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Location of Buried Optical Service Cables, Using a Remote EM-Wave to Modulate the Polarisation State of Guided Light, via the Faraday Effect

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Abstract--- **This paper presents the first results and theoretical examination of a method to locate the position of buried optical cables. A traveling EM-wave (RF), generated from above ground, modulates the state of polarization of the light guided by the fiber to be located. The magnitude and phase of this modulation are detected at the end of the fiber route and the results relayed to the operator. By observing the amplitude of this modulation the lateral position of the buried service can be determined. We have demonstrated 18dB signal/noise ratio, at a buried depth of 1.5m, in wet clay soil, using a radiated RF power of 38W at 144MHz**

I. INTRODUCTION

FIBER optic technology is now essential to the modern telecommunications industry. The optical fibers employed in the construction of such networks consist, generally, of fiber bundles of up to a hundred or so, coaxially reinforced with a steel strength member. Steel-reinforced cables, however, have a high cost of maintenance, are vulnerable to corrosion and, perhaps most importantly, are susceptible to damage by large currents induced by nearby lightning strikes. As might be expected, protection of these fiber links is of paramount importance, as the loss of a fiber link can lose the network operator substantial revenue. It is therefore common working practice to mark the buried position, and an exclusion zone around the telecoms cable, before any contract work is carried out in the vicinity. The ability to quickly and non-intrusively locate buried cables is of high importance to the network operators and several key technologies have evolved to fill this niche market, the most successful existing technology being electromagnetic location. A modulated high voltage is applied to the conducting cable sheath, causing a small (10-500mA peak) current to flow along the cable, which in turn, generates a magnetic field. The magnitude of this field can then be detected from above ground using an array of magnetometers, allowing the location of the buried service to be inferred. This method however, suffers several disadvantages. It requires that the steel sheath, on which it relies, is maintained, as applying a high voltage to a poorly maintained cable sheath can degrade it via anodic erosion at any point of damage. A further disadvantage is its performance in the vicinity of other conductors. The AC field generated by the cable to be located can inductively couple to other nearby conductors, causing them also to radiate a field. It is then possible to incorrectly identify the secondary field instead of your own service, leading to a location error which could leave your own cable vulnerable to damage. To minimize this effect, the frequency of the field modulation is usually extremely low (0.1-10Hz) and schemes have been developed to identify the direction of the current.

Alternatively, communications networks could employ dielectrically reinforced, e.g. "Kevlar", cable bundles. These cables are less expensive, require no sheath maintenance, are immune to corrosion and are, to a high degree, immune to lightning strike damage. However, despite these obvious advantages, such cables have not found wide use, as they render the existing cable location technology ineffective. We now present a novel sensing method capable of inferring the lateral buried position of a dielectrically reinforced cable bundle.

II. PRINCIPLE OF OPERATION

It is proposed that a novel linear magneto-optical (Faraday) effect could be used to locate a buried dielectrically reinforced cable (figure 1)[1].

Light, of known polarization state, is launched into the buried fiber cable that is to be located. This light propagates along the cable, and, at the far end, its state of polarization (SOP) is monitored by a suitable detection system. Above ground, an alternating magnetic field with appropriate characteristics may then be applied, which will induce a change in the SOP of the light guided by the fiber, via the Faraday effect. The amplitude of this modulation, as measured by the polarization-sensitive detection system at the far end of the cable route, may then be relayed to the locator, via a suitable communications link (i.e. Sat-Phone). The amplitude of this polarization modulation varies as a function of the field generator - fibre separation, allowing the location of the buried service to be inferred.

Potentially, this method suffers none of the disadvantages of the previous location technology. The service is located unambiguously i.e. it is impossible to locate another buried service by accident as it was for previous systems. However, nearby conductors could distort the radiated field leading to location inaccuracies. A further advantage, emergent due the fact that access to the fiber itself is required to use this location technology, is that the fiber is rendered secure and virtually impossible to locate by any unapproved person, an important factor in applications when the fiber carries sensitive traffic, i.e. governmental networks.

