Briefs

75 GHz InP HBT Distributed Amplifier With Record Figures of Merit and Low Power Dissipation

E. Cohen, Y. Betser, B. Sheinman, S. Cohen, S. Sidorov, A. Gavrilov, and D. Ritter

***Abstract*—We present an InP heterojunction bipolar transistor (HBT) distributed amplifier with a bandwidth of 75 GHz, gain of 14 dB, and a record low power consumption of 78 mW. The HBTs had a 600-nm-thick collector, and hence a relatively low f_T and $f_{\max}$ of 84 and 150 GHz, respectively. The thick collector is a tradeoff required in optoelectronic integrated receivers, in which the PIN diode layers are the same as the base collector layers. To obtain high PIN diode responsivity, the collector layer needs to be thicker than in optimized HBTs. The amplifier topology comprises an emitter follower at the input and a cascode stage, with a resistor and inductance at the emitter follower output, and a peaking line between the HBTs in the cascode stage. The amplifier exhibits matching at the input better than -10 dB up to 85 GHz. The chip contains 16 HBTs and its size is 1.7 × 0.9 mm^2.**

***Index Terms*—Distributed amplifier, heterojunction bipolar transistor (HBT), indium phosphide, optoelectronic integrated circuit (OEIC).**

I. INTRODUCTION

The performance of an amplifier with a given gain bandwidth product (GBP) is quantified by various figures of merit (FOMs). Widely used FOMs are the ratio between the GBP and the cutoff frequency of the transistors f_T and the ratio between the bandwidth (BW) of the amplifier and f_T [1]. A high GBP $/f_T$ ratio and BW/f_T ratio is desirable in bipolar transistor technology in order to minimize the power consumption of the amplifier. An additional important advantage of high FOM circuits emerges in the InP HBT optoelectronic integrated circuit (OEIC) technology. In monolithic integrated optical receivers, the PIN diode is conveniently fabricated from the same epitaxial layers as the base collector junction of the HBT. To obtain high responsivity of the PIN diode, the collector layer must then be thicker than in optimized HBTs [2]. A thick collector layer requires low doping levels, resulting in a low Kirk effect onset current density. The transistors in the receiver thus need to be operated at a low current density, and hence at lower f_T values than in optimal HBTs.

The natural candidates for broad BW circuits with high FOMs are distributed amplifiers (DAs). Using DAs, the BW can in principle approach f_T of the individual transistors of the circuit. A DA with a bandwidth of 75 GHz and high FOMs is described in this brief. The power consumption of the amplifier is about 35% less than that of previously reported amplifiers with comparable bandwidth.

II. TECHNOLOGY

The InP HBTs were grown by metal–organic molecular beam epitaxy. The carbon doped composition-graded base layer was 28 nm thick. The GaInAs collector was 600 nm thick in order to obtain high responsivity of PIN diodes fabricated of the same layers. Emitter dimensions were 1 × 10 μm. The transistor cutoff frequency versus collector current density is shown in Fig. 1. As mentioned above, due to the thick undoped collector, the Kirk effect threshold current density was low, and the maximum value of f_T was only 85 GHz. In similar devices with a 200-nm-thick collector, we obtained f_T values close to 200 GHz. The passive components in the circuits were 50 $\Omega/\Box$ NiCr resistors and SiN capacitors. Care was taken to minimize crossover line capacitance in our coplanar technology.

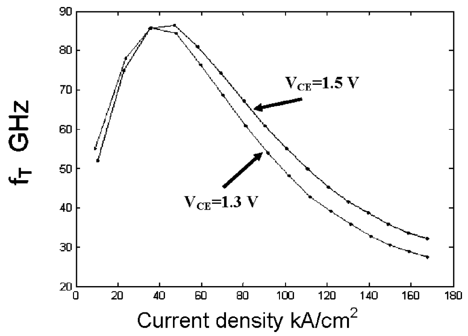

Fig. 1. Variation of f_T with collector current density of the HBTs at two different collector to emitter voltages.

