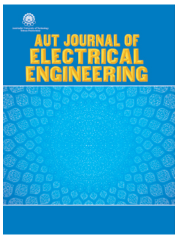

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Electromagnetic susceptibility analysis of a power amplifier against radiated and conducted interferences with the 3D-FDTD method

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ABSTRACT: Electromagnetic susceptibility (EMS) of a power amplifier (PA) against an interfering wave is presented. The interfering waves affect the performance of any circuit, either intentionally or from adjacent equipment. In the case of power amplifiers, this phenomenon can overdrive the PAs into the nonlinear region and if the interfering wave still exists, it can damage the PA. Therefore, circuit designers must design the circuit to be not susceptible to interfering waves, as much as possible. In this article, EMS analysis of a PA against an interfering Gaussian modulated pulse with the 3D finite difference time domain (3D-FDTD) method is presented. In this method, the transistor is replaced with an appropriate transistor nonlinear large-signal EEHEMT circuit model, and the whole circuit of the PA is simultaneously analyzed in the presence of radiated and conducted interferences. This method gives more accurate results than the hybrid methods that analyze the passive and active sections of the amplifier separately. The presented method is exerted on a PA with Wolfspeed's CGHV1J006D discrete GaN on SiC high electron mobility transistor (HEMT) and a hybrid method is proposed to validate the results. The results of the presented method and the validation method have a good agreement.

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finite difference time domain (FDTD) method.

1- Introduction

The electromagnetic susceptibility (EMS) of different circuits is one of the significant challenges in the design of the electronic/electric devices. Interferences from surrounding equipment can affect different circuits through radiation or conduction. In the case of sensitive circuits such as amplifiers, this effect becomes more important. These interferences could drive the amplifier in the nonlinear region and this issue can affect the performance of the whole equipment. Therefore, circuit designers must consider EMS against radiated and conducted interferences in the early stages of their designs.

The importance of the electromagnetic compatibility (EMC) of the electronic/electric equipment is presented in [1]. This has led to the development of various standards for electronic/electric equipment and has required manufacturers to comply with these standards. Among the various methods to predict the EMS of electronic devices, the full-wave methods offer more precise results than the others. The finite difference time domain (FDTD) method is widely used among the full-wave methods due to its good accuracy and simplicity of implementation [2-8].

Electromagnetic coupling on a transmission line excited by a plane wave is evaluated by the FDTD method in [2-5]. In [6], the conducted and radiated emissions on the power cables are presented with the FDTD method. Also in [7], the conducted disturbance on a thin wire is analyzed with the FDTD method. EMS analysis of the passive lumped elements against an electromagnetic wave is presented in [8].

Susceptibility analysis of circuits with linear and nonlinear elements is presented in [9 and 10] with the hybrid scattering matrix method. This method does not consider the active element in the presence of an interference wave. The interfering wave is assumed as the $N+1$-*th* port of the circuit and its effect on the other ports is computed with the scattering matrix. Finally, this effect is imported into any circuit simulation software. In another method, this effect is analyzed by considering the proper voltage and current sources induced by the interfering wave on the circuit ports [11-13]. In these methods, the passive and active sections of the circuit are separately analyzed and the interfering wave is considered independent from the performance of the circuit and so, this leads to less accurate results. For precise EMS analysis of the circuits, the whole circuit including active and passive sections must be analyzed simultaneously in the presence of the interfering wave [14].

In this article, the 3D-FDTD method for analyzing the EMS of a PA in the presence of the radiated and conducted interferences is presented. In this method, the transistor has been replaced with its nonlinear large-signal EEHEMT circuit model and the whole circuit of the PA including the EEHEMT model, matching and biasing circuits is analyzed simultaneously. Also, the interactions between the different

