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On Dual-Band Amplifications Using Dual Two-Tones: Clarifications and Discussion

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On Dual-band Amplifications Using Dual Two-tones: Clarifications and Discussion

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***Abstract*— A significant development of recent research in nonlinear distortion is the expansion of the conventional two-tone test for power amplifiers to the concurrent dual-band transmitters, by Amin et al [1]. A general framework using dual two-tones is developed which shows that the output signal is affected not only by intermodulation (IM) products but also by cross-modulation (CM) products. In this paper, we will make a number of clarifications to [1]. The effects of IM and CM in passband will be discussed, IM represents a reduction for compressive devices and CM reflects an interference caused by the signal from the other band, and followed by the analysis of out-of-band intermodulation. It was concluded that out-of-band intermodulation needs to be taken into consideration for the design of power amplifiers when two bands are very close.**

***Index Terms*—Amplifier distortion, concurrent dual bands, cross modulation (CM), intermodulation (IM), out-of-band intermodulation, power amplifier (PA).**

I. Introduction

DUAL-BAND transmission is attracting much attention in recent development. In article [1], Characterization of Concurrent Dual-Band Power Amplifier Using a Dual Two-Tone Excitation Signal, Amin, et al. proposed a milestone framework to calculate the third-order distortion of dual-band amplification using dual two-tone signals in terms of intermodulation (IM) and cross-modulation (CM). In this paper, we will make a few clarifications to the formulas and figures in [1], and discuss the impact on amplified signals in passband caused by IM and CM. Furthermore, we will analyze the out-of-band intermodulation which may be difficult to be filtered out when two signal bands are close.

This paragraph of the first footnote will contain the date on which you submitted your paper for review. It will also contain support information, including sponsor and financial support acknowledgment. For example, "This work was supported in part by the U.S. Department of Commerce under Grant BS123456".

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II. Clarification

A. One term is Missing When Expressing $\cos\omega_{c1}$ using Euler Identity

Equation (7) in [1] is derived from equation (5). However, the output signal $y_{\omega L}(t)$ is real in equation (5), and became complex in (7), in apparently a step using Euler identity. The $e^{j(\omega_1 t)}$ in equation (7.e) should be written as $\frac{1}{2}(e^{j(\omega_1 t)} + e^{-j(\omega_1 t)})$.

B. CM is Larger than IM

The second error occurs in Fig. 2 of [1] (i.e. Fig. 1 of this paper), in which the amplitudes of inter-modulation at $\pm 3\omega_L$ appear higher than those of cross-modulation at $\pm(\omega_L - 2\omega_U)$ and $\pm(\omega_L + 2\omega_U)$.

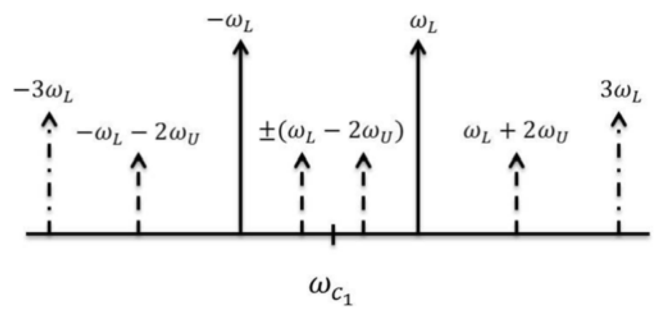

Fig. 1 Illustration of frequency location of IM and CM products of article [1].

However, according to the equations (7c), (7d), and (7e) in [1], the magnitude of CM coefficients is twice as much as that of IM coefficients in time domain, which means that the amplitude of CM is twice as high the amplitude of IM. The coefficients $h_{3_{IM}}, h_{3CM_{Out}}$, and $h_{3CM_{in}}$ in equation (7) are derived from the equation (5), and they are exactly the same as h_3. For example, compared IM @ ω_{c1} term in (5) with the equation (7.c), we can see

$$h_3 = h_{3_{IM}}^{(+)} = h_{3_{IM}}^{(-)} \quad (1)$$

Similarly, we will find

$$h_3 = h_{3_{CM_{Out}}}^{(+)} = h_{3_{CM_{Out}}}^{(-)} \quad (2)$$

$$h_3 = h_{3_{CM_{In}}}^{(+)} = h_{3_{CM_{In}}}^{(-)} \quad (3)$$

Based on (1), (2), and (3), we could conclude that

$$h_3 = h_{3_{IM}}^{(+)} = h_{3_{IM}}^{(-)} = h_{3_{CM_{Out}}}^{(+)} = h_{3_{CM_{Out}}}^{(-)} = h_{3_{CM_{In}}}^{(+)} = h_{3_{CM_{In}}}^{(-)} \quad (4)$$

