictly obey the diffusion equation) and above this frequency it is by no means attenuation free ($\alpha \neq 0$) (i.e., wave behaviour does not strictly adhere to the wave equation). There is simply a progressive rise in the α and β values as frequency increases from zero.

The initial observation to be made here is that from the perspective of fundamental EM theory there is no significant difference between operating in the below $\tan\delta = 1$ frequency range and operating above it. If α is not too large, and β is finite, waveguide action and mode formation can, in principle, occur at any frequency provided a 'smooth' waveguide can be realised. The fact that $\tan\delta$ can get very large at low frequencies does not necessarily mean that mode formation in a wave guiding stratum will not occur. Of course at very low frequencies mode formation is difficult since the waveguide has to be extremely large to form a low order mode. Apart from the Earth-ionosphere waveguide few examples of such waveguides exist. It is perhaps pertinent to note that the Earth-ionosphere waveguide can form a re-entrant cavity, and that the resonant frequencies of this very low frequency cavity have been predicted [7]. An interesting summary of the results of recent finite difference time domain (FDTD) studies of the Earth-ionosphere cavity has been compiled by Simpson et al. [8]. The electrical requirements for electromagnetic wave-guiding behaviour to occur in a large, lossy, geological stratum are explored in more detail in Sections 3 and 4.

3. MODE SIMULATION IN HIGH LOSS WAVEGUIDES/CAVITIES

In order to establish the conditions for the formation of a waveguide mode in a large, regularly shaped, lossy geological stratum, a finite element electromagnetic boundary value model of a rectangular panel with the electrical characteristics of coal has been constructed. The dimension chosen for the panel were typically 300 m wide, 6 m high and 2000 m long. It was assumed that, above and below, the panel was sandwiched between thick layers of wet shale (good conductor) and that the peripheries of the panel where the access roadways would occur could be represented by 'smooth' highly conducting boundaries replicating the lattice work of steel and metal roadway supports. For high frequency electromagnetic waveguides 'smoothness' usually implies that surface roughness, in the form of protuberances or undulations, are less that $\lambda/50$ in magnitude. At frequencies in the vicinity of 200 kHz this means undulations in the waveguide wall formed by the steel protective and supportive lattice work bounding the tunnelled roadway, could be as much as 4 m to 5 m, peak to trough, in magnitude, without contravening the above requirement. Geological evidence suggests that a coal seam of 6–8 m in height will retain this dimension to a constancy that easily meets the above criterion, unless a major disruption of the seam has occurred at some point along its length. The $\lambda/50$ criterion also means that with properly formed boundary tunnels any openings or imperfections in the tunnel lining lattice will generally be too small to undermine the assumption that the seam waveguide boundaries are 'smooth'.

The TM_{00} mode investigated by Hill [4] will not be properly formed in a panel enclosed by metallised roadways and therefore we have directed our attention on the TE_{10} mode, which is more likely to provide guided propagation through the panel if wave-guide behaviour is found to be at all possible. Trial operating frequencies of the coal-seam waveguide simulation was determined by forming $\omega - \beta$ diagrams (in their normalized form $ka - \beta a$) for different values of the coal conductivity σ (Fig. 3). The curves were generated using the complex form of the TE_{10} propagation coefficient γ_{10}, namely:

$$\gamma_{10}^2 = \frac{\pi^2}{a^2} - \frac{\varepsilon_c}{\varepsilon_0} k_0^2 \tag{16}$$

This equation is generated by the solution of Eqs. (5) and (6) in a rectangular box with highly conducting boundaries. This is, of course, an idealized version of the coal panel model, but it is very useful for determining 'trial' operating frequencies. The complex propagation coefficient γ_{10} can be expressed as $\gamma_{10} = \alpha_{10} + j\beta_{10}$ where α_{10} is the TE_{10} mode attenuation coefficient in nep/m while β_{10} is the phase shift constant in rad/m. In Eq. (16), the width of the waveguide $a = 300$ m. Fig. 3 depicts attenuation and phase shift behaviour as a function of frequency for the TE_{10} modes in the coal-seam panel for three values of conductivity representing very dry low-loss 'coal' (0.0001 S/m), moist coal (0.001 S/m), and very wet coal (0.01 S/m). In all cases $\varepsilon_r = 10$ and $\mu_r = 1$. Dry coal is generally found in deep seams reflecting the rise in geological temperature with depth: values of conductivity as low as 10^{-8} S/m have been reported in the literature [9]. Near the surface the presence of moisture in cool low depth seams results in conductivity levels of the order of 10^{-2}–10^{-3} S/m. At a conductivity of 0.0001 S/m the curves are typical of low loss waveguide showing an approximate 'cut-off' at $ka \sim \pi$. For a 300 m wide seam this equates to a frequency of 158 kHz. At $\sigma = 0.001$ S/m the 'cut-off' has virtually disappeared, although the phase shift is not too different from the $\sigma = 0.0001$ S/m case when $ka > \pi$. At $\sigma = 0.01$ S/m the curve shapes are much more

