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Ku-Band Sub-Harmonically Pumped Single Balanced Resistive Mixers with a Low Pass Filter Using Photonic Band Gap

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Abstract

In this paper, sub-harmonically pumped single balanced resistive mixers are presented. Frequency bandwidth is selected for a Ku-band, which is 11.75~12.25 GHz for RF, 5.375~5.625 GHz for LO, and 1 GHz for IF signals. A rat-race hybrid is designed for the accomplishment of single balanced type. A low pass filter (LPF) with photonic band gap (PBG) structure is used for good conversion loss and unwanted harmonics suppression. Two types of mixers are suggested, which are one with no gate bias for no DC power consumption and the other with an IF amplifier for conversion gain. When a LO signal with the power of 6 dBm at 5.5 GHz is injected, a conversion loss of 12.17 dB and a conversion gain of 7.83 dB are obtained for each mixer. For the both mixers, LO to RF isolation of 20 dB and LO to IF isolation of 60 dB are obtained. With the RF power of −30 dBm to −3 dBm, the mixer shows linear characteristic region of IF. This mixer can be applied for Ku-band and other microwave communication systems.

I. INTRODUCTION

Recently, signal processing in communication systems becomes wide-band and digitized due to the diverse demands for the communication services[1]. The FET mixer has attracted much attention in these days because it has good conversion gain and isolation characteristic. Specially, the resistive mixer, which has been first suggested by S. A. Maas, has good noise and IM characteristics compared with other FET mixers, while it has conversion loss[2]. Therefore, it is expected to be applicable to the recent digital communication systems.

In this paper, new single balanced type of resistive mixers with sub-harmonic LO are suggested and discussed. Generally, if the resistive mixer is constructed by single balanced type, the transmission lines at IF port are overlapped each other. Therefore, it is difficult to design the balanced resistive mixer by hybrid circuit, and wire bonding, air bridge, or ribbon should be used for the interconnection even in MMIC[3],[4]. By adopting the sub-harmonic technique to the design of a single balanced type of resistive mixer, this problem can be solved and there is no need for the balun at IF port, which should be included in other balanced FET mixers. In this circuit, the second harmonic LO signals are in phase, while the fundamental LO signal injected to the LO port is out of phase. Therefore, IF output signals are in phase for the second LO signals, although the injected LO signals are out of phase.

Sub-harmonically pumped mixers have the several advantages compared with the mixers using fundamental LO. First, relatively low power and low frequency of LO source for high frequency application such as millimeter-wave range

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are needed. As the frequency of RF source increases, oscillators with stability and power levels for proper mixing are either very expensive or are simply not available[5]. In this paper, the low pass filter using photonic band gap (PBG) technique is applied to the design of the mixer to suppress these unwanted harmonics.

Ⅱ. SUB-HARMONIC RESISTIVE MIXER THEORY

2-1 Resistive Mixer Theory

Fig. 1 shows the equivalent circuit of the MESFET without drain bias voltage[6]. R_g is the gate resistance, and R_d and R_S are the drain and source ohmic contact resistances, respectively. The gate channel capacitance is distributed along the channel, but for simplicity is modeled as two lumped capacitances, C_{gs} and C_{gd}. If the FET is biased into its saturation region, C_{gd} becomes much less than C_{gs}. However, if V_{ds} equals to zero, C_{gs} becomes almost the same as C_{gd} and each is half the gate channel capacitance. The channel conductance is $g(V_g)$.

Since the relatively large value of C_{gd} would couple the RF and LO circuits to an unacceptable degree, RF and LO filters must be used. It is important that the LO voltage should not be coupled to the drain terminal. If it is coupled, the drain voltage will be traveled in the strongly nonlinear part of the I/V curve, increasing the IM level. The RF filter should therefore be designed to be short-circuited in the drain at the LO frequency. On the other hand, If RF signal is coupled to the gate, it is conceivable that intermodulation could be increased because of the nonlinearities in $g(V_g)$. However, if the gate is shorted at the RF frequency, no RF voltage appears to the gate, and thus there is no possibility of IM generation in this way. Thus, open-circuiting the gate effectively halves the capacitance in parallel with the channel resistance and consequent conversion loss should be lower.

