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Overcoming Inherent Narrow Bandwidth and Low Radiation Properties of Electrically Small Antennas by Using an Active Interior-Matching Circuit

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ABSTRACT A technique is described to extend the working frequency-band and increase the radiation gain and efficiency of an electrically small antenna (ESA). The geometry of the proposed ESA is in the shape of an "H" structure. A small gap is included at the symmetry of the H-shape structure to embed an inductive load that is used to connect the two halves of the H-shaped antenna. With the lumped element inductor, the bandwidth of the H-shaped antenna is restricted by Chu-lower bound. However, it is demonstrated by analytical analysis and through 3D full-wave electromagnetic simulations that when the inductive load is replaced with negative reactance from a negative impedance converter (NIC) the antenna's bandwidth, radiation gain and efficiency performance can be significantly improved by ~40%, 3.6 dBi and 55%, respectively. This is because NIC acts as an effective interior matching circuit. The resonant frequency of the antenna structure with the inductive element was used to determine the required inductance variation in the NIC to realize the required bandwidth and radiation characteristics from the H-shaped antenna.

INDEX TERMS Electrically small antenna (ESA), active interior impedance matching network, broad bandwidth, negative impedance converter (NIC), high radiation properties.

I. INTRODUCTION

Miniaturization of electronic circuits has led to numerous wireless applications that have conflicting requirements for their antenna systems [1]–[4]. This has resulted in the demand for electrically small antennas (ESA) that need to be effective and operate over substantial bandwidths. These requirements, however, are conflicting when considering the design of standard ESAs that are inefficient radiators due to their large reactance and low resistance that results in poor impedance matching to RF front-end circuitry. The realization of resistive and reactance based matching networks is a challenging task that presents limitations on the optimized system's overall performance [5]–[7].

There is a resurgence of interest in electrically small antennas because of their use in sensors for 5G and IoT technologies. The Chu limit [8]–[15] defines the minimum radiation Q-factor of an electrically small antenna, and hence its maximum operational bandwidth that is enclosed within a sphere of a specified radius. The Q-factor approaches this Chu limit when the antenna efficiently utilizes the available volume within that radiation sphere. There have been a variety of approaches to achieve this objective including cleverly packing resonant antenna elements into this small volume

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using various geometrical configurations [14], fractal curve antennas [16] and space-filling curve antennas [17], [18].

Matching networks based on Non-Foster (NF) have been proposed to overcome the Chu limit [13], [19]. This is achieved by using negative inductance and capacitance in a NF matching network, which causes the antenna to resonate.

ESA based on metamaterial technology have been shown to be efficient radiators [20]–[23]. This is achieved by incorporating the metamaterial's negative permittivity and/or permeability specifications inside the antenna. Metamaterial inspired antennas exploit parasitic elements to realize excellent matching characteristics, which overcomes the need for an external matching circuit. In [21]–[23] the metamaterial inspired antennas based on Z-shaped structures employ the lumped reactive components that are used to tune the antenna to resonate at a specified frequency by varying the magnitude of the lumped element without affecting the antenna dimensions.

This article presents a theoretical investigation on an H-shaped antenna based on [21]–[23] where an interior matching network comprising an inductor is incorporated between the two half portions that constitute the H-shaped antenna to realize a low Q-ratio value and hence broad bandwidth ESA with higher radiation gain and efficiency over its operating frequency band.

II. H-SHAPED ESA LOADED WITH INDUCTANCE

The ESA's performance is limited by its physical size [8]–[10]. The Q-factor for the Chu limit is defined by [24]–[26]

$$Q_{Chu} = \frac{1}{2}\left[\frac{1+3\,(ka)^2}{(ka)^3\left[1+(ka)^2\right]}\right] \tag{1}$$

where a represents the minimum radius of sphere surrounding the antenna, and the free-space wave number is defined by $k = 2\pi c/f_r$, where c is the speed of light in a vacuum and f_r represents the resonant frequency. The exact derivation for the minimum Q-factor is [24]–[26]

