A Design of InP-HBT 100-GHz Diode Linearizer Toward 6G

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***Abstract*— In this paper, we present a 100-GHz linearizer to improve the linearity of 100-GHz amplifier for sub-THz band (frequency range above 100-GHz) wireless communications in the sixth-generation mobile communication system (6G). The linearizer is designed using the InP-based heterojunction bipolar transistor (InP-HBT) with f_T/f_{MAX} of 450/450 GHz. P-N diode of the base-emitter junction in InP-HBT was used to form the diode. To operate the linearizer in this high-frequency region, we propose the linearizer employing the diode, which has a transmission line (TL) to cancel out a parasitic capacitance of the InP-HBT. To show the validity of the proposed linearizer, we calculated the output-referred 1-dB compression point (OP1dB), gain/phase deviation versus output power, and third-order intermodulation (IM3) of the 100-GHz amplifier with the proposed linearizer using the harmonic-balance simulation. The OP1dB of the amplifier is improved by 1.4 dB at 100 GHz by using the proposed linearizer. The gain/phase deviation and IM3 are also improved at 100 GHz. To the best of the authors' knowledge, this is the first study of the diode linearizer in sub-THz band.**

Keywords*— *linearizer, sub-THz, amplifier, distortion, 6G, InP, HBT, diode

I. Introduction

Sub-THz band (frequency range above 100 GHz) is considered as a good candidate for the implementation of ultra-high-speed (> 100 Gb/s) wireless communication in the sixth-generation mobile communication system (6G) [1]-[3]. In sub-THz band, there is a possibility of using wider bandwidth (BW) such as 1 GHz or more compared to the fifth-generation mobile communication system (5G), e.g., Sub-6-GHz band (BW:100/200 MHz in Japan) or 28-GHz band (BW: 400 MHz in Japan). To realize the wireless system in sub-THz band, the implementation of radio frequency (RF) front-end is a mandatory task. Recently, sub-THz RF front-end is becoming a hot research topic and energetically researched [4]-[10].

Power amplifier (PA) is a key component of an RF front-end to obtain sufficiently high signal-to-noise ratio (SNR). To use a high-order modulation signal such as 64QAM or 128QAM, the amplification of the modulation signal with low distortion is necessary to ensure the SNR. One of the major cause of the distortion in RF front-end is a nonlinearity of the PA. There have been reported various nonlinearity compensation techniques of the PA in lower frequency range below sub-THz region, such as digital predistortion [11], analog predistortion [12], and harmonic injection [13]. However, there are only a few studies about these techniques in sub-THz band.

In this work, we designed a diode linearizer, a kind of analog predistortion technique, and also an amplifier circuit at 100 GHz to investigate a validity of nonlinearity compensation technique in sub-THz band. Considering the high operation frequency, the high-speed transistor is suitable for designing these circuits. We used NTT's in-house 250-nm InP-based heterojunction bipolar transistor (InP-HBT) [14] device model to design these circuits. Both the cutoff frequency (f_T) and maximum oscillation frequency (f_{MAX}) of this InP-HBT are 450 GHz [15]. We proposed a new architecture of the diode linearizer and ensured the nonlinearity compensation of the amplifier using the circuit simulator as described in the following section. To the best of authors' knowledge, this is the first study of the diode linearizer in sub-THz band.

II. Design of 100-GHz Linearizer and Amplifier

The circuit schematic of the designed 100-GHz InP-HBT amplifier is shown in Fig.1. The amplifier consists of two-stage cascaded common-emitter transistor with emitter length of 4 μm. Impedances of input/output of the amplifier and interstage between two transistors are designed to be 50 Ω by matching networks. These matching networks are composed of ideal lossless transmission lines (TLs), lumped capacitances and resistances. The bias circuits for the base and collector terminals of the HBTs are designed using quarter-wavelength stubs with series low resistance (~ 10 Ω) to achieve high stability and sufficient suppression of the out-band gain.

