The end of electric charge and electric current as we know them.
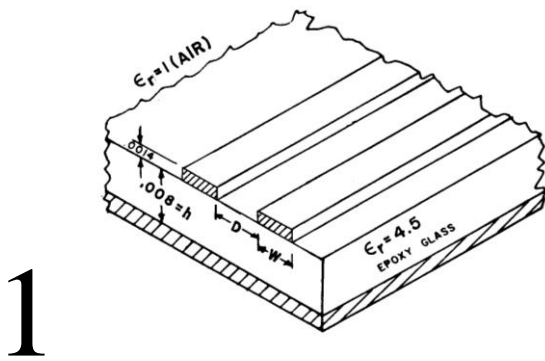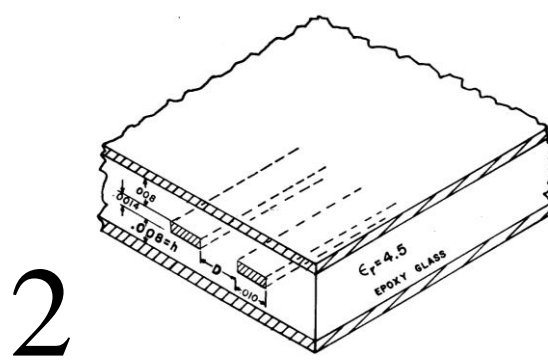
Ivor Catt. 15 July 2010

Under Faraday's Law, $\left(V = -\dfrac{d\phi}{dt} \right)$, which forbids superposition but whose mathematics permits it, we end up with two electric currents travelling in opposite directions down the same conductor.
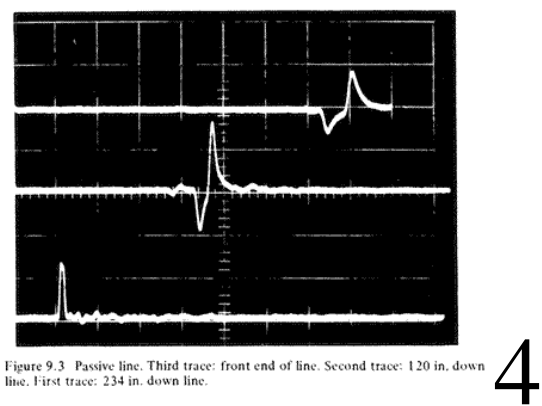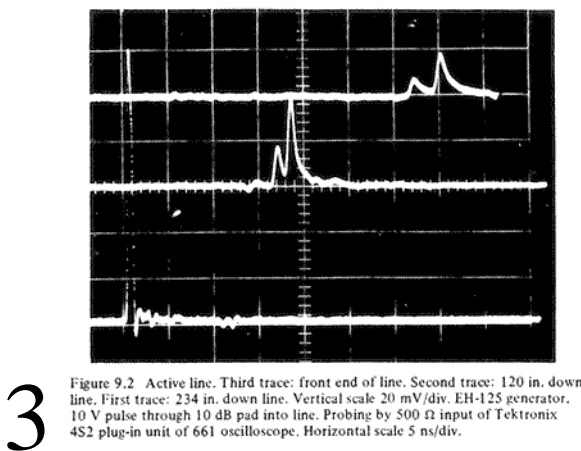
I inject a very narrow voltage spike between the left hand conductor and the ground plane in a surface conductor 1 (microstrip).


1

Surface conductor (Microstrip).

2

Buried conductor (Stripline).

3

Figure 9.2 Active line. Third trace: front end of line. Second trace: 120 in. down line. First trace: 234 in. down line. Vertical scale 20 mV/div. EH-125 generator. 10 V pulse through 10 dB pad into line. Probing by 500 Ω input of Tektronix 4S2 plug-in unit of 661 oscilloscope. Horizontal scale 5 ns/div.

4

Figure 9.3 Passive line. Third trace: front end of line. Second trace: 120 in. down line. First trace: 234 in. down line.

The bottom trace in the left hand photograph 3 shows the introduced voltage spike, and the bottom trace in the right hand photograph 4

shows the smaller spike immediately resulting in the right hand conductor. The later second and first traces show how the signal develops further down the pair of conductors. It separates out into, first, an Odd Mode signal with equal and opposite voltage spikes on the pair of lines, followed by a slower Even Mode signal of equal positive spikes.

