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Intermodulation Radar for P-N Junction Detection

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ABSTRACT

Intermodulation radar is a kind of harmonic radar. These radars not only receive the second and third harmonics but also intermodulation products of the transmitted multi-tone signal. These radars are useful for detection of non-linear electronics which are important for countersurveillance, and many other applications. The most important issue in these radars is to satisfy the low false alarm and correct detection. This work investigates the performances of the single tone harmonic radar and two-tone intermodulation radar in terms of the false alarm and correct detection rate by performing some experiments.

Keywords: Harmonic radar, P-N junction, NLJD

1. INTRODUCTION

Any electronics which contains P-N junctions can be detected by non-linear junction detectors (NLJD). These detectors are also called as Harmonic Radar. The working principle of these radars is based on transmitting at one or multiple frequencies and receive the reflected signals at or close to the harmonic frequencies as in Fig. 1 [1, 2, 3, 4, 5, 6].

This work concentrates on the detection of hidden electronic devices such as electronic bugs. False alarms are a major problem for harmonic radars and can be caused by system internal harmonic leakage, corrosive/junction metals, or the scanned area might have harmonic reactors. Any electronics which have P-N junctions such as diodes and transistors exhibit nonlinear behaviors. These nonlinear electronics reradiate the energy back to the source at doubled and tripled frequencies of the excitation signal, but the second harmonic is much stronger than third harmonic for

semiconductor junctions. On the other hand, corrosive or junction metals also generate harmonics and in this case, the third harmonic will be stronger than second harmonic [7, 8]. Sometimes the strengths of these harmonics might be very close to each other and this cause false alarms.

Single tone harmonic radars have high false alarm rates. This work investigates how to reduce the false alarms by employing the multi-tone harmonic radar (intermodulation radar).

2. SINGLE AND MULTI TONE RADAR CONCEPT

This section investigates single and multi-tone harmonic radar concept. P-N junctions are classified in two categories;

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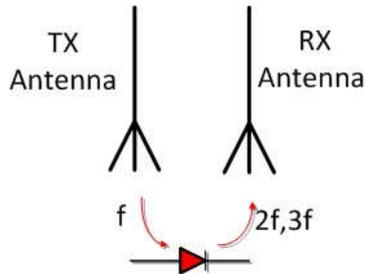


Figure 1: Non-linear junction behavior.

Semiconductor junctions: Transistors, diodes or any P-N junctions are semiconductor junctions. Any electronic consists of these junctions shows non-linear behaviors. Current-Voltage (I-V) characteristic of P-N junction is described by the Ebers-Moll equation [9]. If this equation is expanded by Taylor series, I-V characteristic of P-N junction is given as follow:

$$i = I_s \left[\frac{vq}{kT} + \frac{\left(\frac{vq}{kT}\right)^2}{2!} + \frac{\left(\frac{vq}{kT}\right)^3}{3!} + \dots + \frac{\left(\frac{vq}{kT}\right)^n}{n!} \right] \quad (1)$$

Where i is the P-N junction current, q is the charge in Coulombs, k is the Boltzmann's constant, T is the temperature in Kelvins, I_s is the saturation current of the P-N junction and v is the voltage across the P-N junction. Since the excitation signal is generally sinusoidal, v is the frequency dependent voltage, $v_{pn} \cos(\omega t)$, v_{pn} is a constant. According to Eqn. 1, second harmonic is larger than other harmonics in P-N junction.

Metal junctions: Any metals touching each other (metal-metal contact) or corrosive metals (metal-oxide-metal contact) generate junctions. These junctions cause passive intermodulation distortion (Rusty Bolt effect). Metal-metal or metal-oxide-metal contacts behave like nonlinear resistor [3, 10, 11]. I-V characteristic of non-linear resistors is given as follow:

$$I(V_{NL}) = a_1 V_{NL} - a_3 V_{NL}^3 \quad (2)$$

a_1 and a_3 are coefficients of nonlinear resistor I-V curve in $\Omega^{-3}A^{-2}$. V_{NL} is the voltage across the nonlinear resistor. Since the excitation signal is sinusoidal, V_{NL} is the frequency dependent voltage, $v_{pn} \cos(\omega t)$, v_{pn} is a constant. Based on Eqn. 2, 3rd harmonic is expected to be high in metal-metal or metal-oxide-metal contacts.

2.1. Detection criteria in single tone radar

Detection criteria for single tone radar is as follow:

- Semiconductor junctions: If the condition in Eqn. 3 is satisfied, this target is classified as semiconductor.

$$P_{2f} > P_{3f} + SNR \quad (3)$$

Where P_{2f} is the 2nd, P_{3f} is the 3rd harmonic power level. SNR is the signal to noise ratio. This ratio is used for threshold level for detection. Generally assuming SNR as 5dB is enough for correct decision.

