A 77 GHz mHEMT MMIC Chip Set for Automotive Radar Systems

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A monolithic microwave integrated circuit (MMIC) chip set consisting of a power amplifier, a driver amplifier, and a frequency doubler has been developed for automotive radar systems at 77 GHz. The chip set was fabricated using a 0.15 μm gate-length InGaAs/InAlAs/GaAs metamorphic high electron mobility transistor (mHEMT) process based on a 4-inch substrate. The power amplifier demonstrated a measured small signal gain of over 20 dB from 76 to 77 GHz with 15.5 dBm output power. The chip size is 2 mm × 2 mm. The driver amplifier exhibited a gain of 23 dB over a 76 to 77 GHz band with an output power of 13 dBm. The chip size is 2.1 mm × 2 mm. The frequency doubler achieved an output power of –6 dBm at 76.5 GHz with a conversion gain of –16 dB for an input power of 10 dBm and a 38.25 GHz input frequency. The chip size is 1.2 mm × 1.2 mm. This MMIC chip set is suitable for the 77 GHz automotive radar systems and related applications in a W-band.

Keywords: Automotive radar, MMIC, MHEMT, 77 GHz, amplifier, doubler.

I. Introduction

Millimeter-wave automotive radar systems are a key technology for future adaptive cruise control systems. With an increased awareness and interest in safety issues on vehicular transportation, a variety of obstacle detectors has been researched and developed, among which a forward looking automotive radar has received special attention as it is considered to be an essential element to complete a vehicular safety system [1], [2].

In contrast to infrared or laser based sensors, the major advantage of a millimeter-wave radar system is its excellent performance under adverse weather conditions. Thus, demand for low-cost W-band components has continued to increase, leading to a commercial success of automotive radar systems. A promising way to meet the stringent cost requirements of these systems is the use of a monolithic microwave integrated circuit (MMIC) based on metamorphic high electron mobility transistor (mHEMT) technologies. In addition, the use of GaAs-based mHEMT results in higher circuit performance at even lower cost and a further reduction of chip size.

We developed an MMIC chip set with high performance and a compact chip size.

This paper describes the successful development of an MMIC chip set for automotive radar systems by using a 0.15 μm gate-length InGaAs/InAlAs/GaAs mHEMT technology on a GaAs substrate thinned to 100 μm [3]. The chip set consists of a power amplifier, a driver amplifier, and a frequency doubler. Figure 1 shows a generalized block diagram of the RF front-end of an automotive radar system.

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II. mHEMT Device Characteristics

The high electron mobility transistors (HEMTs), especially InP-based InAlAs/InGaAs HEMTs with high cut off frequency and an excellent noise characteristic, are widely used in the front end of satellite communications, radio astronomy, and satellite direct broadcasting receiver systems at microwave and millimeter frequencies [4], [5]. However, it is difficult to use an InP substrate with a diameter of 4 inches or larger, because an InP-based HEMT wafer is more expensive and fragile than a GaAs-based HEMT wafer. The recently proposed HEMT structure to overcome the above limitation is the GaAs-based InAlAs/InGaAs HEMT with a metamorphic buffer layer on a GaAs substrate, mHEMT. Recently, InAlAs/InGaAs mHEMTs have demonstrated their potential for high performance, high power, and low noise applications. It has been demonstrated that the electrical transport properties of the mHEMT structure are largely affected by the mole fraction of the InGaAs channel layer and metamorphic buffer layer. On the other hand, the reproducible devices should be obtained for the application of mHEMT to monolithic microwave integrated circuits (MMICs) with the use of the reliable fine line gate lithography process to satisfy these requirements. In this paper, passivated 0.15 μm mHEMTs were fabricated by combining a wide head T-shaped gate using a dose split method of electron beam lithography and a highly selective recess etch process based on succinic acid.