In the case of buried conductors 2 (stripline), the two modes travel at the same velocity and do not separate out, as shown in photos 5 and 6.
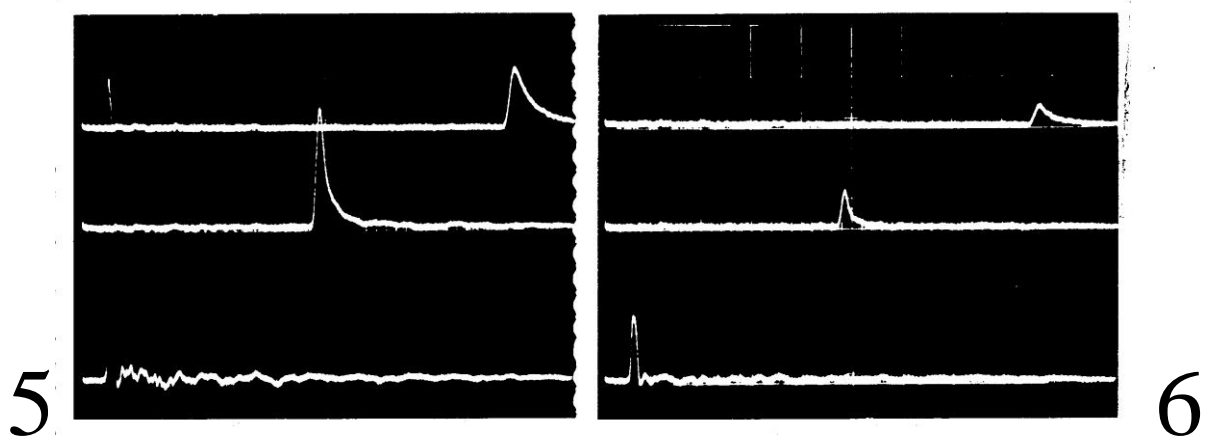

Now let us look at the case of surface conductors 1 when the front end of the right hand passive conductor is shorted to ground so that there can be no voltage there.
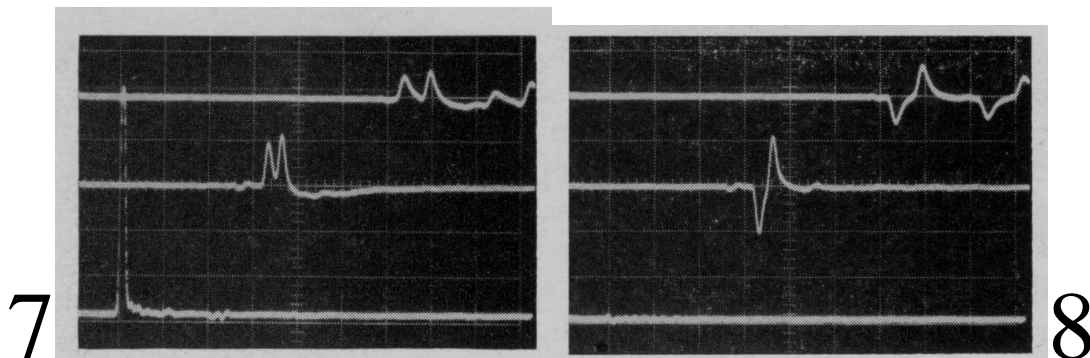
In Figures 7 and 8 we see that in the earliest, bottom traces the initial zero voltage in the right hand conductor must have been two equal and opposite voltages superposed. There must have been equal and opposite charges on the surface of the right hand conductor, and equal and opposite electric currents flowing in and out of this conductor. As we see below in the field patterns, in the Even Mode, the right hand conductor is positive and so electric current flows into the paper, generating the field pattern shown. Meanwhile, in the Odd Mode, the

right hand conductor is negative so electric current flows out of the paper.

