Journal of Electrical and Computer Engineering Innovations
(JECEI)
Journal homepage: http://www.jecei.sru.ac.ir

Research paper

A Novel Analog Predistortion Linearizer Based on a Schottky diode for Communication Applications

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Article Info

Article History:

Received 06 March 2021
Reviewed 10 April 2021
Revised 03 May 2021
Accepted 09 July 2021

Keywords:

Power Amplifiers (PAs)
Schottky diode
Analog Pre-Distorter (APD)
Linearization
AM/AM and AM/PM
Nonlinearity

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Abstract

Background and Objectives: In order to compensate the nonlinearity, several linearization approaches such as feedback, feed-forward, and predistortion have been proposed. Among these linearization methods, the analog predistortion (APD) method is very suitable for the power amplifier and TWTA linearization, because it has a good compromise between complexity, linearity improvement and bandwidth. On the other hand, analog predistortion circuit can be added to existing amplifiers as a separate circuit. Many of the reported linearizer circuits are capable of linearizing power amplifiers with high gain and phase variations. However, these circuits are complex and bulky due to the use of distortion producer, phase shifter, adjustable attenuator, combiner/divider, and control unit. The objective of this paper is increasing the dynamic range of the predistorter by a simple proposed circuit. Hence, linearization capability of the linearizer is boosted.
Methods: A new analog predistortion linearizer based on a coupler and a Schottky diode is presented. The proposed structure satisfies linearization requirements of the solid-state power amplifiers (SSPAs) and traveling wave tube amplifiers (TWTAs). Using a parallel combination of two Schottky diodes along with transmission line in port 2 and 3 of the coupler, the dynamic range of reflection coefficient of each port is increased compared to using a single diode in each branch. By increasing the range of reflection signal, the linearization capability has been increased to linearize power amplifiers and TWTAs. The AM/AM and AM/PM of the linearizer is controlled by changing the bias voltage of power supply.
Results: The simulation results show that about 30° phase shift and 5 dB gain expansion can be compensated for power amplifiers and TWTAs. Because of utilizing two diodes, the linearization capability of the new linearizer is augmented compared to the conventional linearizer.
Conclusion: A novel analog predistortion circuit based on the hybrid coupler and Schottky diodes is presented. The suggested topology increases the dynamic range of reflected power from each port. Using the proposed idea, AM/AM and AM/PM characteristics are expanded such that this characteristic can linearize the power amplifier with high linearity.

Introduction

Recently in advanced communication systems, the rapid development of the transmission and reception of high-volume multimedia data has been taking place [1]. For this reason, a linearization of high power solid-state power amplifiers (PAs) or traveling wave tube amplifiers

(TWTAs) is an essential task so that nonlinearity generated by the power amplifier or TWTA will cause amplitude-to-amplitude (AM/AM) and amplitude-to-phase (AM/PM) distortions [2], [3]. Furthermore, nonlinearity of the power amplifier causes an intermodulation distortion (IMD) which produces interference in adjacent channels [4]-[11].

In order to compensate the nonlinearity, several linearization approaches such as feedback, feed-forward, and predistortion have been proposed [12]-[16]. The feed-forward method has been extensively utilized with power amplifiers and TWTAs, but it consumes a lot of power and its implementation is complicated [6], [17]. Due to stability problems and reduced gain, the feedback circuit is less used as a linearizer in microwave circuits. Among these linearization methods, the analog predistortion (APD) method is very suitable for the power amplifier and TWTA linearization, because it has a good compromise between complexity, linearity improvement and bandwidth [18]. On the other hand, Analog predistortion circuit can be added to existing amplifiers as a separate circuit. This circuit can produce a nonlinear characteristic that is exactly in accordance with the reverse of the power amplifier behavior [7], [8], [9], [10], [19]. In Fig. 1 the schematic diagram of analog linearization is illustrated.

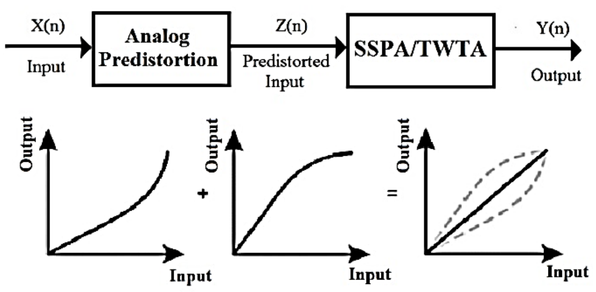

Fig. 1: The schematic diagram of analog linearization is illustrated.

