Optimizing InGaP/GaAs HBT Technology for Distributed Amplifier Applications

Aroonchat Chatchaikarn, Wing Yau*, Yuefei Yang*, and G.P. Li

Integrated Nanosystems Research Facility, University of California, Irvine, CA, 92697 and Global Communication Semiconductors, Inc.*, Torrance, CA, 90505, email: achatcha@uci.edu and gpli@uci.edu

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Abstract

In this paper, the attributes of HBT device parameters to the performance of distributed amplifiers are evaluated. In addition, the guidelines for optimizing InGaP/GaAs HBT technology for broadband amplifier designs are proposed.

INTRODUCTION

Distributed amplifiers (DAs) are widely used in broadband communication systems, electronic warfare, wideband instrumentations, and other various applications. Noticeably, most DAs have been implemented with GaAs Field Effect Transistors (FETs), i.e. MESFETs and HEMTs rather than Heterojunction Bipolar Transistors (HBTs). This is because HBTs have rather lossy input characteristics, a key factor limiting DA gain and bandwidth, attributed to both R_b and R_π, as compared to only R_g in FETs [1]. Thus, it is more challenging to design a high gain-bandwidth HBT DA. However, since the key distance governing the electron transit time is determined by epitaxial growth in bipolar transistor rather than by gate length defined by lithographic tool in FETs, high speed performance is achievable with conventional lithography in HBTs. As a result, HBT f_t and f_{max} of 100-200 GHz are achieved with 1-3 um lithography while the gate dimension of 0.25-0.1 um is needed for achieving the similar f_t and f_{max}. In addition to the less stringent lithography requirement of HBTs, [2] has recently demonstrated that an InGaP/GaAs HBT broadband amplifier implemented with distributed amplification design technique can achieve high gain and wide bandwidth comparable to those FET DAs with a compact chip area. All aforementioned suggest that HBTs become good candidates for delivering solutions for broadband signal amplification applications with high performance, good yield and low cost.

From the foundry perspective, device technology is optimized for each application, i.e. a high f_T process for digital circuits and a high f_{max} process for high frequency amplifiers. A question raised here is which InGaP/GaAs HBT process will be best suited for DA applications and how to optimize the HBT parameters for DAs without compromising reliability. In this work, we address the design guidelines in optimizing the InGaP/GaAs HBTs enabling the DAs to achieve high gain and wide bandwidth with good reliability.

ISSUES IN HBT DISTRIBUTED AMPLIFIER

As previously mentioned, HBTs have rather lossy input characteristics as compared with FETs. Therefore, it is of a great challenge in achieving high gain-bandwidth HBT DAs. In this section, the issues preventing HBT DAs from achieving high gain-bandwidth product (GBP) will be highlighted, and the guideline in optimizing InGaP/GaAs HBT for DA applications will be provided in the next section.

In order to identify which HBT parameters need to be optimized for the distributed amplifiers, the analysis of N-stage HBT DA with generic gain cells, G_N, as illustrated in Fig. 1, is made in this section where Z_0 are the input and output terminated impedances, and L_i and L_o are the inductors forming the input and output artificial transmission lines with transistor input and output capacitors respectively. It is noted that the generic bipolar gain cells in Fig. 1 can be common-emitter, cascode, common-collector followed by common-emitter, and etc. By applying the equivalent small-signal model of the bipolar gain cell shown in Fig. 2 to the DA in Fig. 1 with an omission of C_{bc}, a base-collector capacitor, for a simplicity in derivation and without losing insight, the DA input and output artificial transmission lines can be constructed and illustrated as in Fig. 3 and 4 respectively.

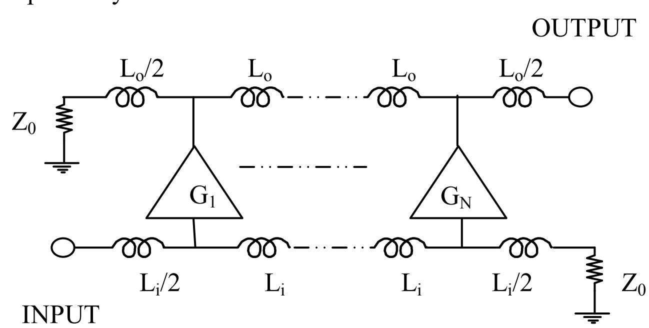


Figure 1: The schematic of N-stage HBT DA with generic gain cells.

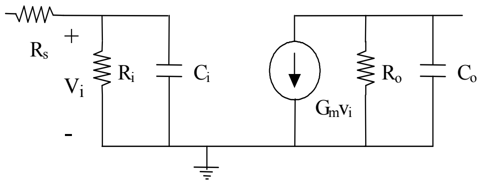


Figure 2: The equivalent small signal model of generic HBT gain cell.