Looking back, this must have been happening in all traces in Figures 5 and 6 and in the bottom traces in photos 3 and 4.
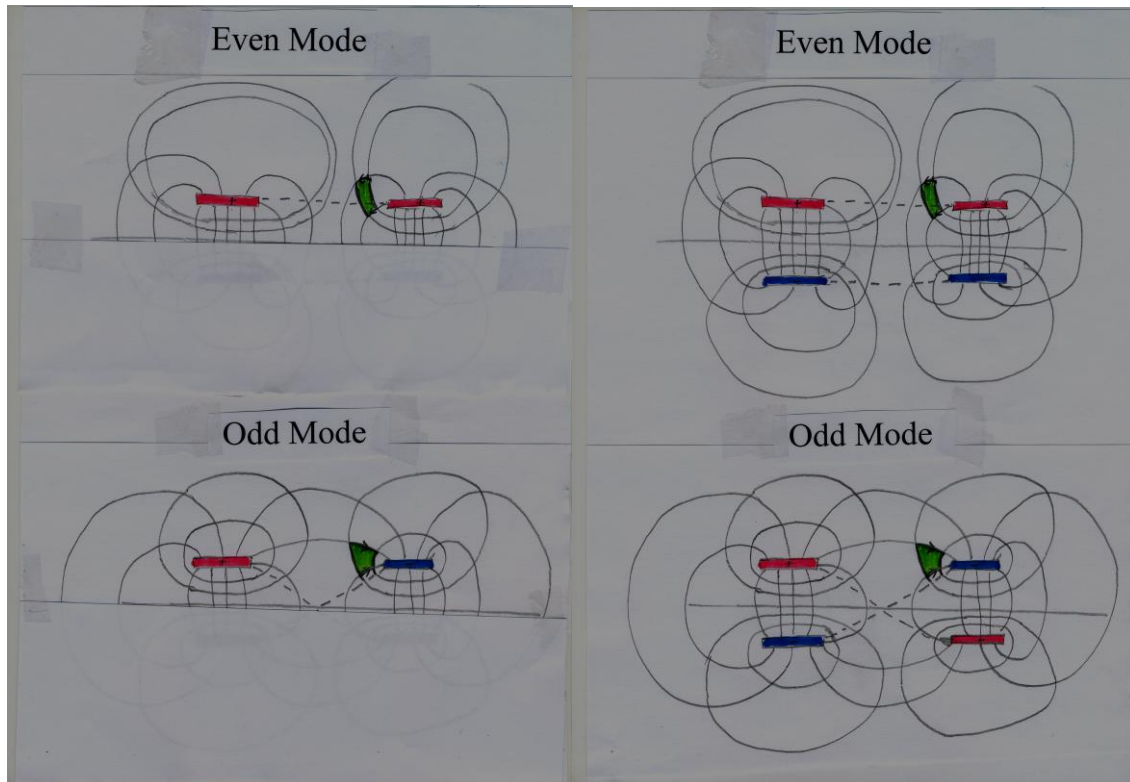
It is simpler to think of four conductors rather than two conductors and a ground plane.

First, assuming a TEM Wave, I mathematically prove that only one voltage/current ratio and one velocity can travel down between a conductor and ground plane.
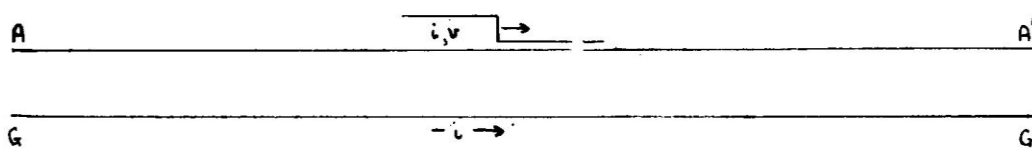

Diagram of a two wire transmission line. (Figure 51.)

Now in time δt, the current step will have traveled a distance δs, where $\delta s/\delta t = c$.

The change of flux in the loop $AA'\ G'G$ will be

$$\delta\phi = L\delta s \cdot i. \qquad (18)$$

Substituting in (17) for $\delta\phi$ brings

$$v_{\text{back EMF}} = -\ Li\frac{ds}{dt} = -\ Lic. \qquad (19)$$

Now the total voltage around the loop $AA'\ G'G$ must be zero, by one of Kirchoff's laws.

So there must be an impressed voltage placed across AG where

$$v_{AG} = -\ v_{\text{back EMF}} = Lic. \qquad (20)$$

Equation (20) gives one necessary condition relating voltage, current and velocity for the current step. There is a second condition, which derives from the principle of conservation of electric charge. Current, and therefore charge, is continually entering the conductor AA' at A, and this current charges the line AA' relative to GG' to a voltage v.

Let C be defined as the capacitance per unit length between the conductors AA' and GG':

$$C = \frac{q}{v}.$$

Now in a time δt, a quantity of charge $\delta q = i\delta t$ will charge up a length of line δs to a voltage v. The capacitance of this length δs is $C\delta s$. Therefore

$$C\delta s = \frac{i\delta t}{v}.$$

Rearranging,

$$v = \frac{i}{Cc}. \qquad (21)$$

Equations (20) and (21) give the two necessary conditions relating voltage, current and velocity for a current step traveling down two parallel lines.

