Initial Verification of a Bandwidth Tunable Ku-Band Power Amplifier Designed by the HySIC Concept

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Abstract: In this letter, an initial verification results of a bandwidth tunable power amplifier in Ku-band designed by the hybrid semiconductor integrated circuit (HySIC) concept is reported. A GaAs monolithic microwave integrated circuit (MMIC) and a Si radio frequency integrated circuit (RFIC) were utilized as the HySIC configuration in the circuit design. For the purpose of initial confirmation of this design validity, the GaAs and Si chips were fabricated and packaged onto the copper tungsten plate with gold plating. As measured results, the lower cut-off frequency was changed from 9.8 GHz to 11.9 GHz, resulting in the bandwidth tunability in Ku-band.

Keywords: Bandwidth tuning, Amplifier, Varactor, Ku-band, Integrated circuit

Classification: Wireless communication technologies

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1 Introduction

Nowadays, wireless communication system has become one of the indispensable infrastructures. Analog circuit technology contributes in the hardware realization such as base stations and terminals. Focusing on a power amplifier circuit that operates in high frequency band, frequency tunable one has been developed for several decades. L-band frequency tunable amplifier using the varactor [1], X-band frequency tunable low noise amplifier (LNA) using tunable filter [2], tunable LNA for 3.1 to 10 GHz ultra wide band system [3] are examples for the frequency tunable amplifiers. Frequency tunable amplifiers in more higher frequency band at Ku-band [4, 5] have been proposed.

On the other hand, packaging technique is also important for fabrication and manufacturing. The hybrid semiconductor integrated circuit (HySIC) concept [6] is one of the attractive technique for integration. We focus on the HySIC concept which utilizes GaAs monolithic microwave integrated circuit (MMIC) and a Si radio frequency integrated circuit (RFIC) for a design of a bandwidth tunable Ku-band power amplifier. Conventional proposals of the combination of GaAs MMIC and Si RFIC [7, 8] were utilized for different power range circuit, for example, low power driver amplifier for Si RFIC and medium or high power amplifier for GaAs MMIC. However, we utilize Si RFIC for frequency tuning function and GaAs MMIC for main circuit of the power amplifier.
This paper presents a validity of bandwidth tunability of a Ku-band single stage power amplifier designed by the HySIC concept. For the tuning capability, a varactor [1, 9] is used in the output matching circuit. Section 2 presents a basic circuit design of the proposed amplifier, Section 3 introduces and discusses the measurement results, and Section 4 presents our conclusions.

2 Circuit Design and Analysis

Fig. 1(a) shows a basic circuit diagram of the proposed bandwidth tunable Ku-band power amplifier. A GaAs MMIC by UMS PH25 process and a Si RFIC by TSMC 0.18 \( \mu \)m CMOS process were utilized as the HySIC integration in the tunable amplifier design. A simple circuit of a single stage common source amplifier was designed in the GaAs MMIC. For the bandwidth tuning operation, a part of the output matching circuit was designed and placed in the Si RFIC. For the tuning operation, a MOS varactor was utilized in the Si RFIC. In this report, only the varactor, a capacitor, and a RF choke inductor were placed on the Si RFIC as an initial trial, but some digital-assisted control circuit for optimum control function (control circuit in Fig. 1(a)) should be integrated at the next phase in near future. This is one of the reasons why Si RFIC was utilized in the initial design. Circuit parameters of \( C_1, C_2, C_3, C_4, C_5, C_6, L_1, L_2, L_3, L_4, L_5, L_6, L_7, L_8, R_1, R_2 \) were 1.6 pF, 1.6 pF, 1.4 pF, 1.6 pF, 3.6 pF, 1.6 pF, 6.0 nH, 0.3 nH, 0.3 nH, 0.3 nH, 0.4 nH, 0.4 nH, 0.1 nH, 9.0 nH, 150 ohm, 5 ohm, respectively. Fig. 1(b) shows photos of the proposed amplifier under measurement using on-wafer probe. Measurement results will be discussed in the next section.

At first, for the initial design, bandwidth tuning capability was evaluated by S-parameter and input-output characteristic using an ideal capacitor in-

Fig. 1. A basic circuit diagram of the proposed bandwidth tunable Ku-band power amplifier.

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Fig. 2. Summary of the simulation results.

stead of the MOS varactor model $C_{v1}$. Fig. 2(a) shows a simulation result of $|S_{21}|$ using the proposed amplifier circuit. The frequency characteristics were dynamically changed around 10 GHz by the capacitance of $C_{v1}$ tuning from 0.85 pF to 1.83 pF, while the characteristics change in upper frequency bands (over 13 GHz) were negligibly small. From this simulation result, we expect the tuning range of lower cut-off frequency from 10.1 GHz to 12.1 GHz, resulting in the bandwidth tunability. In this report, the cut-off frequency was defined as the frequency when the $|S_{21}|$ becomes lower than 10 dB.

