ELectronics EXpress

IEICE Electronics Express, Vol.5, No.15, 568–573

Analysis on high-order intermodulation of frequency multipliers with harmonic injection

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Abstract: For the successful transmission of complex signals through frequency multipliers, high order analysis of IMD responses for a frequency tripler is performed and the optimum solutions for the harmonic injection technique is presented to suppress the high order IMDs in the $3^{\rm rd}$ zone. From the $7^{\rm th}$ order analysis, optimum injection was found to suppress IMDs in the $3^{\rm rd}$ harmonic zone and their optimum phases are shown to be apart by 180 degrees due to the even-ordered Volterra products of the injection. The measurement results showed IMD suppression better than 30 dB, which is consistent with the analysis and the simulated results.

Keywords: frequency multiplier, harmonic injection, intermodulation, power amplifier, predistortion

Classification: Microwave and millimeter wave devices, circuits, and systems

References

[1] Y. Park and J. S. Kenney, "Adaptive Digital Predistortion of Frequency Multipliers," *IEEE Trans. Microw. Theory Tech.*, vol. 51, no. 12, pp. 2516–2522, Dec. 2003.

[2] C. S. Aitchison, M. Mbabele, M. R. Moazzam, D. Budimir, and F. Ali, "Improvement of Third-Order Intermodulation Product of RF and Microwave Amplifiers by Injection," *IEEE Trans. Microw. Theory Tech.*, vol. 49, no. 6, pp. 1148–1154, June 2001.

[3] N. Males-Ilic and J. Randelovic, "The linearization of two multichannel amplifiers connected in cascade by using the second harmonics and fourth-order nonlinear signals," *Proc. Int. Conf. on Cable and Broadcasting Services*, 2007, pp. 389–392.

[4] S. A. Maas, *The RF and Microwave Circuit Design Cookbook*, Artech House, Boston, 1998.

[5] J. S. Kenney and P. Fedorenko, "Identification of RF Power Amplifier Memory Effect Origins using Third-Order Intermodulation Distortion

DOI: 10.1587/elex.5.568
Received June 17, 2008
Accepted July 07, 2008
Published August 10, 2008

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Amplitude and Phase Asymmetry," *IEEE MTT-S Int. Microwave Symp.*, pp. 1121–1124, 2006.

1 Introduction

Frequency multipliers are shown that they can be utilized as frequency translating devices for complex modulated signals with the aid of digital predistortion, where this predistortion is to linearize the distortion on the envelope signal whilst maintaining the nonlinearity associated with the carrier-frequency multiplication [1]. Here, the IMD components of the devices should be suppressed for better signal quality, and are mainly from the memoryless nonlinearity and the electro-thermal interactions between the harmonic components, this phenomenon — called memory effect — is hard to be eliminated without understanding of its generation process. Among a few ways to minimize the memory effect, injection of harmonic signal is a good solution, which cuts off the harmonic interaction process eventually minimizing the phenomenon. However, so far the harmonic injection have been used for the cancellation of IMDs in power amplifiers (PAs) [2, 3], and thereby most research efforts were focused on the reduction of the second or the third order IMDs only. Also, the cancellation of the IMD components were achieved based on the empirical measurements, and thus little estimation of amplitude and phase of the injection were made which is critical for precise digital predistortion techniques. In frequency multiplier cases, since the n^{th} zone response is stemmed from high order nonlinearities, high order IMD should be aimed for the reduction. Therefore, in this paper, an analytic approach is suggested to find solutions for exact cancellation of IMD out of frequency triplers, and its accuracy was verified with simulations and measurements.

2 The 3rd-zone IMD of frequency multipliers with harmonic injection

For the exact extraction of magnitude and phase of high order IMDs, a resistive frequency multiplier is preferred because of its resistive nonlinearity.

The dominant characteristic equation between the input Anode voltage and the output Cathode current of a Schottky diode in a frequency multiplier is expressed as below [4].

$$i_{cathode}(V + v_{in}) = I_{sat}\left\{\exp\left(\frac{q \cdot (V + v_{in})}{\eta \cdot K \cdot T}\right) - 1\right\}, \tag{1}$$

where I_{sat} is the reverse-saturation current with the bias V, q is the electron charge, K is the Boltzmann's constant, T is the temperature, and η is the ideality factor.

