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Traveling-wave antenna based on metamaterial transmission line structure for use in multiple wireless communication applications

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ABSTRACT

This paper introduces a left-handed metamaterial traveling-wave antenna (TWA) based on metamaterial transmission-line structure to enhance the gain and radiation efficiency of the antenna without trading on its fractional bandwidth. The antenna consists of a series of coupled unit-cells comprising “X-shaped” slots which are inductively terminated to ground. Effective aperture of the antenna can be increased by increasing the number of unit-cells. The consequence of this is enhanced gain and radiation efficiency performance with no adverse affect on its fractional bandwidth. The antenna’s characterizing parameters were extracted using 3D electromagnetic simulation tool (HFSS$^{\text{TM}}$), and the antenna was fabricated using standard PCB manufacturing techniques on a 1.6 mm thick dielectric substrate with permittivity of 2.2. The antenna operates from 0.4 GHz to 4.7 GHz. The antenna has an electrical size of $0.017\lambda_0 \times 0.006\lambda_0$ - $\times\ 0.002\lambda_0$, where λ_0 is free space wavelength at 400 MHz. The proposed antenna is significantly smaller than its conventional counterparts. Antenna’s measured optimum gain and radiation efficiency are 2 dBi and 65%, respectively, at 2.5 GHz. These features make the antenna attractive for use in multiple wireless communication applications.

1. Introduction

Printed planar antennas are very popular as they are low profile, light weight, and consist of a metal layer separated from the ground plane by a dielectric substrate [1,2]. Advantages of printed planar antennas are that they radiate energy with moderately high gain in a direction perpendicular to the substrate and can be fabricated using low cost printed circuit board techniques [3–5]. The basic operating principle of a printed antenna is that the space between the metal patch and ground plane acts like a section of parallel plate waveguide. Neglecting radiation loss, the edge of patch is an open circuit, so that energy reflects and remains contained between the patch and the ground plane to create a high-Q factor device with a narrow bandwidth. Hence, patch antennas have limited bandwidth; this means that the specified input impedance of the antenna is maintained only over a small range around its central operating frequency. To overcome this challenge several metamaterial (MTM) structures like Split Ring Resonator (SRR) [6], Spiral, Rod, Omega, S-shape, Symmetric Rings etc. have already been explored by previous researchers [7,8].

This paper introduces a new and distinct metamaterial unit-cell which is used to implement a traveling-wave planar antenna structure referred to here as “X-shaped” antenna. The proposed antenna is based on metamaterial unit cells created using X-shaped slots which are inductively terminated to the ground plane with a metal via-hole. The structure exhibits negative permittivity and permeability over a specific frequency range and negative refractive index. By coupling together a number of these unit-cells in series we can increase the aperture of the antenna thereby increasing its gain and radiation efficiency without adversely affecting the fractional bandwidth of the antenna. This property is contrary to that observed in conventional antennas.

2. Design methodology

The proposed traveling wave antenna, shown in Fig. 1, consists of a rectangular radiation patch on which are constructed four

