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Why Study Electromagnetics: The First Unit in an Undergraduate Electromagnetics Course

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1. Introduction

Maxwell's equations, formulated circa 1870, represent a fundamental unification of electric and magnetic fields, predicting electromagnetic wave phenomena that Nobel Laureate Richard Feynman has called the most outstanding achievement of 19th-century science. Now, engineers and scientists worldwide use computers ranging from simple desktop machines to massively parallel arrays of processors to obtain solutions of these equations. As we begin the 21st century, it may seem a little odd to devote so much effort to study solutions of the 19th century's best equations. Thus we ask the question: "Of what relevance is the study of electromagnetics to our modern society?"

The goal of this unit is to help answer this question. Whereas the study of electromagnetics has been motivated in the past primarily by the requirements of military defense, the entire field is shifting rapidly toward important commercial applications in high-speed communications and computing that touch everyone in their daily lives. Ultimately, this will favorably impact the economic well-being of nations as well as their military security.

2. The Heritage of Military Defense Applications

From the onset of World War II until about 1990, the primary societal relevance of the study of electromagnetics was arguably the need for a strong military defense. The development of ultra-high-frequency (UHF) and microwave radar technology during World War II motivated early work, which proved crucial to the survival of England during the grim early days of the Battle of Britain, and subsequently to the final victory of the Allied forces. During the 45 years of Cold War that followed, the advanced development of radar remained of paramount importance, as both the East and West alliances developed enormous nuclear arsenals on hair-trigger alert. Radar technologies aimed at the early warning of aircraft and missiles were subsequently met with countermeasures, aimed at evading or spoofing radar detection. These were, in turn, met by counter-countermeasures, and so forth.

Radar encompasses a wide range of electromagnetics technology. At the radar site, microwave sources, circuits, waveguides, and antennas are designed to generate, transport, radi-

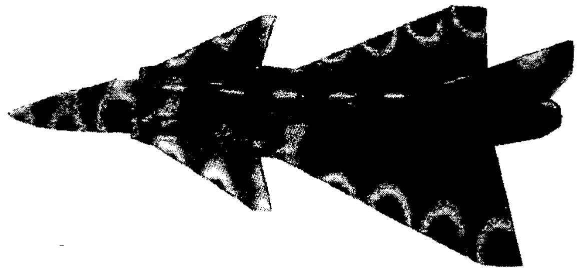

Figure 1. A false-color snapshot of the computed surface electric currents induced on a prototype military jet fighter plane by a radar beam at 100 MHz [1]. The impinging plane wave propagates from left to right at nose-on incidence to the airplane. The surface currents re-radiate electromagnetic energy, which can be detected back at the radar site.

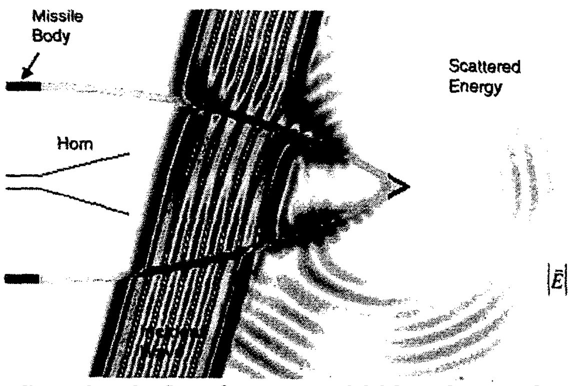

Figure 2a. The first of two sequential false-color snapshots of a microwave pulse penetrating a missile radome containing a horn antenna [2]. The impinging plane wave propagates from right to left at the speed of light, and is obliquely incident at 15° from boresight. Complicated electromagnetic wave interactions visible within the radome structure require solutions to Maxwell's equations to permit effective design.

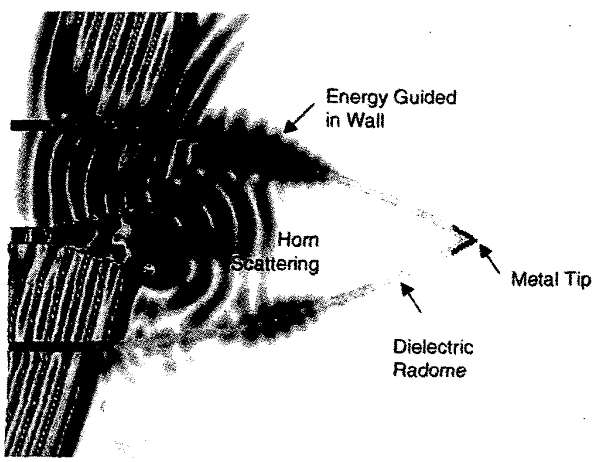

Figure 2b. The second of two sequential false-color snapshots of a microwave pulse penetrating a missile radome containing a horn antenna [2].

