HEMT–HBT Matrix Amplifier

Claudio Paoloni

***Abstract*—A novel matrix amplifier using simultaneously high electron-mobility transistors (HEMT's) and heterojunction bipolar transistors (HBT's) is proposed in this paper. The amplifier includes HEMT's in the first tier and HBT's in the second tier. The HEMT–HBT matrix amplifier in comparison to the HEMT matrix amplifier presents a notable lower dc power consumption without remarkable gain and bandwidth reduction, maintaining the advantage of using HEMT's in the first tier. A theory to demonstrate that the amplifier performance can be optimize if the HBT's in the second tier are properly chosen is also proposed. A comparison among the HEMT–HBT matrix amplifier, HEMT matrix amplifier, and HBT matrix amplifier is also presented.**

***Index Terms*—Distributed amplifier, HEMT, heterojunction bipolar transistor, matrix amplifier, MMIC's.**

I. Introduction

MONOLITHIC-MICROWAVE integrated-circuit (MMIC) matrix amplifiers are one of the most convenient solutions for broad-band applications when a high gain-bandwidth product is required [1]–[5]. High gain on a multioctave frequency range, up to millimeter-wave frequencies, together with compact layout and, consequently, reduced chip cost, are the main characteristics of matrix amplifiers. The high electron-mobility transistor (HEMT), due to its gain and low-noise features, has been demonstrated as the best active device to realize this kind of amplifier. An HEMT matrix amplifier showing 20-dB gain and 5.5-dB noise figure in the 6–21-GHz frequency band was reported in [4]. A frequency band up to 52 GHz and 9-dB gain was obtained for the HEMT matrix amplifier reported in [5].

Nevertheless, the advance in heterojunction bipolar transistor (HBT) technology has permitted the use of HBT's in distributed and matrix amplifiers with remarkable results [6]–[8]. The first HBT matrix amplifier achieved 9.5-dB gain with a 3-dB bandwidth to 24 GHz [7]. A dc power consumption of about 60 mW was also reported. It is noteworthy that this value is significantly lower in comparison to the typical dc power consumption of HEMT matrix amplifier (several hundreds of milliwatts). Typically, HBT matrix amplifiers presents higher noise figure than HEMT matrix amplifiers.

Recently, the introduction of HEMT–HBT-selected molecular beam epitaxy (MBE) integration technology [9], [10] has provided new opportunities to designers. The integration on the same chip of HEMT's and HBT's permits to realize circuits that merge the advantages of the two different active devices.

In this paper, a two-tier matrix amplifier using HEMT's and HBT's simultaneously is proposed. The purpose of this configuration is to obtain high-gain performance in a multioctave frequency band together with low dc power consumption, maintaining most of the advantages of HEMT's (i.e., noise figure, bandwidth). The first tier consists of HEMT's. The HEMT's in the second tier are replaced by HBT's to get gain at low dc power consumption.

Manuscript received April 15, 1998.

The author is with the Department of Electrical Engineering, University of Roma "Tor Vergata," 00133 Rome, Italy.

Publisher Item Identifier S 0018-9480(00)06529-7.

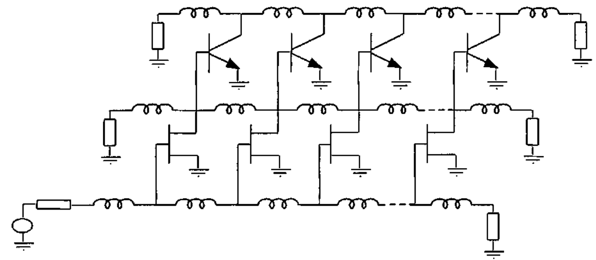

Fig. 1. Schematic of the HEMT–HBT matrix amplifier.

As was demonstrated in [11], the noise contribution of the second tier of the matrix amplifier is a small portion of the amplifier's overall noise figure. Therefore, it is expected that using HBT's in the second tier does not significantly degrade the overall noise figure with respect to the use of HEMT's in the second tier.

A study on the attenuation on the central line of the HEMT–HBT and HEMT matrix amplifiers is also performed. The results will demonstrate that a proper choice of the HBT can optimize the performance of the HEMT–HBT matrix amplifier.

To show the advantages of the proposed solution, the HEMT–HBT matrix amplifier is compared to the HEMT and HBT matrix amplifiers.