$$Q_{Exact} = \frac{1}{(ka)^3} + \frac{1}{ka} \tag{2}$$

If $f_{+,3dB}$ and $f_{-,3dB}$ represent the frequencies above and below the resonant frequency where the radiated power falls to half its maximum value, the 3-dB fractional bandwidth (FBW) corresponds to the radiation Q-factor given by [10–11] $FBW_{3dB} = 1/Q_{3dB}$. The figure of merit associated with the bandwidth is expressed as $Q_R = Q_{3dB}/Q_{Exact}$. The maximum FBW based upon the Chu limit can be calculated from Eqn. (2) as:

$$FBW_{Chu} = \frac{1}{Q_{Exact}} \approx (ka)^3 \quad \text{for } ka \ll 1 \tag{3}$$

Hence, as the electrical size of the antenna is reduced, the minimum Q-factor in free-space increases substantially, causing a corresponding decrease in the FBW of the antenna system. It is well known that the FBW of an antenna is increased if the losses are increased, but at a cost of the total radiated power.

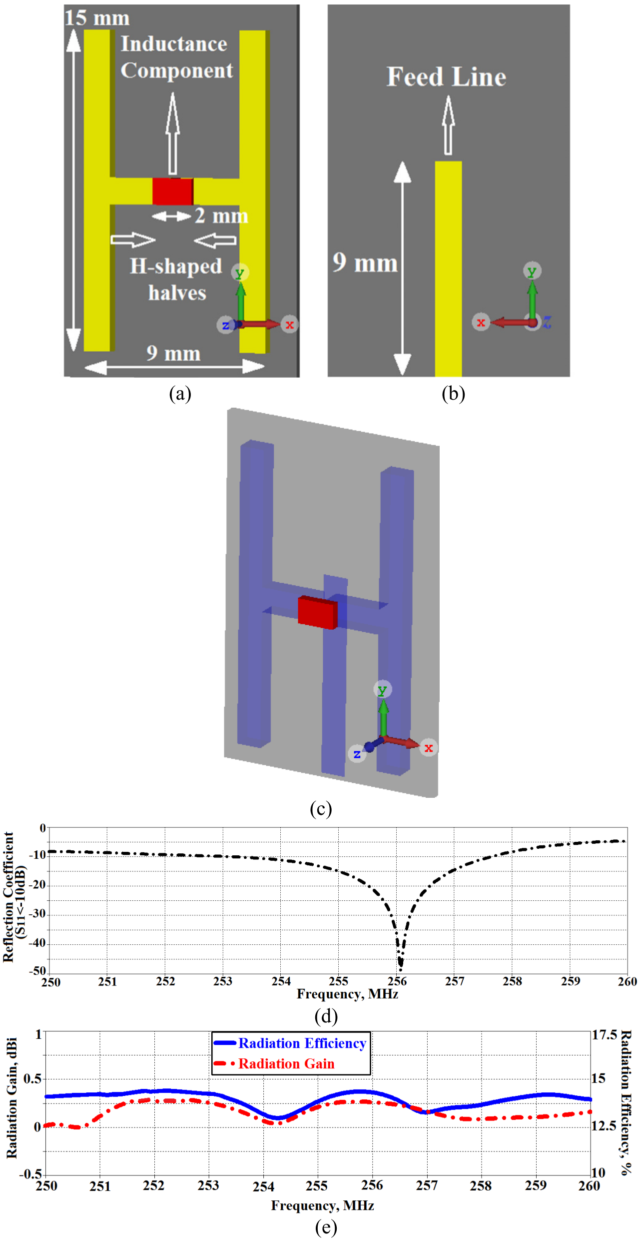


FIGURE 1. **(a) Top view of the proposed H-shaped antenna loaded with 150 nH inductance, (b) Bottom view showing the feedline located under the H-shaped structure, (c) isometric view of the antenna, (d) S_{11} response, and (e) radiation gain and efficiency performance.**

Geometry of the H-shaped antenna is shown in Figs. 1 (a)-(c). This antenna configuration was chosen in this investigation as a reference ESA as it has been extensively studied before and its characteristics of narrow bandwidth and broad beamwidth are well established. The two halves constituting the H-shaped structure is loaded with 150 nH inductance. The magnitude of the inductor was chosen for the antenna to resonate at an arbitrary frequency of ~256 MHz, which can be therefore varied as a function of the employed inductance value. The inductor in the simulation was modeled as ideal lossless component. The antenna is constructed from a lossy copper with conductivity of 5.8×10^7 S/m.

