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Split Ring Resonator (SRR) based Microwave Fluidic Sensors for Electrolyte Concentration Measurements

Paris Vélez, Member, IEEE, Jonatan Muñoz-Enano, Katia Grenier, Member, IEEE, Javier Mata-Contreras, David Dubuc, Member, IEEE, and Ferran Martín, Fellow, IEEE

Abstract— A differential microwave sensor, based on a pair of uncoupled microstrip lines each one loaded with a split ring resonator (SRR), is applied to the measurement of electrolyte concentration in deionized (DI) water. For that purpose, fluidic channels are added on top of the SRR gaps, the most sensitive parts of the structure. The operating principle is based on the measurement of the cross-mode insertion loss, highly sensitive to small asymmetries caused by differences between the reference liquid and the liquid under test (LUT). In this work, the reference liquid is pure DI water (the solvent), whereas the solution, DI water with electrolyte content, is injected to the LUT channel. The proposed sensor is able to detect electrolyte concentrations as small as 0.25 g/L, with maximum sensitivity of 0.033 (g/L)². The sensor is validated by measuring the concentration of three types of electrolytes, i.e., NaCl, KCl and CaCl₂. Finally, the sensor is applied to monitor variations of total electrolyte concentration in urine samples.

Index Terms— Microwave sensors, differential sensors, microfluidics, permittivity measurements, microstrip technology, split ring resonator (SRR), electrolyte concentration.

I. INTRODUCTION

Electrolytes are chemical substances that dissociate into cations and anions when dissolved in polar solvents, such as water, thereby modifying the electric and electromagnetic properties of the solvent. Particularly, changes in the conductivity and loss factor (or loss tangent) of the solvent are expected by the presence of electrolytes in it. Therefore, electrolyte concentration can be measured by means of methods or approaches sensitive to the conductivity or loss factor of the solution, and particularly through microwave techniques.

Electrolytes are physiologically important since they play key roles in various vital functions, such as blood pH and pressure control, body hydration, nerve and muscle functions, etc. [1]. The most important primary ions of electrolytes in blood and urine are sodium (Na⁺), potassium (K⁺), calcium (Ca²⁺), chloride (Cl⁻) and bicarbonate (HCO₃⁻). Imbalances in the concentration of certain ions in blood or urine (the so-called anion gap [2]) are indicative of certain pathologies. For instance, in urine the anion gap is defined as [Na⁺] + [K⁺] − [Cl⁻], where [*] denotes concentration, and typical values in urine samples not subjected to physiological pathologies should be comprised between 0 and ~33 mEq/L. Ion concentration in blood and urine are typically measured by means of electrochemical systems, such as ion selective electrodes (ISE) [3], able to provide the individual concentration of specific ions, and consequently the anion gap. Measuring the total concentration of ions does not determine the anion gap, but may be indicative of an overall excess or deficit of electrolytes, as compared to the typical levels found in “healthy” samples. Therefore determining the total electrolyte concentration in serum, plasma or urine through real-time low-cost systems (as compared to chemical systems) may be useful as a complementary diagnosis method.

Within this context, this paper is focused on the measurement of electrolyte concentration in DI water using microwaves. The sensor is based on the variations of the complex dielectric constant (mostly related to variations in the conductivity or loss tangent) of DI water experienced by the presence of electrolytes dissolved in it. Such variations can be sensitively detected by means of a differential technique based on the measurement of the cross-mode insertion loss in a pair of microstrip lines loaded with split ring resonators (SRRs), and equipped with fluidic channels for liquid injection. The main advantage of this resonator-based approach is the high sensitivity and capability to detect small concentrations of electrolytes in water.