II. Theory

The matrix amplifier (Fig. 1) can be schematized, assuming a unilateral model for the HEMT [see Fig. 2(a)] and the HBT [see Fig. 2(b)], by three artificial transmission lines (input, central, and output) coupled by g_m. According to the distributed amplifier theory, the three transmission lines must have the same phase velocity. The theoretical cutoff frequency of the matrix amplifier is

$$f_c = \frac{1}{\pi\sqrt{LC_i}} \tag{1}$$

where C_i is the input capacitance of the used active device (C_π if HBT or $C_{\rm gs}$ if HEMT) and L is the inductance to define the characteristic impedance of the artificial transmission line $Z_0 = \sqrt{L/C_i} = 50\ \Omega$.

In case of an HBT, the input capacitance C_π is typically higher than the $C_{\rm gs}$ of the HEMT. Even if the g_m of the HBT is higher than the g_m of the HEMT, the gain–bandwidth product

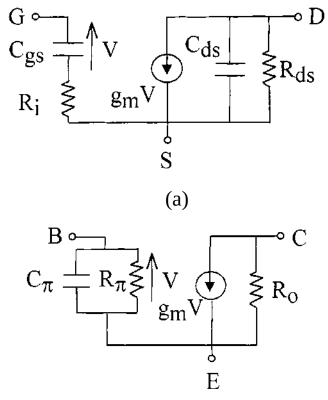

Fig. 2. (a) HEMT unilateral model. (b) HBT unilateral model.

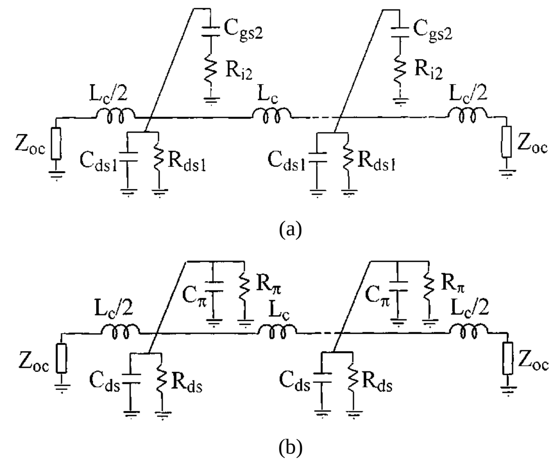

Fig. 3. (a) Central line of the HEMT matrix amplifier. (b) Central line of the HEMT–HBT matrix amplifier.

of the HBT distributed amplifier is lower than the HEMT distributed amplifier [4].

In a matrix amplifier topology where HEMT's are included in the first tier and HBT's are placed in the second tier, this aspect loses part of its importance in terms of frequency band and gain.

The higher input capacitance of the HBT is absorbed in the central line, whose characteristic impedance can be different from 50 Ω without degradation of the input and the output matching.

The characteristic impedance of the central line that provides the same phase velocity of the input line is [12]

$$Z_{0c} = \sqrt{\frac{L_c}{C_{o1} + C_{i2}}} \neq Z_0 \tag{2}$$

where

$$L_c = \frac{1}{\pi^2 f_c^2 (C_{o1} + C_{i2})}$$

C_{o1} is the output capacitance of the devices in the first tier and C_{i2} is the input capacitance of the devices in the second tier. Therefore, L_c determines the cutoff frequency of the central line at the same value of the cutoff frequency of the input line, even if the sum of the output capacitance of the HEMT $(C_{o1} = C_{\rm ds})$ and the input capacitance of the HBT $(C_{i2} = C_\pi)$ is higher than $C_{\rm gs}$.

The effect of the attenuation on the input and output transmission lines on the frequency response of the distributed amplifier was already analyzed [13]. These results are also valid for the matrix amplifier. On the contrary, the attenuation on the central line of the matrix amplifier must be investigated. An expression of the attenuation on the central line of the HEMT matrix amplifier [see Fig. 3(a)] is derived (3), shown at the bottom of this page, according to the theory in [13] where

$$\omega_{cc} = \frac{2}{\sqrt{C_{\rm ds1} L_c}}$$
$$\omega_m = \frac{1}{R_{\rm ds1} C_{\rm gs2}}$$
$$\omega_g = \frac{1}{R_{i2} C_{\rm gs2}}$$
$$\omega_{\rm dd} = \frac{1}{R_{\rm ds1} C_{\rm ds1}}.$$

The subscripts 1 and 2 refer to the HEMT's in the first and second tiers, respectively.

