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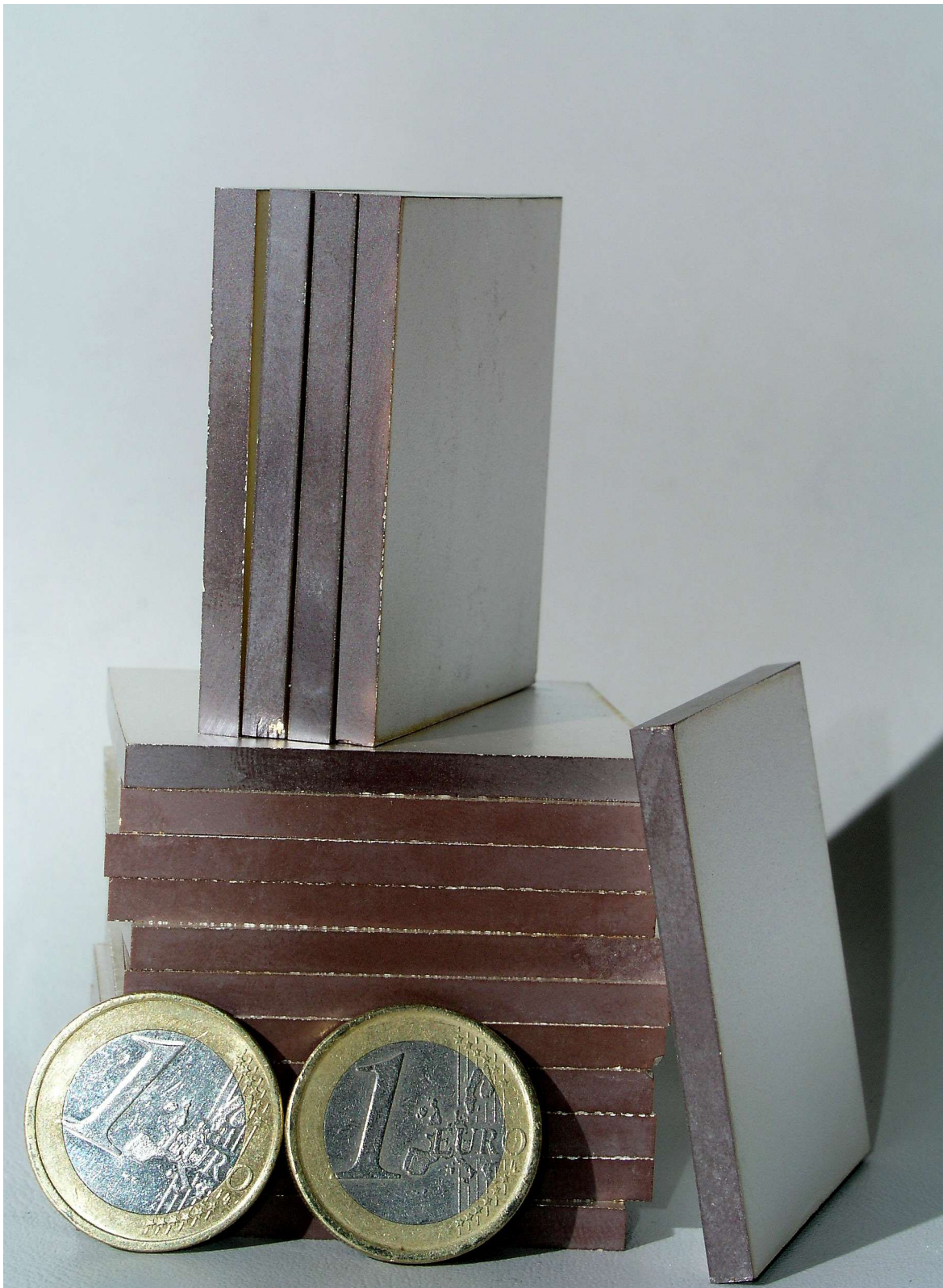