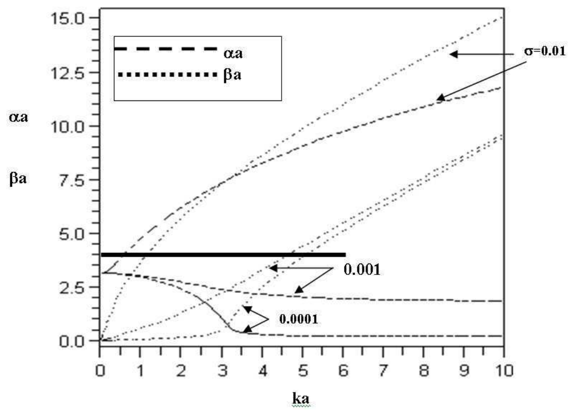


Figure 3. Brillouin diagram for TE_{10} modes in a coal-seam waveguide showing TE_{109} resonance frequencies in shorted waveguide ($\varepsilon_r = 10$, $\mu_r = 1$). Note that in this figure $\alpha \equiv \alpha_{10}$ and $\beta \equiv \beta_{10}$.

reminiscent of highly attenuated plane waves in a very lossy unguided medium.

In a loss-less coal-seam waveguide 'shorted' at both ends, by roadway metal work for example, the TE_{10} mode will reflect at both ends forming a standing wave pattern within the waveguide. Even for a practical example of a dry coal seam, provided the 'coal' is not too lossy, the standing wave can be formed, and resonant frequencies are predicted to occur where $\beta_{10}L = n\pi$, where n is an integer and L is the length of the waveguide. For a waveguide with $L = 2000\,\text{m}$, $n = 9$, and $a = 300\,\text{m}$, this condition produces a horizontal line on βa-ka diagram at $\beta_{10}a = 4.24$ (solid horizontal line on Fig. 3). An integer value of $n = 9$ was chosen to produce resonances not too near the TE_{10} mode cut-off ($ka = \pi$) and reasonably far from the TE_{20} mode cut-off at $ka = 2\pi$. From the diagram, the TE_{109} resonance for $\sigma = 0.0001\,\text{S/m}$ will occur at $ka = 5.3$. Using $a = 300\,\text{m}$ this gives an anticipated resonant frequency (f_r) of about 266.7 kHz. At this frequency the loss tangent of the waveguide medium is 0.67. For wetter coal ($\sigma > 0.001\,\text{S/m}$) a resonance will not occur, since the forward travelling TE_{10} mode will swamp any reflected wave from the end-wall over almost the entire length of the waveguide.

For an 'idealized' coal seam waveguide, Fig. 3 suggests that identifiable modes are unlikely to occur in a seam comprising very wet coal, for which conductivity levels could be of the order of $0.01\,\text{S/m}$, or at any value of σ for which the β curve intercepts the horizontal line at $ka \leq \pi$, the TE_{10} mode cut-off frequency. However, the question still remains — at what range of non-ideal, in other words practical, seam operating conditions will modal propagation be detectable in a well-formed geological stratum? To determine this, a more comprehensive and detailed electromagnetic wave model of the seam waveguide structure has been constructed.

