ANALYSIS OF NONLINEAR MICROWAVE CIRCUITS EXCITED BY MULTI-TONE SIGNALS USING ARTIFICIAL FREQUENCY MAPPING METHOD

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Key words: nonlinear microwave circuits, multi-tone signals, artificial frequency mapping method, WiMAX technology

Abstract: Artificial Frequency Mapping (AFM) is an effective method for analysis of memory-less microwave circuits excited by multi-tone signals. In this paper a new formulation for analysis of these circuits with nonlinear elements (nonlinear capacitance involved) is proposed. This is followed by introducing a linear amplifier suitable for WiMAX technology. Then, AFMT is used to evaluate the performance of the amplifier. So, the numerical results are presented and results of this CAD simulation are confirmed with other methods.

Analiza nelinearnih mikrovalovnih vezij vzbujenih z multitonskimi signali z uporabo metode umetne frekvenčne preslikave

Kjučne besede: nelinearna mikrovalovna vezja, multitonski signali, metoda umetne frekvenčne preslikave (AFM), WiMAX tehnologija

Izvleček: Umetna metoda frekvenčne preslikave, AFM, je učinkovita metoda za analizo mikrovalovnih vezij, ki so vzbujena z multitonskimi signali. V tem članku predlagamo novo metodo za analizo teh vezij z nelinearnimi elementi (nelinearne kapacitivnosti). Sledi predstavitev linearnega ojačevalnika ustreznega za uporabo v WiMAX tehnologiji. Delovanje tega ojačevalnika smo ocenili z metodo AFMT. Sledi predstavitev numeričnih rezultatov, ki jih na koncu potrdimo z drugimi metodami.

1. Introduction

The need for increased data transmission rates in wireless communications is driving the proposal of new types of wireless standards that achieve greater spectral efficiency. WiMAX based on IEEE 802.16 utilizes new modulation formats, require greater bandwidths, and necessitate multi-carrier modulation schemes, orthogonal frequency-division multiplexing (OFDM) /IEEE 802.16 standard/.

Information on system properties of analog and microwave circuits such as intermodulation distortion, noise or transfer characteristics can often be received from steady state behavior. Therefore accurate and reliable CAD tools and numerical algorithms are necessary to meet the design specifications.

As the characterization of nonlinear RF circuits using conventional single and two-tone tests is no longer sufficient to predict the circuit's response in its final operation regime. In order to follow the technology trends and meet the new standards requirements, more complicated analysis and tools is needed in the design process of nonlinear circuits such as RF power amplifiers. Therefore multitone harmonic balance (HB) proposes an appropriate analysis method. Commercial multitone HB utilizes almost periodic discrete Fourier transforms (APDFTs) /1/ or multidimensional Fourier transforms (N-FFTs) /2, 3/. Such schemes are practically limited to five or so discrete carriers. One commercial HB implementation using APDFT can handle up to ten carriers but with excessive simulation times./10/

Artificial Frequency-Mapping Technique (AFMT) is capable of modeling an arbitrary number of carriers and we have used it to handle systems with up to 150 noncommensurate tones /5/. Unfortunately, it is just applicable for memory-less nonlinear circuits /3/.

The main aim of this paper is to consider and formulate the multi-tone artificial frequency-mapping techniques (AFMTs) /2-6/ for applying to Microwave circuits with nonlinear elements – especially nonlinear capacitance – when driven with multi-tone excitation.

In this paper, first, we present the theoretical basis of AFMT applying to microwave circuits. Then, it is proposed a linear amplifier suitable for WiMAX technology. So, software is written to analyze this circuit. Also, numerical results of this CAD are confirmed with other methods. Finally the proposed CAD is used to obtain some important amplifier characteristics such as Total Harmonic Distortion (THD), Power Added efficiency (P_{Added}), Intermodulation Distortion (IMD), Adjacent Channel Power Ratio (ACPR) and etc, play a fundamental role on correct specification of the power amplifier /2/.

