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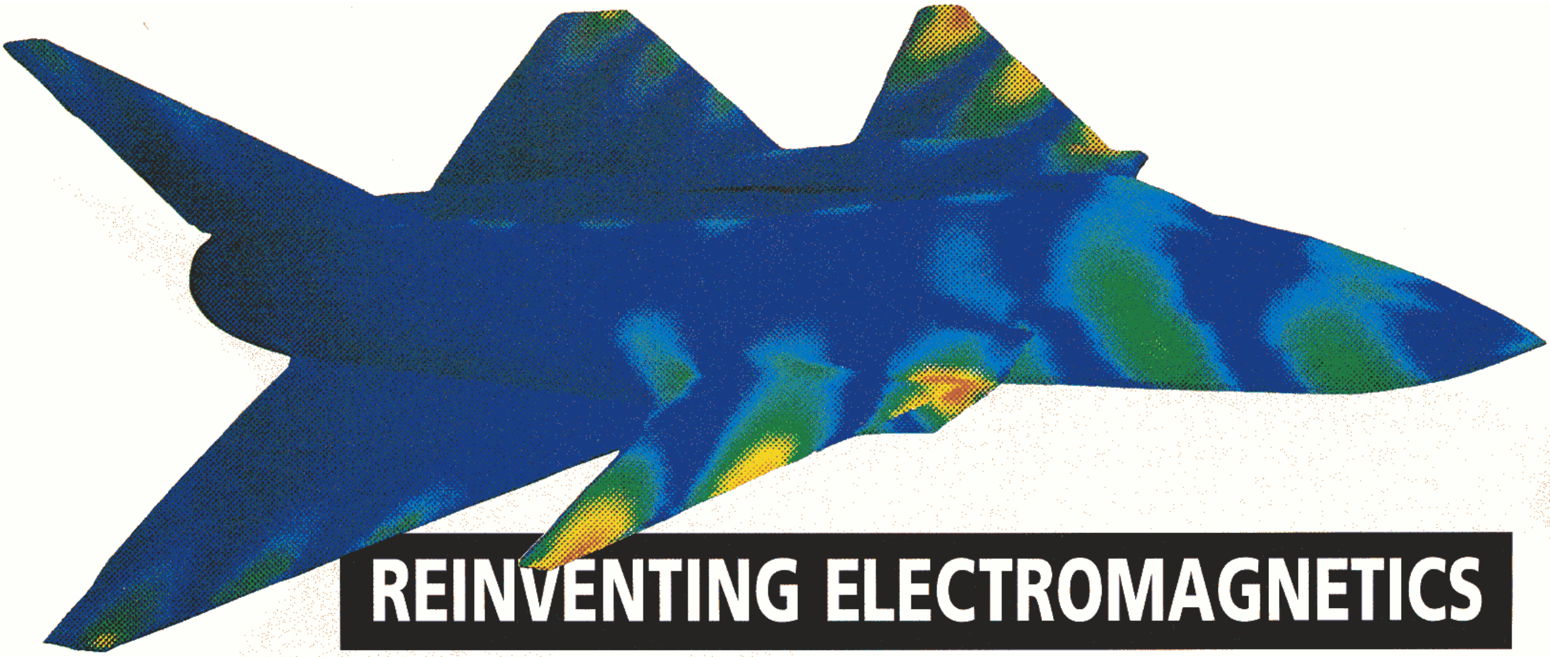
Announcing new hardware and software systems



REINVENTING ELECTROMAGNETICS

New supercomputing solutions to Maxwell's equations

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Figure 1 (above). Snapshot of the induced surface electric currents on the VFY-218 prototype Lockheed fighter aircraft for an illuminating radar frequency of 100 MHz at nose-on incidence. This model was implemented using a beta version of the Cray Research FD-TD software, EMDS (ElectroMagnetic Design System).

Until 1990, defense requirements for low radar cross section aerospace vehicles drove the development of large-scale methods in computational electromagnetics. Interest in finite-difference time-domain (FD-TD) and other direct space-grid Maxwell's-equations solvers for this purpose has grown to challenge the previously dominant frequency-domain integral equation approaches. For example, at the July 1992 IEEE Antennas and Propagation Society International Meeting in Chicago, 92 papers were presented on various aspects of FD-TD and other space-grid techniques.