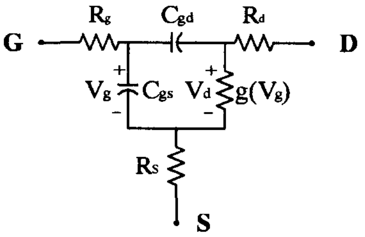


Fig. 1. Equivalent circuit of a GaAs MESFET operated without dc drain voltage.

When these conditions are met, the mixer with the LO and small-signal equivalent circuits can be approximated as shown in Fig. 2 (a) and (b). In this figure, it is assumed that $R_s \cong R_d$, and then, there is no LO voltage across $g(V_g)$. R_g and C_{gs} can be eliminated in Fig. 2 (b) because the reactances of C_{gd} and C_{gs} are much greater

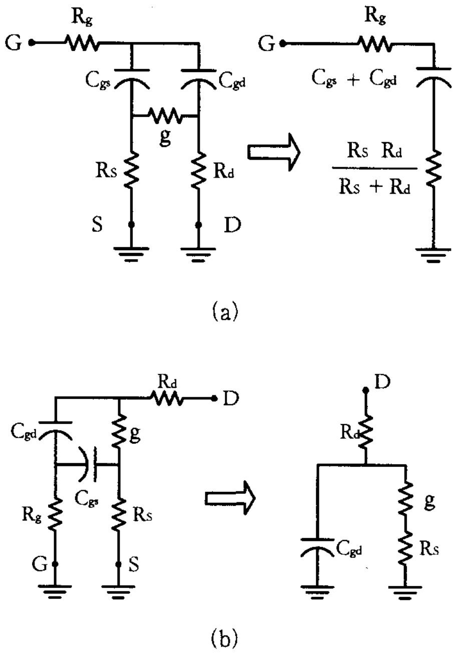


Fig. 2. Small signal equivalent circuits of the MESFET.
(a) LO equivalent circuit
(b) Approximation of small-signal equivalent circuit.

than the resistances of R_g and R_s. The resulting small-signal circuit is identical to that of a diode, and can be analyzed in precisely the same way. First, the large-signal conductance and capacitance waveforms are determined, then a small-signal analysis is performed using conversion matrices.

If the gate is not driven into conduction, the drain is shorted at the LO frequency and the capacitance nonlinearity is weak. One can assume that $V_g(t)$, the LO voltage across C_{gs}, is sinusoidal. In this case the channel conductance can be determined from Shockley theory[7]. For very low drain voltage, the drain current is given by Eq. (1).

$$I(V_g, V_d) = I_1 \{3[u^2(V_g, V_d) - u^2(V_g, 0)] \\ - 2[u^3(V_g, V_d) - u^3(V_g, 0)]\} \qquad (1)$$

where $u(V_g, V_d)$ is the normalized depletion width, which is given by

$$u(V_g, V_d) = \sqrt{(V_d + V_g + \varphi)/V_p} \qquad (2)$$

Here, V_p is the pinch-off voltage, φ is the gate built-in potential, and I_1 is a constant with dimensions of current. The channel conductance $g(V_g)$ is found by differentiating Eq. (1) and setting $V_d = 0$ as follows:

$$g(V_g) = 3I_1(1 - u(V_g, 0))/V_p \qquad (3)$$

The capacitance C_{gd} is modeled as an ideal Schottky-barrier capacitance with uniform epitaxial doping and can be expressed as

$$C_{gd}(V_g) = C_{gd0}(1 - V_g/\varphi)^{-\frac{1}{2}} \qquad (4)$$

To analyze the mixer, the parameters of Eqns. (1) and (2) are determined from I/V curve, and the gate channel capacitance is determined from measured S-parameter. The large-signal analysis is performed by first assuming $V_g(t) = V_b + V_{LO} \cos(\omega_p t)$ where V_b is the gate bias voltage and V_{LO} is the LO voltage magnitude. A straightforward analysis of Fig. 2 (a) gives an expression for the minimum required LO power which is expressed as

$$P_{LO} = 0.5 V_{LO}^2\ \omega^2 (C_{gso} + C_{gdo})^2 \\ \cdot \left(\frac{R_s R_d}{R_s + R_d} + R_g \right) \qquad (5)$$

It is assumed in Eq. (5) that the gate channel capacitance can be approximated by its zero-voltage value, $C_{gs0} + C_{gd0}$.

