CFA: working assumption?

Is it possible to synthesise the Poynting Vector directly? CFA designers M C Hately, F M Kabbary and B G Stewart claim innovation in compact aerial systems.

Radio antenna design has traditionally been based on techniques stemming from Hertz's original use of resonant half-wavelength rods. But Poynting vector synthesis, and the crossed field antenna are demonstrating good early results for an alternative approach.

In the crossed field antenna an intense electric field is stimulated using one half transmit power, and an intense magnetic field is separately stimulated using the other half of the power. The two fields are carefully synchronised in time and crossed in geometry so that together they synthesise a powerful electromagnetic wave according to the theory of the Poynting vector:

$$\mathbf{S}=\mathbf{E}\times\mathbf{H}$$

This is a vector equation stating that S, the radiated power density in W/m^2 is the vector cross product (symbol $\times$) of the electric field **E**, in V/m, with the magnetic field **H**, in A. turns /m. The fields employed are intense, but the crossed field antenna is small, typically 3% of a wavelength. The initial wavefronts generated are therefore correspondingly small, but like all unconstrained waves they naturally expand.

Waves created by the CFA are thus just as useful for radio communication as the waves generated by classical antennas.

Previously the circular magnetic field has been stimulated by a capacitor. This was done to ensure the field lines of the E field were not "shorted out" by zero-resistance current-carrying conductors lying in the electric field zone. The approach was based on stimulating a magnetic field by a capacitor following the Maxwell law.

$$d\mathbf{D}/dt = \nabla\times\mathbf{H}$$

meaning that a vector curl H results from there being a change of displacement charge with time. In other words, an RF electric field causes an RF magnetic field with all the geometric properties of the curl.

To cover fully the principles of the CFA in the patent application, the concept of origination of the magnetic field by a stimulating coil has been covered — and does work to a certain extent. But for first production and experimental versions, development effort has been concentrated on forms of CFA using a D-plate capacitor to originate the magnetic field.

Experiments commenced with HF antennas small enough to be carried through a doorway, using fields of sufficient intensity to radiate the full power allowed by the UK amateur licence (400W PEP). A few initial calculations showed that 400W waves from a small device did not need unreasonably high voltage values, and later measurements confirmed that plate voltages are of the order of 300V. The Maxwell form of CFA is also

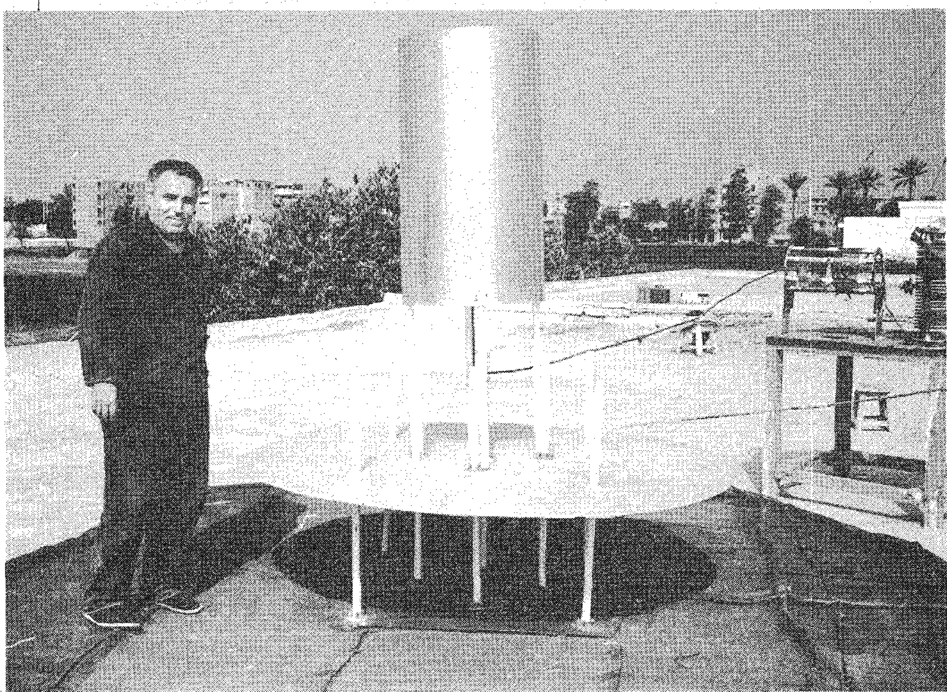


Fig. 1. Experimental medium-wave ground plane CFA radiating 25kW on 350m under test in Egypt.

