March 31, 2019

RESEARCH

University of New Mexico

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. We have identified that there is a relationship between the onset and width of the incident EEMI pulse, and the natural clock-cycle timing of the microcontroller. By studying this relationship further, we have shown that there are regimes where this ascribed relationship varies with the type of instruction being executed. We attribute these regimes to be software-instruction-cycle dependent. We have 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. Experimentally, we have demonstrated this clock-cycle-to-EEMI relationship utilizing a FPGA board and an elementary microcontroller. In addition, we have also demonstrated that such effects can occur for RF injections as well. For future work, we are studying the dependence on register contents and whether it has an impact on this relationship. Finally, all our experimental results this year have focused on clock-side EEMI injection. While we attempted to also study power supply-side EEMI injection, our experimental attempts this year have not been successful due to the inherent capacitance of the PCB that houses the microcontroller. We propose to develop new low-capacitance PCBs in this coming year and continue our research on power-supply-side EEMI injection.

2. CMOS Injection Experiments – The focus of our research activity in the past year was to complete high frequency response models for RF injection in a single device as well as inverter gate which were fabricated through MOSIS in the first year of the COE effort. We successfully demonstrated that our frequency response models for various RF injection scenarios fit very well with experimental data. In addition to this effort, and to continue our investigation on other impacts of RF injection, we have also developed a new analytical model that predicts and characterizes the impact of Electromagnetic Interference (EMI) on the leakage current of CMOS integrated circuits. We found that the impact of RF injection on leakage current is the leakage current is very sensitive to the RF injection power. For example, a small (340 mV or 0.6 dBm) of peak noise can increase the leakage current by factor of 1000. This work was done in collaboration with Prof. Thomas Antonsen at UMD. We have also initiated time-domain experiments to characterize the signal integrity of CMOS inverter chains due to RF injection on the input and supply terminals. In addition, we are also investigating nonlinear characterization of NMOS/PMOS devices due to RF injection.
Future Work: Upon completion of our predictive modeling of linear high frequency response of CMOS devices, we will focus on experimental and mathematical modeling of non-linear high frequency responses. In addition, we will also look into other aspects of RF injections, including data transmission in inverter chain as well as frequency of ring oscillators that have already been fabricated in our test chips. We will utilize the data from our ongoing time-domain and nonlinear characterization experiments to develop high frequency models for CMOS upset.

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 4 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.

Electromagnetic field theory provides the fundamental physics of wireless communications. Over the past decades, electromagnetic theory has played a significant role in the design, performance assessment, and deployment planning of wireless devices and systems. Meanwhile, military and civilian communication and sensor systems are expected to take place in increasingly congested, contested, and competitive environments. Among many other scenarios, communication in wave-chaotic environments is a topic of both fundamental and practical importance. Applications include indoor radio channels, dense urban cells, transmission through diffusive random media, and disordered media, etc. A key challenge emerging is to understand the governing physics of propagation channels in wave-chaotic environments, which is critical for the characterization and assessment of information transmission.

Based on the stochastic wave models we investigated in Years 1-3, the Year 4 research presents a novel mathematical/statistical model analyzing the information transmission in multipath, chaotic environments. It rigorously characterizes the antenna mutual coupling, and resolves the transmitting, propagation, and receiving correlations in the wave propagation. Such model does not appear to be available in the literature. The work has diverse applications to wireless experimentation, time-reversal experiments, wavefront shaping, and sensing and targeting.

4. Investigate EEMI Effects on Optoelectronics through Multi-Physics Analysis – In Year 3, we studied the EEMI effect on laser diode electric characteristics with various injected RF currents. We proposed three models to predict the laser diode’s current-voltage (I-V) curve for (1) small RF injection current, (2) large RF signal analysis, and (3) large RF injection currents at high frequencies. This year we continue to work on predictive models to analyze EEMI effect on Vertical-Cavity Surface-Emitting Lasers (VCSELs) behaviors.

Compared to conventional edge-emitting semiconductor lasers, VCSEL is a type of laser diode that its laser beam emits perpendicular from the top surface. There are several advantages of using VCSELs. Edge-emitters cannot be tested until the end of the production process, while VCSELs can be tested at several stages throughout the process to check if it’s function correctly. Because VCSELs emit from the top surface, it’s suitable for monolithic one-dimensional and two-dimensional integration. VCSEL’s applications include optical computer mice, fiber optic communications, laser printers, face identification units, smart glass, etc.