2-2 Sub-Harmonic Mixer Theory

The primary motivation for using sub-harmonic mixing at millimeter and sub-millimeter-wave frequencies has been the lack of sufficient LO power at the fundamental frequency. Sub-harmonically pumped mixers are very useful at millimeter wave frequencies since low frequency, low cost microwave sources can be used as the LO. In a sub-harmonic mixer, the mixing action is performed between the RF or IF signals and one of the harmonics of the LO. Thus, the nonlinear devices such as diode, MESFET, etc perform both mixing and frequency multiplication[8]. Usually, the conversion loss of sub-harmonic mixer is higher than that of regular mixer. The basic circuit has a $\lambda_{gRF}/2(=\lambda_{gLO}/4)$ short-circuited stub on the LO side for the nonlinear device as shown in Fig. 3. Therefore, nonlinear device is terminated with a short circuit at the RF frequency, while the LO signal is not affected. In this sub-harmonic mixer, anti-parallel Schottky barrier diodes, MESFETs, HEMTs as a nonlinear device could be used. The use of a shorted stub also provides a dc/IF return path to ground, and allows for straightforward dc testing of the mounted diodes[9]. Similarly, a $\lambda_{gLO}/4(=\lambda_{gRF}/2)$ open-circuited stub is located on the RF side of the nonlinear device such that the diodes are terminated with an open-circuit at the LO frequency while the RF signal is not

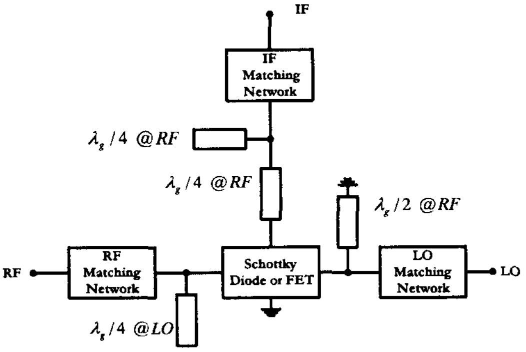


Fig. 3. Schematic of the sub-harmonic mixer.

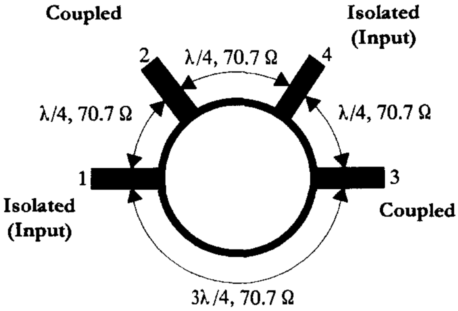


Fig. 4. Rat-race hybrid coupler.

affected.

When the second LO harmonic is used for the mixer, the only isolation of importance is the second LO to RF isolation, which falls within the RF band [10].

The IF signal of the sub-harmonic mixer can be represented by

$$f_{RF} = f_{IF} \pm nf_{LO} \tag{6}$$

where n is an integer.