A double delta-doped mHEMT epitaxial structure on a GaAs substrate has been grown by molecular beam epitaxy (MBE). A cross-section of the mHEMT structure is shown in Fig. 2. A 1 μm thick In graded InAlAs metamorphic buffer layer was grown on a 4-inch diameter semi-insulating GaAs wafer, followed by a 300 nm thick undoped InAlAs buffer layer. We used 18 nm $In_{0.53}Ga_{0.47}As$ as the channel layer. The top and bottom Si-planar doping layers were separated from the active layer by a 3 nm thin undoped $In_{0.52}Al_{0.48}As$ spacer. The undoped $In_{0.52}Al_{0.48}As$ Schottky layer was 20 nm. Then, the 20 nm thick $In_{0.53}Ga_{0.47}As$ cap layer was highly doped with Si of 5×10^{18} cm^{-3} for obtaining parasitic ohmic resistance. Hall measurements of the mHEMT structure yielded an electron sheet density of $n_s = 3.7 \times 10^{12}$ cm^{-2} and a mobility of $\mu_H = 9{,}100$ cm^2/V·s at 300 K.

Figure 3 shows a cross-sectional SEM photograph of a 0.15 μm gate length T-shaped mHEMT with a wide head of about 1.2 μm. The T-shaped gate for a 0.15 μm × 100 μm mHEMT device was sequentially formed using an E-beam lithography process followed by a selective wet etching of InGaAs over InAlAs using a succinic acid and H_2O_2 mixed solution and by a metal lift-off. The selective wet gate recess process using the succinic acid and H_2O_2 mixed solution showed an InGaAs etch rate of 120 nm/min and an etch selectivity of InGaAs to InAlAs layer of higher than 100.

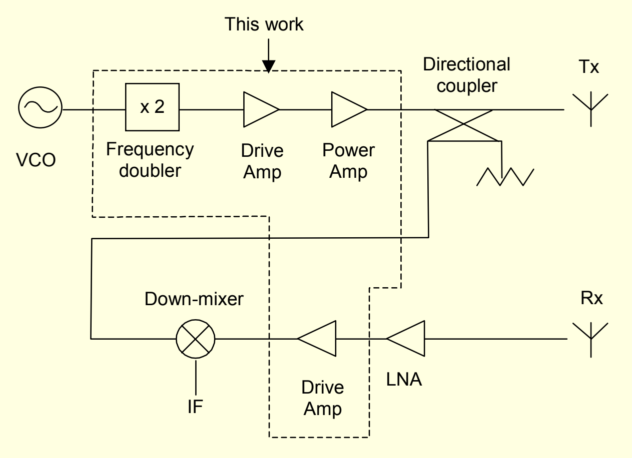


Fig. 1. A generalized block diagram of the RF front-end of an automotive radar system.

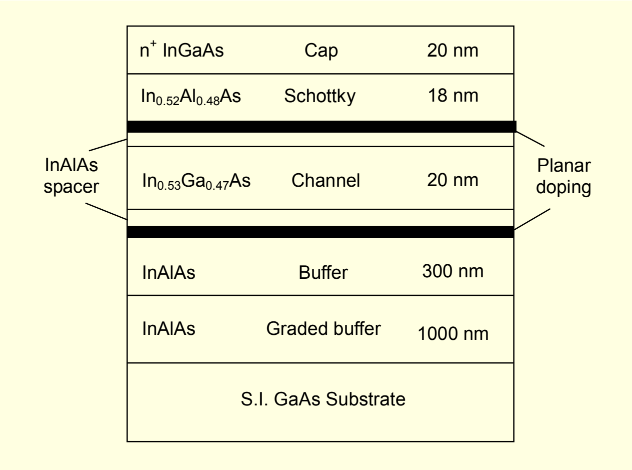


Fig. 2. Cross-section of double-doped mHEMT structure.

