ENGINEERING

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**Annual Report on AFOSR/AFRL COE: Science of Electronics in Extreme Electromagnetic Environments**

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Program Managers: Arje Nachman (AFOSR), Timothy Clarke (AFRL)

Principal Investigator: Edl Schamiloglu

## ABSTRACT

This AFOSR/AFRL-funded Center of Excellence is led by the University of New Mexico with the University of Maryland a partner. This report summarizes progress in Year 5. Dr. Pat Roach is organizing a virtual review for AFOSR in June.

## University of New Mexico

The research tasks that are being investigated are listed below and brief updates are provided for each of them.

**1. Microcontroller Investigations** – Over the past reporting period, we have continued our research effort into understanding the impact of EEMI pulses on the software execution of instructions on an elementary microcontroller. In the last year we demonstrated a relationship between the onset and width of the incident EEMI pulse with respect to the natural clock-cycle timing of the microcontroller and developed a probabilistic model using conditional probabilities to show the probability that a software script, comprising a series of different instruction cycles, will successfully execute/be affected due to EEMI injection. Building up on this research accomplishments, this year, we have demonstrated the impact of machine pipelining architectures and augmented our probabilistic model to include pipelined architectures, which is more relevant to microcontroller architectures today. In addition, we showed a correlation in the susceptibility response of different types of instructions that belong to specific class of instruction cycles (memory, ALU, data operations) and its impact on creating reproducible and predictable outcomes in register contents.

For future work, leveraging our results in reproducibly and predictably altering register contents, we are now studying how EEMI glitching can affect random number generators with its implication for predictably changing the "randomness" of random generators, thereby promising exciting avenues in leveraging EEMI to affect/compromise cyber security software routines.

**2. CMOS Injection Experiments** – The focus of our research activity in the past year was to develop a predictive model for RF injection in data transmission digital systems. The new model predicts and characterizes the impact of Electromagnetic Interference (EMI) on the quality of data transmission, namely eye-diagram parameters. We found that the impact of RF injection on eye height depends primarily on the level of injected noise and its frequency, whereas the width of the eye depends not only on the level of injected noise and its frequency, but it also depends heavily on the bit rate of the data transmission. We also developed a preliminary model for bit-error-rate (BER) as a function of the eye-diagram parameters.

In support of our CMOS injection investigations we have developed an analytical model for the probability of occurrence of out-of-bounds input voltage—and consequent output voltage error—in a CMOS inverter making an output transition at some random instant during the presence of n greater than or equal to 1 complete cycles of a sinusoidal additional voltage induced on the inverter input (nMOSFET and pMOSFET gates) by an external sinusoidal electromagnetic disturbance. This represents well the practical case of such an EMI disturbance occurring randomly in time with respect to a digital circuit performing software execution.

Future Work: Unfortunately, our experimental measurements to verify our predictive models for data transmission (eye diagram) was interrupted due to CoVID-19 pandemic outbreak. Our immediate next step is to continue our experiments to validate our newly developed predictive models for the eye-diagram and BER.

**3. First-Principles Mathematical Model for the Statistical Wave Analysis of Antennas and Electronics in Complicated Enclosures** – The research work by UNM CEM group Year 5 is centralized around first-principles mathematical and statistical model for information transmission in complex multipath environments. The work extends our stochastic Green's function theory and algorithms from confined systems to complex scattering environments. In this work, we exploit scientific advances in chaotic dynamics and chaos theory for the statistical analysis of information transmission. The emphasis is placed on spatial/spectral variance and correlation in the ray-chaotic propagation. The results lay down the theoretical foundation for analyzing channel capacity, coherence bandwidth, and power delay spread in indoor wireless communication. The theoretical research is validated through representative experiments.