- Metal junctions: If the condition in Eqn. 4 is satisfied, this target is classified as metal.

$$P_{3f} > P_{2f} + SNR \quad (4)$$

- False alarm: When the 2nd and 3rd harmonics are close to each other, this causes false alarms. This uncertain area is defined as in Eqn. 5.

$$|P_{2f} - P_{3f}| < SNR \quad (5)$$

2.2. Detection criteria in intermodulation radar

This section investigates the detection criteria for multi tone (intermodulation) radar. Two and three tone signal's products are illustrated as example.

f_1 and f_2 two tones have following harmonic and intermodulation products;

$$f_{2nd} : 2f_1; 2f_2; 3f_1 - f_2; f_1 + f_2; 3f_2 - f_1 \text{ and}$$

$$f_{3rd} : 3f_1; 3f_2; 2f_1 + f_2; f_1 + 2f_2$$

f_1 , f_2 and f_3 three tones have following harmonic and intermodulation products;

$$f_{2nd} : 2f_1; 2f_2; 2f_3; f_1 + f_2; f_1 + f_3; f_2 + f_3 \text{ and}$$

$$f_{3rd} : 3f_1; 3f_2; 3f_3; 2f_1 + f_2; f_1 + 2f_2; f_1 + f_2 + f_3; 2f_3 + f_1; 2f_3 + f_2$$

Multi tone signals do not generate just only harmonics but also intermodulation products. This brings new opportunities to define different detection criterions. One of the detection criteria might be averaging i.e., average of 2nd and 3rd order products can be compared to each other. The

other one might be single by single comparison and decision.



Figure 2: Semiconductor, corrosive metal and metal metal junction targets.

In this work we propose and use maximizing criteria i.e., the strongest products inside the 2nd and 3rd order products are selected and compared to each other. Suggested criteria can be formulated for two tones as follows;

$$Max\{f_{2nd}\} > Max\{f_{3rd}\} + SNR \dots Semi \quad (6)$$

$$Max\{f_{3rd}\} > Max\{f_{2nd}\} + SNR \dots Metal \quad (7)$$

$$|Max\{f_{2nd}\} - Max\{f_{3rd}\}| > SNR \dots False \quad (8)$$

In this work SNR is accepted as 5dB. When the number of tones are increased, this treatment can be extended to all nth-order terms as well. Harmonic response of the target depends on its resonance frequency, impedance, geometry (size and shape), polarization and orientation. Each target has a unique responses as a function of frequency, which is spectral signature and they have a unique radar cross section (RCS). To find the strongest harmonic response, frequency sweeping has also advantage. By sweeping frequency target's resonance frequency, i.e. the strongest harmonic response can be obtained. The capacitive shunting in target's active joints might also cause to diminish the radiated harmonic energy. In this work frequency isn't swept.

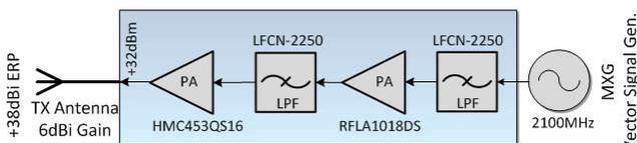


Figure 3: Single tone transmitter test setup.

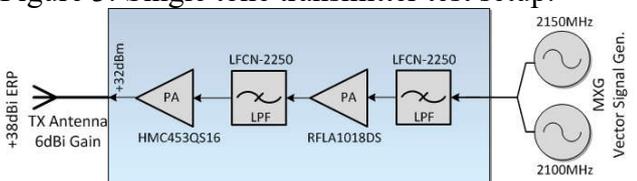


Figure 4: Multi tone (two tones) transmitter test setup.

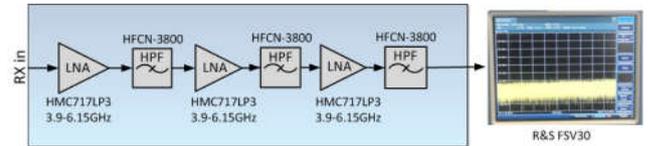


Figure 5: Single and multi tone receiver test setup.

3. EXPERIMENTAL RESULTS

Single and multi tone radars are tested with real targets. Three types of targets are used, semiconductor target (ST-1, several diodes are connected each other on a PCB, 1:85cmx1:85cm), corrosive metal target (CMT-1, 5cm diameter), and metal-metal junction target (CMT-2, paper clips, 5cm diameter). These targets are illustrated in Fig. 2. Multi tone radar is realized as two-tone for simplicity. Single tone frequency is 2100MHz and two-tone frequencies are chosen as 2100MHz and 2150MHz. Frequency value is directly proportional to target resolution but inversely to target distance.

