High Conversion Gain Q-band Active Sub-harmonic Mixer Using GaAs PHEMT

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Abstract— **In this paper, we have designed and fabricated high conversion gain Q-band active sub-harmonic mixers for a receiver of millimeter wave wireless communication systems. The fabricated active sub-harmonic mixer uses 2nd harmonic signals of a low local oscillator (LO) frequency. The fabricated mixer was successfully integrated by using 0.1 μm GaAs pseudomorphic high electron mobility transistors (PHEMTs) and coplanar waveguide (CPW) structures. From the measurement, it shows that maximum conversion gain of 4.8 dB has obtained at a RF frequency of 40 GHz for 10 dBm LO power of 17.5 GHz. Conversion gain from the fabricated sub-harmonic mixer is one of the best reported thus far. And a phase noise of the 2nd harmonic was obtained -90.23 dBc/Hz at 100 kHz offset. The active sub-harmonic mixer also ensure a high degree of isolations, which are -35.8 dB from LO-to-IF and -40.5 dB from LO-to-RF, respectively, at a LO frequency of 17.5 GHz.**

Index Terms— **Sub-harmonic Mixer, MIMIC, CPW, PHEMT, Q-band**

I. INTRODUCTION

Because of limited bandwidth and data capacity of microwaves in daily use, millimeter wave frequency has been an attractive solution providing several advantages in various future system applications. For this reason, many researchers have made great efforts on highly integrated millimeter wave monolithic integrated circuits (MIMIC's) for wireless millimeter wave transceivers [1]. However, there have been problems in obtaining the stable frequency sources for up/down mixers. The fundamental frequency mixers are not suitable for generating LO signals at specially millimeter waves because it is very difficult to achieve the reliable oscillators operating at such a high frequency and therefore they are expensive currently. Sub-harmonic mixers offer an alternative to the fundamental mixers where n-th harmonics of the LO frequency are utilized for conversion. This approach allows the use of the local oscillators operating at a relatively low frequency at which the output power and phase noise performances are superior to the fundamental frequency mixers [2, 3]. However most of sub-harmonic mixers are difficult to obtain conversion gain (G_c). Thus it is essential to adopt additional amplifier stages.

We herein propose the active sub-harmonic mixer to obtain high conversion gain characteristics. We employ a half of fundamental frequency for the LO signal. Libraries for 0.1 μm Γ-gate GaAs PHEMTs and CPW transmission lines have been developed for the design and fabrication of such a sub-harmonic mixer. And then the fabricated sub-harmonic mixers is measured and carefully analyzed with measurement systems.

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II. DEVICE FABRICATION AND COPLANAR WAVE GUIDE LIBRARY

A double delta-doped heterojunction epitaxial structure with the psedumorphic $In_{0.2}Ga_{0.8}As$ channel was used to achieve high performance PHEMTs for the mixers. Cross-sectional schematic of the epitaxial structure is shown in Fig. 1, Atop the 5000 Å undoped GaAs buffer and 2000 Å of super lattice, bottom delta doping ($1{\times}10^{12}$ cm^{-2}), 60 Å undoped spacer, 120 Å undoped $In_{0.2}Ga_{0.8}As$ channel, 40 Å undoped $Al_{0.25}Ga_{0.75}$ As spacer layer, delta doping plane ($5{\times}10^{12}$ cm^{-2}), 250 Å undoped $Al_{0.25}Ga_{0.75}As$ Schottky barrier layer and 300 Å n-type doped GaAs cap (5×10^{18} cm^{-3}) were grown sequentially [4].

With the unit processes for PHEMTs, AuGe/Ni/Au metal systems were used for the drain/source to get lower ohmic contact resistance. Prior to ohmic contact formations, mesa etching process was carried out to isolate the active regions. And then a 0.1 μm Γ-shaped gate, as shown in Fig. 2, was patterned by the triple-layer resist at the 50 keV electron-beam lithography system. After the gate fabrication, the Si_3N_4 passivation to protect the device was made, and air-bridge metals of Ti/Au were then formed to interconnect the isolated electrodes.