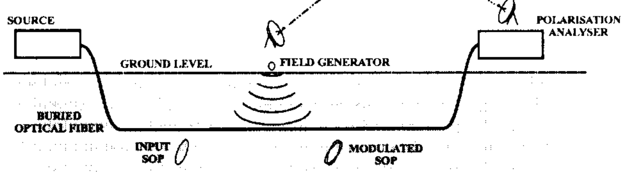

Fig. 1. Schematic of basic non-metallic cable location system concept

The following paper describes the theoretical operation of this proposed system and highlights the main design aspects, such as correct choice of EM-field symmetry, optical design and RF detection schemes before describing the initial results carried out both in the laboratory and in a live field situation.

III. THEORETICAL ANALYSIS

Faraday stated that the plane of polarization of light travelling through a material will be rotated by an angle, ϕ, proportional to the line integral of the magnetic flux density, $\boldsymbol{B}$, along the propagation path of the light, $\boldsymbol{l}$, (1).

$$\phi = V \cdot \int \boldsymbol{B}(\boldsymbol{l}) \cdot d\boldsymbol{l} \tag{1}$$

The constant of proportionality, V, is termed the Verdet constant. The Verdet constant for bulk silica has been quoted as 3.2 rad $(\mathrm{Tm})^{-1}$ (@ 1550nm). [2] The Faraday effect is perhaps most simply described as an induced circular birefringence. The only difference between the magneto-optically induced birefringence and normal optical activity is that the Faraday effect is invariant under time-reversal symmetry. The fiber itself exhibits a small linear birefringence, so as the light propagates along the fiber its SOP will, in general, evolve. In order to achieve a maximum rotation, the SOP of the light directly beneath the field generator has to have a high degree of linear polarization. However, the interaction length of the fiber with the field is of the same order as the beat length of a typical telecoms fiber, i.e. 10-20m. This evolution of the SOP within the interaction length leads to a quenching of the Faraday effect. Cruz et al, defined an effective Verdet constant [3-6],

$$V_{ef} = V \frac{2}{\delta z} \sin\left(\frac{\delta z}{2}\right) \tag{2}$$

where z is the interaction length and δ is the linear birefringence. Note that, for small interaction lengths and low birefringence, this effective Verdet constant approaches the bulk value. Cruz measured an effective Verdet constant of 0.54rad $(\mathrm{Tm})^{-1}$. As this shows, the Faraday effect is extremely small. The peak rotations that we can expect to detect are only of the order of 0.1-10μrads. As shown later, it is therefore necessary to use an extremely low detection bandwidth to achieve the required signal to noise ratio. However, an acquisition time of 1 minute achieves a post-detection bandwidth of 2.6mHz. Considerable frequency accuracy is required to achieve this precision. As described later, it proved necessary to lock the equipment to a Rubidium clock standard

We now discuss the generation of a field appropriate to cause a Faraday shift in the light guided by the fiber. The fiber to be located will, in general, run beneath ground, under the locator, running between two distant points, (i.e. communication regeneration stations). The line integral of the field along this path must be non-zero in order to generate a shift in the SOP of the guided light. The line integral of the magnetic field along any arbitrary closed path can be defined by Maxwell's equations, as shown in (3),

$$\oint \boldsymbol{B} \cdot d\boldsymbol{l} = \mu_0 \int_A (\boldsymbol{J}_f + \frac{\partial \boldsymbol{P}}{\partial t} + \nabla \times \boldsymbol{M} + \varepsilon_o \frac{\partial \boldsymbol{E}}{\partial t}) \cdot d\boldsymbol{A} \tag{3}$$

where, $\boldsymbol{J}_f$, is the free current density, $\boldsymbol{P}$, is the electronic polarization of the material supporting the magnetic field, $\boldsymbol{E}$, is the electric field and $\boldsymbol{M}$ is the magnetization which is assumed to be zero for typical soil types. In order for the field to generate a non-zero line-integral, the integration path must either contain a current or a changing electric field. The derivation of the field equations is outside the scope of this paper, but the conclusions of the analysis of two different types of magnetic field are given to help understand the situation. The field generated by a solenoid can be calculated using the Biot-Savart law. In this situation, a steady current is carried by several coaxially-wound wire turns. As the fiber to be located runs underground beneath the field generator the fiber runs parallel to, but outside, these windings. It is shown that the steady state integral of this field along any path external to this winding is zero. However, if this field were time varying, then the line integral along a path external to the winding, assuming a defined propagation velocity of the optical signal, may be non-zero. The simplest way to generate a time varying field is using an electric dipole.

