FUNDAMENTAL LIMITATIONS ON OUTPUT POWER AND CONVERSION LOSS OF AN EVEN HARMONIC MIXER IN AN UP-CONVERSION OPERATION

Kenji Itoh, Ken'ichi Tajima, Kenji Kawakami, Osami Ishida and Koji Mizuno+
Mitsubishi Electric Corp., +Research Institute of Electrical Communication, Tohoku University
5-i-l Ofuna, Kamakura-city, Kanagawa 247,JAPAN, E-mail : itoh@micro4.isl.melco.co.jp

ABSTRACT

An even harmonic mixer (EHM) with an antiparallel diode pair (APDP) is an effective technique for low spurious transmitters especially in millimeter-wave. The purpose of this study is to clarify general properties of the EHM in an up-conversion operation. For this purpose, fundamental formulas and universal charts are indicated in this paper. As results of the analysis, it becomes clear that output power can be increased and spurious emissions can be reduced in the case of higher LO level. Furthermore conversion loss limitation of 3.9dB is indicated for the EHM with a resistive termination. Measured results indicate good agreements with presented formulas.

INTRODUCTION

In recent years, small sized millimeter-wave transceivers are required for high speed digital transmission systems used in B-ISDN networks[1][2]. For a digital transmission system, low LO (local oscillator) leakage of an up-conversion mixer is required to miniaturize a transceiver. Because a large sized waveguide BPF is used to suppress the LO leakage that appears nearby a desired RF signal. Furthermore good linearity of an up-conversion mixer is also required to narrow bandwidth of a transmission signal. Because a linear modulation method is employed to achieve higher a frequency-use efficiency even in millimeter-wave.

An even harmonic mixer (EHM) with an antiparallel diode pair (APDP)[3] is a familiar configuration especially in millimeter-wave receiver applications[4] because of lower LO frequency. In our papers[5]-[7], we proposed EHMs for transmitter applications. Because an extreme low virtual LO leakage (second harmonics of LO) can be achieved even in 60GHz by the EHM. In past works, there have been many discussions about conversion loss for receiver EHMs[8]. But for transmitter EHMs, there have been no discussions about output power and linearity. Output power and linearity of the EHM is an important subject to investigate for transmitters.

The purpose of this study is to clarify general properties of the EHM in an up-conversion operation. For the purpose, fundamental formulas and universal charts are indicated in this paper. The formulas and charts clarify output power, spurious emissions by higher order non-linearity and conversion loss of the EHM. In the analysis, EHM is under a condition of a resistive termination. Furthermore derived formulas indicate conversion loss limitation of 3.9dB. This is the same value of fundamentally pumped mixers indicated by Mouw[9] and Kelly[lO]. Finally, Measured results on 2GHz indicate good agreements with derived formulas.

OUTPUT POWER AND CONVERSION LOSS FORMULAS

Figure 1 indicates a configuration and output spectra of the EHM in up-conversion operation. The EHM consists of a multiplexer and an APDP. The EHM has extreme low virtual LO leakage *(2fp)* that interferes with desired RF output signal *(2fp+fif)* in an up-conversion operation[5]. Because mixing products $(n \cdot f_p \pm m \cdot f_{if}, n \pm m = odd)$ can be produced and mixing products $(n \cdot f_p \pm m \cdot f_{if}, n \pm m = even)$ can be suppressed by employing well-matched APDP[3][5]. In following discussion, output power and conversion loss of the EHM are indicated by analytical approaches.