A schematics of a conventional and proposed diode linearizer are shown in Fig. 2. In diode linearizer, a diode is placed before the amplifier to compensate the nonlinearity of the amplifier [16]-[18]. The amplitude-to-amplitude distortion (AM-AM) characteristic and amplitude-to-phase distortion (AM-PM) characteristic of a diode and amplifier are opposite each other in general. The diode linearizer uses this nature to compensate the nonlinearity of the amplifier. The ordinally method to implement the diode using an InP-HBT is shown as linearizer (conventional) in Fig. 2. The emitter-base PN junction of the InP-HBT is used to form the diode. Collector of the InP-HBT was grounded via a resistor with a high resistance (3 kΩ) to set its DC voltage to 0 (ground) and its impedance as high as possible. In this case, the base and emitter work as an anode and cathode of a diode, respectively. However, due to the high frequency of 100-GHz, parasitic capacitances of a InP-HBT degrade the AC characteristics of the diode and this conventional diode linearizer will not properly work. To show this issue, we calculated the output-referred 1-dB compression point (OP1dB) of the 100-GHz amplifier (Fig. 1) and the amplifier with this conventional diode linearizer using a circuit simulator (Keysight ADS). OP1dB is determined as the value of the output power where the gain difference from the small-signal gain is 1-dB. The simulation results are shown in Fig. 3. Vertical and horizontal axis are the simulated gain and output power of these amplifiers. The calculated OP1dB of these amplifiers are

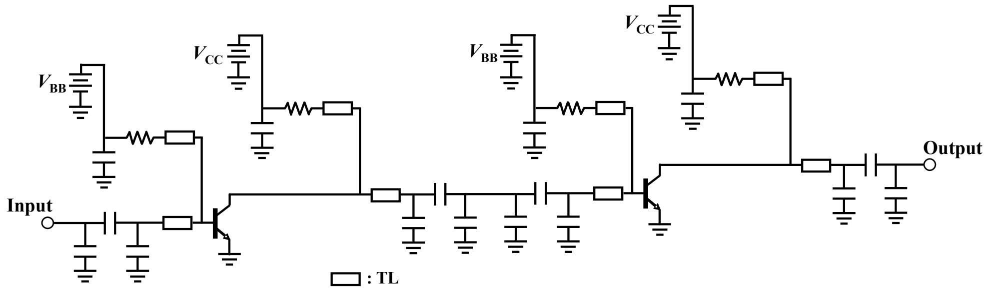

Fig. 1. Schematic of 100-GHz InP-HBT amplifier.

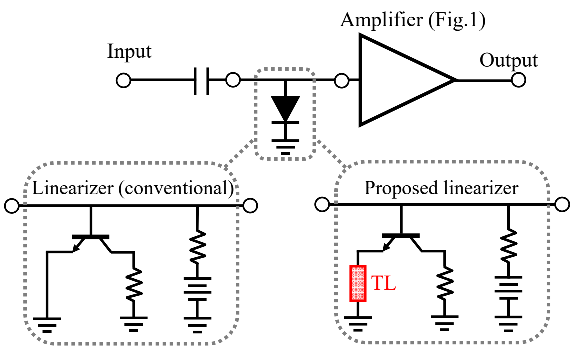

Fig. 2. Schematic of conventional/proposed diode linearizer.

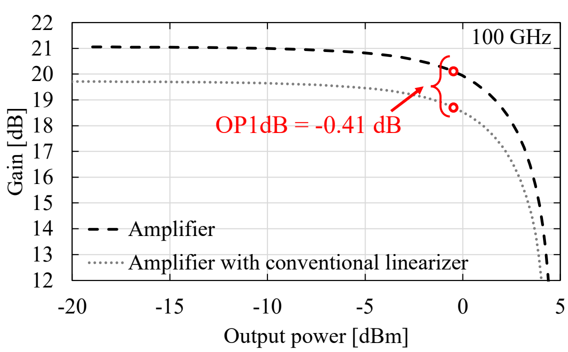

Fig. 3. Simulated OP1dB of 100-GHz InP-HBT amplifier and amplifier with the conventional linearizer.

