The 18th European Conference on Antennas and Propagation (EuCAP)
17 - 22 March 2024

Fundamental equations of electromagnetics from classical to quantum: Theoretical formulation using gauge-invariant field-impulses, efficient computation with fundamental implicit schemes and technology-enhanced learning

Abstract:

This short course will introduce new fundamental equations of electromagnetics (EM) that replace Maxwell's fields/potentials with single physical quantity unifying all electrostatics, magnetostatics, electrodynamics and quantum-EM interactions. Since Maxwell-Hertz-Heaviside era, the longstanding dilemma to use either fields or potentials and gauge for electromagnetics will be discussed. The concept and utilization of field-impulses will then be shown to not only resolve such century-old field-potential/gauge dilemma, but also aptly describe quantum-EM (e.g. Aharonov-Bohm) effects. Theoretical formulation and efficient computation with fundamental implicit schemes of finite-difference-time-domain methods will be presented. Several mobile apps for technology-enhanced-learning of electromagnetics and circuits will also be demonstrated.

Graphical abstract:

Recommended prerequisites for attendees:

The course requires some basic knowledge of:

- Electromagnetic theory, Maxwell's equations
- Fields and potentials in electromagnetics
- Finite-difference time-domain method

Learning objectives:

After the course the participant will be able to:

- Identify the equations in electromagnetics involving different fields and gauged potentials.
- Learn the pros and cons of using fields or potentials and gauges in electromagnetics.
- Understand the concept of field impulses and their utilization in electromagnetics.
- Formulate the fundamental equations of electromagnetics using field-impulses.
- Apply the finite-difference time-domain methods for computational electromagnetics.
- Understand the unconditionally stable fundamental implicit finite-difference time-domain schemes.
- Exploit the mobile apps and 3-D display for technology-enhanced learning of electromagnetics.

Course outline:

The course outline is listed below:

1. Closer look into electromagnetic fields

We shall revisit Maxwell's formulations of his equations and some longstanding dilemmas and issues pertaining to either fields or potentials in electromagnetics. We recall that there is no single physical quantity (real three-vector) known for the past 160 years that can describe all electrostatics, magnetostatics and electrodynamics at one go. In particular, the electric field fails to describe simple magnetostatics, while the magnetic field fails to describe simple electrostatics. Even with both electric and magnetic fields taken together, they fail to describe some quantum-EM (Aharanov-Bohm) effects that are to be explained. We assert that the electric and magnetic fields only under-describe electromagnetics, and are therefore insufficient.

2. Potentials and gauge

We shall discuss the significance of potentials comprising magnetic vector potential and electric scalar potentials. While these potentials can describe quantum-EM (Aharanov-Bohm) effects, they actually over-describe electromagnetics and are more than necessary with gauge redundancy. There is much ambiguity in choosing one gauge condition out of many choices, e.g. Coulomb, Lorenz, etc. We also note the issues of some potentials being non-physical, non-causal (possibly faster than speed of light) and non-measurable.

3. Resolution using new fundamental physical quantity of electromagnetics

We shall provide satisfactory resolution to the above longstanding dilemma of fields, potentials and gauge. In lieu of the traditional fields and potentials, our recently introduced gauge-invariant physical quantities of field-impulses will be presented to formulate new fundamental equations of electromagnetics. Unlike the potentials that are gauge-dependent and may not be physical nor causal, the field-impulses are gauge-independent, physical, causal and measurable. It is also shown that the electric field-impulse alone using single wave equation can provide the complete description of all electrostatic, magnetostatic and electrodynamic phenomena, attributed to all kinds of static, dynamic, steady or non-steady charges and/or currents. We also show that by using the field-impulses, one can derive Maxwell's equations by exploiting only the available findings prior to his time.

4. Computation using FDTD

We shall briefly discuss the explicit FDTD for computation of fields with possible extension to field-impulses. We also present the unconditionally stable FDTD methods, particularly the efficient fundamental implicit schemes that feature matrix-operator-free right-hand-sides. The fundamental implicit schemes unify many of the popular unconditionally stable FDTD methods developed so far.

5. Technology-enhanced learning of EM

We shall address the challenges of teaching and learning of EM. We show how professors can make good use of the mobile apps for engaging interactive teaching of EM in class, and how students can utilize them for self-learning, checking of calculations, exploration etc. Several EM apps are described in more detail to aid teaching and learning of EM wave polarization, propagating, reflection and transmission, as well as RF/microwave circuit design. The EM app can also be supplemented with 3-D displays (3-D TV with 3-D glasses) to enable stereoscopic view and provide depth perception.

Prof. Eng Leong Tan is with the School of Electrical and Electronic Engineering (EEE), Nanyang Technological University (NTU), Singapore. He has published more than 130 papers and book chapters, most of which as a principal author. He has extensive research on electromagnetics and their extensions into multi-disciplinary physics including quantum, acoustics, thermal and circuits. He was the General Chair of Progress in Electromagnetics Research Symposium (PIERS) 2017 in Singapore, which attracted more than 1000 participants from around the world. He was also the Technical Program Committee Chair for several key international conferences, including the 2021 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting. He is a Fellow of the Electromagnetics Academy in recognition of his distinguished contributions to "Computational electromagnetics and education". He also received the undergraduate teaching award from IEEE Antennas and Propagation Society for excellence in teaching, student mentoring and the development of mobile technologies and computational methods for electromagnetics education.

Key bibliography

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