Quantum electrodynamics of optical metasurfaces

Bondarev, I.V., & Shalaev, V.M. (2018*). Quantum electrodynamics of optical metasurfaces*. 2018 International Applied Computational Electromagnetics Society Symposium (ACES), 1-2.

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Abstract:
Recent theoretical and experimental development of optical metasurfaces has been able to address the major issues including high losses, cost-ineffective fabrication, and challenging integration that hamper the full-scale development of the metasurface technology. Future progress utilizing the quantum nature of light is likely to result in ultrathin metasurfaces with increased operational bandwidths and reduced losses. Here we discuss the simplest case of ultrathin plasmonic films as an example to show how quantum electrodynamics and understanding of quantum-dimensional effects therein can help uncover new functionalities of ultrathin metallic nanostructures.

Published in: 2018 International Applied Computational Electromagnetics Society Symposium (ACES)

Date of Conference: 25-29 March 2018

Date Added to IEEE *Xplore*: 24 May 2018

▼ **ISBN Information:**
Electronic ISBN: 978-0-9960-0787-0
Print on Demand(PoD) ISBN: 978-1-5386-4857-5

INSPEC Accession Number: 17803173

DOI: 10.23919/ROPACES.2018.8364252

Publisher: IEEE

Conference Location: Denver, CO, USA

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Quantum Electrodynamics of Optical Metasurfaces

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***Abstract*—Recent theoretical and experimental development of optical metasurfaces has been able to address the major issues including high losses, cost-ineffective fabrication, and challenging integration that hamper the full-scale development of the metasurface technology. Future progress utilizing the quantum nature of light is likely to result in ultrathin metasurfaces with increased operational bandwidths and reduced losses. Here we discuss the simplest case of ultrathin plasmonic films as an example to show how quantum electrodynamics and understanding of quantum-dimensional effects therein can help uncover new functionalities of ultrathin metallic nanostructures.**

Keywords—nanomaterials, ultrathin films, plasmonics, QED.

I. Introduction

Current development of nanofabrication techniques makes it possible to design advanced plasmonic nanomaterials with optical properties on-demand [1], [2]. One type of such nanomaterials are optical metasurfaces [3]. By carefully controlling geometry, structural dimensions and material composition one can fabricate metasurfaces (MSs) for a variety of applications, including optoelectronics, microscopy, imaging, sensing, and probing the fundamentals of light-matter interactions at the nanoscale [4]-[7]. Depending on their material composition and thickness, metasurfaces can restructure the spectral and spatial distribution of both real and *vacuum* electromagnetic (EM) modes. While real modes can still be described semiclassically, the physical consequences of the EM vacuum restructuring can only be fully understood within the framework of medium-assisted quantum electrodynamics (QED) [8] — a rigorous quantized formalism valid *in the presence* of absorbing, dispersive and spatially confined media [9], [10] — to allow one to uncover new physics, new features and functionalities that make ultrathin (quasi-2D) optical MSs distinctly different from optical metamaterials, their 3D counterparts.

II. Medium-Assisted QED and Quantum Confinement

In presence of dispersing, absorbing and spatially confined media, the standard (vacuum) QED field quantization scheme fails to work in view of the fact that absorption makes the operator Maxwell equations non-Hermitian. As a consequence, their solutions cannot be expanded in power orthogonal modes, strictly speaking, and the concept of modes itself becomes more subtle. EM field quantization is necessary for the correct description of light-matter interaction scenarios with *virtual* (vacuum) photon excitations involved such as spontaneous emission and van der Waals interactions, mediated essentially by the virtual photon exchange [10].

In the medium-assisted QED approach we employ herein for optical MSs, absorption and other EM relaxation processes are considered to create random charge fluctuations with their associated (medium-assisted) local fields being superposed on those of physical vacuum (no medium present), to give rise to the vacuum-type medium-assisted EM fields represented by the quantum field operators (Schrödinger picture, Gaussian units):

$$\hat{E}_\alpha(\mathbf{r},\omega)=i\frac{4\pi\omega^2}{c^2}\int d\mathbf{r}'\sum_{\lambda=x,y,z}G_{\alpha\lambda}(\mathbf{r},\mathbf{r}',\omega)\hat{J}_\lambda(\mathbf{r}',\omega)+\text{h.c.} \qquad (1)$$