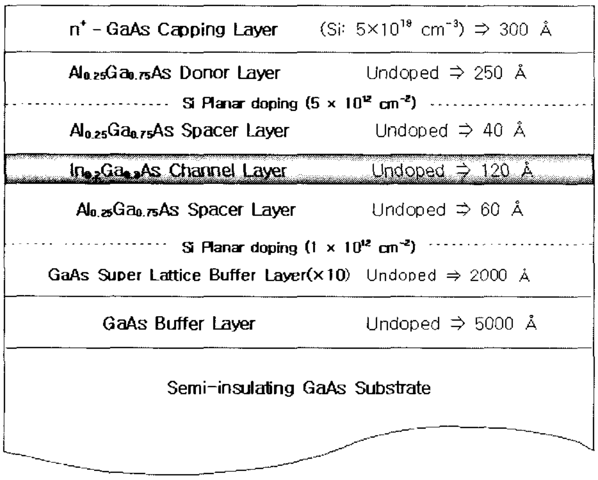


Fig. 1. Epi-structure of the fabricated GaAs PHEMT.

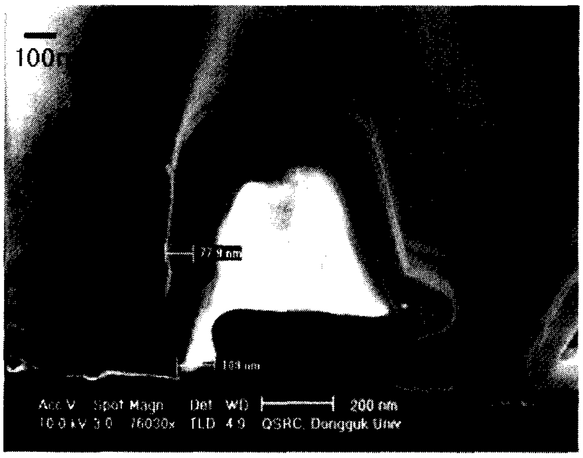


Fig. 2. A SEM photograph of the fabricated 0.1 μm Γ-shaped gate.

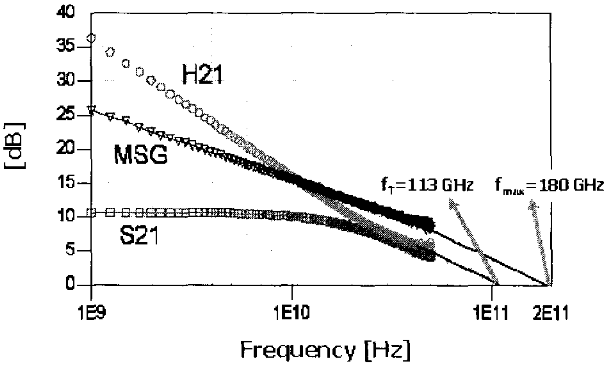


Fig. 3. RF characteristics of the fabricated PHEMT.

The fabricated 0.1 μm PHEMTs have a knee voltage(V_k) of 0.6 V, a pinch-off voltage(V_p) of -1.5 V, a drain-source saturation current(I_{dss}) of 53.8 mA, a maximum drain current density ($I_{d,max}$) of 384.5 mA/mm and a maximum extrinsic transconductance (g_m) of 367.9 mS/mm, a maximum frequency of oscillation (f_{max}) of 180 GHz and a f_T of 113 GHz. The measured RF characteristics of the PHEMTs are shown in Fig. 3.

The sub-harmonic mixers in this work employ the coplanar waveguide (CPW) transmission structures. For the circuit design, we established a library for the CPW transmission lines of various characteristic impedances (35, 50, and 70 Ω) including the discontinuity patterns. The library also includes 800 Å Ti thin film resistors and metal-insulator-metal (MIM) capacitors of 900 Å Si_3N_4 which were used for DC block or bypass of RF inputs and outputs. 29.6~36.5 ohm/□ and 0.485~0.538 fF/μ m^2 were measured from the thin film resistors and the MIM capacitors, respectively [5].