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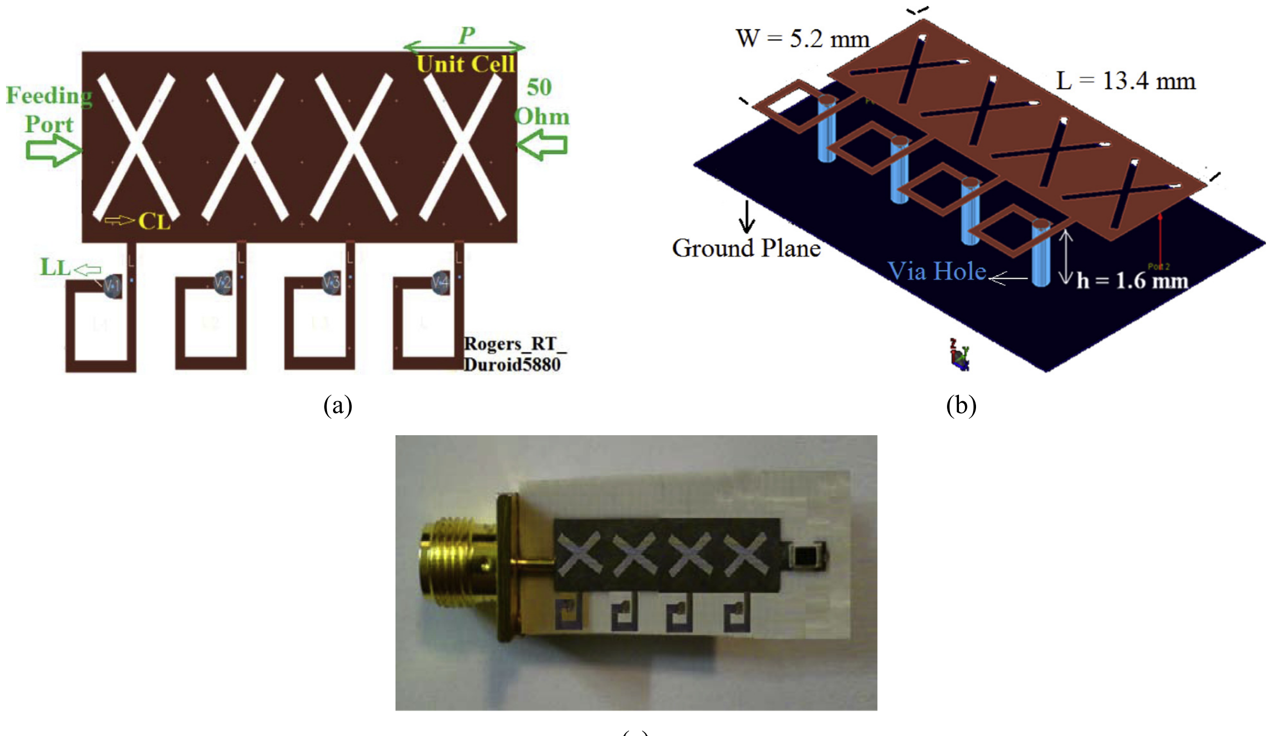

(a) (b) (c)

Fig. 1. Antenna layout, (a) top layer, (b) isometric view of simulation model, and (c) fabricated prototype.

unit-cells comprising the X-shaped slot which is terminated to ground through an inductive stub. The antenna was designed and constructed on Rogers RT/Duroid5880 (low loss) substrate with tanδ = 0.0009, dielectric constant (ε_r) of 2.2 and height (h) of 1.6 mm. Two waveguide ports are defined at the left and right-hand side, as shown in Fig. 1(a), where port-1 is excited by the input signal, and port-2 is matched to 50 ohm load using SMD1206 that is terminated to ground. The proposed antenna configuration provides a guiding structure for a traveling wave as the main radiating mechanism. Here the surface currents that generates the RF signal travels through the antenna in one direction from the input port 1 to a terminated port 2, which is in contrast to conventional standing wave or resonant antenna, such as the monopole or dipole. The results presented below show that the proposed traveling wave antenna, which is a non-resonant structure, exhibits a wider operational bandwidth.

The equivalent circuit model of the antenna unit-cell is shown in Fig. 2(a). The unit-cell essentially acts like the series left-handed (LH) capacitance (C_L), and the rectangular stub acts like a shunt LH inductor (L_L). The shunt right-handed (RH) capacitance (C_R) and the series RH inductance (L_R) represent parasitic effects which are unavoidable as they are generated by gaps between patch and ground plane due to the current flowing over the patch. Losses of the structure are modeled by R_R, G_R, R_L and G_L. R_R and G_R are RH losses and R_L and G_L are LH losses. Essential characteristics of a CRLH unit cell can be inferred from analysis of the loss-less equivalent circuit as described in [8]. At low frequencies, L_R and C_R tend to be short and open, respectively, so that the equivalent circuit is essentially reduced to the series-C_L/shunt-L_L circuit, which is left-handed since it has antiparallel phase and group velocities; this LH circuit is of highpass nature; therefore, below a certain cutoff, a LH stopband is present. At high frequencies, C_L and L_L tend to be short and open, respectively, so that the equivalent circuit is essentially reduced to the series-L_R/shunt-C_R circuit, which is right-handed since it has parallel phase and group velocities; this LH circuit is of lowpass nature; therefore, above a certain cutoff, a RH stopband is present. The analysis in [8] shows that the left-handed structure exhibits negative permeability and permittivity. Unlike conventional or normal right right-handed unit cell based structures, the distinguishing feature of a left-handed structure is its dimensions; in particular, its length is independent of guided wavelength, which makes the structure significantly smaller. Dispersion diagram of the CRLH unit cell structure shown in Fig. 2(b) was determined by substituting the S parameters, which were obtained with HFSS™, in Eq. (1) as described in [8]:

$$\beta = cos^{-1}\left(\frac{1 - S_{11}S_{12} + S_{12}S_{21}}{2S_{21}}\right)\Big/ l \tag{1}$$

The dispersion diagram shows the range of LH characteristics (0.65–2.25 GHz) and the range of RH characteristics (2.25–4.4 GHz). The slow-wave and fast-wave regions have been indicated in Fig. 2(b). The expression of Air-line, which demarcates the fast-wave ($b < K_o$) and slow-wave ($b > K_o$) regions (where K_o is the free space wavenumber) is given by Eq. (2),

$$\text{Air-line} = \frac{\omega p}{c} \tag{2}$$

where p is the period of the unit-cell as shown in Fig. 1, and c is the speed of light.

The characterizing parameters of the antenna structure are: $L = 13.4$ mm, $W = 5.2$ mm, $h = 1.6$ mm, $L_R = 3.25$ nH, $C_L = 4.1$ pF, $C_R = 1.3$ pF and $L_L = 5.2$ nH, which were extracted from the simulation model using HFSS™. The prototype antenna, shown in Fig. 1(c), was fabricated using standard manufacturing techniques. Each of the unit-cell occupies an area of 2.5×5.2 mm^2 ($0.003\lambda_0 \times 0.006\lambda_0$, where λ_0 is free space wavelength at 400 MHz). Considering the size of SMD (3.4 mm), the overall size of the antenna is $13.4 \times 5.2 \times 1.6$ mm^3 or $0.017\lambda_0 \times 0.006\lambda_0 \times 0.002\lambda_0$.

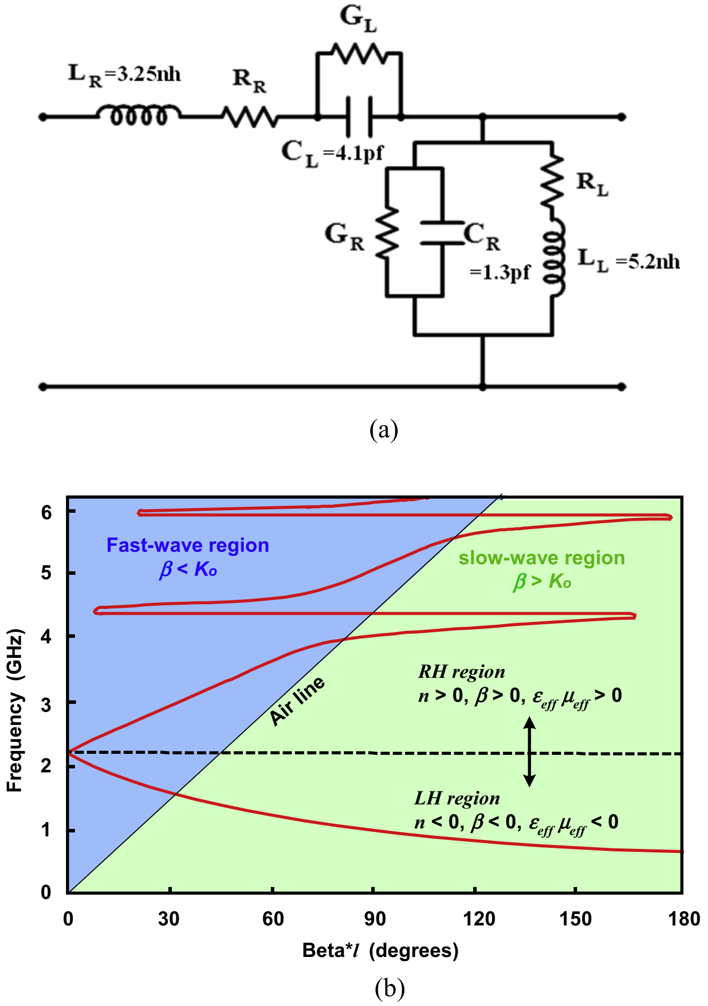

Fig. 2. (a) Equivalent circuit model of the unit-cell, and (b) the dispersion diagram of the loss-less CRLH unit-cell.