In this paper, the second LO harmonic for the mixer is used to generate the IF signal. The resultant IF frequency can be represented by Eq. (7). When the two very closed RF signals, but different frequencies, are driven to the RF port, IMD3 is generated. When input signals are f_{RF1} and f_{RF2}, IMD3 is given by Eq. (8)[11].

$$f_{RF} = f_{IF} + 2f_{LO} \tag{7}$$

$$f_{IMD3} = \mp 2f_{RF2} \pm f_{RF1} - 2f_{LO} \tag{8}$$

2-3 Rat-Race for 180° Hybrid

The microstrip ring resonator has been widely used as a circuit for the measurement of dispersion, phase velocity, and dielectric constant in microstrip lines. Its simple structure has an advantage in the applications such as filters, duplexers, and coupler. Fig. 4 shows the physical configuration of the microstrip rat-race hybrid ring coupler. To analyze the hybrid-ring coupler, an even and odd mode impedance analysis is used. When a unit amplitude wave is incident at port 4 of the hybrid-ring coupler, this wave is divided into two components at the ring junction. The two component waves arrive in phase at port 2 and 3, and 180° out of phase at port 1. In this paper, the rat-race hybrid coupler is designed for the optimum isolation performance between the LO harmonics.

2-4 Low Pass Filter Using Photonic Band Gap

Recently, there has been active research worldwide on photonic band gap(PBG) structures for optical, microwave, and millimeter-wave applications. Photonic band gap materials are periodic structures capable of prohibiting the propagation of all electromagnetic wave within a certain band of frequencies[12],[13]. The PBG structure can make certain stop band for the wave propagation along certain directions over a certain range of frequency [14]. There are several types of PBG structures, such as holes or slots etched in ground plane, periodic structure etched in ground plane[15], and slots etched on the transmission line. In this paper, the simplest PBG which has some etched slots in ground plane is used for the suppression of higher order responses of LPF(low pass filter).

The microstrip LPF of the front side is shown in the Fig. 5. The impedance for the microstrip width of LPF is 50 Ω and the impedance for the narrow transmission line is 80 Ω. This LPF is implemented on the Teflon substrate of CHUKOH, with dielectric constant (ε_r) of 2.6, total height of 0.54 mm, and the conductor thickness of 0.018 mm.

Fig. 6 shows the back-side of the LPF. In this structure, the modeled lumped elements are made as etched several slots for the EM simulation with Ansoft HFSS v.6. Fig. 7 shows the layout of the LPF using PBG. Slots in back-side are located properly by the result of circuit simulation. Figs. 8 and 9 show the results of EM simulation and measurements, respectively. From the figures, it is observed that signals above 5 GHz are effectively suppressed.

The measurement characteristic has good agreement with the circuit and EM simulation results. Therefore, the modeling with lumped elements for PBG can be considered to be accurate. The LPF with PBG has broad and good suppression range at the stop band frequency compared with the LPF without PBG[16].

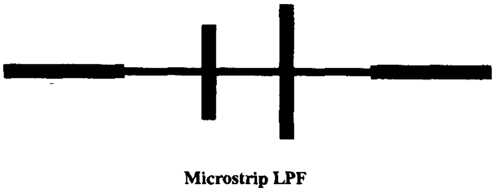


Fig. 5. Front side of the LPF.

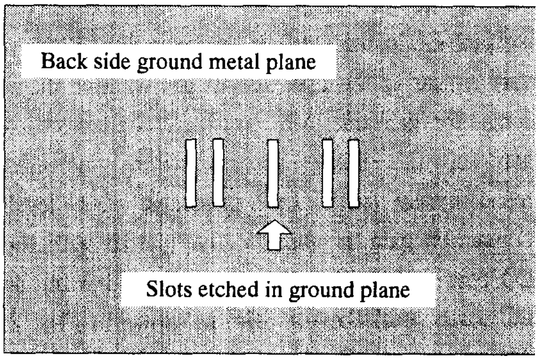


Fig. 6. Back side of the LPF with PBG.

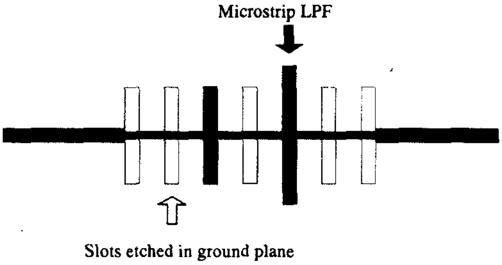


Fig. 7. Layout of the LPF using PBG structure.