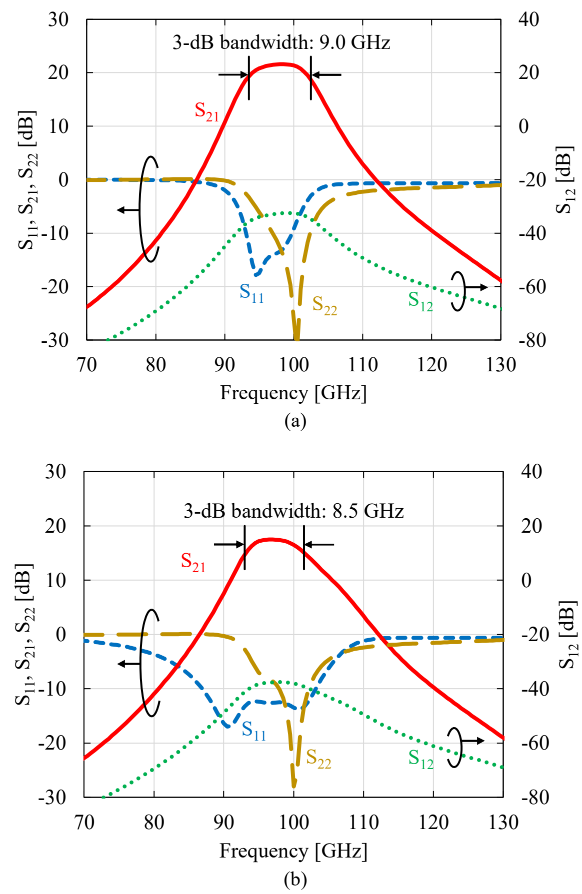

Fig. 4. Simulated S-parameters of (a) Amp-1 and (b) Amp-1-L.

exactly same, -0.41 dBm. This means that the linearity of the amplifier is not improved by the conventional linearizer at 100 GHz. To overcome this issue, we proposed a new architecture of the diode linearizer as shown in Fig. 2. In the proposed linearizer, emitter of the InP-HBT (cathode of the diode) is grounded via a TL. The aim of using this TL is to compensate the parasitic capacitance of the InP-HBT with the inductance of the TL at 100 GHz. Therefore, the parameters of this TL, i.e., characteristic impedance and electrical length are carefully designed to cancel the parasitic capacitance of the InP-HBT. The derived optimum values of the characteristic impedance and electrical length are 50 Ω and 63 degrees. The proposed linearizer with this optimized TL well improved the linearity of the amplifier as described in the next section.

III. Simulation Results of the Proposed Linearizer

We simulated a small-signal, large-signal characteristics of the proposed linearizer using the circuit simulator ADS. To evaluate the effectiveness of the proposed linearizer, we simulated these characteristics for both the 100-GHz amplifier (Fig. 1) and the amplifier with the proposed linearizer (Fig. 2) using the optimized TL parameters. In the following discussion, we call the 100-GHz amplifier as "Amp-1" and amplifier with the proposed linearizer as "Amp-1-L". In both small- and large-signal simulation, the operation mode of the two amplifiers are set to class-A mode. Also, the DC voltage applied to the base terminal of the linearizer in Amp-1-L is set to the threshold voltage of PN diode (0.7 V).

First, S-parameters are evaluated as a small-signal characteristics of these amplifiers. Figure 4 (a) and (b) shows the simulated S-parameters of Amp-1 and Amp-1-L. The maximum small-signal gain (S_{21}) of Amp-1 is 21.6 dB at 98.5 GHz. S_{21} is larger than 20-dB over 95–101 GHz and the 3-dB