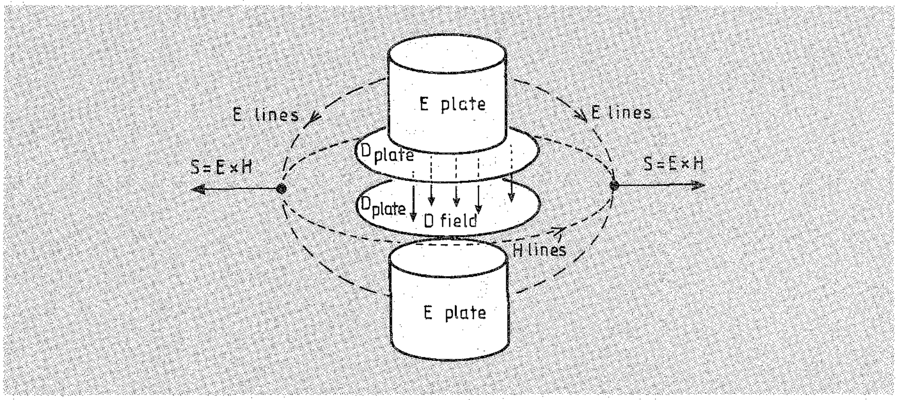


Fig. 2. Barrel-shaped crossed field antenna.

EMC-friendly and not likely to be a danger to users or nearby electronic equipment.

Barrel shaped CFA

When radiating from a small device, wavefronts are small, almost spherical, so the fields are curved.

Unfortunately early experiments used a straight-line electric-field layout, and did not work. When the stimulator electrodes were changed to initiate curved electric fields the antenna immediately became active, with the appropriate phase delay in the feed system.

Very quickly the "barrel shape" structure (**Fig. 2.**) was evolved as the optimum shape for generating omnidirectional vertically polarised radio waves.

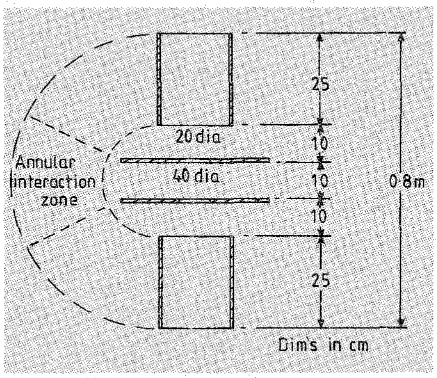


Fig. 3. Dimensions of the barrel-shaped CFA for HF.

In the barrel-shaped CFA the Poynting vector is synthesised in an annular "interaction zone" (**Fig. 3.**) around the centre of the device which is usually mounted upright. From the interaction zone a stream of vertically polarised waves leave and travel outwards to infinity at the velocity of light.

The antenna has circular symmetry in the horizontal plane, so the polar diagram of the intensity of radiation in the horizontal plane is a circle around the antenna.

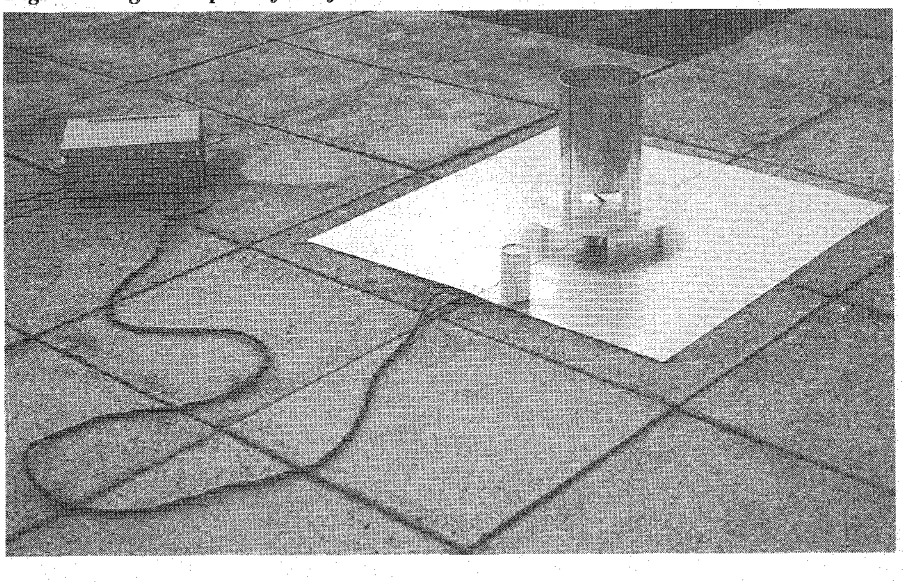
The vertical radiation pattern has a broad maximum in the equatorial plane (provided the antenna is being supported far enough above ground) and there are two minima, one above and one below the CFA.