Many sensing structures based on resonator-loaded lines have been proposed, and they can be categorized in three main groups: (i) frequency variation sensors [4]-[13], (ii) coupling modulation sensors [14]-[22] and (iii) frequency-splitting sensors [23]-[30]. In frequency variation sensors, the output variable is the frequency position of either a notch or a peak in the frequency response of a transmission line loaded with a resonant element (sometimes, the notch depth, or the peak magnitude, is also used as an additional output variable). Sensors based on this approach have been applied to different types of measurements, but, particularly, they have been used for dielectric characterization of solid [8]-[10] and liquid [6],[12],[13] samples. Symmetry disruption is the physical

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principle in coupling modulation sensors [31],[32]. In such sensors, a transmission line is symmetrically loaded with a symmetric resonator uncoupled to it. Such uncoupling is achieved by using resonant elements exhibiting a symmetry plane of different electromagnetic sort than the symmetry plane of the line [31], [32]. However, by truncating symmetry (e.g., by means of a relative linear or angular displacement between the resonator and the line, or by means of an asymmetric dielectric loading), line-to-resonator coupling is activated, thereby generating a notch in the frequency response (with depth intimately related to the level of asymmetry). In such coupling modulation sensors the output variable is thus the notch depth, and they have been mostly applied to the measurement of spatial variables [14]-[22],[33]. Finally, in frequency splitting sensors, a transmission line is symmetrically loaded with a pair of (not necessarily symmetric) resonators coupled to it. Under perfect symmetry, a single notch at the fundamental resonance frequency of the resonant elements appears. However, if the resonators are asymmetrically unloaded, frequency splitting arises. In these sensors, similar to differential sensors, the output variables are the differential frequency and the differential depth of the generated notches, and these frequency-splitting sensors have been mainly applied to differential permittivity measurements [29],[30].

The previous sensors exhibit, in general, acceptable sensitivities and dynamic ranges, but they exhibit limited resolution, not being able to detect small variations of the variable of interest. This aspect is critical for the measurement of solute concentration in highly diluted solutions. Therefore, for the accurate measurement of electrolyte content in DI water solutions exhibiting concentrations in the range 1-10 g/L or even below, as pursued in this paper, novel strategies, highly sensitive to small concentrations, are needed. The above-mentioned sensing approach, based on the measurement of the cross-modal insertion loss in a pair of lines, each one loaded with a resonant element, provides the necessary sensitivity and resolution for the intended application. This approach was first demonstrated in [34],[35] by considering open complementary split ring resonators (OCSRRs) [36] as loading resonators (NaCl was the considered electrolyte in [35]). In this paper, it is demonstrated that sensitivity can be improved by replacing OCSRRs with SRRs. Moreover, sensor validation is carried out by considering three electrolytes, i.e., NaCl, KCl and CaCl₂. An advantage of using SRRs instead of OCSRRs as sensing element is the fact that SRRs do not require vias, hence easing fabrication and contributing to enhance resolution, intimately related to the “level” of symmetry achieved when the differential structure is loaded with identical loads in both resonators (approaching to “perfect symmetry” is more feasible if vias are not present). In the last part of the paper, it is demonstrated that the proposed sensor may be useful to detect variations of total ion concentration in biological samples, particularly urine. This may be of interest for real-time monitoring of potential dysfunctions or anomalies, e.g., during disease treatment in hospital environments, related to extreme ion concentrations in such samples.