The antenna's reflection-coefficient (S_{11}) and radiation characteristics using CST Microwave Studio for a 50Ω source are shown in Figs. 1(d) and (e). The structure's frequency bandwidth for $S_{11} \leq -10$ dB is 4.6 MHz, and the structure resonates at 256.1 MHz. At this frequency, the antenna exhibits an optimum gain and efficiency of 0.25 dBi and 14%, respectively. The fractional bandwidth of the antenna is 1.8%. From Eqn.(3) $Q_{Exact} \approx 54$ and $ka = 0.26$. Since $k = 2\pi c / f_r$ the minimum radiation sphere for this antenna has a radius of $a = 35$ mm. $FBW_{3dB} = 1.32\%$ therefore $Q_{3dB} \approx 75$. Then $Q_R \approx 1.4$, which is less than the Chu-lower bound as the antenna occupies less space than the enclosing radiation sphere.

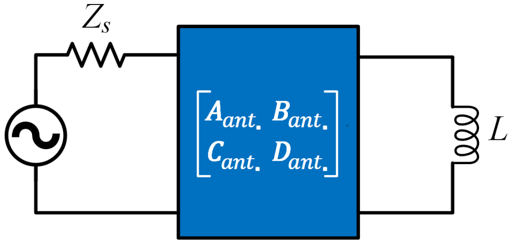


FIGURE 2. Circuit model of the *H*-antenna with an inductor.

In the simulation, the inductor in the *H*-shaped antenna was considered to be a lossy component as is the case in reality. Application for such an antenna is limited because of its narrow fractional bandwidth and low radiation gain and efficiency. The *H*-shaped antenna shown in Figs. 1 (a)-(c) can be theoretically represented in terms of *S*-matrix model, as depicted in Fig.2. The elements of the matrix ($A_{ant.}$, $B_{ant.}$, $C_{ant.}$, and $D_{ant.}$) represents the antenna block.

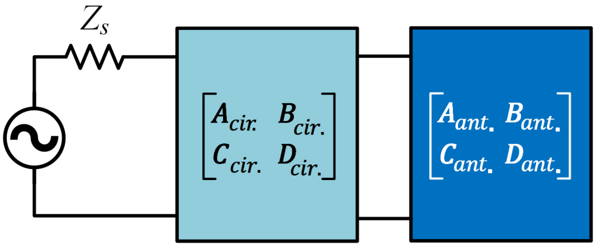


FIGURE 3. Circuit model of the *H*-antenna loaded with the IMC.

The interior matching circuit (IMC) that is proposed here will replace the inductor L. Fig.3 shows the resultant circuit model, where $A_{cir.}$, $B_{cir.}$, $C_{cir.}$, and $D_{cir.}$ are the matrix parameters of the interior matching circuit. To realize a low reflection-coefficient value the antenna's input impedance should be closely matched to the source impedance Z_s. Hence, IMC was designed such that:

$$\begin{bmatrix} 1 & Z_s \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} A_{cir.} & B_{cir.} \\ C_{cir.} & D_{cir.} \end{bmatrix} \begin{bmatrix} A_{ant.} & B_{ant.} \\ C_{ant.} & D_{ant.} \end{bmatrix} \tag{4}$$

The *ABCD* matrix of IMC is then given by:

$$\begin{bmatrix} A_{cir.} & B_{cir.} \\ C_{cir.} & D_{cir.} \end{bmatrix} = \begin{bmatrix} 1 & Z_s \\ 0 & 1 \end{bmatrix} \begin{bmatrix} A_{ant.} & B_{ant.} \\ C_{ant.} & D_{ant.} \end{bmatrix}^{-1} \tag{5}$$