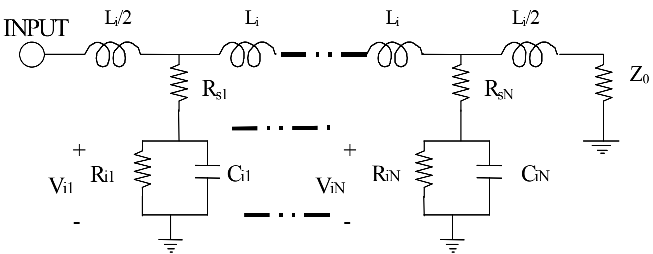


Figure 3: The artificial input transmission line of N-stage HBT DA with generic gain cells.

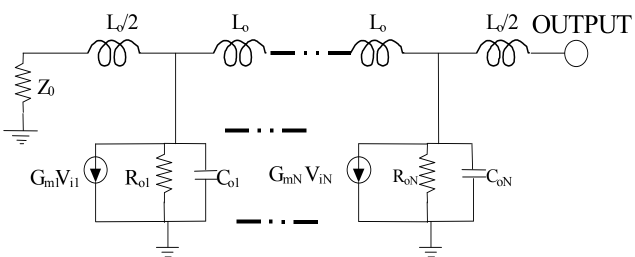


Figure 4: The artificial output transmission line of N-stage HBT DA with generic gain cells.

As observed in Fig. 3 and 4, the equivalent input and output capacitors are absorbed into the artificial lines, thus, the amplifier bandwidth depends on line cut-off frequencies, which are typically high, rather than the 1/RC time constant as in typical amplifiers. In addition, when the input and output artificial transmission lines are designed to be synchronized and the load impedance (Z_L) of 50 ohm being equal to the terminated impedance Z_0 (approximately equal to the characteristic impedance of the output line) is connected to the DA output, the half output current from each stage will be superimposed constructively and directed to the amplifier output. As previously mentioned, when the input and output lines are synchronized, $\beta_i l_i = \beta_o l_o = \beta l$, the gain expression under the assumption that all gain cells in the DA are identical and under the same dc biasing conditions, can be expressed as

$$Gain = -\frac{1}{2}\frac{G_m Z_0}{1+\dfrac{R_s}{R_i}+j\omega R_s C_i}e^{-\beta l(N-1)}$$

$$\sum_{n=1}^{N} e^{-\frac{1}{2}\left[\left(\frac{R_{Li}}{Z_0}+\frac{Z_0}{R_i}\right)(n-1)l_i+\left(\frac{R_{Lo}}{Z_0}+\frac{Z_0}{R_o}\right)(N-n)l_o\right]} \quad (1)$$

where n is the n[th] stage, N is the total number of stages, G_m is the equivalent gain cell transconductance, γ_i is the input transmission line propagation constant, $\gamma_i = \alpha_i + j\beta_i$, α_i is the input transmission line attenuation constant, $\alpha_i \approx \frac{1}{2}\left(\frac{R_{Li}}{Z_0}+\frac{Z_0}{R_i}\right)$, β_i is the input transmission line phase constant, $\beta_i \approx \omega\sqrt{L_i C_i}$, l_i is the line length between each stage in the input transmission line, R_{Li} is the parasitic resistor in inductor L_i, γ_o is the output transmission line propagation constant, $\gamma_o = \alpha_o + j\beta_o$, α_o is the output transmission line attenuation constant, $\alpha_o \approx \frac{1}{2}\left(\frac{R_{Lo}}{Z_0}+\frac{Z_0}{R_o}\right)$, β_o is the output transmission line phase constant, $\beta_o \approx \omega\sqrt{L_o C_o}$, l_o is the line length between each stage in the output transmission line, and R_{Lo} is the parasitic resistor in inductor L_o.

GUIDELINES IN OPTIMIZING InGaP/GaAs HBTS FOR DISTRIBUTED AMPLIFIER APPLICATIONS

In equation (1), a gain expression of HBT DA with generic gain cells, contains both R_s and R_i embedded in the denominator and in the negative exponential term, the input attenuation constant. As clearly observed, larger R_s and smaller R_i will result in lower amplifier gain, furthermore, the smaller R_i will also increase the input attenuation constant, a key factor limiting DA in achieving high GBP. Therefore, equation (1) provides guideline and informs that large R_i with small R_s and C_i are desirable in order to improve the gain and bandwidth of HBT DAs.