III. CIRCUIT DESIGN

We have designed active sub-harmonic mixers and a

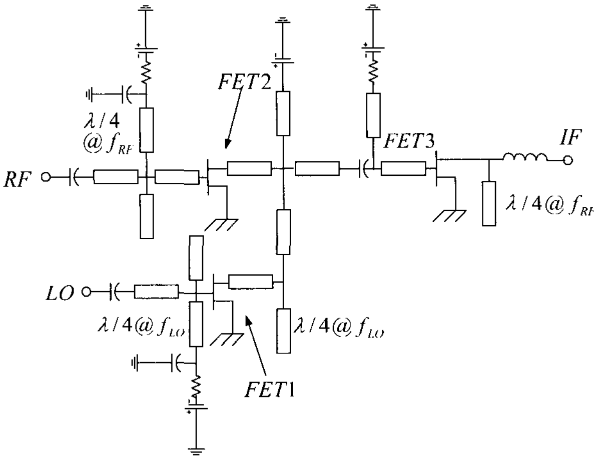


Fig. 4. Designed circuit of the active sub-harmonic mixer.

schematic diagram of the mixer is shown in Fig. 4. The fundamental circuit structures use a gate mixer configuration in order to obtain the high conversion gain and the high isolation [6]. A bias condition at V_{gs}=-1.3 V, V_{ds} = 1.5 V of FET1 is pinched off voltage. In this bias condition, the harmonic components of LO signals are easily generated by the non-linear characteristics of active components [7,8].

A $\lambda/4$ short stub for LO input port is designed to give high impedance to the input node and pass the f_{LO} signal as well as to drive a PHEMTs at LO port as a gate bias line. On the other hand, the $\lambda/4$ open stub of f_{LO} pass $2f_{LO}$ signal by suppression of f_{LO} signal. Therefore $2f_{LO}$ signal is only a major harmonic component at the output port. IF signal is generated from mixed f_{RF} and $2f_{LO}$ signals through a FET3. RF, LO and IF of the active sub-harmonic mixer are 40, 17.5 and 5 GHz, respectively. Matching circuits of both RF and LO stages are composed of CPW transmission lines, and IF output matching networks are composite of a $\lambda/4$ open stub of f_{RF} and a inductor, a $\lambda/4$ open stub of f_{RF} is operated by means of suppressing f_{RF} signal component and it is composite isolation matching circuit with a inductor component through low-pass filter circuit configuration.

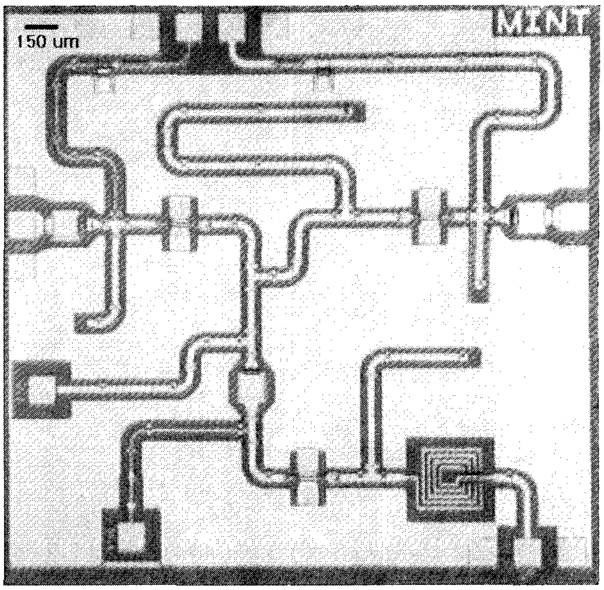


Fig. 5. Top view photograph of the fabricated active sub-harmonic mixer.