Here, $\hat{J}_\lambda(\mathbf{r},\omega)=\sqrt{\hbar\,\mathrm{Im}\,\varepsilon_{\lambda\lambda}(\mathbf{r},\omega)/\pi}\;\hat{f}_\lambda(\mathbf{r},\omega)$ is the quantum noise current density operator responsible for the vacuum-type medium excitations annihilated (created) locally by operators $\hat{f}_\lambda$ ($\hat{f}_\lambda^\dagger$), $G_{\alpha\lambda}$ is a classical EM field Green's tensor calculated for a confined material system of interest under appropriate boundary conditions and the rest is commonly used quantities. Medium excitations are assumed to be of bosonic type so that $[\hat{f}_\alpha(\mathbf{r},\omega),\hat{f}_\lambda^\dagger(\mathbf{r}',\omega')]=\delta_{\alpha\lambda}\delta(\mathbf{r}-\mathbf{r}')\delta(\omega-\omega')$ as required by the Fluctuation-Dissipation Theorem and vacuum QED. Medium composition and medium confinement geometry are included in (1) by means of the dielectric response function $\varepsilon(\mathbf{r},\omega)$ and the Green's tensor, respectively. This makes the formalism extremely useful for calculating observables such as decay rates and Purcell factors for external emitters placed near MSs, which are proportional to the imaginary part of $G_{\alpha\lambda}(\mathbf{r},\mathbf{r},\omega)$, the main factor to represent the local density of photonic states (LDOS). The medium-assisted QED scheme can be extended to include nonlocal effects as well [11].

However, even though both medium composition and confinement geometry are included in the QED scheme above, there is one more important ingredient to add in. Metasurfaces are often based on ultrathin metallic films. In thin films [Fig. 1 (a)], the Coulomb interaction of charges strengthens with the thickness reduction [12] if the film dielectric constant (ε) is much larger than those of the film surroundings ($\varepsilon_{1,2}$). This is because the field produced by the confined charges outside of their confinement region starts playing a perceptible role with its size reduction. When $\varepsilon_{1,2} << \varepsilon$ and the in-plane inter-charge distance ρ is greater than the film thickness d, the increased 'outside' Coulomb contribution makes the interaction between the charges confined much stronger than that in homogeneous medium with the dielectric constant ε. In Fig. 1 (b), we see the pair Coulomb potential vary fast for $\varepsilon_1+\varepsilon_2 << \varepsilon$ and $d << \rho$ (the range of parameters for thin metal-semiconductor MSs), indicating strong spatial dispersion of the dielectric response function in (1) — a solely confinement related effect having nothing to do with the MS material inhomogeneity.

Supported by NSF: ECCS-1306871 (I.V.B), DMR-1506775 (V.M.S.)

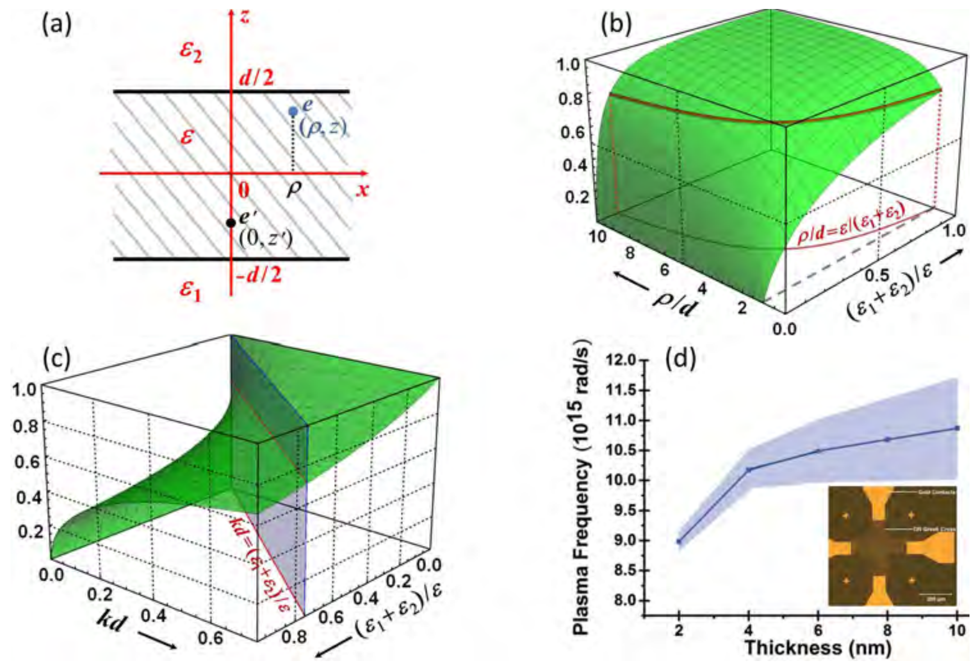

Fig. 1. (a) Schematic of the confined thin film geometry, and (b) the normalized Coulomb interaction (Keldysh [12]) potential, for finite thickness films. (c) Thin film plasma frequency normalized by the bulk plasma frequency one obtains using the Keldysh potential [13]. (d) Plasma frequency extracted from the ellipsometry measurements done on ultrathin TiN films (inset) of varied thicknesses fabricated at Purdue University [2]. See text and [13] for more details.

