Array and Phased Array Antenna Basics

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John Wiley & Sons, Ltd

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Contents

Preface

Array and phased array antennas are gaining in popularity. They seem no longer to be of interest to military (radar) systems only, but are encountered today in many civilian systems, like for example in mobile communications base stations. An array antenna is a group of individual radiators, positioned in such a way as to produce a maximum radiation into a forward direction. With a *phased* array antenna, we mean an array antenna, wherein we change the phases between the array antenna elements - added to the already existing phase differences due to the differences in position - to create maximum radiation in a desired direction.

One should be aware that for some people all array antennas are *phased* array antennas, due to the fact that the array antenna principle is also based on phase differences. In this book we adopt the term *phased* array antenna for *scanned beam array antennas.*

Over the decades many books have been written, dealing solely or partly with array and phased array antenna theory. The books by Mailloux [1] and Hansen [2], are two fine examples of the many excellent books available.

So, why another book on phased array antennas when there are already so many books on the topic available? The reason for this book lies in the fact that more and more engineers nowadays are getting involved in antenna and (phased) array antenna technology. Not all of them are thoroughly trained in electromagnetics or antennas and are easily scared away by texts that assume a basic understanding of electromagnetics or antennas or both, even if this fear is not realistic.

Often the question arises if it is possible to teach antenna technology without using equations. Although the answer to that question is negative, this book tries to create a compromise, providing an easy-to-read text, explaining antennas in general, based on historical development and physical characteristics rather than mathematics. Chapters 1, 2 and 3 are dealing in this way with, respectively, radiation, antennas and antenna parameters. The mathematics are introduced where and when necessary and then it will appear that the mathematics are not that complicated at all. The mathematical treatment starts in chapter 4, dealing with the broadside linear array antenna. The next chapter, chapter 5, is a 'how to' chapter that will provide the reader with detailed information on how to use the acquired knowledge in the design of a microstrip patch array antenna. Chapter 6 deals with linear endfire array antennas and will treat the Yagi–Uda array antenna in more detail. Chapter 7 is concerned with the linear phased array antenna and is followed again by a 'how to' chapter, chapter 8, wherein the design of a frequency scanned, slotted waveguide array antenna will be dealt with in detail. Chapter 9 then extends the acquired knowledge of linear array and phased array antennas to planar array and phased array antennas and in chapter 10 some special array antenna configurations will be discussed. These configurations are conformal and volume array antennas, sequentially rotated and fed arrays for the creation of circular polarisation and reactively loaded array antennas. Finally, in chapter 11, antenna measurement techniques in general and phased array antenna measurement techniques in particular, including the use of the scan element pattern (also known as active element pattern), will be discussed.

As an additional resource, this book is supported by a companion website on which instructors and lecturers can find electronic versions of the figures. Please go to ftp://ftp.wiley.co.uk/pub/books/visser

The aim of *Array and Phased Array Antenna Basics* is to provide an introduction to (phased) array antennas that will allow the reader to move onto specialist books on the topic with a greater understanding.

Therefore, topics like beam synthesis, phased array antenna errors, beam switching, digital beam forming, array thinning and adaptive array antennas will not be treated in this book.

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1. Robert J. Mailloux, *Phased Array Antenna Handbook*, Artech House, Boston, 1994.

2. R.C. Hansen, *Phased Array Antennas*, John Wiley & Sons, New York, 1998.

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I am most grateful to Dianne, for her patience and understanding during the many evening and weekend hours of neglect that - as I understand now - inherently come with the writing of a book.

H.J.V.

