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N. Semezhev, D.A. Bulykin

DIODE POWER DETECTORS IN SOFTWARE DEFINED RADIO APPLICATIONS

(Yuri Gagarin State Technical University of Saratov, Saratov, Russia)

Abstract: In this paper an observation of diode power detectors in software defined radio systems is provided. The mathematical model of such detectors is discussed and its advantages are revealed. The results of computer simulation confirming the theoretical result are given.

Keywords: diode power detector, software defined radio, digital signal processing, continuous wave, modulation.

1. Introduction

In a multi-port receiver, the extremely large bandwidth and the very high maximum frequency is achieved by using semiconductor diodes in a power detector configuration. Cut-off frequencies of Schottky diodes can reach terahertz frequencies [1]. In fact, the diode based power detector can be regarded as a diode mixer with an LPF at the output. Fig. 1(a) shows the process of conventional multiplicative mixing where transistors are used for frequency conversion (i.e. in a Gilbert cell) with subsequent low pass filtering.

(a) Multiplicative mixing (b) Additive mixing (multi-port down conversion)

Fig. 1: Multiplicative versus additive mixing. The additive mixing process is the basis of the multi-port theory

The new concept that is used in multi-port receivers is based on additive mixing as shown in Fig. 1(b). In a multi-port receiver, each of the four output ports is connected to a power detector. The signal addition itself takes place in the interferometer circuit which superposes the radio frequency (RF) and local oscillator (LO) signals under different phase angles Φ_i. It is possible to make such interferometers very broadband [3]. In comparison to conventional IQ mixers with two output ports, the signals at the output ports of the power detectors must be processed further. The baseband IQ signals are calculated from the four power readings after a calibration process.

Linearization of the diode power detectors characteristics is performed to open up limitation of diode power detector’s dynamic range and to extend it without affecting the received signal quality. The output voltage of the diode power detector is used to predict its characteristic and compensate for its nonlinear behavior.

2. Semiconductor Diode Circuit Model

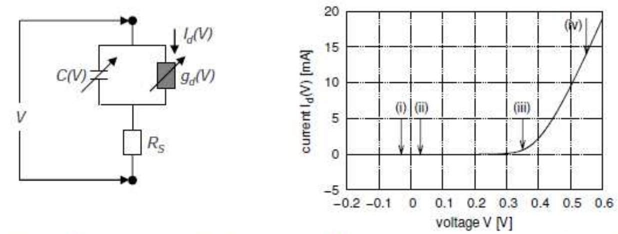
In order to understand the diode power detector, it is necessary to have a circuit model for the Schottky diode. This model has to be valid for both the large signal, nonlinear case as well as for the small signal case [2]. Since the Schottky diode is largely immune to minority carrier effects, the junction capacitance

$$C(V)=\frac{C_{j0}}{\sqrt{1-V/\phi_{bi}}} \qquad (1)$$

and diode current

$$I_d(V)=I_s(e^{\alpha V}-1), \qquad (2)$$

where $\alpha=e_0V/nk_BT$, change almost instantaneously with junction voltage V (C_{j0} is the junction capacitance at zero bias); ϕ_{bi} is the built-in potential from Schottky contact; I_s is the reverse saturation current; e_0 is the charge of an electron, n is the diode ideality factor; k_B is the Boltzmann constant (1.37×10^{-23} J/K); T is the absolute temperature in Kelvin. It is typically between 10^{-6} and 10^{-15} A, and at T=290 K, α=28 mV). Therefore, the DC expressions for these quantities are valid to very high frequencies in the hundreds of GHz. In the large signal diode model, it is assumed that the capacitance and current are functions of the junction voltage alone. This is valid up to at least 250 GHz [5].



(a) Simple equivalent circuit for Schottky diode (b) DC characteristics of Schottky diode with typical regions (i) through (iv)

Fig. 2: Equivalent circuit of Schottky diode and its DC characteristics

A circuit model for the Schottky diode is shown in Fig. 2(a). It consists of a voltage variable resistance (or conductance $g_d(V)$) and capacitance for the junction $C(V)$, and a fixed series resistance RS. Other elements that describe packaging are not included. It is important to differentiate between large signal and small signal diode parameters. For large signal circuits such as the six-port receiver with only a large LO signal applied, the junction current and capacitance have a non-linear dependence on the instantaneous junction voltage ($C(V)$ and $I_d(V)$ are given in Eq. 1 and 2, where V represents the instantaneous voltage of the time varying voltage)[7].