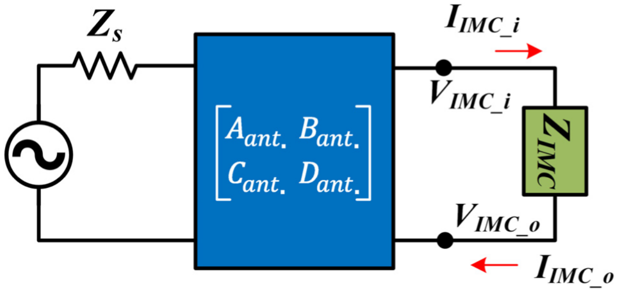


FIGURE 4. Circuit model of the *H*-antenna loaded with an equivalent IMC load.

CST Microwave Studio was used to simulate the antenna's performance and obtain the S-parameters at various frequencies of interest to determine the *ABCD* matrix of IMC in Fig. 4 using Eqn. (5). In Fig. 4, the IMC is connected to the *H*-shaped antenna at its input port and is shorted at its output port. Hence, the *ABCD* matrix of this configuration is given by:

$$\begin{bmatrix} V_{IMC\_i} \\ I_{IMC\_i} \end{bmatrix} = \begin{bmatrix} A_{IMC} & B_{IMC} \\ C_{IMC} & D_{IMC} \end{bmatrix} \begin{bmatrix} V_{IMC\_o} \\ I_{IMC\_o} \end{bmatrix} \tag{6}$$

Current and voltage at the input port of IMC can be represented by V_{IMC_i} and I_{IMC_i}, respectively; and I_{IMC_o} and V_{IMC_o} are current and voltage at its output port. As $V_{IMC\_o} = 0$, then $Z_{IMC.} = B_{IMC.} / D_{IMC.}$. This relation has used to transform the circuit model presented in Fig.3 to the circuit model represented in Fig.4.

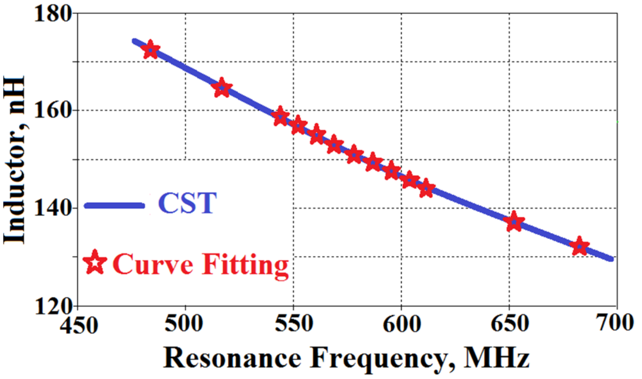


FIGURE 5. Results achieved by curve fitting of the inductor values.

III. RESONANT FREQUENCY OF EMBEDDED INDUCTOR

The relationship between the inductance value of the lumped inductor and resonance frequency that is predicted by CST Microwave Studio is depicted in Fig. 5. An analytical expression of this relationship was obtained by curve fitting using the minimum mean square error approach, which is given by:

$$L = \frac{a_1}{f^2} + a_0 \tag{7}$$

where coefficients $a_1 = 5.24 \times 10^7$ and $a_0 = -3.68$. The units of the inductance, L, and the frequency, f, are nH and MHz, respectively.

The magnitude of the frequency dependent inductor L predicted by Eqn.(7) cannot be realized by a passive lumped component. Realization of negative reactance is only possible by using active components. The impedance, Z_L, corresponding to the frequency dependent inductance L is represented by:

$$Z_L = \frac{1}{j\omega C_e} + j\omega L_e \tag{8}$$

where C_e and L_e represent the equivalent capacitor and inductor, respectively.