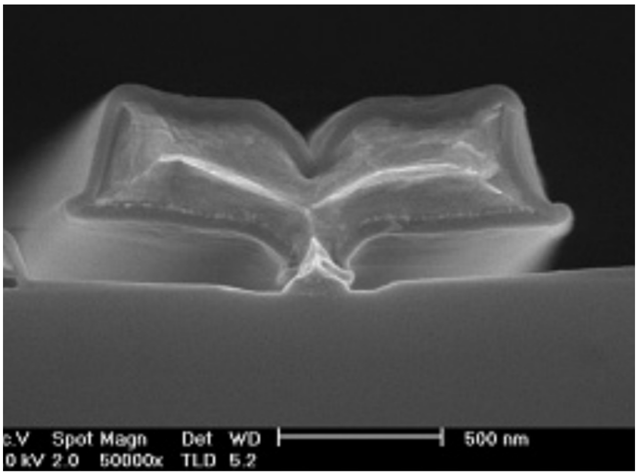


Fig. 3. Cross-sectional SEM of the passivated 0.15 μm gate-length mHEMT with a wide head T-shaped gate.

Figure 4 shows drain-to-source current (I_{ds}) as a function of drain-to-source voltage (V_{ds}) for the 0.15 μm GaAs mHEMT devices. As shown in Fig. 3, the devices exhibit a good pinch-off characteristic at a drain voltage of 2 V. The drain saturation current (I_{dss}) measured at V_{ds} = 2 V and V_{gs} = 0 V is 38 mA. The threshold voltage (V_{th}) is defined by a linear extrapolation of the square root of drain current versus gate voltage to zero current. V_{th} was measured as – 0.9 V.

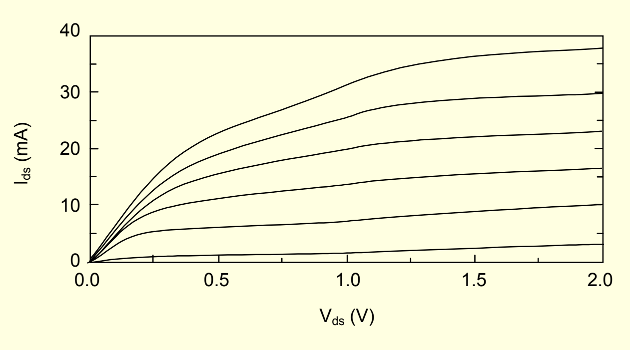


Fig. 4. Drain-to-source current (I_{ds}) as a function of drain-to-source voltage (V_{ds}) for the 0.15 μm gate-length mHEMT device.

The extrinsic transconductance (g_m) and drain-to-source current (I_{ds}) as a function of gate-to-source voltage (V_{gs}) at 2 V of drain voltage were measured and are shown in Fig. 5.

The maximum g_m was measured as 700 mS/mm at V_{gs} = – 0.5 V and V_{ds}=2 V. The typical current gain (|h_{21}|) as a function of frequency for $0.15 \times 100\ \mu m^2$ mHEMT devices is shown in Fig. 6. The cut-off frequency (f_T) was obtained from the extrapolation of the |h_{21}| to unity using a – 6 dB/octave slope, and the maximum frequency of oscillation (f_{max}) was extracted from small signal parameters. The f_T and f_{max} of the devices were 130 and 230 GHz, respectively.

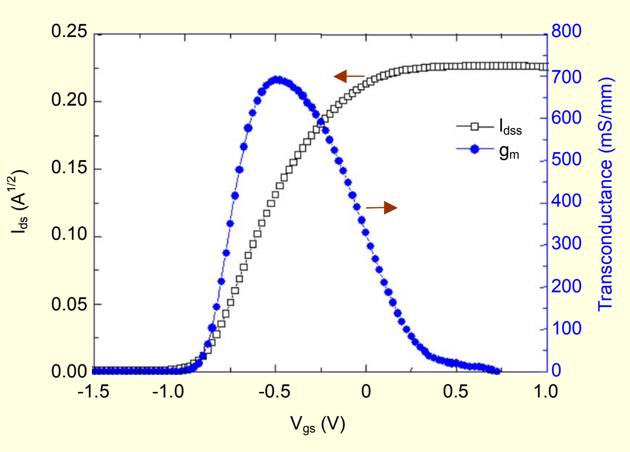


Fig. 5. The extrinsic transconductance and drain-to-source current (I_{ds}) as a function of gate-to-source voltage (V_{gs}).