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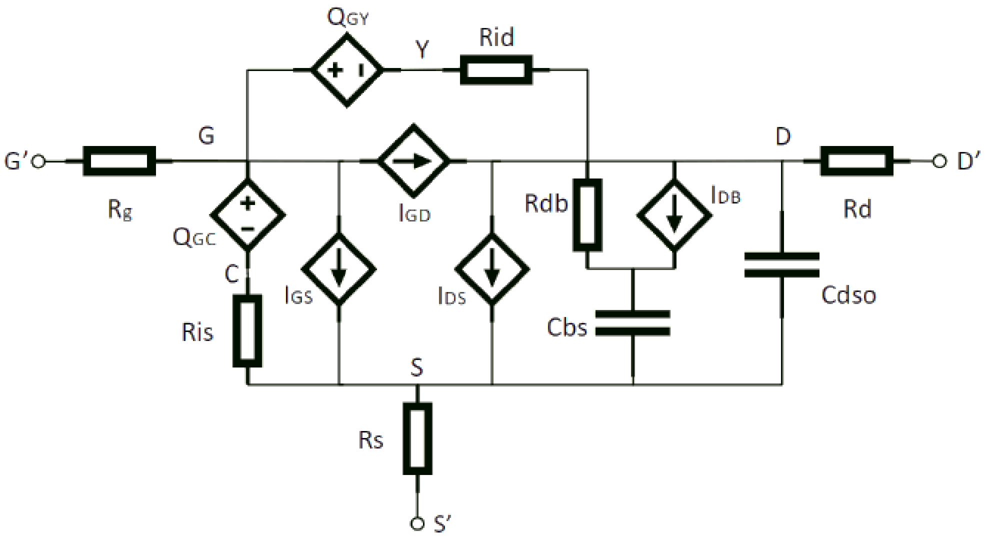

Fig. 1. EEHEMT circuit model [16].

sections of the PA and between the interfering wave and the PA circuit are considered in this method. So, this method is more accurate than the mentioned methods in the literature. The importance of this method is doubled in the case of amplifiers with multi-pad transistors that have comparable dimensions to the wavelength of the radiation field.

This article is organized as follows. The method of implementing the whole of PA in the 3D-FDTD method is presented in section 2. In section 3, the designed PA is presented and the results of the EMS analysis against a Gaussian modulated radiated and conducted interferences and the comparison between the results of this method and the proposed hybrid method is presented. Finally, the conclusion is presented in Section 4.

2- Method

The implementation of the passive elements and constant sources is presented in [15], in detail. As mentioned above, to implement the transistor in the FDTD method, we must replace it with its proper circuit model. This model must express both linear and nonlinear regions of the transistor. In this article, we use the nonlinear large-signal EEHEMT circuit model (Fig. 1), which is a good model for high electron mobility transistors (HEMT).

As seen in Fig. 1, the EEHEMT model has some nonlinear elements including voltage-dependent Drain-Source current (I_{DS}), voltage-dependent Gate-Source current (I_{GS}), voltage-dependent Gate-Drain current (I_{GD}), dispersion current (I_{DB}), Gate-Drain nonlinear capacitor (C_{GY}), and Gate-Source nonlinear capacitor (C_{GC}). Since, the value of these elements at any time depends on the voltages of certain points of the transistor at the same time, to implement these nonlinear elements in the FDTD method, some modifications are required as in [14].

The relations for the nonlinear elements are presented in [16] in detail. For implementing a circuit in the FDTD method, this method meshes the whole structure and computes the electric and magnetic field components of any mesh based on the relationship between voltage and current of that mesh at any time step. For implementing the nonlinear dependent elements in the EEHEMT model of the transistor some certain voltages such as V_{GS} and V_{DS} for computing I_{DS}, as seen in the I_{DS} relations in [16], must be known at any time step. For this purpose, in any time step of the FDTD method, the following procedure must be done.

1- The electric and magnetic field components of the whole structure are updated without considering the I_{DS}.

2- The required voltages such as V_{GS} and V_{DS} for computing I_{DS} are computed with the results of the step 1.

3- Calculate the value of the dependent elements.

4- Complete the calculation of the electric field components of the meshes related to the voltage dependent current sources.

5- Update the values of the nonlinear capacitors.

Updating I_{DS} with this procedure leads to instability because of forcibly changes the values of the electric and magnetic field components of the meshes related to it. This causes unwanted oscillations and to eliminate them, the values of the voltage-dependent current sources of the EEHEMT model are filtered with a numerical Butterworth filter.