Figure 2 indicates equivalent circuits of the EHM in an up-conversion operation. SBD is expressed as a switch that is controlled by the junction voltage. The indicated model is applicable under a condition of much higher signal and LO voltage than SBD's built-in voltage V_t [11]. Current I_j indicated in figure 2 can be expressed as follows:

$$I_j = \begin{cases} \dfrac{V_{gen} - V_t}{R_s + R_0} & (V_{gen} > V_t) \\ 0 & (-V_t \leq V_{gen} \leq V_t) \\ \dfrac{V_{gen} + V_t}{R_s + R_0} & (V_{gen} < -V_t) \end{cases} \quad (1)$$

$$V_{gen} = V_p \cdot \sin \omega_p t + V_m, \omega_p = 2\pi f_p, V_p = 2\sqrt{2R_0 \cdot P_p} \quad (2)$$

where R_s is a resistance of SBD in on-state, R_o is internal resistance of the generator, P_p is power of LO and V_m is DC voltage, respectively. At the first, output current at $2f_p$ is derived in a condition that DC voltage is fed to APDP instead of IF signal. This condition makes Fourier transform easy. By Substituting (2) into (1), one can indicate output current I_{2p}, that is a $2f_p$ component of I_j, by Fourier analysis as follows:

$$I_{2p} = A_{,,} \ cos 2\Theta$$

$$A_{2p} = \frac{V_p}{\pi \cdot R_0 \cdot K_r} \{ \sin \alpha_2 \pi - \sin \alpha_1 \pi$$
$$+ (\sin 3\alpha_2 \pi - \sin 3\alpha_1 \pi)/3 - p \cdot \sin 2\alpha_2 \pi - q \cdot \sin 2\alpha_1 \pi \}$$
$$p = (V_m + V_t)/V_p, \ q = (V_m - V_t)/V_p, K_r = 1 + R_s/R_0 \quad (3)$$

where K_r is a loss factor of the RF signal by R_s, Θ is LO phase, α_1 and α_2 are pulse duty ratio (PDR) [8] of SBD1 and SBD2 respectively. a I and α 2 are given as

$$a, = 0.5 - \theta_1/\pi, \alpha_2 = OS+ \ \theta_2/\pi$$

$$\sin\theta_1 = \begin{cases} \min[1, (V_t - V_m)/V_p] & (V_t - V_m \geq 0) \\ \max[-1, (V_t - V_m)/V_p] & (V_t - V_m < 0) \end{cases}$$

$$\sin\theta_2 = \begin{cases} \max[-1, -(V_t + V_m)/V_p] & (V_t + V_m \geq 0) \\ \min[1, -(V_t + V_m)/V_p] & (V_t + V_m < 0) \end{cases} \quad (4),$$

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where *min[a,b]* and *max[a, b] are* minimum and maximum values between a and b. Figure 3 indicates DC characteristics of an APDP and waveforms of V_{gen} and I_j.

Next, with a substitution $V_{if} \cdot \sin(2\pi \cdot f_{if} \cdot t)$ into V_m, amplitude of the EHM's output current (A_{out_m}) (frequency: $2f_p \pm m \cdot f_{if}$) is calculated by discrete Fourier transform. Figure 4 indicates calculated output current A_{out_m} versus IF signal voltage V_{if}. This result can be applied an APDP with any V_t and R_s, as it is expressed in a universal charts. Figure 4 indicates that a peak of RF signal current A_{out_1} ($2f_p \pm f_{if}$) can be increased and spurious components ($2f_p \pm 3f_{if}$) and ($2f_p \pm 5f_{if}$) can be reduced for higher LO voltage V_p.

Let us discuss a RF output power concerned with spurious level ($3f_{if} \pm 2f_p$) in more detail. By substitution of (4) into (3), RF output current A_{2p} can be given as

