APPLIED COMPUTATIONAL ELECTROMAGNETICS SOCIETY (ACES)

NEWSLETTER

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NEWSLETTER ARTICLES AND VOLUNTEERS WELCOME

The ACES Newsletter is always looking for articles, letters, and short communications of interest to ACES members. All individuals are encouraged to write, suggest, or solicit articles either on a one-time or continuing basis. Please contact a Newsletter Editor.

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OFFICER'S REPORTS

PRESIDENT'S COMMENTS

On behalf of the ACES Board of Directors and the entire ACES membership, I would like to first publicly thank outgoing President Hal Sabbagh for the time and energy he has devoted over an extended period of years to the Society. ACES achieved an important operational goal under Hal's leadership, namely, a fiscally sound basis. This now affords us the flexibility of being able to look forward for years as we plan, and guide, the future of ACES. When Hal began his term, the time horizon for planning was measured in months because of potential financial limitations. It is true that Hal had some excellent assistants, who have been good stewards of the ACES resources accrued largely from membership fees and conference registrations. Jim Logan began some critical long-range planning, and the process has been refined more recently by Andy Peterson in his service as Finance Committee Chair. Along the way, Dick Adler has provided invaluable continuity and sage advice. It is dangerous to start calling names, because someone important always seems to be left out! Others have certainly contributed significantly to this accomplishment, but I think we should individually recognize the contributions of these major players as we begin a new officers' cycle in a financially healthy and relatively secure position.

Three Directors also concluded their terms in March: Pat Foster, Todd Hubing, and Adalbert Konrad. These are names that are familiar to all in ACES, and their work is well known. Pat Foster was instrumental in getting the ACES UK chapter organized and on its feet, while being very active in the Annual Review and numerous other ACES activities on a continuous basis since 1990. Todd Hubing merits special thanks for his work on the ACES Web site and for his service as Treasurer. Our gratitude is extended to Adalbert Konrad particularly for his excellent Special Issue and Associate Editor-in-Chief work with the ACES Journal, and for "diplomatic liaison" missions between ACES and other CEM societies and conferences. All three have earned a brief rest, and have our congratulations for a job well done.

The other officers elected at the Board of Directors meeting in March to two-year terms are John Brauer (Vice President), Eric Michielssen (Secretary), and Andreas Cangellaris (Treasurer). Listings of the nine elected Directors and all the ACES Committee Chairs appear elsewhere in this Newsletter. You should feel free to call on any one of us at any time regarding the operation (or improving the operation) of ACES.

Note that Ahmed Kishk and Allen Glisson are now the new Co-Editors-in-Chief for the ACES Journal. Please support their efforts by contributing manuscripts, reading and using the Journal, and giving them feedback on the fruits of their labor.

After lauding ACES for having become "stable," I must acknowledge that what some folks view as stable is viewed by others as static, so we will resist the temptation to become immobile animals and bask in the sun, and will actively strive to achieve movement which is positive and constructive for the future of our members as CEM professionals.

Your suggestions for how to best capitalize on perceived opportunities for ACES are invited and welcome!

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SECRETARY'S REPORT

The Applied Computational Electromagnetics Society's Board of Directors held its annual symposium business meeting in the El Prado Room, Herrmann Hall, on the Naval Postgraduate School Campus at Monterey, California, on Monday, 16 March 1998. The meeting was called to order at 1228 by Vice President, Pat Foster, presiding in the absence of President Hal Sabbagh. Directors present included Pat Foster, John Brauer, Perry Wheless, and Norio Takahashi. Eric Michielssen acted as authorized proxy for Andreas Cangellaris. Adalbert Konrad's proxy was given to Perry Wheless, and Todd Hubing's proxy was given to Pat Foster. Others in attendance included Bruce Archambeault, Duncan Baker, Jianming Jin, Ahmed Kishk, Don Pflug, Allen Glisson and ACES Executive Officer Richard W. Adler. Meeting highlights of particular interest for this report follow:

ELECTION RESULTS: The three new Directors from the latest election are Bruce Archambeault, Tony Brown, and Eric Michielssen. Their three-year terms began 17 March 1998 and will run until the year 2001. ACES has nine Directors; three terms expire each year on a rotating basis.

ACES '98: The final paper count was quite acceptable, in view of the new requirements for submission of full-length manuscripts for review which was just begun with the 1998 conference. All eight short courses had sufficient enrollment to be offered, and registrations were comparable to the 1997 total. A restriction to three parallel sessions was put in place in 1998 with positive results.

MEMBERSHIPS: Membership level is stable. Over the past year, non-renewals were replaced by approximately an equal number of new members. The decrease was mostly in international membership, which declined (after peaking at about 38%) to a current level of approximately 30%.

FINANCIAL STATUS: ACES assets and cash reserves increased modestly during the past year, and the Society is financially secure.

PENN STATE WORKSHOPS: A Fall three-day symposium of short courses and workshops will be held at the Penn Stater Conference Center Hotel, State College, PA, 28-30 September 1998. Present plans are for 12 courses to be offered at the PSU event, and hardcopy publicity has already been distributed by PSU.

"ANNUAL REVIEW" CONFERENCE SCHEDULING: The ACES Conference Committee has endorsed continuation of the third week of March for the annual ACES Conference.

DIRECTOR NOMINATIONS: The Nominations Committee presently consists of Adalbert Konrad, Duncan Baker, and Pat Foster. Nominations for the next election may be submitted to one of these individuals at any time.

PUBLICATIONS: The new ACES Journal Editors-in-Chief are Dr. Ahmed Kishk and Dr. Allen Glisson. They assumed their editorial duties in March 1998.

NEW OFFICERS: The following were elected to two-year terms: President - Perry Wheless, Vice President - John Brauer, Secretary - Eric Michielssen, and Treasurer - Andreas Cangellaris.

MAJOR AWARD RECIPIENTS: Eric Michielssen for Valued Service, Duncan Baker for the Founders Award, and Norio Takahashi for Best ACES Journal Paper of the past year.

ACES UK: Colin Silence is the new ACES UK Chairman. The chapter is financially stable. A newsletter was issued and a one-day technical meeting held at Imperial College in London since the last BoD meeting. The morning short course by Dr. Gerrit Mur on Finite Element Modeling was well received, and diverse topics were presented in the afternoon session. ACES UK thanks Pat Foster and Tony Brown for their prior (founding(service, and Dick Adler and Jim Breakall for the successful NEC course held in April 1997.

SECRETARY'S REPORT (Cont)

The annual meeting of ACES members began at 0745 on Tuesday, 17 March 1998, in the Glasgow Auditorium. Pat Foster announced the election results for both new Directors and new ACES Officers, and introduced new ACES Journal Editors Ahmed Kishk and Allen Glisson. She cited the financial report which appeared in the most recent Newsletter, and called for further business from the floor. There were no items of new business, and the meeting was adjourned at approximately 0752.

Eric Michielssen's tour of duty as ACES Secretary began in March, and I am closing out my watch with this report. Thank you for your assistance and support during my time as ACES Secretary, and please accept my best wishes for your continued health and prosperity in computational electromagnetics.

Submitted by
W. Perry Wheless, Jr.
Ex-ACES Secretary

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COMMITTEE REPORTS

AWARDS COMMITTEE

Awards presented at the 14th Annual Review of Progress were:

THE 1998 VALUED SERVICE AWARD was presented to Eric Michielssen, for his dedicated leadership as Chairman of the 13th Annual Review of Progress.

THE 1998 FOUNDERS AWARD was presented to Duncan Baker for his outstanding service to the ACES Journal.

THE 1998 OUTSTANDING PAPER AWARD was presented to Norio Takahashi, for his paper published in the November 1997 ACES Journal. His paper was titled "Verification of Softwares for Electromagnetic Field Analysis Using Models Proposed by Investigation Committees in IEE of Japan".

The above awards were presented at the Awards Banquet on Wednesday evening. In addition, a **BEST STUDENT PAPER PRIZE** was later awarded to Daniel S. Weile, Eric Michielssen and K. Gallivan, for their paper "Rational Krylov Reduced Order Modeling of Multiscreen Frequency Selective Surfaces".

Respectfully submitted
John R. Brauer

NOMINATIONS COMMITTEE

In the coming months, ACES members will be asked to vote for three board members. For uniformity, each candidate will be asked to provide a short statement that addresses:

(1) GENERAL BACKGROUND (e.g., professional experience, degrees, employment, etc.).

(2) PAST SERVICE TO ACES (e.g., service on ACES committees, or other contributions).

(3) CANDIDATES' STATEMENTS (e.g., short statement of the candidates views of major issues relevant to ACES). Candidates' statements will be no more than 500 words, unless otherwise directed by the board.

(4) OTHER UNIQUE QUALIFICATIONS (An additional but optional statement).

It is hoped that these areas will provide data on each candidate that might otherwise be obscured in a general, unstructured statement. When the time comes, please take a few minutes to study the candidates' statements and vote.

DIRECTORS-AT-LARGE

John Brauer	1999	Andreas Cangellaris	2000	Bruce Archambeault	2001
Harold Sabbagh	1999	Ray Perez	2000	Anthony Brown	2001
Perry Wheless, Jr.	1999	Norio Takahashi	2000	Eric Michielssen	2001

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The Nominations Committee presently consists of Adalbert Konrad, Duncan Baker, and Pat Foster. Nominations for the next election may be submitted to one of these individuals at any time.

ACES PUBLICATIONS

Ahmed Kishk and Allen Glisson became the new ACES Journal Co-Editors-in-Chief in March, and you are encouraged to support their efforts and new initiatives vigorously. Please feel free to contact Ahmed or Allen to discuss Journal matters and/or volunteer your services. They share the same mailing address: Department of Electrical Engineering, University of Mississippi, University, MS 38677. Note: for express mail delivery of manuscripts, and the like, their delivery "street" address is 302 Anderson Hall. Ahmed's office telephone is 601-232-5385 and his e-mail address is ahmed@olemiss.edu. Allen's office telephone is 601-232-5353 and his e-mail address is aglisson@olemiss.edu. The Journal bundled with this Newsletter is a Special Issue, but the next issue of contributed papers will be here soon. Manuscripts for Journal consideration should be sent directly to either Dr. Kishk or Dr. Glisson.

Atef Elsherbeni has been considering opportunities for ACES in the electronic publishing area in recent months, and we are hopeful that Atef will make himself available in a position of leadership for an extended period of time to help ACES Publications successfully navigate this exciting, but potentially overwhelming, medium in the future.

Ray Perez reports that the ACES Newsletter operation continues to proceed smoothly. However, the rate of contributions has declined somewhat during the past year, and Ray would like to invigorate the Newsletter with some new blood and ideas. Some additional Department Editors would be especially helpful, so please contact Ray directly if you have ideas and/or aspirations to participate actively. He is available by phone at 303-977-5845 (Colorado, USA) or by e-mail at ray.j.perez@ast.lmco.com.

The Publications Committee considered and acted on several items of business prior to the March ACES conference in Monterey, as reported on pages 8 and 9 of the March 1998 Newsletter.

Up through David Stein's tenure as Editor-in-Chief, the jobs of Publications Committee Chair and ACES Journal Editor-in-Chief were consolidated in one. David recommended splitting the duties between two people. Hal Sabbagh agreed with that recommendation, and operated that way throughout his term as ACES President. I have continued just temporarily as Publications Chairman since March because the possibility of recombining the positions is now under serious consideration. The present expectation is that the next Publications Committee report to the Newsletter will be my last as Publications Chair, so more change is on the horizon for ACES Publications.

Enjoy the summer (or winter, for a few of you) and don't take life too seriously - it's only temporary!

Submitted by:
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MODELER'S NOTES

Gerald J. Burke

There are no contributions for Modeler's Notes for this issue, but there are a couple of bug fixes for NEC–4 to report. The first involves the incrementing of angles for an incident plane wave. It turns out that the angles theta and phi for the incident wave were not re-initialized once the loops were completed, so in a frequency loop they would just continue incrementing from their final values. In fact, with just single nested theta and phi loops, the inner loop, phi, would continue incrementing from the final value when the theta loop advanced. Thanks to Benny Neta at NPS and the Nittany Scientific people for finding this. That it stayed hidden for so long shows that I and apparently most other users do not use nested incident-wave loops too often. At least it is very apparent when encountered, since the angles are labeled correctly in the output. This problem can be fixed by saving and restoring the initial angle values in the main program code, as shown below:

```
C
C     EXCITATION SET UP (RIGHT HAND SIDE, -E INC.)
C
53    INC=0
      NPRINT=0
      THSAVE=PSOR1(NSCINC)                    !Add
      PHSAVE=PSOR2(NSCINC)                    !Add
      DO 55 ITHINC=1,NTHINC                   !Change 54 → 55
         :
      IF (IFLOW.EQ.7) THEN
         IF (IXTYP.GT.0.AND.IXTYP.LT.4) GO TO 54
            PSOR1(NSCINC)=THSAVE              !Add
            PSOR2(NSCINC)=PHSAVE              !Add
         IF (NFRQ.NE.1) GO TO 120
         WRITE(3,135)
         GO TO 14
      END IF
C
C     NEAR AND FAR FIELD CALCULATIONS
C
      IF (NEAR.EQ.0.OR.NEAR.EQ.1) CALL NFPAT
      IF (NEAR.EQ.2)CALL NFLINE
      IF (IFAR.NE.-1) CALL RDPAT(PIN,PNLS,PLOSS)
54    CONTINUE
      PSOR2(NSCINC)=PHSAVE                    !Add
55    CONTINUE                                !Add
      PSOR1(NSCINC)=THSAVE                    !Add
```

The second bug involves the reflection coefficient for the field reflected down ($\theta > 90^\circ$) into a dielectric ground (zero conductivity) from a buried wire. This was uncovered when I was trying to check results for a monopole on a buried radial-wire ground screen that Jack Belrose was modeling. A useful check in such a case, especially if conduction currents are not too dominant in the ground, is to set the ground conductivity to zero and integrate the radiated field over the sphere with a command such as

```
RP0, 721, 3, 1002, 0., 0., 0.25, 0.75
```

This is assuming 120 radials, so that the 0.75 degree increment in phi is one quarter of the angle between radials. A theta cut in the plane of a radial or halfway between radials will have no horizontal polarization due to symmetry, but the the cut at 1/4 of the radial spacing may pick up significant horizontal polarization with a sparse screen. The rest of the pattern repeats symmetrically in phi, so does not need to be integrated. The small increment for theta is necessary since the radiation down into a dielectric ground will have a very sharp spike at the critical angle, where a ray traveling up would be totally reflected. Still smaller angle increments might be needed in some cases.

If there are no ohmic losses, the "average gain" from this calculation should come out 1.0 to show that the radiated power is equal to the power computed from voltage and current at the source. However, when I tried this on Jack's antenna the average gain was around 10000. The problem turned out to be a wrong sign for a square root in the reflection coefficient in subroutine ZYSURF. The problem is fixed by adding the four lines following CTH= ... as shown below.

```
C
C     COMPUTE SURFACE IMPEDANCE AND ADMITTANCE OF GROUND
C
      CTHM=SQRT(1.-(ETAX/ETA)**2*(1.-CTH*CTH))
      IF(CTH.LT.0.)CTHM=-CTHM
      IF(ABS(DREAL(CTHM)).LT.ABS(DIMAG(CTHM))*1.E-6)THEN
        IF(CTH*DIMAG(CTHM).GE.0.)CTHM=-CTHM
      END IF
```

With this problem fixed, the average gain for Jack's antenna, a thick monopole on 113 buried thin radials, was 0.995, which looks very good for such a case.

Also, Roy Lewallen has pointed out that a correction included in the March 1996 Newsletter was itself not quite correct. This involved a missing factor of e^{-jkR}/R in the radiated field when the RP1 (ground wave) command is used with perfectly conducting ground. The fix given in March 1996 used the distance from the z axis (RFLD) rather than the distance from the origin. A correct fix in subroutine RDPAT is:

```
        CALL FFLD (THA,PHA,ETH,EPH)
        RDIST=SQRT(RFLD*RFLD+THET*THET)              !NEW
        ETH=ETH*CEXP(-(0.,1.)*XKU*RDIST)/RDIST       !CORRECTED
        EPH=EPH*CEXP(-(0.,1.)*XKU*RDIST)/RDIST       !CORRECTED
        ERDM=0.
        ERDA=0.
      END IF
    ELSE
        CALL FFLD (THA,PHA,ETH,EPH)
    END IF
```

As usual, if anyone can contribute modeling-related material for future newsletters, they are encouraged to contact our editor Ray Perez or Jerry Burke, Lawrence Livermore National Lab., P.O. Box 808, L-154, Livermore, CA 94550, phone: 925-422-8414, FAX: 925-423-3144, e-mail: burke2@llnl.gov.