From this equation, an anti-parallel combination of diodes with accurate harmonic terminations can constitute a wideband frequency tripler, of which the input-output relation can be expressed in a memoryless polynomial equation. Consequently, the output cathode current of the diode can be expressed

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with the conductance polynomials, and the 3rd zone response is expressed as below.

$$i_{cathode}|^{3^{rd}-zone} = g_3 {v_{in}}^3 + g_5 {v_{in}}^5 + g_7 {v_{in}}^7 + \cdots \tag{2}$$

For the extraction of optimum injection, two-tone signal with the injection of normalized coefficient z at $\omega_{\text{inj}} = 2 \cdot \omega_1$ is expressed in Eq. (3).

$$\begin{aligned} v_{in}(t) = a_1&[\exp(j2\pi f_1 t) + \exp(-j2\pi f_1 t)] \\ &+ a_2[\exp(j2\pi f_2 t) + \exp(-j2\pi f_2 t)] \\ &+ z[\exp(j2\pi 2 f_1 t) + \exp(-j2\pi 2 f_1 t)] \end{aligned} \tag{3}$$

When the coefficients a_1 and a_2 are assumed to be identical for the simplicity, the complex coefficient z can be normalized and solved with relative amplitude and phase to a_1. For the solution to optimum z, the highest order of nonlinearity is set as 7 for more accurate analysis whereas it is limited to 3 or 5 in PA cases. After rigorous analysis on the equations, the resulting lower-side IMD components in the 3rd zone can be shown as in Eq. (4)-(7), where the lower-side IMD components are defined as IM7L3, IM5L3, HarL3, SumL3, which represent frequencies of $(5\omega_1 - 2\omega_2)$, $(4\omega_1 - \omega_2)$, $(3\omega_1)$, and $(2\omega_1 + \omega_2)$, respectively. Also, the corresponding upper-side components are IM7H3, IM5H3, HarH3, SumH3.

$$\begin{aligned} IM7L3 = [&21/64 \cdot g_7 + (15/8 \cdot g_5 + 525/32 \cdot g_7) \cdot z^2 \\ &+ 105/16 \cdot g_7 \cdot z^4] \cdot \cos(5\omega_1 - 2\omega_2) \end{aligned} \tag{4}$$

$$\begin{aligned} IM5L3 = [&5/16 \cdot g_5 + 147/64 \cdot g_7 \\ &+ (3/4 \cdot g_3 + 45/8 \cdot g_5 + 1155/32 \cdot g_7) \cdot z^2 \\ &+ (5/4 \cdot g_5 + 315/16 \cdot g_7) \cdot z^4 \\ &+ 105/64 \cdot g_7 \cdot z^6] \cdot \cos(4\omega_1 - \omega_2) \end{aligned} \tag{5}$$

$$\begin{aligned} HarL3 = [&1/4 \cdot g_3 + 25/16 \cdot g_5 + 441/64 \cdot g_7 \\ &+ (3/4 \cdot g_3 + 55/8 \cdot g_5 + 1575/32 \cdot g_7) \cdot z^2 \\ &+ (5/4 \cdot g_5 + 735/32 \cdot g_7) \cdot z^4 \\ &+ 105/64 \cdot g_7 \cdot z^6] \cdot \cos(3\omega_1) \end{aligned} \tag{6}$$

$$\begin{aligned} SumL3 = [&25/8 \cdot g_5 + 3/4 \cdot g_3 + 735/64 \cdot g_7 \\ &+ (1575/32 \cdot g_7 + 45/8 \cdot g_5) \cdot z^2 \\ &+ 525/32 \cdot g_7 \cdot z^4] \cdot \cos(2\omega_1 + \omega_2) \end{aligned} \tag{7}$$

Thus, the optimum z to cancel out IMDs in Eq. (4)-(7) can be identified when the values of g_3, g_5, and g_7 are known from the frequency response test. As a result, a set of optimum z with the given polynomial coefficients is calculated as in Table I, where only the negative magnitudes in dBc are considered as practical solutions due to the stability and efficiency issues of the system.