III. CIRCUIT DESIGN

We have used the Agilent advanced design simulation (ADS) tool and the VBIC transistor model to carry out circuit design. Transistor parameters were extracted by the method described in [3]. In order to choose the optimal DA topology we have evaluated by simulation various known circuit topologies. Our first choice was a cascode configuration as in the circuits reported in [4] and [5]. The cascode configuration had poor input matching and low bandwidth because of the large input capacitance and low input resistance of each gain cell. An additional emitter follower at the input of each cascode stage is referred to as the attenuation compensation topology [1], [6]. It improved the input matching of each cell, but reduced the BW of each cell. An f_T doubler version of the ac topology [7], [8] was evaluated as well. This topology provided more gain, but increased input capacitance, and the resulting bandwidth of the DA was low.

The topology implemented in our circuit is shown in Fig. 2. It is based upon the attenuation compensation concept, but includes several significant improvements. The circuit elements that set the dc bias of the common emitter (CE) stage determine also its ac load, and their values must therefore be carefully optimized. In [1], [6], a single large resistor sets the dc bias of the CE stage. In the circuit presented here, we have replaced the large resistor by a diode connected in series with a small resistor and a peaking inductance. The low ac impedance of the diode compensates the large input capacitance of the CE stage and flattens the frequency response. The low impedance of the diode also eliminates the need for resistive degeneration at the CE stage. A peaking inductance in series with the diode further enhances the bandwidth and maintains input and output match. As shown in Fig. 2, an additional peaking line between the common base and CE stages in the cascode stage was introduced in our circuit. This peaking line reduces the peaking required at the output and hence improves matching and group delay response.

Manuscript received August 17, 2005; revised November 4, 2005. The review of this brief was arranged by Editor M. Anwar.

E. Cohen, B. Sheinman, S. Cohen, S. Sidorov, A. Gavrilov and D. Ritter are with the Department of Electrical Engineering, Technion, Haifa 32000, Israel.

Y. Betser is with Saifun Semiconducts, Netanya 42504, Israel.

Digital Object Identifier 10.1109/TED.2005.862239

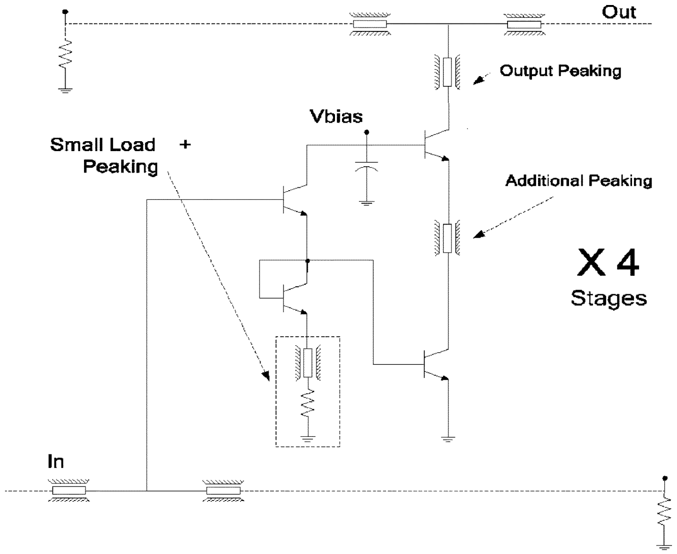

Fig. 2. Schematic circuit of a single stage.