II. STRUCTURE OF THE PROPOSED SENSOR, SENSING PRINCIPLE AND FABRICATION

The proposed differential sensor consists of two parts: (i) the microwave structure, a FR4 substrate with a pair of uncoupled 50 Ω lines each one loaded with a SRR, and (ii) the fluidic channels plus the mechanical accessories for liquid injection to the channels and for channel attachment to the substrate. The topology of the microwave structure is depicted in Fig. 1, where relevant dimensions are indicated. The dielectric constant and thickness of the considered substrate are ϵ = 4.4 and h = 1.6 mm, respectively. The fluidic channels are made of polydimethylsiloxane (PDMS), and are identical to those used in [30]. Channel dimensions are designated by \( h_{ch} \) (height), \( w_{ch} \) (width) and \( L_{ch} \) (length). The mechanical parts consist of a polyether ether ketone (PEEK) structure, that accommodates the fluidic connectors (necessary for liquid injection to the channels), and screws, used to fix the PEEK-PDMS assembly on the substrate. In order to avoid substrate absorption, a dry film of clear polyester, with an estimated thickness of 50 μm and dielectric constant of 3.5, has been deposited on top of the SRRs. The top and lateral views of the channel plus mechanical parts are depicted in Fig. 2. The photograph of the whole sensing structure is shown in Fig. 3.
The working principle of the proposed differential sensor is symmetry disruption, caused by an asymmetric dielectric load in the SRRs. Thus, in a sensing operation, the reference liquid is injected in one of the channels (designated as REF channel), whereas the liquid under test (LUT) is injected in the other channel (LUT channel). The output variable in the proposed sensor is the cross-mode insertion loss (or cross-mode transmission coefficient), highly sensitive to small asymmetries and, hence, very convenient to detect small differences between the REF and the LUT liquids. This is necessary in order to measure small concentrations of electrolytes in DI water (the purpose of this work). Thus, the considered REF liquid will be pure DI water (the solvent), whereas the LUT is the DI water solution with electrolyte content.

According to the port definition of Fig. 1, the cross-mode transmission coefficient is given by [37]

$$ S_{21}^{DC} = \frac{1}{2} (S_{21} - S_{41}) $$

This result is valid as long as the SRR-loaded lines are uncoupled. If the structure exhibits perfect symmetry, it follows that $S_{21}^{DC} = 0$ (note that the cross-mode insertion loss, i.e., the cross-mode transmission coefficient expressed in dB, should be ideally $-\infty$ under perfect symmetry). However, if symmetry is disrupted, as occurs by injecting pure DI water in the REF channel and the electrolyte solution in the LUT channel, the cross-mode insertion loss should take finite values, and the maximum value should be indicative of the level of asymmetry. Therefore, the maximum level of the cross-mode insertion loss is considered the output variable in the proposed sensing structure.

In practice, perfect symmetry is not achievable, as long as sensor fabrication involves several (“imperfect”) processes, including substrate etching, dry film deposition, and mechanical fabrication of the PDMS-PEEK assembly. Thus, certain level of cross-mode insertion loss is expected even by loading the REF and LUT channels with identical liquids. Let us designate the maximum of the modulus of the cross-mode transmission coefficient experimentally found with balanced loads as $|S_{21}^{DC BAL}|$. It is important to minimize $|S_{21}^{DC BAL}|$ as much as possible, since it has direct impact on sensor resolution. Note that tiny differences between the REF liquid and the LUT liquid, which should provide a very small value of $|S_{21}^{DC}]$, may be obscured by $|S_{21}^{DC BAL}|$. Therefore, an accurate and rigorous sensor fabrication process, providing small $|S_{21}^{DC BAL}|$, is demanded for resolution optimization.

### III. Experimental Validation

The fabricated sensor has been validated by considering DI water solutions with different types of electrolytes, particularly, NaCl, KCl and CaCl$_2$. These electrolytes have been considered since they are present in blood and urine and they play key roles in several vital functions.