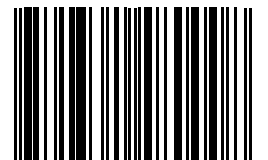
Photo: David Gibson

## CAVE RADIO & ELECTRONICS GROUP

*Novel Cave Radio Antenna uses Small Ceramic Tiles, IP Ratings Revisited, A Caving Light for the 21st Century, Wireless in a Coalmine, Cave Technology Symposium 2008, Web Watch, We Hear, Wet & Dry, Letters.*



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# Novel Cave Radio Antenna uses Small Ceramic Tiles

*Induction loop antennas are often inefficient due to skin and proximity effects, self-capacitance and tuning losses. However, an electric field antenna will generate a magnetic field which, in some circumstances, can exceed the field strength available from a loop antenna of similar mass and power dissipation. The main difficulty is in achieving efficiency at a small size. David Gibson explains how this may be achieved using high-permittivity ceramic tiles.*

Radio communication through the ground requires a low frequency, because high frequency electromagnetic fields are too highly attenuated. The attenuation is conveniently expressed by means of a figure of merit known at the skin depth, but this belies the true picture because the near-field from an antenna is not attenuated in the same way as the far field. Nevertheless, it remains the case that we must seek a method of efficiently generating an electromagnetic wave at a low frequency and in a small antenna. The small size dictates that the antenna will not be an efficient radiator and so we are forced to rely on near-field effects, which usually means making use of magnetic induction.

However, as several past authors (including myself) have noted in this journal, it is possible to use an electric field antenna, provided that care is taken with the design. One of the main problems is that a very small whip antenna has such a low capacitance that it is difficult to steer the current to the ends of the antenna and most will simply leak away. This does not mean that E-field antennas cannot ever be used, as both the HeyPhone and Système Nicola radios rely on E-field effects for their operation. (The commonly held view that they operate by means of loops of current injected in to the ground is rather an over-simplification).

Utilising an electric field antenna does not mean that we are utilising the electric field component itself. A time-varying electric field is always accompanied by a magnetic field. The electric field is subject to severe attenuation in the conducting medium, but the magnetic field survives to provide the communication ability.

## Advantage of the E-field

Conventional geophysical surveys sometimes make use of a long wire antenna, where the wire (perhaps 1km long) is suspended vertically from a balloon. These antennas, where most of the power is dissipated in the antenna material, can be analysed to give rise to a figure of merit in much the same way as

the f.o.m. that I derived for magnetic loop antennas. (Gibson, 1999). Initially referred to as effective aperture, I later re-designated this figure of merit as *specific aperture*; its E-field analogue is *specific length*.

For practical use underground, a long wire would be replaced by a dielectric disc antenna. The analogy is that we replace an air-cored induction loop with a ferrite-cored solenoid to save space. The analysis of both of these 'cored' antennas is more complicated because the losses are a combination of 'copper' losses and 'core' losses.

For a dielectric disc antenna the dielectric losses will be more significant than the copper loss in the plates of the capacitor – which is what such an antenna essentially is. This makes the derivation of a figure of merit easier, as the copper losses can be ignored.

Despite the disadvantage of an E-field antenna, that it produces a magnetic induction field only as an adjunct to the electrostatic near-field, there are a number of potential advantages.

- a) There is the possibility of a greater figure of merit (i.e. the dipole moment obtained for a given power dissipation and mass of material) than a loop antenna, due to absence of a multi-turn winding with its severe skin and proximity effects and inter-winding capacitance.
- b) In free space, the magnetic near field of an E-field antenna drops off with an inverse square rather than an inverse cube law. This means that, although the magnetic field may start off smaller, it does not decay so rapidly and so it can penetrate further; although a careful analysis shows that, in a conducting medium, this advantage is less clear-cut and may require further investigation.
- c) The shape of the magnetic field differs to that from a loop antenna and may be more suitable for the geophysical probing of layered rock. This is probably of more relevance to geo-physicists although it might also be relevant to communications through layered strata.

