



**T A R G E T**  
TOP AMPLIFIER RESEARCH GROUPS  
IN A EUROPEAN TEAM

## Course description: **RF Device Modelling**

### **Modules:**

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1. Introduction to RF Device Modelling
2. Physical Device Modelling, Part I
3. Physical Device Modelling, Part II
4. Parasitic Elements Characterisation and De-Embedding
5. Electrical Equivalent Circuit Modelling
6. Distributed Equivalent Circuit Models
7. IMD Properties
8. Empirical Device Models: Basics
9. Empirical Device Models: Extensions
10. Modelling of GaN Devices
11. Modelling of MOSFETs
12. Modelling of LDMOS Devices
13. Modelling of HBTs: introduction, modelling principles, and noise
14. Modelling of HBTs: large-signal models; measurement and parameter extraction
15. Behavioural Modelling Techniques
16. Large-Signal Measurements Based Modelling

### **Audience:**

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This course is designed for engineers (process engineers, circuit designers ...) and starting PhD students wishing to get an overview on RF device modelling techniques.

### **Preliminary Knowledge:**

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- a BSc or MSc in electrical engineering, with preliminary knowledge of solid state devices and microwave measurement techniques.



**Our presenters:**

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**Iltcho Angelov** (Professor at the University of Chalmers, Sweden)

**Nuno Borges Carvalho** (Associate Professor at the University of Aveiro, Portugal)

**Christian Fager** (Assistant Professor at the University of Chalmers, Sweden)

**Teresa Martín-Guerrero** (Associate Professor at the University of Malaga, Spain)

**Angel Mediavilla** (Professor at the University of Cantabria, Spain)

**José Carlos Pedro** (Professor at University of Aveiro, Portugal)

**Matthias Rudolph** (Senior researcher at the Ferdinand-Braun Institut, Germany)

**Dominique Schreurs** (Assistant Professor at the Catholic University of Leuven, Belgium)

**John Xanthakis** (Professor at the National Technical University of Athens, Greece)

## Module 1 - Introduction to RF Device Modelling

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This module is intended to give an introduction to the course. It starts by comparing the various device modelling strategies, according to a common frame of device representations that goes from the most detailed physical (or transparent-box) models to the behavioural (or black-box) models, passing through the hybrid approach of equivalent-circuit modelling based on the quasi-static approximation. Then, assuming this widely used equivalent-circuit methodology, it discusses the two most important steps of device modelling formulation and extraction, explaining the advantages and pitfalls of global and local models.

**Presenter:** José Carlos Pedro

**Duration:** 2 hours

**Please note:** As this module is a general introduction to RF device modelling, it is recommended to always book it.

## Module 2 – Physical Device Modelling, Part I

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This module essentially presents the classical models i.e., the ones that are based on the solutions of Poisson's equation and possibly of the continuity equation. The motivation for doing so (i.e., what is to be gained) is discussed. Then the differences of the HEMT structure as opposed to the MOSFET structure are analysed and compared. Then all the basic models that have been proposed so far are presented and analysed. Examples are the original models of Delagebaudeuf and Lihn (now found in textbooks), Shur et al, Ku et al. and Lee and Crowell. There will be time for questions and discussion. Schematically the course is as follows.

1. Why "physical layer" modelling? What are the advantages, what is the cost?
2. Review of basic HEMT structures. Basic differences from MOSFET structures.
3. Review of physical models from mid 1980 till present. What are the remaining (and new) problems?

**Presenter:** John Xanthakis

**Duration:** 2 hours

**Please note:** It is recommended to book Module 2 in combination with Module 3.

## Module 3 - Physical Device Modelling, Part II

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The module is a continuation of module 2 and discusses the modifications introduced by calculating the charge in the channel of a HEMT quantum-mechanically i.e., by including Schrodinger's equation in the model. It then discusses the questions of whether we have reached the stage that we can calculate ab initio (i.e. without adjustable parameters) the I-V characteristics of a device. Also whether time-dependent effects can be introduced in the model. Again there will be time for discussion and questions. Among well established results the speaker will present some recent results of his own work. The basic entities of the module are as follows.