From equations 7(c)-7(e) in [1] and (4), the amplitude of CM is twice as much as that of IM. In fact, we could conclude that CM is always larger than IM when the two-tones in both bands are equal in amplitude.

The Fig. 2 correctly describes the relationship between IM and CM in dual two-tone calculation. The IM terms are at $\pm 3\omega_L$, and CM terms are at $\pm(\omega_L + 2\omega_U)$ and $\pm(\omega_L - 2\omega_U,)$, respectively.

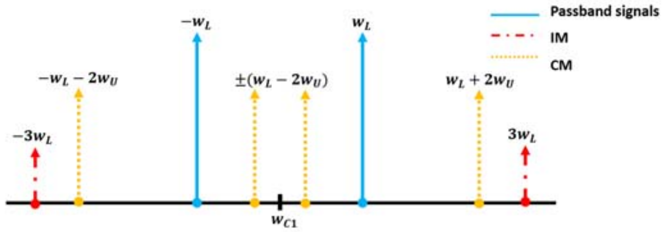

Fig. 2. Illustration of the frequency location of IM and CM products for one tone of dual-band two tones.

C. *Typos occur in Appendix*

There are a number of typos in Appendix of [1], which are listed and corrected in Table I.

TABLE I

TYPOS IN APPENDIX AND CLARIFICATIONS

Equations in [1]	Typos in [1]	With typos corrected
(A.14f)	$\{3\cos(3\omega_L t) + \cos(3\omega_L t)\}\cos(\omega_{3c1} t)$	$\{3\cos(\omega_L t) + \cos(3\omega_L t)\}\cos(3\omega_{c1} t)$
(A.15f)	$\{3\cos(3\omega_U t) + \cos(3\omega_U t)\}\cos(3\omega_{c2} t)$	$\{3\cos(\omega_U t) + \cos(3\omega_U t)\}\cos(3\omega_{c2} t)$
(A.16d)	$\{\cos(\omega_U) + \cos(2\omega_L t)\cos(\omega_{c2} t)\}\cos(\omega_U t)$	$\{\cos(\omega_U t) + \cos(2\omega_L t)\cos(\omega_U t)\}\cos(\omega_{c2} t)$
(A.17d)	$\{\cos(\omega_L) + \cos(2\omega_U t)\cos(\omega_{c1} t)\}\cos(\omega_L t)$	$\{\cos(\omega_L t) + \cos(2\omega_U t)\cos(\omega_L t)\}\cos(\omega_{c1} t)$

III. DISCUSSIONS

A. *IM and CM Effects in Amplified Spectrum*

For a single band two-tone test [2] (which can be chosen from either band of the dual bands [1]), the amplified signals of passband can be derived from equations (5) and (6) in [1] which are

$$(Ah_1 + \tfrac{9A^3h_3}{16})\cos\omega_L t\cos\omega_{c1} t \text{ (5.a)}$$
$$(Ah_1 + \tfrac{9A^3h_3}{16})\cos\omega_U t\cos\omega_{c2} t \text{ (5.b)}$$

where h_3 can be derivrd in [2] as

$$h_3 = \mp\tfrac{8}{3}10^{\left(\frac{-IP_3}{10}+3\frac{G}{20}\right)}$$
$$= \begin{cases} -\tfrac{8}{3}10^{\left(\frac{-IP_3}{10}+3\frac{G}{20}\right)} \text{(for gain compression)} \\ \tfrac{8}{3}10^{\left(\frac{-IP_3}{10}+3\frac{G}{20}\right)} \text{(for gain expansion)} \end{cases} \quad (6)$$

where IP_3 is the third intercept points of power amplifier, and G is the gain of power amplifier. Most of the devices are compressive, thus,$h_3 < 0$.