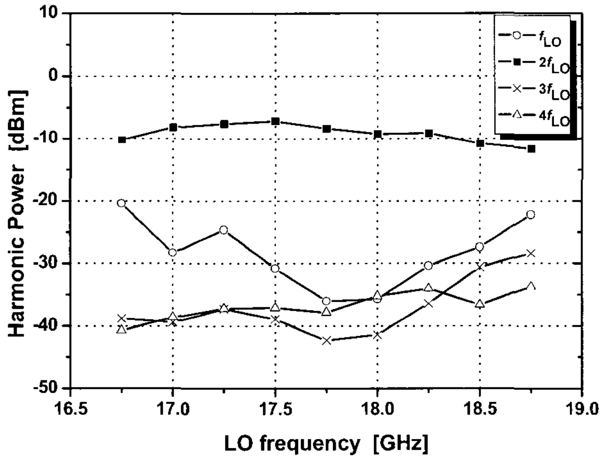
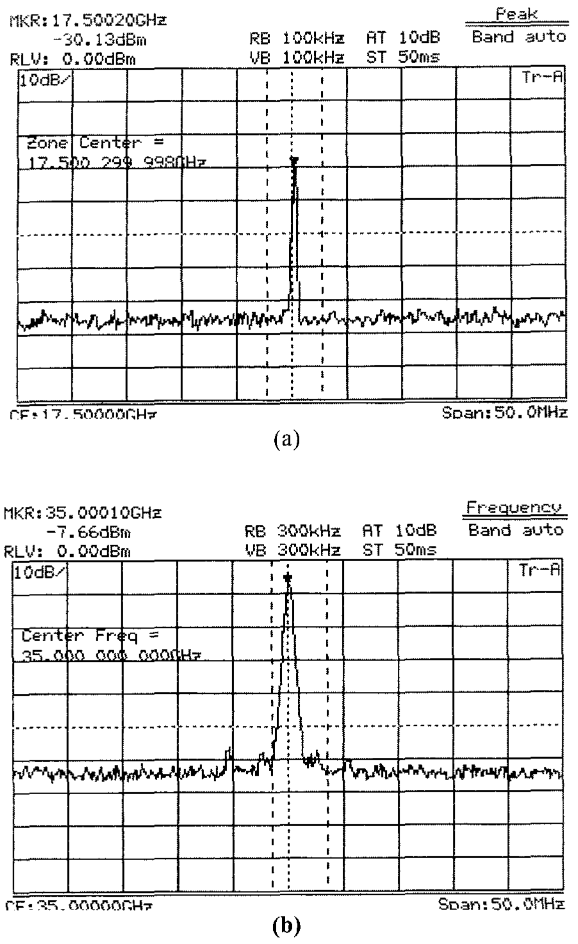


Fig. 6. Harmonic powers of LO signal.

IV. MIXER IMPLEMENTATION AND MEASUREMENT RESULTS

The active sub-harmonic mixers were fabricated by using the MIMIC standard processes established in our lab [4-6]. The integration processes include the fabrications of GaAs PEHMTs, CPW transmission lines, Ti resistors and metal-insulator-metal (MIM) capacitors. Fig. 5 is a top view photograph of the fabricated active sub-harmonic mixer. The total chip size is 1.9 mm × 2 mm.

The fabricated MIMIC mixer was measured using an on-wafer probing system. As shown in Fig. 6, output harmonics of LO signal after the $\lambda/4$ open stub of f_{LO} were achieved from the mixer. Especially fundamental, 2nd, 3rd and 4th harmonics components at 17.5 GHz are -30.13 dBm, -7.66 dBm, -38.9 and -37.1 dBm, respectively. Fig. 7 depicts output spectrum of fundamental and 2nd harmonic components. And phase noise



(a)

(b)

Fig. 7. Output harmonic spectrums of LO signal: (a) fLO and (b) 2nd harmonic (2fLO).