As an example, we have recently calculated plasma frequency spatial dispersion and the complex-valued dynamic dielectric response function for finite-thickness plasmonic films deposited on various substrates [13]. For the plasma frequency, in particular, we have:

$$\omega_p = \frac{\omega_p^{3D}}{\sqrt{1+(\varepsilon_1+\varepsilon_2)/\varepsilon k d}}\,. \qquad (2)$$

Here, k is the electron in-plane momentum absolute value and $\omega_p^{3D} = (4\pi e^2 N_{3D}/\varepsilon m^*)^{1/2}$ is the plasma frequency of the bulk electron gas with electron effective mass m^* and volumetric density N_{3D}. We see that if $(\varepsilon_1+\varepsilon_2)/\varepsilon kd << 1$ (thick MS case), then $\omega_p = \omega_p^{3D}$, whereas one has $\omega_p = [4\pi e^2 N_{2D} k/(\varepsilon_1+\varepsilon_2)m^*]^{1/2}$ in the opposite case of the infinitely thin MS ($N_{2D} = N_{3D}\,d$ is the surface electron density) in full agreement with the plasma frequency dependence of the 2D electron gas.

Fig. 1 (c) shows the ratio ω_p/ω_p^{3D} of (2) as a function of kd and $(\varepsilon_1+\varepsilon_2)/\varepsilon$. The thick/thin film regimes are separated by the vertical plane. While being constant for thick films, the plasma frequency is seen to acquire spatial dispersion typical of 2D materials such as graphene [14], gradually shifting to the red with the film thickness reduction. This explains recent plasma frequency measurements done on TiN films of varied thickness [2], shown in Fig. 1 (d), offering ways to tune spatial dispersion (and thereby magnetic permeability [15]) and other related optical properties of plasmonic films and metasurfaces — not only by varying their material composition but also by precisely controlling their thickness and choosing surrounding substrate and superstrate materials appropriately.

ACKNOWLEDGMENT

We acknowledge fruitful discussions with Alexandra Boltasseva and Harsha Reddy, College of Engineering and Birck Nanotechnology Center at Purdue University.

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2018 International Applied Computational Electromagnetics Society Symposium in Denver (ACES-Denver 2018)

March 25-29, 2018
Denver, Colorado, USA

Sponsors

Lockheed Martin
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IEEE Catalog Number: CFP1856X-ART
ISBN: 978-0-9960078-7-0

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John C. Young, Robert Pfeiffer, Robert J. Adams, and Stephen D. Gedney

31-02 "A Huygens Surface Source Model for Field Prediction Valid from sub-ELF to High Frequencies"
Nastaran Hendijani, Stephen D. Gedney, John C. Young, and Robert J. Adams

31-03 "Micromagnetic Model Simulation of Spin-Torque Oscillator and Write Head for Microwave-Assisted Magnetic Recording – Spin Injection Layer with In-Plane Anisotropy"
Yasushi Kanai, Ryo Itagaki, Simon Greaves, and Hiroaki Muraoka

31-04 "A Finite-Difference Frequency Domain Solver for Quasi-TEM Applications"
J. Patrick Donohoe

Session 32: Advanced FDTD Methods

32-01 "SAR and Temperature Rise Distributions in a Human Head Due to a Multi-Frequency Antenna Source"
Fatih Kaburcuk and Atef Z. Elsherbeni

32-02 "Provably Stable Local Application of Crank-Nicolson Time Integration to the FDTD Method with Nonuniform Gridding and Subgridding"
A. Van Londersele, D. De Zutter, and D. Vande Ginste

32-03 "Model Order Reduction for Finite Difference Modeling of Cardiac Propagation using DMD modes"
Riasat Khan and Kwong T. Ng

32-04 "Numerical Dispersion Analysis for Spherical FDTD"
Ravi C. Bollimuntha, Mohammed F. Hadi, Melinda J. Piket-May, and Atef Z. Elsherbeni