We also investigated a space-time building block methodology for efficient time-domain analysis of multi-scale, locally periodic structures. By leveraging the principles of linear superposition and space-time causality in wave physics, the 4D simulation domain is represented by a few space-time building blocks, which are constructed upon 3D spatial unit cell and 1D time unit. The work results in novel time-evolution schemes, which exhibit high-order accuracy and achieve concurrency and parallelism in both spatial and temporal dimensions. The outcomes lead to significantly reduced computational resources. The capability and benefit of proposed algorithms are illustrated through representative applications.

**4. Investigate EEMI Effects on Optoelectronics through Multi-Physics Analysis – Redirect Effort**

**Note:** With the departure of Yang Shao to the University of Illinois, this task has been taken over by Drs. Sameer Hemmady and Payman Zarkesh-Ha.

Project description: Although optical devices seem to be resilient to electromagnetic interference (EMI), electro-optical devices that are the interface between electrical and optical systems (e.g. optical modulators) can be vulnerable to EMI. The focus of this research work is to analyze the impact of EMI on a commercial optical modulator and then develop an extended predictive model to characterize the impact of EMI on the behavior of any generic optical modulator. The model will be verified by experimental setup and measured data in an electro-optical link under RF injection. This project has just started and is expected to produce the predictive model verified by experimental data in the next reporting period.

**5. Photonic Interconnects and Future Devices** – Effects of EEMI on single photon emitters (collaboration between Professor Balakrishnan's group and Professor Waks' group at UMD).

The focus of the effort this year was to develop quantum dots at specific wavelengths that would suit the characterization equipment at the University of Maryland. Specifically, the effort was focused on achieving quantum dots that emitted in the detector and laser specific wavelength and to do this an offset in the emission wavelength had to be achieved at room temperature since the measurements are done at cryogenic temperatures. An attempt was made achieving both short wavelength quantum dots which emitted below one 1 µm and long wavelength quantum dots which emitted about 1300 nm. These are both non-trivial issues since InAs quantum dots typically emit in the 1100-1300 nm wavelength range and to achieve emission outside of this range requires significant epitaxial optimization. While achieving the shorter wavelength quantum dot was more challenging, the longer wavelength dots were successfully demonstrated, and samples were sent to the University of Maryland for processing and device demonstration. In the coming year we expect to grow a whole ensemble of such quantum samples with additional complexity added to the epitaxial process including features such as distributed drag reflectors.

**6. Research Framework for Uncertainty Quantification and Investigate the Origin of "Randomness" in EEMI Interaction with Electronic Devices and Software Processes –**

We have continued to develop and refine an analytic model to compute the stochastic drain-source current through a single MOSFET as a consequence of (possibly) simultaneously stochastic gate-source and drain-source voltages, and to compute as well for that MOSFET the probability of its functional failure as a consequence of such stochastic gate and drain voltages.

**7. Effects on Software Execution –** During the last year we have made advances in two areas: i) Developing a Hamilton-Jacobi equation for evaluating the effects of EEMI – in this work, we developed a theoretical framework for modeling the empirically observed cascading of software failures on a complicated computing system exposed to EEMI. Our approach is to treat the temporal evolution of the electromagnetic coupling and the resultant cascading series of electromagnetic-induced faults as the "flow" in a dynamic fluid-mechanical system and thereby utilize aspects of the Navier Stokes and Hamilton-Jacobi equations to predict the rate of this flow. Therefore, inspired by the concepts of fluid dynamics, we include a diffusion term in the Hamilton-Jacobi-Isaacs (HJI) equation. We have considered two approaches. In one we apply a Taylor expansion to the optimality principle and consider additional terms; in the other scenario, we simply add a diffusion term in the form of a Laplacian applied to the cost function $H(x, \ldots)$ and some constant c, as it is present in the Navier-Stokes equation for incompressible flow. We found numerical comparisons for both approaches with respect to the original HJI equation where the dynamical vector field corresponds to analytical models of a NOR logic gate. This model is a second-order differential equation that describes the behavior of the gate that incorporates a new term accounting for EEMI injection. ii) Developing a simplified flip-flop gate model for EEMI injection – we developed a second order dynamical system to represent the behavior of a D flip-flop. We employed windowing functions and vector fields to replicate a characteristic found in earlier work, which resorts to switching. The model also takes into account metastable behavior, which can be exploited when studying software execution faults due to an undefined logical state. We conceived the noise injection to be additive noise targeting the transition between the stable equilibrium points. However, the model is flexible, and many parameters can be changed to alter its behavior. We are in the process of acquiring empirical data to validate this work.