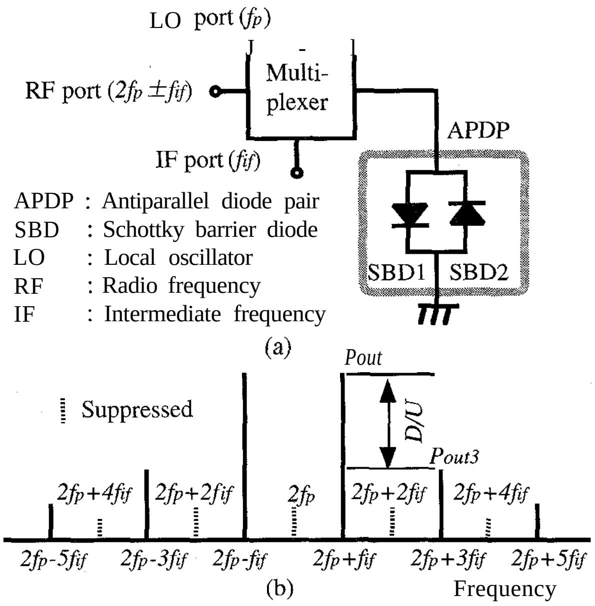


Fig.1. A schematic diagram of (a) an even harmonic mixer (EHM) with an antiparallel diode pair, and (b) output spectra of the EHM as an up-converter.

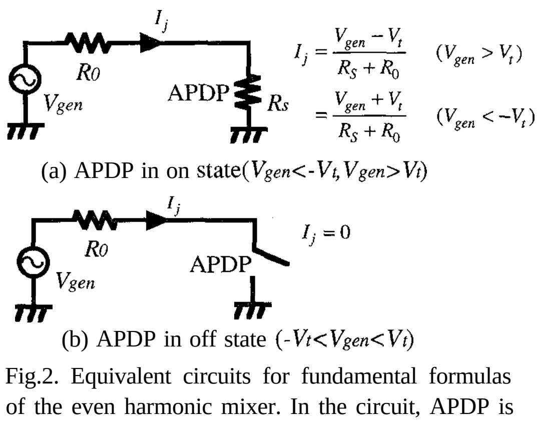


Fig.2. Equivalent circuits for fundamental formulas of the even harmonic mixer. In the circuit, APDP is expressed as a switch controlled by junction voltage.

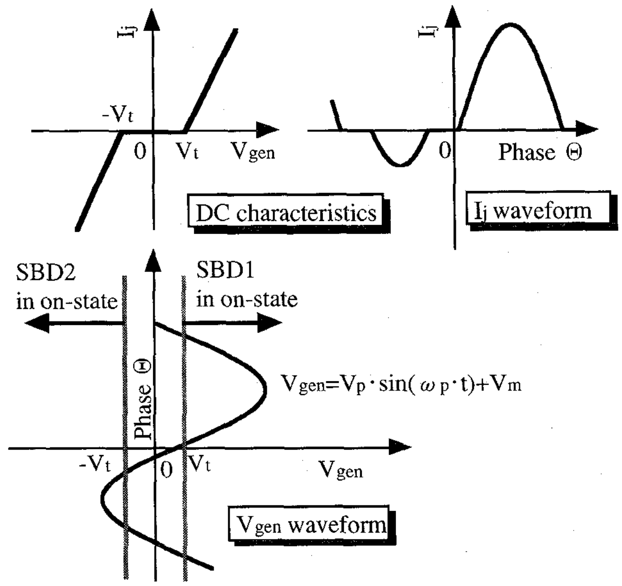


Fig.3. DC characteristics of antiparallel diode pair (APDP) with internal resistance Ro, V_{gen} and I_j. APDP is pumped by LO V_p and DC voltage V_m.