32-05 "Improved FDTD Method around Dielectric and PEC Interfaces using RBFFD Techniques"
Brad Martin, Atef Elsherbeni, Gregory E. Fasshauer, and Mohammed Hadi

Session 33: Electromagnetic Simulation for RF and Microwave Design Optimization

33-01 "GA-MoM Optimization of Slot Arrays"
Sembiam R. Rengarajan

33-02 "Uniform Sampling Procedure for Constrained Surrogate Modeling of Antenna Structures"
Slawomir Koziel and Ari T. Sigurdsson

33-03 "Novel Structure and EM-Driven Design of Miniaturized Microstrip Rat-Race Coupler"
Adrian Bekasiewicz and Slawomir Koziel

33-04 "Coplanar Waveguide-based Lowpass Filters with Non-uniform Signal Trace and Ground Planes"
Qizhen Li, Khair Al Shamaileh, and Vijay Devabhaktuni

33-05 "Nonlinear Neural Network Equalizer for Metro Optical Fiber Communication Systems"
Mahmoud M.T. Maghrabi, Shiva Kumar, and Mohamed H. Bakr

Session 34: Wireless Implants for Biomedical Telemetry – 1

34-01 "Towards Batteryless Wearables and Implants"
Wei-Chuan Chen, Brock DeLong, Ramandeep Vilkhu, and Asimina Kiourti

34-02 "Optimizing Scattering Coefficients of Disordered Metamaterials Using the Finite-Difference Time-Domain Method"
Adam Mock and Sheldon Hewlett

34-03 "Dual-Band (2.4/4.8 GHz) Implantable Antenna for Biomedical Telemetry Applications"
John Blauert and Asimina Kiourti

34-04 "An RF-Driven Lightweight Implantable Insulin Pump"
Bingxi Yan, Brock DeLong, Duo An, Asimina Kiourti, Kathleen Dungan, John Volakis, Minglin Ma, and Liang Guo

34-05 "Miniature Implantable Antenna Design for Blood Glucose Monitoring"
Ayesha Ahmed, Masood Ur-Rehman, and Qammer Hussain Abbasi

Session 35: Low Frequency Computational Electromagnetics – 2

35-01 "Field-Plate Length Variation on GaN Devices for BV and On-Resistance Characterization"
Christopher R. Lashway, Alberto Berzoy, and Osama Mohammed

35-02 "Numerical Analysis of Mutual Transient Voltages in Grounding Systems of Offshore Wind Farms"
R. Araneo, G. Lovat, S. Celozzi, and P. Burghignoli

35-03 "Shielding Effectiveness of Finite Width Shields Against Low-impedance Magnetic Near-field Sources"
R. Araneo, G. Lovat, S. Celozzi, and P. Burghignoli

35-04 "CT Eccentricity Error Evaluation Model Based on the Actual Magnetization Curve"
Hao Zhang, Zeyao Huang, Xiao Zhang, and Abd A. Arkadan

35-05 "Field Analysis of a Moving Current-carrying Coil in OMOP Kibble Balances"
S. Li, M. Stock, F. Biesla, A. Kiss, and H. Fang

Session 36: Celebrating 50th Anniversary of Field Computation by Moment Methods

36-01 "Roger Harrington and Shielded Planar Microwave Electromagnetic Analysis"
James C. Rautio

36-02 "HODLR Direct MOM Solver"
John Shaeffer

36-03 "History of Developments Leading to the Method of Moments"
Donald R. Wilton

36-04 "A Novel Stochastic Integral Equation Method for Wireless Communication in Diffuse Multipath Environments"
Shen Lin and Zhen Peng

36-05 "Spectral Element Boundary Integral Method for Rapid and Accurate Simulations of Inhomogeneous Objects in Layered Media in Nanophotonics"
Yiqian Mao, Jun Niu, and Qing Huo Liu

Session 37: Advances in Electromagnetic Modeling by WIPL-D – 1

37-01 "Robust Feed Modeling of the Asymmetric Planar Mesh Dipole-Type Antenna"
Jennifer Rayno and Derek S. Linden

37-02 "Modeling and Validation of a mm-Wave Shaped Dielectric Lens Antenna"
David C. Mooradd, Alan J. Fenn, and Peter T. Hurst

37-03 "Higher Order Mode Analysis in WIPL-D"
J. Lyn Alford and Milos S. Pavlovic

37-04 "Full-Wave Modeling of RF Exciters Using WIPL-D: Road to Real-Time Simulation and Optimization"
Pranav S. Athalye, Branislav M. Notaros, and Milan M. Ilic