Many researchers have proposed analog distortion circuits that have very simple structures [20]-[25]. But, these linearizers are usually used for linearization of power amplifiers and TWTAs that have low amplitude and phase nonlinearity. In addition, these nonlinear circuits suffer from the impedance matching of input and output ports over the whole operating power region. For this reason, utilization of the isolator on both ports is necessary. Many of the reported linearizer circuits are capable of linearizing power amplifiers with high gain and phase variations [26], [27]. However, these circuits are complex and enlarged due to the use of distortion producer, phase shifter, adjustable attenuator, combiner/divider, and control unit.

In this paper, a novel predistortion circuit based on the hybrid coupler and Schottky diode has been proposed. The proposed circuit can increase the dynamic range of reflection coefficient of each port. As a result, the AM/AM and AM/PM characteristics are expanded such that this characteristic can linearize the power amplifier with high linearity.

This paper is organized as follows: First, design of analog predistortion linearizer based on the hybrid coupler and Schottky diode is proposed. Then, the simulation results of the new analog linearizer are carried out. Finally, the conclusion is expressed.

Design of the Proposed Analog Predistortion Linearizer

The schematic diagram of the proposed APD linearizer is depicted in Fig. 2. A quadrature hybrid coupler in conjunction with Schottky diode is utilized to make an analog linearizer. When input signal is applied to the input of the coupler, the input signal divided between the ports 2 and 3 goes to Schottky diodes and the load resistance. Then, the signals that are reflected from the ports 2 and 3 are collected in the port 4. Due to the inherent characteristic of the coupler, input and output ports are well matched.

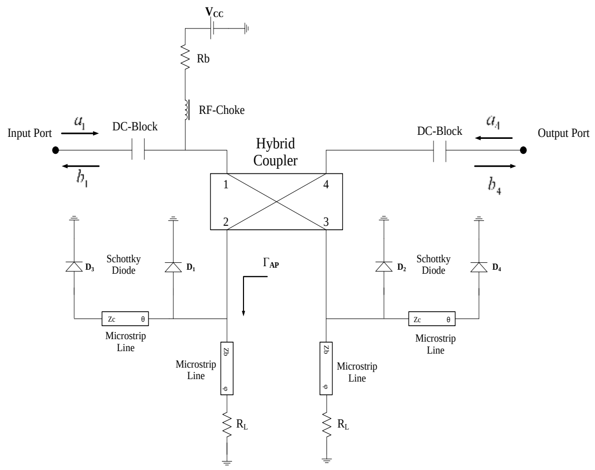

Fig. 2: The schematic of proposed APD linearizer.

Each path produces a nonlinear reflection coefficient, Γ_{AP}, which is proportional to the input signal $\boldsymbol{a}_1$. The scattering matrix is defined as follows [28]:

$$\begin{bmatrix} \boldsymbol{b}_1 \\ \boldsymbol{b}_2 \\ \boldsymbol{b}_3 \\ \boldsymbol{b}_4 \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & 1 & -j & 0 \\ 1 & 0 & 0 & -j \\ -j & 0 & 0 & 1 \\ 0 & -j & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{a}_1 \\ \Gamma_{AP} \cdot \boldsymbol{b}_2 \\ \Gamma_{AP} \cdot \boldsymbol{b}_3 \\ 0 \end{bmatrix} \quad (1)$$

where $\boldsymbol{a}_2$ and $\boldsymbol{a}_3$ are defined as follows:

$$\boldsymbol{a}_2 = \Gamma_{AP} \cdot \boldsymbol{b}_2 \quad (2)$$

$$\boldsymbol{a}_3 = \Gamma_{AP} \cdot \boldsymbol{b}_3 \tag{3}$$

Finally, the reflected signal in the fourth port is defined as follows:

$$\boldsymbol{b}_4 = -j\Gamma_{AP} \cdot \boldsymbol{a}_1 \tag{4}$$

where the input and output signals are displayed as $\boldsymbol{a_1}$ and $\boldsymbol{b_4}$. The final output equation is defined in terms of input power as follows [29]:

$$P_{OUT} = \left|\Gamma_{AP}\right|^2 \cdot P_{IN} \tag{5}$$

Equation (5) shows that the predistortion gain is equal to the square value of reflection coefficient which is seen from each of the second and third ports.