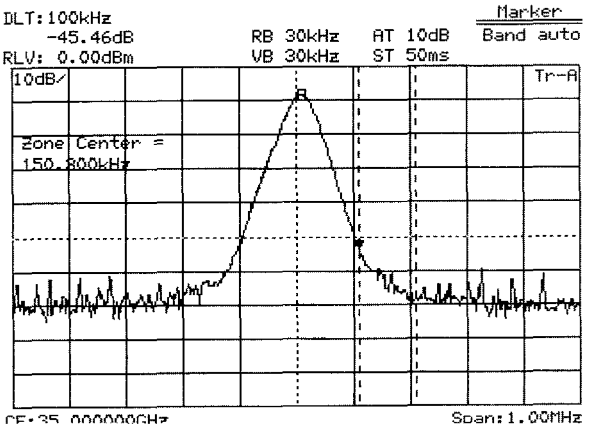


Fig. 8. Phase noise of 2nd harmonic output (35 GHz), (Offset frequency: 100 kHz, Resolution bandwidth: 30 kHz).

of 2nd harmonic (35GHz) was measured as illustrated in Fig. 8, and was -90.23 dBc/Hz at 100 kHz offset.

The measurement results of down conversion gain versus RF input power at various LO input power and an operation RF frequency of 40 GHz are shown in Figure 9. A very high conversion gain was achieved at a RF input power of -22 dBm and a LO input power of 10 dBm. When the conversion gain is measured at fixed LO and RF input powers of 10 and -22 dBm, respectively, with varying the input RF frequency, conversion gains of 4.8 ~ 0.3 dB were obtained in a frequency range of 37.5 ~ 44 GHz as shown in Fig. 10.

We also measured the down conversion gain at various LO powers and at a LO frequency of 17.5 GHz. The measurement results are shown in Fig. 11. The conversion gain is nearly saturated at a LO input power level higher than 10 dBm.

In Fig.12, the LO and 2LO to RF and the LO and 2LO to IF isolations are displayed. As shown in the spectra, the measurement results exhibited a high

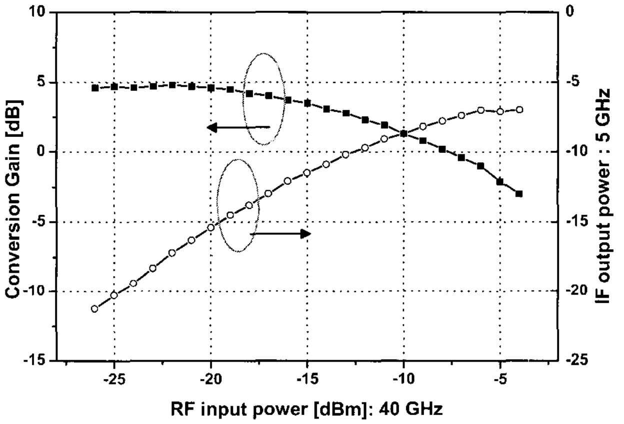


Fig. 9. Conversion gain and IF output vs. RF input (LO frequency: 17.5 GHz, LO power: 10 dBm).

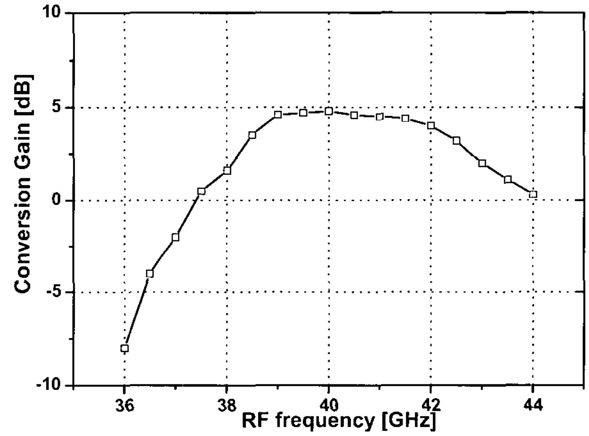


Fig. 10. Conversion gain vs. RF frequency (LO power: 10 dBm, RF power: -22 dBm).

