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NUMERICAL STUDY OF BEHAVIOURAL SUB-HARMONICALLY PUMPED MIXER IN A NOVEL STRUCTURE

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Abstract—A Sub Harmonically Pumped (SHP) mixer suitable for direct conversion receiver in 3G mobile frequency band is presented. This mixer is realized with N anti-parallel diode pairs (APDPs) and designed in self-biased structure to obtain minimum noise figure and conversion loss. In this paper, a simultaneous signal and noise analysis CAD routine to analyze a circuit consists of Arbitrary Number of anti-parallel diode pairs in self-biased structure is proposed. Then the results of this CAD routine are confirmed with other method. The mixer is optimized to obtain a maximally flat conversion gain and minimum Noise Figure over various LO powers. The proposed CAD is used to obtain the optimum number of APDPs. Also the optimum self-biased resistance and output load are calculated.

1. INTRODUCTION

The cost reduction in wireless transceiver design is a key issue to increase the deployment of these systems. Among various realization techniques the direct conversion includes significant reduction of circuit complexity due to the elimination of IF circuitry, including IF filters and generators. In this way, the received RF signal is converted and demodulated directly to base band [2]. So, this implementation reduces the size and cost of the wireless transceivers.

Therefore, in spite of the fact that heterodyne architecture has a better noise performance [3], direct conversion is more suitable for third generation of mobile communication system.

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This structure is simpler than heterodyne counterpart while it offers some benefits. First, due to zero IF (WIF = 0), the problem of image is circumvented. Also, there isn't any need to IF high Q filters and subsequent stages after down conversion [1]. On the other hand, the direct conversion topology suffers from some problems that doesn't exist or aren't as serious as heterodyne counterpart. One of the most important issues is DC Offset problem generated by LO signal leakage to the mixer and LNA inputs and mixed with the LO signal and vice versa. It may saturate the next stages. In order to prevent DC Offset, some methods like using mixer with high IP2 or high pass filtering after down converting are offered. Another method to prevent DC Offset is the use of Even Harmonic Mixer (EHM) or Sub-harmonically pumped (SHP) mixers with anti parallel diode pair in both I and Q paths [1].

The APDP has a balanced structure that suppresses the fundamental mixing products ($\mathrm{mf_{LO}} \pm \mathrm{nf_{IF}}$ where $m + n =$ even). These product flows only within the APDP loop. The SHP with APDP has some advantages that make it very attractive for millimetre-wave transceivers. These advantages are: (1) it can operate with halved LO frequency; (2) in direct conversion transmitter, it can suppress the virtual LO leakage ($2f_{\mathrm{LO}}$) that locates nearby a desired RF signal; (3) it suppresses DC offset in direct conversion receivers [4].

This paper is organized as follows: an efficient structure for SHP mixer using N anti-parallel diode pares [5] is proposed and improved behavior using some methods such as using self-biased structure, filters and matching networks, are introduced. Then, a fast and efficient simultaneous signal and noise analysis CAD routine, suitable for analyzing circuits consist of N anti-parallel diode pairs in self-biased structure is presented. Then numerical results are presented. The calculation results of this CAD are confirmed with other method. Then the proposed CAD is used to obtain the optimum number of APDPs. Finally the optimum self-biased resistance and output load is presented.

2. MIXER CONFIGURATION

The circuit configuration of the SHP mixer is shown in Fig. 1(a). It is designed to operate at RF frequencies of 2110–2170 MHz and suitable for using in direct-conversion receiver in 3G mobile communications frequency band. So it is used the second harmonic of the LO input signal (at $2 * 1070 = 2140$ MHz) to provide the RF signal at DC frequencies. The mixing element is the GaAs Schottky barrier APDP (agilent HSCH-9551). Table 1 shows its parameters. Schottky diode mixers represent the best technological choice as they can operate properly at room-temperature. They are suitable for those commercial applications where cryogenic operation is not possible due to elevated sizes and costs. Contrarily to Schottky mixers, other technologies such as HEB and SIS mixers need to be cooled for high-performance operation [5].

Also this circuit includes open-and short-circuited stubs at each port of the APDP. Both of them have a quarter wavelengths at LO frequency. Using these stubs, the BPF and the LPF, the leakage of each port at other ports is suppressed [6]. The BPF is designed to cover the RF band and it is a third-order chebycheve filter with centre frequency of 2140 MHz.