In space the CFA has the classic doughnut shape of the dipole held well above ground. Although it is less than a metre high it is possible to radiate any frequency from 2MHz to 30MHz; wavelengths from 150m to 10m.

In fact the CFA's size means it is tempting not to hold it at the right height, and to try to radiate from near the ground with wavelengths many times its mounting height.

But the CFA cannot defeat nature and the result of mounting at a small fraction of the wavelength radiated, is partial cancellation of the radiation to low angles of elevation. This is due to destructive summation with the antiphase signal from the bottom half of the device reflected off the ground.

Fig. 4 CFA ground plane form for HF



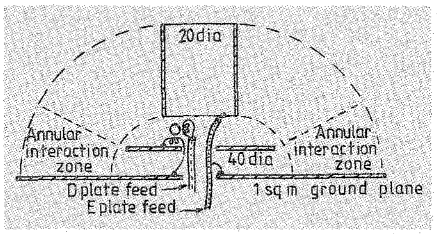
Ground plane CFA

To overcome the problem of radiating long waves from ground height, a form of CFA has been designed in which the CFA is bisected, and the lower half replaced by a reflecting surface; a ground plane (**Fig. 4.**) An addititonal advantage of the GP CFA form is that the feed system to the E plate is unbalanced and hence ideal for direct connection of coaxial cable. Unfortunately the requirement for plate-phase independence demands a transformer, so one is fitted in the D-plate feed and coax is again used.

A hollow cylinder forms the E plate with a single disc electrode forming the D plate. A ground plane, of area about $1m^2$, behaves as the common field-termination surface against which both the E field and the D field are expressed. The magnetic field stimulated around the D plate must flow above the ground plane (eddy currents will keep it away) and the E field cuts and crosses it at right angles. The ground plane CFA operates successfully giving low VSWR figures at the common input port even when the antenna is radiating wavelengths as large as 20–80M plus, and from zero height or low situations, on buildings.

Figure 5 shows the general HF-range ground plane CFA kit for amateur use and commercial evaluation.

Fig. 5. HF ground plane CFA kit for evaluation.