For implementing the radiated interferences, we must update the magnetic and electric field components of the whole structure according to the radiation field specifications as in [15]. In this article, the radiation field is considered as a cosine-modulated Gaussian pulse.

Table 1. EEHEMT model parameters of the designed PA.

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
Vto	-2.923V	Vtso	-10V	Kdb	39.2e-3	Kbk	1e-3
Gamma	0.000103	Is	83.2fA	Vdsm	60V	Vbr	125
Vgo	-2.52V	N	4	C11o	1.58pF	Nbr	2
Vdelt	1V	Ris	3Ohm	C11th	5.5pF	Rd	0.711Ohm
Vch	1V	Rid	45Ohm	Vinfl	-3.75V	Rs	1.8Ohm
Gmmax	0.9	Tau	4psec	Deltgs	0.68	Rg	0.0432Ohm
Vdso	74V	Cdso	0.412pF	Deltds	0.26	Vco	-1.46V
Vsat	1V	Rdb=75	75MOhm	Lambda	0.0015	Vba	0.82V
Kapa	0.002	Cbs	350pF	C12sat	188.89fF	Vbc	0.91V
Peff	40	Gdbm	25e-6	Cgdsat	73.6fF	Deltgm	0.0125

Table 2. The specifications of the designed PA.

substrate	RO4003	Vgs	-2.63V
thickness	10mil	Vds	40V
ε_r	3.55	power gain at 8 GHz	16.92dB
loss tangent	0.0019		

3- Results:

As mentioned above, for implementing the transistor in the FDTD method, we must replace it with its proper model. The circuit's transistor in the designed PA in this article is CGHV1J006D which is a gallium-nitride (GaN) HEMT. The extracted values of the EEHEMT model of this transistor are given in Table 1. The specifications of the designed PA are presented in Table 2. Output power contours of the mentioned transistor and the EEHEMT model are depicted in Fig. 2. Also, I_{DS} versus V_{DS} curve for different values of V_{GS} is depicted in Fig. 3. As shown in Fig. 2 and 3, the extracted EEHEMT model fits well with the CGHV1j006D. As can be seen in Fig. 2, this transistor has the maximum output power (37.19dBm) with Z_{in}=0.95+j*3.4 and Z_{out}= Z_0*(0.211+j*0.641) (Z_0=50 Ohm). The designed PA in ADS is shown in Fig. 4. An 8GHz sine wave with 2V amplitude is applied as a source of the PA. Fig. 5 shows the comparison of the output voltages of the designed PA with CGHV1J006D and the presented EEHEMT model. The output power of the designed PA versus the input power is depicted in Fig. 6. Also, the power gain and power-added efficiency (PAE) of the PA versus the input power is shown in Fig. 7. As seen in Fig. 6, the PA is driven in the saturation area with P_{in}=27dBm and by further increasing the input power, the output power of the PA will decrease.