TECHNICAL FEATURE ARTICLE

Numerical Model of Light-Trapping in Solar Cells

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***Abstract*—**

The light-trapping of a solar cell is controlled and enhanced by surface textures and anti-reflection coatings. The model reported in this paper is based on geometrical optics (ray-trace analysis). This analysis is inherently limited to thick solar cells. The model treats the solar cell as an infinite periodic structure illuminated by sunlight. The model allows many different solar cell geometries to be analyzed. The geometry of the solar cell is defined in general terms so future light-trapping designs can be studied with the present models. Sunlight is defined by its polarization and irradiance spectrum. The output from the model is the absorption spectrum of the solar cell and the maximum achievable current density under a given irradiance spectrum.

The model predicts a significant improvement of light-trapping when surface textures and anti-reflection coatings are used. Thin solar cells offer the promise of being efficient and inexpensive.

I. Introduction

Solar cells are semiconductor devices designed to convert light into electrical power. In order to be cost effective they must be as efficient as possible. Solar cell efficiency is related to the percent of the incident sunlight converted into electrical power. The goal in the design of solar cell devices is to trap and absorb as much light as possible inside the semiconductor. In the language of the solar cell community, the goal is to maximize light-trapping.

One effective way to maximize light-trapping is to coat the semiconductor with a thin film which reduces reflection. This anti-reflective coating ensures a higher percentage of light enters the cell so more light is absorbed. A second effective approach to increase light-trapping is to texture the surface of the solar cell. The texture creates multiple reflections which will lead to increased light-trapping. The specific design of the textures is critical to maximize light-trapping. All commercial solar cell designs include encapsulation to protect the solar cell from nature. The effect of encapsulation on light-trapping is poorly understood. Encapsulation is assumed to be detrimental to light-trapping. The integration of the anti-reflection coating, encapsulation, and texture into the solar cell design determines the overall light-trapping capacity of a solar cell.

Historically, the solar cell industry did not have a means to effectively and accurately predict the light-trapping of a given solar cell geometry. Each solar cell was manufactured and then its efficiency was measured. This is expensive and time consuming. This research fills the need of the solar cell community by quantifying and predicting the light-trapping of a given solar cell design with the aid of a numerical model. The result of this paper is a numerical solar cell model which provides industry a means to quantify the light-trapping capability of many different three-dimensional solar cell designs. By modeling light-trapping, the expensive and time consuming step of fabrication is streamlined. Only the promising designs need to be fabricated and tested. This, in turn, frees valuable resources which can be utilized to design more efficient solar cells.

II. Background

A. Maxwell's Equations

The interaction between sunlight and the solar cell is an interaction between light and matter. Maxwell's equations, therefore, are the fundamental governing equations. The types of materials found in solar cells are lossy. Solar cells absorb energy from light and convert it into electrical current. The absorption of light is included in Maxwell's equations by defining the loss via an electric current density, $\vec{J_e} = \sigma\vec{E}$. The absorbed power, $P_a(t)$, is directly related to light-trapping in solar cells.

Maxwell's equations do not have a closed analytical solution except the most simple cases. This presents an immense challenge to solving problems in design and engineering, including the design of efficient solar cells. The difficulties of solving Maxwell's equations lie at the core of this research and are overcome by applying numerical methods.

B. Optical Properties of Matter

The parameters, $\epsilon = \epsilon_r\epsilon_0$ and σ, describe the optical properties of the solar cell. These properties are quantified directly or through the optical parameters of refractive index, n, and the extinction coefficient, k. The quantities are related by

$$\epsilon_r = n^2 - k^2 \tag{1}$$

$$\sigma = 2nk\epsilon_0\omega \tag{2}$$

where c is the speed of light, ω is the angular frequency of light and ϵ_0 is the permittivity of free space [1].

In actual practice, the light illuminating a solar cell experiences dispersion. Specifically, the index of refraction depends on the wavelength of the incident light. The extinction coefficient also depends on wavelength and determines the amount of light that is absorbed in the solar cell. [2]. The index of refraction varies over a wide range from 3.4 to 5.6 which means dispersion effects are important. The extinction coefficient varies by orders of magnitude. The extinction coefficient becomes small as wavelength increases which means little light is absorbed at the higher wavelengths. The higher wavelengths corresponds to lower energy photons. Solar cell designs must accommodate dispersion to ensure accurate light-trapping predictions. Solar cell designs must also overcome the small extinction coefficient by maximizing light-trapping.

C. A Measure of Light-Trapping

How is light converted to electrical power by a solar cell? The answer to this question provides the measure of light-trapping used in this paper. The following discussion on how a solar cell works summarizes the important issues relating solar cell design to light-trapping [3]. The first solar cell, developed in 1954, consisted of a single p-n junction in silicon [4]. A typical solar cell, shown in Figure 1 [4], is still based on the p-n junction. The front side of the cell

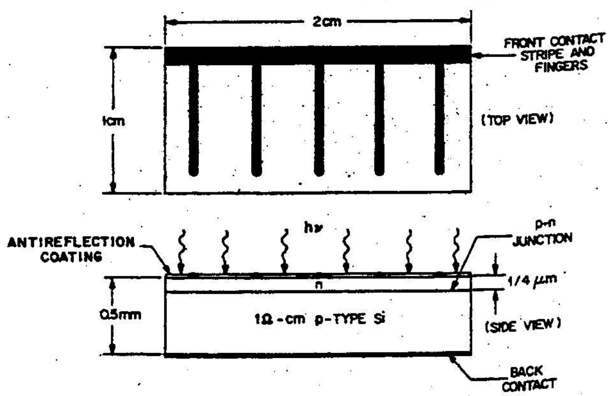


Fig. 1. A typical solar cell configuration.

receives the incident sunlight and has some ohmic "fingers" to collect the carriers of current. The finger shape allows light to enter the solar cell. The back surface is a solid ohmic contact. The back side of the cell, for simplicity of discussion, is far enough away from the front surface to guarantee that no light reaches the back surface. The intensity of light decreases exponentially as a function of depth within the solar cell. J_p is the current density collected at the front side and J_n is the current density collected at the back side of the solar cell. Overall, the total photocurrent as a function of wavelength is

$$J(\lambda) = J_p(\lambda) + J_n(\lambda) + J_{dr}(\lambda) \tag{3}$$

The internal spectral response of the solar cell is defined as

$$SR(\lambda) = \frac{J_p(\lambda) + J_n(\lambda) + J_{dr}(\lambda)}{qF(\lambda)[1 - R(\lambda)]} \tag{4}$$

The total fraction of incident power absorbed by the solar cell is $1 - R(\lambda)$. The denominator, $qF(\lambda)[1 - R(\lambda)]$, is the maximum current density possible when every absorbed photon contributes to the net current.

The total photocurrent density in the solar cell, J_L, is

$$J_L = q \int_0^{\infty} F(\lambda)A(\lambda)SR(\lambda)\, d\lambda \tag{5}$$

where q is the charge of an electron, $SR(\lambda)$ is the internal spectral response of the solar cell, $F(\lambda)$ is the solar spectrum (usually AM1.5 for terrestrial applications) of the incident light, and $A(\lambda)$ is the total fraction of light absorbed in the semiconductor.

The total photocurrent density is used as the basis, throughout this paper, to measure light-trapping in a given solar cell geometry. Equation 5 suggests the higher the total photocurrent density, the better the light-trapping. The solar spectrum and electrical properties of the solar cell are ignored if only $A(\lambda)$ is used to quantify light-trapping. For this reason, the Maximum Achievable Current Density (MACD) of a solar cell is introduced. The MACD takes into account both absorption and the incident solar spectrum by counting the maximum number of photons that can be converted into current. The MACD is based on the assumption that every absorbed photon in the semiconductor creates an electron-hole pair which, in turn, contributes to the net electric current. The MACD is based on the assumption of an ideal internal spectral response. The MACD, J_{sc}, is defined by

$$J_{sc} = q \int_0^{\lambda_m} F(\lambda)A(\lambda)\, d\lambda \tag{6}$$

where q is the charge of an electron, $F(\lambda)$ is the solar spectrum (usually AM1.5) of the incident light, and $A(\lambda)$ comes from the solution to Maxwell's equations. The ideal internal spectral response makes it possible to study light-trapping without reference to any specific semiconductor material used in the solar cell. In this way, silicon as well as any other semiconductor can be studied based solely on optical considerations.

Both the absorption, $A(\lambda)$, and the MACD are used to quantify light-trapping. In the strict sense, absorption is the pure measure of light-trapping. Absorption quantifies how the incident light is absorbed as a function of wavelength but ignores the spectral content of the sunlight. On the other hand, the MACD integrates the effects of both the absorption and solar spectrum into a single quantity, J_{sc}. The MACD gives a more telling characterization of the real operational solar cell than absorption, without limiting itself to any particular semiconductor.

D. How is Light-Trapping Improved?

Light-trapping is governed by the absorption of light in the solar cell. The solar cell which absorbs the most light is the best solar cell, at least from the light-trapping point of view. This is easily said but what parameters can the solar cell designer change to increase absorption? In short, the way to increase absorption is to reduce the front surface reflection and trap light inside the solar cell. There are two primary ways to reduce the front surface reflection. First, thin anti-reflection films are deposited on the surface which lower the reflection. Second, the front surface is textured. Sometimes the front surface is sand blasted to give a random-rough texture [5]. Other times, the surface is chemically etched. The chemical etching process results in geometrically ordered surface textures [6].

The surface of a textured solar cell is a pyramid shaped texture. The angles are constant because of the inherent crystal structure of the silicon. Different etches result in different pyramid shapes. Some solar cell designs are better at light-trapping than others. As a consequence, many different texturing schemes have been proposed to optimize light-trapping. The pyramid and tilted pyramid are known to improve light-trapping. The inverted pyramid design is expected to yield better light-trapping than the pyramid texture design [7]. The corrugated design also traps light effectively and has a calculated short circuit current density of $J_{sc} = 40.91\,\mathrm{mA/cm^2}$ [8]. The most promising light-trapping design, which was first proposed by Geoffrey Landis in 1984, is the perpendicular slat solar cell. The perpendicular slat solar cell promises a short circuit current density of $J_{sc} = 41.7\,\mathrm{mA/cm^2}$ [9]. Finally, a design proposed for very thin, $0.75\,\mu$m thick, solar cells uses a randomized surface texture [10]. The random surface texture is known to increase the intensity of light inside the solar cell by a factor of $2n^2$ over the planar solar cell and the effective absorption enhancement factor is $4n^2$ [11]. The random surface textured leads to a large absorption enhancement of approximately 60 for silicon solar cells.

The anti-reflection coating is a second method used to improve light-trapping. Anti-reflection coatings are deposited on the surface of the solar cell to reduce the reflection of light. Anti-reflection coatings consist of multiple thin layers of dielectrics. Each layer has a thickness that is chosen to be either a quarter- or half-wavelength of the incident light. The choice of thickness, dielectric, and number of layers ultimately determines how well an anti-reflection coating performs.

III. Ray-Trace Model

Geometrical optics leads elegantly to the ray-trace model of light-trapping. The physical dimensions of real solar cells are too large to model completely when including all the important light-trapping parameters in the model. The periodic boundary is introduced to reduce the size of the model and still include the key light-trapping design parameters. The periodic boundary makes a realistic simulation possible with the reasonable computing resources of a personal computer.

Fundamentally, geometrical optics treats light as an infinitesimally thin beam or ray that transports power from the sun to interact with the solar cell. Geometrical optics quantifies the interaction between sunlight and the solar cell through the Law of Reflection, the Law of Refraction, and the Fresnel equations. The critical interaction occurs at the interface between different materials. When a ray of light hits a material interface, the ray's energy splits into a reflected and transmitted ray. The solar cell uses power to create electrical energy.

A. Anti-Reflection Coating

Anti-reflection coatings are based on the interference effects of light waves. To include the effects of anti-reflection coatings in the ray-trace model, some simplifying assumptions are required. The transmitted ray is slightly offset upon exiting [12]. Since the coating is thin, the ray-trace model neglects this offset. The direction of propagation for the reflected and transmitted rays is unaffected by the anti-reflection coating. The anti-reflection coating does change the fraction of power reflected and transmitted from the incident ray. The reflection and transmission coefficients of an anti-reflection coating are detailed below [13]. The reflection coefficient for a two layer film is

$$R_\perp = |r_\perp|^2 \quad R_\parallel = |r_\parallel|^2 \tag{7}$$

where

$$r_\perp = \frac{r_{\perp,1} + r'_\perp e^{-i\delta_1}}{1 + r_{\perp,1} r'_\perp e^{-i\delta_1}} \quad r_\parallel = \frac{r_{\parallel,1} + r'_\parallel e^{-i\delta_1}}{1 + r_{\parallel,1} r'_\parallel e^{-i\delta_1}} \tag{8}$$

and

$$r'_\perp = \frac{r_{\perp,2} + r_{\perp,3} e^{-i\delta_2}}{1 + r_{\perp,2} r_{\perp,3} e^{-i\delta_2}} \quad r'_\parallel = \frac{r_{\parallel,2} + r_{\parallel,3} e^{-i\delta_2}}{1 + r_{\parallel,2} r_{\parallel,3} e^{-i\delta_2}} \tag{9}$$

and by defining $i = 1, 2, 3$ so $\delta_i = \frac{4\pi}{\lambda} n_i t_i cos(\theta_i)$

$$r_{\perp,i} = \frac{\tilde{n}_{i-1} cos(\theta_{i-1}) - \tilde{n}_i cos(\theta_i)}{\tilde{n}_{i-1} cos(\theta_{i-1}) + \tilde{n}_i cos(\theta_i)} \quad r_{\parallel,i} = \frac{\tilde{n}_{i-1} cos(\theta_i) - \tilde{n}_i cos(\theta_{i-1})}{\tilde{n}_{i-1} cos(\theta_i) + \tilde{n}_i cos(\theta_{i-1})} \tag{10}$$

The transmission coefficient is

$$T_\perp = 1 - R_\perp \quad T_\parallel = 1 - R_\parallel \tag{11}$$

These AR equations are generalized to two layer films in which two materials and two thicknesses are required to specify the coating.

In summary, the directions of the rays are determined by the laws of reflection and refraction, as if no anti-reflection coating exists. The model only requires a slight modification in the calculation of power. Instead of using Fresnel equations to calculate the fractions of power, the anti-reflection equations 7 and 11 are used to incorporate anti-reflection coatings into the ray-trace model.

B. Measurement of Light-Trapping

The measure of light-trapping is absorption, $A(\lambda)$. In the ray-trace model, multiple light rays propagate through the solar cell. As the rays pass through the solar cell, energy is removed from the rays and is directly absorbed by the solar cell.

B.1 Accuracy

Geometrical optics dictates the use of some limiting assumptions about the solar cell geometry which affects the accuracy of the ray-trace model. First, the geometrical features of a cell must be large compared to the wavelength of light. As a consequence, the ray-trace model does not accurately model diffraction effects. Second, the calculation of the surface normal is arbitrary near the discontinuity of any texture. The ray-trace model uses the average surface normal. Third, the implementation of anti-reflection coatings in the ray-trace model assumes anti-reflection coatings are thin. The ray-trace model ignores the real offset caused by the finite thickness of the real AR coating. Finally, the incident sunlight is divided into rays. How many rays? If the solar cell is planar, only one incident ray is necessary. If the solar cell is textured, one ray cannot model all the effects. The number of incident rays is decided by using one ray, two rays, four rays ... $2N$ rays until the calculated value of absorption, $A(\lambda)$, remains constant. Overall, the accuracy of the model is limited by the original assumptions of geometrical optics. Therefore, the ray-trace model can only be used in cases when the assumptions of geometrical optics hold true. The solar cells must have features that are "large" relative to the wavelength of the incident light.

B.2 Limitations and Capabilities

The ray-trace model incorporates surface texturing, AR coatings, the solar spectrum, and polarization into a single CAD tool. The solar cell is composed of as many as fourteen different dielectrics. Each dielectric has a complex surface geometry defined by a set of three-node planar elements. The periodic boundary is included in the model. The model works with or without the periodic boundary. The net result of the computer calculations is the absorption spectrum, $A(\lambda)$, and a calculation of MACD. The MACD can be calculated using any solar spectrum given by the user. The internal spectral response can be included by defining a pseudo solar spectrum derived from multiplying the real solar spectrum by the internal spectral response.

The ray-trace model has some major limitations. The ray-trace model is only valid to use for large solar cells. If the periodic boundary is used, the edge loss due to the finite size of the solar cell is neglected. For each wavelength, the complete model needs to be run to account for dispersion effects. Interference properties of light have no effect except when the anti-reflection coatings are used.

