

80-GHz Distributed Amplifiers with Transferred-Substrate Heterojunction Bipolar Transistors

Bipul Agarwal, Q. Lee, Dino Mensa, Raja Pullela, James Guthrie, and Mark J. W. Rodwell

Abstract—We report distributed amplifiers with 80-GHz bandwidth, 6.7-dB mid-band gain. These amplifiers were fabricated in the transferred-substrate heterojunction bipolar transistor integrated circuit technology. Transferred-substrate HBT's have very high f_{\max} (>400 GHz) and have yielded distributed amplifiers with record gain-bandwidth product.

I. INTRODUCTION

TRAVELING-WAVE amplifiers (TWA's) are very broad-band circuits with applications in instrumentation and wide-band radar receivers. Broad bandwidth is achieved by absorbing the transistor parasitics into synthetic input and output $50\text{-}\Omega$ transmission lines. Flat gain is achieved up to the Bragg frequency of the distributed line, and limited by the available gain from the device. Hence, the amplifier gain-bandwidth product depends critically on the transistor f_{\max} . To date, TWA's based on high-electron mobility transistors (HEMT's) have demonstrated considerably higher bandwidths than those based on heterojunction bipolar transistors (HBT's) [1]–[4], primarily due to the higher f_{\max} of HEMT's. Transferred-substrate HBT's have high f_{\max} [5], comparable to that of high-performance InGaAs–InAlAs–InP HEMT's, and have demonstrated feedback amplifiers with very high bandwidths [6]. Hence, TWA's with very high bandwidths should be possible in the transferred-substrate HBT IC technology. Here, we report first results with TWA's fabricated in this technology.

TWA design with HEMT's has been covered in detail in [1]. HBT TWA design differs considerably from that using HEMT's. The HBT transconductance—hence input capacitance ($C_{be} \simeq g_m/2\pi f_{\tau}$)—per unit HBT emitter area is large. To obtain the desired Bragg frequency, either very small HBT's must be used, or input capacitive-division [7] must be employed. The higher HBT input resistance compared to that of HEMT's (r_{bb} versus r_{gate}) favors the use of very high capacitive-division ratios.

In addition to the input line losses due to the transistor input impedance, TWA gain-bandwidth also depends on the output impedance of the transistor. The frequency-dependent output

GalnAs 1000 Å $1 \cdot 10^{19}$ Si	emitter
Grade 66 Å	
AllnAs 834 Å $1 \cdot 10^{19}$ Si	
AllnAs 500 Å $8 \cdot 10^{17}$ Si	
Grade 300 Å	base
GalnAs 300 Å $5 \cdot 10^{19}$ Be	
GalnAs 100 Å $3 \cdot 10^{19}$ Be	
GalnAs 400 Å $2 \cdot 10^{16}$ Si	
GalnAs 50 Å $1 \cdot 10^{18}$ Si	collector
GalnAs 2250 Å $1 \cdot 10^{16}$ Si	
AllnAs 2500 Å	
S. I. InP	

Fig. 1. MBE epitaxial layer structure of transferred-substrate HBT's.

impedance of HBT's introduces large output line losses. This is a second feature of HBT TWA's that differs substantially from HEMT TWA's. The output impedance of a HEMT is—to first order— R_{ds} . For a HBT driven by a resistive generator impedance, the frequency-dependent output impedance arises from feedback through C_{cb} . Cascode connected transistors greatly increase the cell output impedance, decreasing collector line losses to the point where input line losses dominate.

TWA bandwidth is strongly influenced by the frequency-dependent transmission line losses, which become dominant at high frequencies. The transferred-substrate HBT IC process incorporates low-loss microstrip lines on a benzocyclobutene (BCB, $\epsilon = 2.7$) substrate. These low-loss transmission lines make high bandwidths feasible. With these design and technological improvements, we have fabricated TWA's with 6.7-dB gain and 80-GHz 0-dB (where the gain goes below the mid-band gain) bandwidth. The 3-dB bandwidth is 85 GHz. This is the highest gain-bandwidth product reported for a HBT distributed amplifier.