37-05 "Efficient Modeling of Towel Bar Antennas Using Model of Distributed Loading Along Wires"
Milos M. Jovicic, Saad N. Tabet, and Branko M. Kolundzija

Session 39: Modeling Electromagnetic Waves in Plasma Environments

39-01 "Whistler Mode Wave Numerical Raytracing in a Finite Temperature Anisotropic Plasma Medium"
Marek Golkowski and Ashanthi Maxworth

39-02 "Spatial Distributions of Magnetospheric Radio Energy due to Lightning"
Austin P. Sousa and Robert A. Marshall

39-03 "FD-PIC Simulation of Broadband Whistler Mode Wave Interactions with Energetic Electrons in the Earth's Radiation Belts"
Poorya Hosseini, Mark Golkowski, and Vijay Harid

39-04 "Particle-In-CellMethods for Modeling Electromagnetic Propagation in Plasmas"
John R. Cary

39-05 "Late-time Instability in Finite Difference Modeling of Very-Low-Frequency Propagation in the Earth-Ionosphere Waveguide"
Robert A. Marshall, Wei Xu, and Austin P. Sousa

39-06 “Simplified FDTD Model of Electromagnetic Wave Propagation in Magnetized Plasma”
Santosh Pokhrel, Varun Shankar, and Jamesina J. Simpson

39-07 “Nonlinear FDTD Modeling of Ionospheric Cross-Modulation Experiments”
Robert C. Moore and Anthony J. Erdman

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41-01 “Monostatic RCS for General Aviation Aircraft”
Dennis W. Richardson, Ruben P. Ortega, and Saad N. Tabet

41-02 “Comparison of Commercial Simulation Performance for Efficient RCS Analysis”
Dongeun Lee, Sung-Hwan Chi, Do-Young Jang, and Han-Kil Jung

41-03 “Polarimetric Weather Radar Calibration by Computational Electromagnetics”
Djordje Mirkovic and Dusan S. Zrnic

41-04 “On Synthetic Aperture Radar Simulations using WIPL-D Pro”
Nimrod Teneh and Branko Lj. Mrdakovic

Session 42: Wireless Implants for Biomedical Telemetry – 2

42-01 “A Wideband Antenna for Biotelemetry Applications: Design and Transmission Link Evaluation”
Ala Alemaryeen and Sima Noghanian

42-02 “Hybrid Power Transfer and Wireless Antenna System Design for Biomedical Implanted Devices”
Reem Shadid and Sima Noghanian

42-03 “Circuitry Design and Magnetic Susceptibility Evaluation of 7T fMRI Implantable RF Coil”
Rong Wang, Celia M. Dong, Ed X. Wu, Robert C. Roberts, and Li Jun Jiang

42-04 “Power Transfer Efficiency for Distance-Adaptive Wireless Power Transfer System”
D.-G. Seo, S.-H. Ahn, J.-H. Kim, W.-S. Lee, S.-T. Khang, S.-C. Chae, and J.-W. Yu

42-05 “Novel Multiband Flamenco Fractal Antenna for Wearable WBAN Off-Body Communication Applications”
Omar Masood Khan, Qamar Ul Islam, Raed M. Shubair, and Asimina Kiourti

42-06 “Multi-Bandwidth CPW-Fed Open End Square Loop Monopole Antenna for Energy Harvesting”
Nermeen A. Eltresy, Dalia M. Elsheakh, and Esmat A. Abdallah

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43-01 “Quantum Electrodynamics of Optical Metasurfaces”
Igor V. Bondarev and Vladimir M. Shalaev

43-02 “Asymmetric Band Structure Calculations Using the Plane Wave Expansion Method with Time-Modulated Permittivity”
Adam Mock

43-03 “Ultra-thin, High-efficiency Mid-Infrared Huygens Metasurface Optics”
Hanyu Zheng, Jun Ding, Li Zhang, Hongtao Lin, Sensong An, Tian Gu, Hualiang Zhang, and Juejun Hu

43-04 “A High-Order Accurate FDTD Scheme for Maxwell's Equations on Overset Grids”
Jordan B. Angel, Jeffrey W. Banks, and William D. Henshaw

43-05 “Challenges and Opportunities in Modeling and Optimization of 3D Optical Metasurfaces”
D. Bruce Burckel, Aaron J. Pung, and Salvatore Campione