Acronyms

AC	Alternating Current
A/D	Analog to Digital
AI	Aircraft Interception
AM	Amplitude Modulation
ASV	Air to Surface Vessel
AUT	Antenna Under Test
CATR	Compact Antenna Test Range
CH	Chain Home
CRT	Cathode Ray Tube
CW	Continuous Wave
DUT	Device Under Test
HF/DF	High Frequency/Direction Finding
HPBW	Half Power Beam Width
IFF	Identification Friend or Foe
LHCP	Left Hand Circular Polarisation
LORAN	Long Range Navigation
PCB	Printed Circuit Board
PPI	Plan Position Indicator

PRF	Pulse Repetition Frequency
RADAR	Radio Detection and Ranging
RAM	Radar Absorbing Material
RCS	Radar Cross Section
RDF	Radio Detection and Finding
RF	Radio Frequency
RHCP	Right Hand Circular Polarisation
SLL	Side Lobe Level
SGA	Standard Gain Antenna
UHF	Ultra High Frequency
VHF	Very High Frequency
VNA	Vector Network Analyser
VSWR	Voltage Standing Wave Ratio

1

Radiation

The key to understanding phased array antennas is to understand antennas and the key to understanding antennas is to understand electromagnetic radiation. In contrast to what is widely believed, one does not need to be a specialist in integro-differential equations and vector mathematics to grasp the mechanism of electromagnetic radiation. As in Faraday's time, a vast majority of educators prefers the rigor of a mathematical description to the insight of a physical understanding for explaining the mechanism of radiation. It is the author's belief though that the latter is needed first to form the basic understanding and once this understanding has been accomplished, the former may be used to develop this understanding and put it to practical use.

For the basic understanding of electromagnetic radiation one only needs an understanding of electricity and magnetism at a level as educated in secondary school. By following the historical developments in the field of electricity and magnetism, the interaction between the two - electromagnetism - and electromagnetic radiation follows naturally.

1.1 THE EARLY HISTORY OF ELECTRICITY AND MAGNETISM

Research in the field of electricity and magnetism goes back a long way. Hundreds of years BC, experiments dealing with these two phenomena have been described. However, for nearly two thousand years experiments have been concentrated mainly on static electricity. The absence of a source of continuous electrical energy posed a severe limitation in the progress of understanding the underlying physics of the observed electrical and magnetic phenomena. It lasted until the invention of the electric battery

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in 1800 by *Alessandro Volta* (1745–1827) - a logical next step to the famous 'frog-experiments' of *Aloys Galvani* (1737–1798) nine years earlier - before research could be conducted in a reproducible way.

In 1819, the Danish professor *Johannis Ørsted* (1777–1851) observed the change in position of a compass needle, when brought into the vicinity of a current carrying wire, see figure 1.1.

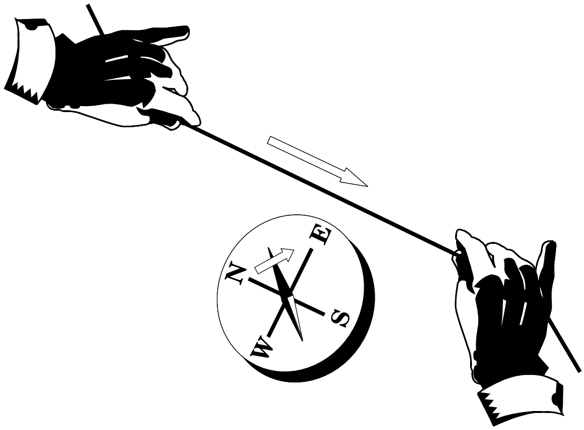

Fig. 1.1 The Ørsted experiment: a current-carrying wire deflects a compass needle such that the needle positions itself perpendicularly to the wire.

This current originated from a voltaic pile. Although Ørsted did not fully understand that the compass needle was not directly influenced by the electric current, but rather indirectly through the induced magnetic field around the current, he did notice the importance of his observation. It opened up the possibility to find a relation between electricity and magnetism. A few months after the publication of his experiences, Ørsted introduced the term *electromagnetism.*

In that same year (1819), the French professor *André-Marie Ampère* (1775–1836) observed a reproduction of the Ørsted experiment at the Parisian Academy. Only a week afterwards he produced a document, giving a theoretical explanation of the experiment. He assumed - correctly - that an electrical current is capable of inducing a magnetic field, see figure 1.2.

It is this magnetic field that explains why parallel currents attract and anti-parallel currents repel. For two parallel currents, the compass needles, indicating the direction of the magnetic induction, are positioned such that they will attract one another, see figure 1.3. For two anti-parallel currents, the compass needles are positioned such that they will repel one another (opposite poles attract, equal poles repel), see figure 1.4.