1. Quantum mechanical simulation of HEMTs. Necessity for it. The Schrödinger-Poisson (S-P) model.
2. One-dimensional S-P modelling. Results
3. Two-Dimensional S-P modelling. Results

**Presenter:** John Xanthakis

**Duration:** 2 hours

**Please note:** Module 2 is a prerequisite for Module 3.

## Module 4 – Parasitic Elements Characterisation and De-embedding

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This module starts with the definition of the problem of parasitic element characterization and de-embedding and its importance in microwave and millimetre-wave active device modelling. In order to define the scene of the problem, most commonly used parasitic elements environments (packaged devices, chip devices and on-wafer devices) are described and the role of test-fixtures and measurement equipments in the extraction procedure are also discussed. At this point, the intrinsic device and its model can be defined. Some remarks regarding the differences between characterizations or modelling of the extrinsic shell are pointed out. A detailed description and analysis of the Cold-FET extraction method is presented starting from the branch immittance approach. The Cold-FET extraction method is described for parasitic inductances, capacitances and resistances; its advantages, disadvantages and limitations are discussed.

**Presenter:** Teresa Martín-Guerrero  
**Duration:** 2 hours  
**Please note:** It is recommended to book Module 4 in combination with Module 5.

## Module 5 – Electrical Equivalent Circuit Modelling

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Starting from a brief introduction to the Device Physics, the origin and the physical meaning of Electrical Equivalent Circuit Models (EEC) is addressed. The practical division between intrinsic and extrinsic equivalent circuit is then defined. The fundamental role of dedicated Measurement techniques and Parameter extraction to model first and second order effects. Low frequency dispersion and breakdown behaviour is described from an experimental point of view and introduced in the EEC model. Advantages and disadvantages of the several analytical equations for empirical modelling. Temperature issues are also covered as a natural extension of electrical equivalent circuit models. Finally, the procedures for EEC model validation, in terms of Scattering, Pulsed I/V, IMD, ACPR, etc. are described.

**Presenter:** Angel Mediavilla  
**Duration:** 2 hours  
**Please note:** Module 4 is a prerequisite for Module 5.

## Module 6 – Distributed Equivalent Circuit Models

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The module starts with an overview of transverse propagation phenomena in FET-type structures that can be considered as multiconductor transmission systems. Different approaches for distributed modelling of microwave and millimetre-wave active devices are described concluding with a distributed model based on active coupled line analysis. This model is defined by means of its equivalent circuit per unit gate width and, this way, the analysis of the linear distributed model is shown. This analysis leads to analytical expressions for the S-parameters for the active device, in order to connect the distributed model with experimental measurements. Some examples for real devices that show distributed effects are presented. Starting from this model, low-order approximations can be obtained that demonstrate how distributed effects appears in short devices. The relationship between distributed effects and parasitic element characterization is explained. Finally distributed models are used for fully scalable equivalent circuit definition.

**Presenter:** Teresa Martín-Guerrero  
**Duration:** 2 hours  
**Please note:** Modules 4 and 5 are prerequisites for Module 6.

## Module 7 – IMD Properties

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Due to Linearity requirements in modern Communication Systems, IMD properties of active devices have to be carefully controlled. The idea of this module, starting from the basis of IMD distortion principles, is to show the convenience and control of small and large signal sweet-spots. Following this premises, the experimental measurement of the High-Order derivatives of a given transistor is discussed, along with their relationship to the IMD behaviour. Examples of Empirical models for accurate IMD control are given, explaining the mathematical nature of their strength and weakness. Finally, advantages of accurate IMD models for device level linearisation techniques are addressed.

**Presenter:** Angel Mediavilla  
**Duration:** 2 hours  
**Please note:** Module 5 is a prerequisite for Module 7.

## Module 8 – Empirical Device Models: Basics

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This module covers the basics of the Empirical FET Models Implementation in CAD tools.

First basic experimental characteristics at DC, like  $I_{ds}$  and  $I_{gs}$  bias dependence are discussed. Experimental S-parameter, capacitance and high frequency, thermal, power and dispersion characteristics are discussed in detail. They are linked with the Small and Large Signal Equivalent circuit of the FET. Implementation of the charge storage elements in the CAD tools like gate capacitance is discussed. Examples are given with some basic FET models as they are implemented in CAD tools. Basic measurements and procedures required for the Small and Large Signal Model extraction at DC, S-parameter, Power Spectrum and LSNA are given as well.

**Presenter:** Ilitcho Angelov  
**Duration:** 2 hours  
**Please note:** It is recommended to book Module 8 in combination with Module 9.

## Module 9 – Empirical Device Models: Extensions

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In this module, it is shown how empirical models can be extended to incorporate physical phenomena like thermal effects and dispersion. This is illustrated by model examples of several transistor types. First, self-heating implementation is discussed in detail. Dispersion phenomena as well as different types of implementations in CAD tools are discussed. As conclusion, the High Frequency Limitations of High Power FET devices are discussed and examples of implementation of these phenomena in CAD tools are shown.