The first set of experiments has been done by injecting DI water solutions with different concentrations of NaCl in the LUT channel. In all the cases, pure DI water has been injected in the REF channel. The measured cross-mode insertion loss for the different NaCl concentrations is depicted in Fig. 4. Note that the cross-mode insertion loss resulting when the LUT channel is filled with pure DI water (balanced loading) is also included. $S_{21}^{DC BAL}$, expressed in dB, is found to be $-38.95$ dB, which is a very reasonable value. NaCl concentrations as small as 0.25 g/L can be perfectly resolved by virtue of the small value of $S_{21}^{DC BAL}$. By increasing the electrolyte concentration, the cross-mode transmission coefficient (or insertion loss) also increases, as expected. In Fig. 5, we have depicted the dependence of the maximum value of the cross-mode transmission coefficient, $|S_{21}^{DC}]_{\text{max}}$, with the concentration of NaCl, i.e., [NaCl]. For small concentrations, the sensitivity, i.e., the variation of $|S_{21}^{DC}]_{\text{max}}$ with [NaCl], is very high, and it progressively decreases as [NaCl] increases. The maximum value of the sensitivity is found to be 0.033 (g/L)$^{-1}$, i.e., higher than the maximum sensitivity of the sensors proposed in [35], based on a similar approach, but using OCSRRs as sensing elements (in [35] the sensors were applied to the measurement of NaCl concentration, as well). From the results of Fig. 5, we have obtained the calibration curve, from which the concentration of NaCl can be inferred by measuring $|S_{21}^{DC}]_{\text{max}}$. Such curve, with a correlation coefficient of $R^2 = 0.99966$, is

$$ [\text{NaCl}] g/L = -0.43 + 0.45 e^{\left(\frac{S_{21}^{DC}}{0.0344}\right)} + 2 \cdot 10^{-5} e^{\left(\frac{S_{21}^{DC}}{0.0051}\right)} $$

### Fig. 4. Cross-mode insertion loss for different values of NaCl concentration.
Repetitiveness of the results is important for the practical use of the proposed sensors. Therefore, we have repeated the previous measurements by subsequently injecting in the LUT channel the DI water solutions with the NaCl concentrations indicated in Fig. 5. The results, also included in Fig. 5 and identified as Measurement 2, reveal that measurements are repetitive by virtue of the small differences with the first experimental campaign (Measurement 1).

In the second set of experiments, KCl has been considered as solute. The variation of the cross-mode insertion loss and \( |S_{21}^{DC}|_{\text{max}} \) with KCl concentration are depicted in Figs. 6 and 7, respectively. Repetitiveness of the results is also demonstrated (see Fig. 7). In this case, the calibration curve, with \( R^2 = 0.99931 \), has been found to be

\[
[KCl] g/L = -0.11 + 0.14e^{0.02147} \tag{3}
\]

and the maximum sensitivity is 0.032 \((g/L)^{-1}\).

Finally, we have prepared several solutions of CaCl\(_2\) in DI water, and we have also measured the cross-mode insertion loss, as well as \( |S_{21}^{DC}|_{\text{max}} \), for the different solute concentrations. The results are depicted in Figs. 8 and 9. The calibration curve, with \( R^2 = 0.99905 \), in this case is

\[
[CaCl_2] g/L = -1.76 + 1.29e^{0.00221} + 3\cdot10^{-6}e^{0.00848} \tag{4}
\]

and the maximum sensitivity is 0.021 \((g/L)^{-1}\).
IV. DISCUSSION AND COMPARISON TO OTHER FLUIDIC SENSORS FOR SOLUTE CONCENTRATION MEASUREMENTS

Note that the dependence of $|S_{21}^{DC}|_{\text{max}}$ with the electrolyte concentration is not identical for KCl, NaCl and CaCl₂, but similar. The relatively high sensitivity of the reported sensors is in part because the presence of electrolytes in DI water modifies substantially its conductivity (or loss tangent), provided the electrolyte molecules dissociate into anions and cations when dissolved in water. For a certain electrolyte concentration, ion concentration is determined by the molecular mass of the electrolyte. Therefore, since the conductivity depends on ion concentration, we cannot expect identical dependences of the cross-mode insertion loss with the electrolyte concentration for the different electrolytes considered. Moreover, conductivity depends also on ion mobility, also related to the atomic mass. Indeed, at intermediate concentrations (between 2.5 g/L and 20 g/L), the electrolyte that produces higher values of the cross-mode insertion loss is NaCl, which is coherent with the low value of the atomic mass of Na, as compared to K and Ca. However, the differences are not significant. On the other hand, for very small values of the electrolyte concentration (< 2.5 g/L), the accuracy is expected to be limited, and for large values (> 20 g/L), $|S_{21}^{DC}|_{\text{max}}$ exhibits a quasi-saturation effect, and the dependence of the conductivity on ion concentration and mobility may be more complex. These facts may explain that at low and high electrolyte concentrations there is not a clear dependence of the cross-mode insertion loss with the ion concentration and atomic mass. Nevertheless, for a given electrolyte, the very good correlation coefficient that results by curve fitting, plus the repetitiveness of the results, reveals that the corresponding calibration curve is useful to determine its concentration.