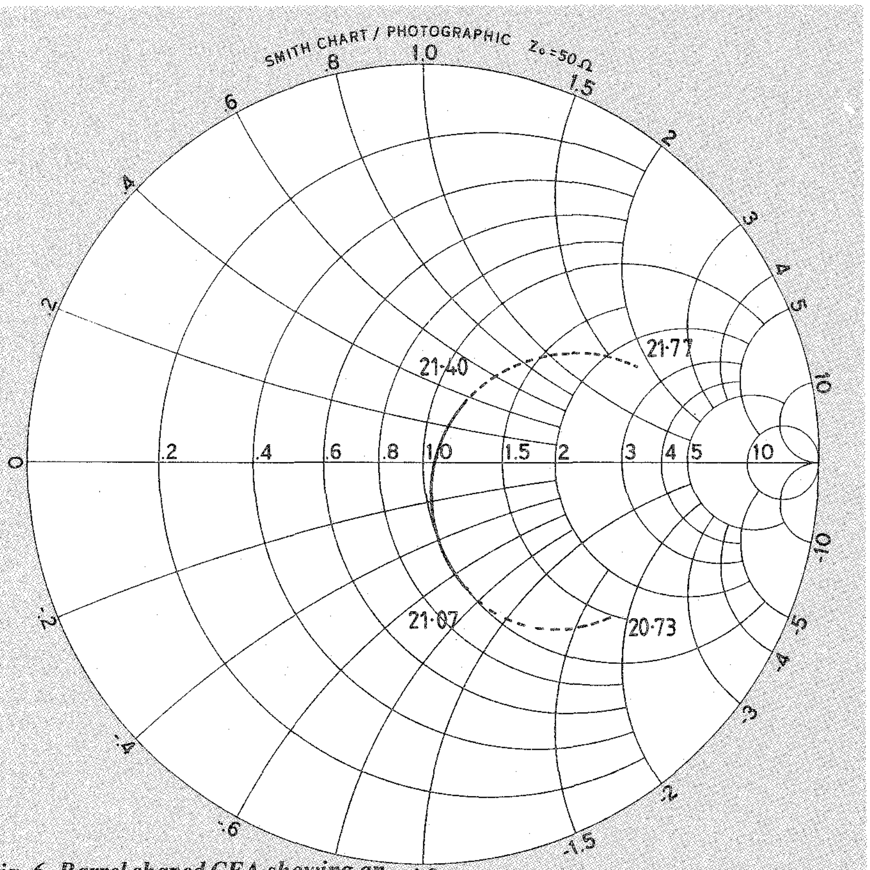


Fig. 6. Barrel shaped CFA showing an unusually wide bandwidth. 21MHz.

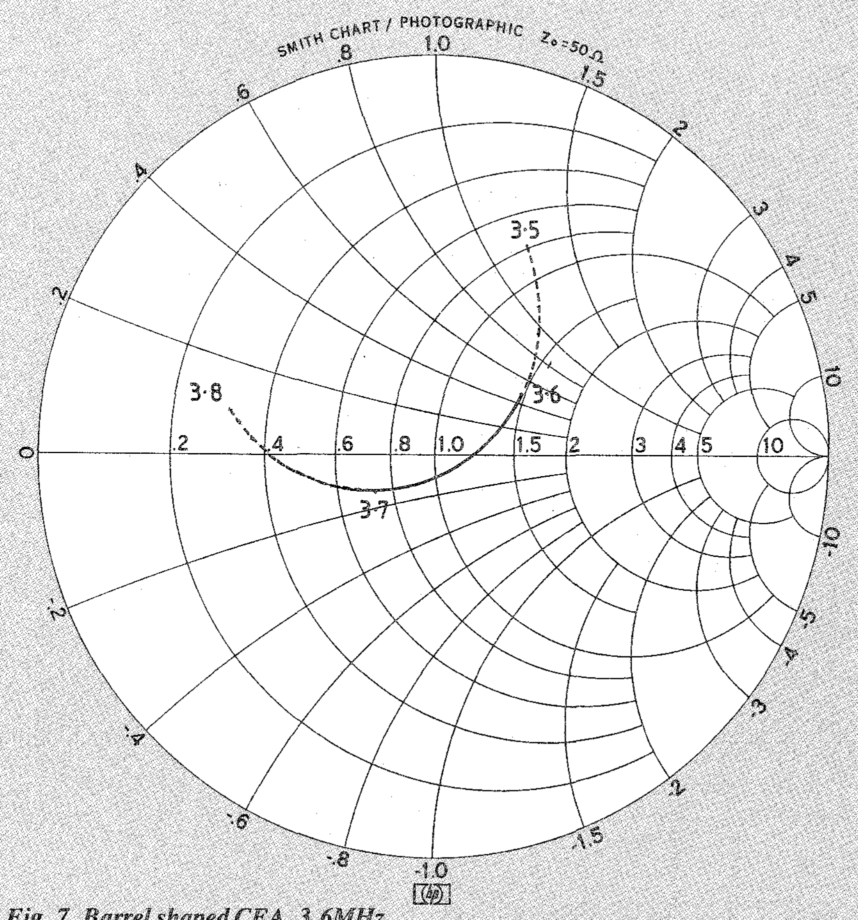


Fig. 7. Barrel shaped CFA. 3.6MHz.

Input impedances

When the CFA is operating, input impedances seen at the two separate electrode input ports are moderately valued and contain resistance, which is itself a cogent evidence of real radiation. The plates may be fed either directly or by using a step-up or step-down transformer. For feed via coaxial cable, primaries are normally constructed as isolating coils.