IV. Ray-Trace Model Light-Trapping Analysis

The ray-trace model is used to analyze various solar cells based on their light-trapping characteristics [14]. The primary goal of the ray-trace model is to make a computer light-trapping model available to the solar cell community at a low cost. The ray-trace model satisfies the low cost constraint by requiring only a modest and inexpensive computer to complete any light-trapping calculation. All of the analyses presented in this section are calculated on an Intel 386 based personal computer with one megabyte of memory.

A. MACD and Light-Trapping

The effect of various front and rear surface geometry combinations on light-trapping is explored in this subsection. Eight different solar cell designs are modeled and compared based on the maximum achievable current density they can produce under AM1.5 solar illumination. The solar cells differ from the simple planar solar cell in their use of surface textures and anti-reflection films to enhance light-trapping. The front surface of the solar cell is textured with a periodic V-groove surface or a randomized surface. The V-groove has a peak angle of 70.4° corresponding to the crystalline structure of silicon. The random surface texture is modeled by choosing a set of random peak angles and heights. All of the front surfaces are coated with a two layer anti-reflection coating consisting of Si_3N_4 (0.0710 μm thick) and SiO_2 (0.0100 μm thick). The rear surface of the silicon is also textured with a periodic or random surface. A planar-polished back surface is also modeled. The rear surface is coated with aluminum in half the models. The aluminum ensures all light which reaches the back surface is reflected back into the solar cell. For comparison, the other half of the solar cells have the aluminum removed from the rear surface. Figure 2 shows the calculated MACD as a function of cell thickness for the eight different solar cell light-trapping designs.

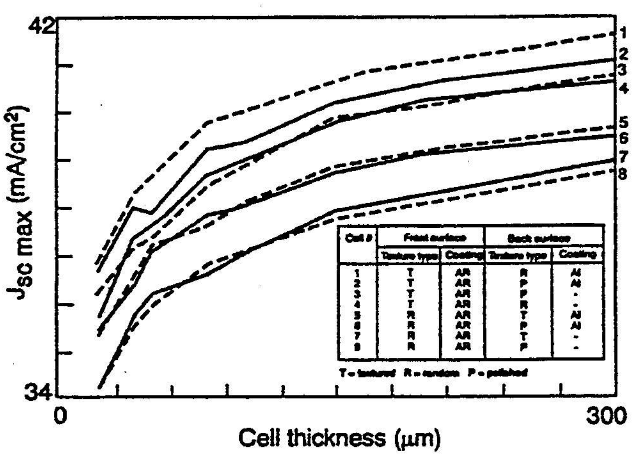


Fig. 2. The calculated MACD for various texture combinations.

B. Where are the Photons Absorbed?

From the pure view of light-trapping, where the photons are absorbed within the solar cell is of no concern. Only the total absorption is important. The consequence of only considering the total absorption leads to a prediction of the best light-trapping design based on the maximum achievable current density. Figure 2 suggests the best light-trapping design utilizes a front texture and is as thick as possible. So why not make a solar cell 300 μm thick? Why not 1000 μm thick? The MACD assumes every absorbed photon contributes to the net current of the solar cell. In the real solar cell, each absorbed photon excites a carrier which diffuses to the ohmic contacts. Some carriers never reach the contacts because they originate too far away from the contacts. Only carriers created within a diffusion length of the contact contribute to the net current. As the thickness of the solar cell increases, less of the carriers contribute to the current. The thickness of the solar cell should be roughly equal to the diffusion length of the semiconductor to collect all the absorbed photons. The MACD only measures optical absorption properties of the solar cell. Insight into the generation of current, where the absorbed photons originate is important information to the solar cell designer.

The textured 250 μm thick solar cell is compared to a 50 μm solar cell in Figure 3. Both cells have exactly the same front surface characteristics. The rear surface of the 50 μm cell has a randomized surface texture with an aluminum coating to maximize light-trapping. The maximum achievable current density is 40.47 mA/cm^2 for the 250 μm thick solar cell which is slightly greater than 38.89 mA/cm^2 for the 50 μm solar cell. Even though the maximum achievable current density is greatest in the 250 μm cell, the inset figure shows the 50 μm actually has the higher photon flux density. As a consequence, the importance of surface recombination increases as the thickness of the solar cell decreases.

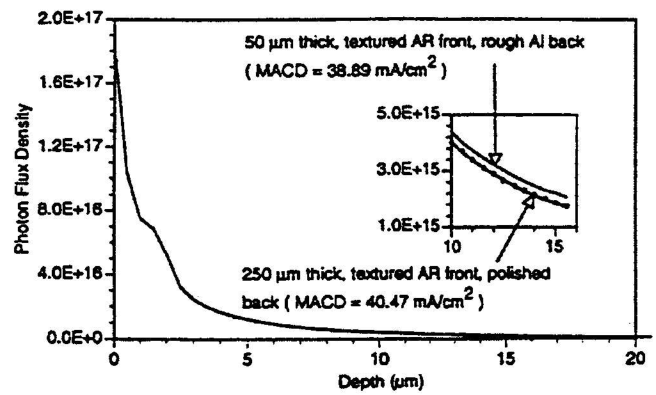


Fig. 3. The photon flux density and solar cell thickness.

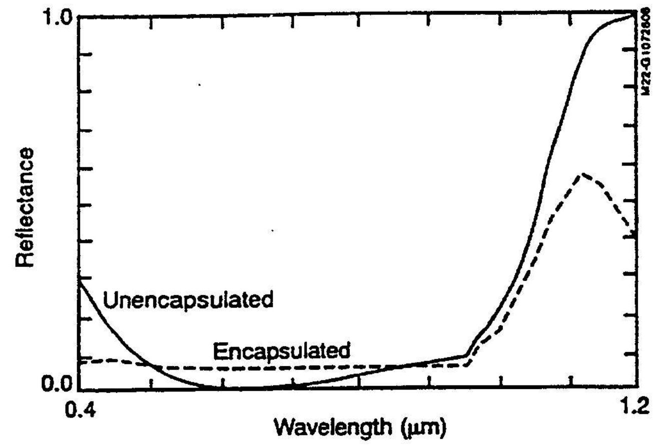
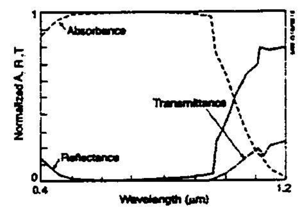
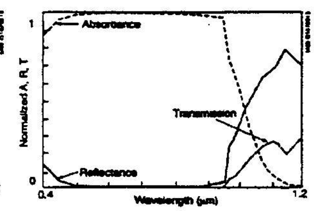


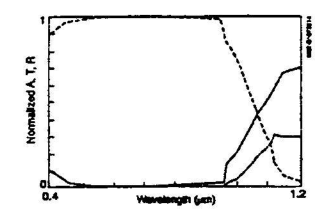
Fig. 4. A reflectance plot showing the effect of encapsulation.



(a) Untilted Pyramids with a MACD=38.06 mA/cm^2.



(b) V-grooves with a MACD=37.38 mA/cm^2.



(c) Inverted Pyramids with a MACD=39.2 mA/cm^2.

Fig. 5. A 50 μm solar cell with different surface textures.

C. The Effect of Encapsulation

A sample solar cell is protected from nature with two encapsulating layers. A 3000 μm thick layer of glass is placed on top of another layer of 2000 μm thick pottant. The absorption coefficient of the pottant is dependent on wavelength [15] and is included in the model. The solar cell is 100 μm thick. The front surface has a randomized surface texture with an AR coating. The back surface is textured with an aluminum coating. Figure 4. demonstrates the encapsulation has a large effect on the light-trapping performance of a solar cell. Encapsulation reduces the maximum achievable current density by about 6% in this particular solar cell. It should be pointed out that there are many different encapsulating schemes. For instance, there are flexible amorphous silicon sheets that cannot use a rigid glass layer.

D. Three-Dimensional Solar Cell Designs

The light-trapping capabilities of three promising light-trapping designs are compared in Figure 5. All of the figures show a nearly identical absorption at the short wavelengths ($< 1\,\mu$m). The improvement in light-trapping is made by increasing the absorption in the wavelength region above 1 μm. Of the figures shown, the solar cell with the inverted pyramids has the best achievable current density of 39.2 mA/cm^2. However, a light-trapping analysis of the perpendicular slat solar cell is predicted to have an even better MACD of $40.32\,mA/cm^2$.

The ray-trace model confirms the results Patrick Campbell and Martin Green [9]. Campbell and Greene calculated the perpendicular slat configuration is better at increasing light-trapping than the front pyramid texture configuration. They predicted a short circuit current density of $41.3\,mA/cm^2$ for the perpendicular slat configuration and $39.0\,mA/cm^2$ for front pyramid texture configuration. Each solar cell is $50\,\mu m$ thick. In their ray-trace model, they assume unity transmissivity regardless of the incident angle of light and wavelength. The ray-trace model developed does not make this assumption. The model calculates the transmissivity based explicitly on the incident angle of light and wavelength. The model predicts an incident transmissivity less than one which explains why our predicted values are about $1.0\,mA/cm^2$ less than Campbell's predicted current densities.

E. Summary

Based on the light-trapping calculations, some general design rules are known. A good light-trapping solar cell design minimizes the front surface reflection. The front surface reflection is reduced when a periodic texture is used in conjunction with an anti-reflection coating. A good light-trapping design also maximizes the optical path length light travels within the solar cell. The optical path length is increased by texturing both the front and rear surfaces of the solar cell. The solar cell design with the highest MACD is the perpendicular slat solar cell. That's to say the perpendicular slat solar cell is the best of the designs analyzed in this section, but not necessarily the absolute best design.

Because most of the photons are absorbed within $20\,\mu m$ of the front surface of the solar cell, the total thickness of a solar cell does not need to be much more than $20\,\mu m$. As solar cells shrink, the photon flux density increases. Surface textures also tend to increase the photon flux density. Surface recombination effects are more important in textured thin solar cells than in planar solar cells because of their higher photon flux densities. The ray-trace model is not accurate when the characteristic dimensions of the solar cell are on the order of the wavelength of light. Thin solar cells promise to yield higher current collection than thick solar cells at a lower cost [6]. Low cost solar cells are usually characterized by short diffusion length semiconductors. Most minority carriers created within the distance equal to the diffusion length contribute to the electrical current of a solar cell. Hence, the solar cell must be thin when low quality materials are used. As solar cells decrease in size, the ray-trace model becomes inaccurate. To accurately predict light-trapping in thin films, the wave nature of light must be taken into account. The FDTD technique is used for similar studies and reported in [16].

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Perspectives in CEM

New Applications in FDTD Modeling: Microcavity Resonators for Photonic Integrated Circuits

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A new class of integrated optical devices has begun to emerge over the past several years. This advent is in part due to progress in materials technology and fabrication techniques which have enabled researchers to seriously consider devices based on optical resonators with physical dimensions on the order of the optical wavelength ($\lambda \simeq 1.0\ \mu m$). The exploration of such resonators, appropriately named microcavities, is fueled by the desire to achieve higher speeds, higher efficiencies, and higher-density integration for future devices associated with optical communications, computing, and signal processing. For photonic or optoelectronic devices to ever succeed in replacing their microelectronic counterparts in large-scale integrated circuits, novel optical micrometer- and nanometer-scale structures must be explored.

Examples of microcavity resonators include those in which the optical mode is confined through multiple reflections, as in vertical-cavity surface-emitting lasers and photonic crystals, and those in which the mode is confined via total internal reflection, as in whispering-gallery-mode microcavity disk resonators. Microresonators offer several desirable properties such as very high quality factors, a large spacing between longitudinal mode resonances, and enhanced spontaneous and stimulated emission rates. Furthermore, they are suitable for large-scale, high-density integration. They have recently been proposed for a rich variety of applications. In optical communications and computing, they have the potential to serve as wideband tunable filters, ultra-fast all-optical switches, low-threshold lasers, and highly efficient light-emitting diodes.

These devices have electromagnetic wave transport phenomena as a critical operating factor. A direct result of the progress in this area is the increased need for accurate models of the electromagnetic field behavior of these novel optical devices. Numerical simulations provide a framework for quick low-cost feasibility studies and allow for design optimization before devices are fabricated, without repeatedly building expensive prototypes. Furthermore, accurate computations can provide a detailed understanding of the complex physical phenomena inherent in microcavity resonators.

The finite-difference time-domain (FDTD) method of solving Maxwell's equations is one of the most popular numerical methods for the analysis of complex problems in electromagnetics. FDTD has been extensively applied to model and design complicated RF and microwave devices and circuits with dimensions comparable to the radiation wavelength. Until recently, most optical devices had distance and/or time scales that made them inappropriate for FDTD analysis where the grid cell size is approximately 10 to 50 nm and the time step is a small fraction of a femtosecond at optical frequencies. For example, to model a conventional semiconductor laser diode at a grid resolution of $\lambda/20$, on the order of a billion grid cells would be required. However, for the emerging class of integrated optical microcavity resonators, FDTD modeling has the potential to play a useful and practical design role.

The FDTD method provides an accurate analysis of the optical radiation, scattering, diffraction, reflection, waveguide dispersion, and polarization effects that are inherent in integrated guided-wave microcavity resonators. Because of its ability to model complicated structures, FDTD has been used for a number of numerical investigations of novel microresonators, including those based on photonic crystals and ring or disk cavities.

Photonic crystals are artificial structures that have a periodic variation of the refractive index in one, two, or three dimensions. Such structures have a frequency stopband over which there is no transmission of electromagnetic waves. Therefore, they are commonly referred to as photonic bandgap (PBG) structures, in analogy to the energy bandgap in pure semiconductor crystals. A small defect introduced into the photonic crystal creates a resonant mode at a frequency within the bandgap. Thus, the defect behaves as microcavity resonator. Using impulsive excitations and discrete Fourier transformations, FDTD simulations of PBG structures provide transmission, radiation, and reflection characteristics that detail the stopband and any resonant modes within. Sinusoidal excitations yield the steady-state field patterns. Numerical investigations have been reported for one-dimensional PBG structures, including waveguides with etched air holes or notches [1, 2] and multilayer dielectric stacks [3]. FDTD modeling has also been used to study two- and three-dimensional photonic crystals [4, 5].

Microcavity ring or disk resonators coupled to adjacent input and output waveguides have also received much attention recently. The sub-micron-wide waveguide composing the ring resonator permits single-mode propagation, while the solid circular "pillbox" composing the disk resonator permits the propagation of whispering-gallery modes. Lord Rayleigh first conceived of such modes when studying the propagation of sound in St. Paul's Cathedral in London. For this reason, microcavity disk resonators have been nicknamed "microcathedrals." FDTD simulations of these microresonators have been used to characterize key optical design parameters, such as the coupling efficiency between the adjacent waveguides and the ring or disk, and the resonant frequencies [6]. Numerical investigations of cascaded or series-coupled microcavity ring resonators have been also been reported [7]. A related class of devices based on the elevated microdisk has been modeled as well [8].

Over the past several years, a number of extensions to the FDTD method have been developed to account for optical material properties including material dispersion with absorption or gain, instantaneous optical nonlinearities, dispersive nonlinear effects, and gain saturation (for example, see [1, 9-22]). As a result of these and other related efforts, the range of modeling applications has been expanded to include temporal and spatial soliton propagation [19, 21-24], self-focusing of optical beams [20], scattering from linear-nonlinear optical interfaces [25], pulse propagation through nonlinear corrugated waveguides [26, 27], pulse-selective behavior in nonlinear Fabry-Perot cavities [28], second harmonic generation in nonlinear waveguides [21], pulse amplification in tilted waveguide traveling-wave amplifiers [18], field dynamics and gain threshold reduction in Fabry-Perot surface-emitting microcavity lasers [1], and ultra-fast pulse interactions with two-level atoms [29].

Microcavity resonators are expected to have wide application in future high-density photonic integrated circuits. Full-wave electromagnetic modeling has been found to be an important element in the design process of this emerging class of integrated optical devices. In fact, the usage of FDTD in micrometer- and nanometer-scale integrated optics should eventually be similar in scope to current FDTD applications in the engineering design of linear and nonlinear microwave circuits.

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The Practical CEMist

- Topics in Practical Communications -

Thanks to Nathan Cohen for submission of the interesting article "Exploring a Fractal Antenna", which is **The Practical CEMist** contribution to this Newsletter. Nathan presented two, (more specific) fractal antenna application papers at the 14th Annual Review of Progress in Applied Computational Electromagnetics symposium earlier this year and, at that time, I asked him to prepare an overview paper specifically for the ACES Newsletter. Only a relatively small fraction of the ACES membership had the opportunity to hear and see his conference presentations, and this gives Nathan an opportunity to expose a larger number of "practical radio communicators" to the electrical characteristics and attractive properties of fractal-element antennas (FEA). Your e-mail comments on this particular paper, or the subject of fractal antennas in general, may be addressed to Nathan at **fractenna@aol.com** and/or me at **wwheless@ua1vm.ua.edu** .