If we bend a current-carrying wire into a loop as shown in figure 1.5, the magnetic inductions of all parts of the wire add up to form distinct poles at the top and bottom of the loop.

Ampère (rightfully) assumed that in solid matter, microscopic parts contain a circulating current and that in a magnet (like a piece of magnetised iron) all these

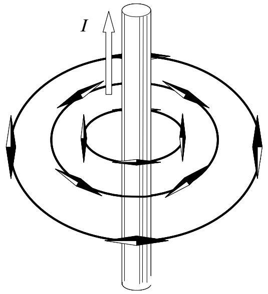

Fig. 1.2 The findings of Ampère: a current-carrying wire creates a magnetic induction around the wire. The direction of the magnetic field may be found by placing compass needles in the vicinity of the wire.

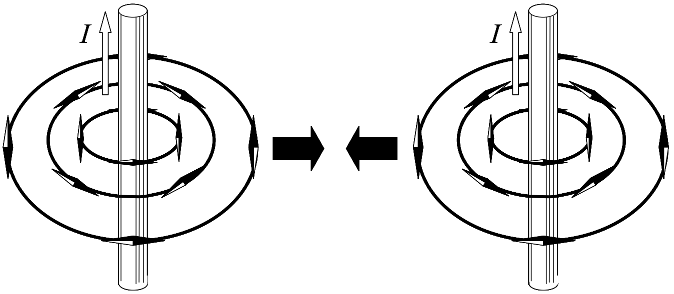

Fig. 1.3 The findings of Ampère: parallel currents attract. The compass needles indicate that the induced magnetic fields are such that the wires will attract. Opposite poles of the compass needles are placed next to each other.

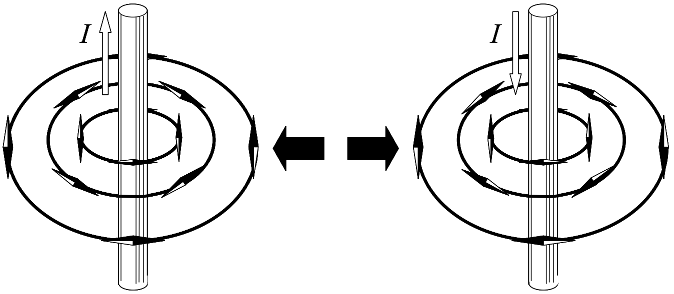

Fig. 1.4 The findings of Ampère: anti-parallel currents repel. The compass needles indicate that the induced magnetic fields are such that the wires will repel. Equal poles of the compass needles are placed next to each other.

microscopic current loops are lined up in the same direction, resulting in the forming of distinct macroscopic magnetic poles. This process is schematically depicted in figure 1.6.

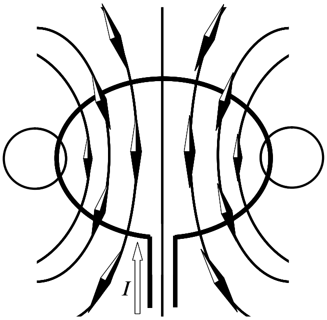

Fig. 1.5 The findings of Ampère: for a current-carrying wire bent into a loop, the magnetic induction of all parts of the wire adds up to distinct poles at the top and bottom of the loop.

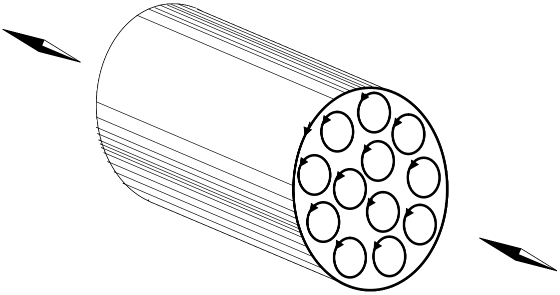

Fig. 1.6 The findings of Ampère: the forming of a macroscopic magnet by the lining up of microscopic current loops.