Figure 3a. A false-color visualization illustrating the coupling and crosstalk of a high-speed logic pulse entering and leaving a microchip, embedded within a conventional dual-in-line integrated-circuit package (Figure 3b). The fields associated with the logic pulse are not confined to the metal circuit paths and, in fact, smear out and couple to all adjacent circuit paths [3].

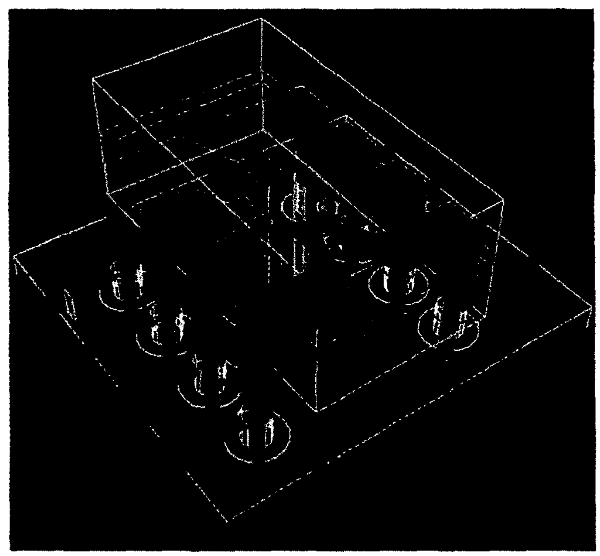

Figure 3b. The dual-in-line integrated-circuit package containing the microchip illustrated in Figure 3a.

ate, and receive electromagnetic waves. For a foe determined to press an attack despite the operation of a radar system, there is the need to understand the scattering of electromagnetic waves by complex structures. Such understanding leads to materials and structure-shaping technologies for designing stealthy aircraft, having reduced radar-backscattering responses. An example of this is shown in Figure 1, which illustrates the results of applying Maxwell's equations to calculate the interaction of a 100-MHz radar beam with a prototype jet fighter [1].

An additional defense need, motivating the study of electromagnetics, emerged after about 1960, when it became clear that a nuclear bomb detonated above the Earth's atmosphere could generate a high-level *electromagnetic pulse*, or EMP. EMP can be sufficiently intense to burn out electrical and electronic equipment on the Earth's surface located hundreds of miles away from the point directly below the detonation. Equipment failures on this geographical scale could leave a nation largely defenseless against subsequent attack. Therefore, substantial efforts were devoted by the defense community to "harden" key systems, to reduce their vulnerability to EMP. Here, electromagnetics technologies were aimed at predicting the level of EMP penetration and coupling into potentially vulnerable equipment, and developing cost-effective means to reduce such coupling to well below the danger point.

A related defense area motivating the study of electromagnetics was explored intensively after about 1980, when technology developments permitted the generation of steerable, *high-power microwave* (HPM) beams. In principle, such beams could neutralize electronics in the manner of EMP, but be applied on a more selective basis for either tactical or strategic applications. On the offensive side, electromagnetics technologies were used to design HPM sources, circuits, and antennas to generate, transport, and radiate high-power beams. Computational solutions of Maxwell's equations were also used to understand electromagnetic wave penetration and coupling mechanisms into potential targets, and means to mitigate these mechanisms. An example of the complexity of these penetration mechanisms is shown in Figure 2, which illustrates the results of applying Maxwell's equations to calculate the interaction of a 10-GHz radar beam with a missile radome containing a horn antenna [2].

3. Applications in High-Speed Electronics

In undergraduate electrical and computer engineering programs, instructors teaching circuits courses may, in passing, mention that circuit theory is a subset of electromagnetic field theory. Invariably, however, the instructors promptly drop this connection. As a result, it is possible for their graduating seniors (especially in computer engineering, who will likely *never* take an electromagnetics course such as this) to have the following rude awakening upon their initial employment with Intel, Motorola, IBM, and similar manufacturers:

> The bedrock of introductory circuit analysis, Kirchoff's current and voltage laws, *fails* in most contemporary high-speed circuits. These must be analyzed using electromagnetic field theory. Signal power flows are *not* confined to the intended metal wires or circuit paths.

Let's be more specific. High-speed electronic circuits have been traditionally grouped into two classes: analog microwave circuits and digital logic circuits.

1. Microwave circuits typically process bandpass signals at frequencies above 3 GHz. Common circuit features include microstrip transmission lines, directional couplers, circulators, filters, matching networks, and individual transistors. Circuit operation is fundamentally based upon electromagnetic wave phenomena.

2. Digital circuits typically process low-pass pulses having clock rates below 2 GHz. Typical circuits include densely packed, multiple planes of metal traces providing flow paths for the signals, dc power feeds, and ground returns. Via pins provide electrical connections between the planes. Circuit operation is nominally not based upon electromagnetic-wave effects.