I just recently received some e-mail from George Hagn regarding my earlier article in the ACES Newsletter, Vol. 12, No. 3, November 1997. George wrote to advise me that there is an apparent error in equations 8 through 10, which are intended to model the behaviors of relative permittivity and conductivity as functions of frequency. The equations themselves are cited as repetitions for convenience from reference [3]. If the reference (ref) value for the relative permittivity in equation 8 is greater than 3, then application of the equation gives a decreasing result with increasing frequency. However, the result INCREASES with increasing frequency if the reference value is less than 3, and that is the cause of concern. George has personally collected considerable data indicating that the relative permittivity is either essentially "constant across the HF band (e.g., at 3 to 4 for dry sand) or it DECREASES with increasing frequency in a manner that depends on the soil moisture content," quoting from his e-mail.

A major objective of the earlier article was to archive some important analytical results pertaining to buried and near-earth wire antennas for HF applications - namely, equations believed to be accurate and in the public domain but perceived as difficult for practical communicators to access on their own. Since the intent is to stimulate successful academic research and experimentation in this area, it is desirable for the equations to reflect reality! George Hagn has suggested some "sanity checks" which I will perform as time permits. Meanwhile, this is to invite additional comments from other interested readers with expertise in this subject. Because George is widely known and respected for his fine technical work in this area, I have asked him to prepare a short article for the ACES Newsletter. Perhaps this public encouragement will speed the submission of his manuscript!

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Exploring a Fractal Dipole

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Introduction

Fractal-element antennae (FEA) comprise a large class of shaped antenna design (Cohen,1995, 1996a,b). Their antenna structure is geometrically described by either a deterministic or random fractal (see, for example, Lauwerier,1991) of finite iteration. Self similarity is attained at some level. Put simply, a wire antenna constructed in a fractal fashion looks severely bent.

Curiously, and continuing with this wire example, FEA are often naively presumed to be of limited utility. This is despite the long-standing study of Landstorfer and Sacher (1985) who showed that optimized wire antennas are bent antennas, and produced some designs which can be described as fractal Brownian motion geometries. Indeed, the continuation of this work in three dimensions with a different optimization algorithm has led to 'genetic antennas', arguably a class of random fractal designs. Here, I briefly describe the characteristics of a simple dipole of a deterministic, Koch fractal design as an aid to demonstrating some of their interesting properties.

These results were obtained with NEC4, with free space modeling and incorporating ohmic losses. Readers are invited to view the web page **http://www.fractenna.com** (after 20 July, 1998) for additional information. A table of the wire segments will be made available from that web site for independent modeling and generating feedback on FEA.

General Properties

As a class, FEA tend to share certain observable attributes. Foremost among these are the lowering of the lowest resonances. This is ascribable to 'fractal loading' (Cohen 1995), akin to the loading achieved by stub structures. Thus one may use the fractal design pattern to achieve a loaded antenna without dielectrics or discrete components. This effect has proven quite efficient in some cases, going against the presumption that, in general, some distributed loads lack efficiency.

Particular care must be exercised in using this effect to make electrically small antennae. Indeed, FEA can easily be made to produce very electrically small radiators—and poor ones at that. In general, from an electrical standpoint, FEA do no better or worse than other methods used to make very electrically small antennae (Cohen,1997a). In particular, the usual tradeoffs of field strength, bandwidth, and size prove just as limiting with very electrically small FEA as other methods for achieving small size. Ergo , despite presentations in the popular press, FEA offer no 'aerial magic'(May, 1998) or revolutionary insight into the problem of very electrically small antennas.

However, as the transition to electrically small is approached, some FEA designs have proved better than other methods, including conventional top loads. In general, FEA present a simple and cost effective way of shrinking an antenna to ½ to ¼ the normal size—at least in one of its dimensions.

Bandwidth issues prove especially curious. With increasing fractal iteration the number of resonances grows exponentially and these 'resonance clusters' merge to produce extremely broad bandwidths. In general, these resonant frequencies do not correspond to 'characteristic lengths' of the fractal structure. Nor are harmonics always readily distinguishable.

Other attributes are also seen from simple stubs: gain caused by phasing; polarization control (such as CP).

In a sense it is reassuring that FEA present attributes shared with other antenna designs and do not require any new physics. They obviously provide for some options in antenna engineering

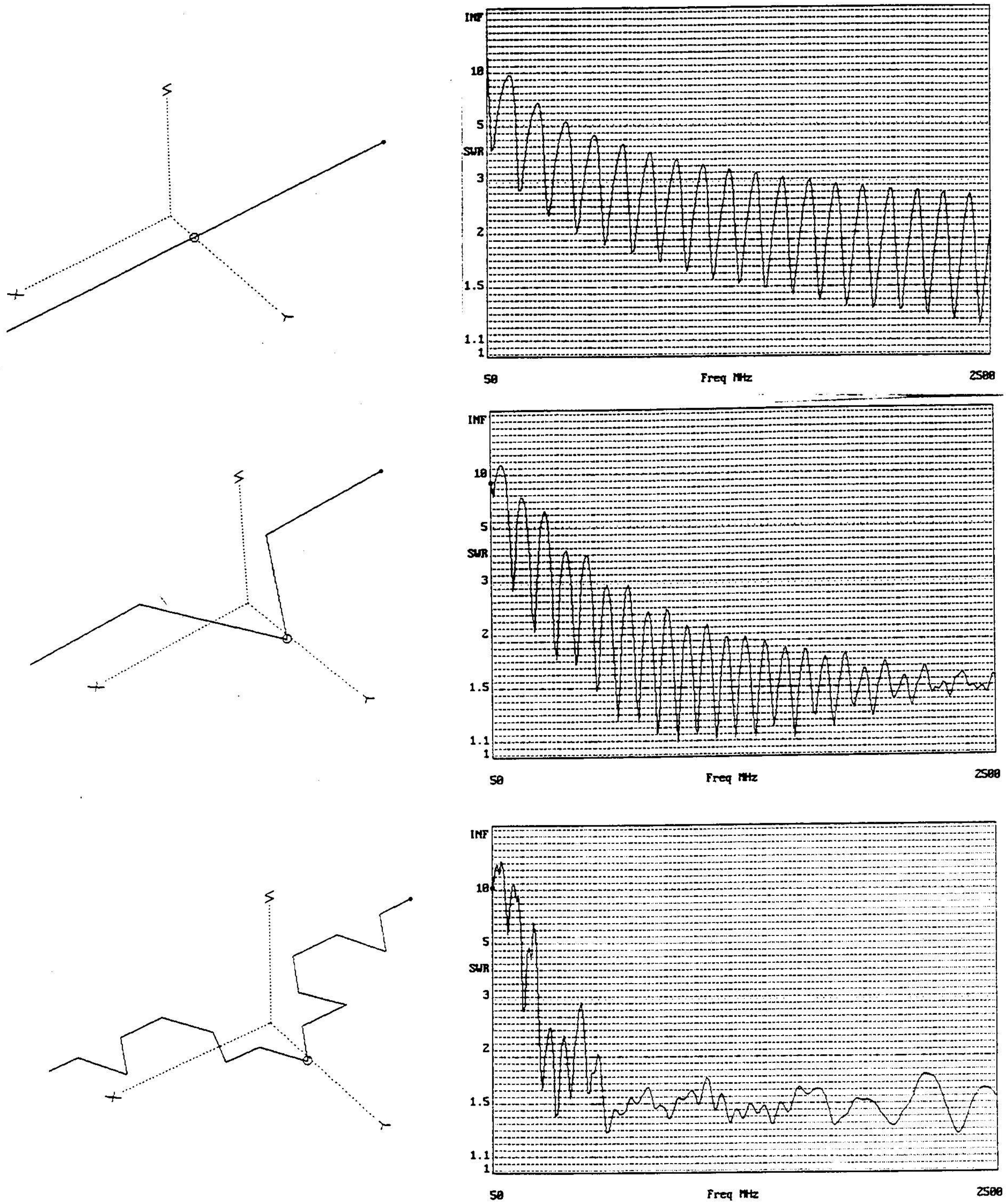

Figure 1

that are novel and, in many situations, preferable from the standpoint of cost, reliability and performance.

Koch Dipole : The Effect of Iteration on Bandwidth

The bandwidth characteristics of FEA are intriguing. **Figure 1** shows the spectral behavior of a dipole, and Koch fractal dipoles of first and second iteration. All three models have wire widths of 0.004 waves, and horizontal lengths of ½ wave, at 65 MHz. The impedance is taken as 300 ohms for iterations 1 and 2 and 190 ohms for the dipole.

There is a clear modulation of the SWR waveform (and thus the impedance as a function of frequency) with application of the fractal iterations. The dipole's usual and well-known harmonic structure gets damped in amplitude and frequency modulated in harmonic separation. This, in itself, is an expected result of application of a load, although this particular result appears to be not generally known.

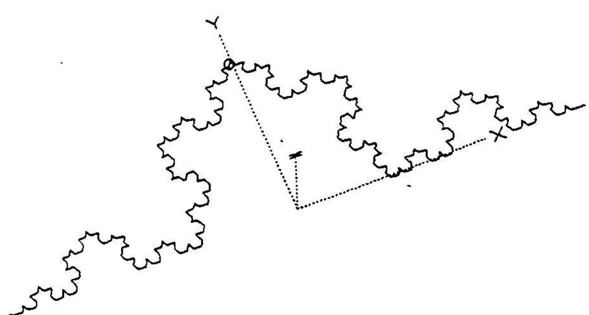

Figure 2

The application of the second iteration produces a far more pronounced amplitude and frequency modulation of the waveform and the feedpoint impedance becomes very broad band at the higher frequencies. What is especially noteworthy is the resonances are not limited to some characteristic lengths caused by the fractalization. Viewed simply, the broad band behavior is most probably due to a superposition of resonances from loading, harmonics and some characteristic lengths. That it is achieved in only 2 iterations is unexpected and implies that even simple fractal structures have utility in broad band and/or multiband applications. It is also of interest to see that the impedance of the broadbanded region is close to that of free space.

Koch Dipole: Characteristics of the Fourth Iteration

Figure 2 presents the Koch dipole with 4 iterations. Again, very broad band behavior is maintained above about 500 MHz. It is maintained to well over 5000 MHz, the limit at which NEC4 results become questionable due to the thickness of the wire compared to the wavelength. The lower resonances are more numerous and lower in frequency than with the second iteration.

Table 1 provides info on the lowest resonances, shown as a blow up in **Figure 3** with SWR to 50 ohms. Note that shrinkage is attained from the fractal loading for the very lowest resonance. Efficiency may be inferred to be reasonable but not optimal for the lowest resonance.

At the second resonance, the fractal pattern provides a phased-echelon effect, with good field strength and good sidelobes, previously noted by the application of a single stub by Landstorfer and Sacher (see Kraus, 1985). It's pattern is shown in **Figure 4**. It has been noted that a general invariance of this gain with iteration is maintained (Cohen, 1997b).

Self Similarity vs. Self-Complementarity

What relation does this fractal dipole have with self-complementary antennae? It is well known that such antennae are both broad band and gain invariant (Mushiake, 1996, Rumsey, 1966). A popular misconception is that such frequency independent antenna--which clearly include fractal arrays such as log periodic arrays--require self complementarity to achieve this effect. There is little doubt that both attributes *together* require self complementarity. However, the broad bandwidth in itself appears achievable in many cases by self complementarity *or self similarity*. Note that the Koch dipoles are by no means self complementary. This means that a new option in broad band antennae exists *through self-similarity*.

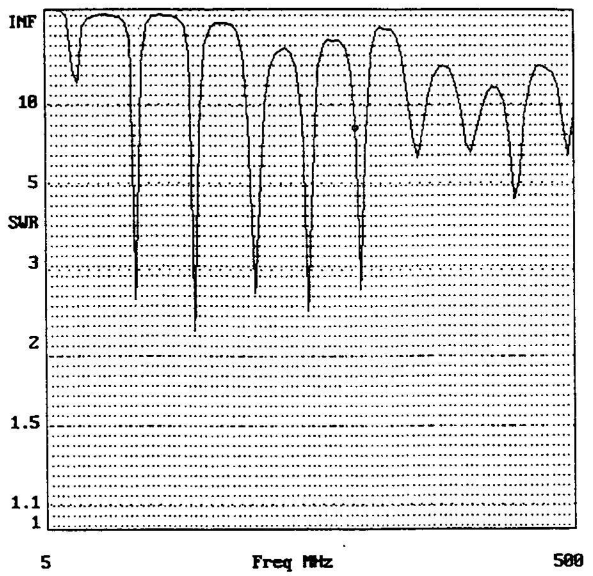

Figure 3

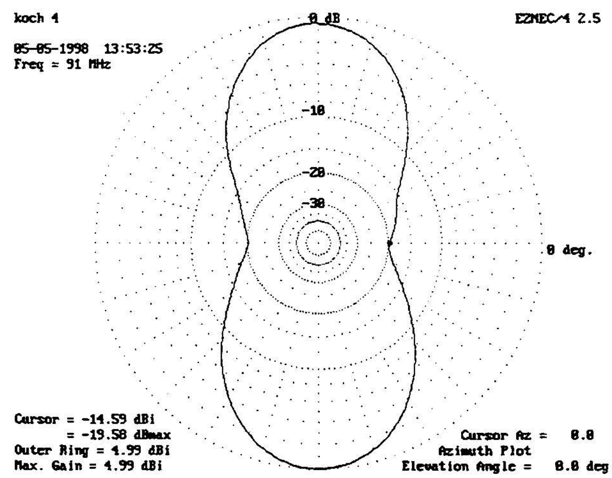

Figure 4

It is an amusing puzzle why a log periodic array is broad banded. It is, after all, both self similar *and* self complementary. Yet when the self complementarity is removed--such as by not mirror-inverting the elements--the structure is no longer broad band (Mushiake, 1996). Log periodic arrays may comprise a subset for which self similarity does not provide broad bandedness but self complementarity does. Certainly one is obligated to find other exceptions, if any, where self similarity in itself does not produce broadband behavior.

Perhaps some further insight may be obtained on the broad bandedness by studying the current distribution as a function of frequency. **Figure 5** is a composite diagram representing that at several frequencies, including the second lowest resonance, which has a phased-gain effect.

It is noteworthy to see that the fractal structure has trap-related behavior at the higher frequencies as a function of frequency. Note that the 'active' region gets smaller with increasing frequency. However the outer fractal structures have a tapering effect rather than truncation of the current, as normally experienced with a trap. Broad band behavior is found with multiple trap systems. Hence the fractal allows for 'traps' without components to get the broad bandwidth.

A last enticing issue with FEA is that they can be made to obey Rumsey's principle--*yet are not log periodic.* For example, **Figure 6** shows a self complementary and self similar version of the second iteration Koch dipole. It is frequency independent. Yet the condition for log periodicity is not met. We, as antenna designers, may experience a novel freedom with these special types of FEA which have 'log periodic behavior' but not log periodic geometry-- as they are not excluded from Rumsey's Principle.

Summary

FEA, as shown by this example, produce useful effects on the bandwidth , field strength, and size of an antennae. As such, it should prove enlightening to see how fractals will impact antenna designs as they present new options.

Acknowledgements

I thank my colleagues for their help in helping me plateau on the learning curve: Robert Hohlfeld; Dwight Jaggard; Douglas Werner; Ping Werner; and Allan Wegner. Aspects of this work are patent pending.