4. 'DRIVEN' SOLUTION

Bounded electromagnetic field problems such as the coal seam waveguide can be modelled on finite element solvers, as either an 'eigenmode' or a 'driven' system. While the eigenmode solver generates the natural modes (eigenmodes) of the *closed* system, a 'driven' solution has excitation sources or ports feeding electromagnetic energy into the region of interest which is not necessarily 'closed'. However, if the sources or ports are 'small' relative to the region of interest the 'driven' solution will also generate resonant modes although these will not strictly be eigenmodes because of the presence of the port, or ports. For very lossy waveguides it is known that eigenmode solvers can be unreliable and therefore attention has been focused here on a driven solution.

Computational intensity can be severe for 'driven' solutions because of the additional requirement to model the ports. Consequently care has had to be applied to the form of the source. In practice, for radio-wave imaging applications, excitation of the panel waveguide would be by means of a loop antenna inserted into the seam from an access roadway. Magnetic coupling using loop antennas represents the currently preferred way of exciting a waveguide of coal seam proportions [5]. The loop is located within the panel in such a way as to couple optimally to the magnetic field of the desired mode. For the TE_{10} mode the magnetic field shape suggests that there is little difference between end-wall or side-wall excitation. Consequently, we have chosen to model the loop, which provides magnetic coupling to the TE_{10} mode, by means of a slot shaped wave-port (magnetic current source) located on an edge face of the panel. This greatly reduces computational intensity, while retaining loop coupling characteristics. The 'driven' model is shown in Fig. 4.

The 'coal' medium in Fig. 4 is modelled with $\varepsilon_r = 10$ and σ_{coal} ranging from 10^{-6} S/m (resistivity $\rho = 10^6\,\Omega$m) up to 0.0001 S/m (10,000 Ωm). Both the $z = 0$ wall and the $x = 0$ wall are formed from a 1 m thick conducting plate which is 6 m high to represent the roadway steel support structure ($\sigma_{metal} = 1.03 \times 10^7$ S/m, $\varepsilon_r = 1$). The coal panel is sandwiched between 10 m thick conducting plates at $y = 0$ and $y = 6$ m to represent geological layers of wet shale

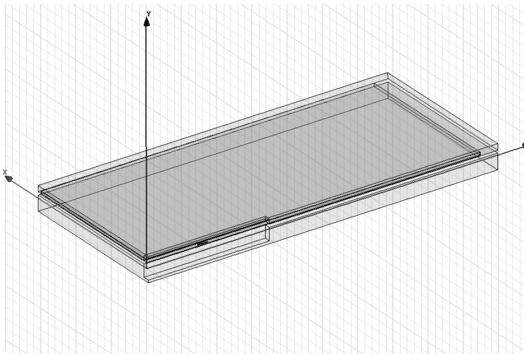


Figure 4. Coal panel section 300 m×6 m×666.66 fed from a 20 m×1 m slot shaped waveport.

($\varepsilon_r = 20$). The conductivity values for the shale ranged in magnitude from $\sigma_{shale} = 1\,\mathrm{S/m}$ ($\rho = 1.0\,\Omega\mathrm{m}$) up to $\sigma_{shale} = 5.0\,\mathrm{S/m}$ ($\rho = 0.2\,\Omega\mathrm{m}$). Memory restrictions, on the work station employed to perform the simulations, restricted modelling to relatively low loss propagation conditions.

Figure 5 shows the TE_{102} standing-wave in a panel of length 444.44 m. It is equivalent to the first two cycles of the TE_{109} mode in a 2000 m coal panel for an idealized very low-loss case. This mode resonates at about 260 kHz which means that for $\sigma_{coal} < 10^5\,\mathrm{S/m}$, $\tan\delta$ is less than 0.07. The mode pattern is almost perfectly formed for this low $\tan\delta$ simulation. The distortion of the pattern close to the wave-port is caused by the direct radiation fields and the stored energy (near) fields of the port. This local pattern is typical of any electromagnetic field distribution in the near vicinity of an electrically small source. It comprises two primary components, namely, the fields of the electromagnetic wave radiating out from an electrically small source, together with the reactive stored energy fields in the near-field of the radiator. For a low-loss waveguide the power required to strongly excite the mode is very small and hence the port local fields are weak by comparison with the modal fields except very close to the port. Consequently they have only a small distorting effect on the mode field pattern as the figure shows. The right hand lobe is well formed, as would be all subsequent lobes to the right of the pattern if we had displayed the full TE_{109} mode over the full 2000 m length of this idealized waveguide. This is no longer true when the material forming the waveguide exhibits conductivity levels which cause mode attenuation (lossy case — Fig. 6).