**Personnel Supported**

**Faculty:** Balakrishnan, Dietz, Heileman (U. Arizona), Hemmady, Peng (U. Illinois), Schamiloglu, Shao, and Zarkesh-Ha

**PostDocs:** S. Addamane

**Students:** S. Lin, E. Dohme, J. Chen, M. Vitovsky, L. Valbuena, N. Sule, Z. Abidi, S. Wang

**UNM Publications – Journals**

1. S. Lin, Z. Peng and T. Antonsen, "A Stochastic Green's Function for Solution of Wave Propagation in Wave-Chaotic Environments," IEEE Trans. Antennas Propag., early access, DOI: 10.1109/TAP.2019.2963568.

2. S. Wang, Y. Shao and Z. Peng, "A Parallel-in-Space-and-Time Method for Transient Electromagnetic Problems," IEEE Trans. Antennas Propag., vol. 67, no. 6, pp. 3961-3973, June 2019.

3. N.H. Sule, Z. Abedi, E. Schamiloglu, Fellow, S. Hemmady, and P. Zarkesh-Ha, "Predictive Modeling of Non-Persistent Effects in MOSFET Response under Large Signal Gate Noise Injection," IEEE Trans. Electromag. Compat. (accepted and to appear 2020).

4. R. Bilalic, D. Guillette, M. Landavazo, M. Martinez-Ramon, S. Hemmady, and E. Schamiloglu, "A Novel Application of Machine Learning Methods to Model Microcontroller Upset due to Intentional Electromagnetic Interference (IEMI)," submitted to IEEE Trans. Electromag. Compat. (2020).

5. J.M. Chen, S. Portillo, G. Heileman, G. Hadi, R. Bilalic, M. Martinez-Ramon, S. Hemmady, and E. Schamiloglu, "Time-Varying Radiation Impedance of Microcontrollers and its Dependence on Software Instruction," submitted to IEEE Trans. Electromag. Compat. (2020).

6. D. Dietz, "Stochastic Drain Current Through a MOSFET as a Consequence of Simultaneously Stochastic Gate and Drain Voltages—Part I: Model Formulation," submitted to IEEE Trans. Electromag. Compat. (2020).

7. D. Dietz, "Probability of Output Voltage Error in a CMOS Inverter Undergoing Stochastic State Transition During the Presence of an Extraneous Input Voltage," submitted to IEEE Trans. Electromag. Compat. (2020).

8. H. Ahmed and V. Babicheva, "Nanostructured Tungsten Disulfide $WS_2$ as Mie Scatterers and Nanoantennas," MRS Advances, 1-8. doi:10.1557/adv.2020.173.

**UNM Publications – Conference Papers**

1. S. Wang and Z. Peng, "A Novel Space-Time Building Block Methodology for Transient Electromagnetic Analysis," 28th Conference on Electrical Performance of Electronic Packaging and Systems, Montreal, Canada, October 2019 (*Best Paper Award*).

2. S. Lin, Z. Peng, E. Schamiloglu, Z.B. Drikas, and T. Antonsen, "A Novel Statistical Model for the Electromagnetic Coupling to Electronics inside Enclosures," 2019 IEEE International Symposium on Electromagnetic Compatibility, Signal & Power Integrity, New Orleans, Louisiana, USA, July 2019 (*IEEE EMC Symposium Best Paper Award*).