In fact, the emergence of supercomputers with throughput in the range of 10 GFLOPS to 1 TFLOPS will permit FD-TD and similar approaches to model the dynamics of billions of field unknowns. Novel FD-TD algorithms incorporating lumped or distributed nonlinear effects over extremely large instantaneous bandwidths may be the key to understanding many types of technology at the core of twenty-first century electrical engineering. These technologies include microwave and millimeter wave antennas, subnanosecond electronic packaging, picosecond transistors, Josephson junctions and electro-optic devices, and femtosecond all-optical logic elements. This is because Maxwell's equations, with nonlinearities and dispersions properly modeled, provide an overarching framework for the physics of electromagnetic wave transport phenomena from direct current to light, and all high-speed devices of interest to modern society have such wave transport behavior as a critical operating factor.

The models discussed here were constructed at Northwestern University and run on CRAY Y-MP8 and CRAY Y-MP C90 supercomputer systems and solved for up to 60 million vector field unknowns in three dimensions.

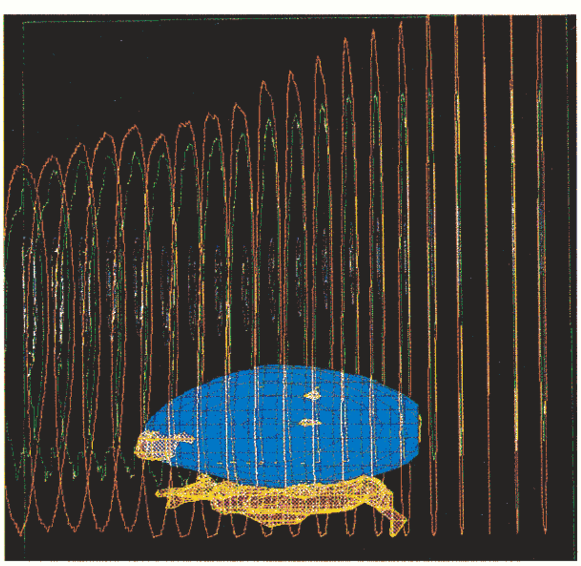


Figure 2. FD-TD-computed iso-loci of specific absorption rate (yellow-magenta = 25 percent of peak power absorption) and induced temperature (blue = 42°C) in a patient-specific model of the human thigh exposed to a waveguide hyperthermia applicator at 918 MHz. (No water bolus is used between the waveguide and the thigh.) A side view of thigh is shown, with the stack of CT planes seen edge-on.

Radar cross section modeling

It currently is feasible to embed an entire jet fighter within an FD-TD space grid to compute its induced surface electric currents and radar cross section for radar frequencies up to at least 500 MHz. For example, Figure 1 is a snapshot of the induced surface electric currents on the VFY-218 prototype Lockheed fighter aircraft for an illuminating radar frequency of 100 MHz at nose-on incidence. This model was implemented using a beta version of Cray Research's EMDS (ElectroMagnetic Design System) FD-TD software, which the Northwestern group helped develop. EMDS incorporates the Lockheed ACAD computer-aided design software to enable engineers to generate complex aerospace structures. The software automatically generates a conformal smooth-surface electromagnetics model of the structure using a highly structured finite-difference mesh. Cray Research's MPGS software, which is integrated into EMDS, provides the color visualization of the computed surface currents.

Bioelectromagnetic systems

FD-TD Maxwell's-equations solvers are being applied extensively in clinical settings to help design electromagnetic hyperthermia therapies. This technology uses electromagnetic wave absorption at radio, ultra-high, or microwave frequencies to heat cancerous tumors inside the human body, rendering them more vulnerable to ionizing radiation or chemotherapy. The Northwestern group has helped pioneer electromagnetic field hyperthermia therapies tailored to individual patients. The group uses computed tomography (CT) imaging to establish a three-dimensional dielectric medium database for the FD-TD solver unique to each patient's tissue structure,[1] thereby modeling the field physics unique to the patient's tissue geometry and selection of electromagnetic applicators. An example of this work is shown in Figure 2, which depicts the FD-TD-computed absorbed microwave power distribution and induced temperatures in a CT-generated patient-specific model of the human thigh for a waveguide hyperthermia applicator at 918 MHz.