However, the distinction between the design of these two classes is blurring. Microwave circuits are becoming very complex systems, comprised of densely packed elements. On the digital-circuit side, the rise of everyday clock speeds to 2 GHz implies low-pass signal bandwidths up to about 10 GHz, well into the microwave range. Electromagnetic-wave effects that, until now, were in the domain of the microwave engineer are becoming a limiting factor in digital-circuit operation. For example, hard-won experience has shown that high-speed digital signals can spuriously:

- Distort as they propagate along the metal circuit paths.
- Couple (cross-talk) from one circuit path to another.
- Radiate and create interference to other circuits and systems.

An example of electromagnetic field effects in a digital circuit is shown in Figure 3, which illustrates the results of applying Maxwell's equations to calculate the coupling and crosstalk of a high-speed logic pulse, entering and leaving a microchip embedded within a conventional dual-in-line integrated-circuit package [3]. The fields associated with the logic pulse are not confined to the metal circuit paths and, in fact, smear out and couple to all adjacent circuit paths.

4. Applications in Ultrahigh-Speed Photonic Integrated Circuits

Microcavity ring and disk resonators are proposed components for filtering, routing, switching, modulating, and multiplexing/demultiplexing tasks in ultrahigh-speed photonic integrated circuits. Figure 4 is a scanning electron microscope image of a portion of a prototype photonic circuit, comprised of 5.0-μm-diameter aluminum gallium arsenide (AlGaAs) microcavity disk resonators, coupled to 0.3-μm-wide optical waveguides across air gaps spanning 0.1-0.3 μm [4].

By computationally solving Maxwell's equations, which are valid literally from dc to light, the coupling, transmission, and resonance behavior of the micro-optical structures in Figure 4 can be determined. This permits effective engineering design. For example, Figure 5 shows false-color visualizations of the calculated sinusoidal steady-state optical electric field distributions for a

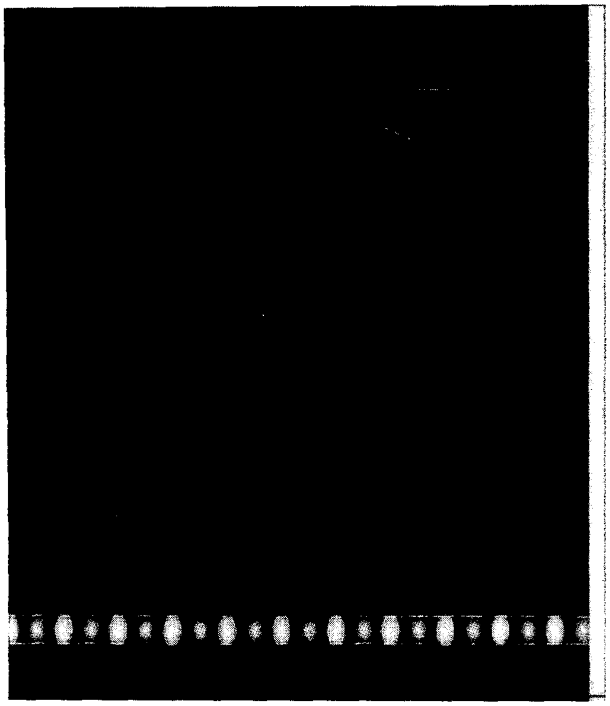

Figure 5a. The first of four false-color visualizations, illustrating the sinusoidal steady-state optical electric field distributions in a 5.0-μm-diameter GaAlAs microdisk resonator, coupled to straight 0.3-μm-wide GaAlAs optical waveguides, for single-frequency excitations propagating to the right in the lower waveguide [5]. This visualization shows an off-resonance signal.