3. S. Lin and Z. Peng, "Physics-Oriented Statistical Analysis of Information Transmission in Wave-Chaotic Environments," IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting (2019 IEEE AP-S/USNC-URSI), Atlanta, Georgia, USA, July 2019 (*Honorable Mention Award in Student Paper Competition*).

4. O. Noakoasteen, S. Wang, and Z. Peng, "Physics-Informed Deep Neural Networks for

Transient Electromagnetic Analysis," 2019 IEEE MTT-S International Conference on Numerical Electromagnetic and Multiphysics Modeling and Optimization, Boston, USA, May 2019 (*3rd place in Best Student Paper Competition*).

5. S. Wang, B. Mackie-Mason, and Z. Peng, "Platform-Aware In-Situ Antenna and Metamaterial Analysis and Design," 2019 International Applied Computational Electromagnetics Society (ACES) Symposium, Miami, Florida, USA, April 2019 (*Best Student Paper Award*).

6. Z. Abedi, S. Hemmady, T. Antonsen, E. Schamiloglu, and P. Zarkesh-Ha, "Electromagnetic Compatibility in Leakage Current of CMOS Integrated Circuits," Proceedings 2019 International Symposium on Electromagnetic Compatibility (EMC Europe 2019) (Barcelona, Spain, September 2-6, 2019), 765- 768.

7. L. Valbuena, G.L. Heileman, S. Hemmady, and E. Schamiloglu, "Simplified Flip-Flop Gate Model for EEMI Injection," Proceedings ICEAA 2019 (Granada, Spain, September 09-13, 2019), 845-850.

8. L. Valbuena, G.L. Heileman, S. Hemmady, and E. Schamiloglu, "Diffusion Term in a Hamilton-Jacobi Equation to Evaluate EEMI Propagation in a Computing System," Proceedings ICEAA 2019 (Granada, Spain, September 09-13, 2019), 851-856.

9. M. Vitkovsky, T.M. Antonsen, Jr., E. Schamiloglu, and S. Hemmady, "Predictive Modeling of Erroneous Software Behavior in Embedded Digital Systems Due to Extreme Electromagnetic Interference," Proceedings ICEAA 2019 (Granada, Spain, September 09-13, 2019), 1304-1307.

10. H. Ahmed and V.E. Babicheva, "Resonant and Scattering Properties of Tungsten Disulfide $WS_2$ Nanoantennas," Proc. SPIE 11289, Photonic and Phononic Properties of Engineered Nanostructures X, 112891R (26 February 2020).

**Awards and Recognition**

- 2019 "Physics-Oriented Statistical Analysis of Information Transmission in Wave-Chaotic Environments" received honorable mention award at 2019 IEEE AP-S Student Paper Competition (Shen Lin and Zhen Peng).
- 2019 3rd place in the student paper competition, "Physics-Informed Deep Neural Networks for Transient Electromagnetic Analysis," 2019 IEEE MTT-S International Conference on Numerical Electromagnetic and Multiphysics Modeling and Optimization, Boston, USA, May 29-31, 2019 (Oameed Noakoasteen, Shu Wang, and Zhen Peng).
- 2019 1st place in the student paper competition – "Platform-Aware In-situ Antenna and Material Analysis and Design," 2019 International Applied Computational Electromagnetics Society (ACES) Symposium, Miami, Florida, USA, April 14-18, 2019 (Shu Wang, Brian MacKie-Mason, and Zhen Peng).
- 2019 Best paper award at IEEE 28th Conference on Electrical Performance of Electronic Packaging Systems (EPEPS) – "A Novel Space-Time Building Block Methodology for Transient Electromagnetic Analysis" (S. Wang and Z. Peng).
- 2019 IEEE EMC Symposium Best Paper Award – "A Novel Statistical Model for the Electromagnetic Coupling to Electronics Inside Enclosures" (Shen Lin, Zhen Peng, Edl Schamiloglu, Zachary B. Drikas, and Thomas Antonsen).
- 2020: Sameer Hemmady, awarded Albuquerque's Forty under 40 award, for his contributions to shaping Albuquerque's STEM community.
- Payman Zarkesh-Ha 2019: Outstanding Teacher Award, Department of Electrical & Computer Engineering, University of New Mexico
- Payman Zarkesh-Ha 2019: STC.UNM Creativity Award
- Edl Schamiloglu 2019: STC.UNM Creativity Award
- Edl Schamiloglu 2019: IEEE Nuclear and Plasma Sciences Society's 2019 Magne "Kris"

