Design of Ku-Band Substrate Integrated Waveguide Phase Shifter

Bouchra Rahali and Mohammed Feham

***Abstract*—Recently, there has been a lot of interest in the substrate integrated waveguide (SIW) technology concept allowing the integration of waveguides in the substrate, replacing the rectangular metal waveguide sidewalls by two rows of metal rods. The electric field distribution in the rectangular waveguide SIW, denoted RSIW, is similar to that of a conventional rectangular waveguide. In this paper, a Ku-band substrate integrated waveguide phase shifter is conceived and optimized by Ansoft HFSS code.**

***Index Terms*—Rectangular wave guide, microwave components , SIW, phase shifter, HFSS.**

I. Introduction

The matching of planar components and rectangular waveguides on the same substrate is quite difficult and expensive. To obtain the benefits of rectangular waveguides while remaining in planar profiles, the SIW technology [1] is interesting. The waveguide in the technology SIW (RSIW) is indeed a compromise between the two; it has some interesting characteristics in terms of easy integration while offering components to a high quality factor. Most microwave components were modeled in SIW technology such as bends [2], filters [3], couplers [4], [5], duplexers [6], sixports junctions [7], [8], circulators [9], [10], phase shifters [11].The phase shifter is a device which serves to change the phase of a signal with minimal attenuation. It is used to measure the phase shift introduced by the components. It is widely used in antenna arrays to change their radiation patterns. Many types of shifters in rectangular guides currently exist and are used in industry for many applications. A lossless, adapted and reciprocal phase shifter has the following scattering matrix S.

$$[S]=\begin{bmatrix} 0 & e^{j\varphi} \\ e^{j\varphi} & 0 \end{bmatrix} \quad (1)$$

There are already some phase shifters SIW technology cited in the literature [11]. They are easy to manufacture by adding to the waveguide RSIW, metal or dielectric cylinders of radius r set at the entrance and/or at the exit of the guide.

II. Design of RSIW

Starting from a dielectric substrate between two metal planes, two rows of holes are drilled and metalized, making contact between the two metal planes of the substrate. The diameter d of holes stems, p the spacing between the holes and W_{SIW} the spacing between the two rows of holes, are physical parameters necessary for designing rectangular waveguide in technology SIW (Fig. 1).

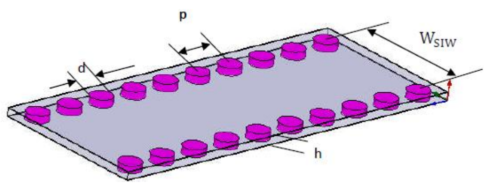


Fig. 1. Rectangular waveguide integrated into a substrate RSIW.

Based on the work [12], empirical equations were derived for determining the width of the equivalent rectangular waveguide, giving the same characteristics of the fundamental mode propagating in the RSIW (Fig. 1) having the same height and the same dielectric.

$$W_{\text{eq}} = W_{\text{SIW}} - \frac{d^2}{0.95\,p} \quad (2)$$

where W_{SIW} and W_{eq} are respectively the width of the rectangular waveguide technology SIW and its equivalent waveguide (Fig. 2 and Fig. 3), d is the diameter of the metal cylinder and p is the distance between two adjacent cylinders, with:

$$p < \frac{\lambda_0}{2}\sqrt{\varepsilon_r} \quad (3)$$

$$p < 4\,d \quad (4)$$

$$\lambda_0 = \frac{c}{f} \quad .$$

The period p should be kept low to reduce leakage losses between adjacent cylinders. The choice of subject is also the problem of losses. The rows of holes in contact with the metalized conductive planes of the substrate define a region of electromagnetic waves propagation which is similar to a metallic rectangular waveguide, as illustrated in Fig. 3.

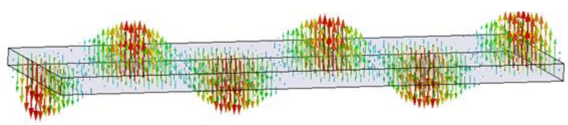


Fig. 2. Electric field of TE_{10} mode rectangular waveguide equivalent, W_{eq}=7.58mm, h=0.508mm, $\varepsilon_r = 4.4$ at frequency f = 15GHz.