The figure again shows in grey scale the magnitude of the y-

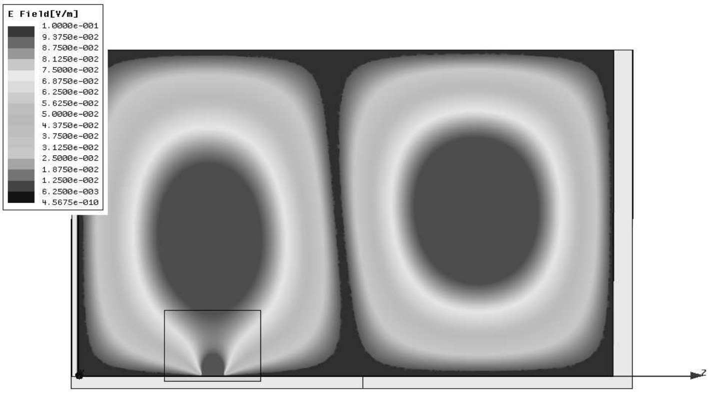
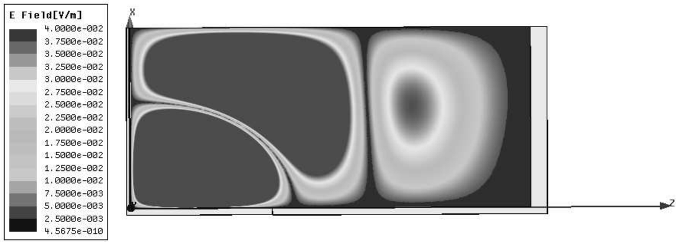
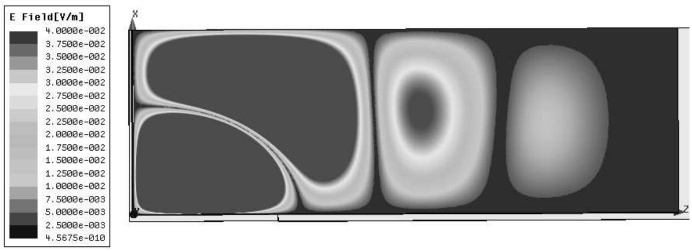


Figure 5. Coal ($\sigma_{coal} = 10^{-6}$ S/m) panel section 300 m × 6 m × 444.44 m fed from a 20 m × 1 m slot shaped waveport showing TE_{102} mode field pattern and stored energy fields in the vicinity of the port. The standing-wave pattern shows the strength of the y-directed E-field in the x-z plane of the panel — strongest ($\geq E = 1.0\times10^{-1}$ V/m) in the two red oval shaped regions and in the small circular region close to the port at the lower left of the pattern. (Idealised case: $\sigma_{coal} < 10^{-5}$ S/m; $\sigma_{shale} > 10^5$ S/m).

directed E-field in the x-z plane of the panel. In this case, the material forming the panel displays a $\tan\delta \approx 1$, and the rapid rate of field attenuation is evident. Even when the wave propagating medium is only slightly lossy ($\sigma_{coal} > 0.0001$ S/m) (real coal is usually much more lossy than this) very much more power is required at the source to establish and sustain the waveguide mode at any significant distance from the source. Power is now disappearing into the coal as resistive heating and coupling to the TE_{10} mode is greatly weakened. For high input power, the directly radiating (non-modal) and stored energy fields near the source are more dominant than in Fig. 5, because of the high power level needed to excite the mode in the guide. Note that the dark high field region at the lower left corner of the panel denotes fields *greater* than 0.04 V/m, in order to display the nascent mode pattern on the right. Consequently the presentation obscures the field decay close to the source. In this x-z plane field presentation, if the field sensitivity scaling were set at the same level as Fig. 5, the right hand lobe in Fig. 6(a) would no longer be in evidence. The TE_{10} modal fields, although present, are swamped by the source fields and the field combination produces the distorted pattern shown. For an input power level of 1 kW the distortion extends about 600 m into the



(a)