While Ørsted was conducting his experiments in Denmark, *Michael Faraday* (1791–1867) worked at the Royal Institution in London. Faraday was a remarkable 'self-made' man. With nothing more than a primary school education, he has become famous for his pioneering work in electromagnetism. Faraday is seen as one of the world's greatest experimenters. He succeeded in turning his limited knowledge of mathematics into an advantage, by deducing concepts directly from observations.

In 1831, Faraday observed that a changing electrical current in a coil, induced an electrical current into another coil. He had discovered *electromagnetic induction.* This was an important discovery. Faraday's ideas concerning conservation of energy had convinced him that, while a (changing) electrical current can create a (changing) magnetic field, the opposite must also be true: 'a changing magnetic field must be able to produce an electric field'. One of his experiments, following the discovery of the electromagnetic induction, showed that a *moving* magnet induced an electrical current, see figure 1.7.[1]

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[1] In his first experiment, the changing electrical current applied to a coil took care of the changing magnetic induction, created by moving the magnet in his second experiment.

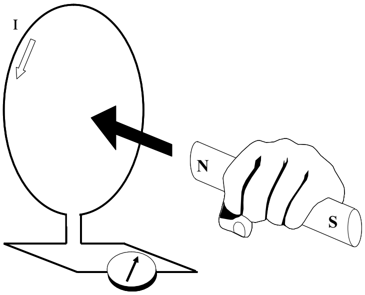

Fig. 1.7 The findings of Faraday: a *moving* magnet induces an electrical current in a loop.

The direction of the current in the loop is such that it opposes the change in magnetic induction. If the north pole of the magnet is approaching the loop, the current in the loop will be directed such that a north pole is formed in the direction of the magnet to repel this magnet. If the north pole of the magnet is moving away from the loop, the current in the loop will be directed such that a south pole is formed in the direction of the magnet to attract the magnet. If the magnet remains static, there will be no current in the loop.

To understand how a magnet influences a wire from some distance, Faraday visualised a 'magnetic field'. He saw this 'magnetic field' as magnetic force lines, laying closer together at places where the field is stronger. These magnetic field lines can be shown by placing compass needles in the vicinity of the magnet, as we have done thus far. These compass needles will direct themselves tangential to the magnetic field lines. More detail can be obtained by using iron filings that may be regarded as very small compass needles. In fact, this is how Faraday constructed his magnetic field lines. In his 1831 notes[2] [1] he wrote,

> By magnetic curves I mean lines of magnetic forces which would be depicted by iron filings.

So, instead of visualising the magnetic field by placing compass needles, as we did in figure 1.2 for a current-carrying wire, we may now draw the magnetic field lines as shown in figure 1.8.

The electrical current, induced in a loop or a (piece of) wire at some distance from the 'source', Faraday expressed in terms of the number of magnetic field lines cut by the loop or wire (flux).

Now, let's have a closer look at the first electromagnetic induction experiment of Faraday, see figure 1.9.

Obviously, we can transport the changing electric field in one coil to an isolated second coil. So, the question arises does this mean that we are dealing with electromagnetic radiation? The answer to that question is: 'No'!

If we take away the changing electric field in the bottom coil, by keeping the switch open or closed, the changing magnetic field vanishes everywhere and no current flows in the top coil. If we had had an electromagnetic radiating system, the changing

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[2] Read at the Royal Society on 24 November 1831.

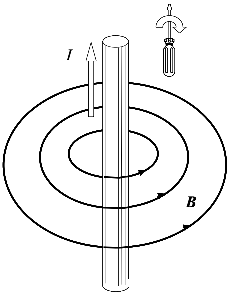

Fig. 1.8 The findings of Faraday: the magnetic field. The direction of the field relative to the direction of the current is dictated by a right-hand screw in the direction of the current. The separation between the field lines is inversely proportional to the magnitude of the field.

