Université d'Ottawa
Faculté de génie

École de science informatique
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University of Ottawa
Faculty of Engineering

School of Electrical Engineering
and Computer Science

Nonlinear Microwave Devices and Effects

ELG 6369

Mustapha C.E. Yagoub

2023 Fall Term

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Course Description

The physical basis and mathematical modelling of a variety of microwave/millimetre-wave devices, (some of which exhibit the most extreme nonlinear behaviour known), how they can be exploited in practical circuits and systems, and how the resulting device/circuit interactions can be analyzed.

Devices include two-terminal nonlinear-resistance elements (varistors) and two two-terminal nonlinear-reactance devices (varactors) based on classical, heterostructure and superconducting technologies: pn and Schottky-barrier diodes, tunnel and resonant-tunneling diodes, BIN and BNN varactor diodes, single-barrier-varactor diodes, high-electron-mobility varactor diodes, Josephson- junction diodes, and SIS quasiparticle tunneling junctions.

Three-terminal nonlinear devices include MESFETs, HBTs, and HEMTs and RHETs.

Circuit applications encompass direct radiation detectors; frequency mixers; resistive, reactive, and active frequency multipliers; as well as reactive and regenerative frequency dividers. Emphasis will be placed on analytical approaches that provide global insight into the nonlinear phenomena.

Course Timetable

The students are invited to regularly check the course timetable.

TA Information

The TAs for the course are

Mohamad Al-Sabbagh	contact: malsabba@uottawa.ca	(in charge of the assignments)
Mamady Kebe	contact: mkebe2@uottawa.ca	(in charge of the projects)

Further Information

The course is mainly based on the following textbooks:

- J.C. Pedro, D.E. Root, J. Xu, L.C. Nunes, *Nonlinear Circuit Simulation and Modeling: Fundamentals for Microwave Design*, Cambridge University Press, 2018.
- G.D. Vendelin, A.M. Pavio, U.L. Rohde, *Microwave Circuit Design Using Linear and Nonlinear Techniques*, Hoboken, NJ: Wiley, 2005.
- F. Giannini, G. Leuzzi, *Nonlinear Microwave Circuit Design*, Chichester, England: Wiley, 2004.
- I. Bahl, P. Bhartia, *Microwave Solid State Circuit Design*, Chichester, England: Wiley, 2003.
- S.A. Maas, *Nonlinear microwave and RF circuits*, Norwood, MA: Artech House, 2003.

General and Specific Learning Outcomes

Marking Scheme:

Project ([a])	*(To be submitted through Brightspace)*		40 %
Report **([b])**	(80%)	**Due on Nov. 16**	
Presentation file (PowerPoint)		**Due on Nov. 21**	
Presentation **([c])**	(20%)	**Nov. 23-Nov. 30**	
Assignment ([d])	*(To be submitted through Brightspace)*		20 %
Report + simulations **([e])**		**Due on Nov. 09**	
Take-home final exam ([f])	*(To be submitted through Brightspace)*		40 %

([a]) The project is an individual work.

Please select a topic from the list provided in the sub-section “Project” (Self-registration on Brightspace).

- Note that self-registration will be open from September 1 to September 20.
- Procedure (Brightspace): In the top navigation bar, click on “Groups” (if it is not visible, click on the More drop-down menu). You will then see the title “Project” and empty spaces with one (01) member per group.
- After the self-registration deadline, the system will automatically close and therefore, fill the empty slots.

([b]) The report should address all the items listed in the sub-section “Project”.

Do not forget to submit a signed declaration of integrity (form available at the end of this document)

([c]) The students should present their work, followed by a period of questions.

([d]) The assignment is an individual work.

Please select a topic from the list provided in the sub-section “Assignment” (Self-registration on Brightspace).

- Note that self-registration will be open from September 1 to September 20.
- Procedure (Brightspace): In the top navigation bar, click on “Groups” (if it is not visible, click on the More drop-down menu). You will then see the title “Assignment” and empty spaces with one (01) member per group.
- After the self-registration deadline, the system will automatically close and therefore, fill the empty slots.

([e]) The report should address all the items listed in the sub-section “Assignment”.

The submitted simulation files should include only the final schematics/simulations files/data.

Do not forget to submit a signed declaration of integrity (form available at the end of this document)

([f]) The final exam is a take-home exam.

Do not forget to submit a signed declaration of integrity (form available at the end of this document)

Course contents

PART I – DEVICE MODELING

1 - CAD for microwave engineers: A review

- Introduction to the concepts of linearity and non-linearity.
- Problem statement.
- Foundations of nonlinearities in circuit theory.
- Effects of nonlinearities in circuit theory.