Antennas that operate in a resonance configuration have limited bandwidth due to the destructive interference of the waves. Bandwidth can be increased by blocking the standing wave and instead using a traveling wave. The proposed antenna provides a guiding structure for a traveling wave as the main radiating mechanism. In this configuration, the voltage and current are in phase and have the same $e^{-j\gamma z}$ distribution along the length, where $\gamma = Kz = \beta - j\alpha$. The lower limit of the leaky wave bandwidth is the frequency at which $\alpha = \beta$ and the upper limit occurs when $\beta = K_o$. In this case the surface currents that generates the RF signal travels through the antenna in one direction from the input port 1 to a terminated port 2, which is in contrast to conventional standing wave or resonant antenna, such as the monopole or dipole. The results presented show that the proposed traveling wave antenna, which is a non-resonant structure, exhibits a wider operational bandwidth.

The simulated and measured reflection coefficient response of the proposed TWA is shown in Fig. 3. It can be discerned from Fig. 3 that the antenna highly receptive at three distinct frequencies, i.e. 1.4, 2.65 and 3.7 GHz. The simulated bandwidth of the antenna (for $S_{11} < -10$ dB) is 4.55 GHz from 300 MHz to 4.85 GHz, which corresponds to a fraction bandwidth of 176.7%. Measurements show the proposed antenna operates across a frequency of 400 MHz to 4.7 GHz (for $S_{11} < -10$ dB), which corresponds to a fractional bandwidth of 168.62%.

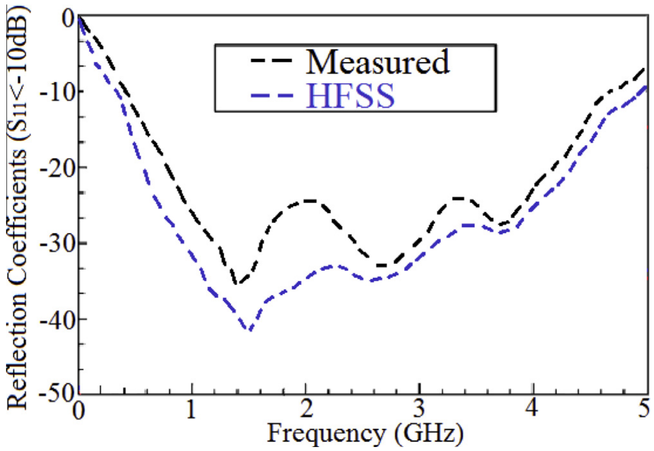

Fig. 3. Simulated and measured reflection coefficients response.

The measured radiation gain and efficiency of the proposed antenna at spot frequencies of 0.4, 1.5, 2.5, 3.5 and 4.7 GHz are 0.05 dBi and 8%, 1.5 dBi and 45%, 2 dBi and 65%, 1.5 dBi and 42%, and 0.8 dBi and 30%, respectively. The maximum gain and efficiency of 2 dBi and 65%, respectively, are achieved at 2.5 GHz. The measured E-plane and H-plane radiation patterns of the