IV. BANDWIDTH EXTENSION OF H-SHAPED ANTENNA LOADED WITH AN ACTIVE INTERIOR MATCHING NETWORK

The bandwidth of the H-shaped antenna is restricted by Chulower bound using a lumped element inductor. Previous studies have shown that bandwidth enhancement can be achieved with the inclusion of active inductors based on negative permittivity and permeability metamaterials [25].

NIC is necessary to realize the negative capacitor and inductor values [21]. NIC is a two-port device whose input impedance Z_{in} is the negative of the load impedance Z_L. In the case of the proposed metamaterial-inspired ESA it is essential that NIC be a miniature device to conserve the size of the antenna. The feasibility of a negative impedance converter based on CMOS technology is demonstrated in [27]. The proposed NIC circuit in Fig. 6 is appropriate for an n-substrate process like CMOS. When port-1 is excited with signal and port-2 is terminated with a resistance, this circuit exhibits a current-controlled negative resistance. Conversely, when port-2 excited by a voltage signal and port-1 is terminated with a resistance, a voltage-controlled negative resistance is created. This enables the active pair M1, M2 to avoid back-gate bias. Any input signal current i_1, at port-1 flows through device M1 (assuming I_B to be an ideal current sink) results its drain current to be I_B - i_1. The unity-gain current mirror MM1, MM2 forces an identical current through the diode-connected transistor M2 to the output port-2. The current sink I_B causes the output current i_2, to equal i_1, and hence the output voltage v_2 across terminating resistance R_T is given by:

$$v_2 = -i_1 R_T \tag{9}$$

If the influences of the channel-length modulation in M1 and M2 can be ignored, their gate-source voltages are identical because they are transporting identical currents. Consequently, the voltage at the input port (v_1) is determined by:

$$v_1 = v_2 = -i_1 R_T \tag{10}$$

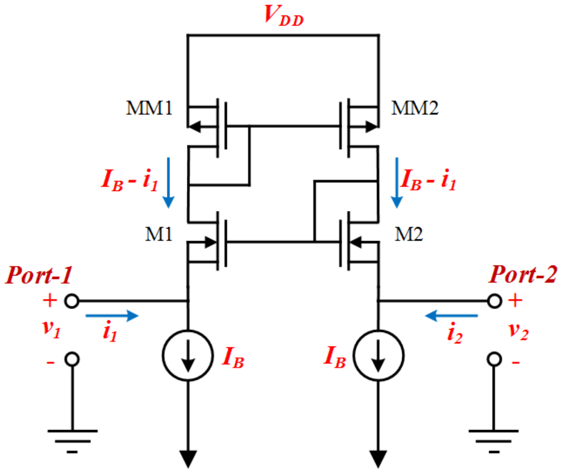


FIGURE 6. **Proposed CMOS negative impedance converter circuit.**

This is a current-controlled negative resistance of magnitude R_T at the input port.

The generalized expression relating the antenna's resonant frequency with its effective inductance (L_{eff}) and effective capacitance (C_{eff}) is given by:

$$f_r = 1/2\pi\sqrt{C_{eff} L_{eff}} \tag{11}$$

The rate of change of f_r with regards to L_{eff} is defined by:

$$\frac{\partial f_r}{\partial L_{eff}} = -f_r/2L_{eff} \tag{12}$$

$L_{eff} = L + L_o$, where L is inductive component and L_o is the antenna's inherent inductance. As $L_0 \ll L$ then $L_{eff} \sim L$ and Eqn.(12) then simplifies to:

$$\frac{\Delta f_r}{f_r} \sim -\Delta L/2L \tag{13}$$

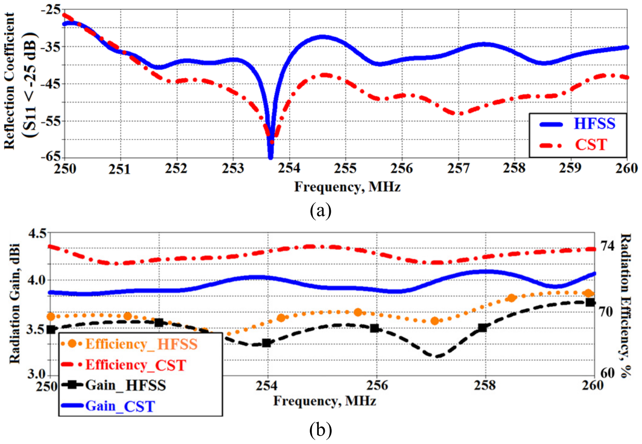
Eqn.(13) can be used to determine the inductance variation required by the NIC to realize the required bandwidth from the H-shaped antenna. This expression indicates that to realize 15% bandwidth, the change in inductance required must be ~25%, which correlates with Fig.5. The proposed technique is restricted by the inherent inductance variation of the NIC circuit.

Two different 3D full-wave electromagnetic computational techniques, i.e., CST-Microwave Studio and HFSS Designer, were used to validate the proposed antenna's reflection-coefficient (S_{11}), radiation gain and efficiency response when implemented with the NIC circuit. HFSS is based on Finite Element Method (FEM) while CST is based upon Finite Integration in Technique (FIT). The results are shown in Fig.7. The reflection-coefficient, radiation gain and efficiency prior to using NIC are shown in Fig. 1. It is discernible that after applying the proposed NIC circuit the reflection-coefficient and fractional bandwidth improve substantially. With NIC, S_{11} becomes better than -25 dB, and the fractional bandwidth is 40%. The results also show with NIC there is also great improvement in the gain and radiation

TABLE 1. Comparison of the Proposed ESA With Other Published Work

Performance	[21]	[22]	[23]	[28]	[29]	Proposed Work
Antenna Geometry	Z-shaped	Z-shaped	Z-shaped	Rectangular patch	Bent monopole	H-shaped
Matching Technique	Active internal matching network	Active internal parasitic lumped inductor	Active internal matching element	Active internal matching network	Active internal matching network	Active internal impedance matching network
Fractional Bandwidth	10%	0.0027%	10%	9.4%	48%	40%
Bandwidth Improvement	Not reported	Not reported	Not reported	7.6%	-2%	38.68%
Ave. Gain with NIC	Not reported	Not reported	Not reported	Not reported	-5 dBi	3.72 dBi
Ave. Efficiency with NIC	Not reported	Not reported	Not reported	Not reported	12%	69%
Ave. Gain Improvement	Not reported	Not reported	Not reported	Not reported	5 dB	3.6 dB
Ave. Efficiency Improvement	Not reported	Not reported	Not reported	Not reported	9%	55.3%

efficiency across the antenna's operating band from 250 MHz to 260 MHz. The average gain predicted by HFSS is 3.9 dBi and CST is 3.54 dBi, and the average efficiency predicted by HFSS is 67% and CST is 71%. Although there is disparity between HFSS and CST results however both tools predict significant approvement in the antenna performance with NIC. These results reveal the advantage of using NIC in ESAs.



(a)

(b)

FIGURE 7. Results from two different 3D full-wave electromagnetic computational techniques (HFSS and CST) of the *H*-shaped antenna with the proposed negative impedance converter (NIC) circuit,
(a) Reflection-coefficient (S_{11}) response, and (b) Radiation gain and efficiency performance.

V. COMPARISON WITH STATE OF THE ART

The proposed NIC topology based on active interior matching circuit is compared with previously published works on ESA in Table 1. For the various antenna geometries, the performance parameters include matching technique employed, fractional bandwidth, and the resulting improvement with NIC in terms of bandwidth, radiation gain and efficiency. It is evident that the proposed H-shaped antenna with NIC substantially improves the antenna's fractional bandwidth, gain and efficiency characteristics.