The mixer uses a high-pass filter for RF range provide the output to RF isolation. Two quarter-wave stubs at RF frequency are used

Table 1. Diode parameters.

Junction capacitance (C_{j0})	0.04 pF
Series resistance (R_s)	5 Ω
Saturation current (I_s)	1.6E–13A
Ideality factor (N)	1.2

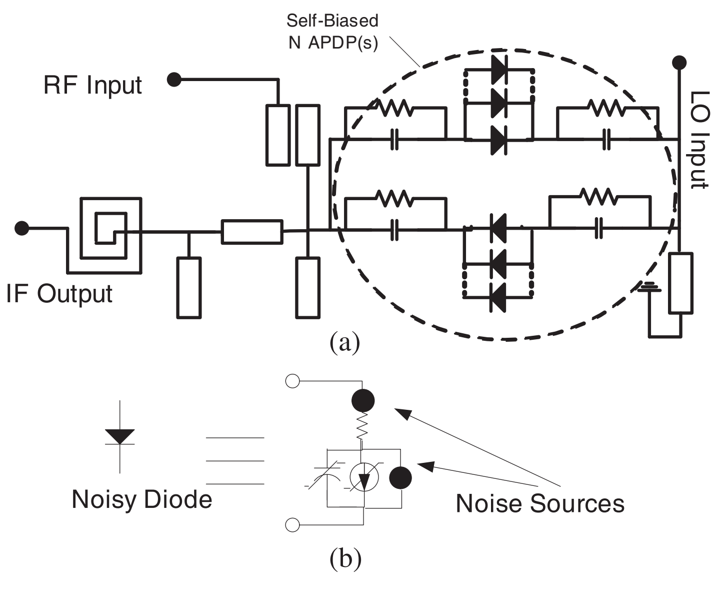


Figure 1. (a) Mixer structure, (b) nonlinear noisy diode model.

to provide RF-to-IF port (output) isolation. At RF frequency input impedance of open-end quarter wave length is zero (short circuit) so eliminates RF frequency at IF and another side of second stub is open circuit and it has not effect on RF frequency [6].

3. SIMULTANEOUS SIGNAL AND NOISE ANALYSIS FOR ARBITRARY NUMBER OF ANTI-PARALLEL DIODE MIXER

In this paper, an efficient simultaneous signal and noise analysis based on large signal/small signal analysis [4] is presented. So it can be decomposed into two main algorithms: The nonlinear steady state solution and linear parametric analysis using L-S approach. Under the large signal excitation of a local oscillator there exist stable, time-periodic solutions for the mixer. In the next step the effect of superimposing the signal (RF signal) and noise on such periodic steady state waveform is analysed. We assumed that the signal and noise spectral components are small compared to local oscillator.

The first step to analysis of nonlinear devices is choosing the appropriate model. Figure 1(b) shows the Schottky diode nonlinear noisy model. The models considered for non-linear elements (capacitor and current source) are as follows:

$$C = \frac{C_0}{\sqrt{\alpha_0 + \alpha_1 V}}, \quad I_D = I_S \left(1 - e^{\alpha V_d}\right) \tag{1}$$

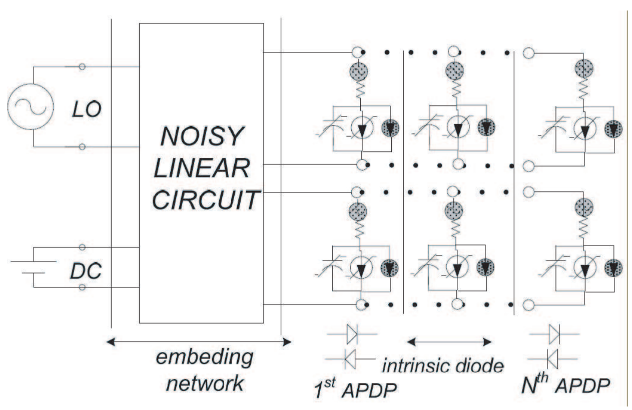


Figure 2. The circuit presentation for the steady state response in simultaneous signal and noise analysis based on HB nonlinear analysis.

The proper presentation of the circuit in the first step of analysis is shown in Figure 2. The nonlinear simulation engine is HB, which is quite mature and generally considered accurate and appropriate for circuits with any degree of nonlinearity [2, 4].