The transferred-substrate HBT IC technology is described first. HBT TWA design is briefly discussed, followed by measurements and conclusions.

II. TRANSFERRED-SUBSTRATE HBT TECHNOLOGY

This section describes the transferred-substrate HBT technology in detail. The fabrication process is discussed first, followed by device dc and RF characteristics.

Manuscript received March 24, 1998; revised August 28, 1998. This work was supported by the Office of Naval Research under Grant N00014-95-1-0688, by the Air Force Office of Scientific Research under Grant F49620-96-1-0019, and by a California Hughes Micro 8960808.

The authors are with the Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106 USA (e-mail: rodwell@ece.ucsb.edu).

Publisher Item Identifier S 0018-9480(98)09204-7.

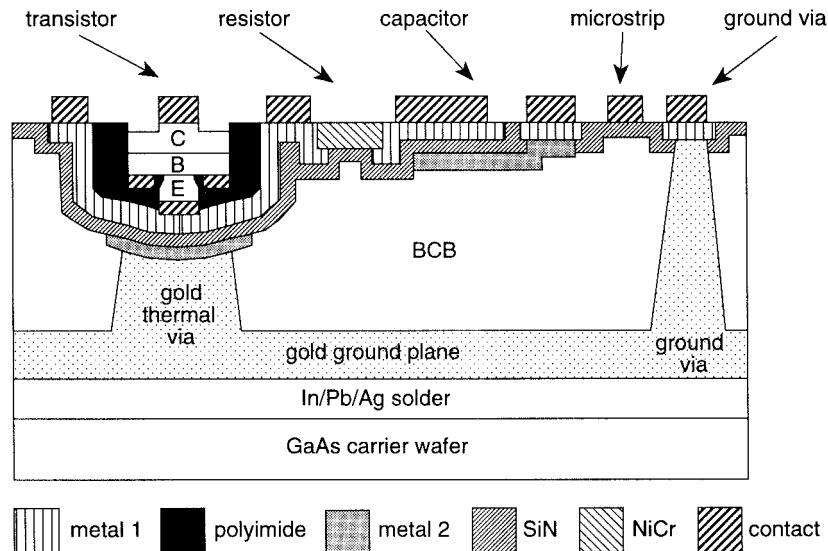


Fig. 2. Schematic cross section of transferred-substrate HBT IC process.

A. Fabrication

Fig. 1 shows the MBE epitaxial layer structure used in this work. The growth is done on a Fe-doped semi-insulating (100) InP substrate, starting with a 2500-Å AlInAs buffer layer. The GaInAs collector is 2700 Å thick, is Si-doped at $1 \times 10^{16}/\text{cm}^3$ and contains a $5 \times 10^{11}/\text{cm}^2$ Si pulse-doped layer 400 Å from the base. The 400-Å GaInAs base is graded in both doping and bandgap. The 100 Å of the Ga_{0.47}In_{0.53}As base immediately adjacent to the collector is Be-doped at $3 \times 10^{19}/\text{cm}^3$. The remaining 300 Å of the base is Be-doped at $5 \times 10^{19}/\text{cm}^3$. By increasing the Ga cell temperature progressively during growth of the 300-Å layer, the Ga:In ratio is gradually increased, introducing a ~ 0.03 -eV bandgap gradient across the 300-Å layer. The base is then graded in 300-Å to the AlInAs emitter. The first 66 Å of the grade is Be-doped at $2 \times 10^{18}/\text{cm}^3$ and the remainder is Si-doped at $8 \times 10^{17}/\text{cm}^3$. The AlInAs emitter is about 1350 Å thick. The first 500 Å are Si-doped at $8 \times 10^{17}/\text{cm}^3$ and the remainder is Si-doped at $1 \times 10^{19}/\text{cm}^3$. This is graded in 66 Å to the InGaAs emitter cap. The emitter cap is n⁺ doped with Si at $1 \times 10^{19}/\text{cm}^3$.