If (20) is divided by (21),

$$\frac{v}{v} = \frac{LicCc}{i}$$

$$\therefore c = \pm\ \frac{1}{\sqrt{LC}}.$$

We neglect the negative solution, because we are interested only in signals traveling from left to right.

$$\therefore C = +\ \frac{1}{\sqrt{LC}}. \qquad (22)$$

Substituting for c in (20) we get

$$\frac{v}{i} = +\ \sqrt{\frac{L}{C}} = \text{characteristic impedance } Z. \qquad (23)$$

Conclusion: If a current voltage step v, i, travels down a pair of parallel lines, the following conditions always apply:

$v = iZ$, where Z is a constant for the lines.
$c = 1/\sqrt{LC}$ where L and C are constant for the lines.

APPENDIX I

Proof that Only One Type of Wave-Front Pattern Can Be Propagated Down a Two-Wire System

In Fig. 51, assume that a current–voltage step i, v, is traveling down the parallel lines AA', GG' from left to right with a velocity c. Assume that no change of current, voltage or electromagnetic fields is taking place except in the plane at right angles to AA' passing through the point where the step is at that moment. At every point to the right of the step, the voltage between the two lines is zero and the current is zero. At every point to the left of the step, the voltage between the two lines is v, the current in AA' is i and the current in GG' is $-i$.

Now use Faraday's law of induction around the loop $AA'\ G'G$. This later became one of Maxwell's equations (reference [15], page 302). The law states that the total voltage induced around a contour C (in this case $AA'\ G'G$) is equal to the negative time rate of change of magnetic flux through this contour

$$v_{\text{back EMF}} = -\ \frac{d\phi}{dt}. \qquad (17)$$

Now define L as the self-inductance per unit length of the pair of conductors AA' and GG'

$$L = \frac{\phi}{i}.$$

Then, again assuming a TEM Wave as shown in photographs 3 to 8, I prove that only two signals, the Even Mode and the Odd Mode, can travel down between two parallel conductors and a ground plane.
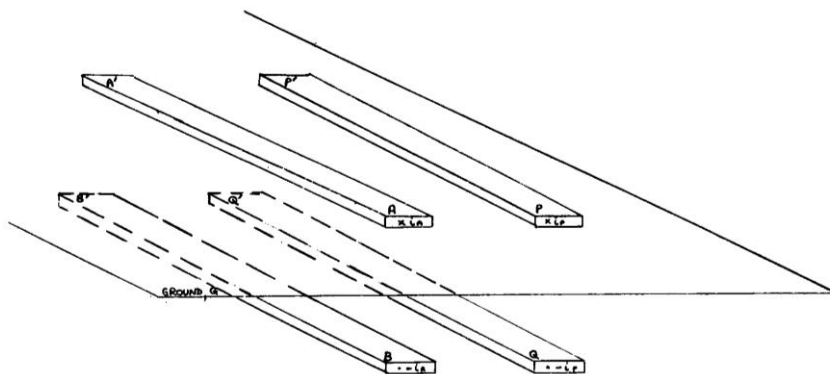

Diagram of two parallel conductors above a ground plane, and their images. (Figure 52.)

APPENDIX II

PROOF THAT ONLY TWO TYPES OF WAVE-FRONT PATTERNS CAN BE PROPAGATED DOWN A SYSTEM OF TWO WIRES AND GROUND PLANE

In Fig. 52, the method of images is used; it is assumed that $i_B = -i_A$, $i_Q = -i_P$. The following terms are defined for steady state conditions:

L = Magnetic flux per unit length between AA' and BB' when unit current flows down AA' and back on BB'.

M = Magnetic flux per unit length between AA' and BB' when unit current flows down PP' and back on QQ'.

C = Charge per unit length on AA' and BB' which produces unit voltage drop between AA' and BB' = 1/coefficient of capacitance.

D = Charge per unit length on AA' and BB' which produces unit voltage drop between PP' and QQ' = 1/coefficient of induction. This could well be called "Mutual Capacitance."

Now assume that a wave front involving current steps i_A and i_P is traveling down the lines with a velocity c.