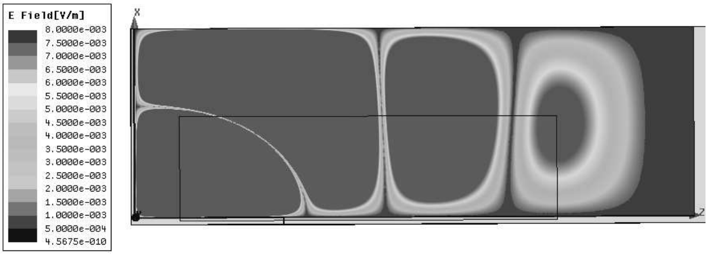


(b)

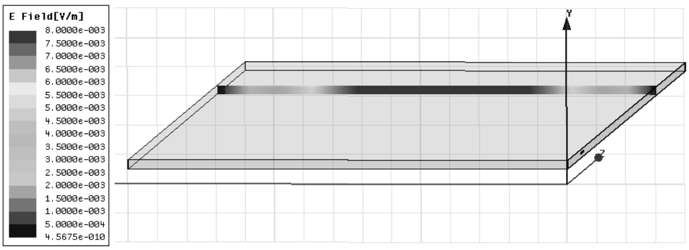
Figure 6. Coal ($\sigma_{coal} = 10^{-4}\,\mathrm{S/m}$) panel section $300\,\mathrm{m} \times 6\,\mathrm{m} \times L\,\mathrm{m}$ fed from a $20\,\mathrm{m} \times 1\,\mathrm{m}$ slot shaped waveport showing the distorted TE_{10} mode field pattern and stored energy fields in the vicinity of the port. The panel length in (a) $L = 666.6\,\mathrm{m}$; and in (b) $L = 888.8\,\mathrm{m}$ (Lossy case: $\sigma_{coal} = 0.0001\,\mathrm{S/m}$; $\sigma_{shale} = 10^5\,\mathrm{S/m}$).

panel. Or to put it another way, the TE_{10} mode uncontaminated by the source fields is present only at a distance of 600 m or more from the source. It is not possible, with the Fig. 5 sensitivity setting, to display the relatively weak modal field pattern in the waveguide, since the sensitivity scale (~ 1000 times from lowest to highest field value) is too coarse.

This is made clearer in Fig. 6(b) where the simulation has been repeated for a longer panel. A second lobe of the TE_{10} mode field pattern is just visible. However when the fields are plotted on a more remote plane (x-y plane at $z = 672\,\mathrm{m}$), the TE_{10} mode field pattern can clearly be seen (Fig. 7(b)). Note that the sensitivity scale has been reduced by a factor of 20 relative to Fig. 6 to display it. It should be emphasized that electromagnetic modelling tools are formed from linear equations. Consequently, by controlling the port scaling and field sensitivity levels it is always possible to identify the modal field patterns at locations remote from the port, no matter how weak the fields This is true for all parameter combinations. What is clear is



(a)



(b)

Figure 7. Coal ($\sigma_{coal} = 10^{-4}$ S/m) panel section 300 m × 6 m × 888.88 m fed from a 20 m × 1 m slot shaped waveport showing TE_{10} mode field pattern (a) in x-z plane and (b) at a cross-sectional, x-y plane, located at $z = 672$ m. (Lossy case: $\sigma_{coal} = 0.0001$ S/m; $\sigma_{shale} = 10^5$ S/m).

that for high coal conductivities ($\tan\delta \geq 1.0$) the modal pattern in the panel waveguide becomes very weak, which is not surprising. More unexpectedly, the modal pattern can be swamped by non-modal fields, particularly close to the port or the source of EM excitation.

Figure 8 represents EM propagation in a panel formed from very low loss 'coal' enclosed in wet shale ($\sigma_{shale} = 1.0$ S/m). This means that the panel waveguide will again be lossy but this time owing mainly to field leakage into the upper and lower shale layers. We have chosen to term this the 'leaky' case. Comparison of the pattern shown in this figure, with that of Fig. 6, shows clearly that the processes described to explain Fig. 6 also apply for the leaky panel, if the rate of power loss into the shale layers becomes significant, as is the case here. The pattern distortion in the vicinity of the port is again evident. However, the second cycle of the TE_{10} mode is much better formed indicating that the loss into the shale is insufficiently severe to inhibit mode formation in locations separated from, but not too remote from the