In proposed SHP mixer no DC bias is needed. The input signal source is omitted and the corresponding port is loaded with generator impedance. The load of IF port is the input impedance of an IF amplifier.

Therefore, as mentioned previously, in the first step HB should be applied to the circuit to obtain the large voltage components of any nonlinear elements. So, the circuit is subdivided into two different linear and nonlinear parts. This circuit with N APDP(s) has 4N nonlinear elements (2N nonlinear current source and 2N nonlinear capacitor). By considering each current source and capacitor in a nonlinear port the number of nonlinear ports reduces to 2N. According to Eq. (2) Krichoff's current law should be satisfied At any harmonic of each port. Which $\mathbf{I}_{\mathrm{L}}$ and $\mathbf{I}_{\mathrm{NL}}$ is linear and nonlinear current vector respectively [4].

$$\mathbf{F}_{NL}(U) = \underline{\mathbf{I}}_L + \underline{\mathbf{I}}_{NL} = 0 \quad \text{in which}$$

$$\underline{\mathbf{I}}_L = \mathbf{Y_L U} = \begin{bmatrix} I_{L1} \\ I_{L2} \\ \vdots \\ I_{L2N} \end{bmatrix}, \underline{\mathbf{I}}_{NL} = \mathbf{j}\Omega\mathbf{Q}_{nl}(\mathbf{U}) + \mathbf{I}_{nl}(\mathbf{U}) + \mathbf{I_S} = \begin{bmatrix} \underline{\mathbf{I}}_{NL1} \\ \underline{\mathbf{I}}_{NL2} \\ \vdots \\ \underline{\mathbf{I}}_{NL2N} \end{bmatrix} \tag{2}$$

$$\underline{\mathbf{I}}_{Ln} = \begin{bmatrix} I_{Ln}(@Dc) \\ I_{Ln}(\omega_{lo}) \\ \vdots \\ I_{Ln}(K\omega_{lo}) \end{bmatrix}, \underline{\mathbf{I}}_{NLn} = \begin{bmatrix} I_{NLn}(@Dc) \\ I_{NLn}(\omega_{lo}) \\ \vdots \\ I_{NLn}(K\omega_{lo}) \end{bmatrix}$$

where

$$\mathbf{Y_L} = \begin{bmatrix} \mathbf{Y}_{11} & \cdots & & \mathbf{Y}_{1(2N)} \\ & \ddots & & \\ \vdots & & \ddots & \vdots \\ \mathbf{Y}_{(2N)1} & \cdots & & \mathbf{Y}_{(2N)(2N)} \end{bmatrix}$$

$$\text{that } \mathbf{Y}_{nn} = \begin{bmatrix} Y_{nn}(@Dc) & 0 & \cdots & 0 \\ 0 & Y_{nn}(\omega_{lo}) & 0 & \vdots \\ \vdots & 0 & \ddots & \vdots \\ 0 & \cdots & 0 & Y_{kk}(K\omega_{lo}) \end{bmatrix},$$

$$\Omega = \begin{bmatrix} \Omega_n & 0 & \dots & 0 \\ 0 & \Omega_n & 0 & \vdots \\ \vdots & 0 & \ddots & 0 \\ 0 & \dots & 0 & \Omega_n \end{bmatrix} \quad \Omega_n = \begin{bmatrix} 0 & 0 & \dots & 0 \\ 0 & \omega_{lo} & 0 & \vdots \\ \vdots & 0 & \ddots & \vdots \\ 0 & \dots & 0 & K\omega_{lo} \end{bmatrix}$$

$\mathbf{Q}_{nl}, \mathbf{I}_{nl}, \mathbf{I}_s$ are nonlinear capacitance charge, current source of diodes and equivalent source vector at the nonlinear ports, respectively.