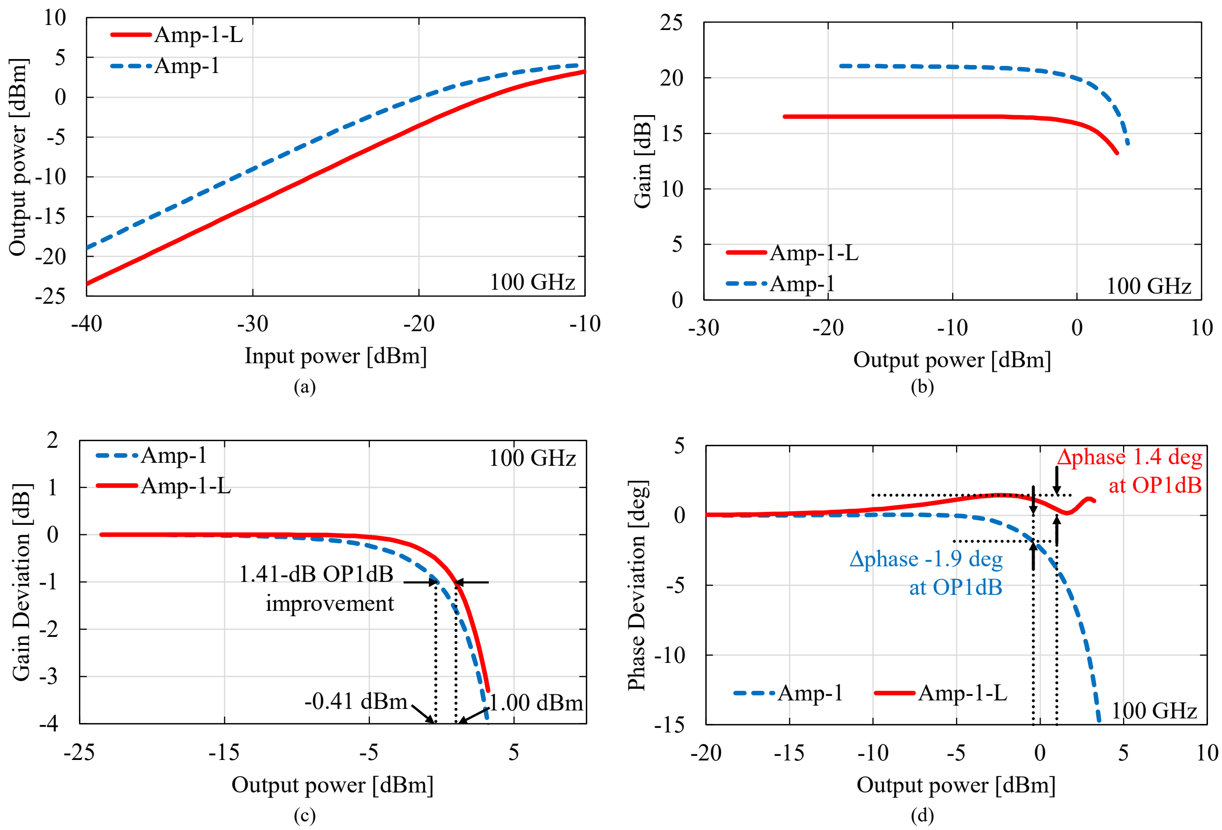

Fig. 5. Simulated (a) input-output characteristics, (b) gain versus output power, (c) gain deviation versus output power, and (d) phase deviation versus output power of Amp-1 and Amp-1-L.

bandwidth is 9 GHz. S_{12} is smaller than -30 dB for 70–130 GHz, which means that the stability of the amplifier is high enough. The small-signal characteristics of Amp-1-L is similar to the ones of Amp-1 as shown in Fig. 4 (b). Maximum small-signal gain is 17.5 dB at 96 GHz, which is 4.1-dB lower than that of Amp-1. A frequency response of input reflection coefficient (S_{11}) of Amp-1-L is broader (better) than Amp-1. These differences are supposed to be caused by the insertion loss of the diode placed before the amplifier in Amp-1-L. The decrease of the gain by the linearizer is acceptable considering that Amp-1-L still has large gain of around 15 dB in its operation frequency of 100-GHz band. 3-dB bandwidth of Amp-1-L is 8.5 GHz, which is also similar to that of Amp-1.