Packaging and metallic interconnect design for digital circuits

The area of packaging and metallic interconnect design for digital circuits involves engineering problems in the propagation, crosstalk, and radiation of electronic digital pulses. This area has important implications in the design of the multilayer circuit boards and multichip modules widely used in modern digital technology. Existing computer-aided circuit design tools can be inadequate when digital clock speeds exceed about 250 MHz. These tools cannot handle the physics of UHF/microwave electromagnetic wave energy transport along metal surfaces such as ground planes, or in the air away from metal paths, that predominate above 250 MHz. Electronic digital systems develop substantial analog wave effects when clock rates are high enough, and full-vector (full-wave) Maxwell's-equations solvers become necessary to understand these effects.

In perhaps the most complex modeling of these effects so far, the Northwestern group constructed three-dimensional FD-TD models of subnanosecond digital pulse propagation and crosstalk behavior in a module consisting of a stack of four 22-layer circuit boards connected by three 50-pin connectors.[2] A uniform resolution of 0.004 inch permitted each layer, via, and pin of the circuit boards and connectors to be modeled. A maximum of 60 million vector field unknowns was solved per modeling run.

Figure 3(a) shows the plan view of an outwardly propagating electromagnetic wave within the top circuit board of the stack generated by the passage of the pulse down the via pin. Although the relatively intense magnetic field (shown by the yellow color) adjacent to the excited via is quite localized, moderate magnetic fields (shown by light blue) emanate throughout the entire transverse cross section of the board and link all of the adjacent via pins, shown as dark dots in a diamond pattern. Figure 3(b) depicts the early-time coupling of magnetic fields from the excited via pin to the adjacent unexcited via pins as seen in a vertical cut through the top 22-layer board and connector of the stack.

Figure 4 shows the magnitude and direction of late-time currents flowing along the vertical cross section of the four-board/three-connector stack for a subnanosecond digital pulse assumed to excite a single vertical via pin in the top 22-layer board. The currents were calculated in a postprocessing step by numerically evaluating the curl of the magnetic field obtained from the three-dimensional FD-TD model. Red denotes downward-directed current, while green denotes upward-directed current. At the time of this visualization, current had proceeded down the excited via through all four boards and all three connectors. Upward-directed