The central line of the HEMT–HBT matrix amplifier [see Fig. 3(b)] has the same topology of the output line of the distributed amplifier. The attenuation is expressed as [13]

$$A_{cc} = \frac{\dfrac{\omega_d}{\omega_c}}{\sqrt{\left(1 - \dfrac{\omega^2}{\omega_c^2}\right)}} \tag{4}$$

where

$$\omega_c = \frac{1}{2\pi f_c} \quad \text{and} \quad \omega_c = \frac{R_{\rm ds} + R_\pi}{(C_{\rm ds} + C_\pi) R_{\rm ds} R_\pi}.$$

To compare the frequency behavior of A_c and A_{cc} for a given couple of HEMT and HBT, the difference A_c–A_{cc} between the two functions was adopted. In Fig. 4, the curves A_c–A_{cc} are plotted as a function of the frequency normalized to the cutoff frequency f_c. The values of the circuit elements $C_{\rm ds}$, $R_{\rm ds}$, R_i, R_π, and C_π were varied according to the range and the reciprocal levels they typically assume in HEMT's and HBT's. The

$$A_c = \frac{\omega_d \left(1 + \dfrac{\omega^2}{\omega_g^2} + \dfrac{\omega^2}{\omega_g \omega_m}\right)}{\sqrt{\left(1 + \dfrac{\omega_{\rm dd}}{\omega_m} + \dfrac{\omega^2}{\omega_g^2}\right)\left(\omega_{cc}^2 \left(1 + \dfrac{\omega^2}{\omega_g^2}\right) - \omega^2 \left(1 + \dfrac{\omega_{\rm dd}}{\omega_m} + \dfrac{\omega^2}{\omega_g^2}\right)\right)}} \tag{3}$$

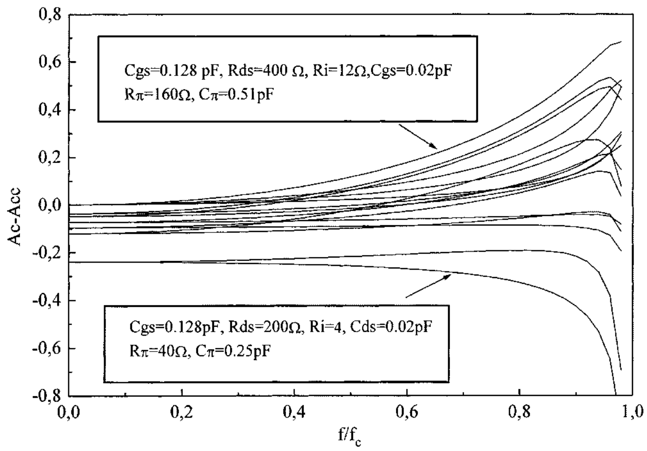

Fig. 4. Difference between the attenuation on the central line of the HEMT matrix amplifier (A_c) and the HEMT–HBT matrix amplifier (A_{cc}) for different couples of HEMT and HBT.

value of $C_{\rm gs}$ was fixed at $C_{\rm gs} = 0.128$ pF without loss of generality. The values of the circuit elements are indicated in the figure for reference to obtain only the upper and lower curves. Besides, to make the figure clear, only a small number of the curves generated with intermediate values of the circuit parameters are plotted. In many cases, the difference A_c–A_{cc} is positive in most of the frequency band. It means that the central line of the HEMT matrix amplifier has higher attenuation than the central line of the HEMT–HBT matrix amplifier. Therefore, if the HEMT and HBT are properly chosen, a less attenuated central line can be obtained with respect to the use of HEMT's only. This is an important outcome since, even if the HBT has performance worse than the HEMT, the matrix topology partially offsets the disadvantage. The difference of the performance between the HEMT and HBT, when HBT's are inserted in the second tier of the matrix amplifier, is reduced. It can be estimated from Fig. 4 that, to obtain a central line with less attenuation, $C_{\rm gs}$ must be lower than C_π (more than two times). Of course, the contribution of the other circuit elements is not negligible, thus, a verification by comparing (3) to (4) is advisable.