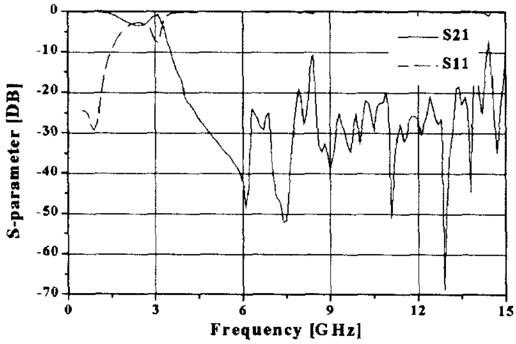


Fig. 8. The result of EM simulation with HFSS v.6.0.

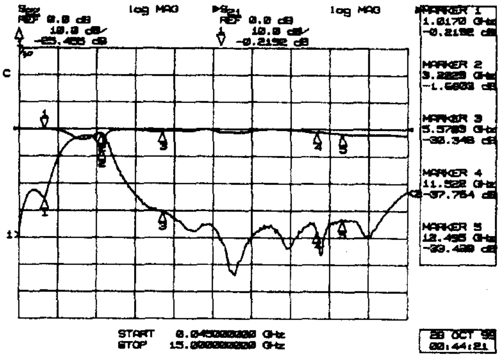


Fig. 9. The result of measurement for the LPF with PBG.

The LPF using PBG can be adopted for the applications such as mixer, oscillator and amplifier to suppress unwanted harmonics for the broad range[17,18].

Fig. 10 shows photographs for the LPF using PBG implemented on the Teflon by direct print

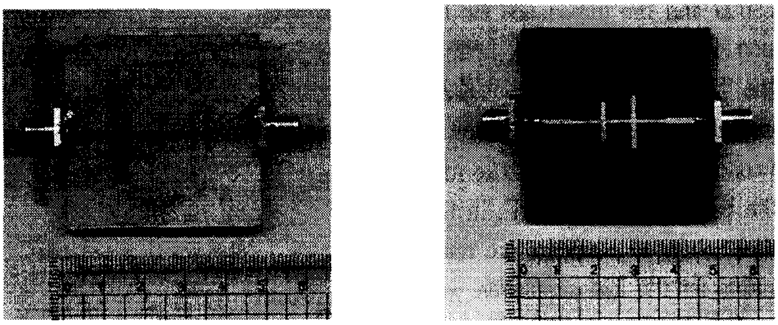

(a) (b)

Fig. 10. Photographs for the LPF with PBG. (a) Front side for the PBG, (b) Back side with PBG slots.

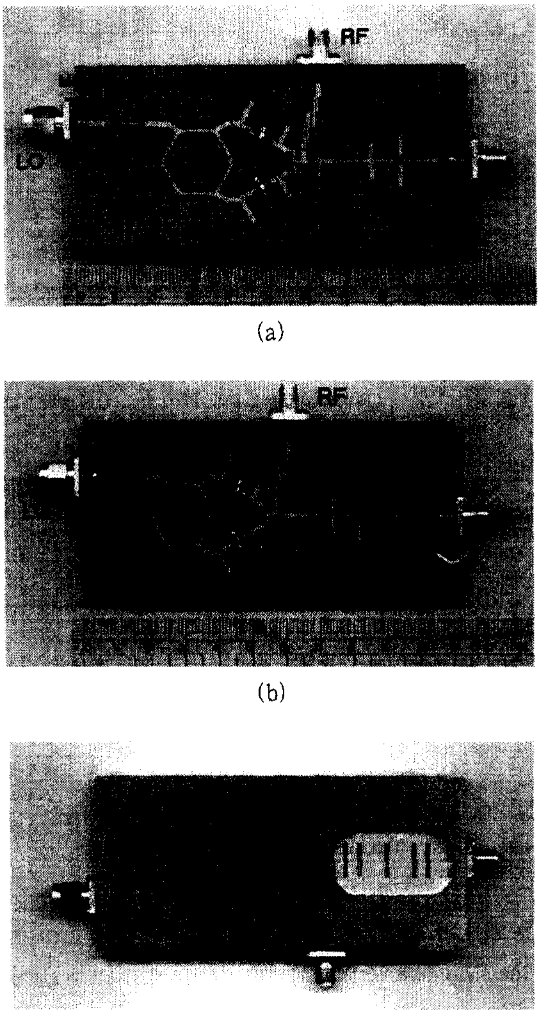
method. Fig. 10 (a) is the front side of the PBG and Fig. 10 (b) is the back-side including PBG slots.

