Unbalance effects of an antiparallel diode pair on the virtual local leakage in an even harmonic mixer

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ABSTRACT

An even harmonic mixer (EHM) with an antiparallel diode pair (APDP) is an effective technique for low spurious transmitters especially in the millimeter-wave region. Because the APDP can suppress the virtual LO leakage that locates nearby a desired RF signal. The purpose of this study is to clarify unbalance effects of an APDP on the virtual local leakage. For this purpose, fundamental formulas are indicated in this paper. As results of the analysis, two conclusions are indicated: (a) Due to unbalance on parasitic resistance of the APDP, the virtual LO leakage is increased by increment of LO power, (b) Due to unbalance on built-in voltage of the APDP, the virtual LO leakage is decreased by increment of LO power. Measured results indicate good agreements with presented formulas.

INTRODUCTION

In recent years, small sized microwave and millimeter-wave transceivers are required for high speed digital transmission systems used in B-ISDN networks[1][2]. For the transceivers, up-converters or PSK modulators are used for generating microwave and millimeter-wave signals. A mixer used in an up-converter or a PSK modulator is required to reduce the LO (local oscillator) leakage. For an up-converter, a large sized waveguide BPF is employed to suppress the LO leakage that is located nearby a desired RF signal. Also this LO leakage degrades vector modulation error. Hence this LO leakage of the mixer should be reduced to improve the overall performance of the transmitter.

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 halved LO frequency. In our papers[5]-[8], EHMs are proposed for transmitter applications like up-converters and QPSK modulators. Because EHMs have the extreme low virtual LO leakage that is the second harmonic of LO. This second harmonic of the LO current flow only within the APDP as the diode loop. So the virtual LO leakage can be reduced by employing a well-matched monolithic APDP. Noting this characteristics, we developed EHMs with monolithic APDPs for an up-converter and a QPSK modulator in microwave and millimeter-wave regions[5]-[7]. Also in our paper[8], fundamental limitations on output power and conversion loss are clarified for the EHM used in a transmitter. But there have been no discussions about the virtual LO leakage of the EHM in past works.

In this paper, unbalance effects of an APDP on the virtual local leakage is described in the analytically approach for EHMs. The purpose of this study is to clarify general properties of the EHM for transmitter applications. For the purpose, fundamental formulas for the virtual LO leakage are indicated in this paper. In the analysis, the APDP is modeled as two unbalanced switches with parasitic resistance and built-in voltage. As results of the analysis, two conclusions are indicated: (a) Due to unbalance on parasitic resistance, the virtual LO leakage is increased by increment of LO power, (b) Due to unbalance on built-in voltage, the virtual LO leakage is decreased by increment of LO power. Finally, measured results on 2GHz indicate good agreements with derived formulas.

FORMULAS FOR THE VIRTUAL LO LEAKAGE

Figure 1 indicates a schematic diagram and output spectrum of the EHM as an up-converter. A single-end type EHM consists of a multiplexer and an APDP with Schottky barrier diodes (SBD1 and SBD2). 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 a well-matched APDP[3][5]. So the virtual LO leakage $2f_p$ is extremely low without any filters. In an up-conversion operation, this virtual LO leakage $2f_p$ interferes with desired RF output signal ($2f_p + f_{if}$) as shown in Figure 1(b) [5]. So the EHM is a good technique for transmitter applications in microwave and millimeter-wave regions. In a following discussion, output power of the virtual LO leakage is indicated by analytical approaches.

Figure 2 indicates equivalent circuits of the EHM. The indicated unbalanced APDP consists of SBD1

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and SBD2 with parasitic resistance of R_{s1}, R_{s2} in on-state and built-in voltage V_{t1}, V_{t2}. SBDs are expressed as switches controlled by junction voltage V_j. This model is applicable under a condition of much higher LO voltage than built-in voltage V_{t1}, V_{t2}[8][9]. Current I_j indicated in figure 3 can be expressed as follows:

$$I_j = \begin{cases} (V_j - V_{t1})/R_{s1} & (V_j > V_{t1}) \\ 0 & (-V_{t2} \le V_j \le V_{t1}) \\ (V_j + V_{t2})/R_{s2} & (V_j < -V_{t2}) \end{cases} \qquad (1)$$

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

Where R_0 is internal resistance of the generator and P_p is LO power. Also figure 3 indicates dc characteristics of the unbalanced APDP and waveforms of V_{gen} and I_j. By the unbalance effect of the APDP, positive and negative currents of I_j become asymmetrical. Because of this asymmetry, the second harmonic $2f_p$ can not be reduced completely and is generated as the virtual LO leakage.