2. Artificial frequency mapping :

Since Discrete Fourier Transform (DFT) is only directly applicable to periodic signals, common HB is not applicable to circuits with multitone excitation (with uncommensurated tones) /2/. If we restrict the nonlinearities' description to being memoryless /5/, their output spectrum coefficients no longer depend on input absolute frequency values, but only on their relative positions. AFMT proposes a method that converts our mixing component's vector into another one where the original proportions between frequency positions are preserved, and is both dense and harmonically related.

Generalization of AFMT, with important practical interest, uses the fact that a multi-tone signal composed of Q equally spaced tones is not characterized by Q independent base frequencies (as in the case of truly uncommensurated tones). Indeed, note that if the Q tones share an exact common separation Δf, then all Q tones can be uniquely identified by the frequency of one of them. It means that the lower frequency can defined as f_0 and others with separation of Δf which $f_q=f_0+(q-1)\,\Delta f$ where q=1, … , Q.

Thus, the total number of mixing products is $N_T=2QK^2 - 2K^2 + 2K + 1$. (Eq.(1)) The mapping functions can be given by

$$\begin{aligned} f_1 &= [K(Q-1)-Q+2]\lambda \\ f_2 &= [K(Q-1)-Q+3]\lambda \\ &\vdots \\ f_q &= [K(Q-1)-Q+q+1]\lambda \\ &\vdots \\ f_Q &= [K(Q-1)+1]\lambda \end{aligned} \tag{1}$$

Therefore

$$f_k = \sum_{q=1}^{Q} k_q f_q \rightarrow \lambda_k = \left[\sum_{q=1}^{Q} k_q f_q\right]\lambda \tag{2}$$

By this mapping technique all positions are a multiple of λ, and the correspondent artificial time-domain signal is periodic, and the DFT can already be used. Therefore piecewise HB can be applied to the circuit. Since λ is arbitrary, 2Πλ or λ can be chosen 1.

So, the circuit is divided into two sub network linear and nonlinear part. According to HB lows Kirchhoffs current low should be satisfied At any harmonic of each port, or equivalently Eq.(3),

$$F(V_0) = Y_L V_0 + j\Omega\tilde{Q}_{nl}(V_0) + \tilde{I}_{nl}(V_0) + \tilde{I}_S = 0 \tag{3}$$

Where $Y_{LSNXSN} = \begin{bmatrix} y_{11} & \cdots & y_{1S} \\ \vdots & \ddots & \vdots \\ y_{S1} & \cdots & y_{SS} \end{bmatrix}$

$$Y_{ii\,NxN} = \begin{bmatrix} y_{ii}(0) & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & y_{ii}(\omega_N) \end{bmatrix}$$

$V_{0\,SN\times SN}$ is voltage vector ports in form of

$$V_0 = [V_1 \cdots V_S]^T$$

and $V_i = [V_i(0) \cdots V_i(\omega_N)]^T$,

$$I_{nl} = [I_{nl1} \cdots I_{nlS}]^T$$

$$I_{nli} = [I_{nli}(0) \cdots I_{nli}(\omega_N)]^T$$

$$Q_{nl\,SNxSN} = \begin{bmatrix} Q_{11} & \cdots & Q_{1S} \\ \vdots & \ddots & \vdots \\ Q_{S1} & \cdots & Q_{SS} \end{bmatrix}$$ and

$$Q_{ii\,NxN} = \begin{bmatrix} Q_{ii}(0) & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & Q_{ii}(\omega_N) \end{bmatrix}$$

also I_s is vector of equivalent current source at each port. S presents the number of nonlinear port and ω_i is related to any mixing component of basic frequencies that is mapped to 2Π ($\lambda_i = i\lambda$). Therefore N is the number of positive mixing frequency components including DC frequency ($N=(N_T+1)/2$).