Ⅲ. EXPERIMENTAL RESULTS

Two sub-harmonically pumped mixers are implemented by direct print method on the Teflon substrate of CHUKOH, with dielectric constant (ε_r) of 2.6, total height of 0.54 mm, and conductor thickness of 0.018 mm. For the experiment, an HP 8510C network analyzer, an HP 8563E spectrum analyzer, a Wiltron 6147B-40 programmable sweep generator, and an HP 83623B sweep signal generator are used. First, the conversion loss of the mixer with no IF amplifier is measured. The conversion loss is defined as the loss of the RF signal power when it is converted to the IF frequency. It includes all losses such as frequency conversion loss, channel resistance loss, mismatch loss, coupler's directivity loss, filter's loss, dielectric loss, transmission line loss, and radiation loss. Fig. 11 shows the photographs for the Ku-Band mixers without and with IF amplifiers, and back-side of the mixer. Two FHX35LG low noise HEMT by Fujitsu are used for the nonlinear active devices. This HEMT has gate length of 0.25 μm and gate width of 280 μm. The HP ADS v.1.1 is used for the simulation. Gate port is matched for the LO frequency range using the open stub and drain port is matched for both RF and IF band. To improve the LO to RF isolation, coupled-line band pass filter with 2-pole is inserted. The size of the mixers are about 5 cm × 10 cm.

The sub-harmonically pumped mixer which is combined with the IF amplifier is tested and then is compared with the results for the mixer without IF amplifier. A HP MSA-3186 silicon bipolar RFIC amplifier is used for the IF amplifier. At the IF frequency of 1 GHz, it has amplifying gain of 19.6 dB and the current level of 29 mA for the optimum device operation.

When the incident RF power is set to −20 dBm at 12 GHz and the LO power is 6 dBm at 5.5 GHz, the conversion gain is obtained to be 7.83 dB. Each of LO to IF isolations are 65 dB and 59 dB for the first and second LO harmonics, respectively. The plot of the conversion loss as a function of the incident LO power level is shown in Fig. 12. It is very similar to the first case mixer, while it shows conversion gain due to IF amplifier. The conversion gain of the mixer appears to be increased monotonically with the increasing LO level. Conversion gain increases to the 7.83 dB with the LO power of 8 dBm and it is saturated with the LO power level above 8 dBm as shown in Fig. 12. The conversion gain as a function of RF frequency is shown in Fig. 13. The conversion gain is found



(a)

(b)

(c)

Fig. 11. Photographs for the mixers. (a) Ku band sub-harmonically pumped resistive mixer without an IF amplifier, (b) Ku band sub-harmonically pumped resistive mixer with an IF amplifier, (c) The back side of the fabricated mixer.

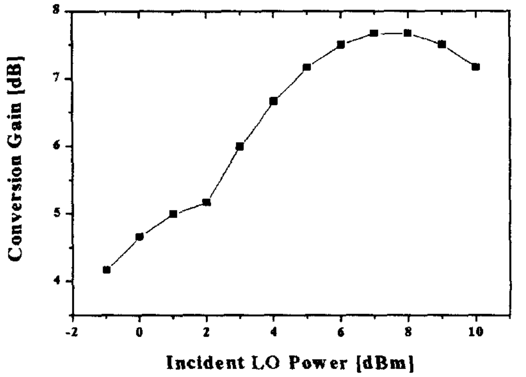


Fig. 12. Conversion gain as a function of LO power for RF signal at 12 GHz.