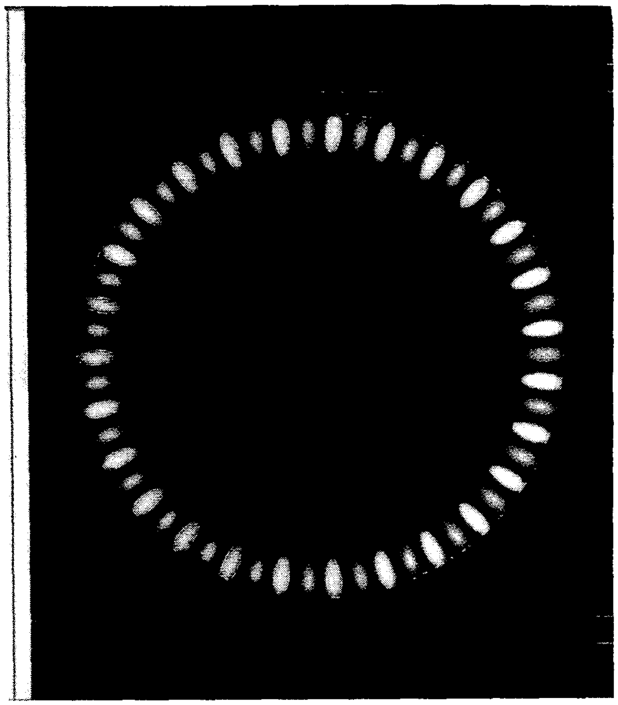

Figure 5b. As in Figure 5a, for an on-resonance signal, first-order radial mode

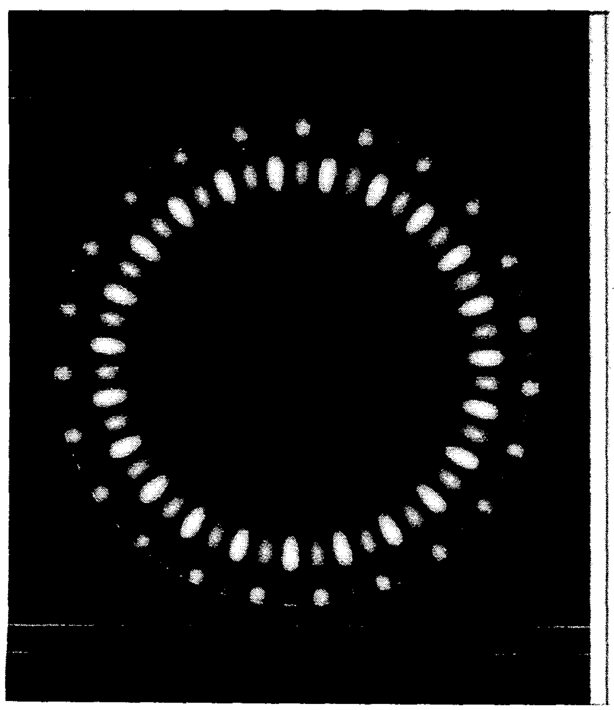

Figure 5c. As in Figure 5a, for the second-order radial-mode resonance.

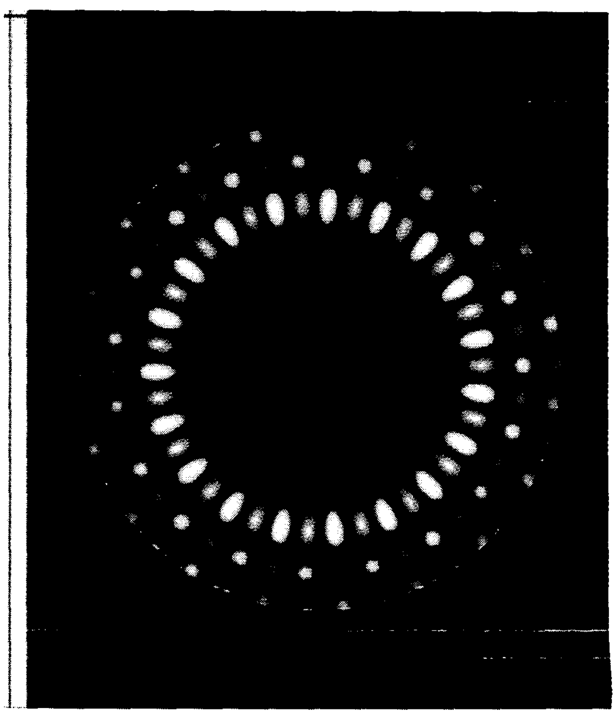

Figure 5d. As in Figure 5a, for the third-order radial mode resonance.

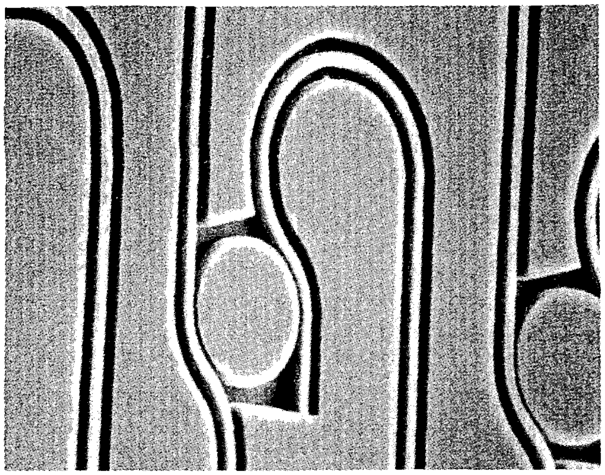

Figure 4. A scanning electron microscope image of a portion of a prototype photonic integrated circuit [4]. The photonic circuit is comprised of 5.0-μm-diameter AlGaAs microcavity disk resonators, coupled to 0.3-μm-wide AlGaAs optical waveguides, across air gaps spanning as little as 0.1 μm.

typical microdisk in Figure 4 [5]. In Figure 5a, the optical excitation is at a nonresonant frequency, 193.4 THz (an optical wavelength, λ, of 1.55 μm). Here, 99.98% of the rightward-directed power in the incident signal remains in the lower waveguide. In Figure 5b, the excitation is at the resonant frequency of the first-order radial whispering-gallery mode of the microdisk, 189.2 THz ($\lambda = 1.585$ μm). Here, there is a large field enhancement within the microdisk, and 99.79% of the incident power switches to the upper waveguide in the reverse (leftward) direction. This yields the action of a passive, wavelength-selective switch.