In the small signal case, it is assumed that the magnitude of the AC junction voltage is very small. There may also be a larger junction voltage component, such as a DC bias or a larger LO signal. If the alternating current (AC) voltage is small enough, the capacitance and junction resistance may be treated as linear quantities, although they may vary as the larger applied voltage is varied. The small signal junction conductance $g_d(V)$ is the derivative of the diode current

$$g_d(V) = \frac{dI_d}{dV} = \alpha I_S e^{\alpha V} = \alpha(I_d(V) + I_S)\,, \qquad (3)$$

which result in the junction conductance being proportional to its current. I_s is very small compared to $I(V)$ for forward conduction and can be ignored.

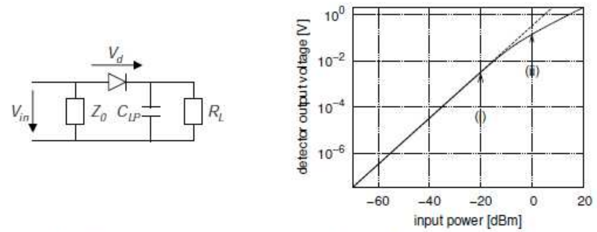
A linear plot of the DC characteristics of a Schottky diode is shown in Fig. 2(b) (different regions are marked). For very small applied voltages V , the current response of the diode can be approximated with its quadratic term from a Taylor expansion of Eqn. 2 (between (i) and (ii)). Higher order terms appear between (ii) and (iii). For higher voltages, the limit for the current is given by the series resistance RS which leads to a linear dependence beyond point (iv). For power detection, the input voltage should stay in the quadratic region of the diode, where the output current I_d is proportional to the square of the input voltage and, therefore, proportional to the input power:

$$I_d \propto V^2 \propto P_{in} \qquad (4)$$

3. Diode Detectors in Multi-Port Applications

The properties of a semiconductor diode are well suited for multi-port applications. What is needed is the quadratic relationship between RF input power and baseband output voltages. Fig. 3(a) shows a simple power detector as it is used in multi-port applications[6].

For broadband RF matching, the input impedance Z_0 should equal the line impedance, which is 50 in most applications. The input power generates an AC voltage V_d across the diode. This AC voltage generates the diode current which is low pass filtered at the output by a capacitance C_{LP}. The load at the output is in the order of M. The detector output voltage V_{RL} is the voltage across the load resistance. In the picture of a power detector, a single sine wave signal generates a DC offset voltage at the output port which, in the quadratic region of the diode, is proportional to the input power. Fig. 3(b) shows the characteristic input power to detector output power relationship. For most semiconductor diodes, the quadratic region goes up to approximately -20 dBm in a 50 Ω environment generating an output voltage in the order of mV [4].



(a) Simple power detector (b) Characteristics of a simple power detector

Fig. 3: Characteristic response to RF power of a simple power detector

For even larger input powers, the diode does not operate any longer in its quadratic region and power is lost to higher order terms (transition region between (i) and (ii)). These higher order terms do not contribute to the DC offset and are filtered by C_{LP}. Due to this, the detector output voltage does not increase linearly with input power. For even larger input voltages V_{in}, the diode operates in rectification mode where the detector output voltage V_{RL} is proportional to the amplitude of the RF input signal $\sqrt{P_{in}}$ (in other words, proportional to the square root of the input power):

$$V_{RL} \propto V_{in} \propto \sqrt{P_{in}} \qquad (5)$$

However, this model of the working principle of the diode detector in a multi-port application is not very accurate. In fact, in multi-port applications, there is not only one single sine wave signal to be detected, but the sum of the RF and LO signal. Therefore, the operation mode of the diode detectors in multi-port applications is rather a mixing of two signals on a non-linearity. This non-linearity is given by the quadratic region of the diode. The superposition, or the addition of the two signals RF and LO, is accomplished by the interferometer circuit.