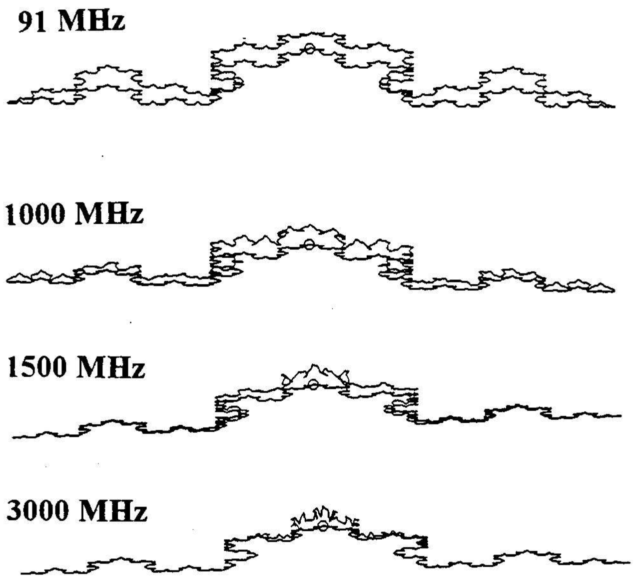

Figure 5

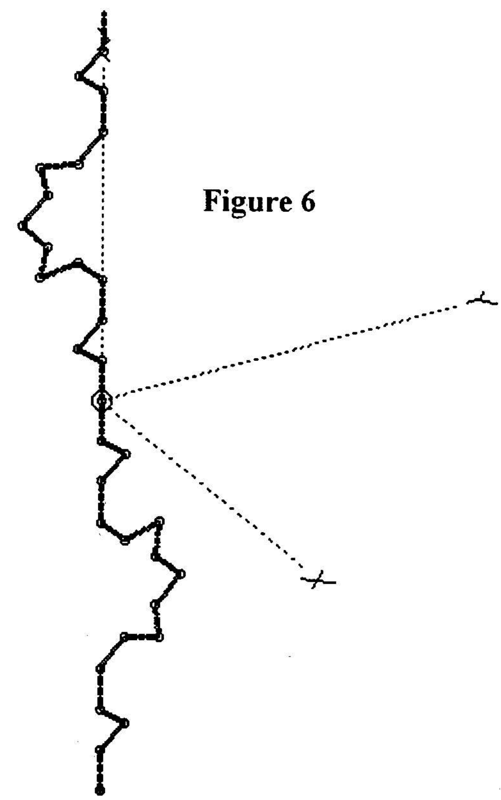

Figure 6

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Table 1

Freq. (MHz)	Size (waves)	F.S. (dBi)	Resistance(ohms)
32.5	0.24	1.6	18
91	0.7	5.0	27
146	1.1	3.5	56
202	1.6	4.4	142
224	1.7	4.8	1184
251	1.9	3.5	111

Patent Fundamentals for ACES Members (Part III). Software Patents.

R. Perez, (Newsletter Editor)

In this article we address some aspects of **patentable** software as outlined in several US court cases.

PATENT PROTECTION

A. Utility Patents

1. What is patentable?

35 U.S.C. S 101 - new and useful or improved processes, machines, manufacture or composition of matter including new use of known processes, machines or discoveries.

Diamond v. Chakrabarty. 447 U.S. at 309 (1972) "anything under the sun that is made by man" is patentable, *except* for judicially determined exceptions which include laws of nature, physical phenomenon, abstract ideas and mathematical algorithms.

2. Computer Program: per se, i.e. a sequence of coded instructions for a digital computer probably not patentable, but not decided by U.S. Supreme Court. M.P.E.P. 2106, Exhibit p.4 states:

"A bare set of computer instructions does not set forth a sequence of steps which could be viewed as a statutory process. Such a computer language listing of instructions, when not associated with a computing machine to accomplish a specific purpose, would not constitute a machine implemented process, but would constitute *non statutory* subject matter as the mere idea or abstract intellectual concept of a programmer, or as a collection of printed matter."

3. New equation or solving a new equation per se, are not patentable - **Gottschalk v. Benson**, 409 U.S. 63, 65.

4. Computer program methods and programmed machine can be statutory.

a) Threshold question:
"What did the applicant invent?"

In **re Abele**, 684 F.2d 902, 907 214. It USPQ 682 (CCPA 1982) or "What is perceived to be the invention?"

If it is just a mathematical equation or algorithm or other - judicially prohibited subject matter, it is not patentable.

If it is the application of an equation or algorithm, the equation itself does not bar patentability.

B. Practice Tips Regarding Computer Program Methods & Programmed Machines.

1. An invention may be patentable if it involves solving an equation and

a) It transforms something physical or
b) It is a method or process for doing something other than merely solving an equation.

2. **Freeman-Walter Test**

In **re Freeman**, 573 F.2d 1237, 197 USPQ 464 (CCPA 1978); In **re Walter**, 618 F.2d 758, 205 USPQ 397 (CCPA 1980)

a) Is a mathematical algorithm claimed?
b) If so, is it applied to physical elements or to a process?

Note Freeman-Walter is not the exclusive test for patentability - In **re Grams**, 888 '-P.2d 835, --12 USPQ2d at 1827 (CAFC 1989)

3. Do emphasize advantages of invention other than finding a solution to an equation, i.e.

a) Enhances the operation of the machine
b) Speeds up machine
c) Reduces required memory space
d) Reduces programming code, time, space
e) Allows a process to be efficiently implemented on a computer

4. Don't argue the patentable feature is solving a new equation

5. In **re Prater**, 415 F.2d 1393, 162 USPQ 541, (CCPA 1969); In **re Bernhart**, 417 F.2d 1395, 163 USPQ 611 (CCPA 1969). In **re Musgrave**, 431 F.2d 882, 167 USPQ 280

5. (cont): (CCPA 1970); In **re Toma**, 575 F.2d 872, 197 USPQ 852 (CCPA 1978)

- Machine implementation of mental steps can be statutory subject matter.

C. Methods & Machines Found to be Statutory

1. By CCPA, CAFC, U.S. Supreme Court

In **re Johnston**, 502 F.2d 765, 183 USPQ 172 (CCPA 1974)

- A machine for automatic record keeping of bank checks and deposits

In **re Deutsch**, 553 F.2d 689, 193 USPQ 645 (CCPA 1977)

- A method of operating a system of manufacturing plants

In **re Toma**, 575 F.2d 872, 197 USPQ 852 (CCPA 1978)

A process for translating a source natural language such as Russian, to a target natural language, such as English

In **re Phillips**, 608 F.2d 879, 203 USPQ 971 (CCPA 1979)

- A process for preparing architectural specifications

In **re Sherwood**, 613 F. 2d 809, 204 USPQ 537 (CCPA 1980)

- Conversion of amplitude versus time seismic traces into amplitude versus depth traces

In **re Tanner**, 681 F 2d 787, 214 USPQ 678 (CCZ-A 1981)

- Conversion of spherical seismic signals into a form representing earth's responses to cylindrical or plane waves.

Diamond v. Bradley, 450 U.S. 381 (1981)

Affirmed CCPA as to a machine that permanently embodied micro instructions in hardware elements

Diamond v. Diehr, 450 U.S. 175 (1981)

Claimed the application of Arrhenius equation for reaction cure time in a rubber molding process.

In **re Twahasha** 888 F.2d 1370, 12 USPQ2d, 1908, (Fed. Cir. 1989)

Solving an equation using specified hardware including a ROM, an adder and an A/D converter

D. Applications of Equations Found Not to be Statutory

Gottschalk v. Benson, 409 U.S. 63 175 USPQ 673 (1972)

Method for converting binary coded decimal numbers to binary numbers

In **re Freeman**, 573 F.2d 1237. 197 USPQ 464 (CCPA 1978)

In **re Walter**, 618 F.2d 758, 205 USPQ 397 (CCPA 1980)

Claim to mathematical steps with final step of recording or displaying

Parker v. Flook, 437 U.S. 584, 198 USPQ 193 (1978).

A claim to an equation with the final step of adjusting an alarm limit

Safe Flight Instrument Corp. v. Sundstrand Data Control Inc., 706 F. Supp. 1146 (D. Del 1989)

A claim to processing a windshear signal to provide an indication of its magnitude

In **re Abele**, 684 F.2d 902, 214 USPQ 682 (CCPA 1982)

A mathematical algorithm with the final step of displaying a shade of grey

In **re Gelnovatch**, 595 F.2d 32, 201 USPQ 136 (CCPA 979)

Calculating one set of numbers from another set of numbers with final steps of storing outputs.

In **re Sarkar**, 588 F-2d 1330, 200 USPQQ 132 (CCPA 1978)

Using a mathematical model to locate and construct an obstruction at a location

In **re de Castelet**, 562 F.2d 1236, 195 USPQ (CCPK 1977)

Calculating and then transmitting the results

In **re Grams**, 888 F.2d 835, 12 USPQ2d 1824 (Fed. Cir. 1989)

- Claims for analyzing results of clinical laboratory tests is for a mathematical algorithm

E. Burden of Proof as to Non-Statutory Subject Matter

Chisum, **The Patentability of Algorithms**, 47 U. Pitt. L. Rev. 959 (1986), suggests that the Federal Circuit moved the burden of proving non-statutory subject matter to the opponent of patentability. See 888 F.2d 835, Footnote 3 of In **re Grams**, 888 F.2d 835, 12 USPQ2d 1824 (Fed. Cir. 1989).

F. Disclosure in Patent Applications

1. Examples of disclosure of computer programs

- Specification describing the program
- Flow diagram of computer program listing
- Block diagram of hardware

2. 35 U.S.C. S 112 first paragraph considerations, See M.P.E.P., Exhibit p. 5

- Adequacy of disclosure
- Best mode

3. See Northern Telecom, Inc. v. Datapoint Corp., 908 F. 2d 931, 15 USPQ2d 1321 (Fed. Cir. 1990) rehearing in Banc decline August 27, 1990

Here the court described the invention as follows:

"In accordance with the 375 invention, the data are keyed into a form that is displayed on the screen; the operator is guided by names and instructions on the screen, and certain entries are subject to automatic as well as-visual checks and edits. A storage area, or buffer, holds the data as it is entered and, when the buffer holds a complete and correct record, the data are transferred to a magnetic tape cassette. (id. at 933)"

- the court:

a) Reversed a holding of inadequacy of disclosure as to claims 1, 3, 5-7, 9-12, 14-20, 22, 29-33 , 35-47 and 44 *even though* a computer program, was not disclosed because:

"The great weight of the expert, testimony on both sides was that a programmer of reasonable skill could write a satisfactory program with ordinary effort. This requires the conclusion that the programs here involved were, to a skilled programmer, routine. The district court's finding that undue experimentation was necessary to write the program is clear error.

The holding that the claims are invalid for lack of enablement- is reversed. (Id. at 943)"

b) Held claims 19-20,22 and 24-28 invalid because inventor knew in advance of filing that the disclosed standard audio tape was not the best mode because he had purchased tapes and cassettes of his own design.

G. Practice Tips to Preserve Trade Secrets in Computer Program

File patent application as early as possible and if possible before computer program is written

H. Disclosure of Computer Program Listing in Patent applications

1) 37 C.F.R. 1.96, Exhibit p. 23

- If computer program listing has 10 pages or less it must be submitted as part of the drawings or in the specification under 37 C.F.R. 1.52

- Computer listing may be submitted as computer printout sheets for use as camera ready copy at end of the specification and before claims

- A computer listing more than 11 pages long may be submitted as an appendix which will not be printed if submitted on microfiche.

I. Inclusion of Copyright or Mask Work Notice in Patent Application

- 1077 O.G. 22, March 20, 1987, Exhibit p. 26, 37 C.F.R. S 1.71 (d) (e) and S 1.84 (o), Exhibit p. 25

1. Use appropriate notice for copyright or mask work adjacent copyright or mask work material

i.e. COPR. 1983 John Doe, or "m" John Doe

and

2. At the beginning or specification insert:

"A portion of the disclosure of this patent document contains material which is subject to "copy-right or mask work," protection. The "copyright or mask work' owner has no objection to the facsimile reproduction by anyone of the patent disclosure, as it appears in the Patent, and Trademark office patent file or records, but otherwise reserves all "copyright or mask work rights whatsoever."

J. Design Patents

1. 35 U.S.C. S 171 - Design patent is available for a new original and ornamental design for an article of manufacture

2. Example

- Icons for screen displays, i.e. Exhibit pp. 27-29

- Screen display

INDEX TO COMPUTER CODE REFERENCES FOR VOL. 12 (1997) OF THE ACES JOURNAL AND THE ACES NEWSLETTER

This computer code index is usually updated annually and published in the second issue of each volume of the ACES Newsletter.

LEGEND:

AJ ACES Journal
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* Pre- or postprocessor for another computational electromagnetics code
** Administrative reference only: no technical discussion (This designation and index do not include bibliographic references)
Page no. The first page of each paper in which the indicated code or technique is discussed

AJ No. 1 - Special Issue on International Computational Electromagnetics
AJ No. 2 - Special Issue on Numerical Field Calculations in Electrical Engineering

NOTE: The inclusion of any computer code in this index does not guarantee that the code is available to the general ACES membership. Where the authors do not give their code a specific name, the computational method used is cited in the index. The codes in this index may not all be general purpose codes with extensive user-orientated features - some may only be suitable for specific applications. While every effort has been made to be as accurate and comprehensive as possible, it is perhaps inevitable that there will be errors and/or omissions. I apologise in advance for any inconvenience or embarrassment caused by these.

Duncan C Baker, Outgoing Editor-in-Chief, ACES Journal.
27 May 1998.

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ABSTRACTS OF ACES JOURNAL PAPERS

VOLUME 12, 1997

This compilation of abstracts is updated annually and normally published in the second issue of the *ACES Newsletter* of the following year. The material was scanned in using a digital scanner and converted to text using a program for character recognition. I extend the sincere thanks and appreciation of the *ACES Journal* to Ms. Alet van Zyl who undertook this task. The document was proofread only once. As Editor-in-Chief, I accept full responsibility for any errors and/or omissions which appear in the text. I apologize in advance for any inconvenience or embarrassment caused by these.

Duncan C. Baker, Editor-in-Chief, *ACES Journal*.
14 January 1998

3B-SPLINES IN THE INTEGRAL EQUATION SOLUTION FOR SCATTERING FROM BODIES OF REVOLUTION

F.L. Teixeira, and J.R. Bergmann

The use of B-Spline functions is investigated in conjunction with the Method of Moments integral-equation solution to the problem of scattering from conducting bodies of revolution. Its computational performance in terms of relative accuracy and storage/CPU time requirements is evaluated against entire-domain and sampling-like basis functions. Particular attention is given to the description of currents near edges. Questions of time (space) and frequency (wavenumber) localization are also addressed. A simple scheme devised to enforce boundary conditions a priori is shown to be potentially capable to stabilize otherwise spurious solutions. **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 6-13]**

ELECTROMAGNETIC PROPERTIES OF A CHIRAL-PLASMA MEDIUM

Hector Torres-Silva, Norma Reggiani, and Paulo H. Sakanaka

The theoretical properties of a composite chiral-plasma medium are developed. Using the reaction theorem, we obtain the proof of nonreciprocity based upon the constitutive relationships between the electromagnetic vectors **E**, **B**, **H**, **D**. Using the Maxwell's equations and the proposed constitutive relations for a chiral- plasma medium, we derive the **E**, and **H**, vector equations and from these equations, dispersion relations and E-field polarizations are found. **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 14-18]**

MTRT - A MODIFIED TRANSVERSE RESONANCE TECHNIQUE

Alfredo Gomes Neto, Creso S. da Rocha, Herve' Aubert, D. Bajon , and H. Baudrand

In this work a modified formulation of the transverse resonance technique (TRT) is presented. The difference between the usual TRT and the formulation presented here, MTRT, is the equivalent network considered. With the MTRT proposed formulation, mode solution identification requires less arduous work. The complete equation set is described. Numerical results are presented for dispersion characteristics of microstrip lines, coupled microstrip lines and conductor-backed coplanar waveguides (CBCW). When compared to results obtained by other methods, a good agreement is observed. **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 19-25]**

EFFECT OF THE MAGNETIC ANISOTROPY ON THE CHARACTERISTICS OF MICROSTRIP ANTENNAS WITH SEVERAL LAYERS

José de Ribamar Silva Oliveira, and Adaildo Gomes d'Assunção

The main objective of this work is to show how the properties of a ferrimagnetic material change the characteristics of a microstrip patch with several layers. Particularly, it is investigated how the resonant frequency and the radiation pattern are changed by varying the ferrimagnetic layer thickness or the magnitude and/or direction of the external applied magnetic field. The analysis is carried on by using Hertz potentials and Galerkin method. **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 26-29]**

DISPERSIVE ANALYSIS OF CIRCULAR CYLINDRICAL MICROSTRIPS AND BACKED SLOTLINES

Laércio Martins de Mendonça, and Adaildo Gomes d'Assunção

In this work, the full-wave analysis of circular cylindrical microstrips and backed slotlines is performed, by using a combination of Hertz vector potentials and Galerkin method. The analysis is developed in the spectral domain. **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 30-33]**

FINITE ELEMENT ANALYSIS AND EVALUATION OF ELECTROMAGNETIC FIELDS GENERATED BY ATMOSPHERIC DISCHARGES

E.H.R Coppoli, R.R. Saldanha, and A. Konrad

A lightning return stroke channel is modeled by a high loss transmission line. The differential equations that represent its dynamic behavior are solved by the application of the one-dimensional finite element method (FEM). By the combination of FEM results with the use of Maxwell equations applied to the dipole method, electric and magnetic (EM) fields are evaluated at various positions in space. **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 34-38]**

POINT-MATCHED TIME DOMAIN FINITE ELEMENT METHOD APPLIED TO MULTI-CONDUCTOR ELECTROMAGNETIC TRANSIENTS ANALYSIS.