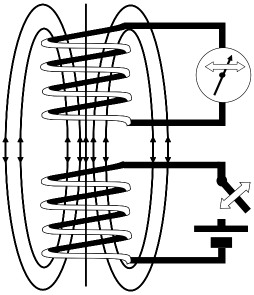

Fig. 1.9 The findings of Faraday: a *changing* electrical current in a coil, induces a changing electrical current into another coil.

magnetic field would have induced a changing electric field, regardless of the presence of the top coil. How the *radiation* mechanism works will be explained further on.

For the moment we will dwell on the bottom coil of figure 1.9 only. If we connect an alternating current (AC) source to the coil, the current through the coil changes continuously and because of that, the magnetic field lines change continuously too. Because of these changing field lines, a current is recreated in this coil. Energy is thus delivered to a magnetic field and this energy is returned to the circuit.

When the magnetic field is increasing, due to the current flowing through the coil, a voltage over the coil is being created. When the current has reached its maximum value and starts to decrease, the magnetic field strength decreases. The coil, however, opposes this change and therefore tries to maintain a voltage over the coil, such that the field remains static. *Therefore the current flowing through a coil lags the voltage over it.*

Thus, because of this energy cycling, the current and voltage of the coil are out of phase. For a radiating electromagnetic field to exist, the electric and magnetic field need to be in phase. The field now is purely a storage field; the energy is stored in the magnetic field surrounding the inductor. If we place a second coil in the vicinity of the first coil, see figure 1.9, we can intercept some of the changing magnetic field lines and thereby create an electric current in the second coil. With the second coil we can thus take energy from the storage field of the first coil.[3]

The field line concept may also be applied to electric fields. Electric field lines are then imaginary lines for which the tangent vector at a given point is directed such as to coincide with the direction in which a positively charged unit charge would accelerate. As with magnetic field lines, the separation between adjacent field lines is inversely proportional to the magnitude of the field. Tightly packed electric field lines indicate a strong field; sparsely packed electric field lines a weak one.

Faraday observed that magnetic field lines (made visible by employing iron filings) originate from one pole of a magnet and terminate on the other. So he imagined that the lines of force of an electrical field would originate on a positive charge and end on a negative charge. It appears that this is not completely true. Magnetised objects always form poles in pairs. Magnetic field lines originate from the north pole of the object and terminate on the south pole of the object. Electrically charged objects however may exist as monopole (positively charged or negatively charged). The field lines are always directed perpendicular to the surface of the charged object. The electric field lines of an isolated, positively charged monopole, start on the monopole and extend radially to infinity, those of an isolated, negatively charged monopole, start at infinity and convert radially on the monopole, see figure 1.10.

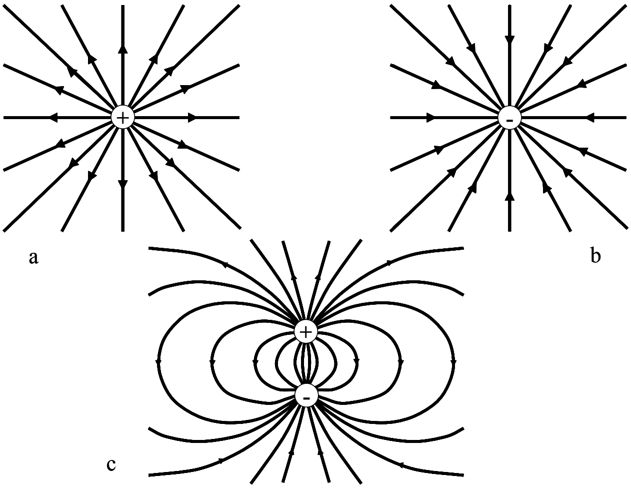

Fig. 1.10 Electric field lines. a: isolated, positively charged point source monopole. b: isolated, negatively charged point source monopole. c: system of one positively and one negatively charged point source.

It was Faraday's belief that the physical lines of force he envisaged were really present everywhere in space, i.e. were an attribute of this space. Even though we know now that this is not true, we do understand that a magnet or electric charge brought into empty space, modifies this space. It is this understanding that formed a breakthrough in the nineteenth century in explaining the action-at-a-distance

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[3] Of course the battery has to replenish the energy taken from the storage field.

which occurs between (magnetic, electrically charged or gravitational) objects. It was Faraday's genius that perceived the concept of a field to explain how e.g. a charged object affects the surrounding space. When another charged object is brought into this space, it becomes affected by the field of the object already present as opposed to the object itself.