Fig. 2 shows a schematic cross-section of the transferred-substrate HBT integrated circuit process. The fabrication process starts with the evaporation of Ti-Pt-Au emitter contacts. A combination of a dry etch, a selective wet etch, and a nonselective wet etch is then used to etch down to the base epitaxial layer. Self-aligned Ti-Pt-Au base metal is evaporated and sintered. Transistors are then isolated by forming mesas, stopping on the AlInAs buffer layer. Thin-film NiCr is evaporated on the wafer to form resistors with $50\Omega/\square$ sheet resistivity. The devices are passivated and the emitters are planarized with polyimide. Polyimide also serves as interconnect crossovers for multiple wiring levels. The first level of metallization (M1), is evaporated at this point. This metal forms most of the transmission lines, interconnect wiring, probe pads, capacitor bottom plate and resistor contacts. Emitters and bases are also contacted by this metal. SiN dielectric is then deposited over the entire wafer by plasma-enhanced chemical

vapor deposition (PECVD). This dielectric serves three purposes: it forms the dielectric for metal-insulator-metal (MIM) capacitors; it forms the insulator for crossovers between M1 and the second level of metallization; and, it forms a insulating layer over the whole wafer prior to the process of substrate transfer. The SiN is selectively etched away followed by the second level of metallization (M2), similar to M1. M2 also forms the top plate for MIM capacitors.

The substrate transfer process starts by coating the wafer with a thick layer of benzocyclobutene (BCB, $\epsilon_r = 2.7$) and curing. Thermal vias on the emitters and ground vias are formed by dry etching openings in the BCB. This etch also etches the SiN insulator layer in the vias. The vias are then filled with thick Au by electroplating. The electroplated Au also forms an electrically and thermally conducting ground plane, thus grounding all emitters. Transistors with nongrounded emitters (required in IC's) are fabricated by protecting the SiN insulator with M2 before applying BCB (Fig. 2). Power supply bypass capacitors could be formed similarly. On transistors not having the layer of M2, the SiN insulator is removed during the via formation etch, thus grounding the emitter.

Microstrip interconnect lines on BCB provide a low-capacitance wiring environment for dense circuits. Ground vias to the thick electroplated ground plane provide low ground return inductance. Thermal vias provide efficient heat-sinking for devices operating at very high current densities.

The wafer is then inverted and bonded to a GaAs transfer substrate. The InP substrate and the AlInAs buffer layer are removed by a wet etch thus exposing all the buried elements of the wafer. Ti-Pt-Au Schottky collector contacts are then deposited. This metal layer could be used as a third level of metallization (M3), if needed, with polyimide as the insulator. Outside the active collector area, about 1500 Å of the collector drift region are then removed by a self-aligned wet etch to reduce collector-base fringing capacitance.

This completes the transferred-substrate HBT IC process. For integrated circuit applications, high device yield is re-

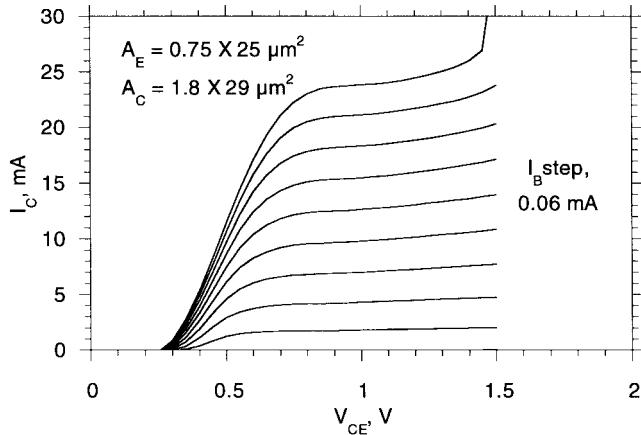


Fig. 3. DC common-emitter characteristics of transferred-substrate HBT's.