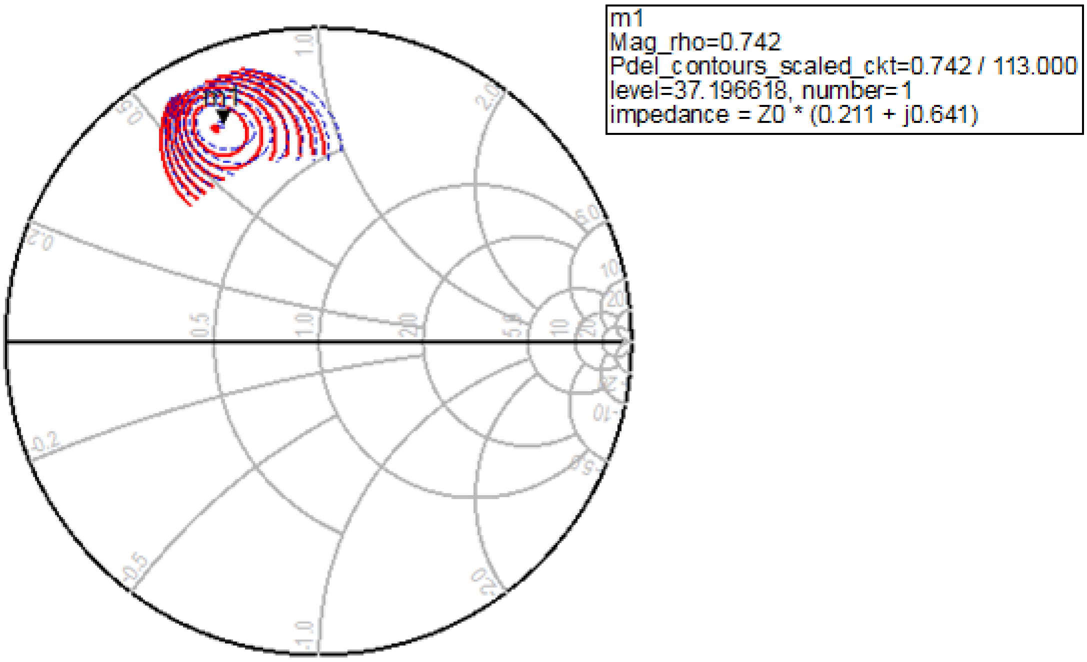

Fig 2. Load pull contours of the designed PA. (Input power=20dBm), (Line: CGHV1j006D transistor, dashed line: EEHEMT model)

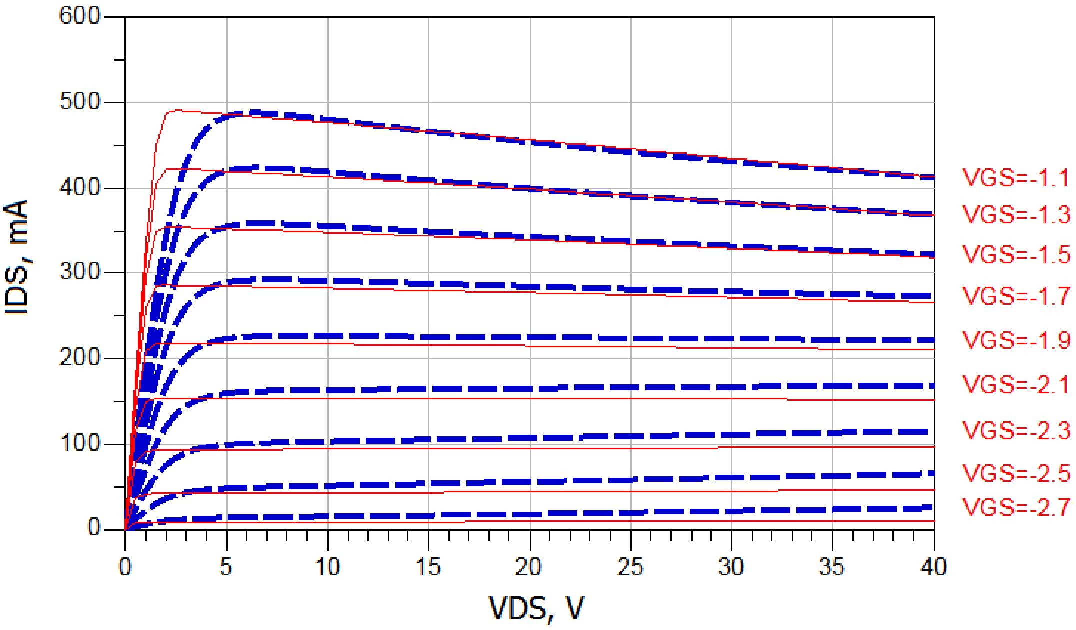

Fig. 3. IDS versus VDS curve for different values of VGS. (Line: CGHV1j006D transistor, dashed line: EEHEMT model)