Kristiansen Award for Contributions to Experimental Nuclear and Plasma Science (Inaugural Recipient)

**UNM Students Who Graduated**

- None

## University of Maryland

**8. Photonic Interconnects and Future Devices** – Our group has been working on integration of photonics and efficient light sources for robust optical interconnects that are insensitive to EM interference. In this phase of the project we have been exploring two approaches. The first is based hybrid integration of III-V semiconductors with Si, which combines the most promising material for light emission with the most scalable optical platform. This project is a collaboration with Dr. Ganesh Balakrishnan, who is providing MBE growth of materials using his state-of-the-art MBE capabilities. In this phase of the project we have successfully integrated quantum dots with a silicon photonic on-chip filter based on a ring resonator. The filter is compact and requires only 10 um footprint, making ideally suited for compact and scalable integration. We showed that the filter could efficiently route light with narrow bandwidth, and further improvements could fast switchable filters that are suitable for high efficiency wavelength and time-division multiplexing. In the second approach, we worked with another promising material platform, thin-film lithium niobate. This emerging material combines the high electro-optic coefficient of lithium niobate with the efficient optical emission of rare-earth ions, which serve as the core technology for fiber amplifiers, the primary workhorses of the internet. This combination enables compact on-chip light emitters that can serve as sources for optical interconnects and transmit data at high bandwidths. This year, for the first time, we have demonstrated integration of rare-earth ions with thin-film lithium niobate. We showed that implanting RE ions in to thin-film LN does not degrade their properties, making them suitable for on-chip light emission.

**9. Efficient Statistical Model for Predicting Electromagnetic Wave Distribution in Coupled Enclosures** – The Random Coupling Model (RCM) has been successfully applied to predicting the statistics of currents and voltages at ports in complex electromagnetic (EM) enclosures operating in the short wavelength limit. Recent studies have extended the RCM to systems of multi-mode aperture- coupled enclosures. However, as the size (as measured in wavelengths) of a coupling aperture grows, the coupling matrix used in the RCM increases as well, and the computation becomes more complex and time consuming. A simple Power Balance Model (PWB) can provide fast predictions for the averaged power density of waves inside electrically-large systems for a wide range of cavity and coupling scenarios. However, the important interference induced fluctuations of the wave field retained in the RCM are absent in PWB. We have combined the best aspects of each model to create a hybrid treatment and studied the EM fields in coupled enclosure systems. The proposed hybrid approach provides both mean and fluctuation information of the EM fields without the full computational complexity of coupled-cavity RCM. We compared the hybrid model predictions with experiments on linear cascades of over-moded cavities. We found good agreement over a set of different loss parameters and for different coupling strengths between cavities. The range of validity and applicability of the hybrid method was tested and discussed.

**10. Wireless Power Distributions in Multi-Cavity Systems at High Frequencies** – A possible way to incorporate site-specific information in EM propagation analyses without reverting back to full-wave solvers, which are far too costly given that typical distances are orders of magnitudes smaller than the wavelength, is using full ray-tracing computations. Ray tracing is efficient as long as the number of possible reflections taken into account is small, but may become inefficient in reverberant environments. Recently, a mesh-based ray-tracing solver called *Dynamical Energy*

*Analysis* (DEA) has been developed. It approximates wave energy transport using energy flow equations written in terms of so-called linear transfer operators, formulated as a boundary integral equation computing power fluxes through interfaces. DEA provides an efficient numerical approximation of these operators in matrix form and can be formulated on computational meshes, such as provided by Finite Element (FE) meshes in two and three dimensions. The advantages compared with standard ray-tracing are that the complexity of the environment (due to complex boundaries) is fully modeled as part of the mesh and multiple reflections can be accounted for by iterations of the linear operator. The size of the DEA mesh is independent of frequency and allows for large variations in cell size.