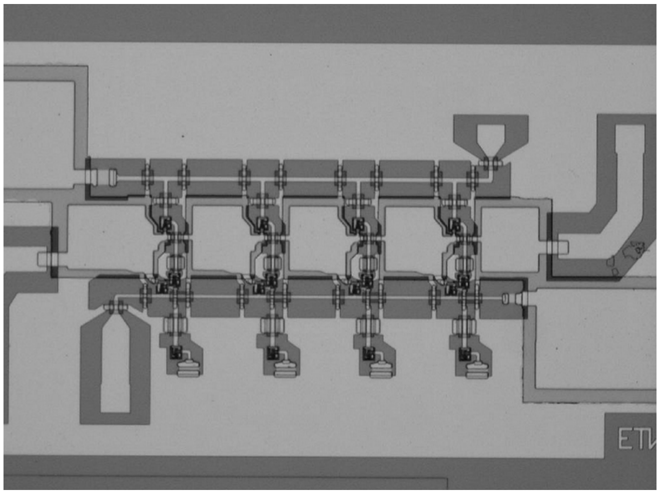

Fig. 3. Micro-photograph of the circuit.

The cascode stage was dc biased to obtain maximum f_T. The common collector (CC) stage, on the other hand, was biased at a lower current because of its higher bandwidth. The lower dc bias of the CC stage reduces the capacitance reflected to the input. The peaking inductance was implemented by a high impedance coplanar line. Much care was taken to minimize inductance between the CC stage and the input line, and between the CC and CE stages.

IV. CIRCUIT PERFORMANCE

Fig. 3 shows a photograph of the 1.7 $\times$ 0.9 mm^2 amplifier. The frequency response of the amplifier was measured on wafer by an Agilent 110 GHz vector network analyzer. The input and output bias supplies were provided directly through the 50 Ω input and output probes. The third bias supply was provided by a dc probe. The obtained frequency response of the circuit is shown in Fig. 4. A bandwidth of 75 GHz and gain of 14 dB was obtained at dc power of 78 mW. Excellent matching at the input better than -10 dB up to 85 GHz was obtained. Input matching is crucial for avoiding input coupling losses and a rippled response. Note that the values of s_{11} are sufficiently low for optical receiver applications. An attractive feature of the circuit is that its gain can be varied in the range of 10–14 dB while maintaining the bandwidth of 75 GHz. The 11 dB gain curve shown in the Fig. 4 was obtained by varying the dc bias of the circuit. The dc power for the 11 dB curve was 61 mW. The amplifier is thus useful for automatic gain control applications.

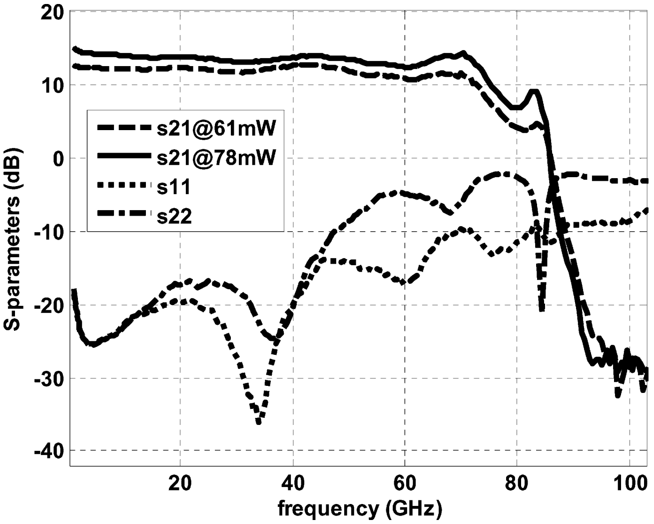

Fig. 4. Measured s-parameters of the distributed amplifier. The two S_{21} curves were measured at two different bias points: total power consumption of (full line) 78 mW and (dashed line) 61 mW.