4. Measurement Test Setup

The test setup to characterize and linearize a diode based peak power detector is shown in Fig. 4. The baseband quadrature amplitude modulation (QAM) modulated symbols are generated on a desktop PC in MATLAB. The baseband symbols are passed through a raised-cosine filter with a roll-off factor 0.3 (up-sampled by 8) and a delay of 3 taps. These pulse shaped symbols are further passed to an *I/Q* modulation generator (AMIQ from Rhode & Schwarz GmbH & Co.) to generate an *I/Q* modulated signal. This pulse shaped and *I/Q* modulated signal is frequency upconverted to a desired carrier frequency (2.5GHz) using a SMIQ03B vector signal generator from Rhode & Schwarz. The power level for the input excitation is set in the SMIQ and this passband signal is then fed to the diode power detector (8472B from Agilent Technologies, Inc.). Voltage generated by the Schottky detector in response to a particular excitation signal is captured using a synchronized dual-channel VSA (89600 series VSA from Agilent Technologies). The captured voltage waveform is used to linearize the diode detector characteristic as discussed in the next section.

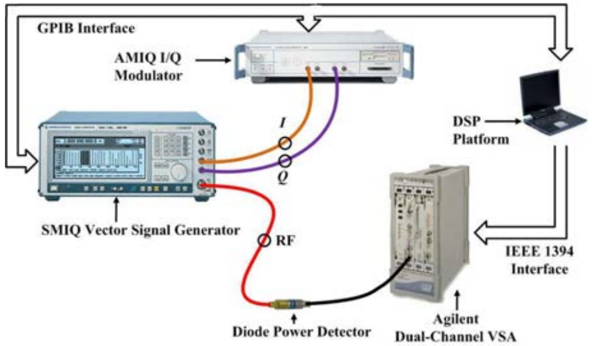


Fig. 4: Test setup for the peak power detector characterization and linearization

5. Measurement Results

The actual input peak power and the corresponding output peak voltage characteristics for the diode power detector in response to different excitation signals are shown in Fig. 5. From the plots in Fig. 5, it is obvious that the peak power detector behaves differently for different input excitation signals. The deviation from the continuous wave (CW) response is much more pronounced as the PAPR of the excitation signal increases. Peak power detector characteristic for the Wideband Code Division Multiple Access (WCDMA) signal having the highest PAPR value (≈ 9.5dB) has the highest deviation from the CW characteristic. Deviation of the peak power detector characteristics for QAM modulated signals (PAPR ≈ 6.8dB) is intermediate of the WCDMA (PAPR ≈ 9.5dB) waveform excitation and the Wireless Local Area Network (WLAN) excitation (PAPR ≈ 6.3dB) as shown in Fig. 5. The carrier frequency for all the excitation waveforms is kept same at 2.5GHz.

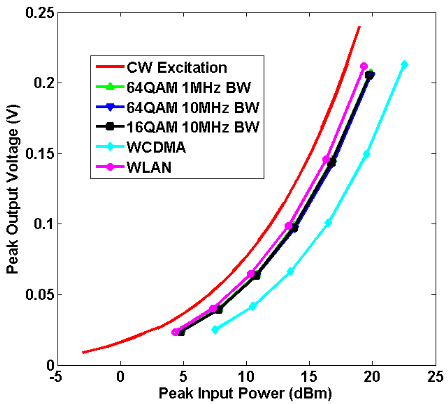


Fig. 5: Peak power detector characteristics for different excitation waveforms at a carrier frequency of 2.5GHz

In order to show the error in the CW linearized output peak power for the peak power detector, we pass the output voltage waveforms from the diode detector to a CW linearizer. The linearized peak power for different test excitation signals is plotted against the actual input peak power of the excitation signal in Fig. 6.