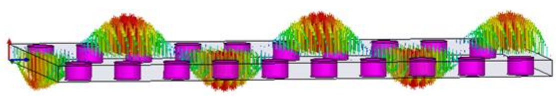


Fig. 3. Electric field of TE_{10} mode of RSIW, W_{SIW}=8.54mm, h=0.508mm, p=2.54mm, d=1.524mm, $\varepsilon_r = 4.4$ at frequency f = 15GHz.

We analyzed the phase shifter designed in Ku-band [12]-[18] GHz from a conventional waveguide [2]. The

Manuscript received July 9, 2013; revised February 27, 2014.
Bouchra Rahali and Mohammed Feham are with STIC Laboratory, University of Tlemcen Algeria, Algeria (e-mail: b_rahali@hotmail.fr).

DOI: 10.7763/IJIEE.2014.V4.438

characteristic parameters of the waveguide RSIW synthesizing a waveguide WR62 with a = 15.799mm, b = 7.898mm, a filled dielectric permittivity ε_r=4.4, tanδ=0.02, height h = 0.508mm and length L = 25.4mm. Following the same approach, cited above [13], to deduce the parameters of the RSIW and the equivalent waveguide (Fig. 4), we found W_{eq} = 7.58mm and W_{SIW} = 8.54mm for p = 2.54mm and d = 1.524mm.

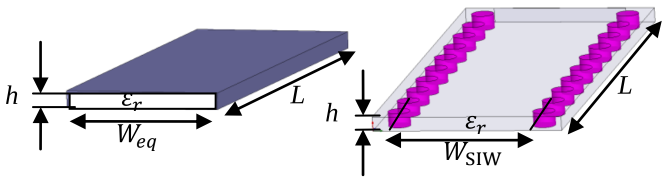
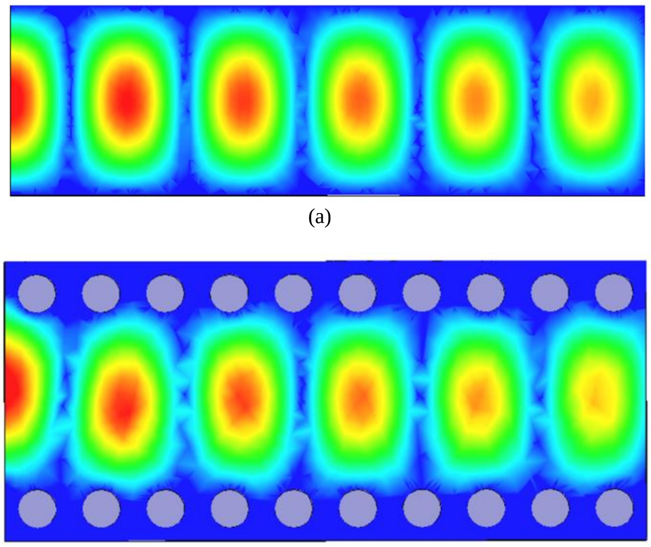


Fig. 4. Equivalent rectangular waveguide and RSIW.

In this paper, the software HFSS [14], based on the finite element method (FEM), has been applied to analyze the SIW devices. It should be noted that the formulas given by equations (2), (3) and (4) are commonly used to obtain initial values W_{SIW}, optimized later by HFSS. This software allows the layout of the cartography of the electromagnetic field of the TE_{10} mode and scatter diagram. Fig. 5 shows the similarity of the electromagnetic field distribution of TE_{10} mode guided in the RSIW guide and its equivalent waveguide.



(a)

(b)

Fig. 5. Electric field distribution of the TE_{10} mode in the equivalent rectangular waveguide (a) and in the RSIW (b) respectively, at frequency f = 15GHz

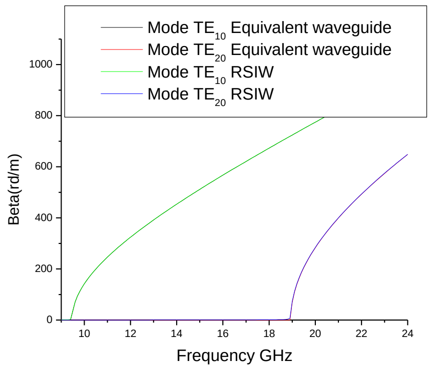


Fig. 6. Dispersion characteristics.

Fig. 6 also shows the consistency of the dispersion characteristics between these two equivalent waveguides. It should be noted that this similarity propagation is valid for all modes TE_{n0}.