The input impedance of prime interest to the antenna user is not that at the electrodes, but that at the single feeder entering the phasing unit. Provided the phasing unit is well designed it can produce voltage magnitudes and phases able to synthesise the Poynting vector around the CFA somewhere in the interaction zone. The common feeder impedance then is close to 50Ω.

When the wavelength becomes very long compared with the physical size of the CFA it is more difficult to adjust the "in-phase" situation for the incoming fields at the interaction zone. In fact if the antenna is set up to radiate say 10MHz and then the transmitter frequency changed, the error in phase angle caused by change in the phasing unit internal impedances becomes evident first in depreciation of the field synchronism at the interaction zone. For a given CFA, the interaction zone size is fixed. Proportion of the band which is in phase relates to the size of the interaction zone as a proportion of a wavelength. Thus the longer the wavelength, the more critical must be the phase accuracy to produce interaction at the zone.

Working bandwidth

Fortunately Maxwell types of CFA are not nearly as narrow band as might be expected. Field stimulators are capacitors and therefore when they go off tune, they both tend to change in the same direction so the resulting error between them is minimised. Had a coil been used for stimulus of the magnetic field, the phase errors would have been opposite and their difference, presumably, more severely affected by frequency change.

A typical Smith chart of the measured single feeder input impedance normalised to 50Ω on a network analyser shows a band of frequency around 21MHz and an unusually wide bandwidth (**Fig. 6**). The antenna used was barrel shaped with dimensions given in Fig. 3. For operation anywhere within the amateur telephony band of 21.15 to 21.45 it is unnecessary to alter the phasing control of the antenna. At a much lower frequency, 3.6MHz (80m), the boundaries of the input SWR rising beyond 1.5 to 1 are surprisingly wide at about 200kHz (**Fig. 7.**).

Figure. 8 shows the input impedance of the ground plane atenna again at the 3.6MHz band where bandwidth is defined to be the frequency band with SWR 1.5 to 1 or less.

As an experiment the phase accuracy of the feed stimuli were deliberately upset by known angles and the power radiated noted. Output power versus electrical degrees phase error plotted for the full range of frequencies of HF (**Fig. 9.**) clearly confirms that the phase accuracy requirement becomes more severe as frequency goes down, at longer wavelengths. **Figure. 10** shows the effect of deliberate phase error on the single-feeder SWR measurements demonstrating that the CFA is a comparatively easy device to adjust.

CFA vs conventional

Two questions inevitably arise; if the CFA fields are so modest, why are the fields around a classical antenna so fierce and extensive? And if the CFA is so small, why do classical antennas have to be so large?

The answer to the first lies in the cycle by cycle inefficiency of classical wire antennas revealed in the typical Q of the average half-wave dipole of around 10. Almost all the energy stimulated by the classical antenna is stored in the induction fields (alternately electric then magnetic) and returned to the system four times each cycle. Only a fraction of the induction field is radiated.

In the CFA most of the energy gets away as radiated field each cycle.

