Electromagnetic Theory (PHAS 3201 - Year 3 - Term 1 : 2016)
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Preliminaries

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1 Foreword

This course has been delivered in the previous years by Dr. Stan Zochowski and before him by Prof. David Bowler. Some of the content of this course will be unaltered, but other parts might have undergone changes and while the core physics is still the same, please keep that in mind if you chance on previous notes or lecture slides. This course also follows *Introduction to Electrodynamics* by D.J.Griffiths quite closely so you can use that text as a reference.

2 Syllabus

The course can be split into three main areas: electric and magnetic fields which do not vary with time, and their interaction with matter; Maxwells Equations and wave solutions for the fields; and, the properties of time-varying fields and their interaction with matter. For each section below the topics discussed are listed, as a guide to the weighting of each section, an approximate number of nominal (if there were lectures) lecture hours is given in square brackets. The subsidiary numbers for each section give a rough breakdown of the material to be covered. Note: Things may change!

Static Fields and Matter

2.1 Introduction [2]

1. Mathematical tools.
2. Brief summary of results from PHAS2201, as needed in this course, including differential form of Gauss law and electrostatic potential V.

2.2 Macroscopic Fields [4]

1. Brief revision of capacitor and dielectric constant.
2. Polarisation **P** as electric dipole moment per unit volume, free and polarisation charge densities - volume and surface. Displacement **D** as field whose divergence is free charge density; relative permittivity and electrical susceptibility. Energy density in electric field, via capacitor.

3. Brief revision of Faraday, Ampere and Biot Savart laws.

4. Introduce magnetic vector potential **A**; **B** as curl **A**, lack of uniqueness (c.f. V), Coulomb gauge.

5. $\mathbf{J}_m$ as curl **M**; magnetic intensity **H** as field whose curl is $\mathbf{J}_f$. Relative permeability and magnetic susceptibility.

6. Boundary conditions on **B** and **D** from pillbox integral. Continuity of lines of force. Boundary conditions on **H** and **E** from loop integral.

2.3 Atomic Mechanisms [4]

1. E-field; pattern of electric dipol from V. Polarisation **P** as electric dipole moment per unit volume, free and polarisation charge densities - volume and surface.

2. Field pattern of current loop (i.e., magnetic dipole), c.f. electric dipole in far field. **A** from current distribution

3. Magnetisation **M** as dipole moment per unit volume, elementary current loops, free and magnetisation current densities - surface and volume.

4. Diamagnetic and paramagnetic materials; brief microscopic explanations, current loops or intrinsic moments.

2.4 Ferromagnetism [3]

1. Intrinsic magnetic moments at atomic level. Qualitative description of short and long range forces, ordering below transition temperature, mention of ferrimagnetic and antiferromagnetic.

2. Ferromagnetic domains, **B** vs **H** plot, hysteresis, major and minor loops, normal magnetisation curve, saturation, scale of ferromagnetic amplification of **B**, remanence, coercivity.

3. **B** and **H** in infinite solenoid compared to uniformly magnetised bar; winding on infinite bar, winding on toroid. Fluxmeter for B and H in toroid to show hysteresis loop.

4. Energy density in magnetic field, via inductor.

Maxwells Equations: Wave Solutions

2.5 Maxwells equations and E.M. waves [4]

1. Displacement current from continuity equation; generalised Ampere law.

2. Maxwells equations in differential and integral form.

3. Wave equations for **E**, **D**, **B** and **H**. Relation between field vectors and propagation vector.
4. Description of types of polarisation: linear, elliptical, circular, unpolarised, mixed.

Time-varying Fields and Matter

2.6 Reflection and refraction at a plane dielectric surface [3]

1. Refractive index.
2. Snells law and law of reflection, reflection and transmission coefficients, Fresnel relations.
3. Brewster angle, critical angle, total internal reflection, mention of evanescent wave.

2.7 Waves in conducting media [2.5]

1. Poor and good conductors; skin depth, dispersion relation.
2. Reflection at metal surface.
3. Plasma frequency, simple plasma dispersion relation, superluminal phase velocity

2.8 Energy flow and the Poynting vector [1.5]

1. Static energy density in electric and magnetic fields. Poyntings theorem and the Poynting vector
2. Pressure due to e.m. waves.

2.9 Emission of radiation [2]

1. Lorentz condition, retarded potentials, retarded time
2. Hertzian dipole, far field pattern of **E** and **B**, radiated power.