VI. CONCLUSION

Radiation performance ESA is limited by its physical dimensions. It is shown here using theoretical analysis and numerical modelling that H-shaped ESA can be realized with a significantly wider fractional bandwidth than is possible otherwise. The theoretical analysis reveals that this is possible by incorporating a frequency dependent negative reactance in the antenna structure, which can be only be accomplished by using an active circuit or negative impedance converter circuit. An analytical expression is developed to show the relationship between the required inductance value and the resonance frequency of the antenna, which enables the determination of the inductance variation required by the negative impedance converter to achieve a given bandwidth from the ESA.

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Dr. Alibakhshikenari was a recipient of the International Postgraduate Research (Ph.D.) Scholarship (IPRS) by Italian Government in 2016 for three years, the 47th and 48th European Microwave Conference (EuMC) Young Engineer Prize, in 2017, Nuremberg, Germany, and in 2018, Madrid, Spain, where he has presented his articles, and two years postdoctoral research grant awarded by the Electronic Engineering Department, University of Rome "Tor Vergata," in November 2019. On August 2019, he gave an invited lecture entitled "Metamaterial Applications to Antenna Systems" with the Department of Information and Telecommunication Engineering, Incheon National University, Incheon, South Korea, which was in conjunction with the 8th Asia-Pacific Conference on Antennas and Propagation (APCAP 2019), where he was the Chair of the Metamaterial Session. He is serving as an Associate Editor for *Microwave and Optical Technology Letters, IET Journal of Engineering*, and the *International Journal of Electrical and Computer Engineering* (IJECE), and as a Section Editor for the *International Journal of Sensors Wireless Communications and Control* and *HighTech and Innovation Journal*, and as a Guest Editor for two special issues entitled "Millimeter-wave and Terahertz Applications of Metamaterials" in *Applied Sciences*, and entitled "Innovative Antenna Systems: Challenges, Developments, and Applications" in *Electronics*. In April 2020, his article entitled "High-Gain Metasurface in Polyimide On-Chip Antenna Based on CRLH-TL for Sub Terahertz Integrated Circuits" published in *Scientific Reports* was awarded as Best Month Paper at the University of Bradford, U.K.

BAL S. VIRDEE (Senior Member, IEEE) received the B.Sc. and M.Phil. degrees in communications-engineering from the University of Leeds, U.K., and the Ph.D. degree in electronic-engineering from the University of London, U.K. He has worked in industry for various companies including Philips, U.K., as an R&D Engineer and Filtronic-Components Ltd., as a Future Products Developer in RF/microwave communications. He has taught at several academic institutions before joining London Metropolitan University, where he is currently a Professor of microwave-communications with the Faculty of Life

Sciences & Computing, also the Head of the Center for Communications-Technology, and also the Director of London Metropolitan-Microwaves. His research, in collaboration with industry and academia, interests include microwave wireless communications encompassing mobile-phones to satellite-technology.

Prof. Virdee is a Fellow of IET. He has chaired technical sessions at IEEE international conferences and published numerous research-articles. He is an Executive-Member of IET's Technical and Professional Network Committee on RF/Microwave-Technology.

FRANCISCO FALCONE (Senior Member, IEEE) received the degree in telecommunication engineering and the Ph.D. degree in communication engineering from the Universidad Pública de Navarra (UPNA), Spain, in 1999 and 2005, respectively. From February 1999 to April 2000, he was the Microwave Commissioning Engineer with Siemens-Italtel, deploying microwave access systems. From May 2000 to December 2008, he was a Radio Access Engineer with Telefónica Móviles, performing radio network planning and optimization tasks in mobile network deployment. In January 2009, as a Co-Founding Member, he has been the Director of Tafco Metawireless, a spin-off company from UPNA, until May 2009. In parallel, he is currently an Assistant Lecturer with the Electrical and Electronic Engineering Department, UPNA, from February 2003 to May 2009. In June 2009, he becomes an Associate Professor with the EE Department, being the Department Head, from January 2012 to July 2018. From January 2018 to May 2018, he was a Visiting Professor with the Kuwait College of Science and Technology, Kuwait. He is also affiliated with the Institute for Smart Cities (ISC), UPNA, which hosts around 140 researchers. He is currently acting as the Head of the ICT Section. His research interests include computational electromagnetics applied to the analysis of complex electromagnetic scenarios, with a focus on the analysis, design, and implementation of heterogeneous wireless networks to enable context-aware environments. He has more than 500 contributions in indexed international journals, book chapters, and conference contributions. He was a recipient of the CST 2003 and CST 2005 Best Paper Award, the Ph.D. Award from the Colegio Oficial de Ingenieros de Telecomunicación (COIT), in 2006, the Doctoral Award UPNA, 2010, 1st Juan Gomez Peñalver Research Award from the Royal Academy of Engineering of Spain, in 2010, the XII Talgo Innovation Award 2012, the IEEE 2014 Best Paper Award, 2014, the ECSA-3 Best Paper Award, 2016, and the ECSA-4 Best Paper Award, 2017.