Besides the work [35], focused on the measurement of NaCl concentration in DI water by using a pair of OCSRR-loaded lines, others report solute concentration measurements in liquid solutions. In [38], the considered solute is also NaCl, whereas in [39]-[42], the proposed sensors are used for the measurement of glucose concentration in liquid solutions. Finally, in [43], both NaCl and glucose concentration measurements in DI water are reported. Table I compares these sensors in terms of maximum sensitivity, resolution and dynamic range. It is remarkable that the sensor reported in [40], with a very good value of the sensitivity, taking into account that the considered solute is glucose, a substance that does not modify the water conductivity (or loss factor) as electrolytes do. If we focus on the sensors devoted to NaCl concentration measurements, we conclude that the sensor proposed in this paper provides the best combination of sensitivity and resolution. Moreover, sensor fabrication is simple (only a single metal layer is etched) and vias are not required. Therefore, the reported differential sensing structure, based on SRRs is very promising for the measurement of electrolyte content in very diluted liquid solutions.

V. CHARACTERIZATION OF URINARY SAMPLES

To further validate the proposed sensor, we have characterized several horse urine samples, with different levels of electrolyte concentrations (Na⁺, K⁺ and Cl⁻), which have been externally measured by means of an ISE electrochemical system (the electrolyte concentration measurements and the urine samples have been provided to us by the Biochemistry and Molecular Biology Department of Universitat Autònoma de Barcelona). From the measured values of the individual electrolyte concentrations (i.e., Na⁺, K⁺ and Cl⁻) for each sample, expressed in mEq/L, we have obtained the total concentrations by a simple addition. Note that the total concentration in mEq/L is proportional to the total ion concentration, a quantity of interest as it may be indicative of certain pathologies if certain limits are surpassed. The real-time monitoring of possible variations in the total ion concentration in urine (or even in blood) may be also of interest to detect possible dysfunctions or anomalies, e.g., during disease treatment in hospital environments. Note that with the proposed sensor system, ion concentration variations as compared to a reference sample can be easily measured.

The urine samples provided to us exhibit the total ion concentrations indicated in the right hand side column of Fig. 10. By considering as reference liquid the urine sample with the highest level of ion concentration (615.8 mEq/L), the cross-mode insertion loss that results by injecting the different samples to the LUT channel are those depicted in Fig. 10. It should be mentioned that for monitoring changes in total ion concentration with time in a real scenario, the reference sample should be, obviously, the urine at the beginning of the test campaign. In our case, we have (arbitrarily) considered that the reference sample is the one with 615.8 mEq/L ion concentration, as mentioned above.

The variation of $|S_{21}^{DC}|_{\text{max}}$ with the total ion concentration is depicted in Fig. 11. The calibration curve, with $R^2 = 0.99422$, is (the total ion concentration has been designated as [*])

\[ \text{mEq/L} = -46.62 + 517.26 e^{-0.0057 S_{21}^{DC}} + 428.6 e^{-0.0016 S_{21}^{DC}} \]  

(5)

and the maximum sensitivity has been found to be $-0.00058$ (mEq/L)⁻¹. From these results, we can envisage the application of this sensing principle to monitor electrolyte concentration variations in biological samples (e.g., urine and blood) in a real scenario.