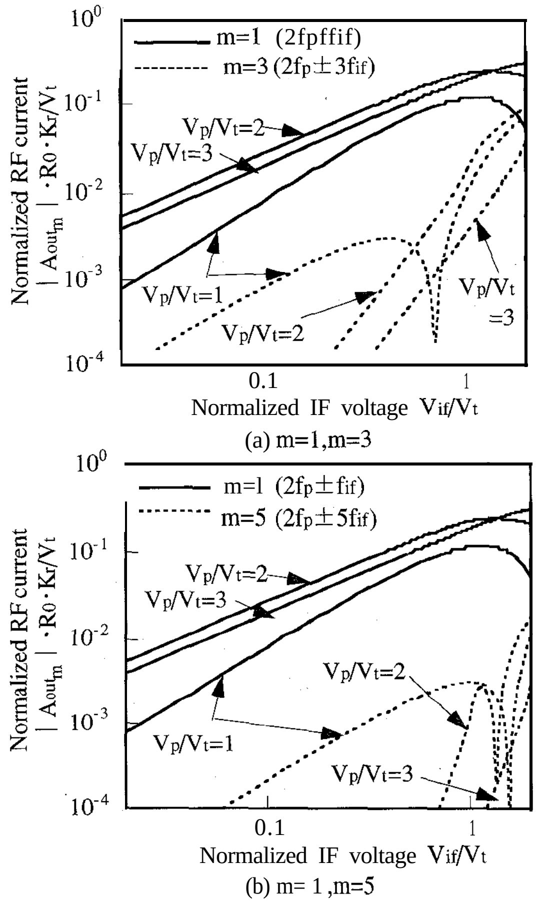


Fig.4. Calculated output current A_{out_m} versus IF signal voltage V_{if}. These charts are in universal expressions.

$$A_{2p} = \frac{2V_p}{3\pi \cdot R_0 \cdot K_r}\left\{(1- p^2)^{1.5} - (1- q^2)^{1.5}\right\}$$
$$\approx -\frac{4}{\pi \cdot R_0 \cdot K_r}\cdot\frac{\gamma}{(V_p/V_t)^2}\cdot\left(V_m - \frac{V_m^3}{6\gamma^4 \cdot V_t^2}\right)$$
$$\gamma^2 \approx (V_p/V_t)^2 - 1,\ |p| \le 1,\ |q| \le 1,\ V_p^2 >> V_t^2 + V_m^2 \qquad (5).$$

By substitution of $V_{if}\cdot \sin(2\pi \cdot f_{if} \cdot t)$ into V_m in (5), the EHM's output current I_{2p} can be approximated as follows:

$$I_{2p} \approx A_1 \cdot V_{if} \cdot \left[A_2\{\sin(\omega_{if} + 2\omega_p)t + \sin(\omega_{if} - 2\omega_p)t\}\right.$$
$$\left. + A_3\{\sin(3\omega_{if} + 2\omega_p)t + \sin(3\omega_{if} - 2\omega_p)t\}\right]$$
$$A_1 = -(2\gamma)\Big/\left\{\pi \cdot R_0 \cdot K_r (V_p/V_t)^2\right\},\quad A_2 = 1 - V_{if}^2\Big/\left(8\gamma^4 \cdot V_t^2\right)$$
$$A_3 = V_{if}^2\Big/\left(24\gamma^4 V_t^2\right) \qquad (6)$$

RF output power P_{out} and spurious ($2f_p \pm 3f_{if}$) power P_{out3} are derived by (6) as follows:

$$P_{our} = \frac{2}{R_0(\pi \cdot K_r)^2}\cdot\frac{\gamma^2}{(V_p/V_t)^4}\cdot\left(1 - \frac{V_{if}^2}{8\gamma^4 \cdot V_t^2}\right)^2 V_{if}^2 \qquad (7)$$
$$P_{our3} = \frac{2}{R_0(\pi \cdot K_r)^2}\cdot\frac{1}{V_p}\cdot\frac{1}{24\gamma^6}V_{if}^6 \qquad (8)$$

A desired to undesired ratio (D/U) defined by P_{out} and P_{out3} is given as follows:

$$D/U \equiv P_{out}/P_{out3} = (3/8)\left(8\gamma^4 \cdot V_t^2/V_{if}^2 - 1\right)^2 \qquad (9)$$

By Substituting (9) into (7), output power P_{out} with the required D/U can be approximated

$$P_{out} \approx 0.993.\ \frac{\left(1 - V_t^2/V_p^2\right)^3}{\sqrt{(D/U)}}\cdot\frac{V_p^2}{R_0 \cdot K_r^2} \qquad (10).$$

Figure 5 indicates calculated output power P_{our} versus LO voltage V_p. Higher P_{out} with better D/U can be achieved by increment of V_p.