By substituting (2) into (1), output current I_{2p} of the virtual LO leakage, which is $2f_p$ component of I_j, is indicated by Fourier analysis as follows:

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

$$\begin{aligned} A_{2p} &= \frac{1}{\pi}\left[\int_{\pi(0.5-\alpha_1)}^{\pi(0.5+\alpha_1)} (I_{p1}\cdot \sin\Theta + I_{t1})\cos 2\Theta \cdot d\Theta + \int_{-\pi(0.5+\alpha_2)}^{-\pi(0.5-\alpha_2)} (I_{p2}\cdot \sin\Theta + I_{t2})\cos 2\Theta \cdot d\Theta \right] \\ &= \frac{1}{\pi}\cdot\left[-(I_{p1}/3)\cdot\{3\sin(\alpha_1\pi) + \sin(3\alpha_1\pi)\} + (I_{p1}/2)\cdot\{3\sin(\alpha_2\pi)+\sin(3\alpha_2\pi)\} \right. \\ &\quad \left. -(I_{t1}\cdot \sin 2\alpha_1\pi + I_{t2}\cdot\sin 2\alpha_2\pi)\right\} \end{aligned}$$

$$\Theta = \omega_p \cdot t,$$
$$I_{p1} = V_p/(R_{s1}+R_0), \quad I_{m1} = -V_{t1}/(R_{s1}+R_0), \qquad (3)$$
$$I_{p2} = V_p/(R_{s2}+R_0), \quad I_{m2} = V_{t2}/(R_{s2}+R_0)$$

Where α_1 and α_2 are pulse duty ratio (PDR) [9] of

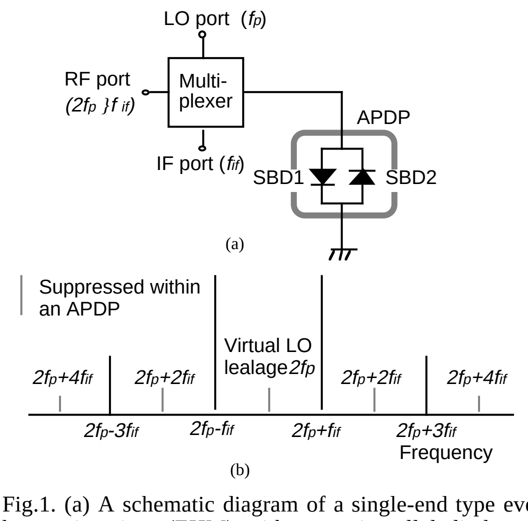

Fig.1. (a) A schematic diagram of a single-end type even harmonic mixer (EHM) with an antiparallel diode pair (APDP). It consists of a multiplexer and an APDP with two Schottky barrier diodes SBD1 and SBD2. (b) Output spectrum of an even harmonic mixer (EHM) as an up-converter. Dashed lines indicate mixing products $n\cdot f_p \pm m\cdot f_{if}$ in which $n \pm m$ is an even integer. These mixing products can be suppressed by employing a well-matched antiparallel diode pair (APDP). So the EHM as an up-converter can achieve an extremely low virtual leakage $2f_p$.