The design targets for the transmitter (TX) and receiver (RX) of harmonic or multi tone radar are quite brief and well defined [1, 2, 3, 4]. Fig. 3 shows single tone TX test setup, Fig. 4 shows multi tone TX test setups and Fig. 5 shows single and two-tone RX test setups. TX antenna has 6dBi gain and bandwidth from 2100MHz to 2150MHz, it is circular polarized. RX antenna is a wideband antenna from 4GHz to 6GHz, its gain about 0dBi and it is circular polarized too.

Both single and two-tone TXs have +32dBm output power and their RX sensitivities are about -130dBm. TX filters are low passed and they have about 60dB rejection rate of TX signal's 2nd and 3rd harmonics. Pass band (TX frequency) insertion loss is about 1dB. RX filters are high passed and they have about 60dB rejection rate on TX frequency. RX filters have about 1dB insertion loss at pass band.

Measurements are performed for different distances from 5cm to 25cm. Measurement area is sterilized of all major harmonic reactors in the range of the radar to prevent false alarms.

Fig. 6a, Fig. 7a and Fig. 8a illustrate two-tone response for the targets CMT-1, CMT-2, and ST-1 respectively. Fig. 6b, Fig. 7b and Fig. 8b illustrate single tone response for the targets CMT-1, CMT-2, and ST-1 respectively. In all figures solid lines illustrate second order products and harmonics, dotted lines illustrate the third order products and harmonics.

In Fig. 6b, CMT-1 is classified as semiconductor up to 10cm distance by single tone radar, it is false alarm. After 10cm, it is correctly classified. In Fig. 6a, CMT-1 is correctly classified for all distances by multi tone radar. $f_1 + 2f_2$ and $2f_1 + f_2$ third order products are quietly powerful than any other second order products. In Fig. 7b, CMT-2 is definitely classified as semiconductor for almost all distances by single tone radar. It is totally false alarm. In Fig. 7a, CMT-2 can not be classified either semiconductor or corrosive metal by two-tone radar. This case is still better than the Fig. 7b case. In last scenario, ST-1 is tested. Fig. 8a shows two-tone response of ST-1 target and Fig. 8b shows single tone response of ST-1 target. Both cases are successful for all distances.

4. CONCLUSIONS

In this work, single and two-tone radar performances are compared for non-linear

junction detection. Two-tone or multi-tone radars bring more comparison criterions than single tone radar. Not only second and third harmonics but also intermodulation products are useful for correct decision in multi tone radar. Based on experimental results, two-tone radar has lower false alarm rate than single tone radar.

Multi tone radar has low false alarm rate advantage but on the other hand it has a disadvantage of more power consumption. Since power amplifiers 1-dB compression point is constant, two-tone signal with each tone power +32dBm requires +35dBm P1dB amplifier, consequently more power consumption and cooling requirements.

As follow-on research topics, targets with a combination of semiconductor and metal-metal will be also tested. Different TX power scenarios will be also tested and compared. Lastly, as follow-on research different classification methods like mean, min, max, and subtraction will be tested and compared.