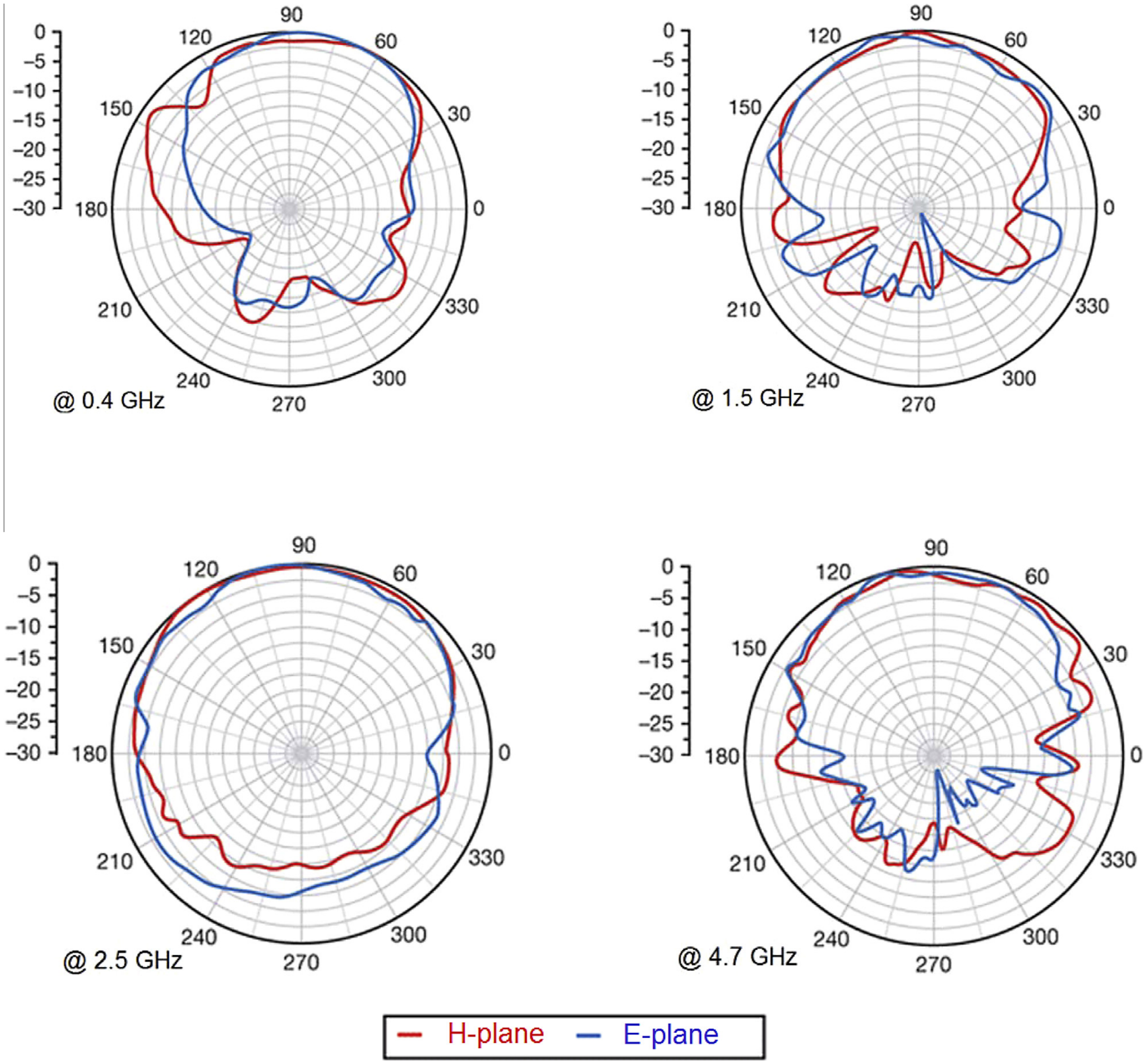

Fig. 4. Measured E-plane and H-plane radiation patterns of the proposed antenna.

Table 1
Comparison of the proposed TWA with other antennas (Gain and Efficiency are optimum values).