Glássio Costa de Miranda

A point-matched time domain finite element method (TDFE) applied to the analysis of electromagnetic transients in multi-conductor transmission line network is presented. The TDFE method solves the partial differential transmission line equations based on a semi-discrete approximation using the finite element method and leap-frog scheme. Some oscillations can occur due to the stability condition of the technique. Using the modal analysis these oscillations can be eliminated. A surge propagation in a simple multi-conductor network is presented and the results are compared with the Electromagnetic Transients Program (EMTP) simulations. **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 39-43]**

ERROR ESTIMATORS IN SELF-ADAPTIVE FINITE ELEMENT FIELD CALCULATION

L. Lebensztajn, and J.R. Cardoso

The aim of this paper is to present different error estimates to improve accuracy in linear and nonlinear self-adaptive finite element field calculation. The first estimator is based on the polynomial theory, the second one makes an estimation of the flux density divergence, the third one is linked to a magnetomotive force associated to elements sides, and the fourth one is based on the use of the bilinear element. All methods were implemented in our software named LMAG2D developed at "Escola Politecnica da Universitade de São Paulo", Brazil. **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 44-49]**

TRANSIENT VOLTAGE AND ELECTRIC FIELD DISTRIBUTIONS IN AIR CORE REACTORS

S. L. Varricchio, and N. H. C. Santiago

This work presents a computational model for the evaluation of transient voltage and longitudinal electric field distributions in single layer air core reactors. The influence of a grounded shielding concentric to the reactor is considered. The validity of the model is verified by comparing computed and measured voltage responses at three taps of a test reactor. Analyses showing the influence of the grounded shielding, front time and front wave shape of the applied voltage on the maximum longitudinal electric stresses along the reactor winding are presented. **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 50-55]**

CALCULATION OF ELECTRIC FIELD CREATED BY TRANSMISSION LINES, BY 3D-FE METHOD USING COMPLEX ELECTRIC SCALAR POTENTIAL

Ricardo Marçal Matias, and Adroaldo Raizer

This paper presents a methodology for tridimensional analysis of the electric field produced by transmission lines. It utilizes the complex electric scalar potential, which makes it possible to consider variation of module and phase in the voltages of supply lines. The Finite Element Method (FEM) is applied to solve the differential equation that describes the phenomenon in the domain of this study. Finally, a comparison is established between the results obtained applying the proposed methodology and the values reached through the classical method of charge simulation. **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 56-60]**

ADAPTIVE FINITE ELEMENT MESH REFINEMENT AND 'A POSTERIORI' ERROR ESTIMATION PROCEDURES FOR ELECTROMAGNETIC FIELD COMPUTATION

K.C. Chellamuthu, Nathan Ida and Q.k. Zhang

Adaptive Finite Element (FE) mesh refinement combined with a robust and functionally reliable error estimate provides nearly optimal solution accuracy. The efficiency of adaptivity depends on the effectiveness of the mesh refinement algorithm and also on the availability of a reliable and computationally inexpensive error estimation strategy. An adaptive mesh refinement algorithm utilizing a hierarchical minimal tree based data structure for 2D and 3D problems is discussed in this paper. Two different 'a posteriori' error estimation schemes, one based on the local element by element method and the other using the gradient of field approach are also presented. The usefulness of the mesh refinement algorithm and the error estimation strategies are demonstrated by adaptively solving a set of 2D and 3D linear boundary value problems. The performance of the error estimates is also verified for adaptive modeling of a nonlinear problem involving the design of a permanent magnet synchronous machine. **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 61-68]**

DESIGN OF ELECTRICAL MACHINES AIDED BY FIELD CALCULATION AND FACTORIAL EXPERIMENTS METHOD

C. Pertusa, S. Astier, Y. Lefevre, and M. Lajoie-Mazenc

An approach for electrical machines design by using magnetic field computation coupled to factorial experiments is presented in this paper. Principles of factorial experiments are briefly reviewed and their application to design optimisation is explained. In this application experiments are replaced by magnetic field calculations. The procedure, which performs automatically all the numerical field calculations required, is described. The whole procedure is applied to a typical problem concerning permanent magnets synchronous motor with polar pieces. **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 69-73]**

LIMITATIONS OF THE CONVENTIONAL METHODS OF FORCE AND TORQUE PREDICTION

Antônio Flavio Licarião Nogueira

The calculation of forces and torques developed in electromechanical devices, and their variation with changes in position or excitation, is often what the designer is, ultimately, interested in. This paper addresses some of the problems associated with the force and torque calculations based on numerical field solutions for 2-D magnetostatic problems. The problem of calculating the cogging torque characteristic of a neodymium-iron-boron permanent-magnet motor is considered and the technique of torque measurement is described briefly. **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 74-79]**

COMPARISON OF CONVERGENCE RATES OF EDGE AND NODAL FINITE ELEMENTS FOR MAGNETOSTATIC PROBLEMS

M. L. y Gonzalez, R. C. Mesquita, and J. P. A. Bastos

Mathematical theory is used to obtain convergence estimations for magnetostatic formulations using nodal and edge elements. Numerical results of two closed boundary problems that confirm the theory are presented. **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 80-83]**

FINITE ELEMENT SIMULATION OF AN OUT-OF-PHASE SYNCHRONIZATION OF A SYNCHRONOUS MACHINE

Silvio Ikuyo Nabeta, Albert Foggia, Jean-Louis Coulomb, and Gilbert Reyne

This paper presents the finite element simulations of the out-of-phase synchronization of a synchronous machine with an external electric system. Two cases were analysed regarding to the phase angle: 120° and 180°. Computed results are analysed and compared to analytical values. **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 84-89]**

A 3D FINITE-ELEMENT COMPUTATION OF STATOR END-WINDING LEAKAGE INDUCTANCE AND FORCES AT STEADY STATE OPERATING CONDITIONS IN LARGE HYDROGENERATORS

Viviane Cristine Silva, and Albert Foggia

The forces acting on the stator end windings of a hydrogenerator at steady state operating conditions, as well as the end-winding leakage inductance, are calculated using a 3D finite element package. A more realistic representation for the geometry of the windings and boundaries is considered. The effects of different representations for the stator core end surface are outlined. The computed values of the inductance from time harmonic and static simulations are presented and compared with classical analytical methods. **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 90-96]**

IMPROVING THE CHARGE SIMULATION METHOD FOR THE COMPUTATION OF HIGH VOLTAGE ELECTRIC FIELDS WITH EFFICIENT LEAST SQUARES TECHNIQUES

J. N. Hoffmann, and P. Pulino

The well known Charge Simulation Method, which is commonly used for electric field calculations, is shown to be a particular and ill-conditioned case of the Least Squares Charge Simulation Method. By solving a practical problem, it is shown how to efficiently handle a least squares problem, thus obtaining results of higher precision if compared to the traditional Charge Simulation Method For the solution of the resulting linear system, several mathematical methods are analyzed and compared, being stated that the optimum combination of higher precision, lesser error propagation, lesser CPU time and lesser computer RAM are simultaneously reached when applying the Least Squares Charge Simulation Method, solved with the QR decomposition and Householder transformations. **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 97-102]**

A HYBRID FINITE DIFFERENCES, AND CHARGE SIMULATION METHOD FOR THE COMPUTATION OF HIGH VOLTAGE ELECTRIC FIELDS

J. N. Hoffmann, and P. Pulino

A new treatment is proposed to the hybrid method of Finite Differences and Charge Simulation for the computation os electric fields, entirely applicable to the similar hybrid method of Finite Element and Charge Simulation. The resulting system of linear equations is solved by using the fixed point theory, the QR decomposition and the Conjugate Gradients Squared method with a preconditioning technique. New procedures are suggested for the discretization of the boundary conditions, which lead to results with higher precision. Case studies are included. **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 103-110]**

FINITE ELEMENT MODELING OF ELECTRICAL MACHINES BY SIMULTANEOUS RESOLUTION OF FIELDS AND ELECTRIC CIRCUITS EQUATIONS

N. Sadowski, R. Carlson, J. P. A. Bastos, and M. Lajoie-Mazenc

In this work, we present a methodology for solving simultaneously the equations of magnetic fields and electric circuits of electrical machines. To consider the magnetic phenomena the Finite Element method is used. The machines are voltage fed and, thus, the electric circuit equations are present in the matricial system which takes into account both physical aspects. A time stepping technique is employed to simulate the steady and transient states. As result, we obtain the magnetic vector potential describing the magnetic behavior of the machine and the current established in the exciting coils. **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 111-116]**

SHAPE DESIGN OPTIMIZATION OF POWER FREQUENCY ELECTROMAGNETIC DEVICES USING NUMERICAL METHODS

Jaime A. Ramirez, Ernest M. Freeman, C. Chat-uthai, and João A. Vasconcelos

This paper presents the mathematical formulation concerning the solution of inverse electromagnetic problems, i.e. the shape optimization of power frequency electromagnetic devices, based on a combination of numerical methods. The optimization problem is solved using deterministic methods in which the electromagnetic field problem is treated as a subproblem of the optimization process. The field problem is calculated using the finite element (FE) method. Three deterministic approaches are studied in detail, the quadratic extended penalty method (QUA), the augmented Lagrange multiplier (ALM) method and the constrained quasi-Newton method (PLBA-CR). The work highlights the advantages and drawbacks of each approach. The search direction for the optimization is found by two distinct methods, the direct differentiation of the FE matrices and the finite difference (FD) method. In total, three problems are discussed in order to show the power and applicability of the theory presented. The PLBA-CR, when combined with the direct differentiation of the FE matrices, appears to offer important advantages over the other methods. **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 117-124]**

DETERMINATION AND ANALYSIS OF CAUSES OF INDUCTION MOTOR MAGNETIC NOISE

Sebastião Lauro Nau, and Solon Brum Silveira

This paper presents the causes of the acoustic noise magnetically generated by three-phase induction electric motors and some results of tests and calculation are discussed. The influence of the rotor slots skewing on the reduction of the magnetic noise is also analysed through calculated values. The paper gives a general view about how the magnetic noise in induction motors is generated and how much its prevision is important during the design stage. **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 125-131]**

GROUND-3D LINKED TO LINE PARAMETERS: A METHOD TO FAULT CURRENT DISTRIBUTION AND EARTH POTENTIAL DETERMINATION

H. O. Brodskyn, M. C. Costa, J. R.Cardoso, N. M. Abe, A. Passaro, S. I. Nabeta, and M. H. Giarolla

In previous work [1,2] the author presents a methodology, based on finite elements method (FEM), to calculate the potential distribution influence on the grounding area. At that time the input of the solver admits as known the split of the system. The aim of this article is to demonstrate the advantages of finite element method (FEM) associated with power systems equations with lumped parameters to intrinsically obtain the distribution of fault current in several offered conductor ways and the potential distribution on the ground, simultaneously. To solve the complex equations system, the methodology adopted was that described by Mesquita [3]. . **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 132-135]**

AN INVESTIGATION OF THE SCATTERING OF SURFACE WAVES AT DIELECTRIC SLAB WAVEGUIDE WITH AXIAL DISCONTINUITY

Creso S. Da Rocha

This paper introduces a technique for studying the radiation due to an abrupt axial discontinuity in the geometry of a planar dielectric waveguide (Slab waveguide) when an even TM surface wave strikes the discontinuity. The mode matching technique is applied at the discontinuity giving rise to formally exact integral equations which are solved by the Method of Moments. **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 136-141]**

ADAPTIVE MESHING IN TWO-VARIABLE STATIC PROBLEMS WITH FIELD BASED ERROR ESTIMATORS USING EDGE AND FACET ELEMENTS

P. Girdinio, P. Molfino, G. Molinari, and M. Nervi

In this paper a family of field-based error estimators for Finite Element analysis of electrostatic and magnetostatic problems in plane and axisymmetric geometries is presented. For the error estimation in magnetostatics, each element is divided in three sub-elements using an edge element approach, whereas for electrostatic problems a subdivision using facet elements is used. The methods and the numerical techniques are described, comparisons with known solutions are performed, some examples of application in cases of practical interest are reported and the obtained results are briefly discussed. . **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 142-147]**

FINITE ELEMENT MODELLING SCHEMES FOR THE DESIGN AND ANALYSIS OF ELECTRICAL MACHINES

D.Rodger, P.J. Leonard, H.C. Lai, and N. Allen

Electrical machines are complex objects. We have found that a variety of numerical techniques are required in order to model them using finite elements. We concentrate here on the different formulations which are useful in modelling such devices. Examples of modelling some of these machines using the MEGA package are described. . **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 148-152]**

THREE DIMENSIONAL MAGNETOSTATICS USING THE MAGNETIC VECTOR POTENTIAL WITH NODAL AND EDGE FINITE ELEMENTS

E. J. Silva, and R. C. Mesquita

In this paper, the three dimensional vector potential magnetostatic problem is solved using nodal and edge finite elements. The influence of the gauge condition A.w=0 in the characteristics of the edge-element generated matrix is analyzed. Three gauge conditions are studied: no gauge, the complete A.w=0 gauge and the incomplete A.w=0 gauge condition. **[Vol. 12, No. 1 (1997), Special Issue on International Computational Electromagnetics, pp 153-156]**

A NEW ITERATIVE MOMENT METHOD SOLUTION FOR CONDUCTING BODIES OF REVOLUTION

F. Obelleiro, J. L. Rodriguez, and A. G. Pino

An iterative solution of the combined field integral equation (CFIE) has been obtained for perfectly conducting bodies. The proposed technique avoids the inversion of the moment method (MoM) matrix by using an iterative algorithm which shows fast convergence properties, mainly for large bodies. The algorithm is applied to several 3D problems involving bodies of revolution (BOR). Accurate currents are computed with important speedups over direct MoM solutions. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering, pp 6-10]**

CALCULATION OF THE FREQUENCY CHARACTERISTICS OF MICROSTRIPS DISCONTINUITIES ON NON-DIAGONAL ANISOTROPIC SUBSTRATES USING FDTD

S. M. Chehrehrazi and A. R. Baghai-Wadji

This paper describes modifications of the conventional finite-difference time-domain (FDTD) method to the full-wave analysis of frequency dependent characteristics of microstrips discontinuities on non-diagonal anisotropic substrates. The application of the conventional FDTD is limited to materials with diagonal-anisotropic material matrices. In this paper it is shown that this restriction can be removed: First, steps for obtaining the FDTD equations for the analysis of microstrips discontinuities on substrates with fully anisotropic permittivity matrices are derived. Then, using the Fourier transform of the computed results in the time-domain, the scattering parameters as functions of the frequency are calculated for several examples. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering, pp 11-15]**

ELECTROMAGNETIC WAVES IN A NONLINEAR DISPERSIVE SLAB

G. Miano, C. Serpico, L. Verolino and G. Panariello

The electromagnetic scattering of a normal incident plane wave from a strongly nonlinear and dispersive dielectric slab is considered. The dynamics of the polarization density vector are described through a forced nonlinear ordinary differential equation of Duffing type, which takes both dispersive and nonlinear effects into account. The aim of the paper is to study the behaviour of the electromagnetic fields by using the Galerkin method. In particular it is shown that shock waves with infinite slope cannot be developed in real media because of the dispersion. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering pp 16-19]**

SENSITIVITY ANALYSIS USING HIGH ORDER DERIVATIVES

J. L. Coulomb, P. Petin, L. Saludjian, N. Nguyen Thanh, and R. Pacaut

In this article, we present a method of sensitivity analysis based on high order derivatives and Taylor expansion. The principle is to find a polynomial approximation of the finite element solution in terms of the sensitivity parameters. We present this method on two dimensional linear magnetostatic and linear magnetodynamic problems. The sensitivity parameters can be either physical parameters or geometric ones. Once the high order derivatives are found, the Taylor expansion allows evaluations for a new set of parameters. The time needed to obtain a new solution is negligible compared to a standard finite element re-analysis. This implies a dramatic change in the use of computational tools. Moreover, the availability of fast evaluations allows a wide use of optimization algorithms. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering, pp 20-25]**

SELF ADAPTIVE FUZZY SETS IN MULTI OBJECTIVE OPTIMIZATION USING GENETIC ALGORITHMS

Ch. Magele, G. Furntratt, B. Brandstatter, and K.R. Richter

Optimization in electrical engineering has attracted an increasing attention over the last few years. Various strategies to solve electromagnetic optimization problems have been introduced, amongst them stochastic, deterministic and hybrid ones. Most of today's real world applications, however, involve multiple conflicting objectives which should be considered simultaneously. The aim of this paper is to introduce self adaptive fuzzy sets to treat vector optimization problems. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering, pp 26-31]**