Figures 5c and 5d are visualizations at, respectively, the resonant frequencies of the second- and third-order whispering-gallery modes, 191.3 THz ($\lambda = 1.567$ μm) and 187.8 THz ($\lambda 1.596$ μm). A goal of current design efforts is to suppress such higher-order modes, to allow the use of microdisks as passive wavelength-division multiplexing devices having low crosstalk across a wide spectrum, or as active single-mode laser sources.

5. Applications in Microcavity Laser Design

Proposed ultrahigh-speed photonic integrated circuits require microcavity laser sources and amplifiers, in addition to the passive optical waveguides, couplers, and cavities considered in Section 4. The accurate design of microcavity lasers requires the solution of Maxwell's equations for complex semiconductor geometries capable of optical gain. In fact, the ability to understand electromagnetic fields and waves via the solution of Maxwell's equations is crucial to achieve a design capability for all future photonic integrated circuits.

We now consider a recent application of the large-scale solution of Maxwell's equations to design the world's smallest microcavity laser sources. These sources are based upon the physics of photonic crystals, which are artificial structures having a periodic variation of the refractive index in one, two, or three dimensions. Analogous to the energy gap in pure semiconductor crystals in which electrons are forbidden, these structures can have a frequency stopband over which there is no transmission of electromagnetic waves. Similar to a donor or acceptor state in a doped semiconductor, a small defect introduced into the photonic crystal creates a resonant mode at a frequency that lies inside the bandgap. The defect in the periodic array behaves as a microcavity resonator.

Figure 6a illustrates how light is contained inside the laser microcavity [6]. First, a $\lambda/2$ high-refractive-index slab is used to trap electromagnetic fields in the vertical direction, by way of total-internal reflection (TIR) at the air-slab interface. Second, the laser light is localized in-plane, using a fabricated two-dimensional photonic crystal consisting of a hexagonal array of 0.180-μm-radius air holes (center-to-center spacing of 0.515 μm), etched into the slab. The periodic variation in the refractive index gives rise to Bragg scattering, which generates forbidden energy gaps for in-plane electromagnetic wave propagation. Thus, the photonic crystal provides an energy barrier for the propagation of electromagnetic waves having frequencies that lie within the bandgap. In the simplest structure, a single air hole is removed from the photonic crystal, thereby forming a resonant microcavity. The light energy in the resonant mode is highly spatially localized in the defect region, and can escape only by either tunneling through the surrounding two-dimensional photonic crystal, or by impinging on the air-slab interface at a sufficiently large angle to leak out in the vertical direction.

The defect laser cavities are fabricated in indium gallium arsenic phosphide (InGaAsP), using metal-organic chemical vapor deposition. Here, the active region consists of four 9-nm quantum wells, separated by 20-nm quaternary barriers with a 1.22-μm band gap. The quantum-well emission wavelength is designed for 1.55 μm at room temperature.

Figure 6b is a false-color visualization of the magnitude of the optical electric field, calculated from Maxwell's equations along a planar cut through the middle of the *InGaAsP slab [6]*. These calculations indicate a resonant wavelength of 1.509 μm, a quality factor, Q, of 250, and an effective modal volume of only 0.03 cubic microns. Nearly all of the laser power is emitted vertically, due to the bandgap of the surrounding photonic crystal. Experimental realization of this microcavity laser indicates a lasing wavelength of 1.504 μm, which is very close to the 1.509 μm value predicted from the electromagnetics model. Ongoing research involves optimizing this and similar laser cavities by performing simulations of Maxwell's equations, tailoring the radii and spacing of the etched holes that create the photonic crystal. The goal is to elevate the cavity Q to above 1,500. This would significantly lower the required pump power, and permit the microcavity laser to operate at room temperature.

6. Light Switching Light in Femtoseconds

In electrical engineering, the phrase "dc to daylight" has been often used to describe electronic systems having the property of very wide bandwidth. Of course, no one actually meant that the system in question could produce or process signals over this frequency range. It just couldn't be done. Or could it?