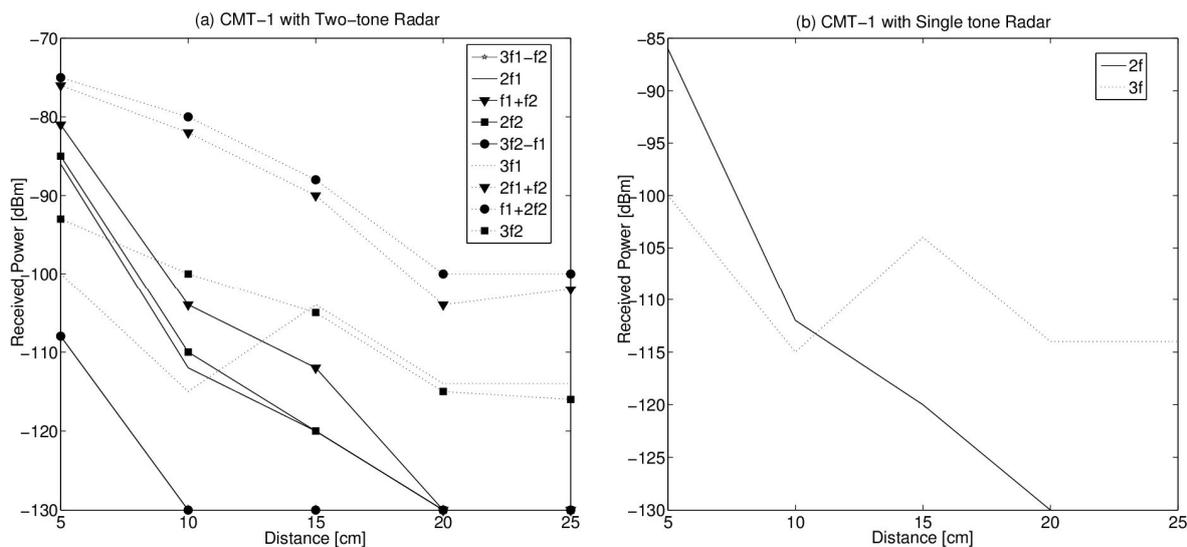


Figure 6: Single and two-tone radar results for CMT-1

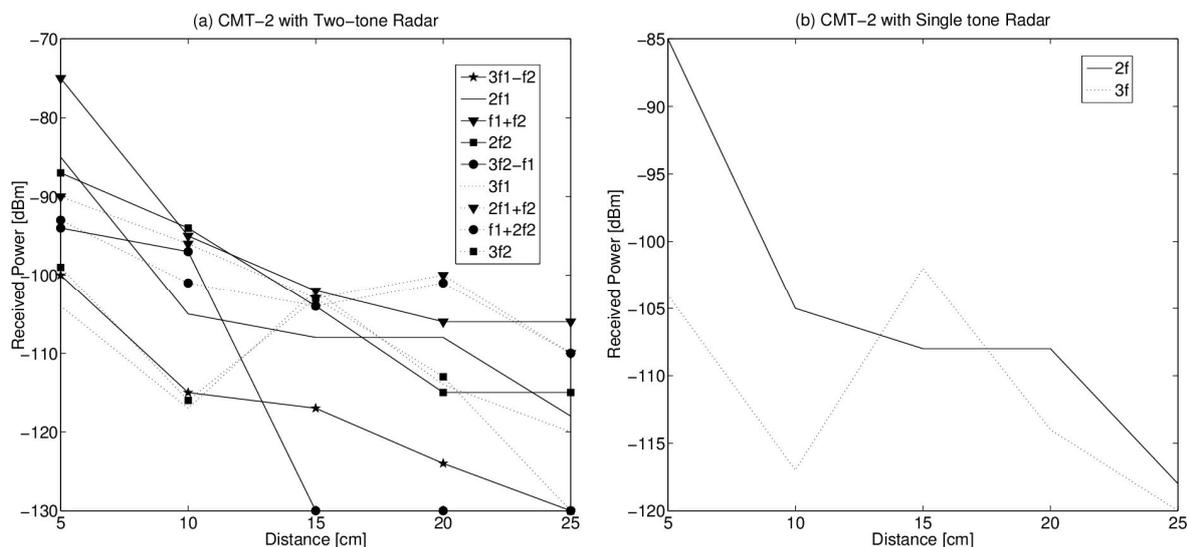


Figure 7: Single and two-tone radar results for CMT-2

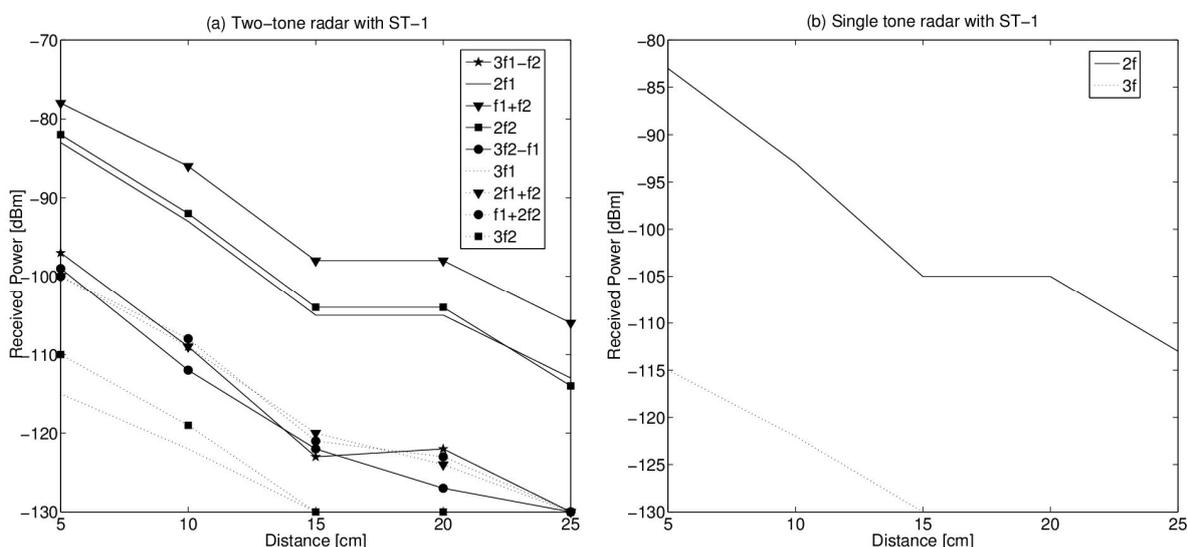


Figure 8: Single and two-tone radar results for ST-1

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