From the table, it is observed that the optimum z to cancel IMD is repeated by 180 degrees due to the limited combination of tones into the Volterra kernel, and thus only the even-order of the injected harmonic can cancel the odd-ordered IMD components at the 3rd zone. Also, interestingly,

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Table I. Optimum z for the IMD cancellation.

IMD / Solution	IM7L3 [dBc∠deg]	IM5L3 [dBc∠deg]	HarL3 [dBc∠deg]	SumL3 [dBc∠deg]
z_{opt} #1	-18.8∠90° -18.8∠-90°	-15.6∠90° -15.6∠-90°	-1.58∠5.7° -1.58∠-174.3°	1.58∠90° 1.58∠-90
z_{opt} #2	8.02∠90° 8.02∠-90°	10.5∠87° 10.5∠-93°	9.82∠-88.9° 9.82∠91.1°	7.88∠90° 7.88∠-90
z_{opt} #3	-	-	11.9∠-90.3° 11.9∠89.7°	-

the optimum phases of z_{opt} #1 for the 3rd zone IMD are closely aligned in phase except for the HarL3, and this opens a possibility of selective cancellation of IMD components only by the control of the magnitude of injection.

In reality, the optimum z will differ since the injected signal also affects the nonlinear coefficients, and thereby the IMD vector will deviate from the optimum solution in phase and magnitude as the injected magnitude varies, which can be called as a self-distortion. Moreover, when the memory effect is significant, the phase-rotated memory components of which the magnitude and phase vary with time would be added up onto the IMD components, and thus the suppression would be more or less limited [5]. However, because this memory effects is from the interactions with the even-order envelope signal and the odd-order IMDs, the phenomenon also can be minimized by the accurate injection of the envelop signal into the even-order frequency out so that eventually no interaction with the odd harmonic is possible.

3 Simulation

For the simulation, a resistive frequency tripler made of anti-parallel Schottky diodes was designed, and an injected signal with controlled power and phase was combined with the two-tone signal. The equivalent circuit model of the Schottky diode consists of a nonlinear resistance in parallel with the junction capacitance and the parasitic series inductance of the package. When two-tone signal is applied, IMD products are generated through memoryless nonlinearity of Eq. (2) and the z_{opt} as in Table I are expected to cancel out the IMD products in the 3rd zone as mehtioned in the previous section. From the results of the IMD7L3 and HarL3 suppression over the normalized injection as shown in Fig. 1 (a), it is observed that two solutions are separated by 180 degrees supporting that the even-order harmonics of the injected signal cancel the IMD in the 3rd zone. The self distortion is also observed by the dragged peak point on the contour planes. Fig. 1 (b) represents the overall comparison of 3rd zone IMD suppression over the power of the injection.

4 Measurement

For the validation of the analysis and simulation, a Schottky-diode based frequency tripler for the 3rd zone output of 2.55 GHz was built. The test setup is made up of vector signal generator for the two-tone generation and a CW signal generator for the magnitude and phase controlled harmonic

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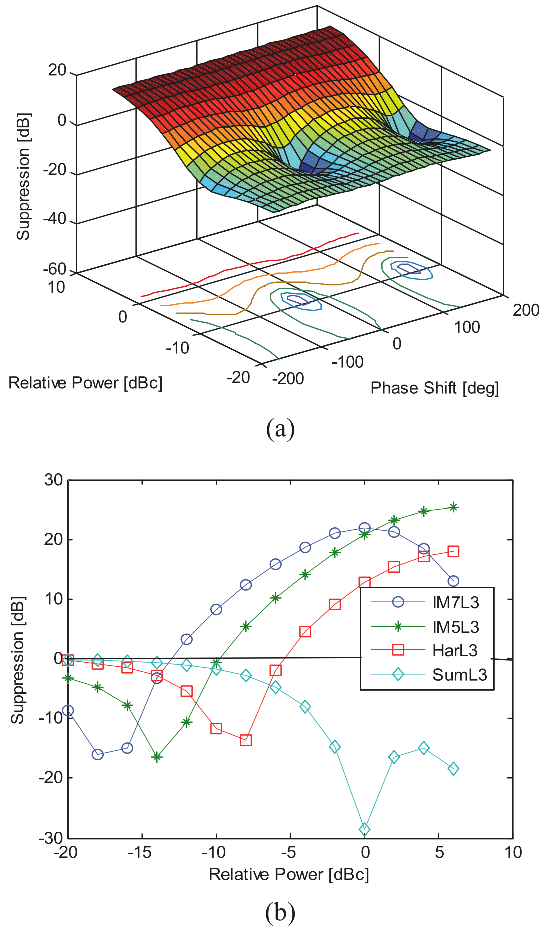