After finding $\mathbf{u}_1$, $\mathbf{u}_2 \dots$ and $\mathbf{u}_{2N}$, the steady state voltage of each nonlinear element, and the currents, obtained by the numerical means, next step is to perform a small signal and noise analysis. That can be presented in form of Fourier series, contain harmonics of local oscillator. Knowing these Fourier series coefficients, it is possible top to construct the small signal conversion matrix for the diode pair.

$$\delta\mathbf{I_i} = \mathbf{Y_i}\delta\mathbf{V_i} \quad i = 1,\, 2,\, \dots,\, 2N \tag{3}$$

where

$$\mathbf{Y_i} = \left[\mathbf{R_{si}} + (\mathbf{G_i} + \mathbf{jC_i}\psi)^{-1}\right]^{-1}_{(2K+1)\times(2K+1)} \quad \text{that}$$

$$\mathbf{R_{si}} = \begin{bmatrix} R_{si} & 0 & \dots & 0 \\ 0 & R_{si} & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \dots & 0 & R_{si} \end{bmatrix}_{(2K+1)\times(2K+1)},$$

$$\mathbf{G_i} = \begin{bmatrix} G_0 & G_1 & \dots & G_{2K} \\ G_{-1} & G_0 & & \vdots \\ \vdots & & \ddots & G_1 \\ G_{-2K} & \dots & G_{-1} & G_0 \end{bmatrix}_{(2K+1)\times(2K+1)},$$

$$\mathbf{C_i} = \begin{bmatrix} C_0 & C_1 & \dots & C_{2K} \\ C_{-1} & C_0 & & \vdots \\ \vdots & & \ddots & C_1 \\ C_{-2K} & \dots & C_{-1} & C_0 \end{bmatrix}_{(2K+1)\times(2K+1)}$$

$$\psi = \begin{bmatrix} -N\omega_{Lo} + \omega_{RF} & 0 & \dots & 0 \\ 0 & \omega_{RF} & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \dots & 0 & N\omega_{Lo} + \omega_{RF} \end{bmatrix}_{(2K+1)\times(2K+1)}.$$

there $C_{\pm k}$ and $G_{\pm k}$ represent the FFT coefficients at frequency $k\omega_{LO} \pm \omega_{RF}$ and $G_k = G^*_{-k}$.

Assuming RF signal is small enough both $\delta\mathbf{I}$ and $\delta\mathbf{V}$ contain components at only the pair of side-frequencies $k\omega_{LO} \pm \omega_{RF}$ [4]. The admittance matrix $\mathbf{Y}$ allows the pumped diode to be treated as a multi-frequency multi-port network with one port for each sideband frequency. Combing this multi-frequency linear representation of nonlinear elements with the linear section, results in an equivalent $\mathbf{Y}$ matrix, Y_{eq}, that may any circuit specification can be extracted of this matrix by properly chosen ports.

This simultaneous signal and noise analysis subdivide the circuit into two linear and Diode sub circuits. Formulation of this method is presented as fallowing. As the steady state voltages of NL elements are known, the conversion matrix of each element is calculated. So $\mathrm{G}_{\mathbf{i}}$ and $\mathbf{C}_{\mathbf{i}}$ are conversion matrix of $\mathbf{g}_{\mathbf{mi}}(\overline{\mathrm{V}})$ and $\mathbf{c}_{\mathbf{i}}(\overline{\mathrm{V}})$, respectively.

Then diode part in each port as illustrated in Figure 3(b) can be replaced with an equivalent circuit, where $\mathbf{Y}_D$ and $\mathbf{I}_{SC/nD}$ are equivalent admittance and noise current source, respectively. It can be shown that:

$$\mathbf{Y}_D = \sum_{i=1}^{N} \left[\mathbf{R}_{Si} + \left[\mathbf{G}_i + j\mathbf{\Omega}\mathbf{C}_i\right]^{-1}\right]^{-1} \tag{4}$$

$$\mathbf{I}_{SC/nD} = \sum_{i=1}^{N} \left[\mathbf{R}_{Si} + \mathbf{G}_i^{-1}\right]^{-1} \left[\mathbf{v}_{ni} - \mathbf{G}_i^{-1}\mathbf{i}_{ni}\right] \tag{5}$$

Also, assuming that all APDPs are alike and use the same small signal model, as the structure are concurrent, it can be replaced with Figure 3(c) where the equivalent elements obtain from fallowing:

$$\begin{aligned} &R'_s = R_{s1}/N, \quad v'_s = v_{s1} \quad G'_s = N \times G_{s1} \\ &C'_s = N \times C_{s1}, \quad i'_s = i_{s1}/N \end{aligned} \tag{6}$$

On the other hand, we can consider this simple approximation from the first and assume that all the diodes are alike and all ports use same diodes. Therefore, as it is shown in Figure 4, an equivalent model can be used for N parallel diode, where its parameters related to the each diode model by Eq.

$$\begin{aligned} &r'_s = r_{s1}/N, \quad c'(v) = N \times c_1(v) \\ &f'_{NL}(v) = N \times f_{NL1}(v) \end{aligned} \tag{7}$$

This assumption facilitate analysis witch nonlinear ports in HB analysis reduce to only two. So, more time and memory are saved.