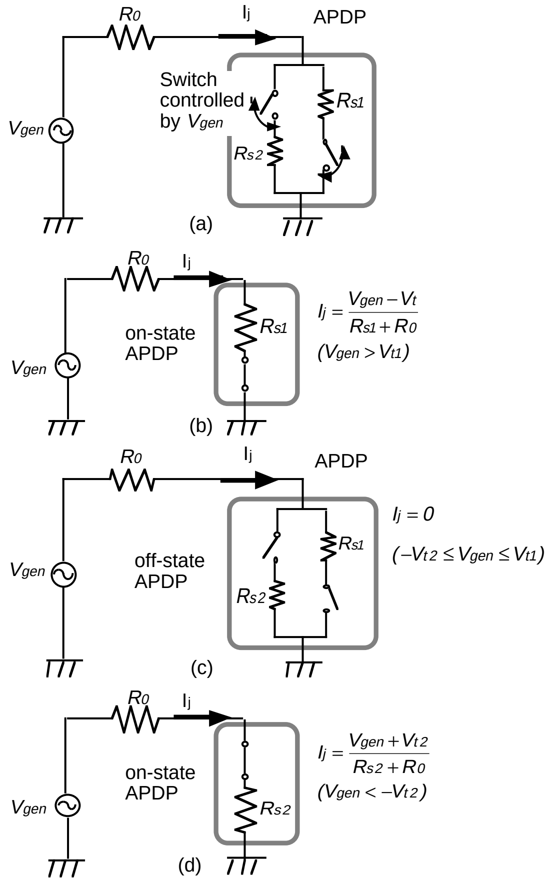

Fig.2. Equivalent circuits of an even harmonic mixer (EHM) with an antiparallel diode pair (APDP). As shown in (a), the APDP is expressed as switches controlled by the generator's voltage V_{gen}. In $V_{gen} > V_{t1}$ and $V_{gen} < -V_{t2}$ as shown in (b) and (d), the APDP is in on-state and can be expressed as a resistor R_{s1} and R_{s2}. In $-V_{t2} \le V_{gen} \le V_{t1}$ as shown in (c), the APDP is in off-state and can be expressed as an open-end.

SBD1 and SBD2, respectively. α_1 and α_2 are given as follows:

$$\begin{aligned} \alpha_1 &= 0.5 - \theta_1/\pi, & \sin\theta_1 &= \min[1, V_{t1}/V_p] \\ \alpha_2 &= 0.5 + \theta_2/\pi, & \sin\theta_2 &= \max[-1, -V_{t2}/V_p] \end{aligned} \qquad (4)$$

Where min[a,b] and max[a,b] are minimum and maximum values between a and b, respectively. As shown in figure 3, SBD1 turns on at phase θ_1 and SBD2 turns off at phase θ_2. The virtual LO power P_{2p} is derived from A_{2p} in (3) as follows:

$$P_{2p} = A_{2p}^2 \cdot R_0/2 \qquad (5)$$

Presented formulas can be applied to any APDPs with any V_t and R_s, as it is expressed in the universal expression.

In next discussion, general properties of P_{2p} are investigated with some approximations. At first, the virtual LO power P_{2p1} generated by unbalance between R_{s1} and R_{s2} is derived with an approximation

$$V_t \equiv V_{t1} = V_{t2}. \qquad (6)$$

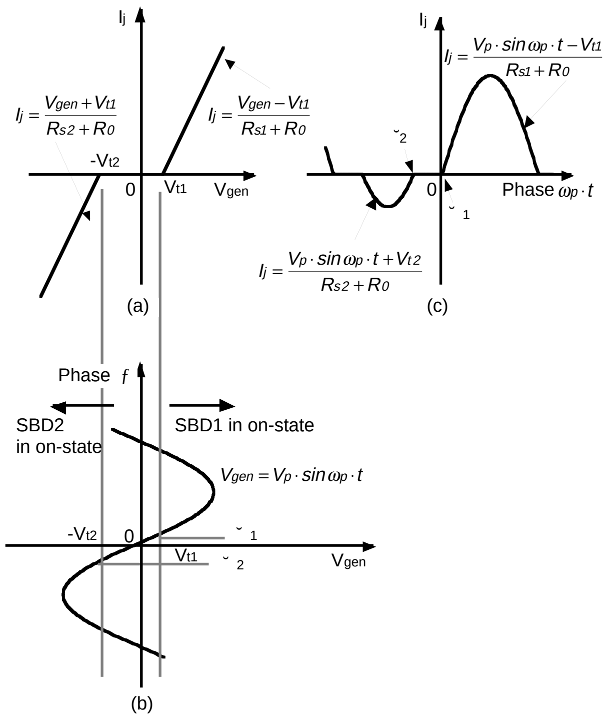

Fig.3. (a) dc characteristics of the unbalanced antiparallel diode pair (APDP) with the internal resistance R0, (b) waveform of generator's voltage Vgen and (c) waveform of a junction current Ij through the APDP. The APDP is pumped by $V_{gen} = V_p \cdot \sin\omega_p \cdot t$ in where V_p is the LO voltage. By this unbalanced APDP, positive and negative currents of Ij become asymmetrical. Because of this asymmetry, the second harmonic *2fp* is produced as the RF output signal.