The IP_3 defined from a two-tone test in a single band [2] could be determined from either band of the dual bands. The fact of two bands or multiple tones does not change the calculation of IP3, thus, does not change the h_3. The coefficient h_3 depends only on the amplifier characters, not the signal(s) under the test.

The amplified signals in two passbands [1] are described as below

$$(Ah_1 + \tfrac{9A^3h_3}{16} + \tfrac{12A^3h_3}{16})\cos\omega_L t\cos\omega_{c1} t \text{ (7.a)}$$
$$(Ah_1 + \tfrac{9A^3h_3}{16} + \tfrac{12A^3h_3}{16})\cos\omega_U t\cos\omega_{c2} t \text{ (7.b)}$$

From (7.a) and (7.b), we could conclude

1) The second terms, $\frac{9A^3h_3}{16} cos\,\omega_L t\, cos\,\omega_{c1} t$ and $\frac{9A^3h_3}{16} cos\,\omega_U t\, cos\,\omega_{c2} t$, are derived from IM and generally reflect the reduction of the signals in passband, as the devices are mostly compressive.

2) The third terms, $\frac{12A^3h_3}{16} cos\,\omega_L t\, cos\,\omega_{c1} t$ and $\frac{12A^3h_3}{16} cos\,\omega_U t\, cos\,\omega_{c2} t$, are derived from CM and represent the interferences from the signals in the other band.

B. *Out-of-band Intermodulation*

If the frequency separation between the two bands is not large enough, the out-of-band intermodulation is difficult to be filtered out. In this situation, the out-of-band intermodulation must be taken into consideration.

The out-of-band intermodulation comes from the following components [1]:

$$3\cos^2(\omega_L t)\cos^2(\omega_{c1} t)\cos(\omega_U t)\cos(\omega_{c2} t) \text{ (8.a)}$$
$$3\cos^2(\omega_U t)\cos^2(\omega_{c2} t)\cos(\omega_L t)\cos(\omega_{c1} t) \text{ (8.b)}$$

(8.a) and (8.b) generate many components at different frequencies. Only the components around $2\omega_{c1} - \omega_{c2} = \omega_{c1} - (\omega_{c2} - \omega_{c1})$ and $2\omega_{c2} - \omega_{c1} = \omega_{c2} + (\omega_{c2} - \omega_{c1})$ are near ω_{c1} and ω_{c2} when $\omega_{c2} - \omega_{c1}$ is small, hence difficult to be filtered out. Those components around $2\omega_{c1} - \omega_{c2}$ and $2\omega_{c2} - \omega_{c1}$ are defined as the out-of-band intermodulation components in [3]. The total number of those components is twelve, six on each side, while it is mistaken as eight, four each side, in the Fig.1 (b) of [3].

TABLE II
FREQUENCY COMPONENTS OF OUT-OF-BAND INTERMODUALTION

$2\omega_{c1}-\omega_{c2}$	$2\omega_{c2}-\omega_{c1}$
$\frac{3}{16}\cos(2\omega_{c1}-\omega_{c2}+\omega_U)t$	$\frac{3}{16}\cos(2\omega_{c2}-\omega_{c1}+\omega_L)t$
$\frac{3}{16}\cos(2\omega_{c1}-\omega_{c2}-\omega_U)t$	$\frac{3}{16}\cos(2\omega_{c2}-\omega_{c1}-\omega_L)t$
$\frac{3}{32}\cos(2\omega_{c1}-\omega_{c2}+\omega_U+2\omega_L)t$	$\frac{3}{32}\cos(2\omega_{c2}-\omega_{c1}+\omega_L+2\omega_U)t$
$\frac{3}{32}\cos(2\omega_{c1}-\omega_{c2}+\omega_U-2\omega_L)t$	$\frac{3}{32}\cos(2\omega_{c2}-\omega_{c1}+\omega_L-2\omega_U)t$
$\frac{3}{32}\cos(2\omega_{c1}-\omega_{c2}-\omega_U+2\omega_L)t$	$\frac{3}{32}\cos(2\omega_{c2}-\omega_{c1}-\omega_L+2\omega_U)t$
$\frac{3}{32}\cos(2\omega_{c1}-\omega_{c2}-\omega_U-2\omega_L)t$	$\frac{3}{32}\cos(2\omega_{c2}-\omega_{c1}-\omega_L-2\omega_U)t$

Deriving from (8.a) and (8.b), the out-of-band intermodulation components are shown in Table II. Fig. 3 illustrates a more complicated output power spectrum of a dual-band two-tone test, including out-of-band IM.