Finally, replacing diode part with its equivalent model, Figure 5 shows a complete view of the circuit including all noise sources. In

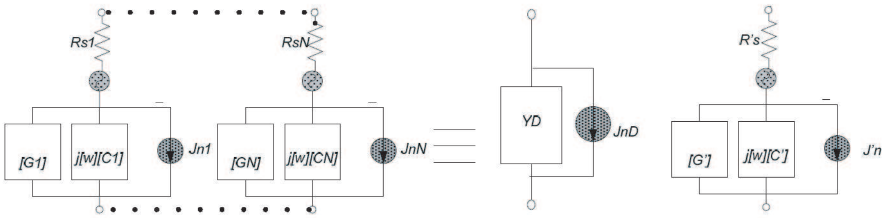


Figure 3. Equivalent diode part for simultaneous signal and noise analysis.

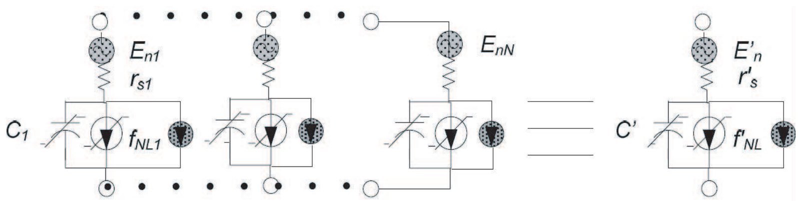


Figure 4. Equivalent diode model for N APDP(s).

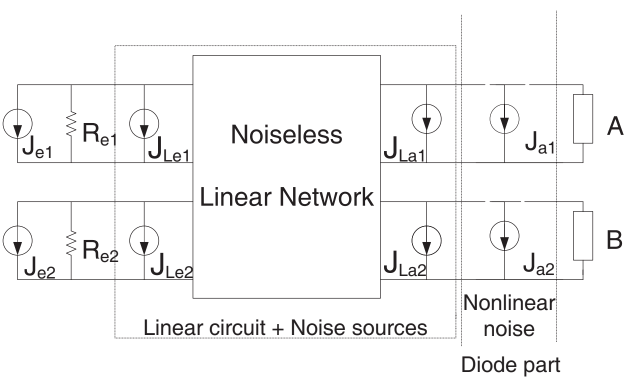


Figure 5. The circuit presentation for the small signal and noise analysis.

this figure, linear part is noiseless and its thermal noise is equivalently assumed as $\mathbf{J_L}$ current noise sources in each port. The a and e subscript consequently indicates linear to nonlinear and linear to external source and load inter connection.

In last method mentioned, $\mathbf{r}_s$ is included in the linear network. So the related thermal noise source is absorbed by $\mathbf{J}_{La1}$ and $\mathbf{J}_{La2}$.

To perform of the noise analysis, noise correlation of each group of the noise sources should be calculated. First noise source group is related to linear network. The correlation matrix is calculated directly from signal parameters of the network.

$$\mathbf{C}_j = 2kT\Delta f(\mathbf{Y} + \mathbf{Y}^{*t}) \tag{8}$$

Second correlation matrix is related to the sources of the signal, represented by $\mathbf{C}$.

$$\mathbf{C} =< \mathbf{J}_{ei}\mathbf{J}_{ej}^{*t} > \text{ when } i \neq j \text{ otherwise } 0. \tag{9}$$

The last noise sources are related to nonlinear elements of the circuit. The shot noise in each diode can likewise be regarded as amplitude modulated Gaussian noise. Due to independent physical process of shot noise generation in two diodes, there is no correlation between the unmodulated noises. The modulation process generates additional sideband at each diode.