43-06 “Inverse Design of Engineered Materials for Extreme Optical Devices”
Sawyer D. Campbell, Danny Z. Zhu, Jogender Nagar, Ronald P. Jenkins, John A. Easum, Douglas H. Werner, and Pingjuan L. Werner

Session 45: Electromagnetic Methods for Devices and Applications – 1

45-01 “Suppression of Anisotropic Birefringence in a Rectangular Waveguide”
Gregory Mitchell

45-02 "Performance Analysis for Linear Minimum Variance Adaptive Beamforming"
Zhitao Yang and Guanglei Zhang

45-03 "The Novel Normalized Method for Interference Suppression at Subarray Level"
Zhitao Yang and Guanglei Zhang

45-04 "The Sidelobe Power Suppression for the Aircraft Circle Phase Array Radar"
Dan Wang

45-05 "Supercapacitor Implementation for PV Power Generation System and Integration"
Tunir Dey, Kowshik Dey, Greg Whelan, and Abdullah Eroglu

45-06 "Design of Dual Band Rectifiers for Energy Harvesting Applications"
Kowshik Dey, Tunir Dey, Rezwan Hussain, and Abdullah Eroglu

Session 46: Wireless Energy Harvesting and Power Transfer

46-01 "A Highly Efficient Miniaturized Microwave Collector for Wireless Power Transmission"
Safiullah Khan and Thomas F. Eibert

46-02 "Harvesting of Aircraft Radar Altimeter Sidelobes for Low-Power Sensors"
Jose Estrada, Philip Zurek, and Zoya Popovic

46-03 "Focused Antenna Arrays for Wireless Power Transfer Applications"
Payam Nayeri

46-04 "A Multi-Linear Polarization Reconfigurable Plus Shaped Dipole Antenna for Wireless Energy Harvesting Applications"
Ami Desai and Payam Nayeri

46-05 "Compact 24GHz Half-slot Antenna for Energy Combining"
M. Aboualalaa, Adel B. Abdel-Rahman, A. Allam, Ramesh K. Pokharel, Kuniaki Yoshitomi, and H. Elsadek

46-06 "Analysis of Two/Four Coils WPT Systems for Embedded PLC Communications"
Sami Barmada and Mauro Tucci

Session 47: Integral Equation Solvers for Real-Life Applications – 1

47-01 "On the Conforming Combination of the Electric and Magnetic Field Integral Equations"
Ahmet F. Yilmaz and H. Arda Ulku

47-02 "Coupled EM-Structural Analysis in Convected Coordinates"
Daniel S. Weile, David A. Hopkins, and Brian M. Powers

47-03 "A Study of Near-Field Imaging and Diagnostic Applications of Surface Equivalent Current Methods"
Arslan Azhar, Thomas F. Eibert, and Li Li

47-04 "Mode Analysis of Waveguides in Layered Media"
Aytac Alparslan

47-05 "Scattering Analysis of Silver Nanoparticles for Solar Cell Applications using Integral Equations"
Ismail Enes Uysal, Huseyin Arda Ulku, Oguz Gulseren, and Hakan Bagci

47-06 "An FFT-Accelerated Inductance Extractor for Voxelized Structures"
Abdulkadir C. Yucel, Ioannis P. Georgakis, Athanasios G. Polimeridis, Hakan Bagci, and Jacob K. White

Session 48: Computational Nanophotonics: Advanced Numerical Methods and Applications – 2

48-01 "Versatile Nanoparticle Manipulation with Designer Thermoplasmonic Metasurface"
Justus C. Ndukaife

48-02 "Time Domain Modeling of Active Materials"
Shaimaa I. Azzam, Ludmila J. Prokopeva, and Alexander V. Kildishev

48-03 "Coupling Electron Transport with Maxwell Equations for Modelling Optically Tunable Photonic Elements"
Michael Povolotskyi, Ludmila Prokopeva, and Alexander Kildishev

48-04 "Efficient Multiphysics and Multiscale FDTD Methods for Terahertz Plasmonic Devices"
Shubhendu Bhardwaj

48-05 "Frequency-Domain versus Time-Domain Analysis of Slow-light Mesophotonic Waveguides: Theoretical Insights for Practically Realizable Devices"
Stavroula Foteinopoulou

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49-01 "Estimation of 1090 MHz Signal Environment on Airport Surface by using Multilateration System"
Junichi Honda, Yasuyuki Kakubari, and Takuya Otsuyama

49-02 "A Novel Compact Microstrip Bandstop Filter (BSF) Using Spurline & Stepped-Impedance Resonator (SIR)"
Hamad G. Alrwuili and T. S. Kalkur