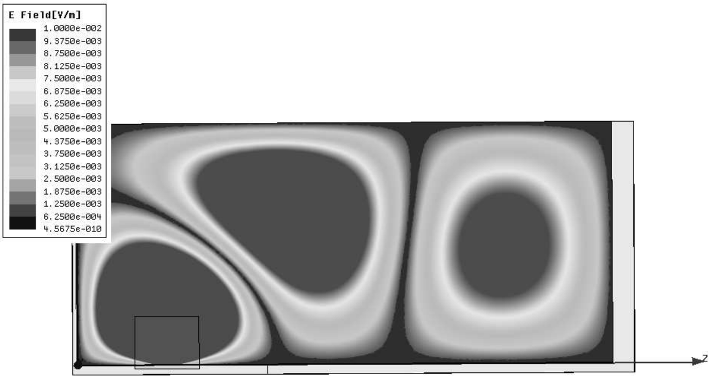
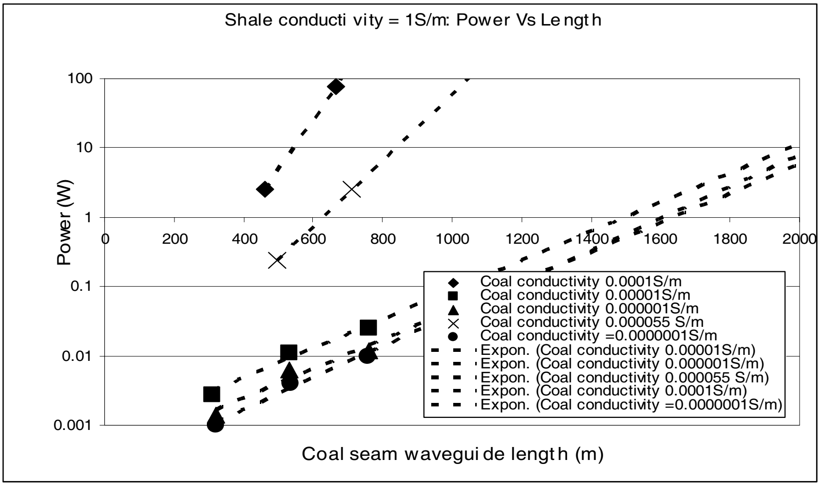


Figure 8. Coal ($\sigma_{coal} = 10^{-6}$ S/m) panel section 300 m × 6 m × 666.66 m fed from a 20 m × 1 m slot shaped waveport showing distorted TE_{102} mode field pattern and stored energy fields in the vicinity of the port. (Leaky case: $\sigma_{coal} = 10^{-6}$ S/m; $\sigma_{shale} = 1.0$ S/m).

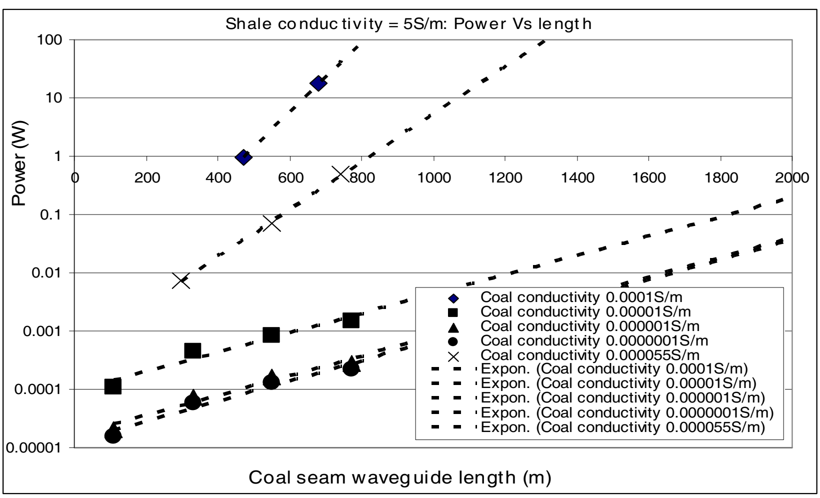
port. It is clear, from this figure that for a coal panel sandwiched between shale layers, high shale conductivity (low resistivity) is critical to effective EM propagation within the seam.