Ref.	Dimensions	Freq. BW/Fractional BW	Gain (dBi)	Efficiency (%)
[1]	$20.4 \times 6.8 \times 0.8$ mm^3 ($0.39\lambda_0 \times 0.13\lambda_0 \times 0.015\lambda_0$ @ 5.8 GHz)	5.8–7.3 GHz/23%	4.8	78
[2]	$7.2 \times 5 \times 0.8$ mm^3 ($0.11\lambda_0 \times 0.079\lambda_0 \times 0.012\lambda_0$ @ 4.7 GHz)	4.7–6.7 GHz/35.08%	3.6	60.3
[9]	$12 \times 12 \times 3.33$ mm^3 ($0.09\lambda_0 \times 0.09\lambda_0 \times 0.02\lambda_0$ @ 2.34 GHz)	2.34–2.54 GHz/8.19%	1	20
[10]	$20 \times 25 \times 0.8$ mm^3 ($0.22\lambda_0 \times 0.28\lambda_0 \times 0.009\lambda_0$ @ 3.45 GHz)	3.45–3.75 GHz/8.33%	2	25
[11]	$60 \times 5 \times 5$ mm^3 ($0.16\lambda_0 \times 0.013\lambda_0 \times 0.013\lambda_0$ @ 0.82 GHz)	0.82–2.48 GHz/100.6%	0.45	53.6
This work	$13.4 \times 5.2 \times 1.6$ mm^3 ($0.017\lambda_0 \times 0.006\lambda_0 \times 0.002\lambda_0$ @ 0.4 GHz)	0.4–4.7 GHz/168.62%	2	65

antenna at spot frequencies of 0.4, 1.5, 2.5 and 4.7 GHz are plotted in Fig. 4. It is clear from Fig. 4 that the radiation patterns of the proposed antenna have unidirectional characteristics. In addition, the antenna configuration effectively increases the size of the antenna's aperture to enhance its gain and radiation characteristics.

Compared to traditional capacitor based CRLH unit cell, the paper introduces (i) a novel method of implementing the CRLH unit cell by etching a slot in the transmission-line which is inductively shorted to ground; and (ii) the unit cell is used to realize a traveling wave radiator which is significantly shorter than a traditional traveling wave antennas as the dimensions of the antenna are independent of the wavelength. The features of the proposed antenna are: (i) compactness (with physical dimensions of $13.4 \times 5.2 \times 1.6\,\text{mm}^3$ and electrical dimensions of $0.017\lambda_0$ - $\times\ 0.006\lambda_0 \times 0.002\lambda_0$ at 400 MHz); (ii) low profile and lightweight; (iii) broad bandwidth performance of 4.3 GHz from 0.4 to 4.7 GHz, which corresponds to a large fractional bandwidth of ~170%; (iv) unidirectional radiation patterns in both E- and H- planes over the entire operating frequency band; (v) and maximum gain and efficiency of 2 dBi and 65%, respectively, at 2.5 GHz. These features make the antenna attractive for use in multiple wireless communication applications.

The measured results of the proposed traveling-wave antenna are compared with other CRLH unit-cell and conventional antennas in Table 1. These results show the operating frequency and fractional bandwidth of the proposed antenna is superior to CRLH unit-cell antennas presented in references [1] and [2]. The operating frequency is better than antennas in [1] and [2] by a factor of 2.87 and 2.15, respectively; and the fractional bandwidth is better than antennas in [1] and [2] by a factor of 7.33 and 4.8, respectively.

3. Conclusion

A novel traveling-wave planar antenna is presented based on metamaterial technology for enhanced gain and radiation efficiency without adversely affecting is bandwidth performance. The miniature antenna consists of coupled metamaterial unit-cells comprising X-shaped slots and shunted inductive stubs, which are implemented on a rectangular patch. The proposed antenna is easy to fabricate using conventional PCB manufacturing techniques.

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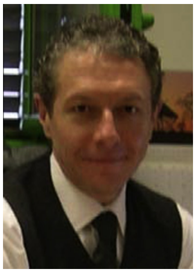

Ernesto Limiti is a full professor of Electronics in the Engineering Faculty of the University of Roma Tor Vergata since 2002, after being research and teaching assistant (since 1991) and associate professor (since 1998) in the same University. His research activity is focused on three main lines, all of them belonging to the microwave and millimetre-wave electronics area. 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 as well as devices on diamond substrates. Novel methodologies have been developed and equivalent-circuit modelling strategies have been implemented both for small and large-signal operating regimes for different device technologies. Design methodologies and characterisation methods for low noise devices and circuits are also in focus, as well as the analysis and design methodologies for linear and nonlinear microwave circuits. The above research lines have produced more than 300 publications on refereed international journals and presentations within international conferences. Ernesto Limiti acts as a referee of international journals of the microwave and millimetre wave electronics sector and he is in the steering committee of international conferences and workshops.