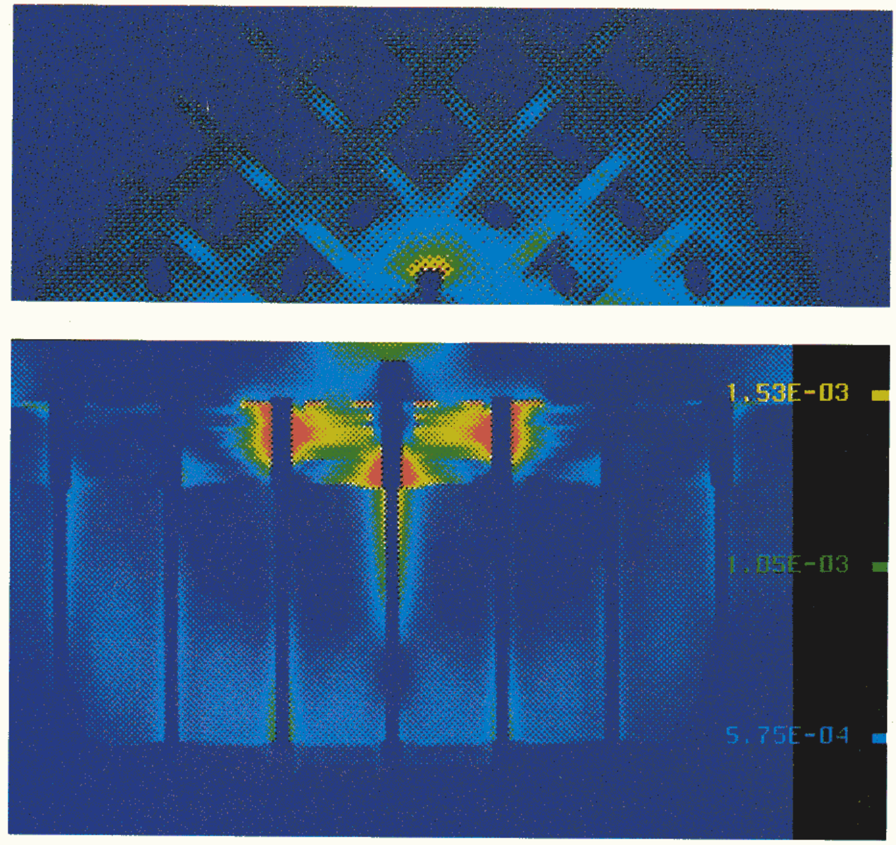


Figure 3. FD-TD-computed electromagnetic wave effects in the top 22-layer circuit board of the four-board/three-connector stack generated by the passage of a subnanosecond pulse down a single vertical via pin. (a) Plan view of outwardly propagating electromagnetic wave within the board. Color scale: yellow = maximum; light blue = moderate; dark blue = negligible. (b) Early-time coupling of magnetic fields from the excited via pin to the adjacent unexcited via pins as seen in a vertical cut through the top board and connector. Color scale: red = maximum; yellow = moderate; green = low-level; dark blue = negligible.

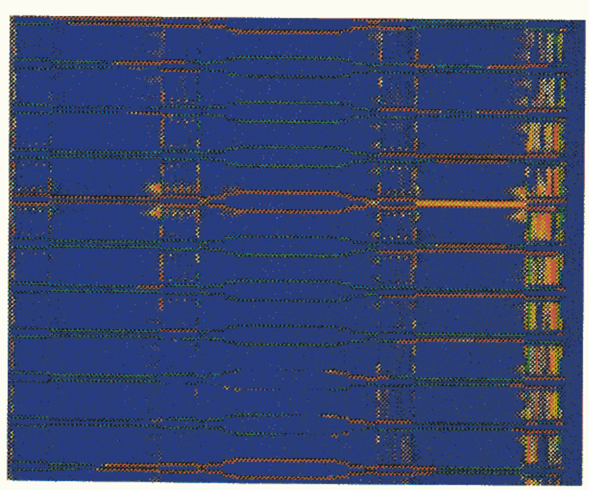


Figure 4. FD-TD-computed magnitude and direction of late-time currents flowing along the vertical cross section of the complete connector module for a subnanosecond digital pulse assumed to excite a single vertical via pin in the top 22-layer board. Color scale: red = downward-directed current; green = upward-directed current; dark blue = negligible.

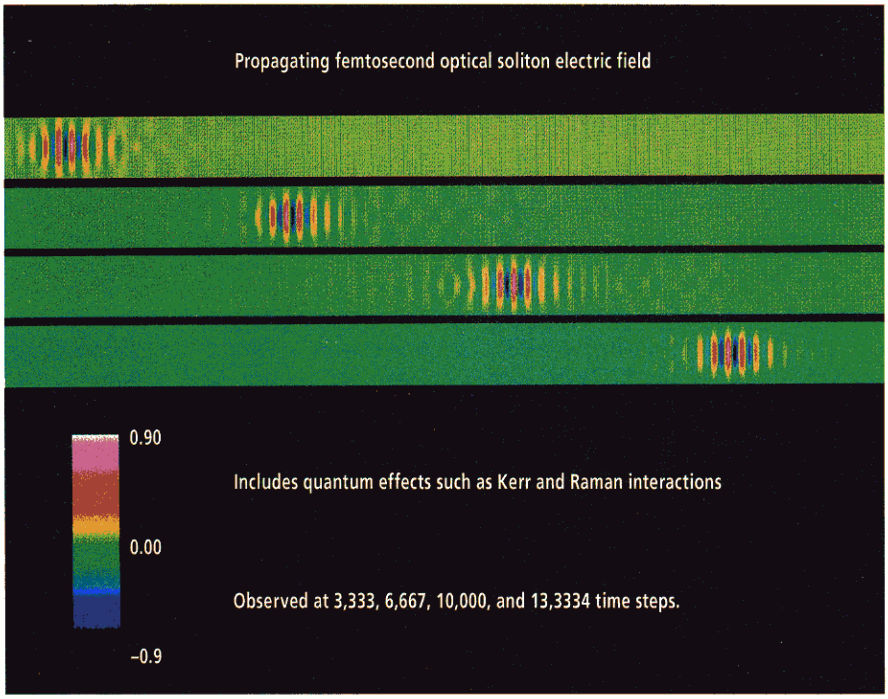


Figure 5. FD-TD-computed electric field of an initial 30-femtosecond duration optical carrier pulse (wavelength = 2.19 microns) propagating in a 1-micron thick nonlinear dispersive dielectric waveguide, showing the formation of a temporal soliton.

current, however, is seen to flow on the adjacent vias. This represents an undesired ground-loop coupling to the digital circuits using these vias that is capable of jamming the operation of these circuits.