III. RSIW Matching

In our study, we are interested in transitions to interconnect RSIW to the planar transmission lines; we mention in particular the microstrip transition taper [15]. The transition between RSIW and microstrip can be designed on the same substrate, which has an excellent mechanical tolerance and does not have to be tuned [16]. There is a tapered section which is used to match the impedance between a 50 Ω microstrip line and the RSIW. The 50 Ω microstrip line in which the dominant mode is quasi-TEM, can excite well the dominant mode TE_{10} of the RSIW, as their electric field distributions are approximate in the profile of the structure.

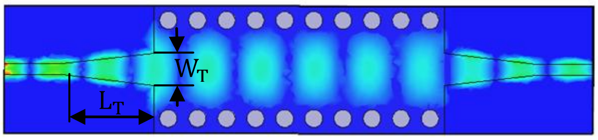


Fig. 7. Electric field distribution of TE_{10} mode at f = 15 GHz in the matched RSIW.

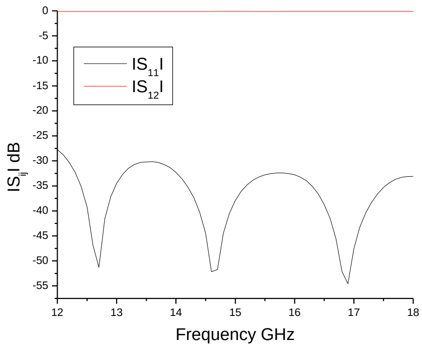


Fig. 8. Transmission coefficients S_{21} and reflection S_{11} of the RSIW.

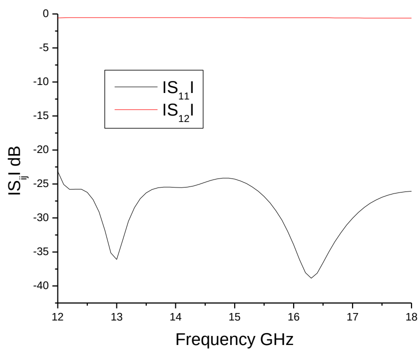


Fig. 9. Transmission coefficients S_{21} and reflection S_{11} of the matched RSIW with taper.

This study is based on the determination of the taper initial parameters W_T and L_T from several formulas given [17], following by an optimization of these parameters using HFSS [14]. The optimization is even faster than the starting point is located near the optimal point. Fig. 7 shows the proposed configuration of two back-to-back transitions of microstrip line to RSIW. It allows the design of a completely integrated planar circuit of microstrip and waveguide on the same substrate without any mechanical assembly. Fig. 8 and Fig. 9 show the results of the RSIW analysis without transition and with a coplanar taper of dimensions L_T and W_T.

They also show that S_{11} is less than -15dB over the whole band and the transmission coefficient S_{12} is around -0.458dB over the entire band.

IV. Design of RSIW Phase Shifter

One of the simplest approaches to design a phase shifter in technology SIW is to use a waveguide RSIW with variable length L. The phase introduced by such device is equal to $\beta_g L$. To vary this phase, it suffices to change the length L by changing the number of metal cylinders. Using this approach, we simulated three structures RSIW with lengths L, $L1$ and $L2$ respectively, and $L1 < L < L2$. Fig. 10 shows the mapping of the electric field of the TE_{10} mode, guided from the input to the output of the phase shifter at frequency of 15 GHz. Fig. 11 illustrates the phase of the transfer function S_{12} of this phase shifter with lengths L, $L1$ and $L2$ respectively, corresponding to 10, 9 and 11 metal cylinders (Vias). We deduce from this figure that the phase varies between -180 ° and 180 ° across the operating band.

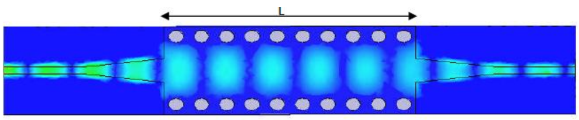


Fig. 10. The electric field distribution of the TE_{10} mode of the phase shifter SIW at f = 15 GHz.