By a substitution of (6) into (3) and some arrangements, P_{2p1} is given as follows:

$$P_{2p1} = A_{2p1}^2 \cdot R_0/2$$

$$A_{2p1} = \frac{2}{3\pi} \cdot \frac{R_{s1} - R_{s2}}{(R_0 + R_{s1})(R_0 + R_{s2})} \cdot \left(1 - \frac{V_t^2}{V_p^2}\right)^{1.5} \cdot V_p \qquad (7)$$

Where $V_p > V_t$ is assumed as the condition of convergence of (7). Also (7) can be approximated as follows:

$$A_{2p1} \approx \frac{2}{3\pi} \cdot \frac{\Delta R_s}{(R_0 + R_s)^2} \cdot \left(1 - \frac{V_t^2}{V_p^2}\right)^{1.5} \cdot V_p \qquad (8)$$

$$\Delta R_s = R_{s1} - R_{s2}, \quad R_{s1} \approx R_{s2} = R_s$$

The virtual LO power P_{2p1} generated by unbalance between R_{s1} and R_{s2} is increased with increment of LO voltage V_p as shown in (8).

Similarly, the virtual LO output power P_{2p2} generated by unbalance between V_{t1} and V_{t2} is derived with an approximation

$$R_s \equiv R_{s1} = R_{s2}. \qquad (9)$$

By a substitution of (9) into (3) and some arrangement, P_{2p2} is given as follows:

$$P_{2p2} = \frac{A_{2p2}^2 \cdot R_0}{2}$$

$$A_{2p2} = \frac{2}{3\pi} \cdot \frac{1}{R_0 + R_s} \cdot \left\{ \left(1 - \frac{V_{t2}^2}{V_p^2}\right)^{1.5} - \left(1 - \frac{V_{t1}^2}{V_p^2}\right)^{1.5} \right\} \cdot V_p \qquad (10)$$

Where $V_p > V_{t1}$ and $V_p > V_{t2}$ are assumed as the conditions of convergence of (10). Furthermore (10) can be approximated under the condition of $V_p >> V_{t1}$ and $V_p >> V_{t2}$ as follows:

$$A_{2p2} \approx \frac{1}{\pi} \cdot \frac{1}{R_0 + R_s} \cdot \frac{2V_t \cdot \Delta V_t}{V_p} \qquad (11)$$

$$\Delta V_t = V_{t1} - V_{t2}, \quad V_{t1} \approx V_{t2} = V_t$$

The virtual LO power P_{2p1} generated by unbalance between V_{t1} and V_{t2} is decreased with increment of LO voltage V_p as shown in (11).

By formulas indicated above, conclusions can be obtained as follows:

(a) Due to unbalance by parasitic resistance R_{s1}, R_{s2}, the virtual LO leakage is increased by increment of LO voltage V_p,

(b) Due to unbalance by built-in voltage V_{t1} and V_{t2}, virtual LO leakage is decreased by increment of LO voltage V_p.

In other words, the dominating reason is clarified by a measurement of the virtual LO power P_{2p}.

MEASUREMENTS ON 2GHz

For the experimental investigation, we employed a beam-lead type GaAs APDP (SANYO SBL803A) that is connected between a microstrip line and a ground plane as shown in Fig.4. Cut-off frequency of a SBD of the APDP is 796 GHz. *fp* of 1 GHz is employed for reducing influences by the junction capacitance. The virtual LO leakage generated by APDP is observed by the spectrum analyzer.