Based on the previous initial simulation results, a varactor was designed. We selected a MOS varactor in the Si RFIC instead of a varactor diode in GaAs MMIC, because capacitance variable range of the PH25 process was limited from 80 fF to 300 fF, resulting in out of the desired capacitance tuning range. This was another reason why the part of the output matching circuit was designed in the Si RFIC. Structural parameters of the MOS varactor were determined based on the simulation results shown in the Fig. 2(a). Finalized values of Finger number, group number, width per finger, and finger length were 46, 6, 1 $\mu$m, and 1 $\mu$m, respectively. Simulation results of the relationship between bias voltage and varactor capacitance were summarized in the Fig. 2(b). The capacitance was able to be changed from 0.77 pF to 1.84 pF while the bias voltage was changed from $-3$ V to 3 V. The capacitance range from 0.85 pF to 1.83 pF is realized by changing the bias voltage from

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−1 V to 1 V. Fig. 2(c) shows a \(|S_{21}\)| simulation result of the proposed power amplifier circuit using the varactor model. Obtained results have same trend as the initial simulation result, shown in Fig. 2(a). The frequency tuning range of the lower cut-off frequency was from 10.2 GHz to 12.2 GHz, as for the Fig. 2(c).

Fig. 2(d) shows the simulation results of the input-output characteristics of the proposed power amplifier circuit using the varactor model. We simulated at 10.0 GHz, 12.0 GHz, 14.0 GHz, and 19.5 GHz, however, only to be shown one result at 12.0 GHz because the variation of the characteristic is simply recognized from the \(|S_{21}\)| simulation results. The simulation results at \(V_{\text{dctr}} = 0\) V and 1 V have same trend, but little bit high gain and power added efficiency (PAE) as for the result of \(V_{\text{dctr}} = 1\) V. And The result at \(V_{\text{dctr}} = -1\) V have degraded characteristic compared with other simulation results. This discussion was easily expected from the \(|S_{21}\)| simulation results at 12.0 GHz, shown in the Fig. 2(c). Other simulation results at 14.0 GHz and 19.5 GHz have little variation with around 30% maximum PAE when the \(V_{\text{dctr}}\) was changed. On the other hand, at 10.0 GHz, the simulation results greatly moved by the \(V_{\text{dctr}}\) change. Summarizing the Fig. 2(d), maximum value of the PAE was 28.5% when \(V_{\text{dctr}} = 1\) V under the condition of 6.0 dBm input power. 1 dB compression point \(P_{1dB}\) was 13.2 dBm. These S-parameters and harmonic balance simulations were performed by Advanced Design System (ADS) software of Keysight Technologies.

3 Fabrication and Measurement

The proposed circuits of GaAs MMIC and Si RFIC were fabricated using foundry service provided by UMS PH25 and TSMC 0.18 \(\mu\)m processes, respectively. Both two chips of the MMIC and the RFIC were mounted onto CuW (copper tungsten) plate with gold plating shown in Fig. 1(b). Silver paste was used to fix these two chips onto the CuW plate. Ground-signal-ground pads with pitch of 150 \(\mu\)m were used for input and output interconnection terminals of the two chips. Wedge type gold wire bonding technique was used for the interconnection between two chips. Also, this wire bonding technique was utilized for another interconnection. Ideal thickness of the GaAs MMIC and the Si RFIC were 100 \(\mu\)m and 300 \(\mu\)m, respectively. Therefore, 200-\(\mu\)m-thickness CuW subcarrier with 1 mm square was used under the GaAs MMIC for height adjustment. This was because level distance should be minimized for the short gold wire bonding between the two chips. The Air Coplanar Probe (ACP) by FormFactor was used for the RF input and output. S-parameters and input-output characteristics were measured to evaluate the bandwidth tunability function in Ku-band. Bias conditions of the GaAs MMIC were \(V_g = -0.3\) V and \(V_d = 3.0\) V as same as the simulation.

Bias voltage \(V_{\text{dctr}}\) dependence on small signal S-parameters was measured using a vector network analyzer. Fig. 3(a) shows the measured result of \(|S_{21}\)|. As expected in the simulation, frequency characteristics changes depending on \(V_{\text{dctr}}\), and same trend that the cut-off frequency gradually raises while \(V_{\text{dctr}}\)
reduces, was observed. The tuning range of the lower cut-off frequency was from 9.8 GHz to 11.9 GHz. Also, we have confirmed same trend as expected as the initial simulation result shown in Fig. 2(c).

Bias voltage $V_{dctr}$ dependence on input-output characteristics was measured using a signal generator and a spectrum analyzer. Fig. 3(b) shows the measured results. At first, we have confirmed the gain under the condition of $V_{dctr} = 1$ V at small signal region was higher than other bias conditions, as same as the simulation. Maximum value of the PAE was 30.3 % when $V_{dctr} = 1$ V under the condition of 10.8 dBm input power. 1 dB compression point $P_{1dB}$ was 13.2 dBm. Also, both simulation and measurement results have same trend, therefore, we have confirmed the validity of the simulation.

From these simulation and measurement results, we have confirmed the bandwidth tunable capability at lower frequency region in Ku-band by using the proposed power amplifier circuit.

4 Conclusion

Applicability of the HySIC concept to a Ku-band bandwidth tunable power amplifier was tested in this letter. A GaAs MMIC and a Si RFIC were utilized for the amplifier circuit. As measured results, frequency tunable range of the lower cut-off frequency from 9.8 GHz to 11.9 GHz was measured. Maximum value of the PAE was 30.3 % when $V_{dctr} = 1$ V under the condition of 10.8 dBm input power. 1 dB compression point $P_{1dB}$ was 13.2 dBm. From the simulation and measurement results, we have confirmed the validity of the proposed concept as an initial proposal for future digital-assisted bandwidth tunability of a Ku-band power amplifier.

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