**Presenter:** Ilitcho Angelov  
**Duration:** 2 hours  
**Please note:** Module 8 is a prerequisite for Module 9.

## Module 10 – Modelling of GaN Devices

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This module gives an overview of GaN device models.

Specific model artefacts related to the technology are also addressed, mainly due to the equivalent circuit and the nonlinear current model. Small and Large signal IMD distortion are covered as they play a major modelling challenge in high power transistors. Due to that fact thermal related phenomena are also referred.

Finally a brief overview of long-term memory effects in IMD distortion is also covered.

**Presenter:** Nuno Borges Carvalho  
**Duration:** 2 hours  
**Please note:** Module 5 is a prerequisite for Module 10.

## Module 11 – Modelling of MOSFETs

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This module focuses on the modelling of MOSFET devices, and more specifically on the differences with III-V material based FET models. One aspect is the more complicated de-embedding due to the losses in the Si substrate. A second aspect is that traditionally compact model representations are being used for MOSFETs, due to the history of digital and low-frequency analogue applications. Next to presenting an overview of the currently available compact models, a comparison with equivalent circuit based MOSFET models is made.

**Presenter:** Dominique Schreurs  
**Duration:** 2 hours  
**Please note:** Modules 4 and 5 are prerequisites for Module 11.

## Module 12 – Modelling of LDMOS Devices

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This module is intended to give an insight into the operation and modelling of LDMOS devices.

First, a detailed treatment of the fundamentals LDMOS device physics is given and used to explain measured LDMOS dc characteristics. These results provide background for development of a large signal model where each distinct operating region resulting from the MOSFET/JFET interaction is represented independently in the model equations. An overview of industry standard LDMOS models shows that an increased flexibility in representing the different details in the device characteristics can thereby be achieved. As a result, an accurate prediction of e.g., intermodulation distortion characteristics is possible.

**Presenter:** Christian Fager  
**Duration:** 2 hours  
**Please note:** Module 11 is a prerequisite for Module 12.

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**Module 13 – Modelling of HBTs: introduction, modeling principles, and noise**

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This module gives an introduction into the operation and electrical performance of HBTs. It is discussed which effects are to be accounted for in compact modelling in order to yield good simulation accuracy. A focus is on self-heating and transit-time effects, and the differences between SiGe, and III-V devices.

Then, it is discussed how these effects can be accounted for in a compact model, i.e., how the HBT physics can be represented by an equivalent circuit. Finally, RF and 1/f noise modelling is addressed with regard to linear and nonlinear circuit simulation.

This course should enable to know what to expect from a compact HBT model and how it internally works.

**Presenter:** Matthias Rudolph  
**Duration:** 2 hours  
**Please note:** It is recommended to book Module 13 in combination with Module 14.

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**Module 14 – Modelling of HBTs: large-signal models; measurement and parameter extraction**

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This module presents an overview over publicly available compact HBT models. The focus lies on recently developed III-V HBT models, which are currently not as widely known and well documented as Si-based models. The models addressed are the SPICE Gummel-Poon, VBIC, UCSD-HBT, Agilent HBT and FBH HBT models.

The second half of the course is dedicated to parameter extraction. The topics addressed are measurement and extraction of extrinsic elements, small-signal equivalent circuit, DC parameters, (large-signal) capacitances and transit-times, and thermal resistance parameters.

**Presenter:** Matthias Rudolph  
**Duration:** 2 hours  
**Please note:** Module 13 is a prerequisite for Module 14.

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**Module 15 – Behavioural Modelling Techniques**

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This module is intended to introduce the concepts of behavioural (or black-box) modelling of RF devices. It starts by a brief distinction between physical, equivalent-circuit and behavioural approaches, to then explain how it is possible to compensate the lack of knowledge of the internal (physical) device operation by gathering appropriate information from measured (behavioural) data. Beginning with the basics of behavioural modelling for linear devices (like the Y, Z or the S-parameter matrices) it then addresses some theoretical ways of extending these concepts to nonlinear devices. So, Polynomial (or Volterra series) and Artificial Neural Network model structures will receive a particular attention.

**Presenter:** José Carlos Pedro  
**Duration:** 2 hours  
**Please note:** Module 1 is a prerequisite to Module 15.

## **Module 16– Large-Signal Measurements Based Modelling**

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This module focuses on models that are based on large-signal time-domain measurements. A distinction is made between equivalent circuit and behavioural modelling approaches. Concerning the former, both direct extraction and optimisation techniques are covered. The importance of experiment design is highlighted. The theory is illustrated by examples on several device technologies.

**Presenter:** Dominique Schreurs  
**Duration:** 2 hours  
**Please note:** Module 15 is a prerequisite for Module 16.