The nonlinear noise current at each active port is nominated by $\mathbf{J}_{ai}\, i = 1, 2$. Therefore $\mathbf{C}_{ja}$ is given

$$\mathbf{C}_{ja} = \left\langle \begin{pmatrix} \mathbf{J}_{a1} \\ \mathbf{J}_{a2} \end{pmatrix} (\mathbf{J}_{a1}^{*}\mathbf{J}_{a2}^{*}) \right\rangle \tag{10}$$

where $\mathbf{J}_{\text{ai}} = [J_{ai}(-K\omega_{Lo} + \omega_{RF}) \ldots J_{ai}(\omega_{RF}) \ldots J_{ai}(K\omega_{Lo} + \omega_{RF})]^T$.

Since their un-modulated components are not correlated, there will be no correlation between the modulated noises components thus $\mathbf{C}_{ja}$ is a diagonal matrix.

$$\mathbf{C}_{ja} = \begin{bmatrix} \mathbf{C}_{ja\,1} & 0 \\ 0 & \mathbf{C}_{ja\,2} \end{bmatrix},$$

$$\mathbf{C}_{jan=1,2} \begin{bmatrix} \mathbf{C}_{ja}(-K\omega_{Lo}+\omega_{RF}) & 0 & \ldots & 0 \\ 0 & \mathbf{C}_{ja}(\omega_{RF}) & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \ldots & 0 & \mathbf{C}_{ja}(K\omega_{Lo}+\omega_{RF}) \end{bmatrix}_{(2K+1)\times(2K+1)}$$

Proper combination of this correlation matrices result in a global correlation matrix. By this matrix, noise power of output port at any harmonic is determined. For calculating the noise figure, $|\bar{V}(\omega_{IF})|^2$ component of the matrix is used.

Thereupon, with choosing IF frequency, SSP Noise Figure is calculating from [7]:

$$NF = \frac{\overline{|V(\omega_{IF})|^2}}{4KTR_cG} \tag{11}$$

where K and G are the Boltzman constant conversion gain between radio frequency to intermediate frequency.

4. NUMERICAL RESULTS

In the first step of numerical analysis the harmonic balance is applied to the circuit excited by LO signal only, to obtain the steady state large signal voltage of nonlinear ports. In Figure 6, the results of proposed CAD are confirmed with commercial software results. Then, simultaneous signal and noise analysis is applied to this mixer. Figure 7 shows calculated conversion gain versus LO power. Also, as the RF central frequency is twice LO frequency, it can be calculated directly by HB only. As may be seen, the calculated results in two ways agree well with the simulated results. As we know, series resistance ($\mathbf{R}_s$) of Schottky diodes is a major factor in diode mixer conversion loss. And also the junction capacitance increases the conversion gain. If two parallel Schottky diodes are substituted for each diode in APDP, effective $\mathbf{C}_j$ and $\mathbf{R}_s$ of the structure will be respectively multiplied and divided by an approximate factor of two and the conversion loss will be decreased [6]. Also use of more diodes instead of each diode causes more decrease in mixer conversion loss. Since the circuit is passive improving signal performance will lead to improved noise results and vice versa. Figure 8 shows the conversion gain and noise figure for N APDPs. As we can see in this figure, increasing the number of APDPs results improving in both conversion gain and noise figure, but it converge and for $N > 3$ we can not see an ample improvement. So the optimum N is chosen by 3. The most advantage of increasing N is to obtain more conversion gain and less noise figure for lower LO powers. In order to have the best mixer behaviour, self-biased

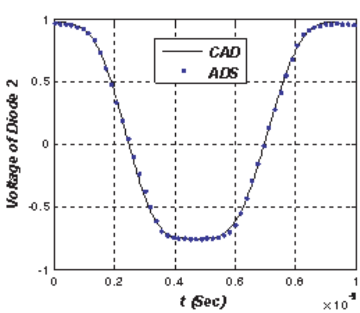


Figure 6. Steady state large signal voltage of nonlinear port.