Typical VCSELs have relatively severe heating and so it has strong thermally dependent electrical and optical parameters. Beside considering the electric characteristics for laser diodes, we need to consider important effects including light versus current characteristics and its thermal dependence. The goal of the research is to investigate a compact optoelectronic predictive model to characterize VCSELs behavior with RF injections through multi-physics analysis.

VCSELs’ electrical, optical and thermal characteristics are measured under various injected continuous wave (CW) currents at different DC bias. Measurement results show that the RF current at high power level significantly affects the cut-off voltage and I-V curve of the laser.
From the measured current-light (I-L) curves, we observe the effect of carrier leakage at high power RF current injections, which shows by the optical output power roll over and then complete turn-off of the laser.

We have developed a rate-equation-based thermal predictive model to analyze the VCSEL behavior. The model introduced a temperature dependent offset current to account for carrier leakage in the active region.

1. It can be used to predict VCSELs’ electrical, thermal and optical characteristics respect to different input current, voltage, light output and ambient temperature.

2. The predictive model can accurately model the light output power turns on, rolls over and turns off when injected current increases in the measurement data.

3. It also predicts significant reduction in the maximum output power and slope efficiency when the ambient temperature increases.

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).

Prior to this year, we were able to successfully realize single photon emission from InAs nanostructures (quantum dots and quantum dashes) around telecom wavelengths of 1.3 and 1.55 µm. During this year, we focused on increasing the efficiency of transmission and control of photons by integrating the single photon sources with a photonic crystal and distributed Bragg reflectors (DBRs). This is a critical step towards fabricating practical quantum systems which in turn will lead the way to understanding the effects of EEMI on single photon emitters. Towards this goal, multiple quantum dot-based samples were grown using molecular beam epitaxy (MBE) at UNM. In order to be compatible with existing characterization equipment, the emission wavelength of the quantum dots was to be tuned to 900-1000 nm at 4 K. After exploring multiple options (submonolayer QDs, GaSb QDs, QDs on metamorphic buffers), we chose to grow InGaAs QDs due to the ease of tuning emission wavelength by changing the InxGa1-xAs composition. The samples were then shipped to Prof. Waks’ group at UMD for optical characterization and further processing. With these results, we intend to be able to fabricate on-demand single photon emitters and then study the effect of EEMI on these devices.


We are continuing to develop analytic models to compute the stochastic signal propagation time delays through collections of CMOS inverters resulting from a stochastic power supply V\text{dd} driving the inverter gates or resulting from a stochastic external electromagnetic disturbance inducing voltages on those gates; and to compute as well the probability of failure, as a consequence of such gates’ voltages, of any digital circuit employing such inverters. We have this year completed this development for a pair of CMOS inverters for the general case when the \( V_{\text{dd}} \) on the two inverter gates are not necessarily (but may be) statistically independent and have completed a manuscript detailing this work for submission in Year 5. We have also further progressed on the extension of our models to any number of CMOS inverters. Also, in Year 5 we will continue that extension as well as begin to investigate stochastic behavior of CMOS logic gates formed via combinations of inverters, as a consequence of stochastic \( V_{\text{dd}} \).

In a separate but related effort we have developed 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; we have completed a manuscript detailing this work for submission in Year 5.
7. Effects on Software Execution – During the last year we have focused on completing essential dynamics modules of the predicting hybrid automata model, that is, we have worked on formulating a tractable model for the (data) flip-flop gate. This model is derived from a study on the metastability of first order flip-flops and it is combined with concepts of artificial potential fields and window(ing) functions. This flip-flop model has been conceived under the premise of avoiding the “curse of dimensionality” present on the approaches studied about calculation of backwards/forwards reachable sets. We have the model implementation done in MATLAB but we are currently migrating it to T-Spice.

We have conducted the analysis of backwards reachability on the available (realistic) models for the inverter and NOR gate. We have found that the time propagation is very small (~3 orders of magnitude) compared with the period of the clock signal. This has motivated us to look for a different Hamilton-Jacobi equation that involves more phenomena. The original form of the Hamilton-Jacobi equation only has a convection term. We believe that the inclusion of a convection term could provide more insight. We are making the implementation on a common toy model to have comparison material.