From $v = d\phi/dt$ between AA' and BB', we get (as in (19)),

$$v_{AB} = Li_A c + Mi_P c. \tag{24}$$

Similarly $v = d\phi/dt$ between PP' and QQ', so

$$v_{PQ} = Li_P c + Mi_A c. \tag{25}$$

Also, from $v = q/C$, (as in (21)),

$$v_{AB} = \frac{i_A}{Cc} + \frac{i_P}{Dc} \tag{26}$$

$$v_{PQ} = \frac{i_P}{Cc} + \frac{i_A}{Dc} \tag{27}$$

First find c.
Eliminate voltages from (24) through (27).
From (24) and (26),

$$Li_A c + Mi_P c = \frac{i_A}{Cc} + \frac{i_P}{Dc}$$

$$Li_A c^2 + Mi_P c^2 = \frac{i_A}{C} + \frac{i_P}{D}$$

$$\therefore \frac{i_A}{i_P} = -\frac{\left(Mc^2 - \dfrac{1}{D}\right)}{\left(Lc^2 - \dfrac{1}{C}\right)}. \tag{28}$$

Similarly, from (25) and (27),

$$\frac{i_A}{i_P} = -\frac{\left(Lc^2 - \dfrac{1}{C}\right)}{\left(Mc^2 - \dfrac{1}{D}\right)}. \tag{29}$$

Eliminate i_A and i_P from (28) and (29) to get

$$c = \pm \sqrt{\dfrac{\dfrac{1}{C}+\dfrac{1}{D}}{L+M}} \quad \text{or} \quad \pm \sqrt{\dfrac{\dfrac{1}{C}-\dfrac{1}{D}}{L-M}}.$$

So in the forward direction there are two possible velocities of propagation,

$$c_e = +\sqrt{\dfrac{\dfrac{1}{C}+\dfrac{1}{D}}{L+M}}$$

or

$$c_o = +\sqrt{\dfrac{\dfrac{1}{C}-\dfrac{1}{D}}{L-M}}.$$

Returning to (28) and using the results for c, we find that the following two wave fronts are possible:

1) EM wave
$$c_e = \sqrt{\dfrac{\dfrac{1}{C}+\dfrac{1}{D}}{L+M}}$$

$$Z_{0e} = \sqrt{(L+M)\left(\dfrac{1}{C}+\dfrac{1}{D}\right)}$$

$$i_A = i_P$$
$$v_{AB} = v_{PQ}.$$

2) OM wave
$$c_o = \sqrt{\dfrac{\dfrac{1}{C}-\dfrac{1}{D}}{L-M}}$$

$$Z_{0o} = \sqrt{(L-M)\left(\dfrac{1}{C}-\dfrac{1}{D}\right)}$$

$$i_A = -i_P$$
$$v_{AB} = -v_{PQ}.$$

This was "proved" by the upper two traces in photographs 3, 4, 7 and 8. However, for 43 years I failed to notice that the bottom traces in these photographs, and all the traces in photographs 5 and 6, give an illegal asymmetrical, third mode, which is a combination of an Even Mode and an Odd Mode. On their own, Even Mode and Odd Mode are symmetrical with respect to the four conductors.

Clearly, physical reality was disproving a conclusion derived mathematically from Faraday's Law, that only the Even Mode and the Odd Mode were permissible. Faraday's Law does not permit the superposition of two permissible modes, which become a third, illegal mode. One reason why it is illegal is that the electric currents in the right hand conductor are in opposite directions for the two modes, and classical theory says there cannot be two electric currents in opposite directions along a single conductor. However, two electromagnetic waves (or light rays) can be in the same point in space, for instance

when we shine a torch at another lighted torch pointing in the opposite direction, or when we send two pulses from left and right through each other down a coaxial cable. Similarly, the Even and Odd Mode TEM Waves in our photographs can coexist, but not their associated electric charges and currents.

A clue to the resolution of this problem is in the article;

Cause and Effect in Mathematics

Electromagnetic theory grew out of the perusal of such things as magnets, electrically charged bodies and the rest. This led to such concepts as electric charge and electric current, static electric field and static magnetic field. Faraday discovered that a slowly changing magnetic field generated electric current. Much later, dubious mathematics was applied to such steady state things by Maxwell, expanding to slowly changing "electric currents" and thence to displacement current, the latter deriving from theoretical problems with slowly changing electric current and the capacitor. Maxwell's invention of Displacement current led to the idea that sunlight was electromagnetic.