In fact, a simple Fourier-analysis argument shows that recent optical systems that generate laser pulses down to 6 fs in duration approach this proverbial bandwidth. From a technology standpoint,

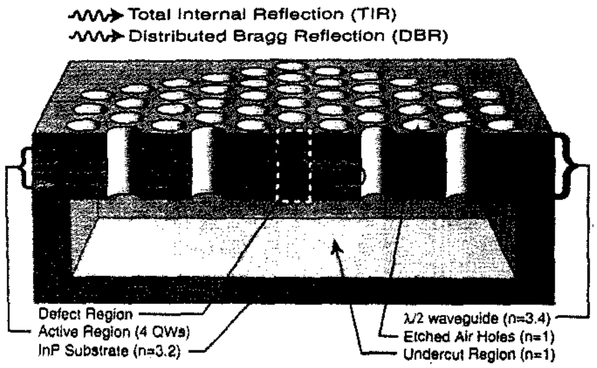

Figure 6a. The geometry of a photonic crystal microcavity laser [6].

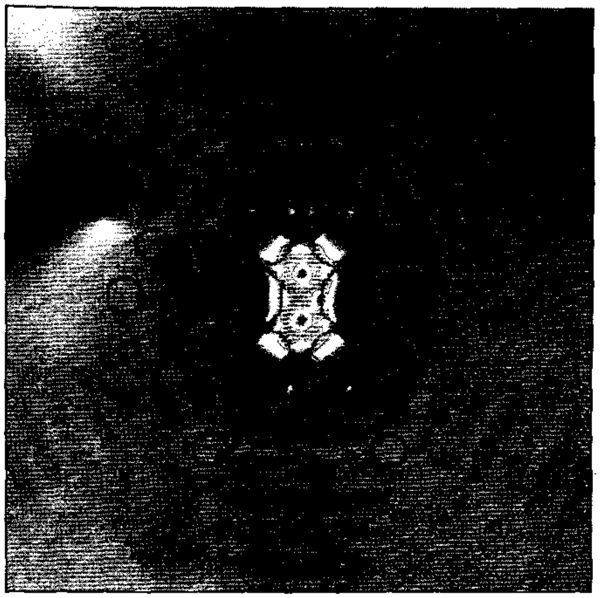

Figure 6b. A false-color visualization of the optical electric field distribution along a planar cut through the middle of the laser geometry shown in Figure 6a.

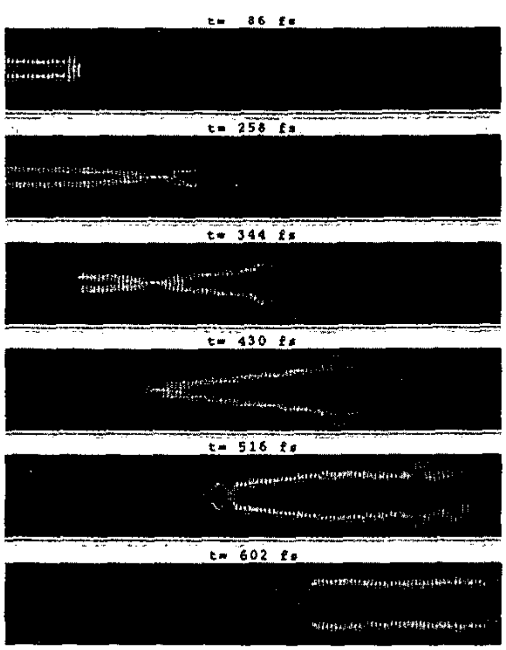

Figure 7. Sequential false-color snapshots of the electric field of equal-amplitude, in-phase, 100-fs optical spatial solitons, co-propagating in glass [7]. The optical pulses propagate from left to right at the speed of light in glass. This illustrates the dynamics of a potential all-optical "AND" gate, i.e., light switching light, that could work on a time scale 1/10,000th that of existing electronic digital logic.

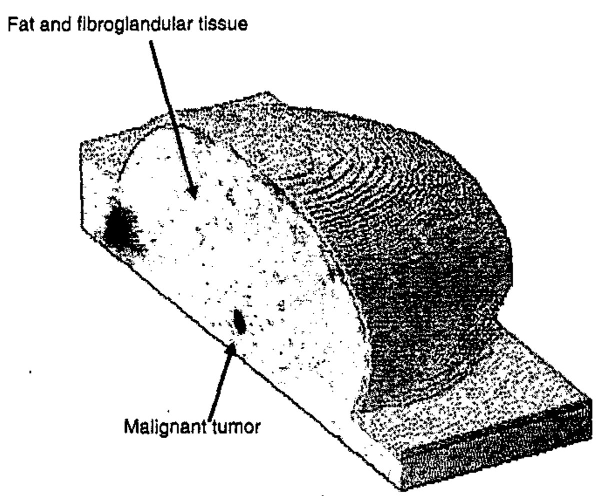

Figure 8. A realistic breast-tissue model, derived from high-resolution magnetic resonance imaging (MRI), used to define the dielectric materials in the tumor-imaging study [8].

it is clear that controlling or processing these short pulses involves understanding the nature of their interactions with materials over nearly "dc to daylight," and very likely in high-beam-intensity regimes, where material nonlinearity can play an important role. A key factor here is material dispersion, having two components: (1) linear dispersion, the variation of the material's index of refraction with frequency at low optical power levels; and (2) nonlinear dispersion, the variation of the frequency-dependent refractive index with optical power.