## Analysis of Performance

Analysing a long thin-wire antenna is difficult because the formula for its capacitance is complicated and, especially at low frequencies when its capacitance is very low, it is affected by electrostatic coupling to nearby structures. But, if we imagine a 'top-hat' type of design utilising a couple of large well-spaced metal discs and we completely ignore any edge effects then the capacitance between the discs of surface area  $A$  and spacing  $\ell$  is  $C = \epsilon_0 A/\ell$ . If we apply a voltage  $U$  at angular frequency  $\omega$  then the current is  $I = U \cdot j\omega C$  and so the electric dipole moment,  $m_e = |I\ell|$ , is given by

$$m_e = U \cdot \omega \epsilon_0 \cdot A \quad (1)$$

Notice the interesting point that the dipole moment depends on the area of the plates and the permittivity, but not on their separation. This may seem counter-intuitive, but it is because (1) expresses the dipole moment in terms of the voltage, not the antenna current.

This observation leads to the speculation that we could make an antenna out of a pair of capacitor plates placed close together, and filled with a high-permittivity dielectric. The purpose of the dielectric is essentially to reduce the voltage that is necessary to achieve a certain dipole moment. If an air dielectric required 1000V across the plates, a dielectric with  $\epsilon_r = 200$  would require only 5V to achieve the same dipole moment. (This is essentially a similar argument to that which shows that a magnetic cored solenoid requires a smaller current to achieve the same dipole moment as an air-cored solenoid).

An antenna with large plates might be unwieldy and could be fragile but the area could be reduced by stacking small antennas in parallel like a multi-layer capacitor.

At this point, it becomes useful to quote some equations although, to save space in this short article, the derivations of the formulas will not be given. Firstly, as a reminder, the magnetic dipole moment of a magnetic loop antenna is given by

$$m_d = \Phi_m \sqrt{P}, \text{ with } \Phi_m = \frac{1}{2} a \sqrt{M \frac{\sigma}{\rho}} \quad (2)$$

where  $\Phi_m$  is the *specific aperture* of the magnetic loop antenna and  $P$  is the power dissipation in its winding. (There is negligible radiation or external resistance and we assume that there is no skin or proximity effect). With these assumptions,  $\Phi$  is independent of the number of turns and is describable in terms of the antenna's mass and radius, the conductivity of the winding material  $\sigma$  and its mass density  $\rho$ .

A similar expression for the *specific length* can be derived for an electric field antenna, where

$$p_d = \Phi_e \sqrt{P}, \text{ with } \Phi_e = \sqrt{M \frac{\sigma}{\rho}} \quad (3)$$

but this does not take into account the significant effect caused by unwanted electrostatic coupling to nearby objects. It is only applicable to long, isolated wires.

The point at issue is whether we can derive a similar expression that can be used with a dielectric-filled antenna in which we assume the copper losses to be negligible, but where there are significant dielectric losses. It turns out that such an expression is

$$\Phi_e \sqrt{M \frac{\sigma_d}{\rho}}, \text{ with } \sigma_d = \frac{\omega \epsilon}{d} \quad (4)$$

where  $d$  is the dissipation or loss factor of the dielectric. Note the extreme similarity of this to the previous expression but, instead of  $\sigma$  representing the copper conductivity, it represents a property of the dielectric.

A practical method of a manufacturing such an antenna would be to use a high-permittivity ceramic to make a tile, which was metallised on its two opposite faces to form a capacitor. It is clear that the performance of such an antenna depends on the mass of the dielectric and not on the area of the tile or its thickness, which are mere 'operational' constraints that govern the voltage and current that we might require.

This is, of course, a similar argument to that which I have presented for induction loop antennas. To recap: for a loop, each individual turn will carry a specified current and dissipate a certain power. The turns can, essentially, be connected in series or parallel, which affects the overall voltage and current, but does not affect the power dissipation or the magnetic moment. The same is true of a ceramic tile antenna where the tiles, taking the form of capacitors, will each will carry a specified current and dissipate a certain power as a dielectric loss. The tiles can, essentially, be connected in series or parallel, which affects the overall voltage and current, but does not affect the power or moment.

Another point that arises out of a full analysis is that whilst the Q-factor of an air-cored induction loop is proportional to  $\Phi^2 / a^3$ , the Q-factor of a dielectric disc is simply  $\epsilon_r / d$  and can easily be very high.