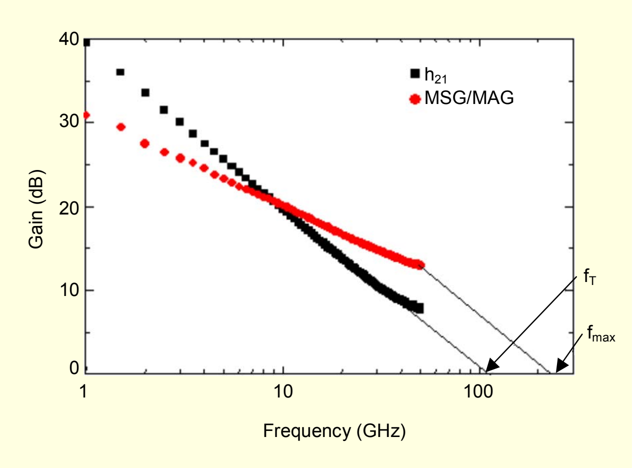
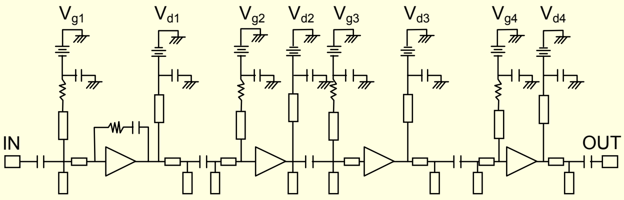


Fig. 6. Typical current gain, |h_{21}|, as a function of frequency for the 0.15 μm gate-length mHEMT device.

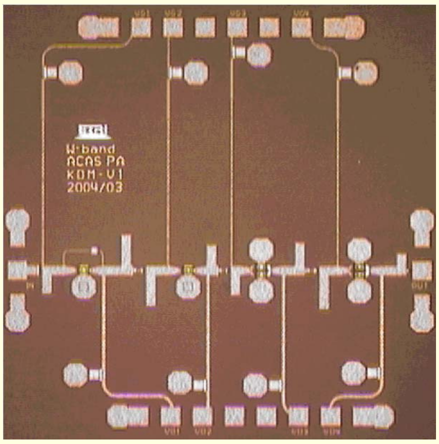
III. Circuit Design and Experimental Results

1. Power Amplifier and Driver Amplifier

A 4-stage MMIC power amplifier (PA) and driver (DA) were designed by using mHEMT devices of 2-finger 100 μm (2f100) and 4-finger 200 μm (4f200). In order to increase the stability of the mHEMT device, negative feedback was employed by a resistor network. In the case of employing parallel feedback, the gain was decreased to some extent. There are some advantages such as a broadband and a remarkably increased stability. In addition, the effect of the feedback is to make the input and output impedance more convenient for matching. The MMIC amplifiers were designed as single-ended 4-stage types. The first two stages used mHEMTs with a 100 μm gate width and operated as class A amplifiers for gain consideration, while the last two stages employed 200 μm devices for power and efficiency requirements and operated at class A. All input/output matching, interstage matching, and biasing networks were included in the MMIC design. In each stage of the MMIC, a microstrip line, an open stub, and a capacitor are connected between the HEMT and an input/output node to achieve both a good return loss and a good rejection characteristic of the undesired frequency bandwidth. All grounded parts of the PA were processed by via-holes. The front- and back-side dimensions of the via-holes were 60 μm and 120 μm, respectively. A microstrip thin film capacitor provided by ETRI library was applied to DC-block circuits for isolation between the stages and the combination of RF signals. The bias networks consisted of high impedance transmission lines, with decoupling capacitors, serving as RF short circuits. Also, the gate bias circuits were designed using a 580 Ω NiCr resistor to obtain low-gain flatness for the operating frequency. The circuit simulation was accomplished by the use of the harmonic balance simulator