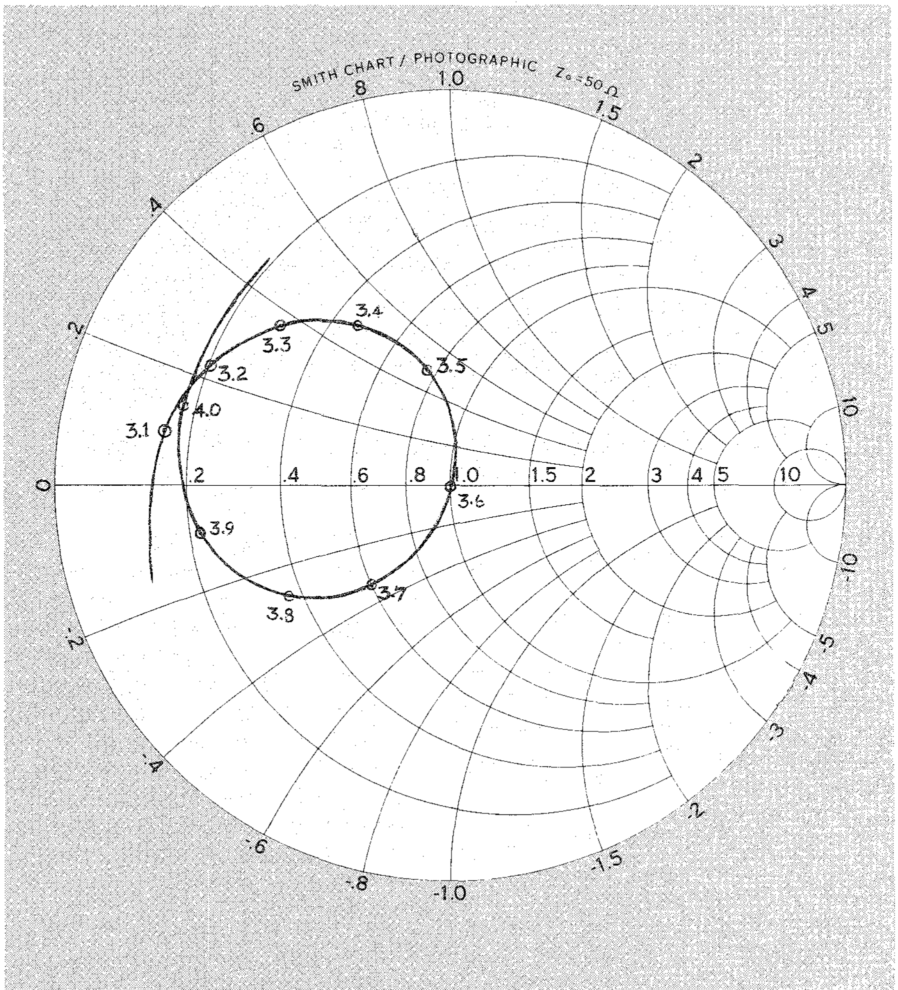


Fig. 8. Ground plane CFA. 3.6MHz.

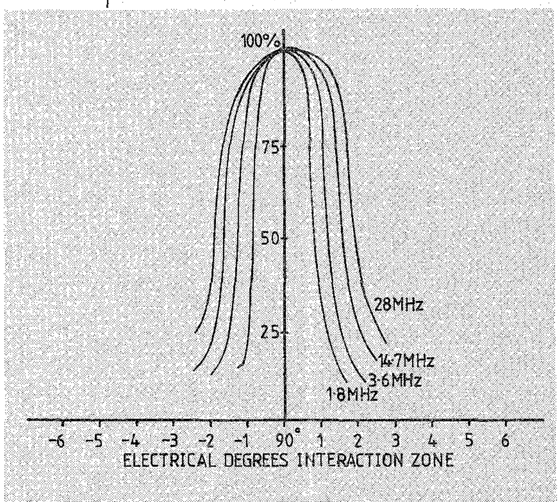


Fig. 9. % radiated power vs plate phase difference shows phase accuracy requirement becomes more severe as frequency goes down.

There is a very small induction field around the device; the interaction zone field(s). This can be verified by experiment or by consideration of the values of SWR — almost 1 for correctly phased input energies. The phasing unit can typically arrange correct phase for the feeds over a 10 to 1 frequency working band.

The second question concerns correct timing of the two field components to produce the Poynting vector.

It is a feature of the CFA that the crossed and superposed E and H fields have to be carefully synchronsied in phase. This is achieved by splitting the power into half at the phasing unit, passing the two halves into separate, adjustable 45° phase lead and phase lag circuits, and then feeding to separate stimulating electrodes.

In contrast to the CFA, the classical antenna cannot achieve field time-synchronism close to itself (cf a resonant wire where current maximum and voltage maximum occur a quarter of a cycle apart). But if the antenna wire is large enough, it can achieve field phase synchronism for that part of the induction field fluxes which are located a significant distance away — a fortuitous accident ensuring success.

It may be explained using **Fig. 11.** The magnetic field flux spreads from the wire in a radial manner. But the electric field lines spread from the conductor parts well away from the centre of the wire antenna along circumferential paths. So they are longer and experience more delay.

