Fundamental Limitations of Conversion Loss and Output Power on an Even Harmonic Mixer with Junction Capacitance

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***Abstract* — An even harmonic mixer with an anti-parallel diode pair is an effective technique for low spurious transmitters and direct conversion receivers. This paper describes general representation of conversion loss and output power on the even harmonic mixer with junction capacitance. For the anti-parallel diode pair, the switch model with resistance and non-linear capacitance is employed for the analytical approach. The analyses clarify fundamental limitation of the characteristics on the even harmonic mixer with the optimized junction dimension. This paper contributes to the design methodology for the even harmonic mixer used in millimeter wave systems.**

I. INTRODUCTION

An even harmonic mixer (EHM) with an anti-parallel diode pair (APDP) is an effective technique especially for millimeter-wave (MMW) region, because of halved LO frequency [1]. For many years, this technique has been used for MMW receivers [2]. Also the EHM has unique technical features of extreme low even-order spurious responses and emissions. Even-order mixing products are suppressed as loop-currents inside the APDP. In the case of the well-matched MMIC APDP, these mixing products can be cancelled extremely. Based on this superior feature of the EHM, the authors proposed applications as follows:

- Even harmonic type up-converter with extreme low virtual LO leakage [3]-[5].
- Even harmonic type PSK modulator with extreme low carrier leakage [6].
- Even harmonic type direct conversion receiver with high IIP2 characteristics [7]-[11].

The applications with the EHMs simplify radio terminals as follows:

- X-band satellite communication transceiver with the even harmonic type direct conversion receiver and PSK modulator [13].
- 1.9GHz-band PHS receiver and 2GHz-band W-CDMA receiver with the even harmonic type direct conversion receiver [14][15].

RF system performance can be improved with the use of the EHM techniques. These techniques can be applied in future MMW radio systems.

In addition, the authors described general behavior of the EHM as follows:

- Fundamental limitations of output power and conversion loss [16].
- LO leakage by unbalance effect of an APDP [17].

These previous works clarify general behaviors of the EHM in an up-conversion operation. The formulas in the paper [16] indicate conversion loss limitation of 3.9 dB that is the same value of fundamentally pumped mixer [18], [19]. The results are analyzed with the switch model of the APDP without junction capacitance. Therefor the results are applied to the EHM in enough low frequency than the cutoff frequency of the APDP. Degradation effect by junction capacitance should be clarified for MMW utilization. Such a kind of degradation effect has been clarified with several approaches for the fundamentally pumped mixer [20].

In this paper, general behavior of the EHM with junction capacitance is described for the MMW applications. The switch model with junction capacitance is employed in the analysis. Conversion loss of the EHM with junction capacitance is derived with the harmonic balance method. Calculation result clarifies fundamental limitation of conversion loss on the well-designed EHM with the optimized junction dimension. Furthermore, output power degradation by junction capacitance is analyzed with the same model. Calculated result is in good agreement with measured one. Behavior of the EHM with junction capacitance can be clarified by the analyses. The clarified results contribute to the MMW EHM design.

II. CALCULATION MODEL

Figure 1 indicates the configuration and output spectra of the EHM in the up-conversion operation. The EHM consists of a multiplexer and an APDP. The EHM has the extreme low virtual LO leakage $(2f_p)$ that interferes with desired RF output signal $(2f_p + f_{in})$ in the up-conversion operation [3]. Because even-order mixing products ($m \cdot f_p + n \cdot f_{in}$: $m \pm n = even$) become loop currents inside the APDP, and can be suppressed without any external components like balun circuits [1]. With employment of the well-matched APDP, extreme attenuation of the even-order mixing products can be achieved even in MMW region [3]-[5].

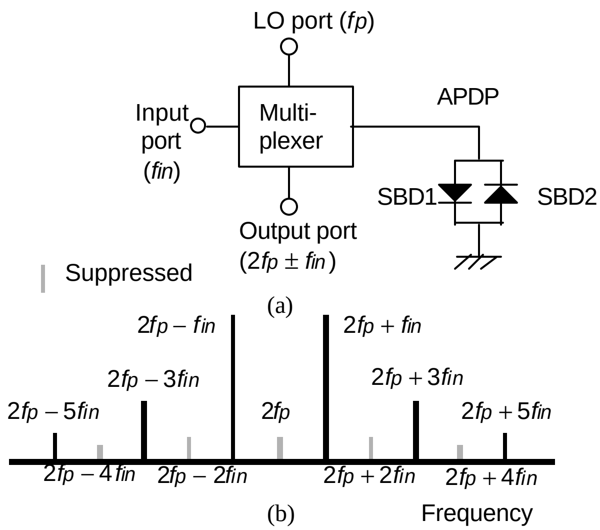

Fig.1. Schematic diagram of (a) an even harmonic mixer (EHM) with an anti-parallel diode pair, and (b) output spectra of the EHM as an up-converter.