### Choosing a Dielectric

We can see that it will be important to choose a material which has the highest possible ratio  $\epsilon_r / \rho d$ . The first candidate to eliminate is, of course, air. For air, the ratio  $\epsilon_r / \rho$  is about  $0.8 \text{ kg/m}^3$ , but the loss factor is essentially zero, making  $\sigma_d$  infinite. The reason we cannot use air as the dielectric is that it would result in too high a voltage and it would require metal plates in order to be self-supporting, so the mass would be high. We are therefore limited to solid<sup>1</sup> dielectrics that we can separate with a thin metal foil, and which have a) a reasonably high permittivity, to keep the voltage low and b) a reasonably low dielectric loss. Unfortunately, most substances only have a low permittivity and a moderate dissipation factor. Polyethylene, for example, has  $\epsilon_r \approx 2.3$  and  $d \approx 0.0002$ , giving an  $\epsilon_r / \rho d$  figure of just **12**.

The difficulty in choosing a material is that many of the material properties listed on the Internet are not attributable to any reliable source or are not listed for a frequency of 100kHz. Also, the properties are highly dependent on the purity and the manufacturing method. For example, some materials absorb water and this can change their properties drastically.

A supposedly-readily-available material with a somewhat better performance than polyethylene is alumina (aluminium oxide) which is manufactured as ceramic tiles for a number of engineering applications. For a very high-purity material,  $\epsilon_r$  approaches 10 and  $d$  can be as low as 0.0001. With a specific gravity of 3.9 the figure of merit  $\epsilon_r /$

$\rho d$  is about **25**. Another option is titania or rutile (titanium dioxide). In some processes this is claimed to have  $\epsilon_r = 200$  and  $d = 0.0005$ . With a specific gravity of about 4.0 the figure of merit  $\epsilon_r / \rho d$  is about **100**.

There are more 'exotic' materials than this – particularly the perovskite ceramics – but although these can have an extremely high permittivity, they also have a high loss factor. High- $\epsilon$  materials make good capacitors, but these tend to have dissipation factors of 0.001 or much worse.

### The Eventual Design

My eventual choice for a suitable ceramic was the perovskite, barium strontium titanate ( $\text{Ba}_{1-x}\text{Sr}_x\text{TiO}_3$ ) for which  $\epsilon_r$  is about 2500 at 100kHz. The loss factor  $d$  is 0.0015 and the specific gravity is 5.55, resulting in the figure of merit  $\epsilon_r / \rho d$  being around **300**. I arranged for a ceramics company to supply me with 16 tiles of this material, each  $4 \times 50 \times 50\text{mm}$ . (See photo, left, and on front cover) and I will be conducting experiments shortly.

Each tile has a capacitance of around 12nF and the total mass of the stack is 1kg. The tiles have top and bottom metallisation and are, essentially, high voltage ceramic capacitors made from a 'Z5U' material. The individual tiles can be connected in a number of ways including a conventional multi-layer stack without affecting the dipole moment.

The intended power dissipation is 1W, resulting in an electric dipole moment of around 40 mAm. The reason for choosing to limit the dissipation to 1W is mainly because driving the antenna at higher power levels will be difficult because of its extremely high Q factor. A conventional 'cave radio' would require the antenna to be tuned which is not only difficult, but would drastically reduce its Q-factor (Gibson, 1995) so for initial experiments the antenna will probably be used untuned in a wideband experiment. I successful, this antenna has a number of possible advantages over existing designs, not least that it is portable. However it remains very much an experimental device.

To covers thinking of experimenting with such devices, one potential problem is the cost. My pack of 16 tiles cost nearly £1800 (€ 2300, US\$ 3000). This work is part of a research project of mine at the UK's Mines Rescue Service and is funded, in part, by the Research Fund for Coal and Steel of the European Community.

### References

- Gibson, D. (1995). *Losses in Tuning Capacitors*. CREGJ 19(12-14), March 1995.  
 Gibson, D. (1999). *A Methodical Approach to Loop Antenna Design*. CREGJ 37, 17-20, Sept. 99

1 A lightweight plastic foam bonded to aluminium foil is not a candidate because, although the possible high loss in the dielectric is mitigated by the foam structure, the low density then implies that a high volume is required. Moreover, the low  $\epsilon$  implies a high voltage.