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The formation of charge from a travelling electromagnetic wave by reduction of the effective velocity of light to zero

R C Jennison
The Electronics Laboratories, University of Kent, Canterbury, Kent CT2 7NT

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Abstract. An experiment is described in which an electromagnetic wave is retarded in a slow-wave structure and finally brought to rest relative to the laboratory by revolving the structure, in the opposite sense, at the same angular frequency as that of the wave. The static field system formed from the wave may be considered as electric charge having its origin in the distributed wave field.

Slow-wave structures have been constructed in which the effective velocity of light is reduced to the velocity of extremely fast particles of matter, but no experiment has been performed previously which achieves Einstein's dream of bringing the velocity of light to zero in the laboratory. In the experiment to be described, it has proved possible not only to reduce to zero the velocity of propagation of an electromagnetic wave, but also to reverse the direction of propagation, without reflection or refraction. When the velocity of propagation is reduced to zero, the electromagnetic wave system forms a static field system, thus reversing the usual roles wherein an electromagnetic wave is considered to have its origin in a moving charge.

The velocity of light in free space is related to the permittivity, ε_0, and permeability, μ_0, of free space, $c=(\mu_0\varepsilon_0)^{-1/2}\,\mathrm{ms}^{-1}$, where $\varepsilon_0=8.85\times10^{-12}\,\mathrm{Fm}^{-1}$ and $\mu_0=4\pi\times10^{-7}\,\mathrm{Hm}^{-1}$.

This relationship is universal for the rectilinear propagation of light in empty space, although it is just possible that there may be other values for special modes in which the propagation path is closed within a fundamental particle.

The *effective* velocity of light, c', may be reduced by employing a dielectric. Thus we have the phenomenon of Cherenkov radiation which, in reverse, may be considered somewhat analogous to the phenomenon described in this paper. The dielectric may be in a transmission line. The wave velocity in a transmission line is given by the reciprocal of the square root of the product of the inductance and capacitance for unit length (e.g. Bleaney and Bleaney 1976):

$$c'=(LC)^{-1/2}=(\mu\varepsilon)^{-1/2}=c/(\mu_r\varepsilon_r)^{1/2} \tag{1}$$

which is the same as for an electromagnetic wave in the medium when no conductors are present.

In order to achieve exceptionally slow velocities of propagation it is usual to increase μ_r and ε_r or, *equivalently*, to increase the capacitance and inductance per unit length by the use of 'lumped' circuits in which discrete large values of L and C are cascaded to form a continuous line of discrete sections. The physical principles in such a line remain the same electromagnetic principles as those in a continuous distributed line which, for an equivalent propagation velocity, would require impractical values of permittivity and permeability in equation (1). *The line used in this experiment could have been a simple continuous strip line using a dielectric* $\varepsilon > 1000$. It would still work and the macroscopic description would have been identical. Phenomenologically the set of lumped circuits in the present experiment forms a dense medium, whereas, at low frequencies, the molecules in a 'continuous' dielectric behave, on a microscopic scale, as separate systems below resonance.

The arrangement in the present experiment uses a lumped circuit transmission line in which there are 32 sections giving a total delay of 120 ms. There is a small loss, of the order of 1 dB, in each section of the line and small linear repeater amplifiers are included in the circuit to compensate for this loss. The complete line is looped on itself in a geometrically circular configuration as in figure 1.

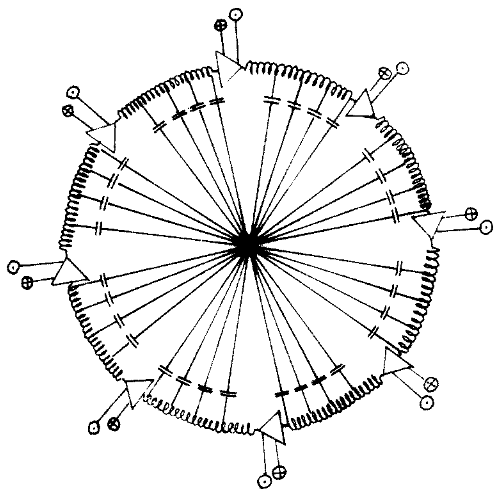

Figure 1. A representation of the transmission line in which a sinusoidal electromagnetic wave continuously propagates around the system in a clockwise direction. The triangles represent small linear repeater amplifiers which compensate for losses in the line. The circled crosses and dots are red and green light-emitting diodes which illuminate respectively on the positive crests and negative troughs of the wave. The complete system is rotated in an anti-clockwise direction to bring the wave system to rest in the laboratory.