In previous predistortion circuits, i.e. [17] and [18], a single Schottky diode was used on the ports 2 and 3. But in the proposed circuit, a combination of two Schottky diodes along with the transmission line is utilized in each branch. Using this idea, the dynamic range of reflection coefficient of each port is increased compared to using a single diode in each branch. In Fig. 3, the circuit in port 3 with its equivalent circuit is shown. In general, the equivalent circuit of a Schottky diode includes equivalent conductance $1/G_D$ and susceptance β_D. Equivalent admittance seen in load consists of equivalent conductance G_L and susceptance B_L. In Fig. 3(*b*) for the first and third diodes, their equivalent circuit is shown.

The Schottky diode can be expressed as a variable conductance so that its conductance changes with respect to the input power level. In Schottky diodes, conductance variations are dominant compared to susceptance variations. The reflection coefficient, Γ_{AP}, on the third coupler port is given as follows:

$$\Gamma_{AP} = \frac{G_0 - (G_L + G_{d1} + G_{d3}) - j(B_L + B_{d1} + B_{d2})}{(G_0 + G_L + G_{d1} + G_{d2}) + j(B_L + B_{d1} + B_{d2})} \tag{6}$$

Equations for the amplitude and phase of the reflection coefficient are expressed as the following equations:

$$Mag[\Gamma_{AP}] = \sqrt{\frac{(G_0 - G_L - G_{d1} - G_{d3})^2 + (B_L + B_{d1} + B_{d2})^2}{(G_0 - G_L - G_{d1} - G_{d3})^2 + (B_L + B_{d1} + B_{d2})^2}} \tag{7}$$

$$Ang[\Gamma_{AP}] = \tan^{-1}\left[\frac{-(B_L + B_{d1} + B_{d2})}{(G_0 - G_{d1} - G_{d2} - G_L)}\right] - \tan^{-1}\left[\frac{(B_L + B_{d1} + B_{d2})}{(G_0 + G_{d1} + G_{d2} + G_L)}\right] \tag{8}$$

Regarding (7) and (8), it can be seen that the amplitude and phase of the linearizer are controlled by the parameters such as G_D, G_L, B_D, and B_L. The simulation of reflection coefficient as in Fig. 3(*a*) circuit, as single and two diodes is done in advanced design system (ADS) software. As is shown clearly in Fig. 4, the dynamic range of the reflection coefficient for the two-diodes state is increased compared to single diode state. Using this idea, the dynamic range is almost doubled. By increasing the range of reflected signal, the linearization capability is increased to linearize the power amplifiers.

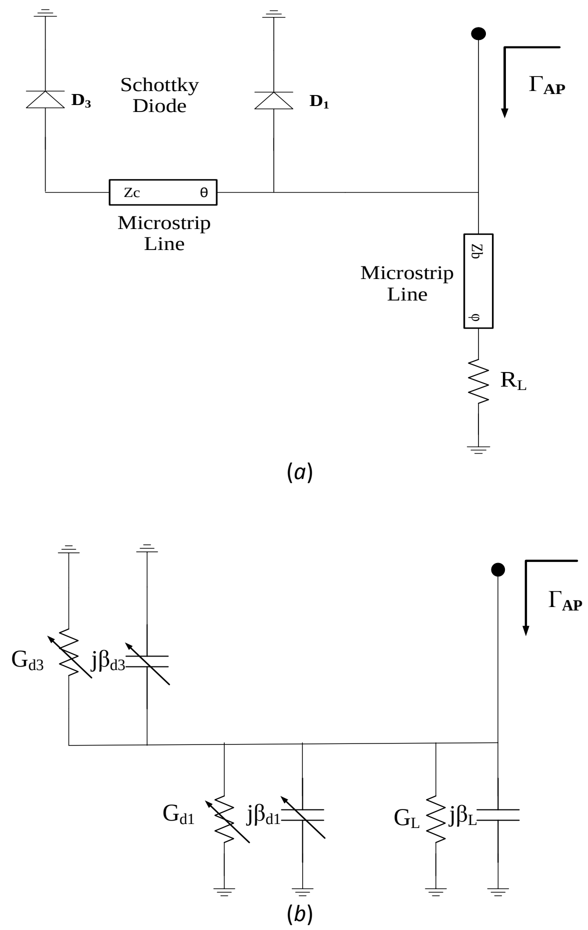

Fig. 3: (*a*) The circuit of left side of coupler port (*b*) Equivalent circuit of two Schottky diodes and load resistance seen at the coupler port.