ERNESTO LIMITI (Senior Member, IEEE) received the Laurea and Laurea Magistrale degrees in electronic engineering from the University of Rome "Tor Vergata". He has been a Full Professor of electronics with the Engineering Faculty, University of Rome "Tor Vergata," since 2002, where has also been a Research and Teaching Assistant since 1991 and an associate professor since 1998. He represents the University of Rome "Tor Vergata" in the governing body of the Microwave Engineering Center for Space Applications (MECSA), an inter-university center among several Italian Universities. He has been elected to represent the Industrial Engineering Sector, Academic Senate of the University, from 2007 to 2010 and from 2010 to 2013. He is actually the President of the Consortium "Advanced Research and Engineering for Space," ARES, formed between the University and two companies. He is actually the President of the Laurea and Laurea Magistrale degrees from the University of Rome "Tor Vergata." His research interest includes microwave and millimetre-wave electronics. The first one is related to characterisation and modelling for active and passive microwave and millimetre-wave devices. Regarding active devices, the research line is oriented to the small-signal, noise and large signal modelling. Regarding passive devices, equivalent-circuit models have been developed for interacting discontinuities in microstrip, for typical MMIC passive components (MIM capacitors) and to waveguide/coplanar waveguide transitions analysis and design. For active devices, new methodologies have been developed for the noise characterisation and the subsequent modelling, and equivalent-circuit modelling strategies have been implemented both for small and large-signal operating regimes for GaAs, GaN, SiC, Si, InP, and MESFET/HEMT devices. The second line is related to design methodologies and characterisation methods for low noise circuits. The main focus is on cryogenic amplifiers and devices. His collaborations are currently ongoing with the major radioastronomy institutes all around Europe within the frame of FP6 and FP7 programmes (RadioNet). Finally, the third line is in the analysis methods for nonlinear microwave circuits. In this line, novel analysis methods (Spectral Balance) are developed, together with the stability analysis of the solutions making use of traditional (harmonic balance) approaches. The above research lines have produced more than 250 publications on refereed international journals and presentations within international conferences. He acts as a referee of international journals of the microwave and millimetre wave electronics sector and is in the steering committee of international conferences and workshops. He is actively involved in research activities with many research groups, both European and Italian, and he is in tight collaborations with high-tech Italian (Selex - SI, Thales Alenia Space, Rheinmetall, Elettronica S.p.A., Space Engineering . . .) and foreign (OMMIC, Siemens, UMS, . . .) companies. He contributed, as a researcher and/or as unit responsible, to several National (PRIN MIUR, Madess CNR, and Agenzia Spaziale Italiana) and international (ESPRIT COSMIC, Manpower, Edge, Special Action MEPI, ESA, EUROPA, Korrigan, RadioNet FP6, and FP7 . . .) projects. Regarding teaching activities, he teaches, over his institutional duties in the frame of the Corso di Laurea Magistrale in Ingegneria Elettronica, "Elettronica per lo Spazio," within the master's course in Sistemi Avanzati di Comunicazione e Navigazione Satellitare. He is a member of the committee of the Ph.D. program in telecommunications and microelectronics from the University of Roma Tor Vergata, tutoring an average of four Ph.D. candidates per year.

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