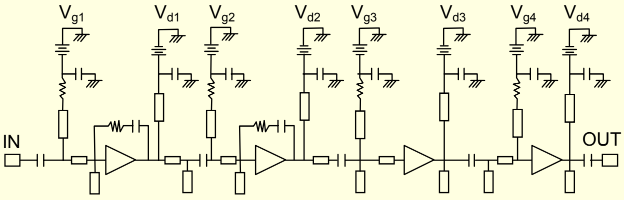


(a) Circuit schematic of the MMIC PA

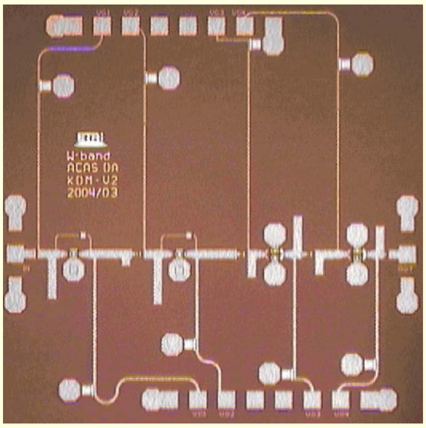


(b) Photograph of the MMIC PA

Fig. 7. The circuit schematic and photograph of the MMIC power amplifier.



(a) Circuit schematic of the MMIC DA



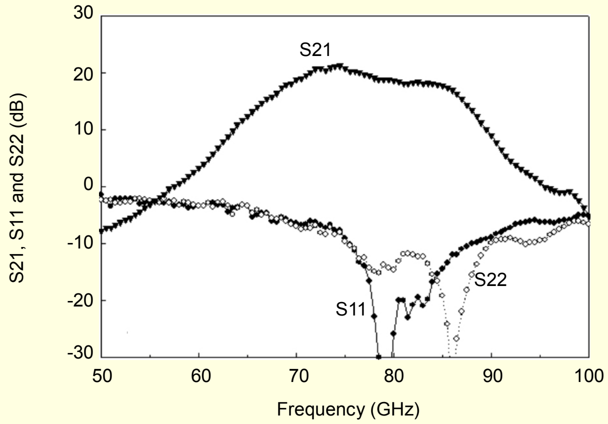
(b) Photograph of the MMIC DA

Fig. 8. The circuit schematic and photograph of the MMIC driver amplifier.

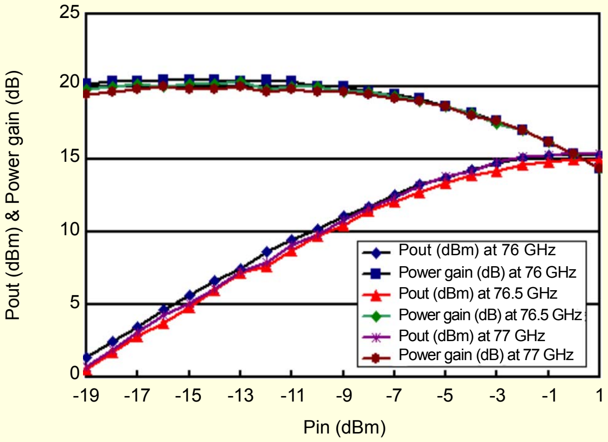
with the HP root model for the active device. The external DC biasing conditions of V_d and V_g were 1.5 V and – 0.3 V, respectively, and the total current consumption of the MMIC PA was 180mA. In the case of the DA, the external DC biasing conditions of V_d and V_g were 1.5 V and – 0.4 V, respectively, and the total current consumption was 150 mA.

The on-wafer measurement was performed using an HP PNA N5250A 110GHz network analyzer. The circuit schematics and photographs of the fabricated MMIC PA and DA are presented in Figs. 7 and 8, respectively.

The PA demonstrated a measured small signal gain of over 20 dB from 76 to 77 GHz with a 15.5 dBm output power. The chip size was 2 mm × 2 mm. The DA exhibited a gain of 23 dB over a 76 to 77 GHz band with an output power of 13 dBm. The chip size was 2.1 mm × 2 mm. The measurement results of the fabricated MMIC PA and DA are presented in Figs. 9 and 10, respectively.