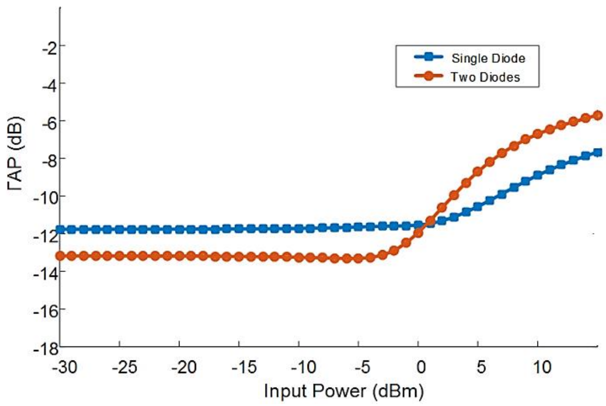

Fig. 4: Gamma simulation on the third port of the coupler with single and two diode states.

Simulation Results

The proposed analog predistortion linearizer has been designed at the frequency of 10.95-11.20 GHz. Specifications of the proposed linearizer are simulated by momentum method of the ADS software. As known, this method simulates the structure in full wave, therefore the results of simulation will be accurate. The Schottky diode used in simulations is MA4E2054 of MACOM. The substrate used is Rogers RT/Duroid 5870 with a thickness of 10 mils and dielectric constant of 2.33. In all of simulations, the Schottky diodes are modeled with HSPICE parameters. The amplitude and phase specifications of the proposed linearizer with different bias points are shown in Fig. 5 and Fig. 6, respectively. The load resistance R_L is 60 Ω, the electrical lengthes of ϑ_b and ϑ_c are 103° and 110°, respectively. Also, the impedance characteristic of the two transmission lines Z_b and Z_c, is 50 Ω. As the bias voltage increases in Fig. 5, the dynamic range of the amplitude changes is reduced. The diode bias voltage can vary from 50 mV to 300 mV. The gain expansion of the linearizer over a 45 dB input power dynamic range at the frequency of 11 GHz is about 5.3 dB. The trend of linearizer phase variation with bias voltage changes is similar to amplitude variation. As is shown in Fig. 6, the maximum phase expansion of the linearizer over a 45 dB input power dynamic range at the frequency of 11 GHz is about 33°. By changing the bias voltage, it is possible to control the amplitude and phase expansion.

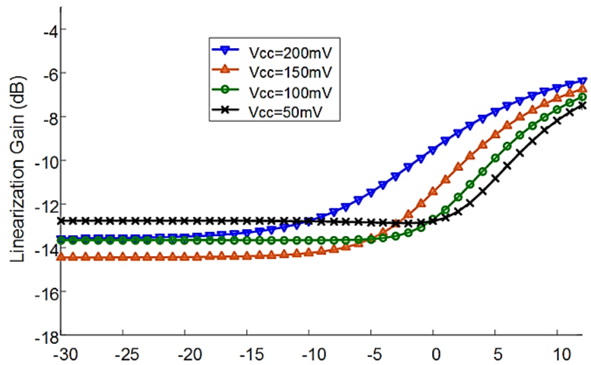

Fig. 5: The amplitude response of the linearizer.

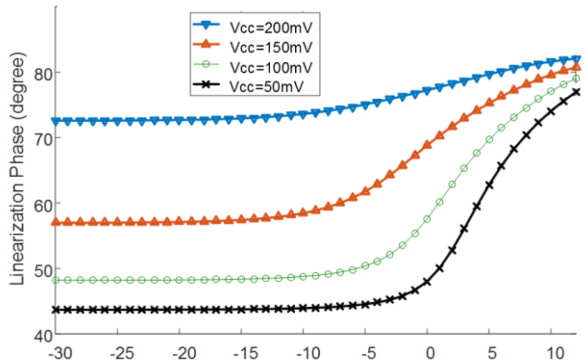

Fig. 6: The phase response of the linearizer.

Comparison of the AM/AM characteristic between the proposed linearizer (using two diode and transmission line at the second and third port of the coupler) and conventional linearizer (using a diode at the second and third port of coupler) is shown in Fig. 7. It is clear that the amplitude expansion of the proposed linearizer is better about 2.9 dB. Using this idea, the linearization capability of the proposed linearizer is augmented compared to conventional linearizer.