Field patterns such as those depicted in Figs. 5, 6, 7 and 8 have been constructed for a coal panel as described above, in which the conductivity levels for the coal and for the surrounding shale, have been examined over a wide range of parameter values. In all cases, it has been assumed that the support structures in the peripheral roadways represent good conducting walls at the frequency of interest. The results clearly demonstrate the difficulties of forming guided waves in coal mines. For all conductivity levels examined, the fields of the TE_{10} mode at 266 kHz in a 2000 m long panel terminated by a conducting roadway wall can, in principle, be modelled for all possible parameter combinations in the linear, noise free, full-wave model. The only limit is computer power. However, for coal conductivities in excess of 0.0001 S/m (independent of shale conductivity), these field levels become so low, several hundred metres into the panel, that they are effectively zero for all practical purposes, i.e., the predicted field levels are below the background EM noise in a deep mine. Studies of EM noise in mines in [10] have suggested that much of it is due to mining activity associated with blasting, drilling, motors, air doors, ventilation fans, shaft noise, chute activity, power tools, welding, power surges and water pumps. Seismic activity can also be a source of noise as has been shown by Frid et al. [11–13] who have concluded that natural EM emissions in coal mines lie in a narrow band from

30 kHz to 150 kHz, and that these emissions are caused be stresses in the coal and nearby rock strata. Measured results extracted from the cited papers, and others, seem to suggest that spurious EM signals in a coal mine, from man-made sources are likely to be most troublesome



(a)



(b)

Figure 9. Injected power in watts required to establish a 0.25 mV/m E-field versus distance L into the panel for $300\,\text{m} \times 6\,\text{m} \times L\,\text{m}$ coal panel, with coal conductivity as parameter. ($\varepsilon_{r-coal} = 10$; $\varepsilon_{r-shale} = 20$).

and that these could contribute an E-field magnitude in the seam at around 250 kHz of up to 0.25 mV/m. Using this, possibly pessimistic, figure as the criterion for modal detectability the following curves of injected power required to establish a mode, versus both distance and seam conductivity, have been generated. Some extrapolation has been necessary because of computer memory limitations for high loss cases. These extrapolated curves are based on the use of Eq. (16), and the fact that in an idealized seam waveguide it is known that field decay is exponential.

Figures 9(a), 9(b) and 10 summarise the results of extensive modelling. They demonstrate clearly that for lossy coal ($\sigma > 0.0001$ S/m) sandwiched between layers of shale (5 S/m and 1 S/m respectively) it will not be possible to detect the presence of the TE_{10} mode at the far end of a 2000 m coal panel unless a very high level of power can be injected into the seam. Note that the symbols in Fig. 9 represent the computed points while the trend lines assume exponential field decay. Fig. 9(a) shows that even at a relatively low conductivity level for coal of $\sigma = 0.0001$ S/m (very dry conditions) and with 100 W injected into the panel, the modal E-field magnitude drops to less than

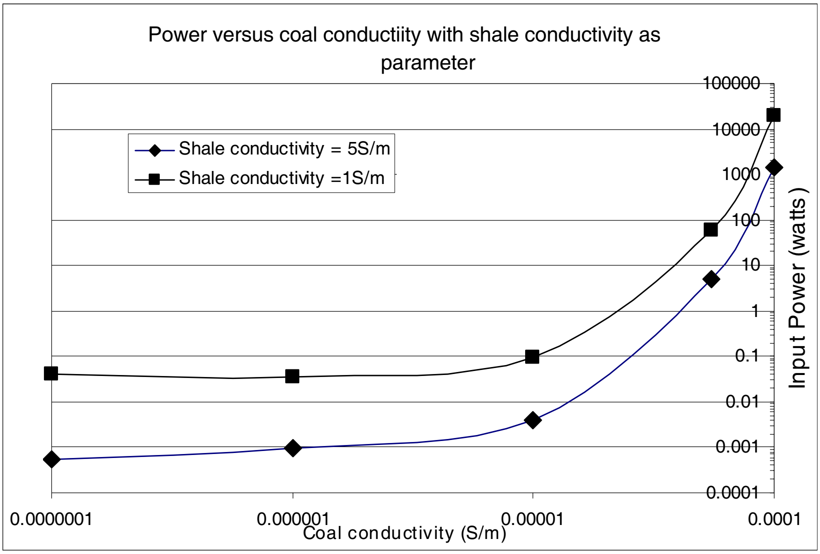


Figure 10. Injected power in watts to establish a E-field magnitude of 0.25 mV/m at 1000 m from input versus coal conductivity for 300 m wide by 6 m high coal panel, with shale conductivity as parameter. ($\varepsilon_{r-coal} = 10$; $\varepsilon_{r-shale} = 20$).