Energising the linear repeater amplifiers in the completely closed circular loop causes an oscillation to build up in which a sinusoidal wave with a period of approximately 120 ms propagates around the system in a clockwise direction. A slight roll-off in the response of the system, together with the maintenance of just sufficient gain to compensate for the losses, ensures that the waveform remains sinusoidal for long periods of time. The continuity of the continuously cycling sinusoidal wave places the system in the general category of phase-locked particles (Jennison and Drinkwater 1977, Jennison 1978, 1980, 1981), the particular mode corresponding to one complete wavelength around an annular system.

The whole system is arranged mechanically in a well balanced configuration on a strong laminated plastic disc, and power to the repeaters is supplied from two small batteries strapped symmetrically behind the disc. At the centre of the disc there is a hub which is firmly attached to a small variable speed electric motor.

Upon energising the repeater amplifiers, a travelling wave moves round the system in a clockwise direction and the travelling field may be sampled at take-off points associated with each of the capacitors. The 32 elements, given a sufficiently close approximation to a continuous line and a reasonably pure sinusoidal wave, may be detected passing each of these points. An alternative display system consists of a set of red light-emitting diodes, each of which glows upon the passage of the positive crests of the wave, and a set of green light-emitting diodes, each of which glows upon the passage of the negative troughs. The disc when at rest then exhibits a circle of rapidly flickering red and green lights corresponding to the circular rotation of the wave system at about 8 Hz.

The disc is now spun in an anti-clockwise sense at such an angular frequency that it is precisely equal and opposite to that of the wave. At this velocity, the wave, whilst still travelling relative to the disc, becomes stationary in the laboratory. The resulting potentials may be sampled to confirm the stationary state of the field system, but the most vivid demonstration of its state is given by the light-emitting diodes which form two stationary arcs, one of positive (red) and the other of negative (green) potential. With careful adjustment of the speed of rotation, this static dipole electric field may be maintained indefinitely in the laboratory.

It should be stressed that the effect is truly that of a static field and neither a rapidly reversing field, as in standing wave systems, nor a stroboscopic artefact. The crests and troughs of the travelling wave are truly brought to rest in the laboratory and, indeed, it is possible to reverse the original direction of propagation by increasing the rotational speed of the motor. The production of a static field system from the travelling wave system implies that charge has been produced from a travelling wave, and this has a bearing on the basic 'chicken-and-egg' concept of their relative fundamental roles. Quantised fundamental charges occur in particles where they co-exist with clearly exhibited quantised magnetic fields and quantised angular momentum, and it is an open question whether or not these fundamental charges are themselves formed from a singular permitted quantity of rotating and, possibly, convoluted electromagnetic field which gives rise to the effects of charge and magnetic moment. In the case of a transmission line connected to an external antenna, radiation from free space falling upon the antenna will supply electromagnetic energy into the line, which will force the ambient conduction electrons into appropriately induced patterns which mirror the propagation of the wave down the line. The prime-moving energy is nevertheless that of the wave. In the present case it can be argued, on similar grounds, that the field system forms a charge where no charge existed before, and that the conduction electrons are simply induced by the wave field to maintain an appropriate distribution in the laboratory but do not themselves create the static charge, for the energy and the prime-moving field have come from the original travelling wave.

An interesting conceptual problem arises with regard to the magnetic field of the wave. I am grateful to Dr J A Ratcliffe and others for very interesting discussions on this conundrum. The particular apparatus described here is not designed in such a way that the magnetic field may be sampled and there can be two schools of thought on whether or not it is also stationary. One argument is that, as the charges are not moving in the laboratory, there ought to be no magnetic component. The other argument is that, as the travelling wave has a magnetic field in phase with the electric field, this magnetic field should appear stationary when the electric field is rendered stationary. It appears that the first argument is fallacious, for it ignores the motion of the system relative to the wave, and there is also no known mechanism whereby the Maxwellian property of the wave system should break down even when the velocity, relative to the observer, is reduced to zero. There is again an analogy with the fields of fundamental particles, but in order to produce a unipolar electric field together with a dipolar magnetic field, the original wave may have to be convoluted, perhaps into the form of a Mobius strip, without constraint by the transmission line, for the field must twist relative to itself and this cannot be achieved by twisting the relatively moving line.

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