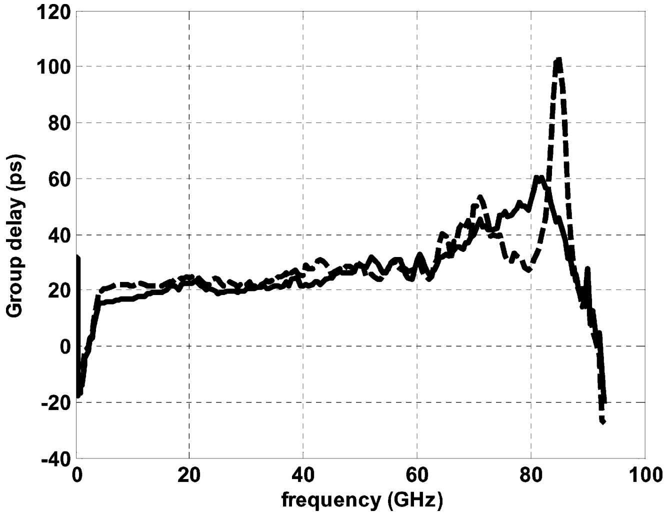

Fig. 5. Measured group delay of two different amplifiers with different peaking lines at the output. The full line corresponds to the amplifier whose s-parameters are shown in Fig. 4. The dashed line corresponds to a different amplifier with higher peaking values, which achieves somewhat larger bandwidth at the expense of a more rippled group delay.

It is important to optimize both bandwidth and group delay in optoelectronic high bandwidth links. Fig. 5 shows the measured group delay of two different circuits with different peaking line lengths at the collector. The circuit with the flatter group delay curve has a shorter peaking line. The circuit with the longer peaking line exhibited a broader bandwidth, but its group delay had undesirable peaking.

Table I summarizes the FOMs of various HBT based distributed amplifiers reported in the literature. The FOMs of the circuit described in

TABLE I
FIGURES OF MERIT OF VARIOUS HBT DISTRIBUTED AMPLIFIER TOPOLOGIES

Type [Ref]	**Gain [dB]**	**BW [GHz]**	f_T **[GHz]**	$f_{\max}$ **[GHz]**	**BW/**f_T	**GBP/**f_T	**DC power [mW]**
This work	11	75	81	150	0.92	3.3	61
(Same circuit at two bias points)	14	75	84		0.9	4.47	78
Modified AC [8]	16	80	152	173	0.53	3.3	293
Capacitively coupled [9]	6.7	80	160	370	0.5	1.1	250
Cascode [5]	13	74	160	140	0.46	2.1	120

this work are clearly record values. Note also the record low power consumption of our amplifier.

V. DISCUSSION

Kobayashi *et al.* [1] first introduced the BW/f_T FOM of traveling wave amplifiers (TWAs). However, since the bandwidth of TWAs depends on both f_T and $f_{\max}$ the relevance of this FOM may be questioned. In the topology presented in the manuscript we have observed by simulation that increasing $f_{\max}$ at the expense of f_T does not improve the bandwidth. Best results are obtained when the values of f_T and $f_{\max}$ are comparable. The BW of the amplifier is approximately set by two independent limits: the BW of the transmission lines and the BW of the basic cell. The transmission line BW is determined largely in our topology by the input and output capacitance set by C_{bc}. Since C_{bc} also determines $f_{\max}$ one may conclude that the transmission line BW is mainly affected by $f_{\max}$. On the other hand, the BW of the basic cell is set mainly by the value of f_T. In our design the BW is limited by the basic cell and not by the transmission line or output capacitance. Since the BW of the cells limits the BW of the amplifier we have introduced the additional peaking lines in the basic cell to enhance the BW of the basic cell and hence of the BW of the amplifier. We thus conclude that for our topology the BW/f_T FOM is of much significance, and that high $f_{\max}$ values are not sufficient to obtain a large BW. High $f_{\max}$ values are not sufficient for obtaining a large BW also in other topologies. In [9] where $f_{\max} = 370$ GHz a BW of 80 GHz was obtained, and in [5] where $f_{\max} = 140$ GHz a BW of and 74 GHz was obtained.

We would like to finally mention that it is sometimes argued that the group delay variation (GDV) of TWAs limits their usefulness for broadband communication systems. However, no previous publications on bipolar TWAs present GDV plots. Here, the GDV was simulated and measured, and found very small even tough high peaking was used. The design concept that helped us reduce GDV was adding more peaking between the inner stages and hence less peaking at the CB output.