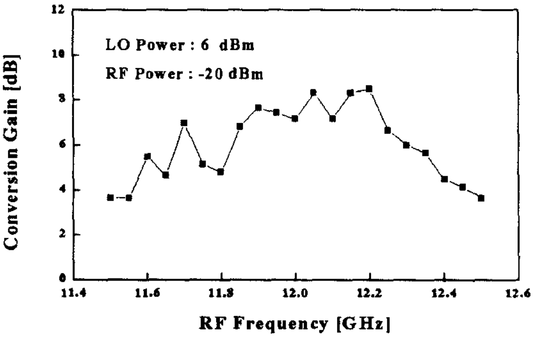


Fig. 13. Conversion gain as a function of RF frequency (P_{LO} = 6 dBm@5.5 GHz).

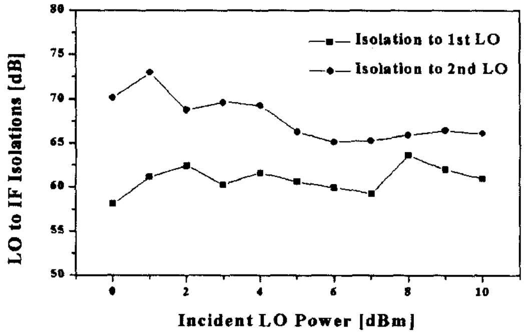


Fig. 14. LO to IF isolations for the first and second LO signal as a function of LO power (P_{RF} = −20 dBm@12 GHz).

to be rather flat as ±0.835 dB within the RF frequency range of 400 MHz centered at 12 GHz except for data at 11.8 GHz, while ±1.835 dB within whole bandwidth of 400 MHz, and about ± 2.5 dB in the 1 GHz full range. Isolation characteristics between the first LO and IF, and the second LO and IF are shown in Fig 14. From the figure, both isolation characteristics are observed to be over 58.17 dB and 66 dB, respectively. These improved characteristics are believed to be due to the

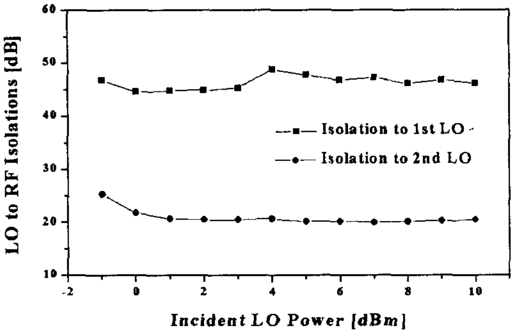


Fig. 15. LO to RF isolations for the first and second LO signal as a function of LO power (P_{RF} = −20 dBm@12 GHz).

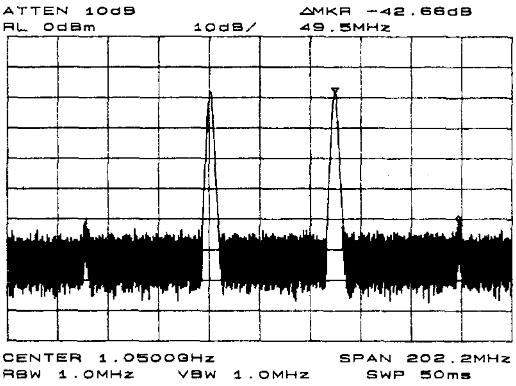


Fig. 16. The output spectra for two RF signals.

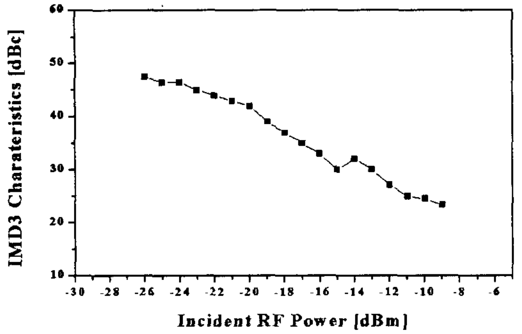


Fig. 17. IMD3 characteristics for two RF signals.