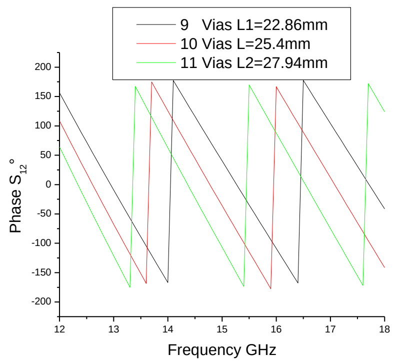


Fig. 11. The phase of the transfer function S_{12} for different lengths of RSIW.

Another way to introduce an additional phase shift in the guide RSIW, involves inserting disturbing rods. This phase shift depends on the position and size of the disturbing element. Fig. 12 shows the electric field map of the TE_{10} mode of this shifter at the frequency 15 GHz. The phase shift introduced by the component can be easily controlled by the addition of a disturbing rod of radius r, placed at the input and/or the output of the RSIW, the change in its dimension r and/or its position xp reflecting the distance between this rod and a row of the metallic rods. Fig. 13 illustrates the phase change of the transfer function S_{12} of this phase shifter depending on the position xp and the radius r of the disturbing element reflecting an air hole at frequency of 15 GHz. We note that the phase increases with the radius r of the air hole for a given position xp. This phase is maximum for xp = 4.27mm corresponding to the middle of W_{SIW}, position at which the disturbing element introduces a great influence.

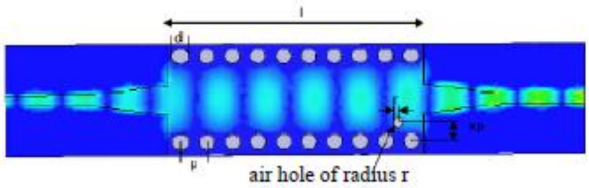


Fig. 12. Electric field distribution of TE_{10} mode SIW phase shifter for r = 0.5mm at f = 15 GHz

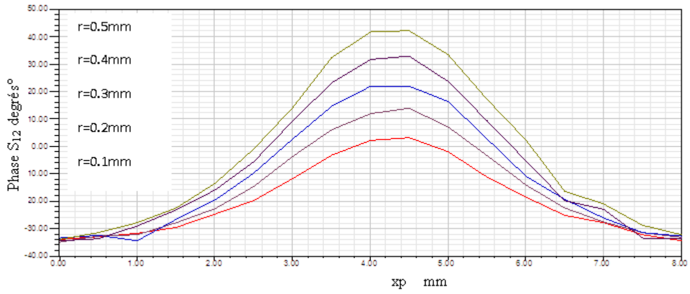


Fig. 13. Phase of S_{12} as a function of radius r and position xp air hole at f = 15 GHz.

Then, in the same waveguide RSIW, we inserted at two extremities, two identical metal rods with radius r and xp position. Fig. 14 exposes the distribution of the electric field of the TE_{10} guided mode at the frequency f = 15 GHz. Fig. 15 represents the change of the phase of the transfer function S_{12} of this phase shifter depending on the position xp and the radius r of the two disturbing elements position at the frequency f=15 GHz. We notice that the phase increases with radius r for a given position xp. This phase is maximum for xp = 4.27mm corresponding to the middle of W_{SIW}; position at which the disturbing elements introduce a great influence.

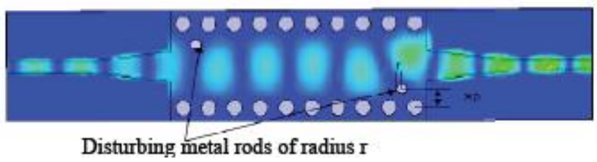


Fig. 14. Electric field distribution of TE_{10} mode SIW phase shifter at f = 15 GHz.

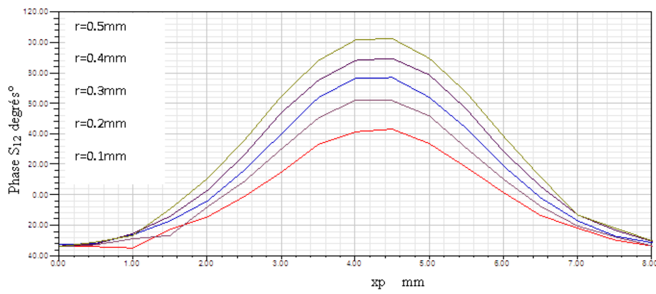
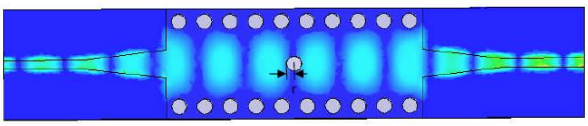


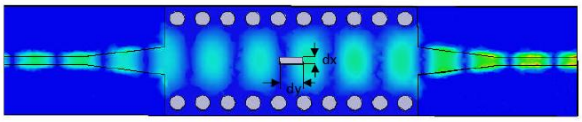
Fig. 15. Phase of S_{12} as a function of radius r and the position xp of two disturbing elements at f = 15 GHz.