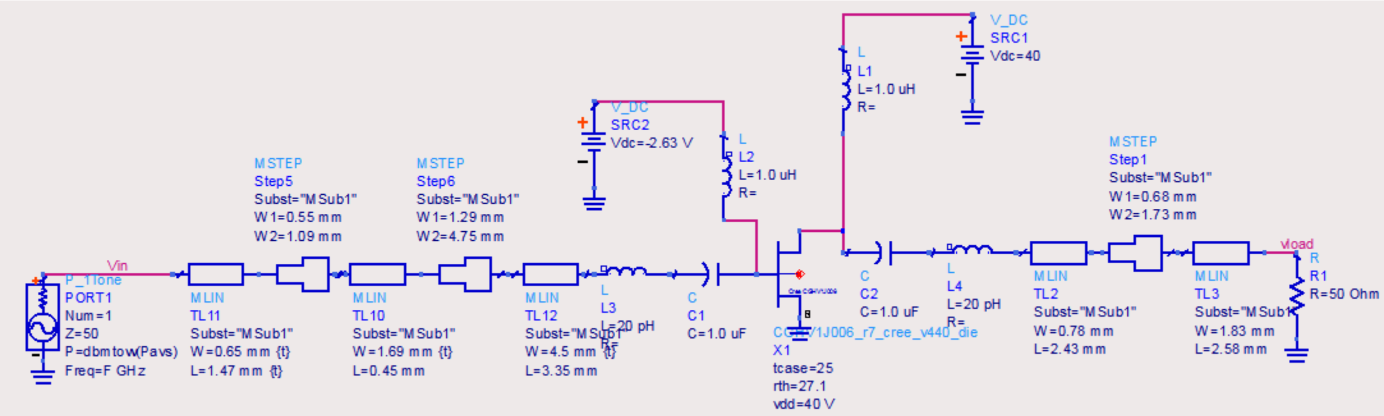

Fig. 4. Schematic of the designed PA in ADS.

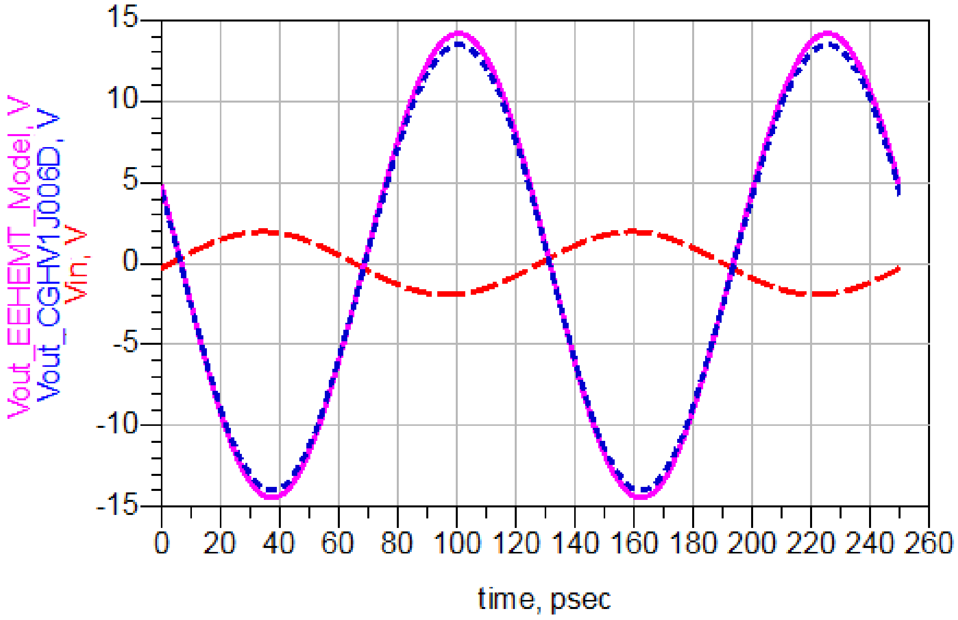

Fig. 5. Comparison of the output voltage of the designed PA between CGHV1J006D transistor and EEHEMT model in ADS.