Recent advances in computational techniques for solving the time-domain Maxwell's equations have provided the basis for modeling both linear and nonlinear dispersions over ultrawide bandwidths. An example of the possibilities for such modeling is shown in Figure 7, which is a sequence of false-color snapshots of the dynamics of a potential femtosecond all-optical switch [7]. This switch utilizes the collision and subsequent "bouncing" of pulsed optical spatial solitons, which are pulsed beams of laser light that are prevented from spreading in their transverse directions by the optical focusing effect of the nonlinear material in which they propagate.

Referring to the top panel of Figure 7, this switch would inject in-phase, 100-fs pulsed signal and control solitons into ordinary glass (a Kerr-type nonlinear material) from a pair of optical waveguides on the left side. Each pulsed beam has a 0.65-μm transverse width, while the beam-to-beam spacing is of the order of 1 μm. In the absence of the control soliton, the signal soliton would propagate to the right at the speed of light in glass with zero deflection, and would then be collected by a receiving waveguide. However, as shown in the remaining panels of Figure 7, a co-propagating control soliton would first merge with and then laterally deflect the signal soliton to an alternate collecting waveguide. (Curiously, the location of the two beams' merger point would remain stationary in space, while the beams would propagate at light-speed through this point.) Overall, the optical pulse dynamics shown in Figure 7 could provide the action of an all-optical "AND" gate, working on a time scale about 1/10,000th that of existing electronic digital logic.

Application of the fundamental Maxwell's equations to problems such as the one illustrated in Figure 7 shows great promise in allowing the detailed study of a variety of novel nonlinear optical-wave species that may one day be used to implement all-optical switching circuits (light switching light), attaining speeds 10,000 times faster than those of the best semiconductor circuits today. The implications may be profound for the realization of "optonics," a proposed successor technology to electronics, which would integrate optical-fiber interconnects and optical microchips into systems of unimaginable information-processing capability.

7. Imaging of the Human Body

The final topic introduced in this unit involves the prospect for advanced imaging of the human body, enabled by detailed Maxwell's equations solutions of the interaction of electromagnetic waves with complicated material geometries. Figures 8 and 9 illustrate one such problem of great societal importance: detection of malignant breast tumors at the earliest possible stage.

Recently, several researchers have conducted theoretical investigations of the use of ultrawideband pulses for early-stage breast-cancer detection. In principle, this technique could detect smaller tumors over larger regions of the breast than is currently

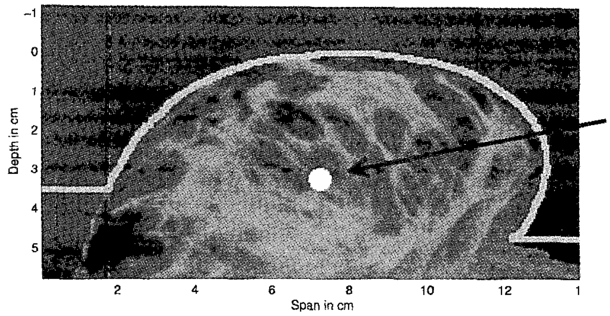

Figure 9a. An MRI-derived breast model. The arrow indicates the location of the assumed actual 6-mm-diameter malignant tumor, at a depth of 3 cm.

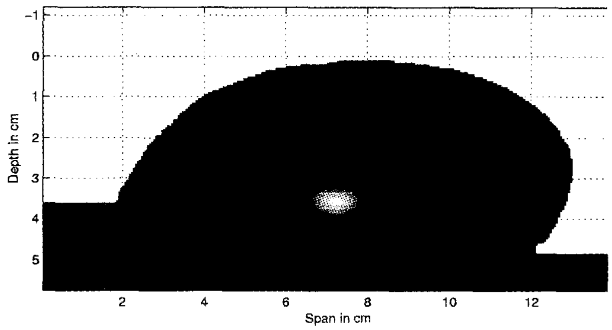

Figure 9b. An image reconstructed from backscattered waveforms obtained by solving Maxwell's equations, for the model shown in Figure 9a [8].

possible using X-ray mammography, and could further avoid exposing the patient to potentially hazardous ionizing radiation. In this proposed technique, an array of small antennas would be placed on the surface of the breast, to emit and then receive a short electromagnetic pulse, lasting less than 100 ps. Signal-processing techniques would then be applied to the pulses received at each antenna element to form the breast image. In work to date, large-scale computational solutions of Maxwell's equations have provided simulated test data, and allowed optimization of the imaging algorithms. As shown in Figures 8 and 9, the numerical simulations show promise for imaging small, deeply embedded malignant tumors in the presence of the background clutter due to the complicated surrounding normal tissues [8].