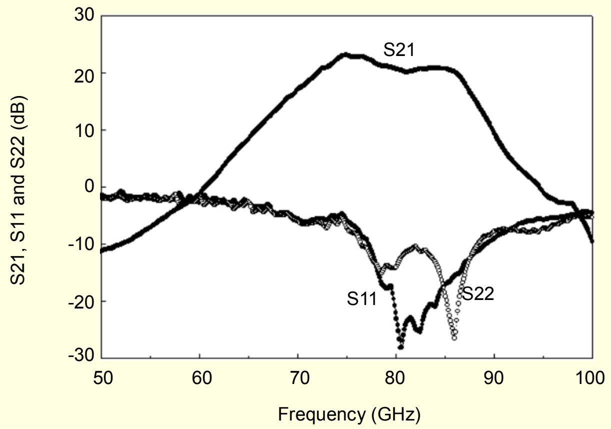


(a) Small signal gain (S21), input return loss (S11), and output return loss (S22) as a function of frequency (50 to 100 GHz) for the fabricated MMIC PA

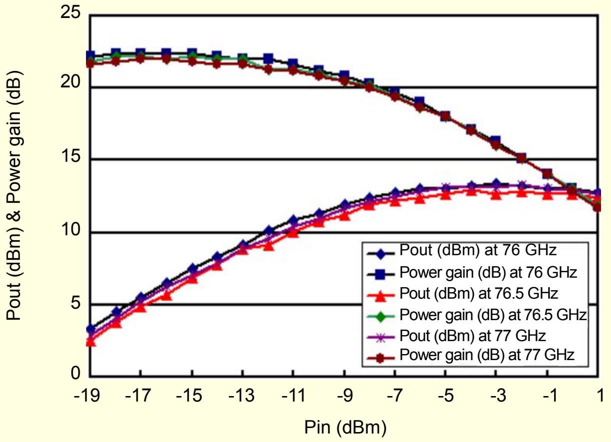


(b) Output power and power gain as a function of input power at 76 to 77 GHz 1 tone for the fabricated MMIC PA

Fig. 9. Measured results of the MMIC power amplifier.



(a) Small signal gain (S21), input return loss (S11), and output return loss (S22) as a function of frequency (50 to 100 GHz) for the fabricated MMIC DA



(b) Output power and power gain as a function of input power at 76 to 77 GHz 1 tone for the fabricated MMIC DA

Fig. 10. Measured results of MMIC driver amplifier.

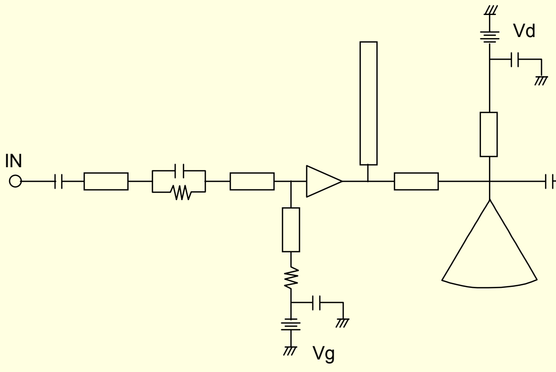
Table 1. Comparison of the data of previously published W-band PAs with this work.

Frequency (GHz)	Process (All GaAs based)	Pout (dBm)	Gain (dB)	Chip size (mm^2)	Ref.
71-80	0.15 µm pHEMT	12	13.5	1.5 × 1.2	1
77	0.15 µm pHEMT	14.5	8.5	0.5 × 0.6	6
76.5	0.15 µm pHEMT	14	13	1.5 × 1.2	7
76.5	0.13 µm pHEMT	15	10	2 × 1	8
76	0.12 µm pHEMT	13	11	2 × 1	9
77-78	0.1 µm pHEMT	21.5	12	3 × 2	10
76-77	0.15 µm pHEMT	15.5	20	2 × 2	This work