OPTIMISATION OF THE SHAPE OF THE FERROMAGNETIC CORE OF FLUXSET TYPE MAGNETIC FIELD SENSORS

Jozsef Pavo

A method is presented for the optimisation of the shape of the ferromagnetic core of fluxset type magnetic filed sensors. The objective of the optimisation is to find a core shape that guarantees the most homogeneous magnetisation of the core due to a given external magnetic field. By finding the optimal shape of the core the sensitivity of the sensor is improved. Since the thickness of the ferromagnetic conducting ribbon core used for fluxset sensors is considerably smaller than its other dimensions, the presence of the core is modelled by magnetic and conducting surface currents flowing in a mathematical surface representing the core. The electromagnetic field is calculated by solving an integral equation derived from the assumption of impedance type boundary conditions on the two sides of this surface. The core shape is optimised by minimising the magnetisation differences at different locations of the core. Simulated annealing procedure is used for the optimisation. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering, pp 32-37]**

NUMERICAL TECHNIQUES FOR THE INVERSION OF EDDY CURRENT TESTING DATA

Guglielmo Rubinacci and Antonello Tamburrino

In this paper, we discuss two techniques for the reconstruction of conductivity profiles in the low frequency limit. The first one is based on the second order approximation of the scattered field operator. In the second procedure, the problem is linearized at the expense of an increase in the number of unknowns including, in this case, the current density and the electric field. Some simple 2D examples are presented to point out and compare the main features of the two approaches. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering, pp 38-43]**

MAGNETIC MATERIAL PROPERTY IDENTIFICATION USING NEURAL NETWORKS

Hamadou H. Saliah and David A. Lowther

In the numerical solution of field problems for many devices, the modeling of the hysteresis properties of a material is extremely important. While considerable work has been published on models for handling this behavior, it is still difficult to obtain the parameters for these models from measured data. This paper proposes the use a neural network for this operation. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering, pp 44-49]**

OPTIMIZATION OF A SMES DEVICE UNDER NONLINEAR CONSTRAINTS

B. R. Brandstatter and Wolfgang Ring

In this paper a method to calculate the gradients for the TEAM 22 problem is presented. Furthermore an objective function different from the one proposed in the benchmark is used where the energy requirement was handled as an equality constraint. The so derived gradients of the objective function and the constraints together with a standard optimization routine are used to solve the problem. In the last section some new results concerning the presence of local minima for the problem are given. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering, pp 50-53]**

RECONSTRUCTION OF INHOMOGENEOUS LOSSY DIELECTRIC OBJECTS IN ONE DIMENSION

W. Rieger, M. Haas, C. Huber, G. Lehner, and W.M. Rucker

The 1D inverse scattering problem of reconstructing the material properties of an inhomogeneous lossy dielectric slab is considered. The material properties are reconstructed using scattering data from time harmonic electromagnetic plane waves. The incident plane waves are either TE or TM polarized. The inverse scattering problem formulated as a nonlinear optimization problem by means of integral equations is numerically solved using an iterative scheme and Tikhonov regularization. Numerical examples with both types of polarization are presented. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering, pp 54-59]**

LAGRANGIAN BEM-FEM SOLUTION OF ELECTROMAGNETIC-MECHANICAL COUPLED PROBLEMS

A. Formisano, R. Martone, and F. Villone

In the framework of the electro-mechanical coupled problems, the coupling between the magnetic diffusion and the elastic deformation equations is treated numerically. A mixed BEM-FEM approach for the electromagnetic part, and a FEM approach for the mechanical part, are proposed. Advantages are taken from a Lagrangian formulation of the problem. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering, pp 60-65]**

MODELLING OF DEGAUSSING COILS EFFECTS ON SHIPS

F. Le Dorze, J. P. Bongiraud, J. L. Coulomb, G. Meunier, and X. Brunotte

This paper presents our work on magnetic modelling of ships, especially their degaussing coils. We first focus on these coils effects in the FEM computations. The main reason of bad results is a locally inadequate mesh. We propose a method named " reduced potential jump" to avoid the use of a very fine mesh. Then, comparison of results is presented for a simple geometry. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering, pp 66-70]**

A THREE-DIMENSIONAL ANALYSIS OF MAGNETIC SHIELDING WITH THIN LAYERS

H. Igarashi, T. Honma, and A. Kost

This paper describes a numerical method for the analysis of the magnetic shielding with thin layers in three dimensional, time-harmonic magnetic fields. In this method, FEM is employed to solve a couple of differential equations which express the surface impedance of the thin shielding materials. The magnetic fields in air regions are modeled by means of BEM. The above formulations are coupled to evaluate the shielding properties. The resultant matrix equation includes unknowns of two times the number of nodal points. This method can analyze not only a shielding system with closed surfaces but also that with open surfaces without introducing fictitious boundaries in air region. The method is shown to give accurate shielding factors of a spherical shell over tested range of frequencies. The eddy currents on a shielding plate are successfully obtained using the present method. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering, pp 71-74]**

FAST-MOM: A METHOD-OF-MOMENTS FORMULATION FOR FAST COMPUTATIONS

A. R. Baghai-Wadji

An overlooked fact in the application of the method of moments (MoM) has been pointed out which may allow an increase of MoM-performance by up to two orders of magnitude. Various problems, such as device modeling and antenna design, often require the calculation of "interaction coefficients" (ICs) millions to billions times. ICs are Fourier-type definite multiple integrals with complex-valued integrands, which are generally available in numerical form. The ICs depend on the operating frequency and the co-ordinates of the interacting elements, and their numerical calculation can be very time consuming. Our goal in this work is to introduce Fast-MoM. This technique allows the generation of frequency-independent, coordinate-free universal functions which can be calculated beforehand and stored; merely constitution relations of the medium are required. The speed for the computation of ICs then becomes essentially limited by the time necessary for retrieving data from the storage medium chosen. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering, pp 75-80]**

A C.A.E. TOOL TO UNDERSTAND MAGNETOSTATICS

F. Buret, D. Muller, A. Nicolas, and L. Nicolas

We present in this paper a Computer Aided Education package allowing to visualize the magnetostatic field in and around the magnetic circuit of a double-U shaped contactor. The modeling of this device is performed by solving in real time a non-linear finite element problem. The implementation of this method is optimized greatly in order to allow to animate field patterns in real time in reaction to any user interaction. An evaluation of the improvements brought by this technique to the learning capabilities of students is presented. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering, pp 81-84]**

NUMERICAL MODELLING OF AN AXIAL-FIELD SOLID DISK INDUCTION MACHINE

Marco Angeli, Nunzio Esposito, Antonino Musolino, and Bernardo Tellini

In this paper a method for the steady-state analysis of an axial-field induction motor with a solid disk rotor is proposed. The boundary condition for the axial component of the magnetic flux density has been calculated by means of an analytical procedure. Accordingly the simulation region is restricted to the air-gap and the rotor. Then the axial component of the diffusion equation is solved for by using a finite difference scheme. Subsequently the azimuthal component of the magnetic flux density and the current density induced in the rotor come out from the field's laws. The validity of the proposed method has been tested by comparing the numerical results with data measured on a double-stator prototype. Finally the numerical procedure has been used for the analysis of the performance of a motor for light vehicle propulsion and the results of the simulation are shown. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering, pp 85-89]**

MODELLING DYNAMIC HYSTERESIS IN FERROMAGNETIC SHEETS UNDER TIME-PERIODIC SUPPLY CONDITIONS

Oriano Bottauscio, Mario Chiampi, and Maurizio Repetto

This paper presents an application of the Dynamic Preisach Model as proposed by Bertotti, to the analysis of electromagnetic phenomena inside a ferromagnetic lamination subject to imposed time-periodic magnetic flux. The field problem, considered as one dimensional, is formulated in terms of magnetic field and the Fixed Point technique is used for the treatment of the hysteretic nonlinearity. The solution is carried out in the harmonic domain by means of the Finite Element method. The original implementation of the Dynamic Preisach Model is detailed and comparisons with measurements are presented in the case of sinusoidal excitations. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering, pp 90-95]**

DYNAMIC OPERATION OF COILS WITH FERROMAGNETIC CORES TAKING MAGNETIC HYSTERESIS INTO ACCOUNT

Janos Fuzi

The computation of electromagnetic field diffusion in ferromagnetic and conductive media is coupled to circuit analysis problems, involving coils with iron cores. The classical Preisach model provides the relationship between magnetic field intensity and flux density at the local level, inside the core. Combined with a 2D eddy current simulation, carried out by a time stepping method, the dynamic operation of the core is modelled. The circuit equations are solved taking the effects of hysteresis and skin effects caused by eddy currents induced in core sheets into account. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering, pp 96-101]**

A STRONG COUPLING MODEL FOR THE SIMULATION OF MAGNETOMECHANICAL SYSTEMS USING A PREDICTOR/MULTI-CORRECTOR ALGORITHM

M. Kaltenbacher, H. Landes, and R. Lerch

A recently developed modeling scheme for the numerical simulation of coupled magnetomechanical systems is presented. The scheme allows the calculation of dynamic rigid motions as well as deformations of magnetic and anti-magnetic materials in a magnetic field. The equations governing the magnetic and mechanical field quantities are solved using a combined Finite Element /Boundary-Element-Method (FEM-BEM). To circumvent the nonlinear system of equations resulting from a direct coupling of the magnetic and mechanical systems, the calculation of the magnetic forces is based on predictor values of the magnetic quantities. Therewith, a decoupling into a magnetic and mechanical matrix equation can be achieved. To ensure the strong coupling between the magnetic and mechanical quantities, a sophisticated Predictor/Multicorrector Algorithm is used resulting in an efficient iteration between the two matrix equations within a single time step. Computer simulations of an electromagnetic forming system and a magnetomechanical transducer immersed in an acoustic fluid (acoustic power source) show good agreement between simulation results and measured data. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering, pp 102-106]**

RESULTS OF PARALLELISATION OF EXISTING ELECTROMAGNETIC FINITE ELEMENT CODES ON SOME DIFFERENT PARALLEL ARCHITECTURES

M. Dracopoulos, K. Palrot, G. Molinari, M. Nervi, and J. Simkin

In this paper the results obtained from the parallelisation of some 3D industrial electromagnetic Finite Element codes within the ESPRIT Europort 2 project PARTEL are presented. The basic guidelines for the parallelisation procedure, based on the Bulk Synchronous Parallel approach, are presented and the encouraging results obtained in terms of speed-up on some selected test cases of practical design significance are outlined and discussed. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering, pp 107-112]**

THE NEWTON-RAPHSON METHOD FOR COMPLEX EQUATION SYSTEMS

Dieter Lederer, Hajime Igarashi, Arnulf Kost

A formulation for the complex Newton-Raphson method is proposed. The derivation is obtained on the assumption of a non-analytical system. The method is applied to the finite element calculation of shielding problems with sinusoidal ex-citation and ferromagnetic material. An application example for which measurement data are available is given in order to judge the convergence characteristics and the reliability of the proposed method. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering, pp 113-116]**

SOME ASPECTS OF MAGNETIC FORCE COMPUTATION USING BEM-FEM COUPLING

Joachim Fetzer, Stefan Kurz, Gunther Lehner, and Wolfgang M. Rucker

For the calculation of magnetic forces with the Maxwell stress tensor the normal and the tangential derivatives of the vector potential A have to be known. We choose C^0-continuous elements, therefore A and its tangential derivatives are continuous. In contrast, the normal derivative $\partial A/\partial n$ calculated with the finite element method is continuous only in a weak sense. When BEM-FEM coupling is used however, the value of $\partial A/\partial n$ is uniquely available on the coupling surfaces from the BEM formulation. Two methods of magnetic force computation using $\partial A/\partial n$ either from FEM or from BEM data will be presented. Their accuracy will be compared by means of several examples. **[Vol. 12, No. 2 (1997), pp Special Issue on Numerical Field Calculations in Electrical Engineering, 117-120]**

THE NUMERICAL TREATMENT OF SINGULAR INTEGRALS IN BOUNDARY ELEMENT CALCULATIONS

C.J. Huber, W. Rieger. M. Haas and, W.M. Rucker

In this paper a general method for the evaluation of singular boundary element integrals over three-dimensional isoparametric boundary elements of higher order is presented. This method permits an efficient integration of strongly singular kernels of order $O(1/r^2)$ and of nearly strong singular kernels on curved surfaces. For numerical examples the proposed integration scheme is compared with analytical test examples showing high efficiency and accuracy. This new method has full generality and, therefore, can be applied in any field of electromagnetics. The actual computation can be easily included in any existing computer code, e. g. for the solution of electromagnetic scattering problems. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering, pp 121-126]**

VARIOUS APPROACHES TO TORQUE CALCULATIONS BY FEM AND BEM

Mladen Trlep, Anton Hamler, and Bozidar Hribernik

Different algorithms for the torque calculation by Maxwell stress method (MSM) are dealt with in the paper. The aim of designing these algorithms was to reduce the influence of the choice of the integration path and discretization of the air gap between the stator and rotor on the accuracy of the results. In some of these algorithms the connection between the stator and rotor is released For the magnetic field calculation the finite element method (FEM), boundary element method (BEM), and hybrid finite element - boundary element method (HM) were used. The calculation results were tested on a permanent magnet DC motor and a single phase brushless motor. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering, pp 127-130]**

MODELLING EDDY CURRENTS INDUCED BY ROTATING SYSTEMS

C. R. I. Emson, C. P. Riley, and D. A. Walsh

As part of a Japanese funded project, a transient eddy current code is being extended to allow for rotational systems. By allowing the system to rotate, induced eddy currents must be modelled. The system being developed uses the "lock-step" approach to model the rotation. As other facilities are included (non-linear materials for example), the solution time of the final code becomes sufficiently large that special care must be taken, and investigations into using parallel hardware becomes necessary. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering, pp 131-134]**

BEM-FEM COUPLING IN ELECTROMECHANICS: A 2-D WATCH STEPPING MOTOR DRIVEN BY A THIN WIRE COIL

Stefan Kurz, Joachim Fetzer, Thomas Kube, Gunther Lehner, and Wolfgang M. Rucker

This paper deals with the transient numerical analysis of 2-d electromechanical devices driven by thin wire coils.

Their dynamical behavior is described by the Maxwell equations, by the constitutive relations, and by the equations of motion. For the solution of the electromagnetic problem the BEM-FEM coupling method is used. A two-dimensional watch stepping motor is presented as an example. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering, pp 135-139]**

HYBRID FORMULATIONS FOR 3D MAGNETOSTATIC AND EDDY CURRENT PROBLEMS

Kimmo Forsman and Lauri Kettunen

Hybrid formulations for solving nonlinear 3D magnetostatic and eddy current problems in terms of magnetic field H are presented. In the proposed formulations integral operators are utilized as if the boundary conditions for a partial differential equation were solved within the system of equations. A good correspondence between the results of the presented methods and measurements or other methods is obtained for some test problems. **[Vol. 12, No. 2 (1997), Special Issue on Numerical Field Calculations in Electrical Engineering, pp 140-144]**

DOMAIN DECOMPOSITION STRATEGIES FOR SOLVING THE MAXWELL EQUATIONS ON DISTRIBUTED PARALLEL ARCHITECTURES

Douglas C. Blake and Thomas A. Buter

Domain decomposition strategies for solving hyperbolic systems of partial differential equations on distributed-memory parallel computing platforms are investigated. The logically-rectangular computational domain is divided either one, two, or three dimensionally into a series of computational blocks, and each block is assigned to a single processor. Theoretical predictions using standard parallel performance models indicate that higher-dimensional decompositions provide superior parallel program performance in terms of scalability. The theory is tested using a finite-volume time-domain (FVTD) Maxwell equations solver to compute the electromagnetic fields inside a rectangular waveguide using various grid sizes and processor numbers on three different parallel architectures- the Intel Paragon, the IBM SP2, and the Cray T3D. The specific performance of the FVTD algorithm on the three machines is investigated, the relation between processor connection topology and message passing performance of a typical grid-based hyperbolic equation solver are identified, and the results are used to augment the classical parallel performance model. Although clear performance trends emerge in terms of the dimensionality of the decomposition, results indicate that higher-dimensional decompositions do not always provide superior parallel performance. **[Vol. 12, No. 3 (1997), pp 4-15]**

MOMENT METHOD SURFACE PATCH AND WIRE GRID ACCURACY IN THE COMPUTATION OF NEAR FIELDS

Robert Paknys and Leslie R. Raschkowan

The accuracy of surface patch and wire grid moment method models for the of near fields is investigated. A sphere and a flat plate with plane wave illumination are examined.