This work is leading to the direct time-domain Maxwell's-equations modeling of the metallic interconnects and packaging of general-purpose digital circuits operating at clock speeds above 250 MHz. The example clearly shows that the analog coupling effects for such devices can be so complex that there may be no way to design them and make them work in a timely and reliable manner without such modeling.

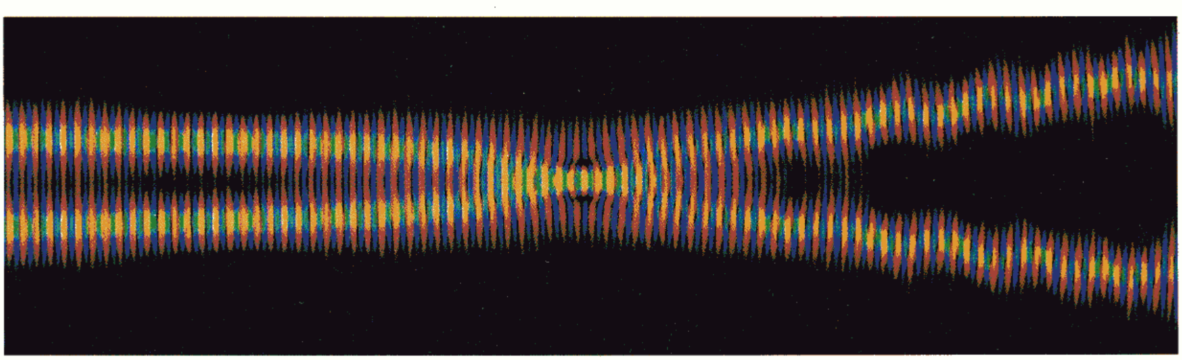
Application to all-optical devices

In the last two years, the Northwestern group, working with Peter Goorjian of the NASA-Ames Research Center, has pioneered FD-TD solutions of the vector nonlinear Maxwell's equations for femtosecond optical soliton propagation and scattering, including carrier waves, in one and two dimensions.[3,4] Our FD-TD approach efficiently implements second-order (Lorentzian) linear and nonlinear dispersive convolutions for the electric polarization, with the nonlinear convolution accounting for two key quantum effects, the Kerr and Raman interactions. By retaining the optical carrier, the new method solves for fundamental quantities—the optical, electric, and magnetic fields in space and time—rather than a nonphysical envelope function as did all previous approaches.

In this spirit, the researchers present first-time calculations from the vector nonlinear Maxwell's equations of temporal optical solitons propagating in a two-dimensional dielectric waveguide.[4] Here, a dielectric waveguide 1 micron thick and surrounded by air is considered. The calculations are for pulses with a carrier frequency of 1.37 x 10^{14} Hz (wavelength = 2.19 microns) and an initial width of only about 30 femtoseconds. (One femtosecond = 1 millionth of one nanosecond). Figure 5 depicts snapshots of the FD-TD-computed electric field for such a pulse as it travels down the dielectric waveguide. The dielectric is assumed to have anomalous linear dispersion due to a single Lorentzian relaxation and a dispersive nonlinearity due to the Kerr and Raman quantum interactions. Figure 5 clearly shows that the optical pulse retains its modal distribution as it propagates in the nonlinear dispersive waveguide, a property characteristic of a temporal optical soliton. Numerical experiments indicate that this is due to a balance of nonlinearity and dispersion; slightly reducing the dielectric nonlinearity causes the computed pulse to spread out progressively and attenuate as it propagates.