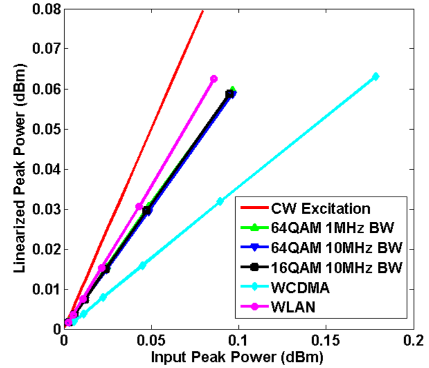


Fig. 6: Linearized peak power versus the actual input peak powers for different types of excitation signals

The ideal slope for such plots should be equal to unity, if the linearizer block is linearizing perfectly as expected from the theoretical analysis. In practice, the linearizer providing the slope closest to the unity offers the best performance. According to the plots as shown in Fig. 6, we observe that the signal having the highest PAPR (WCDMA) deviates the maximum from the unity slope of the linearized peak power versus the actual input peak power line plot. The slope of the CW excitation when linearized with the CW characterization data is unity. Slopes for all other excitation signals are constant for each of the signals but are other than unity. Based on these observations, it is concluded that the behaviour of the power detector changes depending on the type of excitation.

6. Conclusion

In this paper we saw that the behaviour of the diode power detector is different for different excitation signals. This behaviour is remarkably altered from the continuous wave (CW) characteristic of the diode power detector. The CW linearizers based on CW characterization of the diode power detectors result in error when the voltages generated in response to the real modulated signals are given as input to the CW linearizers for linearization, therefore there is a problem creating a new linearizer for diode power detectors. This problem was partly solved in [8].

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A.A. Solopekina, N. Semezhev, E.G. Umnova

PRINCIPLES OF MEASUREMENT UNCERTAINTY

(Yuri Gagarin State Technical University of Saratov, Saratov, Russia)

I. The measurement concept

The concept of measurement has deep roots in the human culture since the origin of civilization. Measurements have always been the bridge between the empirical world of phenomena and the abstract world of concepts and knowledge. For this reason, the measurement activity is the basis of knowledge gleaned from experimental results. Apart from science, it even applies to the quantitative assessment of goods in commercial transactions, the assertion of a right, and so on. become more and more important. Galileo Galilei put experimentation at the base of science, showing that it is the only possible starting point for the validation of any scientific theory. More than one century ago, William Thomson, Lord Kelvin, reinforced this concept by stating (in a lecture to the Institution of Civil Engineers, United Kingdom, on 3 May 1883).

II. The GUM Approach to Uncertainty: Definitions and Methods for Its Determination

The great merit of the GUM is to provide an operative definition of uncertainty and operative prescriptions of how to estimate it. The mathematical background of all definitions and prescriptions is probability theory, which is the bestknown and most effective mathematical theory for handling incomplete information. The main assumption of probability theory is "the result of a measurement has been corrected for all recognized significant systematic effects." Under this assumption, the remaining effects that cause the "dispersion of the values that could reasonably be attributed to the measurand" are random effects.

Therefore, this dispersion can be represented by a probability density function (pdf), which can be characterized by its first two moments: the mean value and the standard deviation. The mean value is taken as the measurement result x, and the standard deviation, called "standard uncertainty" $u(x)$ is used as the "parameter that characterizes the dispersion of the values that could reasonably be attributed to the measurand" [1].

Type A Evaluation

As far as the evaluation of the uncertainty components is concerned, the GUM suggests that some components may be evaluated from the statistical distribution of the results of a series of measurements and can be characterized by experimental standard deviations. Of course, this method can be applied whenever a significant number of measurement results can be obtained, by repeating the measurement procedure under the same measurement conditions. The evaluation of the standard uncertainty by means of the statistical analysis of a series of observations is defined by the GUM as the "type A evaluation."

Type B Evaluation

Other components of uncertainty may be evaluated from assumed probability distributions, where the assumption may be based either on experience or on other information. These components are also characterized by the standard deviation of the assumed distribution. This method is applied when the measurement procedure cannot be repeated or when the confidence interval about the measurement result is known a priori , i.e., by means of calibration results. The evaluation of the standard uncertainty by means other than the statistical analysis of a series of observations is defined by the GUM as the "type B evaluation."

III. Around values attributed to the measurand confidence interval evaluation

The method for expressing and evaluating uncertainty should also provide a confidence interval, which is an "interval about the measurement result within which the values that could reasonably be attributed to the measurand may be expected to lie with a given level of confidence" [1].

The probability theory ensures that the probability density function associated with the dispersion of the measurement result is known (or assumed); the width of such a confidence interval can be obtained by multiplying the standard uncertainty by a suit-