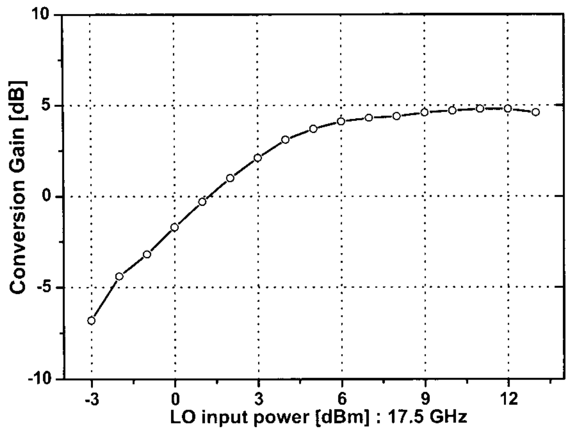


Fig. 11. Conversion gain vs. LO input power (RF frequency: 40 GHz, RF power: -22 dBm).

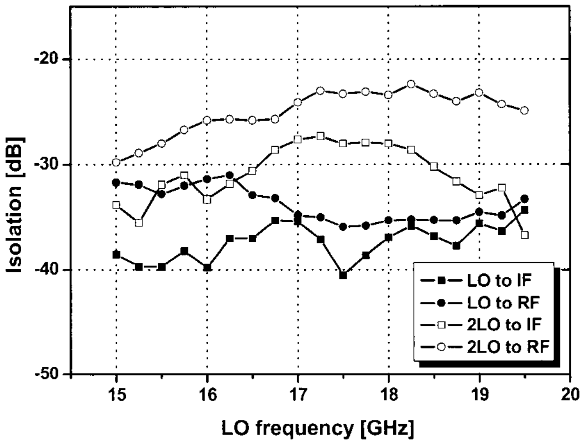


Fig. 12. Measured results of isolation characteristics.

Table 1. Comparison of Gc of the active sub-harmonic mixer with that of other mixers.

Mixer Topology	LO mixing harmonic	Maximum Conversion Gain (dB)	Reference
Gate injection HEMT	Fundamental	4.2	[9]
Gate injection HEMT	Fundamental	1.5	[10]
Gate injection HEMT	2nd harmonic	1.1	[9]
Harmonic resistive HEMT mixer	2nd harmonic	-2.5	[11]
Anti-parallel diode pair	2nd harmonic	-11.5	[12]
Anti-parallel diode pair	2nd harmonic	-15	[13]
Active sub-harmonic mixer	2nd harmonic	4.8	This Work

degree of isolation characteristic. In the cases of the LO-to-IF and the LO-to-RF isolations, the best measurement results were -40.5 and -35.9 dB, respectively, at a LO frequency of 17.5 GHz. These good LO-to-RF isolations are due to great difference of frequency between LO and RF.

In table 1, the fabricated active sub-harmonic mixer has a remarkably high conversion gain characteristics compared with ever reported mixers for Q-band frequency.

V. CONCLUSION

High conversion gain Q-band active sub-harmonic MIMIC mixer circuit is proposed and demonstrated in this work for the millimeter wave down converter applications. The fabricated active sub-harmonic mixer uses 2nd harmonic signal of a low local oscillator (LO) frequency. The fabricated mixer was successfully integrated by using 0.1 µm GaAs PHEMTs and CPW structures. From the measurement, maximum conversion gain of 4.8 dB has obtained at a RF frequency of 40GHz. Conversion gain from the fabricated sub-harmonic mixer is one of the best reported thus far.

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REFERENCES

[1] Tae-Shin Kang and Jin-Koo Rhee, "Design of Broad Band Amplifier Using Feedback Technique," *J. Semiconductor Technology and Science,* vol. 3, no. 1, pp 42-46, 2003.

[2] M. Cohn, J. E. Degenford, and B. A. Newman, "Harmonic Mixing with an antiparallel diode pair," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-23, no. 8, pp. 667-673, 1975.