49-03 "High-density Compact Chipless RFID Tag for Item-level Tagging"
Ayesha Habib, Hafsa Anam, Yasar Amin, and Hannu Tenhunen

49-04 "Design Method for Wide-Beam Waveguide Antenna"
Chong-Hwan Park, Seung-Real Ryu, Jae-Yoon Shin, Dong-Su Choi, and Jong-Myung Woo

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50-01 "Recent Developments in the Application of Contactless Inductive Flow Tomography"
Matthias Ratajczak, Thomas Wondrak, and Frank Stefani

50-02 "Simulation Model to Predict EM Scattering due to Different Parameters of Dust/Sand Storms"
Sharif Iqbal Mitu Sheikh and Mahfuz Ullah

50-03 "Examination on a Self-Mixing Circuit"
Congying Chen, Adalbert Beyer, Winfried Simon, Rudiger Follmann, Peter Waldow, and Dominique Schreurs

Session 51: Integral Equation Solvers for Real-Life Applications – 2

51-01 "Circulant Preconditioning in the Volume Integral Equation Method for Nanophotonics"
Samuel Groth, Jacob White, and Athanasios Polimeridis

51-02 "On Complexity Reduction in Solution of Scattering Problems on Well-Conducting 3D Objects With Surface-Volume-Surface EFIE"
Jamiu Mojolagbe, Reza Gholami, and Vladimir Okhmatovski

51-03 "Linear-Complexity Direct Integral Equation Solver with Explicit Accuracy Control for Large-Scale Interconnect Extraction"
Miaomiao Ma and Dan Jiao

51-04 "Optical Couplers for Sharply Bended Nanowires: Sensitivity to Coupler Nanoparticles"
Askin Altinoklu and Ozgur Ergul

51-05 "Analytical Evaluation of Matrix Elements of Electromagnetic Integral Equations with RWG basis Functions for Arbitrarily Oriented Pairs of Triangular Surface Elements"
Elizabeth Bleszynski, Marek Bleszynski, and Thomas Jaroszewicz

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Qi Zeng, Jingshen Liu, Jianfeng Zheng, Tom Lloyd, Leonardo M. Angelone, Wolfgang Kainz, and Ji Chen

52-02 "Hyperthermia Study in Cancer Treatment"
H. F. Guarnizo Mendez, J. J. Pantoja, and M. A. Polochè Arango

52-03 "Co-simulation of a Reactor Assisted by Microwaves"
Carlos Rivera, John J. Pantoja, and Felix Vega

Session 54: Tunable RF Filters

54-01 "Simulation and Fabrication of BST FBAR Resonator"
Abdulhamid Matoug, Daw Asderah, and T. S. Kalkur

54-02 "A Tunable Microstrip Bandstop Filter Using Compact Spiral Folded Spurline For RF Microwave Systems"
Hamad G. Alrwuili and T. S. Kalkur
54-03 "A Balanced Dual-Band Tunable Bandpass Filter"
Dubari Borah and Thottam S. Kalkur
54-04 "UHF-Band Bandpass Filters With Fully-Reconfigurable Transfer Function"
Dakotah J. Simpson, Roberto Gómez-García, and Dimitra Psychogiou

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Sebastian Hegler, Klaus Wolf, Christoph Statz, Niels Neumann, and Dirk Plettemeier
55-02 "Design of a Cost-Effective Analog Lock-In Amplifier Using Phase Sensitive Detector"
Fardin Humayun, Riasat Khan, Shatil Saadman, and Rezwanul Haque
55-03 "The Novel Adaptive Method for Interference Suppression"
Zhitao Yang and Guanglei Zhang
55-04 "Advanced Subspace Projection Method for Interference Suppression in Phase Array Radar"
Zhitao Yang and Guanglei Zhang
55-05 "The Adaptive Interference Suppression Method Based on Householder at Subarray Level"
Dan Wang and Guanglei Zhang

Session 56: Parallel and GPU EM Comput
56-01 "Massively Parallel Frequency Domain Electromagnetic Simulation Codes"
William L. Langston, Joseph Kotulski, Rebecca Coats, Roy Jorgenson, S. Adam Blake, Salvatore Campione, Aaron Pung, and Brian Zinser
56-02 "The Parallel Implementation and Accuracy of Matrix Compression in the Method of Moments code EIGER"
Joseph D. Kotulski
56-03 "HIPERCONE FDTD: Vectorized Highly Scalable Full-Wave Electromagnetic Solver"
Sergei Belousov, Sergey Khilkov, Vadim Levchenko, Anastasia Perepelkina, and Ilya Valuev