Finally, we discuss conversion loss limitation of the EHM in a linear operation. IF input power is given as $P_{if} = V_{if}^2/(8R_0)$. So conversion loss L_{mix} defined by P_{if} and P_{out} can be approximated

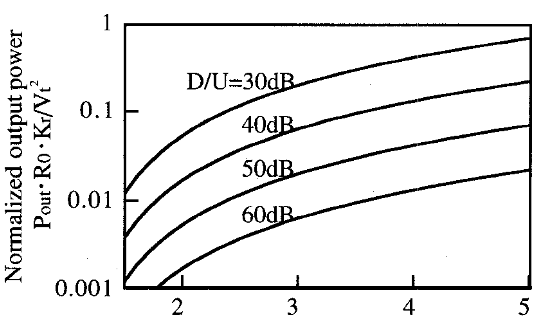


Fig.5. Calculated output power P_{out} concerned with D/U versus LO voltage V_p.

$$L_{mix} = P_{if}/P_{out} \approx \frac{\pi^2}{16}\frac{(V_p/V_t)^4}{(V_p/V_t)^2 - 1}\cdot K_r^2$$
$$V_{if}^2 << 8\left\{(V_p/V_t)^2 - 1\right\}^4 \cdot V_t^2 \qquad (11).$$

Figure 6 indicates calculated conversion loss L_{mix} and PDR of the EHM by (11). As shown in the figure, a minimum value of L_{mix} is given as

$$L_{mix} = \pi^2 K_r^2/4 \quad \text{at } V_p = \sqrt{2}V_t \qquad (12).$$

PDR of a SBD α is 0.25 under the condition shown in (12). L_{mix} becomes lowest at this condition. Because the second harmonics of SBD's junction conductance becomes the highest level with this condition. From (12), following conclusions are obtained.

(a) A condition of V_p for the lowest L_{mix} concerns with V_t.

(b)The limitation of L_{mix} is determined by K_r which is defined by R_0 and R_s.

(c)The limitation of L_{mix} is 3.9dB even though R_s is suppressed completely. This value (*3.9dB*) is the same value as fundamental pumped mixer with a resistive termination[9][10].

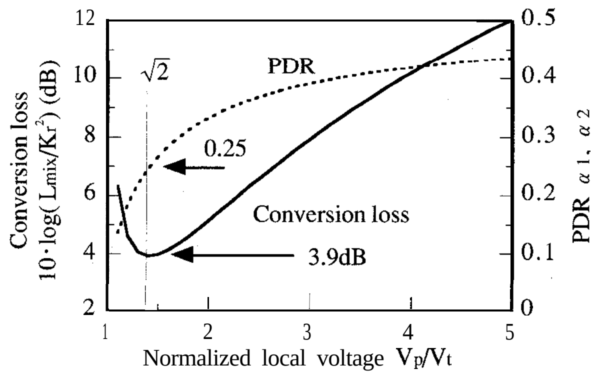


Fig.6. Calculated conversion loss and PDR of the EHM as up-converters. This result indicates fundamental limitation 3.9dB on conversion loss of the EHM.

MEASUREMENTS ON 2GHz

For measurements, we employed beam-lead type APDP (SANYO SBL803A) that is connected between microstrip line and ground plane. Cut-off frequency of a SBD in the APDP is 796GHz, and f_p of 1GHz and f_{if} of 1MHz are employed for reducing influences by junction capacitance. Figure 7 shows DC characteristics of the APDP. In the figure, dots indicate measured current and solid line indicates calculated one by employing the model. Measured and calculated currents are in good agreement except around V_t.

Figure 8 shows output RF signal ($2f_p+f_{if}$) power and spurious ($2f_p+m \cdot f_{if}$) power versus IF signal power. In the figure, solid line indicates calculated results by DFT with (5) and (6), and dotted line indicates measured results. Calculated and measured RF output power ($m=1$) are in good agreement. Calculated and measured spurious components ($m>1$) have the same dependence versus IF signal power. In addition, measured results indicated that higher LO power can improve RF output power ($m=1$) and can reduce spurious level ($m>1$), as described in calculated results.