### Table I

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Max. sensitivity (dB/g/L)</th>
<th>Resolution (g/L)</th>
<th>Dynamic range (g/L)</th>
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<td>0.25</td>
<td>80</td>
</tr>
<tr>
<td>[38]</td>
<td>0.005</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>[39]</td>
<td>0.003</td>
<td>1</td>
<td>300</td>
</tr>
<tr>
<td>[40]</td>
<td>1.75</td>
<td>1.5</td>
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<tr>
<td>[41]</td>
<td>0.017</td>
<td>10</td>
<td>150</td>
</tr>
<tr>
<td>[42]</td>
<td>0.003</td>
<td>5</td>
<td>300</td>
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<td>60</td>
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In summary, novel differential microwave fluidic sensors for electrolyte concentration measurements in diluted aqueous solutions, based on pairs of uncoupled lines loaded with split ring resonators (SRRs), have been reported. The working principle of the sensor is the variation of the cross-mode insertion loss generated by an asymmetric dielectric load of the SRRs. Thus, by loading the fluidic channel of one of the SRRs with the reference liquid (the solvent), and the other fluidic channel with the liquid under test (the solution), it follows that solute concentration determines the cross-mode insertion loss level, which is used as output variable. Sensor validation has been carried out by considering three types of electrolytes: NaCl, KCl and CaCl₂. Repetitiveness of the results has been demonstrated, and it has been found that the dependence of the cross-mode insertion loss with electrolyte content does not experience significant variations when the different electrolytes are considered. The combination of sensitivity and resolution of the reported sensor for NaCl concentration measurements in DI water, as compared to those of other sensors (also focused on NaCl measurements), has been found to be very competitive. With these high sensitivities and small resolutions, these differential sensors are of general interest for measuring small solute concentrations in liquids, as well as to detect changes in the properties of liquids (related to variations in the complex dielectric constant), as compared to a reference. In the last part of the paper, the sensor has been applied to the characterization of urine samples with different levels of ion concentrations, and the potential of the approach for real-time monitoring of total ion concentration in biological samples in a real scenario, has been pointed out.

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REFERENCES


Paris Vélez (S’10–M’14) was born in Barcelona, Spain, in 1982. He received the degree in telecommunications engineering, specializing in electronics, the Electronics Engineering degree, and the Ph.D. degree in electrical engineering from the Universitat Autònoma de Barcelona, Barcelona, in 2008, 2010, and 2014, respectively. His Ph.D. thesis concerned common mode suppression differential microwave circuits based on metamaterial concepts and split ring resonators. He is currently involved in the subjects related to metamaterial sensors for fluids detection at LAAS-CNRS through a TECNIOspring fellowship cofounded by the Mari Curie program. His current research interests include the miniaturization of passive circuits RF/microwave and sensors-based metamaterials.

Dr. Vélez was the recipient of a predoctoral teaching and research fellowship by the Spanish Government from 2011 to 2014. He is a Reviewer for the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES and for other journals.

Jonathan Muñoz-Enano was born in Mollet del Vallés (Barcelona) Spain, in 1994. He received the Bachelor's Degree in Electronic Telecommunications Engineering in 2016 and the Master's Degree in Telecommunications Engineering in 2018, both at the Autonomous University of Barcelona (UAB). Actually, he is working in the same university in the elaboration of his PhD, which is focused on the development of microwave sensors based on metamaterials concepts for the dielectric characterization of materials and biosensors.