Figure 2 indicates the equivalent circuit of an EHM, and its d.c. characteristics. A SBD is expressed as a switch that is controlled by junction voltage. Also series resistance R_s and junction capacitance C_j are added for prediction of degradation effects. The equivalent circuit is applicable under the condition of much higher LO voltage than SBD's built-in voltage V_t [21]. As in figure 2, I_j is represented as

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

where V_{gen} is terminal voltage of the generator and R_0 is internal resistance of the generator. The junction capacitance C_j is represented as

$$C_j = \frac{C_{j0}}{\sqrt{1 - V_j / V_t}} \qquad (2)$$

where C_{j0} is the junction capacitance at zero bias and V_j is the junction voltage. In each switching state of the SBD, the equivalent circuit of the APDP is represented in figure 3. In the on-state, SBD is expressed as resistance R_s. In the off-state, SBD is expressed as a series circuit with R_s and C_j. With C_j, leak current during the off-state of the SBD is added in the simulation. This leak current degrades the mixer characteristics. The cutoff frequency f_c of the SBD is represented as follows:

$$f_c = \frac{1}{2\pi\sqrt{R_s \cdot C_{j0}}} \qquad (3)$$

The APDP is pumped by V_{gen} represented as

$$V_{gen} = V_p \cdot \sin(\omega_p \cdot t) + V_{in} \cdot \sin(\omega_{in} \cdot t)$$
$$\omega_p = 2\pi \cdot f_p,\ V_p = 2\sqrt{2R_0 \cdot P_p} \qquad (4)$$
$$\omega_{in} = 2\pi \cdot f_{in},\ V_{in} = 2\sqrt{2R_0 \cdot P_{in}}$$

where V_p, f_p, V_{in}, f_{in} are LO voltage, LO frequency, input voltage and input frequency, respectively. In the following discussion, the up-conversion operation with IF input signal is employed as the model in previous papers [16], [17].

With the models and equations, rectified current can be calculated by the harmonic balance method. With the harmonic balance method, mixing products generated at R_0 can be derived from spectra of rectified current.

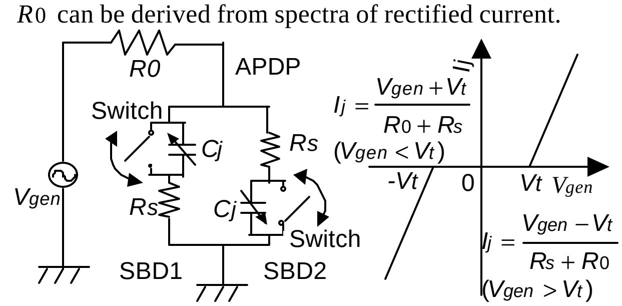

Fig.2. Equivalent circuit of an even harmonic mixer with junction capacitance C_j, and its d.c. characteristics.

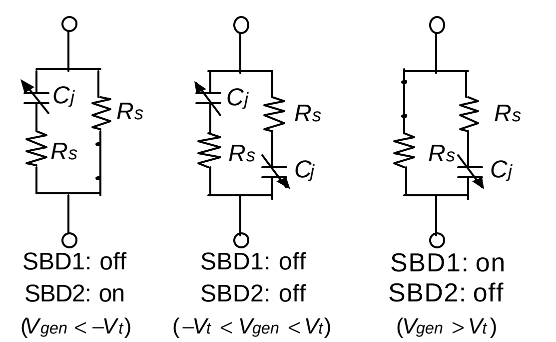

Fig.3. Equivalent circuit of an APDP in each switching state.

III. CALCULATED RESULTS AND EXPERIMENTAL INVESTIGATIONS

Figure 4 indicates the calculated conversion loss of the EHM with junction capacitance C_j. In the figure, output frequency is normalized by cutoff frequency f_c of the diode. In low frequency region, conversion loss degradation by C_j is small, and it is the same value as derived conversion loss limitation given by

$$L_c = 20 \cdot \log\left\{\frac{\pi}{2}\cdot\left(1+\frac{R_s}{R_0}\right)\right\} \quad \text{(dB)} \qquad (5)$$

in [16]. In the figure, envelope of curves represents fundamental limitation of conversion loss. With this figure 4, the APDP for the EHM can be designed to optimize junction dimension for improving conversion loss. This is very effective for the EHM design especially in MMW region.

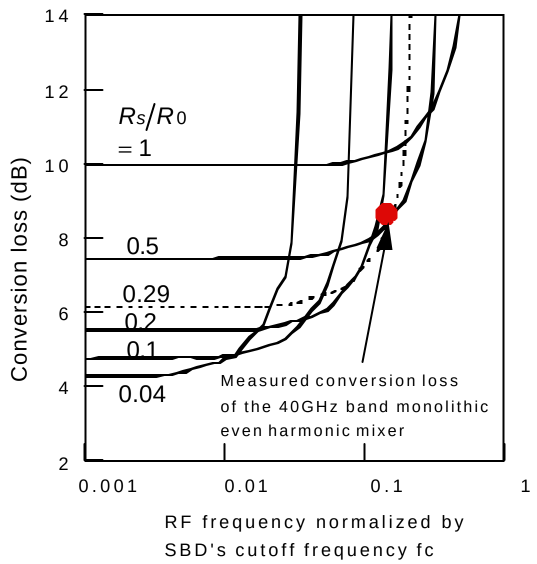

Fig.4. Calculated conversion loss of the even harmonic mixer with junction capacitance C_j. Also a measured result in 40GHz is indicated. Envelope of curves represents fundamental limitation of conversion loss.