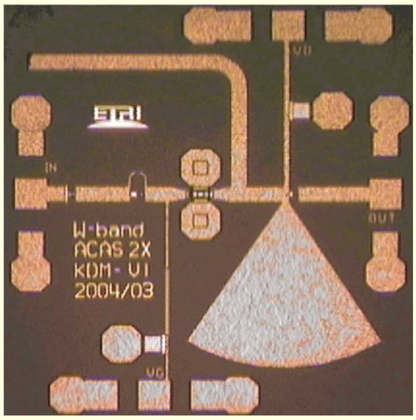
Recently reported 77 GHz PA results of other studies are compared with this work in Table 1. Our PA results demonstrated the highest output power and gain among all the reported 77 GHz MMIC PAs for automotive radar systems using 0.15 µm GaAs HEMTs.

2. Frequency Doubler

Figure 11 shows the circuit schematic and photograph of the frequency doubler. We designed an input circuit and output circuit to match at 38.25 GHz and 76.5 GHz, respectively. The input matching circuit fulfills the requirements of stabilization in the whole frequency range, matching the fundamental at 38.25 GHz and the optimum load at 76.5 GHz. The parallel combination of resistor and capacitor to stabilize the mHEMT was used for the input match at 38.25 GHz. In the output matching circuit, a radial stub was necessary to achieve a high suppression of the fundamental in the output signal of more than 30 dBc. The output was matched at 76.5 GHz with the long open stub, which was also used for the suppression of



(a) Circuit schematic of the MMIC frequency doubler



(b) Photograph of the MMIC frequency doubler

Fig. 11. The circuit schematic and photograph of the MMIC frequency doubler.

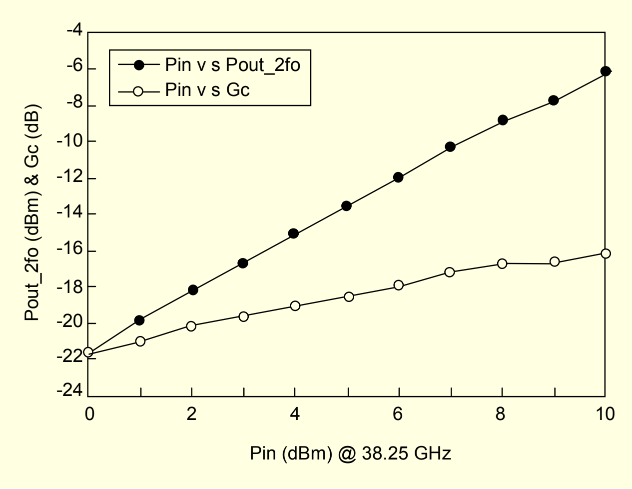


Fig. 12. Measured output power and conversion gain of the frequency doubler as a function of the input power level at 38.25 GHz.

Table 2. Comparison of the data of previously published frequency doublers with this work.

Frequency (GHz)	Process (All GaAs based)	Gc (dB)	Fundamental suppression (dBc)	Chip size (mm^2)	Ref.
38.25/76.5	0.2 μm × 320 μm pHEMT	-11.3	-	1.0 × 1.25	2
38.5/77	0.12 μm × 100 μm MESFET	-11	-	-	11
38.25/76.5	0.15 μm × 100 μm mHEMT	-16	37	1.2 × 1.2	This work

the fundamental. The operating conditions were near the pinch-off region so that high, even harmonic power levels were generated. The external DC biasing conditions of V_d and V_g were 1.5 and –0.7 V, respectively, and the total current consumption was 8 mA.

Figure 12 shows the measured output power and conversion gain of the frequency doubler as a function of the input power level at 38.25 GHz. The frequency doubler achieved an output power of – 6 dBm at 76.5 GHz with a conversion gain of –16 dB for an input power of 10 dBm and a 38.25 GHz input frequency. The frequency doubler also achieved a fundamental suppression of 37 dBc in a 76.5 GHz output frequency. The chip size was 1.2 mm × 1.2 mm. Table 2 shows a comparison of the data of previously published frequency doublers with this work.