In its simplest form, an electric dipole consists of two opposite charges separated by a distance d. When this charge distribution is modulated, charge flows from one end to the other. Is this case, a more suitable representation would be that of a finite element of current, varying in time, $\boldsymbol{J}(t)$. In order to derive the field radiated by this modulating charge structure, we first make the following assumptions.

- The current has a sinusoidal time variance.
- The magnitude of the current, as a function of distance between the charge separation, is constant, J_0.
- The charge separation is small compared to the radiated field wavelength, $2\pi / \beta$, where β is the wave-number of the radiated EM field.

It can be shown that the vector potential set-up by this current element is given by (4),

$$\boldsymbol{A} = \frac{\mu I_0 d}{4\pi} \cdot \frac{e^{-j\beta r}}{r} \tag{4}$$

where $\boldsymbol{r}$ is the displacement vector from the center of the dipole, I_0 is the peak current carried between charges, and d is the charge separation (dipole length). The resulting electric and magnetic field components, generated by this modulated charge, can therefore be calculated via the relationships; $\boldsymbol{B} = \nabla \times \boldsymbol{A}$ and similarly $\boldsymbol{E} = (1/j\omega\varepsilon)\nabla \times \boldsymbol{H}$ [7],

$$H_\varphi(t) = \mathrm{Re}\left[\frac{-I_0 d}{4\pi} \beta^2 \sin\theta \left[\frac{1}{j\beta r} + \frac{1}{(j\beta r)^2}\right] e^{j(\omega t - \beta r)}\right] \tag{5}$$

where ω is the angular frequency of the EM-radiation and ε is the permeability of the medium through which the wave is propagating. As can be seen from these equations, the fields generated by a modulating dipole create an EM-wave with a time-variance are the same as that of the current modulation. The magnetic field generated always lies along the spherical polar unit vector $\boldsymbol{i}_\varphi$ which follows the tangent of a circle, prescribed around the axis of the dipole. Fig. 2. shows the arrangement of dipole and fiber direction for the following discussion.

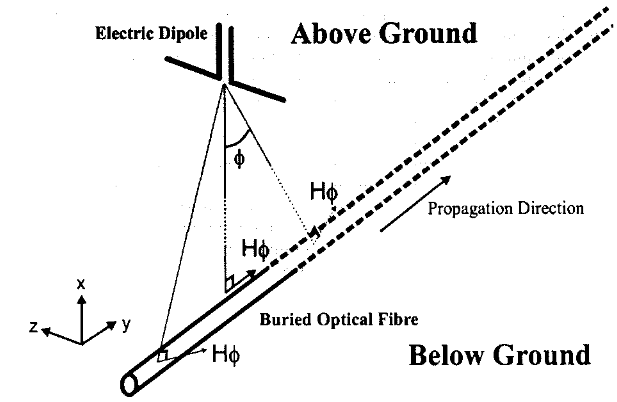

Fig. 2. Orientation of dipole in relation to buried optical fibre. We have an electric dipole situated **above ground**. We choose a co-ordinate system such that the dipole lies along the z axis and that the ground surface lies in the zy plane. The dipole is aligned such that the fibre runs along the y axis. The magnetic field generated by the dipole has only a i_ϕ component. **NOTE: The H_ϕ components of the magnetic field and the displacement vectors from the dipole lie in the xy plane**

At any instant in time, the magnetic field generated by the dipole, has a component running in the same direction as the fiber route and hence in the direction of propagation of the light. In order to calculate the line integral of this field along the path of the fiber, we must take into account the time-variance of the radiated EM-field and both the propagation velocity of the light along the fiber and the EM-wave through the ground.