Next, we evaluated the large-signal characteristics of Amp-1 and Amp-1-L using the harmonic balance simulation. Figures 5 (a), (b), (c), and (d) show the simulation results of input-output characteristics, gain versus output power, gain deviation versus output power, and phase deviation versus output power of these amplifiers. The simulation frequency was set to 100-GHz. The input power range was -40 to -10 dBm. In Fig. 5 (c) and (d), the gain and phase values at input power of -40 dBm are used as reference values to calculate the gain and phase deviations. As shown in Fig. 5 (a) and (b), the gain of Amp-1-L is lower than that of Amp-1. This is caused by the insertion loss of the linearizer. The gain curve of Amp-1-L is flatter than that of Amp-1. Actually, Amp-1-L has 1.41-dB higher OP1dB than Amp-1 as shown in Fig. 5 (c). It means that the proposed linearizer well compensates the nonlinearity of the amplifier. This OP1dB improvement is not accomplished by the conventional linearizer as shown in Fig. 3. Therefore, these results show the validity of the proposed linearizer using the TL to cancel out the parasitic capacitance of the InP-HBT. The OP1dB values of Amp-1 and Amp-1-L are -0.41 dB and 1.00 dB, respectively. Both amplifiers has the same saturated output power (Psat) of 4.0 dBm. Phase deviation is also improved by the proposed linearizer. The phase deviation of Amp-1-L is smaller than that of Amp-1 as shown in Fig. 5 (d). The phase deviation value at OP1dB (Δphase in Fig. 5 (d)) of Amp-1 and Amp-1-L are 1.9 and 1.4 degrees, respectively.

The frequency dependences of the OP1dB for both Amp-1 and Amp-1-L are also simulated to evaluate the operation bandwidth of the proposed linearizer, i.e., bandwidth where the proposed linearizer compensates the nonlinear characteristic of the amplifier. The simulation results are shown in Fig. 6. Amp-1 has OP1dB of -1.0 ~ -0.3 dBm over 95–110 GHz. Amp-1-L has higher OP1dB than Amp-1 for 95–109 GHz. This means that the operation bandwidth of the proposed linearizer is 14 GHz. The maximum OP1dB value of Amp-1-L is 2.3 dBm at 105 GHz.

Finally, we simulated the third-order intermodulation distortion (IM3) [19] for both Amp-1 and Amp-1-L. In this simulation, two equal-power continuous wave (CW) tone (100 GHz and 100.1 GHz) were input to these amplifiers and power of the IM3 (99.9 GHz and 100.2 GHz) are measured. The simulation results are shown in Fig. 7. The horizontal and vertical axis means the input power per tone and output power per tone. The solid- and dash-line indicate the fundamental

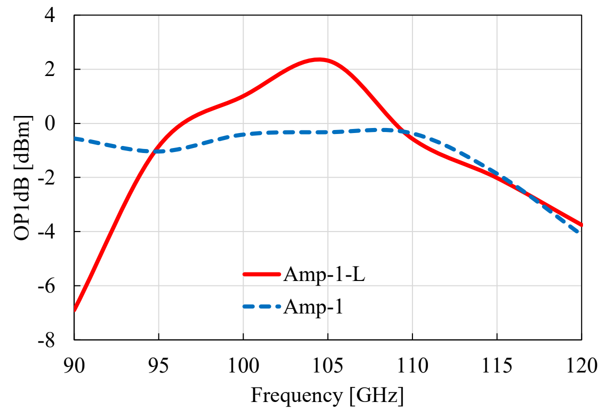

Fig. 6. Simulated frequency dependence of OP1dB for Amp-1 and Amp-1-L.