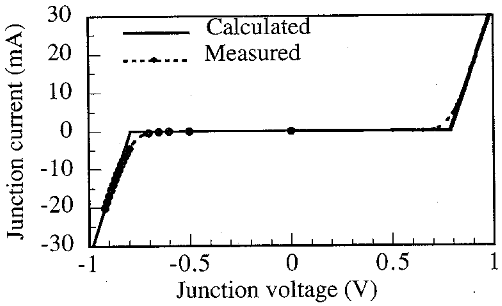
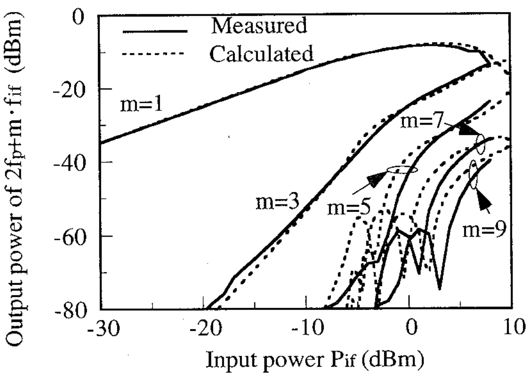
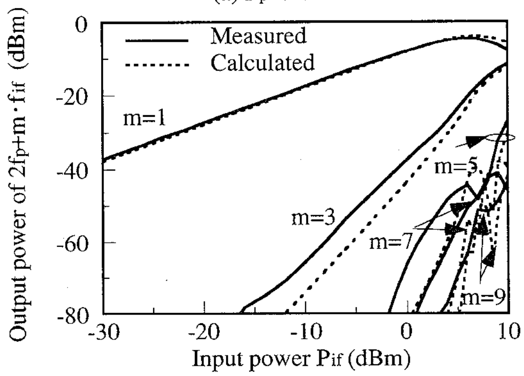


Fig.7. DC characteristics of the APDP.



(a) Pp=5 dBm



(a) Pp=10 dBm

Fig.8. Output RF signal (m=1, $2f_p+f_{if}$) power and spurious (m>1, $2f_p+m\cdot f_{if}$) power versus IF signal power (f_{if} : 1MHz, f_p : 1GHz) .

Figure 9 shows conversion loss of the EHM. In the figure, solid line and dotted line indicate calculated and measured results, respectively. From *Pp=5dBm* to *12dBm*, Calculated and measured results are in good agreement within *0.5dB*.

As mentioned above, presented formulas in this paper express fundamental characteristics of the EHM clearly.

CONCLUSION

This paper presented fundamental formulas and universal charts of the EHM in an up-conversion operation. As results of the analysis, it was founded that higher LO power

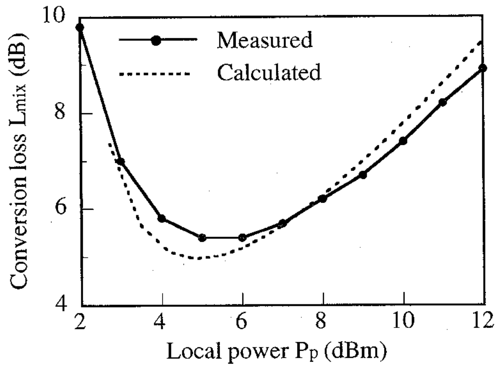


Fig.9. Conversion loss of the EHM in an up-conversion operation (f_{if} : 1MHz, f_p : 1GHz, P_{if} : -20dBm) .

achieves higher output power and lower spurious emissions. Furthermore conversion loss limitation of 3.9dB was indicated. Measured results indicated good agreements with presented formulas. By this analysis, fundamental limitation of characteristics have been more clearly.

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