III. HEMT–HBT Matrix Amplifier Performance

The advantages of the HEMT–HBT matrix amplifier are demonstrated in the following. The performance of the HEMT–HBT 2 $\times$ 4 matrix amplifier is compared with the HEMT 2 $\times$ 4 matrix amplifier and the HBT 2 $\times$ 4 matrix amplifier. The same active devices, same topology, and same design constraints were adopted in the three cases to obtain the best performance from each amplifier. HEMT's [14] and HBT's [6] reported in literature were used for the purpose of this paper since a circuit realization is beyond the scope of this paper. Even if these active devices belong to different technological processes, it can be assumed that equivalent performance could be achieved if they were devices of the same process. It must be considered important, not the absolute value of the performance of each amplifier, but the relative difference in performance among the three amplifiers. This approach is applied only with the scope of demonstrating the validity of the theory exposed in the previous sections.

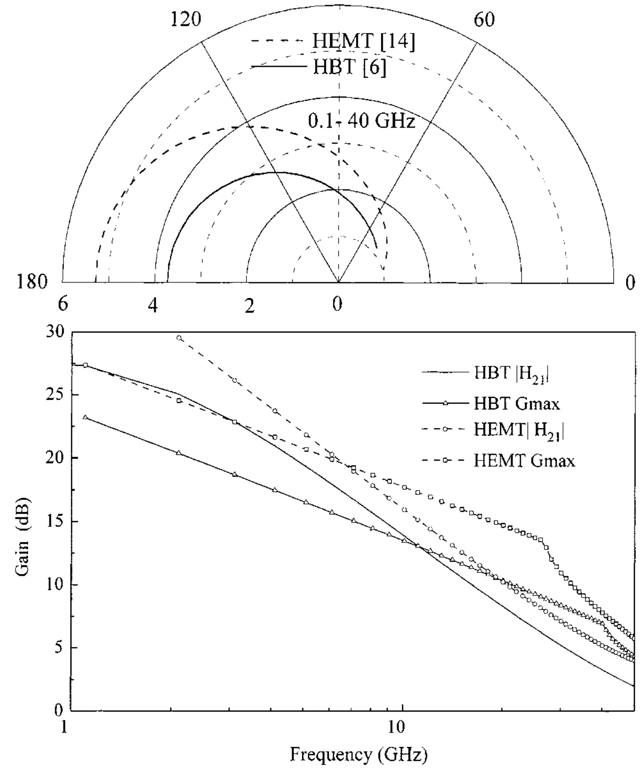

Fig. 5. (a) S_{21}, (b) $|H_{21}|$, and $G_{\max}$ of the HEMT in [14] and the HBT in [6].

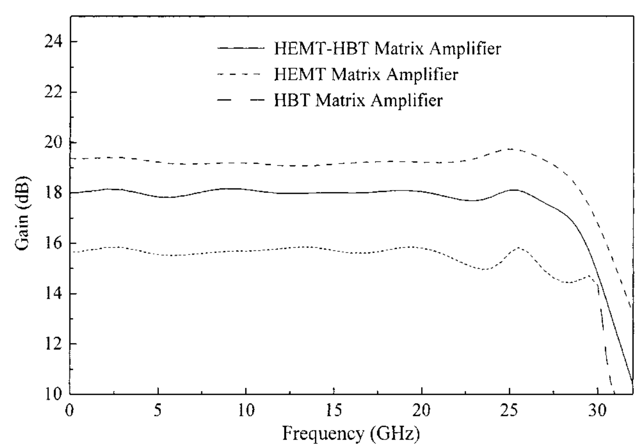

Fig. 6. Gain of the HEMT–HBT matrix amplifier compared to the HEMT matrix amplifier and the HBT matrix amplifier.

For reference, S_{21}, $|H_{21}|$, and $G_{\max}$ of the chosen HEMT and HBT are shown in Fig. 5. It can be noticed that the HEMT has higher gain in a wider frequency band than the HBT.

The three matrix amplifiers were designed and simulated at a layout level imposing flat gain and less than -12 dB of input and output return loss on a 3-dB bandwidth to 30 GHz. All the simulations were performed with Libra.