Table 1 shows the performance comparison of proposed and reported tunable APD linearization. The proposed linearizer achieves proper tuning performances with a simple circuit structure. The proposed linearizer shows good shape tuning characteristic with a simpler structure and better linearization effect. It should be noted that by selecting diodes with higher dynamic range, better results will be obtained.

Also for the input and output ports, the return loss of the new proposed linearizer has been simulated with ADS. The input and output return loss response of the linearizer are plotted in Fig. 8 which shows that good input and output return losses are achieved at 11.1 GHz.

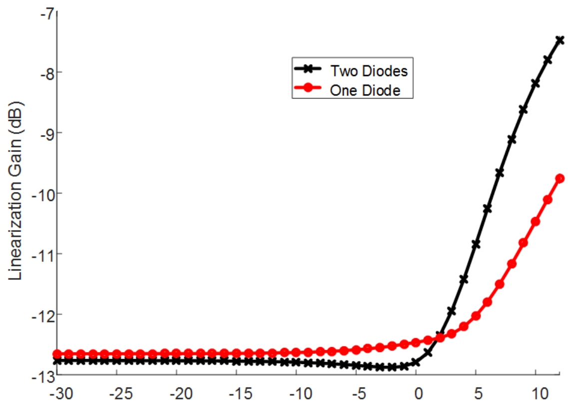

Fig. 7: The AM/AM characteristic for the linearizer with/without second diode.

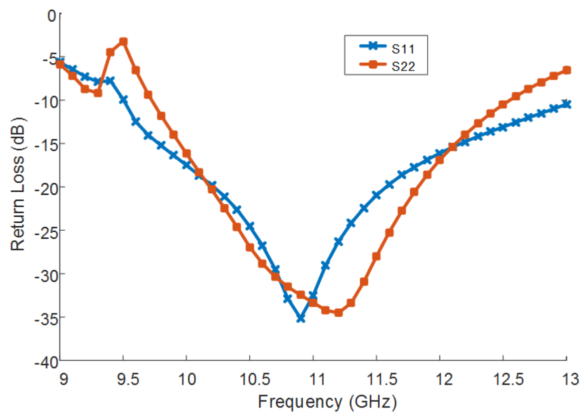

Fig. 8: Input and output return loss response.

Table 1: Comparison with similar apd linearizers

Ref.	Freq. (GHZ)	Independent tuning range of gain conversion	Independent tuning range of phase conversion	structure
[30]	8.38-8.58	1.4	N/A	medium
[26]	29-30	Not mentioned	20^0	medium
[24]	29-31	4.5	23.4^0	simple
This work	10.5-12	5.3	33^0	simple

Conclusion

A novel analog predistortion circuit based on the hybrid coupler and Schottky diodes is presented. The suggested topology increases the dynamic range of reflected power of each port. Using the proposed idea, AM/AM and AM/PM characteristics are expanded such that can linearize the power amplifier with high linearity. The amplitude expansion and phase shift of the proposed analog predistortion are adjusted by changing the bias voltage. The simulation results show that about 30° phase shift and 5 dB gain expansion can be compensated for power amplifiers and TWTAs. The superiority of the proposed approach compared to the conventional linearization were shown by the simulation results.

Author Contributions

This article is the output of a research study sponsored by the Communication Research Institute. R. Karimzadeh Baee was the project manager. All of the authors contributed in designing and simulation and data analysis. A. Rahati Belabad collected data, interpreted the results and wrote the manuscript.

Acknowledgment

The authors gratefully thank the anonymous reviewers and the editor of JECEI.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

Abbreviations

SSPA	solid-state power amplifiers
TWTA	traveling wave tube amplifiers
APD	Analog Predistortion
AM/AM	Amplitude-to amplitude distortions
AM/PM	Amplitude to phase distortions
IMD	intermodulation distortion
ADS	advanced design system

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How to cite this paper:

A. Rahati Belabad, H.R. Moazzen, R. Karimzadeh Baee, A.H. Ahmadi, "A novel analog predistortion linearizer based on a schottky diode for communication applications," J. Electr. Comput. Eng. Innovations, 10(1): 101-106, 2022.

DOI: 10.22061/JECEI.2021.7851.440

URL: https://jecei.sru.ac.ir/article_1570.html