We analyzed the usefulness of the DEA methodology compared with standard ray tracing methods, but also compared to full FE methods and simplified power balance relations, offering an example of multiply connected and open indoor environments.

**11. Coherent Perfect Absorption on a Network** – We have experimentally demonstrated coherent perfect absorption (CPA) in the complex network system with and without time-reversal symmetry. Importantly, the proposed platform, based on a complex network design, is reconfigurable, allows one to directly harvest the output signal, and demonstrates 99.99+% absorbance efficiency. On the fundamental level, based on a standard model of wave chaos, our platform can inspire studies of CPAs in complex/chaotic systems where traditional tools from semi-classics and Random Matrix Theory can be utilized for the design of efficient CPA traps. We expect that this work will motivate practical applications, including designing extremely efficient absorbers/detectors, enabling practical long-range wireless power transfer, developing secure communication links, and associated high-efficiency energy conversion systems. Our work creates a new paradigm for CPA and opens many new opportunities to exploit this concept for both fundamental and practical directions.

**12. Nanoscale Device Level Modeling of EMI Induced Vulnerability** – We are investigating the vulnerability of electronics to EMI at the small circuit, device (transistor) and sub-device level. These vulnerabilities can lead to both Soft Errors and Hard Failures. The Soft Error is due to bit flips and system latch-ups that can be corrected by re-booting. The Hard Failure is a permanent damage to the individual devices (transistors), which are mainly Metal-Oxide Semiconductor Field Effect Transistors (MOSFETs); the EMI-related Hard Failures can degrade or even destroy the operability of the circuit. For Soft Errors, we study the internal mechanisms within a MOSFET that can be activated by transient high-level EMI disruptions, including impact ionization and the Snapback phenomenon. For Hard Failures, we focus our investigation on MOSFET gate oxide damage and rupture, due to high voltages and thermal effects.

**Soft Error:** Our earlier works on Soft Errors included device-level simulation and analysis of the impact ionization effect, which is significantly enhanced/worsened by high terminal voltages and high internal fields caused by transient EMI disruptions; as well as the parasitic bipolar-junction transistor (BJT) structure, which is occurring by the MOSFET design, but only activated under extreme conditions together with the impact ionization effect. These device-level phenomena can drastically change the affected transistor's input-output relations, e.g. abnormal, exponential current amplification and even locking the device into erroneous states, and that eventually cause circuit-level abnormal events that may need rebooting to remove.

In the past year, we studied several aspects of the issue. We conducted experimental tests using MOSFET devices to verify the underlying theories, and realistic data for further analysis and modeling. The experiments confirmed our expectation that depending on specific device geometrical and electrical structures, Soft Error may occur under high-voltage disruptions, while the physical MOSFET structure is unharmed or only minimally degraded. We established the theoretical foundations and a workflow for compact modeling. The compact model covers the structural information from device designs (e.g. oxide thickness, doping profile, gate length), and reduces the underlying physical mechanisms into simplified input-output relations, which are ideal for higher-level simulations involving multiple transistors. We devised a model extraction technique that is suitable for our analytical, circuit-level Soft Error model, which can be incorporated with both experimental and computational data. The extraction technique is based on a heuristic-search algorithm which suitable, for not only the proposed Soft Error model, but also various extraction tasks involving closed-form equations that are not easily differentiable or optimizable. In the upcoming year, we will demonstrate a working example of extracting a compact circuit-level model from device-level data. The supposed model can be applied in SPICE simulations by circuit designers to evaluate the EMI-related Soft Error vulnerabilities.