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Bahadir Kilic, Taha Imeci, Oguzhan Salih Gungor, Mustafa Imeci, Negar Majidi, and Mohammad Rahim Sobhani
57-02 "Design of a Quad Element Patch Antenna at 5.8 GHz"
Negar Majidi, Goksen Goksenin Yaralioglu, Mohammad Rahim Sobhani, and Taha Imeci
57-03 "Design and Analysis of a Bandpass Hairpin Filter"
Rafsan Ahmed, Shpetim Emiri, and S. Taha Imeci
57-04 "Microstrip Patch Antenna with Triangular Slits"
Anil Elakas, Gurhan Ali Imrak, Mert Sencan, S. Taha Imeci, and Tahsin Durak
57-05 "Circular Shaped Microstrip Patch Antenna at 14.6 GHz"
Furkan Atalah, Mustafa Imeci, Oguzhan Gungor, S. Taha Imeci, and Tahsin Durak
57-06 "E-Shaped Patch Antenna at 4.87 GHz"
Ezgi Kucuk, Burak Bayram, S. Taha Imeci, and Tahsin Durak
57-07 "Roof Shaped Rectangular Slotted Patch Antenna at 18.3 GHz"
Melis Ecem Koca, Tahsin Durak, and S. Taha Imeci

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59-01 "Effect of Random Antenna Element Displacements on Sparse-UCA-Root-MUSIC Direction-of-Arrival Estimation"
Veronique Inghelbrecht, Jo Verhaevert, Tanja Van Hecke, Dries Vande Ginste, Hendrik Rogier, Marc Moeneclaey, and Herwig Bruneel
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Troy Butler

59-03 "Accurate and Efficient Bayesian Parameter Inversion Based on Low-Fidelity Model Solutions"
Yaning Liu

59-04 "Multi-Fidelity Approach for Polynomial Chaos Based Statistical Analysis of Microwave Networks"
Aditi K. Prasad and Sourajeet Roy

59-05 "Augmented Surrogates for Predictive Extrapolation in Electromagnetics"
Varis Carey

59-06 "Vector Parabolic Equation Modeling of Wireless Propagation in Tunnels with Statistically Rough Surface Walls"
Xingqi Zhang and Costas D. Sarris

59-07 "Ridge Approximation and Dimension Reduction for an Acoustic Scattering Model"
Paul G. Constantine, Jeffrey M. Hokanson, and Drew P. Kouri

59-08 "Wavelet Model of Multivariate Prior Covariance"
Aime Fournier

Session 60: Numerical Methods for Analysis, Design and Measurement of Antennas – 2

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Kyle Patel, Robert Jones, and Atef Elsherbeni

60-02 "Efficient Modeling of Antennas with Finite Conductivity using Calderon Preconditioning"
Michiel Gossye, Dries Vande Ginste, Daniel De Zutter, and Hendrik Rogier

60-03 "Domain Decomposition Method for Scattering from an Aircraft with Jet Engine Inlet Cavity"
Miodrag Tasic, Branko Kolundzija, and Tomislav Milosevic

60-04 "Improved Shaping of Reflector Antennas using a New Minimax Initialization Strategy"
Anders Eltved, Martin S. Andersen, and Oscar Borries

60-05 "Fast and Rigorous Method for Solving Low-Frequency Breakdown in Full-Wave Finite-Element-Based Solution of General Lossy Problems"
Li Xue and Dan Jiao

60-06 "Design and Optimization of Two-Dimensional Nano-Arrays for Beam Steering"
Askin Altinoklu, N. Rasoolzadeh, and Ozgur Ergul

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61-01 "Pattern Synthesis of Irregular Antenna Arrays with Small Element-Counts"
Robert P. Scheeler, James L. McDonald, Arian C. Lalezari, and Joseph R. Mruk

61-02 "The General Sidelobe Cancellation Based on Linear Minimum Variance at Subarray Level"
Dan Wang and Guanglei Zhang

61-03 "Design Concepts for Broadband Antenna Arrays with Constant Half-Power Beamwidth"
Christopher Gay, Matthew Cullen, and Dimitra Psychogiou

61-04 "Comparison of an Isotropic Point Source and a Spherically Distributed Antenna Array"
Kristopher Buchanan, Timi Adeyemi, Carlos Flores-Molina, Sara Wheeland, and Steven Weiss

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May 2, 2018

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Yours Sincerely,

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