But there are some differences between $F(v_0)$ in HB and AFM. Because Ω is the diagonal matrix of harmonic frequencies and in AFM absolute frequencies is changed. Since Ω is related to capacitive current it should be depend on original absolute frequencies (Eq.(4)). It means that frequency domain equivalent of $\frac{dq_{NL}(v_o(t))}{dt}$ is $j\omega_q Q_k$. Thus by substituting Ω by a diagonal matrix of original mixing frequency, OMEGA results in Eq.(5)

$$q_{NL}(v_0(t)) = q_{NL}\left(\sum_k V_{0k}\, e^{jk\omega_0 t}\right) = \sum_k Q_k\, e^{jk\omega_0 t}$$

$$\frac{dq_{NL}(v_0(t))}{dt} = \frac{d(\Sigma_k Q_k e^{jk\omega_0 t})}{dt} = jk\omega_0 \sum_k Q_k e^{jk\omega_0 t} \tag{4}$$

$$F(V_0) = Y_L V_0 + jOMEGA\,\tilde{Q}_{nl}(V_0) + \tilde{I}_{nl}(V_0) + \tilde{I}_S = 0 \tag{5}$$

Consequently

$$OMEGA_{SNxSN} = diagonal[\omega_{11} \cdots \omega_{SS}]^T \; and \; \omega_{ii} = diagonal[0 \cdots \omega_N]^T$$

instead of:

$\Omega_{ii} = diagonal(2\Pi[\lambda_0\ \lambda_1 \cdots \lambda_i \cdots \lambda_{N-1}]^T$ where $\lambda_i = i\lambda$

In the next section this method is applied to a power amplifier when driven by Multi-tone or two tone excitation signal.

3. Simulation and results

In this section one-stage class A power amplifier with 16 dBm of gain and output power of 18 dBm suitable for use in Fixed WiMAX technology based on IEEE 802.16 d standard. It is designed to work at WiMAX profile with 200MHz bandwidth centered at frequency of 3.5 GHz. The amplifier includes input and output Micro-strip matching networks and the necessary DC bias circuitry. The Pseudomorahic InGaAs/ AlGaAS/GaAs HEMT /8/ is used to realized power amplifier. According to reduction of harmonic distortion on output power, it is biased in class A so V_d =6 V and V_g =0 V is chosen. Matching networks are designed and optimized to obtain maximum output power and minimum harmonic distortion.

Within the H-B simulator, they were represented by appropriate multi-port admittance matrices. The active device includes three nonlinear ports corresponding to gate-source, gate drain and drain-source control voltages and currents. For its equivalent circuit nonlinear elements, the nonlinear Curtice 3 model /9/ was adopted. Figure 1 shows the power amplifier circuit schematic. *This power-amplifier circuit was excited by four different types of signals:*

1) Sinusoidal input—one tone;
2) Sinusoidal input—two tones;
3) Sinusoidal multi-tone tone;

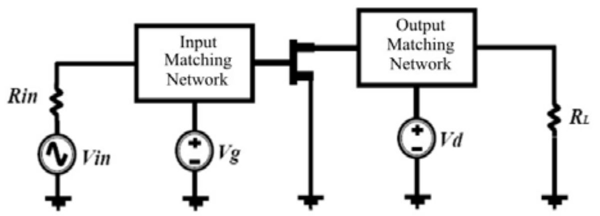

Fig. 1 .Schematic of circuit.

1) One-Tone Test: The first test step consisted of several continuous wave (CW) experiments to evaluate transducer power gain (Gain), output power , and PAE versus input drive level. Results of one-tone excitation is obtained from a one dimensional HB simulator. As seen in figure 2 the PA presents a 1-dB compression point of P1dB= 18.33 with an associated Gain of 16.23 dB and PAE of nearly 19%. Figure 3 shows the simulated output power and its harmonic levels at center frequency. So a Total Harmonic Distortion (THD) /3/ of THD 34.027 dBc, at this P1dB level, was deduced from Figure 3. Fundamental component of output power for the single tone input 2dBm at different frequencies are illustrated in Figure 4.