In a conventional shifter, we try to get the best possible adaptation to minimize reflection losses. The structure must also provide a constant phase shift in the operating frequency band. A method that best applies to RSIW [12], consists in placing a dielectric rod at the center of the guide. Of course, this creates some disturbing reflection, but they are generally less than those generated by metal rods.

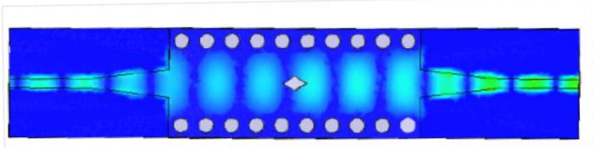
The additional phase shift is of course obtained by comparing the phase of the phase shifter with that of the same guide RSIW undisturbed at its center. Fig. 16 shows the structure of a phase shifter conceived by insertion in the middle of the waveguide RSIW, a dielectric rod formed of an air hole (*eps*= ε_r=1). We then analyzed a guide RSIW for different rod sections, cylinder (Fig. 16 (a)), rectangle (Figure 16.b) and rhombus (Fig. 16 (c)) with identical surface. The graph in Fig. 17 shows that the additional phase shifts induced by various forms of disturbing rods with similar surfaces are very close, as shown by their frequency response over the entire frequency band (Fig. 18).



(a)



(b)



(c)

Fig. 16. The electric field distribution of the TE_{10} mode of the phase shifter SIW at *f* = 15GHz, with: (a) cinlinder rod, (b) restangular rod, (c) rhombus rod.

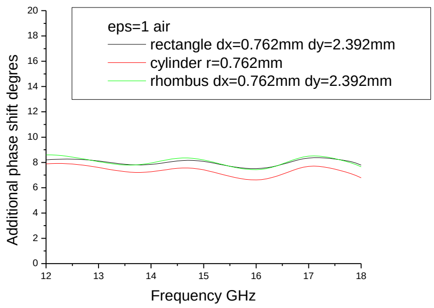


Fig. 17. Additional phase shift as a function of the disturbing shape.

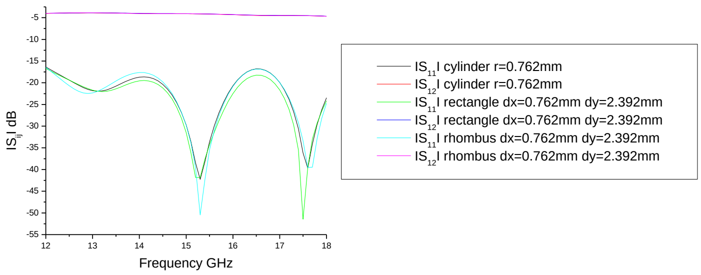


Fig. 18. Frequency responses of the guide RSIW for three different disturbing elements.

After all these analysis, we can conclude that the insertion of disturbing elements, of various shapes, in a RSIW guide generates phase shifts. Moreover, this phase depends on the permittivity and the size of the section of the disturbing rod and not on its shape [17].

V. Conclusion

In this paper, an analogue phase shifter in low cost SIW technology has been presented. The phase shift is determined by inserting rods of different diameters and placed at different locations in the RSIW or by inserting disturbing elements of various shapes. Moreover, this phase depends on the permittivity and the size of the section of the disturbing rod and not on its shape. To validate the proposed concept, a Ku-band phase shifter is designed and optimized. Feasibility of this phase shifter is validated by simulated results got from HFSS. The proposed phase shifter SIW is compact, easy for fabrication, and has an attractive application prospect for design of complex microwave and millimeter-wave circuits systems such array antenna.

References

[1] D. Deslandes and K. Wu, "Design consideration and performance analysis of substrate integrated waveguide components," in *Proc. Europ. Microw. Conf.*, Oct. 2002, pp. 1-4.