During this development of electromagnetic theory, there were no rapidly changing fields, and no electromagnetism travelling very fast, for instance at the speed of light. Later, in around 1880, Oliver Heaviside first addressed fast travelling electromagnetism in a sophisticated way.

Now supposing, instead of with static fields and devices such as stationary magnets, we had started with sunlight, which we have always known about. Had we had the appropriate instruments, we would have found out, if it was not already obvious, that sunlight was two dimensional energy density, and travelled in the third dimension at the speed of - light.

In the early case of Maxwell, the Transverse Electromagnetic (TEM) Wave, or light, is the result of much mathematical manipulation, starting with magnets, electrically charged bodies and the like.

Now all this mathematical manipulation from electricity and fields to light is reversible, since mathematics ignores causality, or even direction in its equations. Since we know about sunlight, it is equally legitimate to start with sunlight, or the TEM Wave, and work backwards using the same mathematics towards electric field, magnetic field, electric charge and electric current. Only a historical accident caused us to progress in the traditional direction.

In this case, particularly if we accept Occam's Razor, each of the items we derive mathematically have to justify their existence as physically real, rather than merely the results of mathematical manipulation of things which really are physically real. It turns out that, in electromagnetic theory, electric charge and electric current remain merely mathematical manipulations of what went before from our starting point with light, or the TEM Wave. In the case of a battery connected by two wires to a resistor or lamp, they have no function. This is proved by "The Catt Question" because of the dubious, contradictory "answers" by leading experts. We see that

electricity is not quick enough to do the job in hand. This can only be done by the original sunlight, or TEM Wave, which has the necessary speed to get the energy from battery to lamp. This energy travels at the speed of light.

Now we come to the difficult bit. It is pretty clear that the concept of electricity as perceived today started its life in the above role, of helping a battery to heat a resistor or light a lamp. Rubbing a glass rod with cat's fur played a subsidiary role in the origins of "electricity". What are the other, surviving roles for "electricity" in today's science? I can think of the Bohr atom and the cathode ray tube.

The Bohr atom. Part of its role is to supply the "electrons" which expedite the flow of "electricity" from battery to lamp. But this role is discredited by "The Catt Question". However, surely other roles remain today for the "electrons" in the Bohr atom.

The Cathode Ray Tube (CRT). First, a digression. My co-author the late Dr. Arnold Lynch told me he was giving the keynote speech in the IEE to celebrate the centenary of J J Thomson's discovery of the electron. When I asked him why he was chosen, he replied, "Because he told me about it." Now in Heaviside's "Energy Current" approach to electromagnetic theory, the energy current, or TEM Wave delivered by the HT power supply approaches the CRT sideways between anode and cathode, or in the case of the signal input, between grid and cathode. The movement is at right angles to the alleged movement of the "electron". Now the interaction between the TEM Wave arriving as "HT" and the TEM Wave arriving as "signal" is complex. However, since they collide at 180 degrees, their collision should be handled to some degree by the discussion in my book. However, the detail still has to be worked out. When we address the electron, apparently travelling in the wrong direction at the wrong speed, it is useful to consider a wave in the sea approaching us. White foam on top of the wave appears to travel at a lower speed at right angles to the approaching wave.

Tradition

In case it should be feared that the transition described above moves us from a secure foundation to uncertainty, an analysis of the slovenly way in which the journey from "electricity" and fields to light was made, is called for. This is to be found at "Maxwell's Equations Revisited" and "The Hidden Message in Maxwell's Equations.". My article "The Heaviside Signal" discusses how academia cleave to two mutually contradictory versions of the TEM Wave (or light), mostly keeping to the false "Rolling Wave". The flaw in "The Rolling Wave" is concealed by general ignorance about the relative phases of the E field and the H field. When we keep to the truth, that they are in phase, "The Rolling Wave" collapses.

If we begin with light and the TEM Wave and work our theory and mathematics backwards, we can retain everything up to and excluding electric charge and electric current. For other reasons I excluded them in 1976, relegating them to merely being mathematical manipulations of the electric field and magnetic field (or more accurately, of the electromagnetic field). There is a difference. For instance, the

gradient in electric field density (which equals electric charge) does not have mass, whereas electric charge does have.

This article develops from Ivor Catt; "Crosstalk (Noise) in Digital Systems", pub. IEEE Trans. Comput., vol. EC-16, no. 16, December 1967, now at http://www.ivorcatt.co.uk/x0710.htm and http://www.ivorcatt.org/x0710.htm