The gains of the three amplifiers are compared in Fig. 6. The HEMT matrix amplifier obtains the higher gain (more than 19 dB), while the HBT matrix amplifier shows the lower gain (less than 16 dB). It is noteworthy that the gain of the

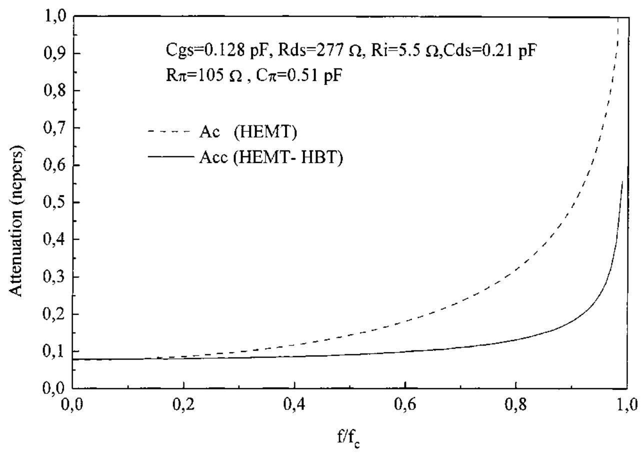

Fig. 7. Attenuation on the central line of the HEMT–HBT matrix amplifier (A_{cc}) compared to the HEMT matrix amplifier (A_c).

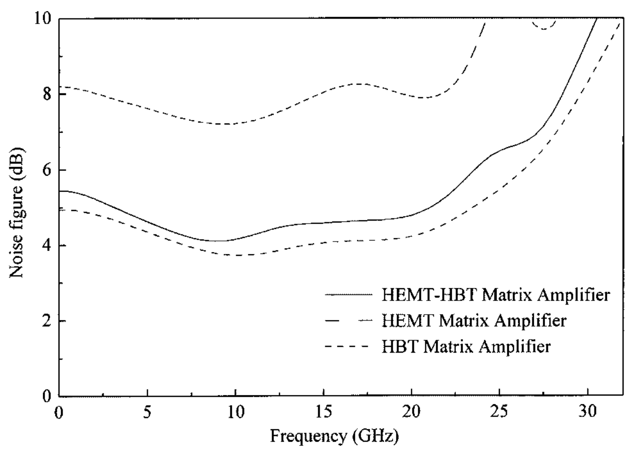

Fig. 8. Noise figure of the HEMT–HBT matrix amplifier compared to the HEMT matrix amplifier and the HBT matrix amplifier.

HEMT–HBT matrix amplifier (18 dB) is only 7% lower than the gain of the HEMT matrix amplifier. By analyzing these data, it can be deduced that the gain of the HEMT–HBT matrix amplifier is at least 0.5 dB higher than it should be. This result can be explained comparing the attenuation on the central line for the HEMT and the HEMT–HBT matrix amplifier (Fig. 7). The central line of the HEMT matrix amplifier has a higher attenuation than the central line of the HEMT–HBT matrix amplifier. This phenomenon is particularly evident in the upper side of the frequency band. Therefore, even if the HEMT gains more than the HBT, the last one, when placed in the second tier, suffers less attenuation.

Another important result regards the dc power consumption. Assuming a bias of 5 V, the HEMT matrix amplifier consumes about 760 mW, against about 420 mW of the HEMT–HBT matrix amplifier. More than 40% dc power-consumption reduction is obtained.

The noise figures of the three amplifiers are compared in Fig. 8. The noise parameters of the HBT were derived by using the SPICE noise model. According to the noise theory for matrix amplifiers [11], the noise figure of the HEMT–HBT matrix amplifier does not significantly degrade with respect to the noise figure of the HEMT matrix amplifier.

IV. Conclusions

A novel topology of matrix amplifier including HEMT's in the first tier and HBT's in the second tier has been presented. The electrical characteristics of HEMT's and HBT's have been combined to optimize the amplifier performance. The HEMT–HBT matrix amplifier presents the gain and bandwidth comparable with the HEMT matrix amplifier, even in the case of an HBT with a worse performance than the HEMT. In addition, a remarkable reduction of dc power consumption is demonstrated. Combining HEMT's and HBT's represents a new opportunity to design low dc power-consumption matrix amplifier for broad-band application up to millimeter frequency with a noise-figure level that only HEMT's can guarantee. It is also evident that the degrees of freedom in the design of the HEMT–HBT matrix amplifier are numerous, depending on the characteristics of the active devices that the technological process can provide.