If we consider the simplest case, i.e. that for a single photon traveling along the fiber with a phase velocity of c/n, where c is the speed of light in a vacuum and n is the refractive index of the fiber. We will assume that the radio-frequency EM-wave generated by the dipole propagates through a lossless medium towards the buried fiber, at a speed equal to the vacuum speed, c. This in general will not be the case, but a full analysis of the ground propagation at this point is not needed. We shall assume, also, that the time at which the photon is directly below the dipole is t = 0. As a function of displacement of the photon along the fiber, y,

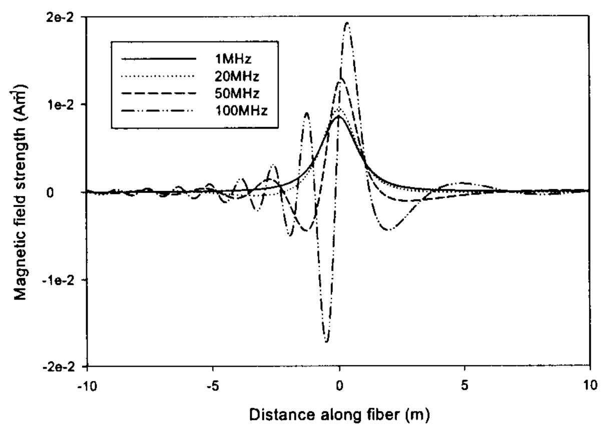

Fig.3. Magnetic field "observed" by a propagating photon, simulated results. A photon propagates along an optical fiber at a speed of c/n. The field it "observes" emitted by an electric dipole 1m above and 0.5m laterally offset is dependent on the emitted radiation frequency.

the time delay for propagation along the route can be shown to be ny/c.

The change in field shape is analogous to that of "Doppler-shifting" although no actual change in radiated field frequency occurs. It can also be noted that this effect becomes more pronounced as the radiated frequency increases. It can further be shown that the line integral of this "observed" field is non-zero along the fiber's path, but that the "Doppler-shifting" effect quenches this integral. Assuming a shot-noise-limited optical system, simulations have shown that given a nominal ground RF attenuation of $5dBm^{-1}$ and a buried depth of 1m a signal to noise ratio of between 20-30dB should be achievable at 100MHz, within a detection bandwidth of 2.6mHz (1 minute acquisition time).

IV. EXPERIMENTAL

The experimental set up consisted of four separate sections. The optical network apparatus, the RF detection electronics, the signal processing hardware and the above-ground RF transmitter.

The optical launch system consisted of a 2mW, fiber-coupled 1554nm semiconductor diode DFB laser module (Nortel LC111F-18), isolated by a single-stage isolator (Oykoden AMS-1550-R-S), followed by a fiber-coupled polarizer (Lamipol LP-15-A) with a 55dB extinction ratio. The detection system consisted a polarization division multiplexer (L2KPDM-1-1-21-11 Laser 2000) with an extinction ratio of 30dB and a nominal insertion loss of 0.6dB. The optical detector modules used were constructed by Analogue devices (AD713A-7) and had a transimpedance gain of 20kΩ, i.e. 18V/mW with a detection bandwidth of 200MHz, a noise equivalent power of 8pW and a sensitivity of –39.5dBm.

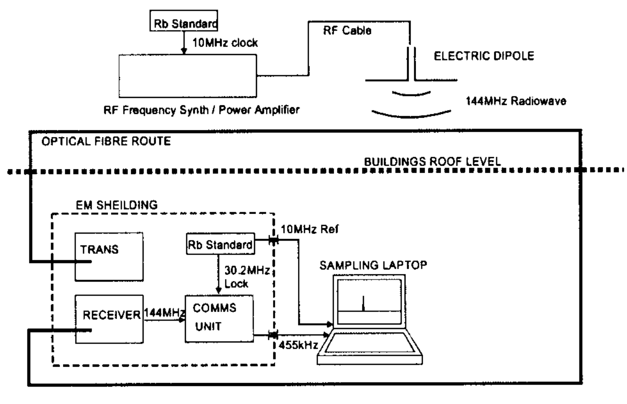

Fig.4. Schematic of laboratory based ultra-low bandwidth detection system for Faraday location experiment. Both the field emitter and the detection system are locked to Rubidium standards to reduce frequency drift. It is then possible to achieve coherent detection bandwidths below 1mHz.

Although the choice of excitation frequency was arbitrary, we were constrained by regulations to a set of allowable radio frequencies. These ranges were 50-52, 70-72, 144-146 and 430-434MHz. Although we have predicted that the effect would be reduced with increasing frequency, we chose to investigate the effect with a radiated field frequency in the 144MHz band. Primarily this decision was due to the fact that the resonant dipole length at 144MHz is of the order of 1m, an easily manageable size and secondly by the fact that, in order to achieve a shot-noise limited system, we required a high transimpedance value. Current low-cost technology limited the detection bandwidth of this module to 200MHz.