2 - Nonlinear active microwave devices: Nonlinear modeling

- Introduction to microwave active devices.
- Device modeling: approaches and challenges.
- Two-terminal devices: Diodes.
- Three-terminal nonlinear devices: Transistors.
- Four-terminal devices: Dual-gate FETs.

PART II – CIRCUIT DESIGN

1 – Circuit analysis and optimization

- Introduction to microwave circuits.
- Analysis of linear and nonlinear circuits.
- Time- and frequency-domain analysis methods.
- Hybrid analysis methods.
- Harmonic-balance.

2 – Non-linear circuit design

- Amplifiers.
- Frequency multipliers.
- Oscillators and harmonic generators.
- Mixers.

3 – Appendix: Filters

Course Format

All notes required for this course will be posted on Brightspace.

Note that part of the course could be conducted online. Information on the course material used online will be available to students through Brightspace.

Students must regularly consult this support (Brightspace) during the regular session. Attendance is compulsory.

Project

Please select one device (on Brightspace) from the list below (non-exhaustive list):

P-1. Gunn Diodes – Equations and models for linear/nonlinear performance.

P-2. Gunn Diodes – Different types. Advantages/limitations, areas of applications, Examples of circuits in which they are mainly involved, frequency band of operation.

P-3. PIN Diodes – Equations and models for linear/nonlinear performance.

P-4. PIN Diodes – Different types. Advantages/limitations, areas of applications, Examples of circuits in which they are mainly involved, frequency band of operation.

P-5. SRD Diodes – Equations and models for linear/nonlinear performance.

P-6. SRD Diodes – Different types. Advantages/limitations, areas of applications, Examples of circuits in which they are mainly involved, frequency band of operation.

P-7. IMPATT Diodes – Equations and models for linear/nonlinear performance.

P-8. IMPATT Diodes – Different types. Advantages/limitations, areas of applications, Examples of circuits in which they are mainly involved, frequency band of operation.

P-9. Schottky Diodes – Equations and models for linear/nonlinear performance.

P-10. Schottky Diodes – Different types. Advantages/limitations, areas of applications, Examples of circuits in which they are mainly involved, frequency band of operation.

P-11. Varactor Diodes – Equations and models for linear/nonlinear performance.

P-12. Varactor Diodes – Different types. Advantages/limitations, areas of applications, Examples of circuits in which they are mainly involved, frequency band of operation.

P-13. Tunnel Diodes – Equations and models for linear/nonlinear performance.

P-14. Tunnel Diodes – Different types. Advantages/limitations, areas of applications, Examples of circuits in which they are mainly involved, frequency band of operation.

P-15. RTD Diodes – Equations and models for linear/nonlinear performance.

P-16. RTD Diodes – Different types. Advantages/limitations, areas of applications, Examples of circuits in which they are mainly involved, frequency band of operation.

P-17. TRAPATT Diodes – Equations and models for linear/nonlinear performance.

P-18. TRAPATT Diodes – Different types. Advantages/limitations, areas of applications, Examples of circuits in which they are mainly involved, frequency band of operation

P-19. HBT Transistors – Equations and models for linear/nonlinear performance.

P-20. HBT Transistors – Different types. Advantages/limitations, areas of applications, Examples of circuits in which they are mainly involved, frequency band of operation.

P-21. MESFET Transistors – Equations and models for linear/nonlinear performance.

P-22. MESFET Transistors – Different types. Advantages/limitations, areas of applications, Examples of circuits in which they are mainly involved, frequency band of operation.

P-23. MOSFET Transistors – Equations and models for linear/nonlinear performance.

P-24. MOSFET Transistors – Different types. Advantages/limitations, areas of applications, Examples of circuits in which they are mainly involved, frequency band of operation.

P-25. HEMT Transistors – Equations and models for linear/nonlinear performance.

P-26. HEMT Transistors – Different types. Advantages/limitations, areas of applications, Examples of circuits in which they are mainly involved, frequency band of operation.

P-27. FinFET Transistors – Equations and models for linear/nonlinear performance.

P-28. FinFET Transistors – Different types. Advantages/limitations, areas of applications, Examples of circuits in which they are mainly involved, frequency band of operation.

P-29. GaN on SiC Transistors – Equations and models for linear/nonlinear performance.

P-30. GaN on SiC Transistors – Different types. Advantages/limitations, areas of applications, Examples of circuits in which they are mainly involved, frequency band of operation.

Topics not listed above can also be proposed by the students as long as they are related to the course contents (please contact the professor for more details).