2*) Two-Tone Test:* As another classic linearity evaluation, the IMD performance was tested. The excitation was a two tone centered at 3.5GHz and separated by 100 MHz. The simulation is performed using AFMT. So two-tone spectrum, which was truncated to fifth order. The extension of this AFM to two-base frequencies diamond truncated up to order K gives 2K2+2K+1=61 as the total number of mixing products, therefore the mixing product matrix has a dimension of 31. By applying mapping technique, the output fundamental power per tone and single sideband IMD power results shown in Figure 5. A direct reading of this plot immediately provides IMR as a function of input drive level (shown in Figure 5), while the extrapolation of output fundamental and IMD power from the small-signal regime, leads to a third-order intercept point of nearly IP3 = 27.5 dBm.

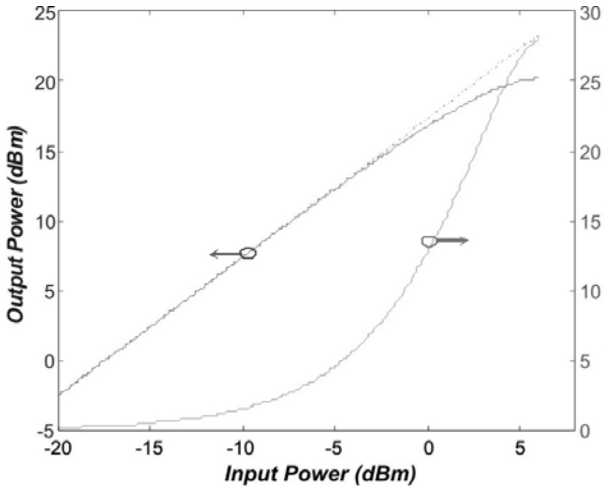

Fig. 2. PA output power and Power added Efficiency versus input drive level.

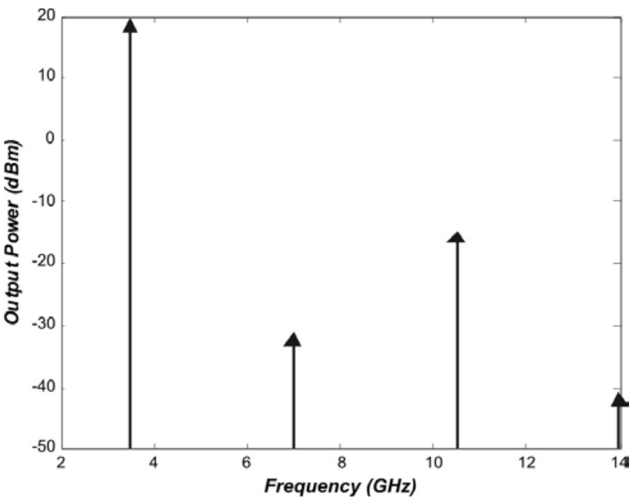

Fig. 3. Output power spectrum when subject to a one-tone excitation of P1dB (18.33 dBm) output power level.

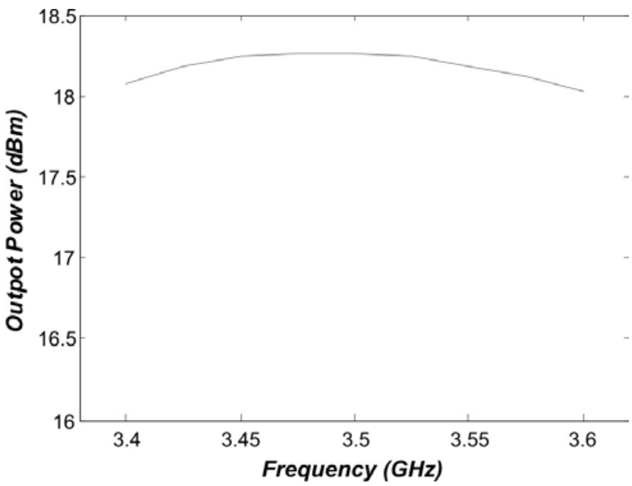

Fig. 4. Output spectrums for single tone input versus frequency in desired bandwidth