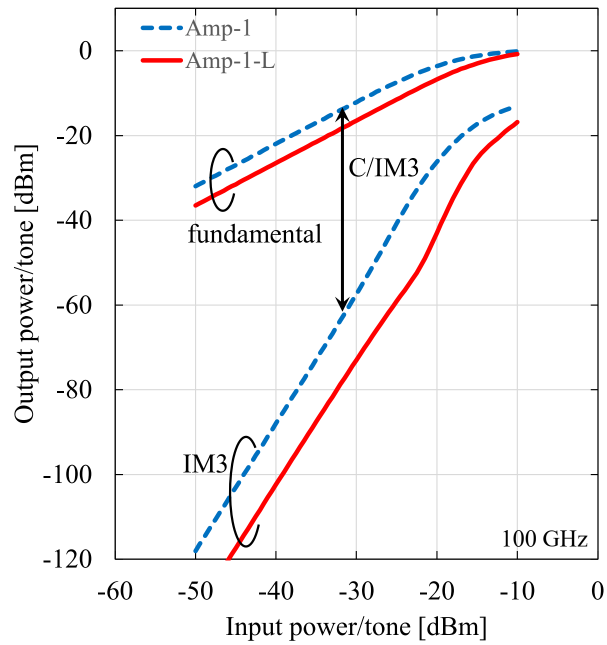

Fig. 7. Simulated fundamental and IM3 power per tone of Amp-1 and Amp-1-L.

wave and IM3. In this graph, 99.9-GHz or 100.2-GHz, whichever larger one is shown as the IM3. We used the carrier over IM3 (C/IM3), which is equal to the fundamental wave power divided by the IM3 as shown in Fig. 7, as the index of IM3 reduction. Relationship between the output power of the fundamental wave and C/IM3 derived from Fig. 7 is shown in Fig. 8. The C/IM3 of Amp-1-L is higher than that of Amp-1. The improvement of C/IM3 is larger than 3 dB for the output power range of -12.5 to -6 dBm. Maximum improvement of C/IM3 is 5 dB at the fundamental output power of -8 dBm. These results indicate that the proposed linearizer well compensates the IM3 of the amplifier, which can be considered as the main reason of OP1dB improvement in Amp-1-L.

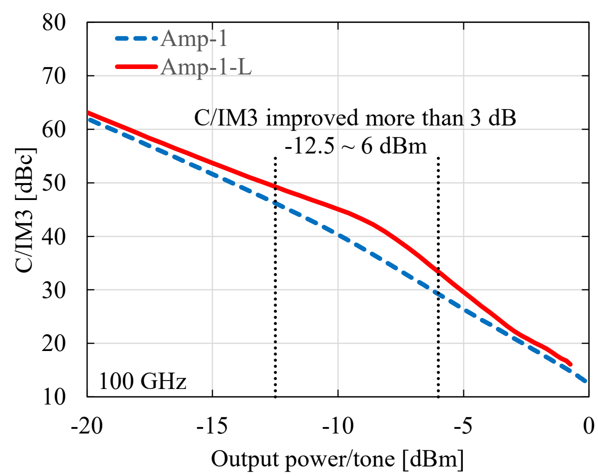

Fig. 8. Simulated C/IM3 of Amp-1 and Amp-1-L.

IV. Conclusion

A 100-GHz InP-HBT linearizer was designed to improve the linearity of an RF amplifier for sub-THz wireless communications toward 6G. We proposed the diode linearizer with TL to cancel the parasitic capacitance of the InP-HBT and improve its nonlinearity-compensation characteristic. The validity of the proposed linearizer is confirmed by calculating the large-signal characteristics of the 100-GHz amplifier with the linearizer using the circuit simulator ADS. The amplifier with the proposed linearizer achieved the OP1dB of 1.0 dBm, which is 1.41-dB higher than the amplifier without linearizer. Phase deviation at OP1dB was also improved from 1.9 to 1.4 degrees by adding the proposed linearizer. Furthermore, C/IM3 is improved for more than 3-dB in the output power range of -12.5 to -6 dBm.

Acknowledgment

This paper includes a part of results of “R&D for Expansion of Radio Wave Resources (JPJ000254),” commissioned by The Ministry of Internal Affairs and Communications, Japan.

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