Consequently only a small fraction of the electric and magnetic lines achieve synchronism, occuring within an annular region some λ/π about (0.318

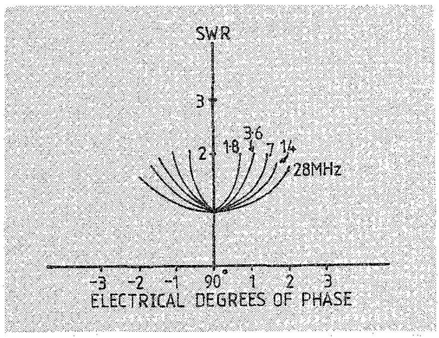


Fig. 10. SWR plotted against plate phase differences suggests the CFA is comparatively easy to adjust.

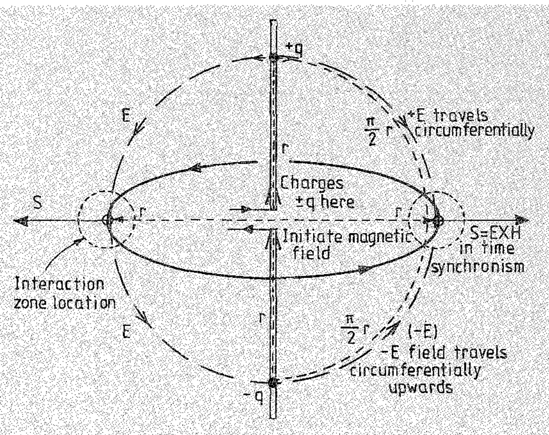


Fig. 11. Radiation by a half-wave dipole.

Phase advance is +time; phase delay is −time. All effects move with velocity of light c.

The crossed fields successfully launch a Poynting vector from a comparatively narrow annular interaction zone (IZ), distance r from the dipole, where the phase error is zero. It is desired to calculate r.

E has come from charges ±q stationary at the instant shown, distance r along the conductors, having entered the dipole time +r/c before, from the balanced feeder on the left. The E field travels circumferentially around the paths $\pi/2$ r long and arrives at the IZ delayed by additional time $-\pi r/2c$.

H has come from moving charges ±q which entered from the feeder half a cycle earlier; at time $+\lambda/2c$. This magnetic effect has expanded radially, distance r, to reach the IZ as shown also delayed by −r/c.

Totalling all the effects to zero time error, r can be calculated:

$$0 = +\frac{r}{c} - \frac{\pi r}{2c} + \frac{\lambda}{2c} - \frac{r}{c} \qquad \frac{\lambda}{2} = \frac{\pi r}{2}$$

$$0 = -\frac{\pi r}{2c} + \frac{\lambda}{2c} \qquad r = \frac{\lambda}{\pi}$$

wavelength) away from the wire.

It is not surprising then that cycle-by-cycle efficiency is so poor; most of the intensely field-stressed volume near the wire contains energy that cannot co-synchronise to synthesise a Poynting vector and fly away as a wave. Every quarter cycle the induction-magnetic or induction-electric fields collapse back to the antenna giving it self inductance and self capacity.

By contrast the properly adjusted CFA has good cycle-by-cycle efficiency, a low Q, wide bandwidth, and fair efficiency with comparatively low plate voltages. Performance limitations of the CFA are set by impedance and phase variations with frequency.

Given a sufficiently adaptable phasing unit, a single CFA can be adjusted to radiate any frequency, within a decade (or more), and is, in this sense, an aperiodic antenna.

Equivalent CFA circuit

Two points should be noted;

1. If either of the fields ceases, the radiation stops.
2. If the phase of the feed to one of the electrodes is reversed, the action ceases, because the electrodes develop high impedance and refuse to accept power. The CFA does not pile up energy inside itself as has been suggested.

A proper equivalent circuit for the CFA has not yet been evolved but will be the electrical equivalent of a chemical reaction or a thermodynamic change of state. Departure of power to space from the two interacting fields represents a unique form of load. The prime fields interact to produce radio waves which fly away to the infinite energy sink of space. An appropriate equivalent circuit must behave in a manner exactly similar to these unusual characteristics.

Broadcasting tests

Successful experiments are proceeding in Egypt with the use of the ground plane form of the CFA for medium wave broadcasting at approximately 0.85MHz (wavelength 350m). Figure 1 shows an experimental ground plane CFA adjusted to radiate 25kW. The original antenna used for this service was a tuned monopole about 75m high. Transmission is satisfactorily received in day-light at a range of 90km, and has a wider band width than the mast and its tuning unit.