8. Conclusions

Whereas the study of electromagnetics has been motivated in the past primarily by the requirements of military defense, the entire field is shifting rapidly toward important applications in high-speed communications and computing and biomedicine that will touch everyone in their daily lives. Ultimately, this will favorably impact the economic and social well-being of nations, as well as their military security.

In fact, the study of electromagnetics is fundamental to the advancement of electrical and computer engineering technology as we continue to push the envelope of the ultracomplex and the ultra-fast. Maxwell's equations govern the physics of electromagnetic wave phenomena from dc to light, and their accurate solution is essential to understand all high-speed signal effects, whether electronic or optical. Students who well understand the basis of electromagnetic phenomena are well-equipped to attack a broad spectrum of important problems to advance electrical and computer engineering and to directly benefit our society.

9. Availability of this Article on the Internet

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10. References and Figure Credits

1. A. Taflove, *Computational Electrodynamics: The Finite-Difference Time-Domain Method,* Norwood, MA, Artech House, 1995, pp. 11, 15, 516, 517.

2. A. Taflove and S. C. Hagness, *Computational Electrodynamics: The Finite-Difference Time-Domain Method, Second Edition,* Norwood, MA, Artech House, 2000, pp. 9, 20, 687-690.

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5. A. Taflove and S. C. Hagness, *Computational Electrodynamics: The Finite-Difference Time-Domain Method, Second Edition,* Norwood, MA, Artech House, 2000, pp. 14, 25, 26, 810-819.

6. O. Painter, R. K. Lee, A. Scherer, A. Yariv, J. D. O'Brien, P. D. Dapkus, and I. Kim, "Two-Dimensional Photonic Band-Gap Defect Mode Laser," *Science,* **284**, June 11, 1999, pp. 1819-1821.

7. A. Taflove and S. C. Hagness, *Computational Electrodynamics: The Finite-Difference Time-Domain Method, Second Edition,* Norwood, MA, Artech House, 2000, pp. 16, 28, 29, 404-407.

8. Graphics courtesy of Prof. Susan Hagness, Department of Electrical and Computer Engineering, University of Wisconsin – Madison, Madison, WI; E-mail: hagness@engr.wisc.edu.

Introducing the Author

Allen Taflove was born in Chicago, Illinois, on June 14, 1949. He received the BS, MS, and PhD degrees in Electrical Engineering from Northwestern University, Evanston, Illinois in 1971, 1972, and 1975, respectively. After nine years as a research engineer at IIT Research Institute, Chicago, Illinois, he returned to Northwestern in 1984. Since 1988, he has been a Professor in the Department of Electrical and Computer Engineering of the McCormick School of Engineering. Currently, he is a Charles Deering McCormick Professor of Teaching Excellence and Master of the Lindgren Residential College of Science and Engineering.

Since 1972, Prof. Taflove has pioneered basic theoretical approaches and engineering applications of finite-difference time-domain (FDTD) computational electromagnetics. He coined the FDTD acronym in a 1980 IEEE paper, and, in 1990, was the first person to be named a Fellow of IEEE in the FDTD area. In 1995, he authored *Computational Electrodynamics: The Finite-Difference Time-Domain Method* (Artech House, Norwood, MA). This book is now in its second edition, co-authored in 2000 with Prof. Susan Hagness of the University of Wisconsin – Madison. In 1998, he was the Editor of the research monograph, *Advances in Computational Electrodynamics: The Finite-Difference Time-Domain Method* (Artech House, Norwood, MA). In addition to these books, Prof. Taflove has authored or co-authored 12 invited book chapters, 73 journal papers, approximately 200 conference papers and abstracts, and 13 US patents. Overall, this work has resulted in his being named to the "Highly Cited Researchers List" of the Institute for Scientific Information (ISI) for 2002.

Prof. Taflove has been the thesis adviser of 14 PhD recipients, who hold professorial, research, or engineering positions at major institutions, including the University of Wisconsin – Madison, the University of Colorado – Boulder, McGill University, Lincoln Lab, Jet Propulsion Lab, and the US Air Force Research Lab. Currently, he is conducting research in a wide range of computational-electromagnetics modeling problems, including the propagation of bioelectric signals within the human body, laser-beam propagation within samples of human blood, UHF diffraction by buildings in urban wireless microcells, microwave cavity resonances in subatomic particle accelerators, electrodynamics of micron-scale optical devices, novel wireless interconnects for ultrahigh-speed digital data buses, and extremely low-frequency geophysical phenomena.