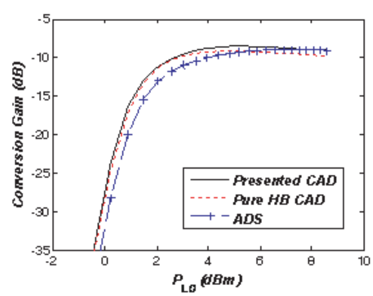
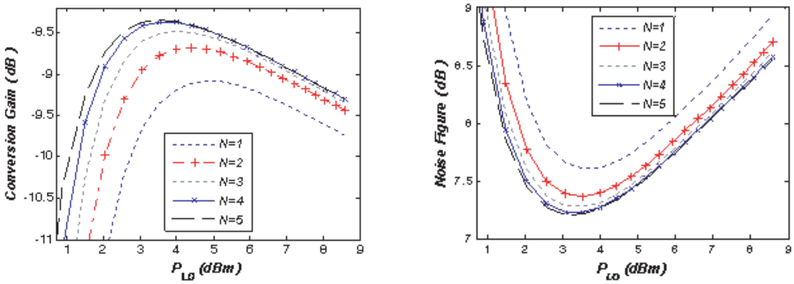
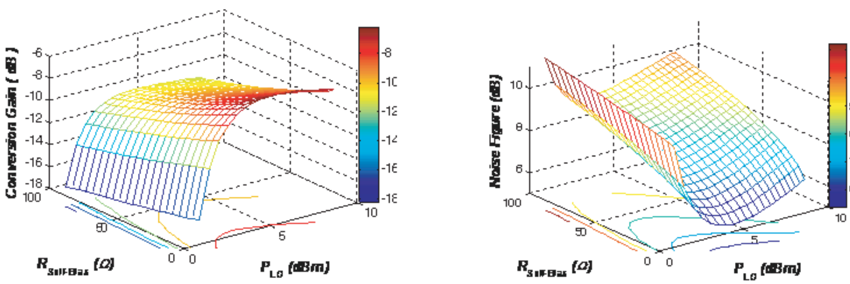


Figure 7. Conversion gain calculated in three ways.



(a) (b)

Figure 8. (a) Conversion gain for N APDP(s), (b) noise figure for N APDP(s).



(a) (b)

Figure 9. (a) Conversion gain and (b) noise figure versus self-biased and $\mathbf{P}_{\mathrm{LO}}$.

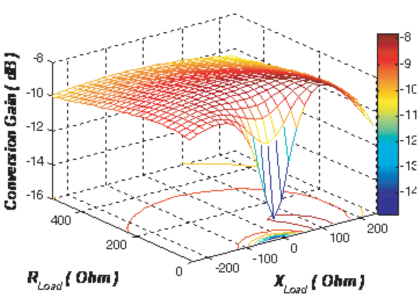


Figure 10. Conversion gain for swap $\mathbf{Z}_{\mathrm{Load}} = \mathbf{R}_{\mathrm{Load}} + \mathbf{jX}_{\mathrm{Load}}$.

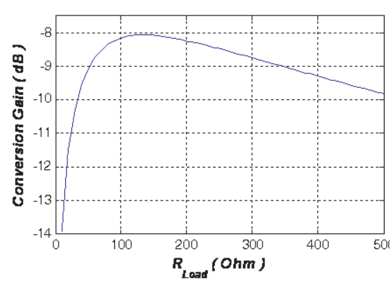


Figure 11. Conversion gain verus various $\mathbf{Z}_{\mathrm{Load}} = \mathbf{R}_{\mathrm{Load}}$.

APDP is used to reach to a flat conversion gain versus different LO powers. But as illustrated in Figure 9 increasing self-biased resistance, flattening Conversion gain, increases the noise figure. Therefore, it should be chosen by trading off between flatness and low noise figure. The optimum choice in this paper used for presiding results is $50\,\Omega$ for each side of diodes. In this work, we also, calculated conversion gain for various output impedances. Figure 10 depicts the results. The maximum conversion gain occurs in $\mathrm{ZL} = 10 + \mathrm{j}110\,\Omega$. Computation over pure resistive output impedances is illustrated in Figure 11. Note that output the output impedance does not affect on noise figure witch supposed to be noiseless there.

5. CONCLUSION

A SHP mixer with N anti-parallel diode pairs (APDPs) has been used to realize a direct conversion demodulator. This mixer utilizes N APDPs results in better signal and noise performance. It has been designed in self-biased structure to obtain maximally flat conversion gain and noise figure. Then an appropriate CAD routine for simultaneous signal and noise analysis of mixer consist of arbitrary number of APDP(s) has been proposed. The CAD presents and completely facilitates the analysis and also, more time and memory are saved. At last, conversion Gains and noise figures of this mixer with variable number of APDP(s) were compared. Consequently, it was shown that conversion gain and noise figure are improved by increasing the number of APDP's and optimum N for obtaining this structure.

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