1.2 JAMES CLERK MAXWELL, THE UNION OF ELECTRICITY AND MAGNETISM

In the year that Michael Faraday discovered electromagnetic induction (1831), *James Clerk Maxwell* (1831–1879) was born in Edinburgh, Scotland. In contrast to Faraday, Maxwell received an academic education and evolved not into a experimental scientist but a brilliant thinker and mathematician.

Although Maxwell has performed monumental scientific work, like for example proving that the rings of Saturn are made up of dense particles (1859) and demonstrating the first ever colour photograph (1860)[4] [2], he is best known for what are currently called the *Maxwell equations* (1873).

The remarkable thing about the Maxwell equations is that he did not derive all of them, but rather saw the connection between Ampère's, Faraday's and Gauss's law. By extending Ampère's law with what he called a *displacement current* term, electricity and magnetism became united into electromagnetism. With this displacement current term added, the equations governing electricity and magnetism allow electromagnetic waves to exist, light being one out of a spectrum of waves. Maxwell predicted the existence of electromagnetic waves tens of years before he was proven right by the generation and reception of radio waves.

Before we move on to the mechanism of electromagnetic radiation, we will first pay some attention to electromagnetic waves. Therefore we will have to dwell a bit longer on the *displacement current*.

The equations governing electricity and magnetism before Maxwell were incomplete. This was evident in analysing a capacitor in a circuit supporting a changing current, see figure 1.11.

Although the capacitor prevents a physical current flowing through the plates, the circuit still supports a current. The explanation for this effect, Maxwell attributed to what he called the *displacement current*, which turns out to be the time rate of change of the electric field between the capacitor plates.

Let's assume that we look at the capacitor in figure 1.11 at the moment that the capacitor is fully charged. The charge on the right plate is Q, the charge on the opposite plate is the negative of that, $-Q$. Because of these charges, the current in the circuit will start flowing to the right. The electric field between the plates is directed to the left. Since a current is flowing to the right, the strength of the electric field is decreasing, so the direction of *change* of the electric field is to the right. Attached to this *changing* electric field is a surrounding magnetic field, its direction connected to

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[4] And - as the rumour goes and denied by Maxwell - at Trinity College, Cambridge, inventing a method of throwing a cat out of a window in such a way that it cannot land on its feet.

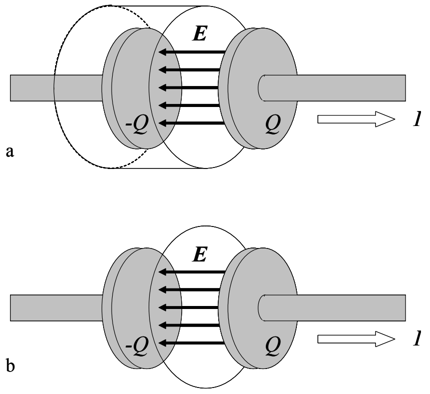

Fig. 1.11 Capacitor in a circuit supporting a changing current, i.e. before steady state. a. A current is flowing through the transparent surface. b. No current is flowing through the transparent surface.

the direction of *change* like a right-hand screw.[5] Since this magnetic field could have been due to a physical current - one cannot tell the source from the magnetic field alone - Maxwell named the source, the changing electric field: *displacement current.*

It is this specialty - that a changing electric field creates a (changing) magnetic field - that makes the existence of electromagnetic waves possible. It means that once you create the 'correct'[6] changing electric field, this field will create a changing magnetic field that in turn will create a changing electric field and so on. This expansion of the disturbance in space will continue, even when the source has ceased to exist. This is what we call *wave propagation.* This process is depicted in figure 1.12.