IV. Conclusion

This paper describes the successful development of an MMIC chip set for automotive radar systems using ETRI's 0.15 μm InGaAs/InAlAs/GaAs mHEMT technology on a 4-inch 100 μm thick GaAs substrate. The chip set consists of a power amplifier, a driver amplifier, and a frequency doubler. This MMIC chip set is suitable for 77 GHz automotive radar systems and related applications in a W-band.

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Dong Min Kang received the MS degree in electronics engineering from Kwangwoon University, Seoul, Korea. From 1998 to 2000, he was with MCC, where he worked on RF module developments for wireless telecommunications. In 2000, he joined Electronics and Telecommunications Research Institute (ETRI), where he has been engaged in research on micro-/millimeter wave MMIC design for wireless telecommunications systems and automotive collision avoidance systems. Since 2004, he has been a Member of Senior Research Staff of the High Speed SoC Department of ETRI. His research interests include MMIC design, RF front-end module development, and packaging.

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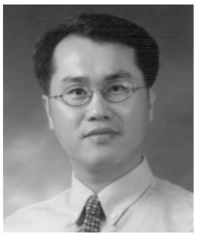
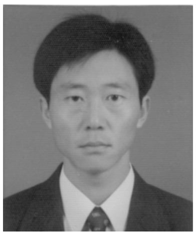


Jae Yeob Shim received the BS, MS, and PhD degrees in metallurgical engineering from Yonsei University in Seoul, Korea, in 1991, 1993, and 2000. Since 2000, he has been with ETRI, Korea, as a Senior Researcher, where he has been engaged in research on compound semiconductor device fabrication. His research interests are in the development of GaAs pHEMT, MHEMT, and InP pHEMT devices, especially e-beam lithography process, and micro-/millimeter wave MMIC for wireless telecommunications systems and their system applications.

Jin-Hee Lee received the BS degree in physics from Youngnam University, Korea, in 1980, and the MS and PhD degrees from the same University in 1982 and 1987. He joined ETRI in 1984. From 1984 to 1992, was involved in developing fine-line lithography, multi-level interconnection, and a fabrication process of GaAs MESFETs. In 1993, he was dispatched to University of Tokyo in Japan for one year to do international research activities. After returning to ETRI, he has been involved in the development of high speed devices and their integrated circuits. He is now a principal member of the Research Staff in the Department of Compound Semiconductors in ETRI. His current research interests include the fabrication and characterization of low noise GaAs and InP-based HEMTs for millimeter wave MMIC applications, nanometer devices, and optical devices.

Hyung-Sup Yoon received the BE degree in electronic materials engineering from Kwang Woon University, Korea, in 1980, and the ME and PhD degrees in 1984 and 1991 in applied physics from Inha University, Korea. He joined ETRI in 1984. From 1984 to 1992, he was involved in developing silicon processes and devices. Since 1993, he has been a principal researcher in the Department of Compound Semiconductors in ETRI. His current research interests include the process development, fabrication, and characterization of low noise GaAs and InP-based HEMT devices for millimeter wave MMIC applications.



Kyung Ho Lee received the BS and MS degrees in metallurgical engineering from Seoul National University in Seoul, Korea, in 1980 and 1982. He earned the PhD degree in materials science and engineering from Stanford University in Stanford, USA, in 1989. From 1989 to 1996, he was with Electronics and Telecommunications Research Institute (ETRI) of Korea, as a member of Senior Research Staff, where he was engaged in R&D on the advanced compound semiconductor device fabrication. From 1996 to 1998, he was with Eaton Semiconductor Korea, where he had been the Director of Applications heading the troubleshooting and development of Eaton ion implanter-related processes and hardwares. In 1998, he rejoined ETRI as a member of Principal Research Staff of the Department of Compound Semiconductors to manage national research projects on micro-/millimeter-wave MMIC developments for wireless telecommunications and THz optical communications systems. He also headed in establishing the basis of a foundry service of ETRI's 4″ compound semiconductor fabrication facility. He is currently leading up the InP IC team. His research interests are in the development of advanced compound semiconductor devices and ICs for their system applications.