Optimizing InGaP/GaAs HBT Technology for Distributed Amplifier Applications

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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 instruments, 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 $R_e$, 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.
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 \( Z_0 \) 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

\[
\text{Gain} = -\frac{1}{2} \frac{G_m Z_0}{1 + \frac{R_s}{R_i}} e^{-\beta l(N-1)}
\]

where \( n \) is the \( n \)th stage, \( N \) is the total number of stages, \( G_m \) is the equivalent gain cell transconductance, \( \gamma_i \) is the input transmission line propagation constant, \( \gamma_o \) is the output transmission line phase constant, \( \alpha_i = \alpha_o = \gamma_i + j\beta_i \), \( \alpha_o = \gamma_o + j\beta_o \) are the input and output transmission line attenuation constant, \( \beta_i \) is the input transmission line propagation constant, \( \beta_o = \omega_i L_i C_i \), \( l_i \) is the line length between each stage in the input transmission line, \( R_i \) is the parasitic resistor in inductor \( L_i \), \( \gamma_o \) is the output transmission line propagation constant, \( \alpha_o = \frac{1}{2} \left( \frac{R_o}{Z_0} + \frac{Z_o}{R_o} \right) \), \( \beta_o \) is the output transmission line phase constant, \( \beta_o = \omega_i L_o C_o \), \( l_o \) is the line length between each stage in the output transmission line, and \( R_o \) 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 \( R_s \) 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 \( R_s \) with small \( R_i \) 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 \( g_m/C_\pi \), is not an indicative parameter limiting the DA GBP. Thus, it is argued that both transistor \( f_{max} \) and \( R_\pi \) are more important parameters to be optimized in bipolar DA applications. Since \( R_s \approx \beta_0 / g_m \), larger \( R_\pi \) can be achieved when the
transistor has either higher $\beta_o$, 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 $\beta_o$ 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 $\beta_o$ than the second one. As expected, the DA with higher $\beta_o$ achieves higher gain-bandwidth product than the one with lower $\beta_o$ as illustrated in Fig. 5. This confirms that the provided guideline is correct.

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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 $f_{\text{max}}$ process is expected to achieve higher gain-bandwidth product [4]. In contrast to that, it is found that the DA implemented with higher $I_0$ and $f_t$ with slightly lower $f_{\text{max}}$ achieves higher gain and bandwidth as illustrated in Fig. 7. This is because $I_0$ determines $R_e$, 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 $f_{\text{max}}$ and $R_e$ for DA applications be essential.

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

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/$f_{\text{max}}$ of 2.87, which is among the best in single chip DAs implemented in any bipolar technologies. It is noted that GBP/$f_{\text{max}}$ 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 $f_{\text{max}}$ of 58 and 65 GHz respectively with MTTF of $0.8 \times 10^6$ 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 $f_{\text{max}}$ and $R_e$ 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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REFERENCES


ACRONYMS

HBT: Heterojunction Bipolar Transistor
DA: Distributed Amplifier