List of tasks to complete:

PLEASE do some preliminary research on the topic you wish to work on before formally selecting it. This will save you from dealing with a subject for which you would not have the necessary information to successfully complete it.

- For the "Equations and models for linear/nonlinear performance" topics:

  i. Part 1: Introduce the selected device.

  ii. Part 2: Perform an exhaustive state-of-the-art of the device modeling approaches.
  Introduce and explain the physical structure(s) of the device.
  Link between physical and electrical parameters/components.
  Introduce and explain its small-signal (linear) electrical equivalent model(s).
  Discuss the linear equations that govern its small-signal model(s).
  Compare between the existing topologies/models of the linear equivalent circuit(s), if any, in terms of reliability, complexity to model/use, frequency of operation, method(s) of parameter values extraction … Summarize your conclusions in a table.
  Explain the linear electrical behaviour of the device.

  iii. Part 3: Introduce and explain its large-signal (nonlinear) electrical equivalent model(s).
  Discuss the nonlinear equations that govern its large-signal model(s).
  Compare between the existing topologies/models of the nonlinear equivalent circuit(s), if any, in terms of reliability, complexity to model/use, frequency of operation, method(s) of parameter values extraction … Summarize your conclusions in a table.
  Explain the nonlinear electrical behaviour of the device.

  The project report **should be** based on a solid state-of-the-art literature review. Each statement should be clearly supported by solid reference(s). Similarly, each step/claim **should be** supported by detailed calculations and/or solid references.

- For the "Different types. Advantages/limitations, areas of applications, Examples of circuits in which they are mainly involved, frequency band of operation" topics:

  i. Part 1: Introduce the selected device.

  ii. Part 2: Perform an exhaustive state-of-the-art of the device.
  Introduce its variants, if any, define their behaviour, and compare their respective advantages and disadvantages. Summarize your conclusions in a table.
  Compare the selected device performance vs. similar replacement devices.

  iii. Part 3: For each variant, discuss its areas of application.
  Discuss the circuits in which such device(s) is(are) used.
  Explain in detail their operation and the way the device(s) is(are) used.
  Highlight the main parameters that justify the use of such device(s) vs. similar ones. Summarize your conclusions in a table.

  The project report **should be** based on a solid state-of-the-art literature review. Each statement should be clearly supported by solid reference(s). Similarly, each step/claim **should be** supported by detailed calculations and/or solid references.

Do not forget to submit a signed declaration of integrity (form available at the end of this document)

Assignment

The aim is to simulate a transistor from Excelics.

Please select one device (on Brightspace) from the list below (non-exhaustive list):

Datasheets available on Brightspace (downloaded from www.alldatasheet.com)

A-1. EFA018A
A-2. EFA025A
A-3. EFA040A
A-4. EFA060B
A-5. EFA080A
A-6. EFA120A
A-7. EFA120B
A-8. EFA160A
A-9. EFA240B
A-10. EFA240D
A-11. EFA480B
A-12. EFA480C
A-13. EFA720A
A-14. EFA960B
A-15. EFA1200A
A-16. EPA018A

A-17. EPA025A

A-18. EPA040A

A-19. EPA060A

A-20. EPA060B

A-21. EPA080A

A-22. EPA090A

A-23. EPA120A

A-24. EPA120B

A-25. EPA160A

A-26. EPA240B

A-27. EPA240D

A-28. EPA480B

A-29. EPA480C

A-30. EPA720A

A-31. EPA960B

A-32. EPA1200A

List of tasks to complete:

i. Implement the small-signal equivalent circuit using the data files provided on Brightspace.
ii. From the small-signal equivalent circuit, plot the I-V curves of the device.
iii. Explain and justify the obtained curves.
iv. Plot the S-parameters. Compare with the S-parameters data provided in the datasheets.
v. Explain and justify the discrepancies, if any.
vi. Implement the large-signal equivalent circuit using the files provided on Brightspace.
vii. From the large-signal equivalent circuit, plot the I-V curves of the device.
viii. Explain and justify the obtained curves. Compare the two sets of I-V curves you plotted.
ix. Plot the S-parameters. Compare with the S-parameters data provided in the datasheets.
x. Explain and justify the discrepancies, if any.

The simulations incorporated in the report **should include** a screen capture of the simulation **as well as** the corresponding results. The simulation setup should be explained, and the results obtained discussed. Name the related simulation file according to the figure in the report (see below).

- Attach **all** files used in the assignment (Simulation files, Excel files …).
- Name each file according to its first use in the report (e.g., figure #1, #2 ….).