The example applying the common-emitter as a bipolar gain cell where $G_m = g_m$, $R_s = R_b$, $R_i = R_\pi$, and $C_i = C_\pi$ are used as a demonstration to identify which HBT parameters need to be optimized to achieve high gain and bandwidth. Since bipolar input and output capacitances are absorbed into the construction of artificial transmission lines, the f_T, which is proportional to g_m/C_π, is not an indicative parameter limiting the DA GBP. Thus, it is argued that both transistor f_{max} and R_π are more important parameters to be optimized in bipolar DA applications. Since $R_\pi \approx \beta_0 / g_m$, larger R_π can be achieved when the transistor has either higher β_0, the small-signal current gain, and/or smaller g_m, which can be obtained by decreasing the transistor biasing collector current. However, decreasing g_m will result in a lower amplifier gain as illustrated in (1). Therefore, this implies that the HBT with high β_0 should result in a higher gain with smaller input attenuation constant in HBT DA and consequently increase the amplifier gain and bandwidth.

In order to verify the above guidelines, computer simulations of two four-stage DAs are conducted. HBTs in both DAs are operated with the same collector currents, thus, transistor transconductances, g_m, in both DAs are identical. However, the first DA is composed of the HBTs with higher β_0 than the second one. As expected, the DA with higher β_0 achieves higher gain-bandwidth product than the one with lower β_0 as illustrated in Fig. 5. This confirms that the provided guideline is correct.

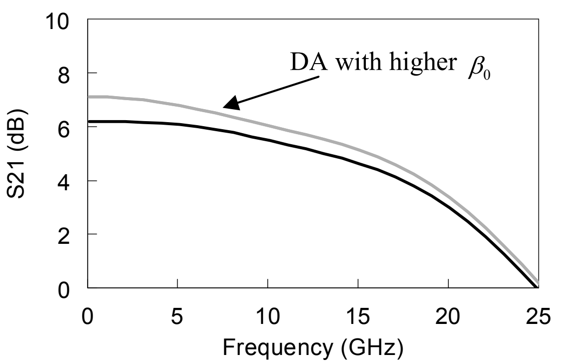


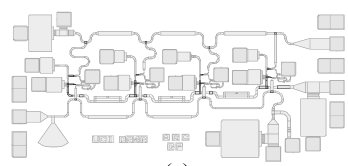
Figure 5: The comparison of two DAs in which one of them has higher β_0.

It is worthwhile mentioning that adding more stages in a DA will ideally result in higher GBP, however, the lossy elements in both passive and active prevent this to happen in practice, especially in a bipolar DA having rather lossy input characteristic as expressed in (1). With this large attenuation constant dominated by R_π in common-emitter gain cells, adding more numbers of cascaded stages, N, in a bipolar DA will result in even larger attenuation factor in the negative exponential term in (1). Therefore, simply cascading more stages in HBT DA is not an effective solution in improving amplifier GBP because high frequency signal will be largely attenuated and will not be amplified in the later stages away from the input. Recently, the modified bipolar gain cell [2], using common-collector followed by the cascode with loss compensation circuit [1, 3], achieving $R_s \approx R_b + R_n$, $R_i \approx (1+\beta(j\omega))R_\pi$, and $C_i = R_\pi/(1+\beta(j\omega))$, where R_n is the negative resistance generated by the impedance transformation via the common-collector, has been proposed to alleviate the deficiency in achieving high gain bandwidth in HBT DAs and further improve the amplifier gain and bandwidth. Therefore, the modified gain cells are applied in the HBT DA implementation as will be demonstrated in the next section in achieving optimum GBP.

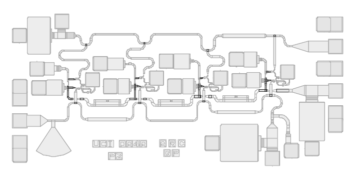
EXPERIMENTAL RESULT

To demonstrate the optimization guidelines, DAs are designed with two different InGaP/GaAs HBT processes from GCS, Inc. The first has higher β and f_t with lower f_{max}, and the second has lower β and f_t with slightly higher f_{max}. Both DAs employ the same HBT device layout with an emitter size of 2x6 um^2 and are optimized for highest gain and bandwidth. Similar collector biasing currents are applied to both of them.

Based on our studies, it is found that three keys elements are essential in optimizing the DA performance. The first key element is the input transmission line. Since both processes have different characteristics, differences in f_t mainly result in the differences of input capacitances, which determine DA bandwidth and the characteristic impedance of DA input line. Thus, the input line needs to be adjusted to achieve high cut-off frequency and good input matching respectively. The second key element is the output transmission line, whose characteristic impedance is adjusted to achieve good output matching, and synchronization between the forward in-phase output current from each stage enabling the DA to achieve high gain and bandwidth. The third is the line connecting each gain cell to the output line, which also synchronizes the output signal of DA and generates the gain peaking that increases the DA bandwidth.