**Hard Failure from Dielectric Breakdown:** The gate terminal dielectric is a key structure in MOSFET devices, which insulates the carrier flow from the source to drain by applying the gate terminal voltage. They are extremely thin (in modern, advanced devices, they can be only a few nanometers thick) and vulnerable to EMI, as they can easily be ruptured by EMI-induced voltages between the electrodes. The damage to the gate dielectric is usually unrecoverable, and hence can cause Hard Failures in circuits.

One way to describe and model the damage to the dielectric, or oxide breakdown (BD), is by using the bond breaking process, which is treated as a chemical reaction that requires the presence of electrons in the gate dielectric, which is normally an insulator, and can further be accelerated by the oxide field (from the applied gate voltages and enhanced by EMI disruptions) and the lattice (or electronic device) temperature (which can be affected by Joule heating from the EMI disruptions). In the past year, we have developed a computer program that takes the device structure (gate dielectric properties, thickness, doping profile, etc.) as well as applied terminal voltage as inputs, and simulates the penetration of electron wavefunctions into the insulating dielectric, indicating the presence of conduction electrons in the gate oxide, which should ideally by a pure dielectric. The simulation also showed that depending on the applied gate voltage, the amount of electron penetration could vary from minimal to significant, which could determine the speed of the device degradation, or equivalently, the lifetime before a permanent BD event. The existence and change of wavefunctions is believed to be instant, so transient EMI disruptions may lead to different consequences than constant stress. We will continue to collect more simulation data while improving the methodologies. Together with the chemical reaction-based theory, we will derive a modeling technique to describe the BD progress in a circuit simulation environment and under transient EMI conditions.

**Personnel Supported**

**Faculty:** Antonsen, Ott, Anlage, Waks, Goldsman

**Students:** T. Cai, S. Aghaeimeibodi, Z. Luo, F. Adnan, C. Darmody, Z. Cui, S. Ma, S. Chandra, T. Ghutishvili, S. Banik, M. Rahaman, S. Dutta, L. Chen

**Publications**

1. S. Dutta, E.A. Goldschmidt, S. Barik, U. Saha, and E. Waks, "Integrated Photonic Platform for Rare-Earth Ions in Thin Film Lithium Niobate," Nano Letters, vol. 20, 741-747 (2020).

2. J-H. Kim, S. Aghaeimeibodi, J. Carolan, D. Englund, and E. Waks, "Hybrid Integration Methods for On-Chip Quantum Photonics," Optica, vol. (2020) .

3. S. Aghaeimeibodi, C-M. Lee, M. Atabey Buyukkaya, C.J.K. Richardson, and E. Waks, "Large Stark Tuning of InAs/InP Quantum Dots," Appl. Phys. Lett., vol. 114, 071105 (2019) .

4. S. Aghaeimeibodi, J-H. Kim, C-M. Lee, M. Atabey Buyukkaya, C. Richardson, and E. Waks, "Silicon Photonic Add-Drop Filter for Quantum Emitters," Optics Express, vol. 27, 16882–16889 (2019).

5. B. Addissie, J. Rodgers, and T. Antonsen, “Extraction of the Coupling Impedance in Overmoded Cavities,” Wave Motion, vol. 87, 123-131, (2019).

6. M. Zhou, E. Ott, T.M Antonsen Jr., and S.M Anlage, “Scattering Statistics in Nonlinear Wave Chaotic Systems,” Chaos, vol. 29, 033113 (2019).

7. S. Ma, B. Xiao, Z. Drikas, B. Addissie, R. Hong, T.M Antonsen, E. Ott, and S.M Anlage, “Wave Scattering Properties of Multiple Weakly Coupled Complex Systems,” Phys. Rev. E, vol. 101, 22201 (2019).

8. S. Lin, Z. Peng and T. Antonsen, “A Stochastic Green’s Function for Solution of Wave Propagation in Wave-Chaotic Environments,” IEEE Trans. Antennas Propag., early access, DOI: 10.1109/TAP.2019.2963568.