It is found that wire grids exhibit stronger near field anomalies than surface patches, which have the current more distributed over the surface. Nevertheless, good results can be obtained with a wire grid, provided that a small distance from the wire grid surface is maintained

The surface patch results are obtained using the Junction code. Wire grid results are with both the MBC and NEC codes. Validation the sphere is by comparison with an exact solution obtained from the NECBSC code. **[Vol. 12, No. 3 (1997), pp 16-25]**

USING THE FDTD METHOD TO MODEL THE REFLECTION COEFFICIENT OF A VIVALDI TAPERED SLOT ANTENNA FED THROUGH A PLANAR BALUN

G. Biffi Gentili, R Braccini, M. Leoncini

In this paper, the Time-Domain (FDTD) method was used to determine the reflection coefficient vs. frequency of a Vivaldi Tapered Dual-Slot Antenna fed through a planar balun. The reflection coefficient at the input port of the feed stripline was determined through the separate computation of the reflection coefficient of representation of the antenna section and the scattering matrix of the balun, assuming that the electromagnetic coupling between these sections was negligible. Experimental results, which were obtained on a prototype of this structure, confirmed the validity of the proposed approach and demonstrate that the coupling of the model. **[Vol. 12, No. 3 (1997), pp 26-30]**

FINITE-DIFFERENCE TIME-DOMAIN MODELING OF LIGHT-TRAPPING IN SOLAR CELLS

Todd Marshall and Melinda Piket-May

To maximize light-trapping, the absorption of light in the solar cell is maximized. The ways to increase light-trapping are to texture the surfaces of the solar cell and to use anti-reflection coatings. The power spectrum of sunlight also plays an important role in light-trapping. In general, a solar cell consists of multiple layers of dielectric materials. Each dielectric has a complicated surface texture geometry to increase light-trapping. This paper concentrates on solving Maxwell's equations for the general solar cell configuration under illumination from the sun. The absorption and maximum achievable current density are calculated and used to quantify light-trapping in a given solar cell design. Thin solar cells promise to yield higher current collection than thick solar cells at a lower cost [1]. Low cost solar cells are usually characterized by short diffusion length semiconductors. Most minority carriers created within the distance equal to the diffusion length contribute to the electrical current of a solar cell. Hence, the solar cell must be thin when low quality materials are used. As solar cells decrease in size, the ray-trace model becomes inaccurate as previously demonstrated in [2]. A full-wave Finite-Difference Time-Domain (FDTD) light-trapping model is demonstrated to accurately study light-trapping of thin-film solar cells. **[Vol. 12, No. 3 (1997), pp 31-42]**

MODELLING EDDY CURRENTS IN UNBOUNDED STRUCTURES USING THE IMPEDANCE METHOD

Daniel James, David V. Thiel

In this paper extensions to the impedance network method are presented. In particular the method has been applied to problems with boundaries extending to infinity. The infinite boundary condition can also be applied to lines of symmetry in the given geometry. Two dimensional surface models have been verified by comparison of numerical and experimental results in which the potential was measured along the edge of copper sheeting of various shapes located in a uniform, quasi-static magnetic field. The method has potential for modelling three dimensional structures including anisotropic earth planes, arbitrarily shaped buried objects, and both finite and infinitely long faults, dykes, pipes, cylinders and cracks. **[Vol. 12, No. 3 (1997), pp 43-49]**

VERIFICATION OF SOFTWARES FOR ELECTROMAGNETIC FIELD ANALYSIS USING MODELS PROPOSED BY INVESTIGATION COMMITTEES IN IEE OF JAPAN

Norio Takahashi

In order to investigate methods for analyzing electromagnetic fields and to compare the accuracy and the CPU time of various codes and so on, investigation committees were set up in IEE of Japan. In this paper, the activities of various investigation committees relating electromagnetic field analysis are described from the viewpoint of the verification of software. **[Vol. 12, No. 3 (1997), pp 50-61]**

VIEWS OF THE 14TH ANNUAL REVIEW

Eric Michielssen, 97 Conference Chair, accepting the Valued Service Award, from John Brauer

Norio Takahashi accepting the Best Journal Paper Award for 1997, from John Brauer

VIEWS OF THE 14TH ANNUAL REVIEW

Duncan Baker, accepting the Founders Award, from John Brauer

W. Perry Wheless, new President, Pat Foster, ex Vice President, and John Brauer, new Vice President.

VIEWS OF THE 14TH ANNUAL REVIEW

from left to right, Chris Trueman, Stan Kubina, Henry A. Nott, and others.

from left to right, Simon Walker, Eric Michielssen,
Andrew Efanov and Ross Speciale

VIEWS OF THE 14TH ANNUAL REVIEW

from left to right, Ray Perez, new ACES attendee, Andy Peterson, Todd Hubing, Henry Karwacki, and Simon Walker

from left to right, Perry Wheless, John Brauer, Norio Takahashi, Brian Zook, Atef Elsherbeni, Allen Glisson, and Randy Haupt, C98 Conference Chair

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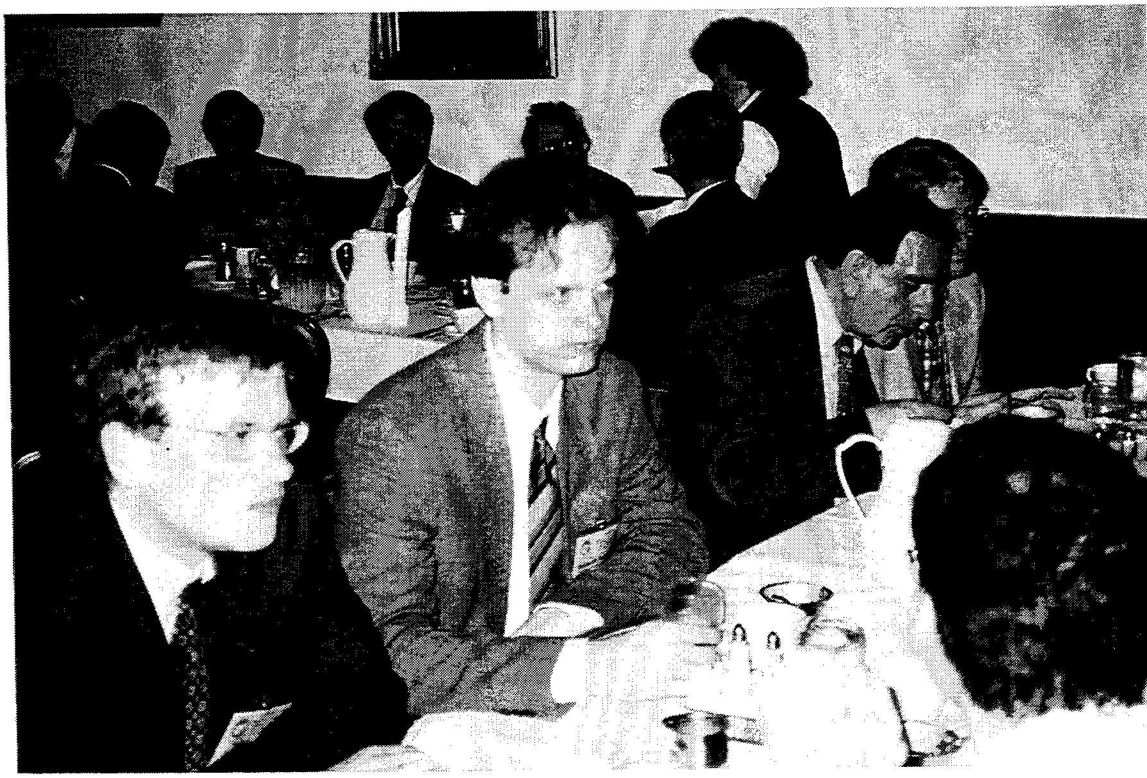

We were not able to identify all the attendees in the pictures on pages 50, 51, and 52, so in order not to offend, we did not identify anyone.

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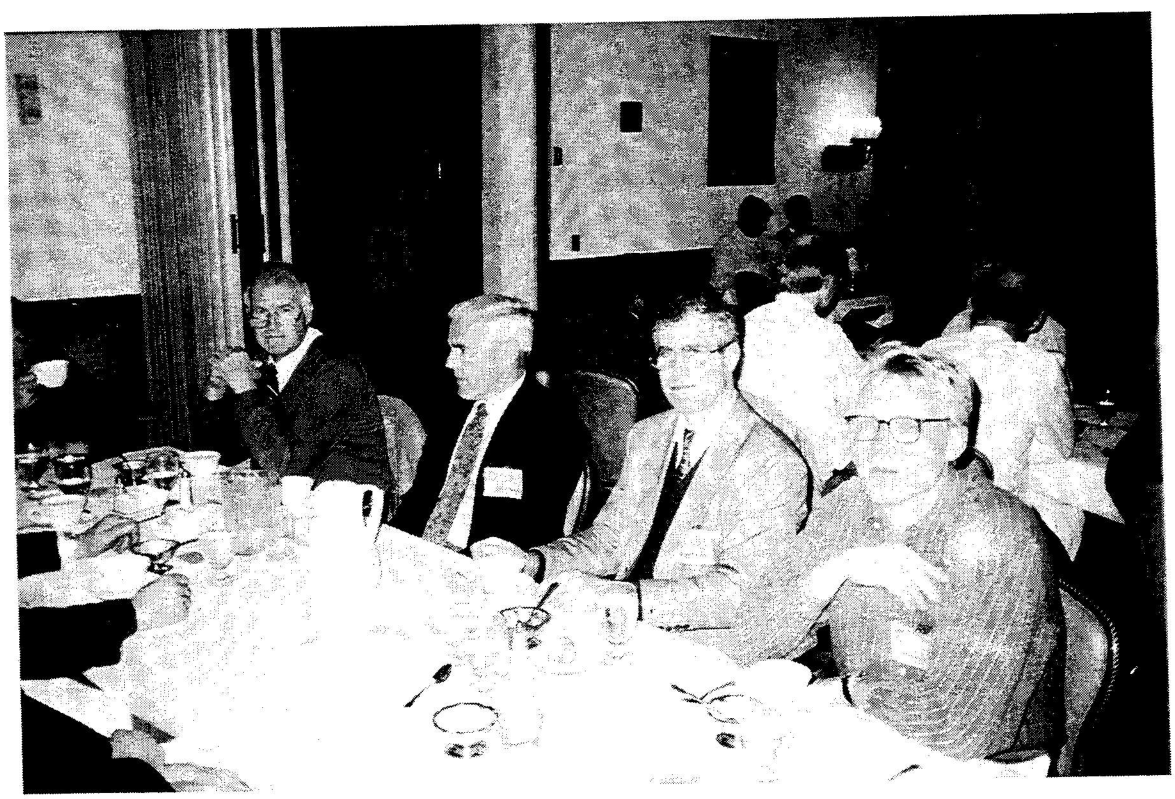

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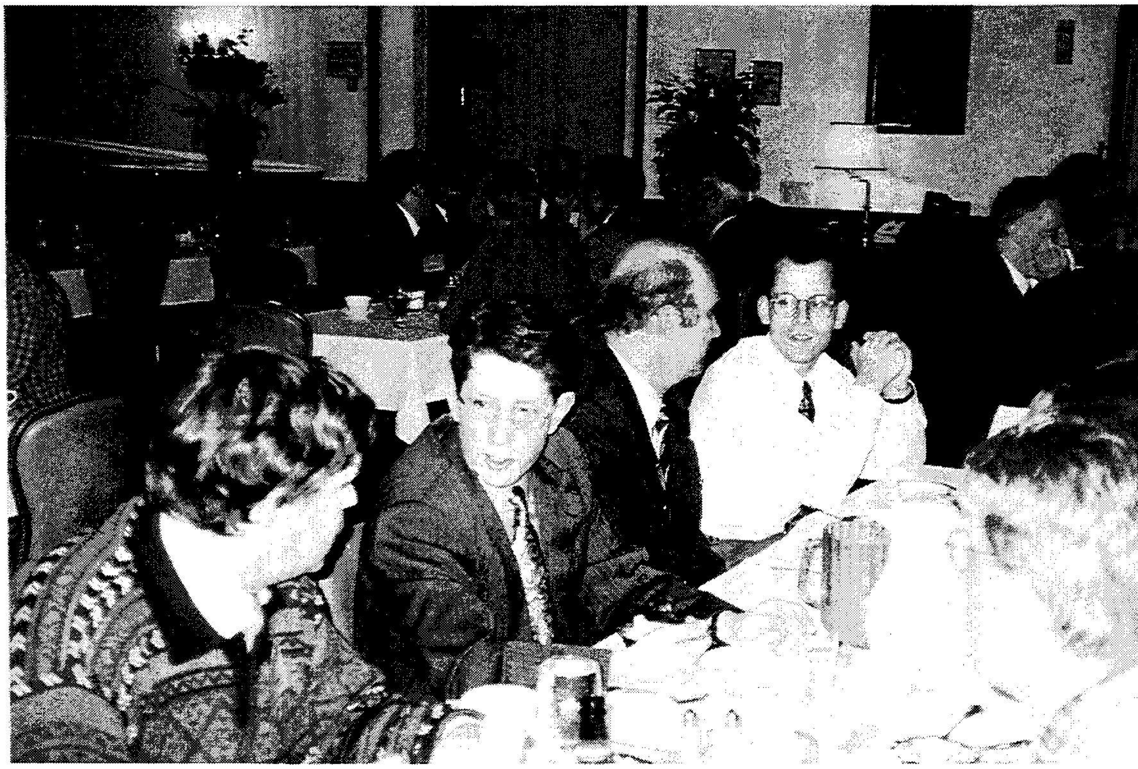

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INSTRUCTIONS AND TIMETABLE FOR AUTHORS

November 20, 1998: Submission deadline. Submit four copies of a full-length, camera-ready paper to the Technical Program Chairman. Please supply the following data for the corresponding author: name, address, email address, FAX, and phone numbers.
See below for instructions for the format of paper.

December 21, 1998: Authors notified of acceptance.

PAPER FORMATTING REQUIREMENTS

The recommended paper length is 6 pages, with 8 pages as a maximum, including figures. The paper should be camera-ready (good resolution, clearly readable when reduced to the final print of 6 x 9 inch paper). The paper should be printed on 8-1/2 x 11 inch papers with 13/16 side margins, 1-1/16 inch top margin, and 1 inch on the bottom. On the first page, place title 1-1/2 inches from top with author and affiliation beneath the title. Single spaced type using 10 or 12 point front size, entire text should be justified (flush left and flush right). No typed page numbers, but number your pages lightly in pencil on the back of each page.

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Short courses will be offered in conjunction with the Symposium covering numerical techniques, computational methods, surveys of EM analysis and code usage instruction. It is anticipated that short courses will be conducted principally on Monday March 15 and Friday March 19. Fees for **Half-day course** will be: $90 per person if booked before 1 March 99; $100, if booked from 1 March to 15 March 99; and $110 if booked at Conference time. **Full-day Courses** will be: $140 if booked before 1 March 1999; $150 if booked from 1 March to 15 March; $160 if booked at Conference time. **Short Course Attendance is not covered by the Symposium Registration Fee!**

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WINNERS OF THE 1998 BEST STUDENT PAPER AWARD

A paper titled "Rational Krylov Reduced Order Modeling of Multiscreen Frequency Selective Surfaces" by Daniel S. Weile, Eric Michielssen and K. Gallivan, Department of Electrical and Computer Engineering at the University of Illinois at Urbana-Champaign, won the Best Student Paper Award at the 14th Annual Review of Progress in Applied Computational Electromagnetics, at the Naval Postgraduate School, in Monterey, CA.

Prizes for Daniel and Eric, the student and Principal Adviser, consist of (1) free Annual Review Attendance for 1999; (2) free short course during the 1999 Annual Review and (3) a $200 check to share.

Since the winning paper was announced after the 14th Review ended, we wish to thank Daniel, Eric and K. Gallivan, at this time for submitting a high quality Paper.

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CREDIT CARD USERS

SIGNATURE AND ADDRESS OF CARD HOLDER IS MANDATORY.

IF YOU ARE PAYING VIA ANOTHER PERSONS CARD, HE/SHE MUST PRINT AND SIGN NAME AND ADDRESS.

PRINT CARD HOLDER NAME: ____

CREDIT CARD HOLDER SIGNATURE: ____

CREDIT CARD EXPIRATION DATE: ____/____

CREDIT CARD HOLDER ADDRESS: ____

CREDIT CARD ACCOUNT # ☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐

July 1998