(a)



(b)

(c)

Figure 6: (a) The layout of 4-stages DA in lower f_{max} and higher β_O and f_t process, (b) The layout of 4-stages DA in slightly higher f_{max} and lower β_O and f_t process, and (c) The chip microphotograph of DA in Fig. 6(a).

As clearly observed in the DA layouts with different processes as shown in Fig. 6(a) and (b), input and output lines, as well as the lines connecting each gain cell to the output lines are optimized differently to achieve highest gain and bandwidth. It is noted that die areas in both processes are identical. Based on the common practice, a DA implemented with slightly higher f_{max} process is expected to achieve higher gain-bandwidth product [4]. In contrast to that, it is found that the DA implemented with higher β_0 and f_t with slightly lower f_{max} achieves higher gain and bandwidth as illustrated in Fig. 7. This is because β_0 determines R_π, which is also a key parameter limiting the input line loss and dictating DA GBP, as previously discussed. Therefore, these results suggest that our guidelines in optimizing both f_{max} and R_π for DA applications be essential.

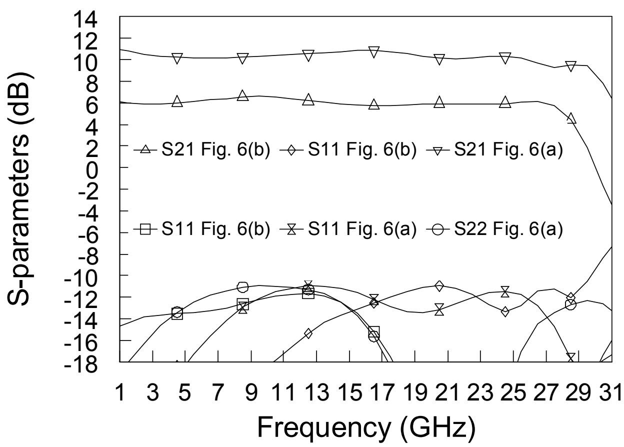


Figure 7: The S-parameters comparisons of DAs in Fig. 6(a) and 6(b).

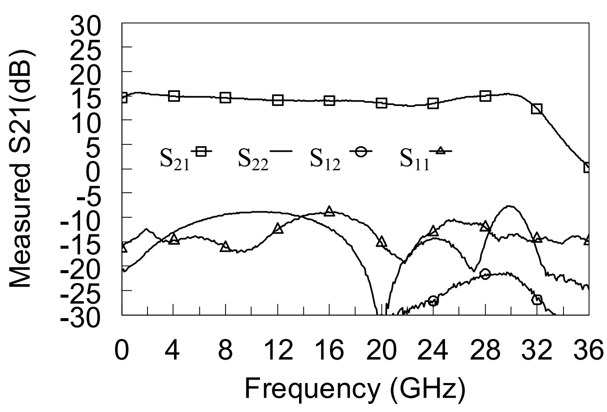


Figure 8: The measure S-parameters of DAs in Fig. 6(c).

Based on the preliminary results, the first process is then chosen for the implementation with the chip microphotograph illustrated in Fig. 6(c). Fig. 8 illustrates the DA measured S-parameters. The DA achieves 15.3 dB gain and 32 GHz bandwidth with the GBP/f_{max} of 2.87, which is among the best in single chip DAs implemented in any bipolar technologies. It is noted that GBP/f_{max} is a figure of merit measuring circuit design technique in enhancing DA gain and bandwidth. S_{11} and S_{22} mostly better than –10 dB are achieved over all operating frequencies. The supply voltage of 5 V is used, and the DC power consumption is 203.8 mW. At this biasing condition, the HBTs have f_T and f_{max} of 58 and 65 GHz respectively with MTTF of 0.8×10^6 hrs. These results suggest that InGaP/GaAs HBT DAs provide an economical solution for broadband amplifier applications with high gain and bandwidth, and good reliability and manufacturability.

CONCLUSION

In summary, the design guidelines in optimizing the InGaP/GaAs HBTs enabling the DAs to achieve high gain and wide bandwidth have been addressed. It is suggested that f_{max} and R_π of HBTs are more important parameters, which need to be optimized in bipolar DA applications. In addition, it has also been demonstrated that one can achieve a HBT DA with high gain and wide bandwidth comparable to a FET DA when HBTs are properly optimized and selected, and the design techniques in enhancing HBT DA gain and bandwidth are applied.

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ACRONYMS

HBT: Heterojunction Bipolar Transistor
DA: Distributed Amplifier