Measured and calculated dc characteristics of the APDP are shown in Fig.5. In the figure, dotted curve indicates a measured current and the solid line indicates calculated one by (1). Figure 6 indicates the measured and calculated virtual LO leakage *P2p*. In the figure, dots indicate measured virtual LO leakage and lines indicate the calculated ones *P2p*, *P2p1*, *P2p2* by formulas (5), (7), (10). For these calculations, dc parameters of APDP *Vt1*, *Vt2*, *Rs1*, *Rs2* are extracted from measured dc characteristics and the measured virtual LO leakage. Extracted dc parameters are indicated in table I. By using indicated parameters, measured and calculated results are in good agreement as shown in Fig.5 and Fig.6. Unbalance by parasitic resistance *Rs* is 1.9% as shown in table I. This is higher value compared with unbalance by built-in voltage *Vt* that is 0.31%. And it is clarified that unbalance of parasitic resistance is the dominating reason for the measured virtual LO leakage as shown in Fig.6. Considering nature of the semiconductor, this results are rational.

As mentioned above, formulas presented in this paper can express the unbalanced effect on the virtual LO leakage of EHMs clearly.

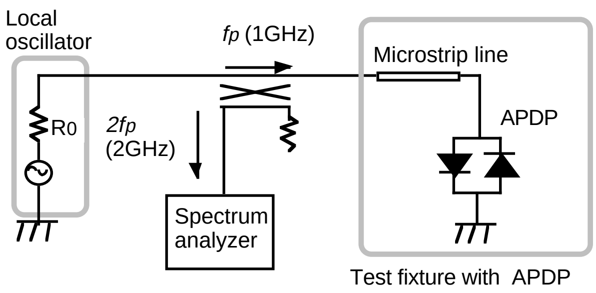

Fig.4. An experimental setup at 2GHz as virtual LO leakage. For the experimental investigation, we employed a beam-lead type GaAs APDP (SANYO SBL803A) that is connected between a microstrip line and a ground plane. Cut-off frequency of a SBD of the APDP is 796GHz, and *fp* of 1GHz is employed for reducing influences by the junction capacitance.

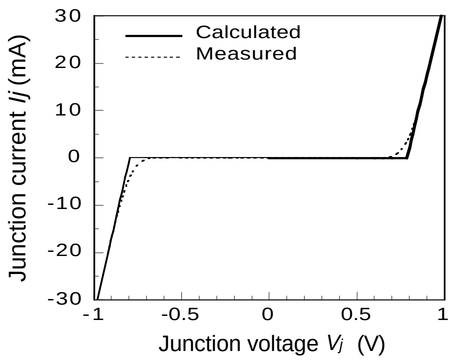

Fig.5. Measured and calculated dc characteristics of the antiparallel diode pair (APDP). Measured and calculated currents are in good agreement except around built-in voltage.

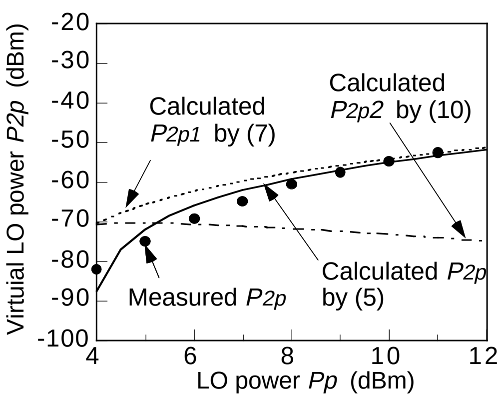

Fig.6. Measured and calculated virtual LO leakage *P2p*. In the figure, dots indicate measured values and lines indicate calculated virtual LO leakage *P2p*, *P2p1*, *P2p2* by equations (5), (7), (10). And it is clarified that unbalance of parasitic resistance is the dominating reason for the measured virtual LO leakage as shown in the figure.

Table I. Extracted dc parameters of the measured APDP (SBL-803(A)).

@ @Parameter		Value
SBD1	V_{t1}	0.786V
	R_{s1}	6.51 ¶
SBD2	V_{t2}	0.7863V
	R_{s2}	6.39 ¶

CONCLUSION

This paper presented fundamental formulas of the unbalance effects on the virtual LO leakage for the EHM. As results of analysis, it is founded that the dominating reason can be be clarified by the measured virtual LO leakage. Measured results indicate good agreements with calculated results by presented formulas. This analysis gives the general property of the virtual LO leakage more clearly, and results are useful for the EHM design.

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