Fig. 1. Simulated results of (a) HarL3 suppression in the 3rd zone over the magnitude and phase variation of the injected signal (b) The 3rd zone IMD products over the injected signal power.

injection.

The output was taken from a spectrum analyzer. The total power of the two-tone was 1 dBm at 850 MHz and the tone separation was chosen as 100 kHz to avoid the measurement uncertainty from the frequency response of the device. From the measurements, optimum z are observed with 180 degrees apart as in Fig. 2 (a), which can be seen in the simulation results. In addition, the variation of the optimum z due to the self-distortion is observed as a dragged optimum location over the magnitude of z, of which the amount is relatively salient than expected from the simulations. In Fig. 2 (b), the suppression of low side IMD components is presented over the magnitude of the injected harmonic showing good agreement with the simulated result in Fig. 1 (b).

5 Conclusions

For the accurate cancellation of IMD components out of frequency multipliers, sources of IMD of the devices are presented, and the calculation of the optimal complex coefficients of the injected harmonic is analytically addressed.

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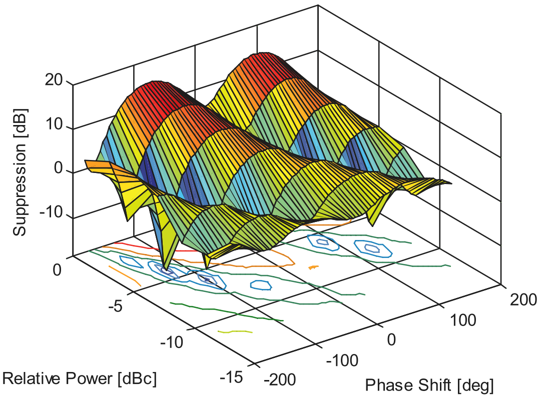
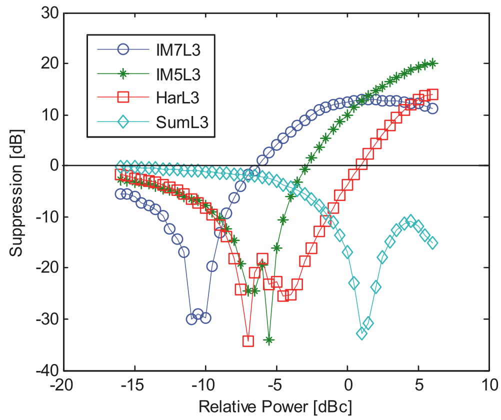


(a)



(b)

Fig. 2. Measured results of (a) HarL3 suppression in the 3rd zone over the magnitude and phase variation of the injected signal (b) The 3rd zone IMD products over injected signal power.

Simulations and measurements are performed to validate the accuracy of the calculation on a Schottky-diode based frequency tripler at 2.55 GHz, and the results support that the even order distortion of the injected signal is dominant by showing the optimum solutions are repeated with 180 degrees apart. Also, the measurement shows that the self-distortion of the injection makes a group of optimum phases rather than a pin-pointed solution over the magnitude of the injection, and therefore this low sensitivity can ease the system requirements for the predistortion of the frequency multipliers.

Acknowledgments

This work was supported by Hankuk University of Foreign Studies Research Fund of 2008.

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