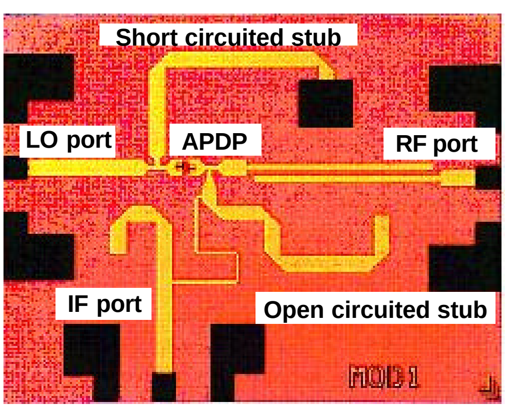

Fig.5. Photograph of the 40GHz band monolithic even harmonic mixer[3]. Chip size is 1.7mm x 2.2mm. The circuit is constructed with open and short circuited stubs in quarter wave length of LO.

The 40GHz band monolithic EHM [3] is employed for experimental investigations. Figure 5 indicates photograph of the mixer. This EHM employs an APDP with R_s of 14.5 Ω ($R_s / R_0 = 0.29$) and C_j of 0.04 pF. The cutoff frequency f_c of the APDP is 274GHz. Measured conversion loss is 9.5 dB. In the mixer, calculated insertion loss from APDP to the RF port is 0.9 dB. Thus measured conversion loss of the EHM is 8.6 dB with the loss correction. As shown in figure 4, calculated conversion loss is 8.4 dB for $R_s / R_0 = 0.29$. Calculated and measured results are in good agreement. Table I indicates conversion loss estimation from theoretical limitation of 3.9 dB. This clarifies effectiveness of the discussion described in this paper.

Furthermore, output power of the EHM with C_j is analyzed with the same model and the harmonic balance method. Figure 6 indicates output power of the EHM including theoretical limit [16], theoretical power with R_s, and calculated one with R_s and C_j. Also, measured and calculated results of the 40GHz band EHM are indicated. The indicated curves represent the same dependence on input power. Measured and calculated output powers at 1dB gain compression point are -16.5dBm and -15.4dBm, respectively. They are in good agreement. Output power degradation has almost the same dependence on C_j, as in the case of conversion loss degradation. Thus output power degradation by C_j can be predicted with the use of figure 4, approximately.

It is clarified that the represented APDP model is effective to predict conversion loss and output power especially in MMW region.

IV. CONCLUSION

For millimeter-wave applications, fundamental limitations of conversion loss and output power on the even harmonic mixer are described clearly. Represented analyses are in good agreements with measured ones, and contribute to the design methodology of the millimeter-wave even harmonic mixer.

Table I
Conversion loss estimation for the 40GHz band monolithic even harmonic mixer.

Theoretical limitation without Rs and Cj	3.9 dB
additional loss by Rs (14.5Ω)	+ 2.2 dB
additional loss by Cj (0.04pF)	+ 2.3 dB
additional insertion loss of RF circuit	+ 0.9 dB
Estimated conversion loss	9.3 dB
Measured conversion loss	9.5 dB

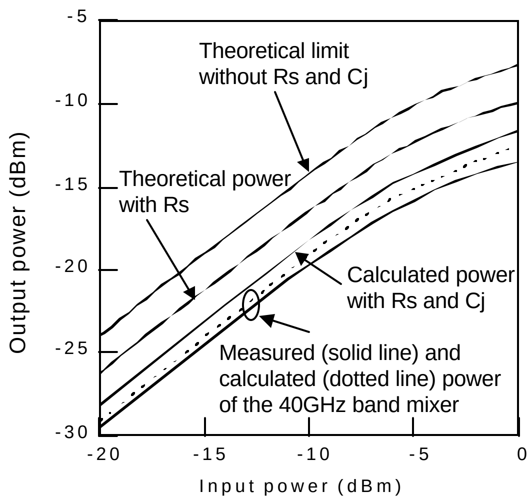

Fig.6. Output power of the even harmonic mixer including theoretical limit [16] (*P1dB*=-10.6dBm), theoretical power with Rs (*P1dB*=-12.7dBm), calculated one with *Rs* and *Cj* (*P1dB*=-14.5dBm). Also, measured and calculated results of 40GHz band even harmonic mixer are indicated. Measured *P1dB* is -16.5dBm, and calculated *P1dB* is -15.4dBm .

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