We have also been identifying critical modules for each of the instructions of the 4-bit simulated processor to establish the regions inside the set of all the trajectory orbits that deters the instruction to be executed. We will call these collections of subset as $S$. Now we have all the models that we need. Then, for some software execution path $P$ and a $P'$, we employ a particular element of $S$ depending on the difference between $P$ and a $P'$, and execute the calculation of backward/forward reachable sets.

University of Maryland

8. Photonic Interconnects and Future Devices

Photonic interconnects using low dimensional materials (Waks group): Coupling single photon emitters to surface plasmons provides a versatile ground for on chip quantum photonics. However, achieving good coupling efficiency requires precise alignment of both the position and dipole orientation of the emitter relative to the plasmonic mode. We demonstrate coupling of single emitters in the 2-D semiconductor, WSe2 self-aligned with propagating surface plasmon polaritons in silver-air-silver, metal-insulator-metal waveguides. The waveguide produces strain-induced defects in the monolayer which are close to the surface plasmon mode with favorable dipole orientations for optimal coupling. We measure an average enhancement in the rate of spontaneous emission by a factor of 1.89 for coupling the single defects to the plasmonic waveguide. This architecture provides an efficient way of coupling single photon emitters to propagating plasmons, which is an important step towards realizing active plasmonic circuits on chip.

Plasmonic nanostructures provide an efficient way to control and enhance the radiative properties of quantum emitters. Coupling these structures to single defects in two-dimensional materials provides a particularly promising material platform to study emitter–plasmon interactions because these emitters are not embedded in a surrounding dielectric. They can therefore approach a near-field plasmonic mode to nanoscale distances, potentially enabling strong light–matter interactions. However, this coupling requires precise alignment of the emitters to the plasmonic mode of the structures, which is particularly difficult to achieve in a site-controlled structure. We present a technique to generate quantum emitters in two-dimensional tungsten diselenide coupled to site-controlled plasmonic nanopillars. The plasmonic nanopillar induces strains in the two-dimensional material, which generate quantum emitters near the high-field region of the plasmonic mode. The electric field of the nanopillar mode is nearly parallel to the two-dimensional material and is therefore in the correct orientation to couple to the emitters. We demonstrate both an enhanced spontaneous emission rate and increased brightness of emitters.
coupled to the nanopillars. This approach may enable bright site-controlled nonclassical light sources for applications in quantum communication and optical quantum computing.

9. Combining the Finite Element Method (FEM) and the Random Coupling Model (RCM) for Quasi 2D Cavities

The Random Coupling Model (RCM) is a method for making statistical predictions of induced voltages and currents for objects and components contained in complicated (ray-chaotic) over-moded enclosures and subjected to RF fields. On the other hand, the Finite Element Method (FEM) is a widely used computational method that solves the wave equations numerically. We showed a combination of the two methods where we considered an aperture backed by a wave chaotic cavity. The FEM gridding is usually required for the entire geometry. But in this work, we showed that one can grid the region close to the aperture while rest of the cavity can be modeled by the RCM. We modeled a quasi 2D cavity with an aperture. This was done in the commercial software HFSS. Perfectly Matched Layers (PMLs) were placed on one side of the aperture, while on the other side the boundary was treated as a port and the fields were represented in modes.

We determined numerically the power through the aperture without simulating the entire cavity, only the aperture. The influence of the cavity was be described by the RCM. In particular, the scattering matrix relating the modes on the cavity side of the aperture were simulated by the RCM. We excited the cavity side of the aperture with each of the 25 modes and recorded the far field patterns at the PML. We then used these profiles and the principle of reciprocity to find the current on the port for an incident plane wave from outside the cavity and found the admittance matrix on the aperture side of the port. This allowed us to calculate the power coupled into the cavity for various types of cavities.

10. Statistics of Fields in Nonlinear Wave Chaotic Systems

Nonlinearity in electromagnetic systems is manifested as harmonic generation and amplitude dependent responses. We studied the statistics of harmonics excited by a source in a nonlinear wave system by adding an active frequency multiplier to the 1/4-cavity microwave billiard. To create amplitude dependent responses, we introduced different sources of nonlinearity into the cavity. Observing nonlinearity usually requires that we be in the high amplitude regime, hence a high power vector network analyzer (VNA) is implemented to measure the S- parameters up to ~+40 dBm.