The RF detection apparatus was constructed from commercially available components. In order to achieve the required detection bandwidth (i.e. 1mHZ) at 144MHz we require a frequency accuracy of 10^{-11}. This, at the time, was not possible using a temperature-controlled-oven oscillator. We therefore employed a 10MHz Rubidium standard with a quoted accuracy of 10^{-13} over 10min. A reference of 30.2MHz was then generated using a digital synthesizer (HP 3325B) used to clock a standard RF communications receiver (ICOMS IRC8500). The signal generated at the optical detector was then AC coupled and fed into the communications receiver. The IF of the communications receiver at 455kHz was then under-sampled at a frequency of 450kHz by a laptop PC (Toshiba Tecra 780DVD) via a national instruments 12-bit DAQ-Card-A1-16E-4. The alias of the IF signal at 5kHz was then observed and processed through a narrowband FFT and data-windowing algorithm, able to achieve a detection bandwidth in the mHz range. For laboratory-based experiments, the entire RF sensitive section of the apparatus was housed within an EM-screened cabinet to prevent direct pickup. The cabinet had a quoted isolation of 80dB at 144MHz, but it was also necessary to filter the mains input to the cabinet and the IF feed-through. The noise floor of this detection system was shown to be limited by the shot-noise limited front-end and therefore was not measured. However, a further complication was that the commercial communications receiver had an AGC built into the IF stage, making direct comparison between signal level difficult. The SNR of the signal was measured in preference to its peak level. For the later experimental field trial, this RF-detection apparatus was replaced with a custom built spectrum analyzer, designed specifically to detect within a very narrow band around 144MHz. It, however, had no AGC section to allow direct signal level comparison. Again this detection system was shot-noise limited by the detector front end. Several experiments were carried out in the laboratory. A Kevlar reinforced cable was laid around the building and across the roof. Outside the building, an EM-wave could be safely applied to the cable. The field generator in this case was again locked to a Rubidium clock standard. The relative response of several antenna types was investigated and the response as a function of fiber antenna separation was measured, as shown in figure 5. Using a half-wave antenna, peak SNRs of **49dB** and **33dB** were recorded for fiber dipole separations of **0.1m** and **1.2m** respectively at 144MHz, 25W of radiated power in air with a detection bandwidth of **2.6mHz**.

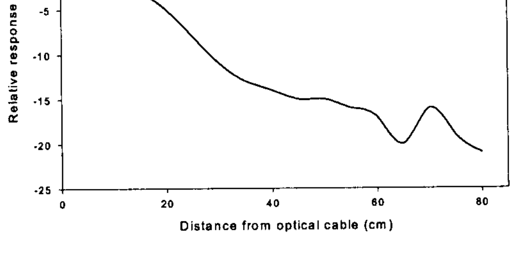

Fig. 5. Variation in the observed Faraday induced signal amplitude as a function of the distance between the dipole and the optical cable.

To investigate the performance of this system in an actual field situation, a portable apparatus was constructed. The optical source was replaced with a fiber DFB laser, with a 30kHz linewidth to minimize the effects of polarimetric interference. Over a fiber length of 50km, using a radiated power of 38W and a four element YAGI array 6dB gain antenna a SNR of **18dB** was observed, at a buried depth of approximately **1.5m** through **wet clay type soil,** within a **7mHz** detection bandwidth reducing to an SNR of 13dB, when 1m laterally offset. The cable type was Lucent Kevlar-reinforced.

V. CONCLUSIONS

In conclusion we have for the first time shown that a dielectric cable can be located using an externally-applied traveling EM-RF wave, by inducing a detectable modulation in the SOP of a guided optical wave. The interaction is via the linear Magneto-optical (Faraday) effect. We have demonstrated in first laboratory and field trials that the sensitivity appears sufficient to create a practical cable location system, even in water-sodden clay, that is expected to exhibit a higher RF propagation loss than dry sandy or loamy soil types. We were able to not only observe a signal but also show it varying with the separation of the fiber from the field generator, proving the location concept.

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