References

[1] K. B. Niclas and R. R. Pereira, "The matrix amplifier: A high-gain module for multioctave frequency bands," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 296–306, Mar. 1987.
[2] S. L. G. Chu, Y. Tajima, J. B. Cole, A. Platzker, and M. J. Schindler, "A novel 4–18 GHz monolithic matrix distributed amplifier," in *IEEE MTT-S Int. Microwave Symp. Dig.*, June 1989, pp. 291–295.
[3] A. P. Chang, K. B. Niclas, B. D. Cantos, and W. A. Strifler, "Monolithic 2-18 GHz matrix amplifiers," *IEEE Trans. Microwave Theory Tech.*, vol. 37, pp. 2159–2162, Dec. 1989.
[4] K. W. Kobayashi, R. Esfandiari, W. L. Jones, K. Minot, B. R. Allen, A. Freudenthal, and D. C. Streit, "A 6–21-GHz monolithic HEMT 2×3 matrix distributed amplifier," *IEEE Microwave Guided Wave Lett.*, vol. 3, pp. 11–13, Jan. 1993.
[5] R. Heilig, D. Hollman, and G. Baumann, "A monolithic 2–52 GHz HEMT matrix distributed amplifier in coplanar waveguide technology," in *IEEE MTT-S Int. Microwave Symp. Dig.*, San Diego, CA, 1994, pp. 459–462.
[6] K. W. Kobayashi, L. T. Tran, J. C. Cowles, T. R. Block, A. K. Oki, and D. C. Streit, "Extending the bandwidth performance of heterojunction bipolar transistor-based distributed amplifier," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 739–748, May 1996.
[7] K. W. Kobayashi, R. Esfandiari, M. E. Hafizi, D. C. Streit, A. K. Oki, L. T. Tran, D. K. Umemoto, and M. E. Kim, "GaAs HBT wide-band matrix distributed and Darlington feedback amplifiers to 24 GHz," *IEEE Trans. Microwave Theory Tech.*, vol. 39, no. 12, pp. 2001–2009, Dec. 1991.
[8] K. W. Chang, B. L. Nelson, A. K. Oki, and D. K. Umemoto, "2–19-GHz low DC-power and high-IP3 monolithic HBT matrix amplifier," *IEEE Microwave Guided Wave Lett.*, vol. 2, pp. 17–18, Jan. 1992.
[9] K. W. Kobayashi, D. K. Umemoto, T. R. Block, A. K. Oki, and D. C. Streit, "A novel monolithic LNA integrating a common-source HEMT with an HBT Darlington amplifier," *IEEE Microwave Guided Wave Lett.*, vol. 5, pp. 442–444, Dec. 1995.
[10] K. W. Kobayashi, A. K. Oki, D. K. Umemoto, T. R. Block, and D. C. Streit, "A monolithic integrated HEMT–HBT S-band receiver," in *IEEE GaAs IC Symp. Dig.*, Orlando, FL, 1996, pp. 197–200.
[11] K. B. Niclas and A. P. Chang, "Noise in two-tier matrix amplifier," *IEEE Trans. Microwave Theory Tech.*, vol. 36, pp. 11–20, Jan. 1988.
[12] C. Paoloni and S. D'Agostino, "A design procedure for monolithic matrix amplifier," *IEEE Trans. Microwave Theory Tech.*, vol. 45, pp. 135–139, Feb. 1995.
[13] J. B. Beyer, S. N. Prasad, R. C. Becker, J. E. Nordman, and G. K. Hohenwarter, "MESFET distributed amplifier guidelines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, pp. 268–275, Mar. 1984.

[14] M. Schlechtweg, W. Reinert, P. J. Tasker, R. Bosch, J. Braunstein, A. Hulsmann, and K. Kohler, “Design and characterization of high performance 60 GHz pseudomorphic MODFET LNA’s in CPW-technology based on accurate S-parameter and noise models,” *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 2445–2451, Dec. 1992.

Claudio Paoloni was born in Rome, Italy, in 1959. He received the Laurea degree in electronic engineering from the University of Roma “La Sapienza,” Rome, Italy, in 1984

He was consultant at the Fondazione Bordoni on millimeter-wave oscillators, and at Micrel s.r.l., where he was involved with the field of high-performance low-noise microwave amplifiers. He is currently a Research and Teaching Assistant in the Department of Electronic Engineering, University of Roma “Tor Vergata,” Rome, Italy. In the framework of his research, he has participated in a study in the field of active antennas for satellite applications supported by the European Space Agency (ESA). He also participates in the European Community ESPRIT Project COSMIC on front-end for optical communication systems. He has authored or co-authored papers pertaining to the fields of passive components for microwave circuits, MMIC ultra-wide-band amplifiers, yield of MMIC circuits, and TWT’s.