We showed the results of the nonlinear S- parameters in two nonlinear systems. One system is a diode-loaded 1/4-bowtie microwave cavity where the diode acts as a point nonlinearity in a wave chaotic system. By attaching the diode to the excitation port, we observed the statistics of the impedance change substantially with the excitation power. We also found that the short orbits between the port and a nearby wall were strongly modified. Other unexpected changes were also observed. We found that many of these changes were due to the fact that the admittance of the diode changes with the excitation power. The nonlinear diode competes with the cavity admittance, substantially altering the response of the system. By implementing the lossy port model extension of the RCM, the results were well explained by the changing radiation efficiency of the diode-loaded port. This configuration may have potential application in protecting electronic circuits from EMI.

Another source of nonlinearity in microwave billiards is the nonlinear surface impedance $Z = R + iX$ of a material on the interior surface of the cavity. In particular we considered nonlinear superconducting materials coating the walls of a cavity. A cut-circle quasi-2D microwave cavity, which is made of Pb-plated copper, can present nonlinear boundary conditions at temperatures $T < T_c$, where $T_c = 7.2$ K. We have previously characterized the linear response properties of this
extremely low loss system \((\alpha = 0.02)\) at 6.6 K using an in-situ broadband cryogenic calibration technique. By putting the cavity in a dilution refrigerator, the base temperature reached 500 mK, allowing us to enter a strongly nonlinear regime. The power dependent S-parameters showed that the cavity has a mainly resistive nonlinear response. The quality factor, \(Q\), of many of the modes decreased as input power increased.

Applying the RCM, we found that the impedance statistics also changed with power. The results of this analysis may give insight into the statistical properties of generic nonlinear systems. Furthermore, as a complement to the nonlinear resistive superconducting billiard, we also proposed an experiment on a TiN-coated Si wafer cut-circle billiard, where the TiN superconducting films are reported to have a dominant nonlinear reactive response.

11. Wave Chaotic Properties of Cascaded Complex Enclosures

The RCM predicts the statistical properties of waves inside a cavity by using Random Matrix Theory and also incorporating system specific features, which can be determined by structure dimensions and material properties. Previously, studies of 2-port single cavity experiments have been conducted. Statistical properties, such as the probability density function of the impedance matrix elements were in good agreement with RCM predictions.

Since arranging full sized cavities \((-1m^3\) per cavity) is difficult in regular-sized rooms, we used the scaling relationship from Maxwell’s equations to obtain a scaled-down in-size cavity system, while preserving the loss parameter of the full-scale cavity. Experiments showed that the statistics of the single cavity two-port impedance matrix elements for full scale and scaled enclosures that have the same loss parameter matched with each other.

We next studied the transmission properties for a multi-cavity cascade system. The cavities were connected by circular or rectangular shaped apertures. We studied the trans-impedance and the input impedance of the cavity system. To model these quantities, we used the RCM to characterize the single cavities within the cavity-cascade chain. To establish the theory for connected cavities, we adopted the theory proposed by Gradoni et al., that characterizes an aperture by an admittance matrix based on expansion of fields in modes of the aperture cross section. This approach is still being tested, and results are being compared with those of other theories.

12. Assessing the Effects of RF Interference on Maintenance of Coherence of a Group of Drones

The Kuramoto model, originally motivated by the dynamics of many interacting oscillators, has been used and generalized for a wide range of applications involving the collective behavior of large heterogenous groups of dynamical units whose states are characterized by a scalar angle variable. One such application in which we are interested is the alignment of velocity vectors among members of a drone swarm. Despite being commonly used for this purpose, the Kuramoto model can only describe swarms in 2 dimensions, and hence the results obtained do not apply to the often-relevant situation of swarms in 3 dimensions. Partly based on this motivation, we studied the Kuramoto model generalized to D dimensions, focusing on the 3-dimensional case. We show that in 3 dimensions, as well as for all odd dimensionality, the generalized Kuramoto model for heterogenous units has dynamics that are remarkably different from the dynamics in 2 dimensions. In particular, for odd D the transition of the time asymptotic equilibrium state to coherence occurs discontinuously as the coupling constant \(K\) is increased through zero, as opposed to the D=2 case (and, as we will showed, also the case of even D) for which the transition to coherence occurs as \(K\) increases through a positive critical value \(K_c\). In addition, we have shown that the effect on our model of interfering RF noise is to lower \(K\), and, based on the previous result, this might be expected to have a more dramatic effect on two-dimensional swarm coherence as compared with three-dimensional coherence.
13. Graph Treatment of Electromagnetic Topology

The problem of understanding how electromagnetic waves couple to and propagate through complex structures such as buildings, aircraft, and ships is very challenging. A number of approaches have treated the problem in terms of scalar energy flow through interconnected compartments. These methods ignore wave effects (e.g., interference), and therefore provide only a mean-field description of energy distribution. We want to extend these approaches by including wave propagation effects and interference to understand deviations from the mean.