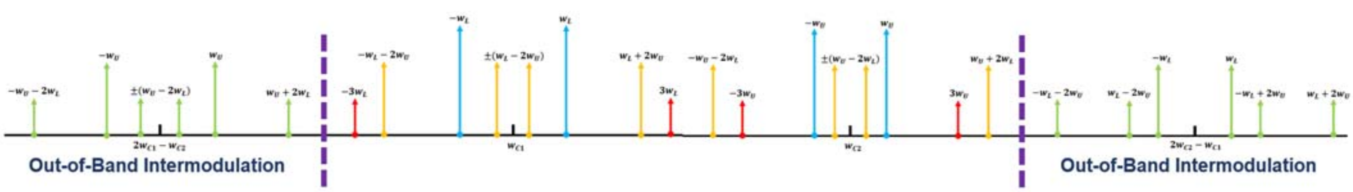

Fig. 3. output power spectrum of a dual two-tone test including out-of-band intermodulation.

IV. EXPERIMENTAL VERIFICATION

Fig. 4 shows the experimental setup of spectral measurement, which include a ZFL-1000LN RF power amplifier of Mini-Circuit with a 13 dBm third-order intercept point and an output gain of 21 dB, also used in the setup is an Agilent E4438 ESG vector signal generator, and a Tektronix RSA 6120A real-time spectrum analyzer. The synthesized dual-band two-tone signals are based on $\omega_{c1}=0.89GHz$ and $\omega_L=3MHz$, and $\omega_{c2}=0.917GHz$ and $\omega_U=7MHz$.

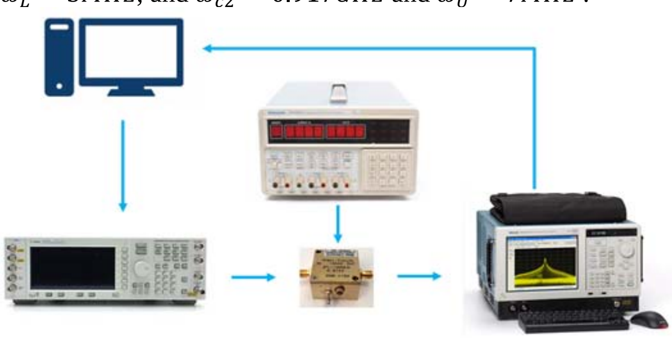

Fig. 4. Experimental set up

The Fig. 5 describes the amplified signal. We could clearly find there are six frequency components located at each side of the dual two-tone signal. In this situation, the out-of-band intermodulation is hard to filtered out.

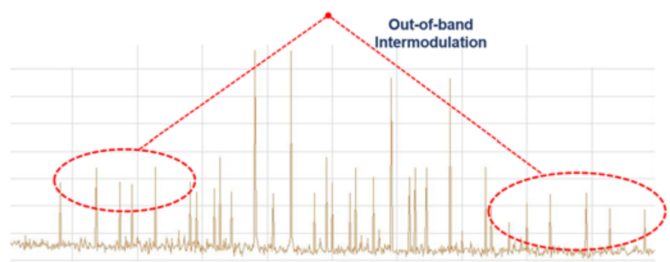

Fig. 5. Amplified even dual two-tone signal. The out-of-band intermodulation is so close to the passband signals that cannot be easily filtered out.

It could be observed from the experimental results in the Fig 5, the out-of-band components are indeed hard to be removed when ω_{c1} and ω_{c2} are too close. This verifies the conclusion in section 3.

V. CONDLUSION

In this paper, we made a number of clarifications to [1] which provides very useful results. Further we discussed the effect of IM and CM in the passband. We also concluded and verified that out-of-band intermodulation needs to be taken into consideration when two bands are very close.

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