First-time calculations from the vector nonlinear Maxwell's equations of light switching light are presented last.[5] The group uses FD-TD to model spatial soliton propagation and scattering, including carrier waves, in a two-dimensional homogeneous nonlinear dielectric medium. Figure 6 shows the FD-TD-computed electric field of two initially parallel, equal-amplitude optical carrier beams co-propagating in a two-dimensional homogeneous nonlinear medium. Numerical experiments indicate that one such beam propagating alone retains its transverse profile due to self-focusing effects caused by the nonlinear medium, a property characteristic of a spatial optical soliton. Two co-propagating spatial solitons mutually interact via alternating attraction and repulsion and separate at a substantial deflection angle. After spatial filtering of either soliton, this deflection mechanism can provide the basis for a fast-acting photonic (all-optical) switch. The Northwestern group is investigating just how fast this switching action might ultimately be and whether the power

Figure 6. FD-TD-computed electric field of two initially parallel, equal-amplitude optical carrier beams co-propagating in a two-dimensional homogeneous nonlinear medium. Note the mutual interaction of the beams (spatial solitons) via alternating attraction and repulsion, followed by separation at a substantial deflection angle. This illustrates the phenomenon of light switching light.



in one beam can be reduced well below that of the other. The ultimate goal would be femtosecond-regime angular deflection (switching) accompanied by optical gain. This would provide the basis of a femtosecond all-optical transistor.

The Northwestern group's novel approach to computational nonlinear optics achieves robustness by rigorously enforcing the vector field boundary conditions at all interfaces of dissimilar media in the time scale of the optical carrier, whether or not the media are dispersive or nonlinear. As a result, the new approach is almost completely general. It assumes nothing about the homogeneity or isotropy of the optical medium, the magnitude of the nonlinearity, the nature of the material's dispersive properties, or the shape, duration, or vector nature of the optical pulse(s). It has the potential to provide an unprecedented two- and three-dimensional modeling capability for millimeter-scale integrated optical circuits having submicron-engineered inhomogeneities.

If successful, this work may lead to the modeling of all-optical digital logic devices switching potentially in 10 to 50 femtoseconds at room temperature. This is about 1000 times faster than the best transistor today and 100 times faster than a Josephson junction operating under liquid helium. The implications may be profound for the realization of "optonics," a proposed successor technology to electronics in the twenty-first century that would integrate optical fiber interconnects and all-optical processors into systems of unimaginable information processing capability.

Conclusions

Supercomputers of the late-1990s, which promise to achieve rates from 0.1 to 1 TFLOPS, will permit us to attack some grand challenges in electromagnetics. One such challenge remains from the radar cross section technology side—the airplane-in-the-grid. In fact, using this new class of supercomputers and the new class of space-grid time-domain Maxwell's solvers, it certainly will be possible to obtain whole stealth fighter models in the 1 to 3 GHz range, and jet-engine-inlet models up to perhaps 5 to 10 GHz, with predictive dynamic ranges up to 70 dB.

Moreover, the same algorithms implemented on the same computers could attack other grand challenges in electromagnetics:

- ☐ Patient-specific, whole-body electromagnetic hyperthermia cancer therapies
- ☐ Sub-nanosecond passive metallic interconnects, packaging, and multi-chip modules for electronic digital circuits
- ☐ Logical operation of transistors and other active digital elements at clocks above 1 GHz self-consistently incorporating device nonlinearities and electromagnetic effects
- ☐ Novel picosecond transistors exploiting interactions of electromagnetic and charge waves
- ☐ Novel femtosecond all-optical logic elements or even more exotic nonlinear wave species yet to be discovered

In fact, the ultra-large-scale solution of Maxwell's equations using time-domain grid-based approaches may be fundamental to the advancement of technology as we continue to push the envelope of the ultra-complex and the ultra-fast. Simply speaking, Maxwell's equations describe the physics of electromagnetic phenomena from direct current to light, and accurately modeling them is essential to understand high-speed signal effects exhibiting wave transport behavior. The goal is the computational unification of full-vector electromagnetic waves; charge transport in transistors, Josephson junctions, and electro-optic devices; surface and volumetric wave dispersions (including those of superconductors); and nonlinearities due to quantum effects. Then we can attack some computational grand challenges to markedly advance electrical engineering and directly benefit society.

Acknowledgments

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Allen Taflove is a professor of electrical engineering and computer science at Northwestern University McCormick School of Engineering. In 1990, he was named an IEEE Fellow for his pioneering FD-TD methods in computational electromagnetics since 1973.

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