[3] K. Itoh, Y. Sasaki, A. Iida, and S. Urasaki, "A 40GHz band monolithic even harmonic mixer with an antiparallel diode pair," *1991 IEEE MTT-S Int, Microwave Symp, Digest*, pp. 879-883, 1991.

[4] S. C. Kim, B. O. Lim, H. S. Kim, S. D. Lee, B. H. Lee, W. S. Sul, D. H. Shin, and J. K. Rhee, "Sub 0.1 ㎛ asymmetric Γ-gate PHEMT process using electron beam lithography," *in proceedings of 28th International Symposium Compound Semiconductors*, pp. 95-100, 2001

[5] Tae-Sin Kang, Seong-Dae Lee, Bok-Hyoung Lee, Sam-Dong Kim, Hyun-Chang Park, Hyung-Moo Park, and Jin-Koo Rhee, "Design and Fabrication of a Low-Noise Amplifier for the V-band," *J. Korean Phys. Soc.*, vol. 41, no. 4, pp. 533-538, 2002.

[6] D. An, B. H. Lee, Y. S. Chae, H. M. Park, H. C. Park, and J. K. Rhee, " Low LO Power V-band CPW Mixer Using GaAs PHEMT." *32^{nd} European Microwave Conference 2002*, vol. 2, pp. 773-776, 2002.

[7] C. Rauscher, "High-Frequency Doubler Operation of GaAs Field- Effect Transistors," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-31, no. 6, pp. 462-472, 1983.

[8] M Schefer, "Intergrated Quardrupler Circuit in Coplanar Tchnology for 60 GHz Wireless Applications." *Microwave Symposium* Fabrication of a Low-Noise Amplifier for the V-band," *J. Korean Phys. Soc.*, vol. 41, no. 4, pp. 533-538, 2002.

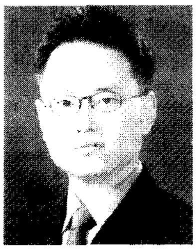
[9] M. Kim, B. Hacker, E. A. Sovero, D. S. Deakin and J.H. Hong, "A Millimeter-Wave Multifunction HEMT Mixer," *IEEE Microwave and Guided Wave Letters*, vol. 9, no. 4, pp. 154-156, 1999.

[10] Stephen A. Maas, "Design and Performance of a 45 GHz HEMT Mixer," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-34, no. 7, pp. 799-803, 1986.

[11] S. Nam, T. Gokdemir, A. H. Baree, I. D. Robertson, A. D. Plews, M. J. Howes, C. M. Snowden, J. G. Leckey, A. D. Patterson and J. A. C. Stewart, "Fully Integrated Q-band MMIC Transmitter and Receiver Chips using Resistive PHEMT mixers," *IEEE Radio Frequency Integrated Circuits Symposium*, pp. 279-282, 1998.

[12] H. I. Fujishiro, Y. Ogawa, T. Hamada, T. Kimura, "SSB MMIC mixer with subharmonic LO and CPW circuits for 38GHz band applications," *Electronics Letters*, vol. 37, no. 7, pp. 435-436, 2001.

[13] Y. L. Kok, M. Ahmadi, H. wang, B. R. Allen and T. Line, "A Ka-band Monolithic Single-chip Transceiver Using Sub-harmonic Mixer," *1998 IEEE MTT-s Digest*, pp. 309-311, 1998.



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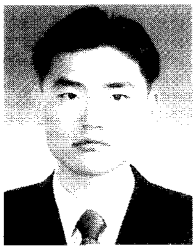

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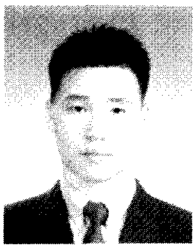

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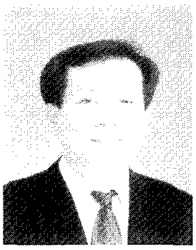

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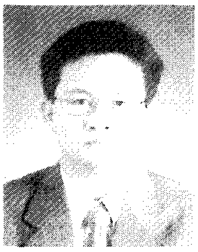

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