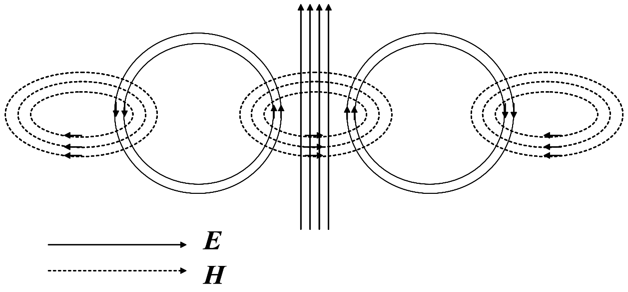

Fig. 1.12 The process of wave propagation. In reality the process is three dimensional and waves expand spherically.

We have seen that a coil (an inductor), when connected to an AC current source, produces an electromagnetic field. Energy is delivered to a magnetic field and this energy is returned to the circuit. The field is purely a storage field; the energy is

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[5] Just like the direction of the magnetic field attached to the current in the circuit.

[6] We will get to the definition of 'correct' later on.

stored in the magnetic field surrounding the inductor. In a similar way a capacitor, when connected to an AC voltage source, produces an electromagnetic field. Energy is delivered to an electric field and this energy is returned to the circuit. When the AC cycle starts on its down slope, the charge in the capacitor holds the voltage (opposing the change) until the current leaves and then it starts to discharge, causing the voltage to lag the current. Also for a capacitor the current and voltage are out of phase. Again the field is purely a storage field; the energy is stored in the electric field surrounding the capacitor.

The question that remains is how to create the *correct* changing electric field, i.e. how to create the source of electromagnetic wave propagation; how to get changing electric and magnetic fields to be in phase. The Maxwell equations reveal that the source of electromagnetic radiation is *accelerated charge*. Rather than elaborating on the Maxwell equations, we will discard the mathematics and explain the radiation of accelerated charge by physical reasoning.

1.3 RADIATION BY ACCELERATED CHARGE

When looking at an electric charge, either positively or negatively charged, the electric field lines extend radially from this charge to infinity, see figure 1.13a.

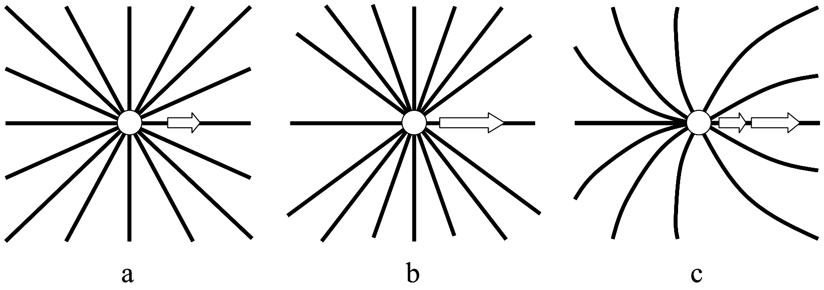

Fig. 1.13 Electric charge and field lines. a. Static or slowly moving charge. b. Fast moving charge. c. Accelerated charge.

The electric field lines for a slowly moving charge, i.e. having a velocity well below that of light, behave identical to that of a non-moving or static charge, figure 1.13a. This is a consequence of the *principle of relativity in the restricted sense* [3],

> If, relative to K, K' is a uniformly moving co-ordinate system devoid of rotation, then natural phenomena run their course with respect to K' according to exactly the same general laws as with respect to K.

In other words: 'An observer moving at the same speed as the charge still sees only static fields.'

When the charge is moving fast, i.e. at velocities approaching the velocity of light, the electric field lines tend to compress in the direction perpendicular to the direction the charge is moving, see figure 1.13b. This is also a consequence of the principle of relativity [3]. Only when a charge is accelerated, that is acted upon by an external force, can it radiate. The electric field lines will bend, see figure 1.13c, thus creating a transversal component - next to the radial components - in the electric field that propagates away from the charge at the speed of light. We will explain this by having a closer look at figure 1.13c.

Let's assume that a charged particle is uniformly moving along a horizontal line as depicted in figure 1.14. At a certain moment of time the particle is accelerated for a short period of time and, afterwards, it continues its uniform movement, see figure 1.14.