2.10 Relativistic transformations of electromagnetic fields [2]

1. Revision of 4-vectors ($\mathbf{r}$,t) and ($\mathbf{p}$, E). Invariance of 4-vector dot product
2. Continuity equation as 4-div of ($\mathbf{J}$,ρ); Lorentz condition as 4-div of ($\mathbf{A}$,ϕ). Transformation of E and B fields.

3 Aims and Objectives

3.1 Prerequisites

The mathematical prerequisites are PHAS1245&PHAS1246 (*Mathematical Methods I* and *II*) in the first year and PHAS2246 (*Mathematical Methods III*) in Physics & Astronomy in second year, or equivalent mathematics courses. Although this is not set as a compulsory prerequisite, students taking this course should have also taken PHAS2201: *Electricity and Magnetism*, or equivalent. If this is not the case, extra effort should be invested in reviewing the material indicated in the first two lectures which give a review of PHAS2201.

3.2 Aims

The aims of the course are:

- to discuss the magnetic properties of materials;
- to build on the contents of the second year course, Electricity and Magnetism PHAS2201, to establish Maxwells equations of electromagnetism, and use them to derive electromagnetic wave equations;
- to understand the propagation of electromagnetic waves in vacuo, in dielectrics and in conductors;
- to explain energy flow (Poyntings theorem), momentum and radiation pressure, the optical phenomena of reflection, refraction and polarization, discussing applications in fibre optics and radio communications;
- to use the retarded vector potential to understand the radiation from an oscillating dipole;
- to understand how electric and magnetic fields behave under relativistic transformations.

3.3 Objectives

After completing the course the student should be able to:

- understand the relationship between the E, D and P fields, and between the B, H and M fields;
- derive the continuity conditions for B and H and for E and D at boundaries between media; distinguish between diamagnetic, paramagnetic and ferromagnetic behaviour;
- use the vector potential A in the Coulomb gauge to calculate the field due to a magnetic dipole.

- calculate approximate values for the B and H fields in simple electromagnets.
- understand the need for displacement currents;
- explain the physical meaning of Maxwells equations, in both integral and differential form, and use them to:
  - i) derive the wave equation in vacuum and the transverse nature of electromagnetic waves;
  - ii) account for the propagation of energy, momentum and for radiation pressure;
  - iii) determine the reflection, refraction and polarization amplitudes at boundaries between dielectric media, and derive Snells law and Brewsters angle;
  - iv) establish the relationship between relative permittivity and refractive index;
  - v) explain total internal reflection, its use in fibre optics and its frustration as an example of tunnelling;
  - vi) derive conditions for the propagation of electromagnetic waves in, and reflection from, metals;
  - vii) derive the dispersion relation for the propagation of waves in a plasma, and discuss its relevance to radio communication;
  - viii) understand how an oscillating dipole emits radiation and use the vector potential in the Lorentz gauge to calculate fields and energy fluxes in the far-field;
- be able to transform electric and magnetic fields between inertial frames.

3.4 Lectures, Assessment & Textbook

Lectures : Lectures take place as per the UCL Timetable. Topics will be addressed during lecture with examples and exercises embedded in the lecture. As the course unfolds I might agree to focus more on examples and exercises if these are needed. A specific time for additional discussion and specific questions regarding any topics explained during lectures will be arranged after consultation with students present at the first lecture. (to avoid re-arranging multiple times due to timetable clashes).

Assessment is based on the results obtained in the final examination (90%) and from the best 3 out of 4 problem sets (10%). The problem sets will be available on the Moodle page at least one week before they are due. The due dates will be on the following Tuesdays (not set in stone: see individual papers):

- 24th October (23:59)
- 14th November (23:59)
- 12th December (23:59)
- 12th January (23:59)

Coursework should be uploaded to the appropriate Moodle site in pdf format before the deadline: **no paper copies will be accepted**, they will be returned via the Moodle page as well.

Lecture notes will be available on Moodle before the associated lecture, with the complete set of notes available as a single PDF file at the end of term.

Textbook : *Introduction to Electrodynamics*, 3rd edition by D.J. Griffiths (Prentice Hall), although any intermediate text in EM Theory will do!

3.5 Communication

The course Moodle page will be my main source of communication outside the lectures. Please check it from time to time! I may e-mail as well, if its very urgent. Also, try to use the Moodle Forum for this course to communicate with each other, or me! I dont mind a collective spirit working on problems.

Finally, if theres something about the course you are not comfortable with, whether its material or presentation, please do not hesitate to drop me a line but be gentle! Ill try to adapt to the wishes of the many.