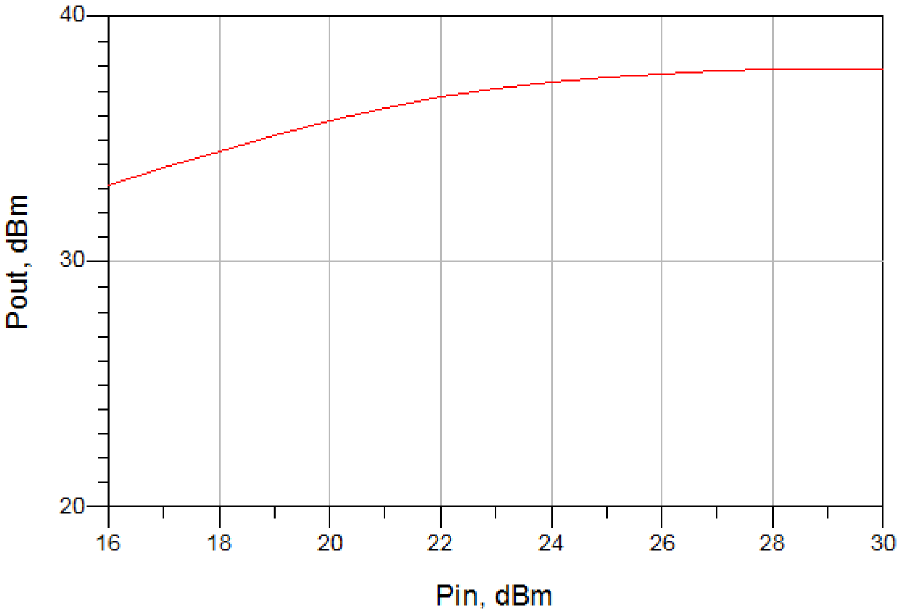

Fig. 6. Output Power of the designed PA versus the input power.

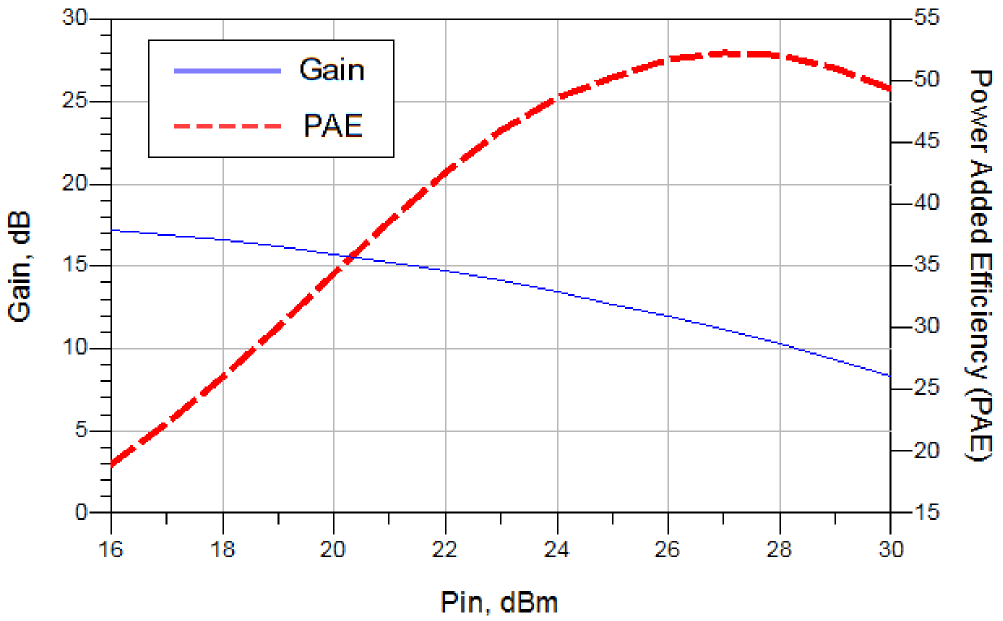

Fig. 7. The power gain and power-added efficiency (PAE) of the designed PA versus the input power.