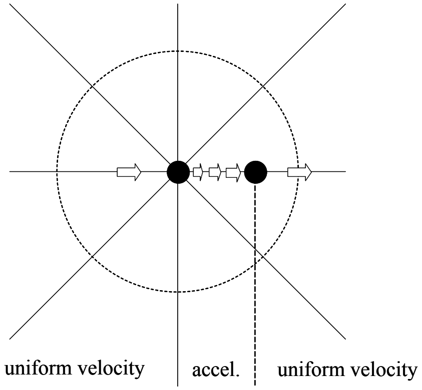

Fig. 1.14 A charged particle, uniformly moving along the horizontal axis is accelerated for a brief moment of time.

In the figure we have indicated the position of the particle at the start and finish of the acceleration. Some of the static electric field lines at the start position are shown, those at the finish position are left out for the sake of clarity. Also indicated in figure 1.14 is the position of an observer that has moved with the speed of light along a static electric field line from the particle, for the duration of the acceleration.

In figure 1.15 we repeat figure 1.14, but now also indicate the static field lines associated with the particle at the end of its acceleration.

If we now think of ourselves positioned anywhere on the 'observer circle' and accepting the fact that nothing can move faster than the velocity of light, we see that everywhere from the circle to infinity, the static field lines must follow those from the initial particle position. Everywhere inside the circle, the static field lines must follow those associated with the final particle position. Since electric field lines must be continuous, so-called *kinks* must exist at the observer position to make the field lines connect, see figure 1.16.

For a continuously accelerated charge, we would have found the field lines as shown in figure 1.13.

Now that we know how to construct the electric field lines of an accelerated, charged particle, we can take a look at these field lines for different times inside the time interval of acceleration. This has been done in figure 1.17 for subsequent moments within the acceleration time frame.

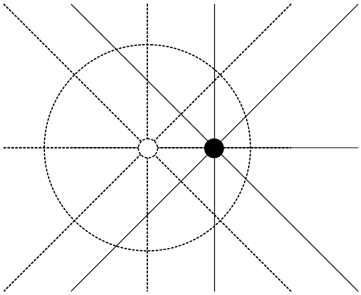

Fig. 1.15 An accelerated charged particle. Static field lines are shown for the particle at the beginning and at the end of the acceleration. The circle indicates the position of an observer that travelled outward with the field lines at the start, for the duration of the acceleration, with the speed of light.

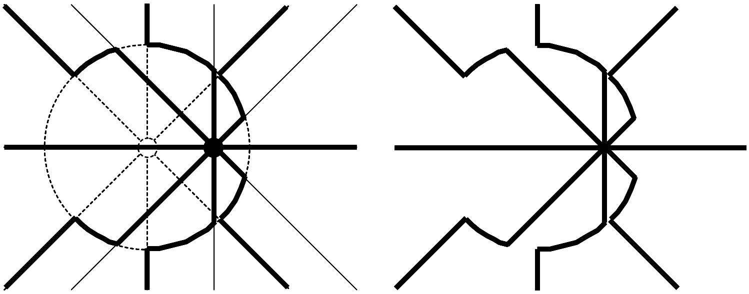

Fig. 1.16 The electric field lines of a shortly accelerated particle must form *kinks* in order to connect the field lines associated with the end and initial position of the particle to form continuous field lines.

When we take the disturbances, i.e. the transverse components of the electric field, taken at the subsequent moments and add them in one graph, see figure 1.17d, we see that these disturbances move out from the accelerated charge at the speed of light. Associated with this changing electric field is a changing magnetic field. Unlike the situation as described for the coil or the capacitor, the electric and magnetic fields are *in phase* now, due to the fact that they were produced by a single event, the acceleration of charge. The electric and magnetic field travel along in phase, their directions being perpendicular to one another, see also figure 1.12. This is what we call an *electromagnetic wave.*

In real life we will find accelerating and decelerating[7] charges in time-varying currents. Charge acceleration or deceleration in an electrically conducting, wire object may be found where the wire is curved, bent, discontinuous or terminated. All these origins of radiation are shown in figure 1.18 [4].

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[7] Deceleration is a negative acceleration and will therefore be treated as acceleration.