VI. CONCLUSION

A distributed amplifier with an improved topology using thick collector InP/GaInAs HBTs was presented. The thick collector HBTs are suitable for OEIC optical receiver applications in which the base collector junction layers serve also as the PIN diode layers. The DA exhibited 14 dB gain with BW of 75 GHz. The maximum f_T of the HBTs was 84 GHz, hence the DA exhibits record BW to f_T values. Using smart peaking a very flat response and group delay was obtained for improved sensitivity. The calculated transimpedance gain is 48 dBΩ with current noise of 30 pA/Hz$^{1/2}$. The DA presented in this brief is therefore an excellent choice for OEIC receivers for the next generation of high data rate lightwave communication system reaching 100 Gb/s at non return to zero (NRZ). Simulations show that our topology can reach a bandwidth of 95 GHz and beyond with narrower collector HBTs.

ACKNOWLEDGMENT

The authors would like to thank R. Doerner and M. Rudolph of the Ferdinand Braun Institut für Hüchstfrequenztechnik, Berlin, for providing the high-frequency measurements setup and their kind assistance in the measurements.

REFERENCES

[1] K. W. Kobayashi, R. Esfandiari, and A. K. Oki, "A novel HBT distributed amplifier design topology based on attenuation compensation techniques," *IEEE Trans. Microw. Theory Tech.*, vol. 42, no. 12, pp. 2583–2589, Dec. 1994.

[2] M. Agethen, D. Keiper, G. Janssen, A. Brennemann, P. Velling, C. van den Berg, and R. M. Bertenburg, "InGaAs PIN detectors for frequencies above 100 GHz," in *Proc. IPRM*, May 2002, pp. 673–676.

[3] B. Sheinman, E. Wasige, M. Rudolph, R. Doerner, V. Sidorov, S. Cohen, and D. Ritter, "A peeling algorithm for extraction of the HBT small-signal equivalent circuit," *IEEE Trans. Microw. Theory Tech.*, vol. 50, no. 12, pp. 2804–2810, Dec. 2002.

[4] K. W. Kobayashi, "A 50 MHz – 55 GHz multidecade InP-based HBT distributed amplifier," *IEEE Microw. Guided Wave Lett.*, vol. 7, no. 10, pp. 353–355, Oct. 1997.

[5] Y. Baeyens, R. Pullela, J. P. Mattia, H.-S. Tsai, and Y.-K. Chen, "A 74-GHz bandwidth InAlAs/InGaAs-InP HBT distributed amplifier with 13-dB gain," *IEEE Microw. Guided Wave Lett.*, vol. 9, no. 11, pp. 461–463, Nov. 1999.

[6] S. Mohammadi, J. Park, D. Pavlidis, J. Guyaux, and J. Garcia, "Design optimization and characterization of high-gain GaInP/GaAs HBT distributed amplifiers for high-bit-rate telecommunication," *IEEE Trans. Microw. Theory Tech.*, vol. 48, no. 6, pp. 1038–1044, Jun. 2000.

[7] S. Krishan, D. Mensa, S. Jaganathan, T. Mathew, Y. Wei, and M. J. W. Rodwell, "Broadband HBT amplifiers," in *Proc. IEEE/Cornell Conf.*, Aug. 2000, pp. 6–10.

[8] Y. Arayashiki, Y. Ohkubo, Y. Amano, A. Takagi, M. Ejima, and Y. Matsuoka, "16 dB 80 GHz InGaP/GaAs HBT distributed amplifier," *Electron. Lett.*, vol. 40, no. 4, pp. 244–245, Feb. 2004.

[9] B. Agarwal, Q. Lee, D. Mensa, R. Pullela, J. Guthrie, and M. Rodwell, "80-GHz distributed amplifiers with transferred substrate heterojunction bipolar transistors," *IEEE Trans. Microw. Theory Tech.*, vol. 46, no. 12, pp. 2302–2307, Dec. 1998.