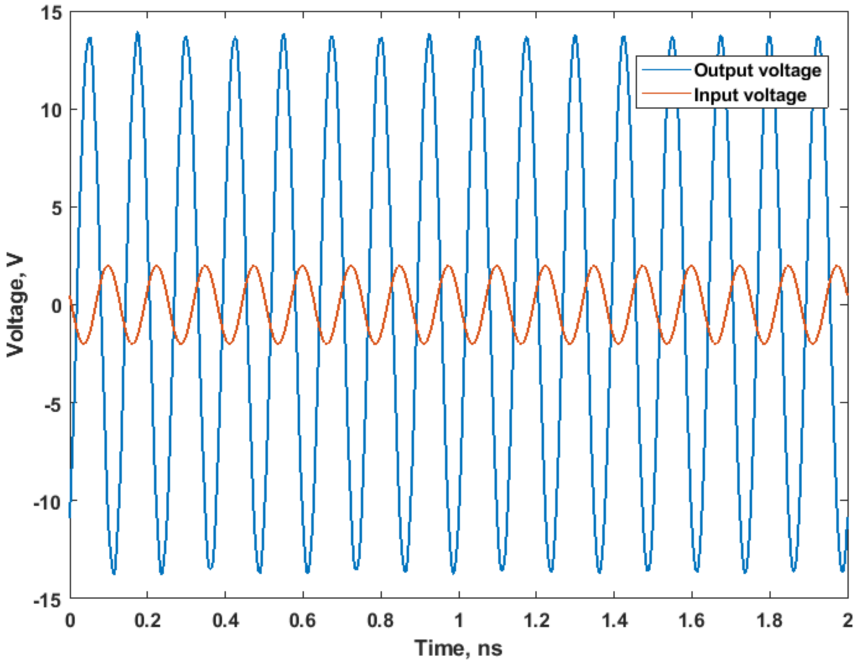

Fig. 8. Output and input voltages of the designed PA with the FDTD method.

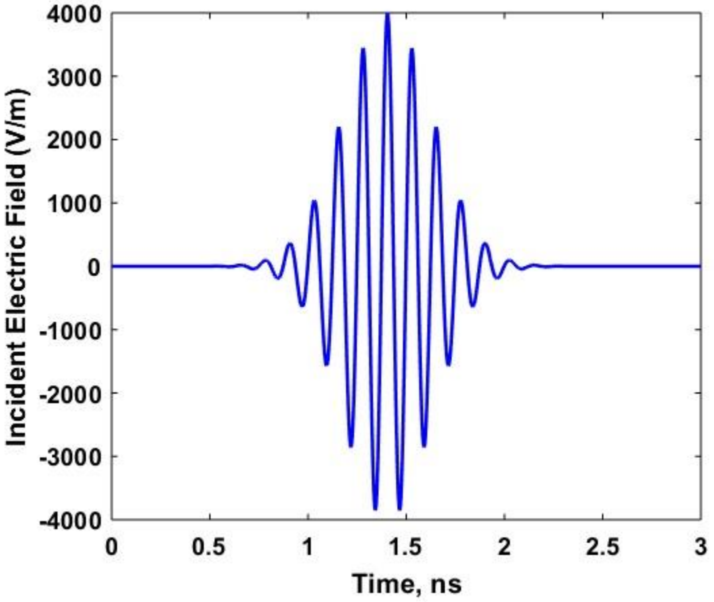

Fig. 9. Gaussian modulated pulse.

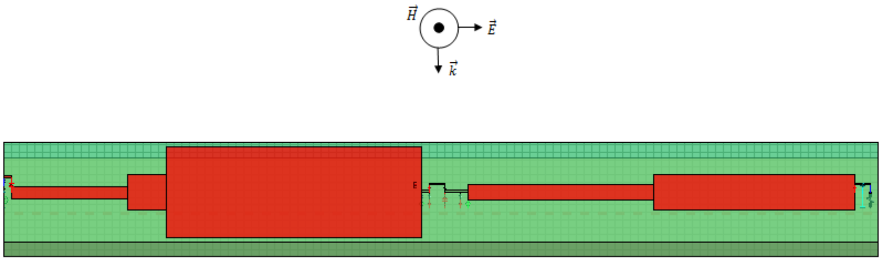

Fig 10. The whole circuit of the PA is vertically illuminated by the cosine-modulated Gaussian pulse.