Katia Grenier (S’99, M’03) received her M.S. and Ph.D. degrees in electrical engineering from the University of Toulouse, Toulouse, France, in 1997 and 2000, respectively. She was engaged in microelectromechanical systems (MEMS) circuits on silicon. She was a Postdoctoral Fellow at Agere Systems (Bell Labs). In 2001, she joined the Laboratory of Analysis and Architecture of System of the National Scientific Research Center (LAAS-CNRS), Toulouse, France. From 2007 to 2009, she was with the Laboratory for Integrated Micromechatronic Systems CNRS (LIMMS-CNRS) Institute of Industrial Science (IIS), University of Tokyo, Tokyo, Japan, where she was engaged in launching research activities on microwave-based biosensors. Her research interests in LAAS-CNRS are now focused on the development of fluidic-based Microsystems, notably for...
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Javier Mata-Contreras was born in 1976 in Málaga (Spain). He received the Ingeniería de Telecomunicación Degree from the Universidad de Málaga (UMA) in 2000 and the PhD degree from the same university in 2010, with the Thesis “Distributed Amplifiers and Mixers with Transmission Lines based on Metamaterials”. In 2000, he joined the UMA Department of Ingeniería de Comunicaciones UMA as Assistant Professor. He is currently working at CIMITEC and the Universitat Autònoma de Barcelona as Visiting Professor. His research interests include active and passive microwave devices and active distributed circuits based on metamaterials, among others.

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Ferran Martín (M’04-SM’08-F’12) was born in Barakaldo, Spain, in 1965. He received the B.S. degree in physics and Ph.D. degree from the Universitat Autònoma de Barcelona (UAB), Barcelona, Spain, in 1988 and 1992, respectively. From 1994 to 2006 he was Associate Professor in Electronics at the Departament d’Enginyeria Electrònica (Universitat Autònoma de Barcelona), and since 2007 he is Full Professor of Electronics. His research activity has been very broad, including the modelling and simulation of electron devices for high frequency applications, millimeter wave and THz generation systems, the application of electromagnetic bandgaps to microwave and millimeter wave circuits, and the application of metamaterial concepts to the miniaturization and optimization of microwave circuits and antennas. He is now very active in the development of microwave sensors for dielectric characterization and motion control, and also in the topic of chipless-RFID. He is the head of the Microwave Engineering, Metamaterials and Antennas Group (GEMMA Group) at UAB, and director of CIMITEC, a research Center on Metamaterials supported by TECNIO (Generalitat de Catalunya). He has organized several international events related to metamaterials, including Workshops at the IEEE International Microwave Symposium (years 2005 and 2007) and European Microwave Conference (years 2009, 2015, 2017, and 2018), and the Fifth International Congress on Advanced Electromagnetic Materials in Microwaves and Optics (Metamaterials 2011), where he has acted as chair of the Local Organizing Committee. He has acted as Guest Editor in several Special Issues, mainly related to Metamaterials, in various International Journals. He has authored and co-authored over 580 technical conference, letter, journal papers and book chapters, he is co-author of the book on Metamaterials entitled *Metamaterials with Negative Parameters: Theory, Design and Microwave Applications* (John Wiley & Sons Inc. 2008), author of the book *Artificial Transmission Lines for RF and Microwave Applications* (John Wiley & Sons Inc. 2015), co-editor of the book *Balanced Microwave filters* (John Wiley & Sons Inc. and IEEE-Press 2018), and he has generated 19 PhDs. Ferran Martín has filed several patents on metamaterials and has headed several Development Contracts.

Prof. Martín is a member of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S), member of the European Microwave Association (EuMA), and member of the Institution of Electronics and Technology (IET). He is reviewer of dozens of journals, including IEEE journals such as IEEE Transactions on Microwave Theory and Techniques, IEEE Microwave and Wireless Components Letters, and IEEE Sensors Journal, among others, and he serves as member of the Editorial Board of IET Microwaves, Antennas and Propagation and International Journal of RF and Microwave Computer-Aided Engineering. He is also a member of the Technical Committees of the European Microwave Conference (EuMC) and International Congress on Advanced Electromagnetic Materials in Microwaves and Optics (Metamaterials). Among his distinctions, Ferran Martin has received the 2006 Duran F bear Prize for Technological Research, he holds the Parc de Recerca UAB – Santander Technology Transfer Chair, and he has been the recipient of two ICREA ACADEMIA Awards (calls 2008 and 2013). He is Fellow of the IEEE since 2012 and Fellow of the IET since 2016.