Do not forget to submit a signed declaration of integrity along with your assignment/exam/report document (form available at the end of this document)

Software facilities

Any EM design can be achieved using one of the following commercial simulators:

· Ansoft-HFSS (Available but with limited number of licences)
· Ansoft-designer. A free student version is downloadable at

http://www.ansoft.com/about/academics/ansoftdesignersv/index.cfm

· Momentum-ADS (available at any EECS Solaris host)

· Sonnet-Lite. A free version is downloadable at

http://www.sonnetusa.com/products/lite/

· Sonnet-em, full version (available at ELEMENT lab)

Any RF design can be achieved using one of the following commercial simulators:

· Keysight-ADS (available at any EECS Solaris host).
· Cadence

Note that the software licenses are from CMC and can be run only from Canada.

Plagiarism

Beware of academic fraud!

Academic fraud is an act by a student that may result in a false evaluation (including papers, tests, examinations, etc.). It is not tolerated by the University. Any person found guilty of academic fraud will be subject to severe sanctions.
Here are some examples of academic fraud:

- Plagiarism or cheating of any kind;
- Present research data that has been falsified;
- Submit a work for which you are not the author, in whole or part;
- Submit the same piece of work for more than one course without the written consent of the professors concerned.

Please consult this webpage: it contains regulations and tool to help you avoid plagiarism.

An individual who commits or attempts to commit academic fraud, or who is an accomplice, will be penalized.

Here are some examples of possible sanctions:

- Receive an "F" for the work or in the course in question;
- Imposition of additional requirements (from 3 to 30 credits) to the program of study;
- Suspension or expulsion from the Faculty.

You can refer to the regulations on this webpage:

https://www.uottawa.ca/administration-and-governance/academic-regulation-14-other-important-information

Avoid le plagiarism

- Works submitted in this course will be analyzed using a plagiarism detection tool to examine textual similarities and help you avoid plagiarism. Once analyzed, the works will be included as source documents in the tool's reference database, where they will be used only for the purpose of detecting similarities with other student works.
- Before submitting your work, you can voluntarily and anonymously verify it with the Ouriginal tool available to you in Brightspace. Login and register to use Ouriginal. (Ouriginal (saea-tlss.ca)).

Further Information

Student Services

Academic Writing Help Centre

At the AWHC you will learn how to identify, correct and ultimately avoid errors in your writing and become an autonomous writer.
In working with our Writing Advisors, you will be able to acquire the abilities, strategies and writing tools that will enable you to:

- Master the written language of your choice
- Expand your critical thinking abilities
- Develop your argumentation skills
- Learn what the expectations are for academic writing

Career Services

Career Services offers various services and a career development program to enable you to recognize and enhance the employability skills you need in today's world of work.

Counselling Service

There are many reasons to take advantage of the Counselling Service. We offer:

- Personal counselling
- Career counselling
- Study skills counselling

Access Service

The Access Service acts as intermediary between students, their faculty and other University offices to ensure that the special needs of these students are addressed and that the best possible learning conditions are being offered.

Note that the University of Ottawa is affiliated with AERO and ACE services for the adaptation of accessible academic materials for students with perceptual disabilities. If you have any questions, please contact the Accessibility Librarian or the Access services for textbooks.

Policy – Prevention of Sexual Violence

The University of Ottawa will not tolerate any act of sexual violence. This includes acts such as rape and sexual harassment, as well as misconduct that take place without consent, which includes cyberbullying. The University, as well as various employee and student groups, offers a variety of services and resources to ensure that all uOttawa community members have access to confidential support and information, and to procedures for reporting an incident or filing a complaint. For more information, please visit www.uOttawa.ca/sexual-violence-support-and-prevention/.

Regulation I-8.5

Except in programs and courses for which language is a requirement, all students have the right to produce their written work and to answer examination questions in the official language of their choice, regardless of the course's language of instruction

Personal ethics agreement concerning university assignments

DECLARATION OF INTEGRITY

Please sign the following declaration of integrity by typing your name and student ID in the space provided.

See following page

Personal Ethics Agreement Concerning University Assignments

Individual Assignment

Declaration of Integrity

I understand the importance of professional integrity in my education and future career in engineering or computer science. I hereby certify that I have done and will do all work on this examination entirely by myself, without outside assistance or the use of unauthorized information sources. Furthermore, I will not provide assistance to others.

I submit this assignment and attest that I have applied all the appropriate rules of quotation and referencing in use at the University of Ottawa, http://web5.uottawa.ca/mcs-smc/academicintegrity/documents/2011/academic-integrity-students-guide.pdf. I attest that this work conforms to the regulations on academic integrity of the University of Ottawa.

_____ _____ U. Ottawa (☐) Carleton U. (☐)

Name, Capital letters Student number

_____ _____

Signature Date