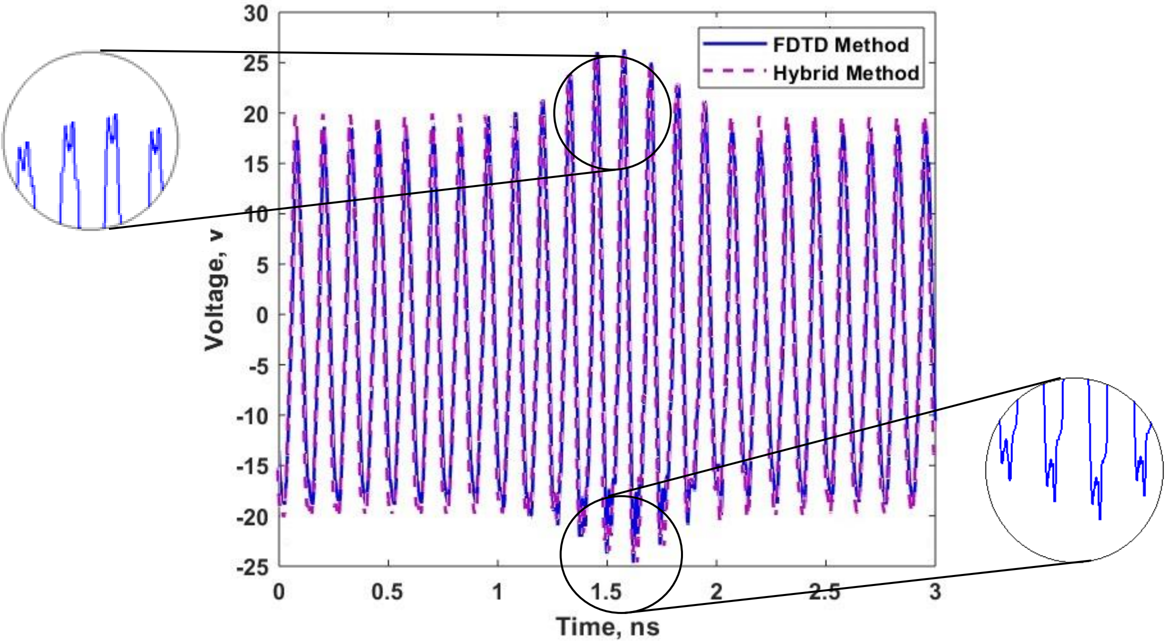

Fig. 11. The output voltage of the PA in the presence of the interferences.

After modeling the transistor, this model is used in the presented 3D-FDTD method to analyze the EMS of the PA against radiated and conducted interferences. To validate the FDTD method in the small-signal region, similar to Fig. 4, an 8GHz sine wave voltage source with 2V amplitude is applied to the PA. Fig. 8 shows the output and input voltages of the PA with the FDTD method. Then, to analyze the nonlinear performance of the PA in the presence of the interfering wave, an 8 GHz sine wave with 3.5V amplitude (P_{in}=21dBm) is applied as the voltage source and a 4kV/m Gaussian pulse modulated at 8GHz and bandwidth of 3GHz with a pulse width of 2*ns* (Fig. 9) is considered as the incident wave that illuminates the amplifier vertically (Fig. 10). In the following, to investigate the effect of the conducted interference on the performance of the amplifier, a 3V Gaussian pulse with the above-mentioned specification is considered as a conducted interference on the input cable on the PA. These interferences have the same effect on the input of the PA and the maximum input power of the PA in the presence of them is 28dBm. As can be seen in Fig. 11, the PA is driven in the nonlinear region because of these interferences.

To validate the results of the radiated interference, the entire PA circuit except the transistor is introduced in the CST Studio Suite® software and the resulting induced voltage at the input of the transistor is achieved. Then, we add this interference as an interference source in the designed PA in ADS. For the conducted interference, the mentioned Gaussian pulse is considered as a voltage source in the input of the PA in ADS.

4- Conclusion

The simultaneous EMS analysis of the whole of a PA against radiated and conducted interferences presented in this article offers accurate results because of full-wave analysis of the whole of the structure. By applying this precise analysis, circuit designers will be able to determine the maximum tolerable interferences and design the circuits by considering these limitations. In the case of the amplifiers with multi-pad transistors, the importance of this method will be doubled because of the comparable dimensions of these circuits to the wavelength of the interfering wave.

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