Quantum graphs provide a setting to formulate a more complete model of energy propagation in complex structures. Such graphs are a natural outcome of the electromagnetic topology approach. There is a hope that the statistical properties of wave and energy distribution on these graphs can be understood using an approach based on the RCM.

We employed an experimental setup consisting of a microwave coaxial cable network. The networks, which were large compared with the wavelength of excitations, were constructed from coaxial cables connected by T junctions. The distributions of impedance values from an ensemble of tetrahedral networks were measured. The RCM was applied in an attempt to uncover the universal statistical properties of the experimental data obtained from this system. Deviations from RCM predictions were observed in that the statistics of diagonal and off-diagonal impedance elements were different. It is argued that because of the small size of the networks used here there will be deviation from random matrix predictions.

We have extended these simple microwave networks by replacing the T-junctions with quasi-two-dimensional microwave cavities that display wave chaotic properties. This models realistic scenarios in which overmoded enclosures are interconnected through multiple ports, including cables, apertures and waveguides (ducts). We will next relate the results of these experiments to the general question of how to estimate induced voltage statistics on electronics deep inside a network of complex enclosures.

14. Nanoscale Device Level Modeling of EMI Induced Vulnerability

Vulnerability of modern nanoscale and microscale electronics to EMI is being investigated. The investigation has focused on the key elements of Silicon CMOS device vulnerability. The most common electronic devices are metal oxide silicon field effect transistors (MOSFETs), which represent approximately 99% of the semiconductor transistors in operation today. Most integrated circuits are composed of MOSFETs. Our work focus entails studying and quantifying the vulnerability of MOSFETs to EMI, with respect to both soft and hard error. Soft errors typically cause devices to malfunction, which in turn give rise to circuit errors and system crashes. These errors are not permanent and typically require a system reboot. Hard errors are permanent and occur when nanoscale devices are permanently damaged causing circuit failure. We have been focusing our attention on three likely mechanisms of failure that can result due to EMI induced voltage spikes that can propagate as unintended input onto MOSFET terminals. Two of these mechanisms are oxide dielectric breakdown and thermal breakdown, which are typically permanent effects. We are also looking at EMI induced internal voltage spikes as another mechanism which lead to soft error, especially the snap-back and latch-up phenomena. Our earlier work on these mechanisms was largely theoretical where we developed distributed and lumped device and circuit models to help explain the phenomena. At the device level, we solve the Semiconductor Partial Differential Governing Equations to quantify what occurs internally to the MOSFET device if an EMI-induced voltage spike occurs on one of its terminals. The spike will generate a large internal electric field, which can cause impact ionization and even avalanche multiplication giving rise to very large internal current densities, and therefore unstable internal voltage levels, and Joule heating. We have developed methodologies to model all of these phenomena with the goal of not only explaining the events but have predictive capabilities as
To help verify and improve our model development, as well as to gain additional insight, we have devoted considerable time to developing experiments to induce these device effects on the laboratory bench. Specifically, we have designed and fabricated numerous silicon MOS devices using the nanofabrication cleanroom facility at the University of Maryland. Since we made the devices ourselves, we have detailed knowledge of the internal structure, which removes guesswork from the input of our simulations. In addition, since we have the fabrication capability, we can design new devices of different geometry to calibrate the EMI-induced effects. Using our bench setup for testing the effects of voltage spikes on the MOSFET devices that we fabricated, we have been focusing on hard error due to dielectric breakdown where data indicates that oxide fields of 8MV/cm are required.

In the future, more data will be taken, and the mechanisms of failure resulting from large terminal voltage spike application will be simulated to verify models with experimental data. Device structures will be varied to help determine how EMI vulnerability is affected by MOSFET geometry and feature size.