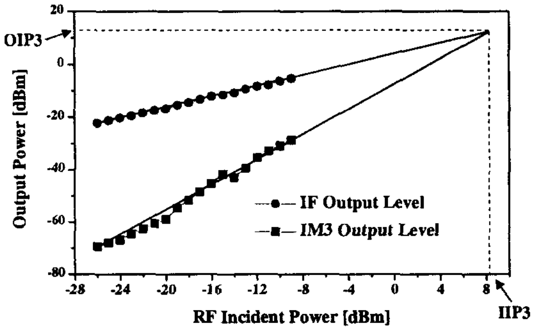


Fig. 18. RF incident power vs. output power.

return loss characteristic of IF amplifier. Fig. 15 shows the LO to RF isolations for the both first LO and second LO as a function of LO power at 5.5 GHz. It is observed to be over 20 dB and 45 dB, respectively for the both LO harmonics.

The IMD3(Third Order Intermoulation Distortion) spectra are shown in Fig. 16. RF frequencies are found to be 12.05 GHz and 12.0 GHz for RF1 and RF2, respectively. From the figure, the IMD3 frequencies are observed to be 1.1 GHz and 0.95 GHz. Input RF powers for both signals are −20 dBm and the incident LO power is 6 dBm at 5.5 GHz. The IM level is −60 dBm, and thus the difference with the IF signal is −42.66 dBc. Fig. 17 shows the IMD3 characteristics as a function of RF power level. As the RF signal power level is decreased, the IM characteristics become better. It shows −42 dBc at the RF power of −20 dBm. When incident RF power comes down below this level, the IM3 level can not be observed, because the IM3 level is within the noise level.

Fig. 18 shows output power level [dBm] as a function of RF incident power [dBm]. From the figure, the IF power and IM3 are increased with increasing RF power, and IIP3(input 3^{rd} order intercept point) and OIP3(output 3^{rd} order intercept point) can be found to be 8.3 dB and 12.3 dB, respectively.

The sub-harmonic resistive mixer without IF amplifier has been characterized in the similar way. Table 1 summarizes the data for the conversion loss and isolation characteristics for the two mixers.

Table 1. Conversion gain and isolation characteristics for two mixers.

	The mixer without an IF amp.	The mixer with an IF amp.
Conversion gain @ P_{LO} = 6 dBm, f_{RF} = 12 GHz	-12.83	+7.83
1st LO to RF isolation [dB]	20	20
2nd LO to RF isolation [dB]	35	45
1st LO to IF isolation [dB]	61	65
2nd LO to RF isolation [dB]	60	56

Ⅳ. CONCLUSIONS

In this paper, new single balanced types of sub-harmonic mixers with an 180° rat-race hybrid, where the AM noise due to the LO signal can be minimized and the spurious signals can be removed, have been suggested and fabricated. Resistive mixer is selected to be basic mixing structure for improving the IMD characteristics. Also, a LPF using PBG is adopted for the suppression of unwanted harmonics.

For the case of the mixer with the IF amplifier, isolation and conversion gain characteristics are improved considerably compared with the results for the mixer without the IF amplifier. The conversion gain of 7.83 dB with the LO power of 6 dBm and the RF power of −20 dBm is obtained. LO to IF isolation characteristic with the same LO power is observed to be over 60 dB and 65 dB for the cases of the first LO to RF and the second LO harmonic to RF, respectively. The first LO to RF and the second LO harmonic to RF isolations are greater than 20 dB and 45 dB, respectively.

IMD3 characteristic shows as −42.66 dBc, and IIP3 and OIP3 are observed to be about 8.3 dB and 12.3 dB, respectively. It is expected to be improved in IMD3 characteristic if the gate bias is applied while there is more dc power consumption and the conversion loss is increased.

These new sub-harmonically pumped resistive mixers with the LPF using PBG are applicable to the Ku-band communication systems.

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