[2] R. Bochra, F. Mohammed, and J. Tao, "Design of optimal chamfered bends in rectangular substrate integrated waveguide," *IJCSI, International Journal of Computer Science Issues*, vol. 8, issue 4, no. 2, July 2011.

[3] A. Adabi and M. Tayarani , "Substrate integration of dual inductive post waveguide filter," *Electrical Engineering Department IUST University Narmak, Iran Progress In Electromagnetics Research B, Tehran*, 2008, vol. 7, pp. 321–329.

[4] K. J. Tan and X. Z. Luan, "Compact directional coupler based on substrate integrated waveguide," *IEEE Microwave and Wireless Components Letters*, September 2009.

[5] Z. C. Hao, W. Hong, J. X. Chen, H. X. Zhou, and K. Wu, "Single-layer substrate integrated waveguide directional couplers," *IEE Proc.-Microw. Antennas Propag*, vol. 153, no. 5, October 2006.

[6] Z. C. Hao, W. Hong, J. X. Chen, X. P. Chen, and K. Wu, "Planar diplexer for microwave integrated circuits," *IEE Proc.-Microw. Antennas Propag*, vol. 152, no. 6, December 2005.

[7] X. Y. Xu, R. G. Bosisioand, and K. Wu, "A New six-port junction based on substrate integrated waveguide technology," *IEEE Transactions on Microwave Theory and Techniques*, vol. 53, no. 7, July 2005.

[8] L. N. Wu, X. C. Zhang, C. M. Tong, and M. Zhou, "A new substrate integrated waveguide six-port circuit," *2010 IEEE*, Missile Institute of Air Force Engineering University, Sanyuan, Shanxi, China, 713800.

[9] W. Q. Chen, X. J. Ji, and E. K. N. Yung, "Miniaturized planar ferrite junction circulator in the form of substrate-integrated waveguide," *International Journal of RF and Microwave Computer-Aided Engineering*, 2008.

[10] Z. L. Shi and Z. H. Shao, "Design of ka-band substrate integrated waveguide circulator," in *Proc. International conference on Computational problem solving (ICCP)*, pp. 260-262, 2010.

[11] K. Sellal, L. Talbi, T. Denidni, and J. Lebel, "A new substrate integrated waveguide phase shifter," in *Proc. 36th European Microwave Conference*, 2006, pp. 72-75.

[12] Y. Cassivi, L. Perregrini, P. Arcioni, M. Bressan, K. Wu, and G. Conciauro, "Dispersion characteristics of substrate integrated rectangular waveguide, " *IEEE Microw. Wireless Comp. Lett.*, vol. 12, no. 9, pp. 333-335, 2002.

[13] N. A. Smith, "Substrate integrated waveguide circuits and systems," Thesis for the degree of Master of Engineering, Department of Electrical & Computer Engineering McGill University Montréal, Québec, Canada, May 2010.

[14] User's guide–High Frequency Structure Simulator (HFSS), *Ansoft Corporation*, vol. 11.0.

[15] D. Deslandes and K. Wu, "Integrated micro strip and rectangular waveguide in planar form," *Microwave and Wireless Components Letters, IEEE*, pp. 68-70, 2001.

[16] D. Deslandes, "Design equations for tapered microstrip-to-substrate integrated waveguide transitions," *Microwave Symposium Digest, IEEE MTT-S International*, pp. 704-707, 2010.

[17] R. Bouchra, “Contribution à la modélisation electromagnétique des structures complexes hyperfréquences en technologie siw,” Thèse de doctorat, Département de Génie Electrique et Electronique, Faculté de Technologie, Université Abou Bekr Belkaid de Tlemcen Algérie Mai 2013.

Rahali Bouchra received a magister degree in physics electronics from, University of Tlemcen (Algeria), in 1986, and the PhD degree in electromagnetic modeling of complex structures in Microwave Technology SIW in 2013.Since 1982, she has been assistant professor and been involved in several research projects at STIC laboratory. Her main area of interest is the simulation of microwave circuits in SIW technology.

Feham Mohammed received the Dr. Eng. degree in optical and microwave communications from the University of Limoges (France) in 1987, and his PhD in science from the University of Tlemcen (Algeria) in 1996. Since 1987, he has been assistant professor and professor of microwave and communication Engineering. He has served on the Scientific Council and other committees of the Electronics and Telecommunication Departments of the University of Tlemcen. His research interest now is mobile networks and services.