0.25 mV/m at a distance into the seam waveguide of only 800 m. With lower shale conductivity the situation is worse as Fig. 9(b) indicates. In Fig. 10, the power requirements are illustrated even more starkly. Here the injected power required to set up a modal E-field of 0.25 mV/m at a distance of 1000 m into the panel is presented as a function of coal conductivity, with shale conductivity as parameter. At this distance into a coal panel waveguide, powers in excess of 1000 Watts will have to be efficiently injected into it, in order to detect the TE_{10} mode, if the coal conductivity exceeds 10^{-4} S/m. But, as we have seen, at these kinds of power levels the modal fields are liable to be swamped by the source near fields closer to the port.

5. CONCLUSION

In this paper, we have examined closely the conditions for establishing an electromagnetic waveguide mode in a large lossy regularly shaped, 'electrically smooth' geological structure such as a panel of coal. On the basis of fundamental propagation studies, supported by full-wave electromagnetic simulations of lossy panel waveguides, the following conclusions can be deduced:

1. The formation of a trapped electromagnetic wave or mode in a large 'regular' geological stratum is not impossible, as is often assumed, if the loss tangent is close to or greater than unity. Moding can occur in structures with $\tan\delta \geq 1$ provided the electrical conductivity of the material forming the stratum is not too large.
2. The modelling evidence is that there is an injected power level 'window' within which a detectable or discernable mode can be set up in a lossy geological stratum such as a coal seam. If the injected power is too low the modal fields are lost in noise, if they are too high, in order to overcome high power loss, the modal fields may be undetectable because they are swamped by the local non-modal source fields. For example, with 1 kW of injected power (easily generated by a vacuum tube based transmitter), for a panel with $\sigma_{coal} > 0.0001$ S/m and $\sigma_{shale} = 5.0$ S/m, the TE_{10} mode will be distorted at < 600 m and no longer detectable at > 900 m.
3. TE_{10} mode propagation is predicted to be detectable 1000 m into a 300 m wide by 6 m high rectangular coal panel for which $\varepsilon_r = 10$ at a frequency $f > 158$ kHz, and at an injected power level of ~ 1 kW, provided the conductivity of the coal (σ) is less than 0.0001 S/m ($\tan\delta \approx 1$). This implies that the coal cannot be too wet. These conditions are most likely to be met in deep seams.

4. The modal behaviour of a coal panel of the above dimensions embedded in shale layers is insensitive to the conductivity of roadway metal supports which form the electromagnetic wave boundaries at the edges of the panel (in the range $1.03\times10^7\,\mathrm{S/m} \leq \sigma_{metal} \leq 5.8\times10^7\,\mathrm{S/m}$), and not too sensitive to the parameter values used for the 'wet shale', which is assumed to bound the coal panel, provided the shale remains much more conducting than the coal. Only a few of the many cases examined are presented in the paper.
   (The range examined was $0.1\,\mathrm{S/m} \leq \sigma_{shale} \leq 10\,\mathrm{S/m}$ and $20 \leq \varepsilon_r \leq 40$).
5. For a panel with reflecting end walls a longitudinal standing wave pattern is predicted for the 300 m wide by 6 m high by 1000 m long panel provided the conductivity of the coal is less than 0.0001 S/m. This figure will depend on the particular standing wave pattern which is formed. For a coal seam with the above dimensions and for which $\varepsilon_r = 10$ and $\sigma = 0.0001\,\mathrm{S/m}$ the TE_{109} standing wave resonance occurs at 260 kHz, and at a power level in the range 1 kW to 10 kW.
6. In a very wet or electrically lossy geological layer ($\sigma > 0.003\,\mathrm{S/m}$), TE_{10} mode formation will not occur in a layer which is more than ~ 50 m wide. Computations indicate that the highly attenuated spreading wave from the electromagnetic wave source essentially disappears 50 m ($\sim \lambda/4$) from the source.

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