9. S. Ma, S. Phang, Z. Drikas, B. Addissie, R. Hong, V. Blakaj, G. Tanner, T.M. Antonsen, E. Ott, and S.M. Anlage, “Efficient Statistical Model for Predicting Electromagnetic Wave Distribution in Coupled Enclosures” arXiv preprint arXiv:2003.07942.

10. S. Ma, B. Xiao, R. Hong, B. Addissie, Z. Drikas, T. Antonsen, E. Ott, and S. Anlage, “Classification and Prediction of Wave Chaotic Systems with Machine Learning Techniques,” arXiv preprint arXiv:1908.04716

11. F. Adnan, V. Blakaj, S. Phang, T.M. Antonsen, S.C. Creagh, G. Gradoni, and G. Tanner, “Wireless Power Distributions in Multi-Cavity Systems at High Frequencies, submitted to Proc. R. Soc. A (2020).

**Conference Papers**

1. S. Anlage, S. Ma, S. Phang, Z. Drikas, B. Addisie, R. Hong, V. Blakaj, G. Gradoni, G. Tanner, T. Antonsen, and E. Ott, “Efficient Hybrid Model of Field and Energy Flow in Interconnected Wave Chaotic Systems,” Bull. Amer. Phys. Soc., W25.00004 (2020).

2. S. Ma, T. Antonsen, E. Ott, S. Chandra, and S. Anlage, “Experimental Realization of Reservoir Computing with Wave Chaotic Systems,” Bull. Amer. Phys. Soc., M34.00009 (2020).

3. M. Vitkovsky, T.M. Antonsen, Jr., E. Schamiloglu, and S. Hemmady, “Predictive Modeling of Erroneous Software Behavior in Embedded Digital Systems Due to Extreme Electromagnetic Interference,” Proceedings ICEAA 2019 (Granada, Spain, September 09-13, 2019), 1304-1307.

4. G. Gradoni, T.M. Antonsen, and E. Ott, “Influence of Multi-Path Fading on MIMO/OAM Communications,” Proceedings ICEAA 2019 (Granada, Spain, September 09-13, 2019), 1230-1230.

5. S. Lin, Z. Peng, E. Schamiloglu, Z.B. Drikas, and T. Antonsen, “A Novel Statistical Model for the Electromagnetic Coupling to Electronics inside Enclosures,” 2019 IEEE International Symposium on Electromagnetic Compatibility, Signal & Power Integrity, New Orleans, Louisiana, USA, July 2019 (*IEEE EMC Symposium Best Paper Award*).

6. S. Phang, S. Ma, S.C. Creagh, G. Gradoni, S.M. Anlage, D.W.P. Thomas, T. Antonsen, and G. Tanner, “High-Frequency Electromagnetic Coupling Calculation Using the Dynamical Energy Analysis by Discrete Flow Method,” 2019 ESA Workshop on Aerospace EMC (Aerospace EMC, Budapest, Hungary, May 20-22, 2019) 1-6.

7. S. Aghaeimeibodi, C. Lee, M. Buyukkaya, A. Karasahin, J. Kim, C. Richardson, and E. Waks, “Integrated Quantum Photonic Circuits with Quantum Dots,” IEEE Photonics Conference (San Antonio, TX, October 2019).

8. S. Aghaeimeibodi, B. Desiatov, J.H. Kim, C.M. Lee, M.A. Buyukkaya, A. Karasahin, C.J. Richardson, R.P. Leavitt, M. Lončar, and E. Waks, “Integration of Quantum Emitters with

Lithium Niobate Photonics," CLEO: QELS_Fundamental Science (San Jose, CA, May 2019), FM1M-3.

9. S. Aghaeimeibodi, C.M. Lee, M. Buyukkaya, C. Richardson, and E. Waks, "Large Stark Tuning of InAs/InP Quantum Dots," APS March Meeting (Boston, MA, March 2019), V24.010.

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