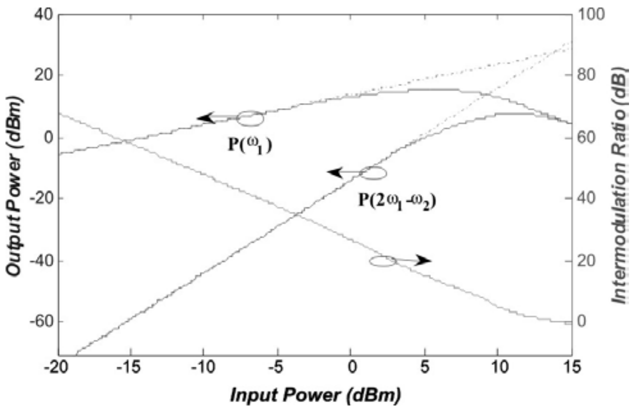

Fig. 5. Fundamental, IMD output power per tone, and inferred two-tone IMR, as a function of PA's input drive level per tone.

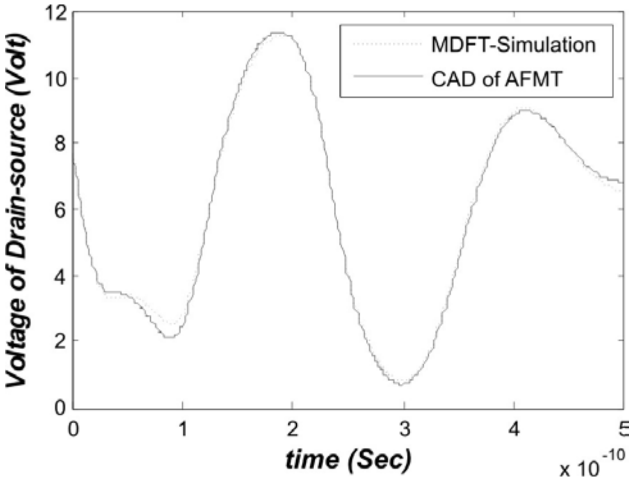

Fig. 6. Voltage of Drain-Source simulated with two different methods

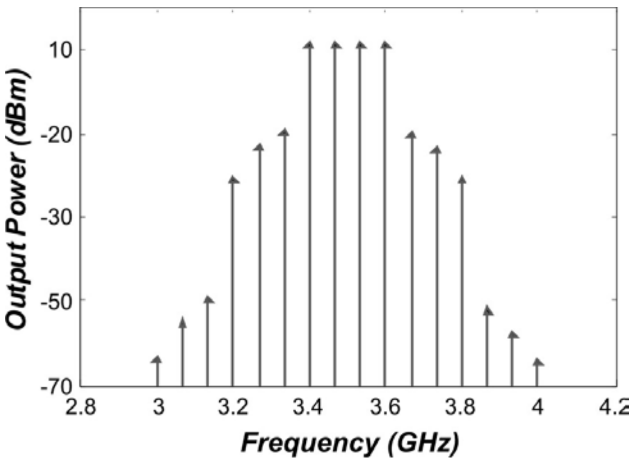

Fig. 7. Output power spectrum of PA exited by 2dBm multi-tone signal

3)Multi-Tone Test: After these two-tone tests, our designed amplifier was subject to a Multi-tone input signal. The amplifier's driving signal was composed of four tone distributed at desired bandwidth started at 3.4 GHz and exact common separation of 667 MHz. since Q=4 and K=5 according to Eq.(1) the number of mixing products is 161 and the dimension of mixing product matrix is 81. The results of simulation with AFM are confirmed with Multi Dimensional Discrete Fourier Transform (MDFT) method. It is illustrated in figure 6. Figure 7 shows the inband portion of the output spectrum. Calculated value of Total Adjacent-Channel Power Ratio /3/ ($ACPR_T$), about 22.1 dB was obtained.

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