The CFA total height is 2m and the ground plane is only 4m in diameter. Ground conditions at the site are normal moist earth, as the locaton is in the Nile delta area.

In a letter, Mahmoud Khattab, Head of Projects at the Egyptian Radio and Television Union has reported some initial results:

"The half-balanced CFA using a ground plane could be designed and adjusted successfully to get an input pure resistive impedance of 34Ω. 50Ω (or more) antenna input impedance can be easily reached by the same arrangements. . .

"In our case the transmitter output impedance was 250Ω, matched to the ground plane CFA radiating 25kW at MF, with no power reflection.

"More field measurements and signal monitoring with modulation are under evaluation at different locations."

"Transmission is satisfactorily received in daylight at a range of 90km, and has a wider bandwidth than the 75m mast and tuning unit"

Receiving capabilities

Does the CFA receive? In short yes. Receiving properties display characteristics of the electromagnetic wave having been analysed; just as the transmitted waves have been synthesised. The phasing unit setting affects the received signals, the setting for maximum received signal is the same as that for low SWR at the input to the phasing unit and maximum transmitted power. Any station using the CFA for transmit can always hear the target stations. The CFA is therefore a practical two way radio communication antenna.

Future applications

The CFA will be of immediate interest for radiating from city centre sites on HF, for example diplomatic and amateur stations. MF broadcasting applications are also expected to develop rapidly since it is small enough to be sited on a building in the centre of a city, and so will be more appropriate to provision of a satisfactory service. Highest signal strengths will be where they are required — in the city centre where RF noise levels are highest.

Radiating to a city from outlying suburban sites, necessary for siting huge antennas for efficiency and protection of nearby listeners from strong induction fields will be unnecessary.

On long wave, LF antennas can be made more efficient, wider in bandwidth and less fussy in tuning, than present antennas.

Experiments are proceding with users of modest powers at LF for navigation aids.

ELF users may be interested when the system is fully proved, since their antennas are very large, expensive and inefficient.

It is also apparent that since waves emanating from the CFA are so small, they can be deflected by a small reflector. Experiments have been performed using a CFA 20cm in size radiating on the 15m amateur band, located at the focus of a 1.5m parabolic dish. The result was not only front to back ratio but also directivity.

Before the CFA, sources of radiation were always so large that this experiment could not be attempted. The traditional belief that a surface must be a large fraction of a wavelength before it can be used to reflect radiation will require modification: "a reflector must be a large fraction of a *wave-front* before it can reflect energy".

Frequency re-use

Crossed field antennas look to have major advantages over conventional antennas in terms of size, efficiency, and lower working voltages. The CFA is not a resonant antenna as its structure is substantially smaller than the radiated wavelength, and it is low Q and broad banded.

Fundamental differences to conventional wire antennas mean it is not surprising that the CFA has attracted hostility from some experts. However the fact that it works, indicates its basis is credible. Furthermore, the theory may be said to have passed the most severe test of a new hypothesis in that it can be used to design new devices.

Poynting vector synthesis has universal application as a design method for compact, efficient, electrically-small antennas, with demonstrated successful application at MF and HF, and experiments at VHF and LF. The technique could provide the solution to the difficult problem of efficient ELF radiation.

In addition the property of small-reflector directivity introduces some interesting possibilities. For instance a medium wave broadcaster could achieve frequency re-use. For example in the north-midland of a country, a ground plane CFA (probably only 4m in size) radiating 300m set on the north side of a flat reflecting screen some 20m high and 20m wide, would direct most of the radiation northwards and provide a service for the audience speaking the language spoken by the people in the north.

In the south-midland (say about 100km distant) a ground plane CFA radiating the same frequency set on the south side of a flat reflecting screen of similar size would direct most of its energy southwards simultaneously providing a different language service for the south region.

On short wave a moving reflector-CFA system could be used to radiate to different target areas at different times of the day. As the CFA can be phased to radiate any frequency, within a decade, even changes required night-to-day can be accommodated, all on the same antenna on a small site, or on a city roof top. ■

Reference

1. Maxwell's equations and the crossed field antenna. F M Kabbary, M C Hately, and B G Stewart, *Electronics World & Wireless World*, March 1989 pp. 216 to 218.