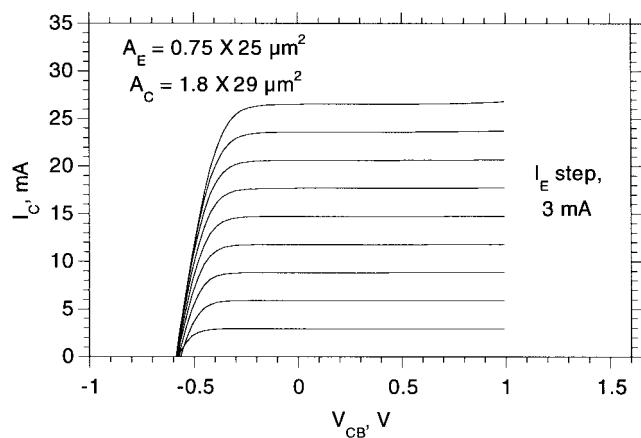


Fig. 4. DC common-base characteristics of transferred-substrate HBT's.

quired. The transferred-substrate HBT IC technology is constantly being improved toward this goal. The technology is currently capable of yielding circuits with few tens of transistors.

B. Device Characteristics

Common-emitter dc characteristics of the devices are shown in Fig. 3. The devices have $0.8 \mu\text{m} \times 25 \mu\text{m}$ emitters and $1.8 \mu\text{m} \times 29 \mu\text{m}$ collectors. The small signal current gain at dc, β , is 50. The common-emitter breakdown voltage BV_{CEO} is ~ 3 V, decreasing to 1.5 V at 10^5 A/cm^2 . The low breakdown voltage is due to the narrow-bandgap InGaAs collector material.

The dc characteristics of the devices with $0.75 \mu\text{m} \times 25 \mu\text{m}$ emitters and $1.8 \mu\text{m} \times 29 \mu\text{m}$ collectors were measured in the common-base configuration also. Fig. 4 shows these characteristics. The common base current gain α is 0.98. The common-base breakdown voltage BV_{CBO} is ~ 6 V, decreasing to 1.5 V at 10^5 A/cm^2 .

The devices were characterized by on-wafer network analysis to 50 GHz. Fig. 5 shows the maximum available/maximum stable gain MAG/MSG, the short-circuit current gain h_{21} , and Mason's invariant (unilateral) power gain U of the transistor. Pad parasitics have not been stripped. Device dimensions and

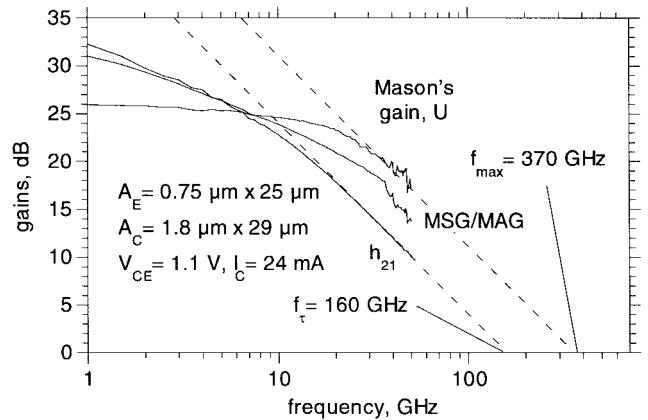
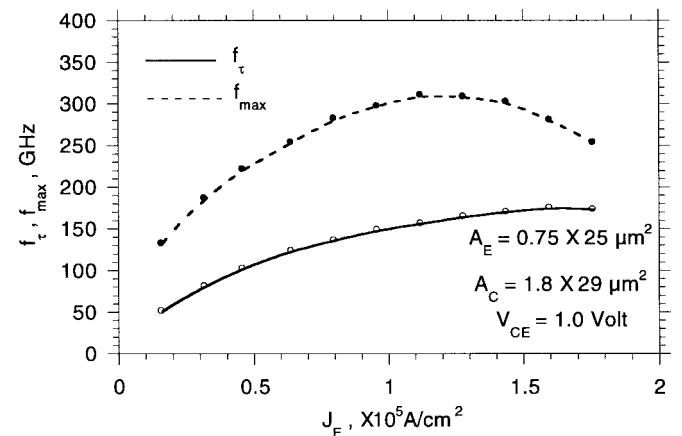
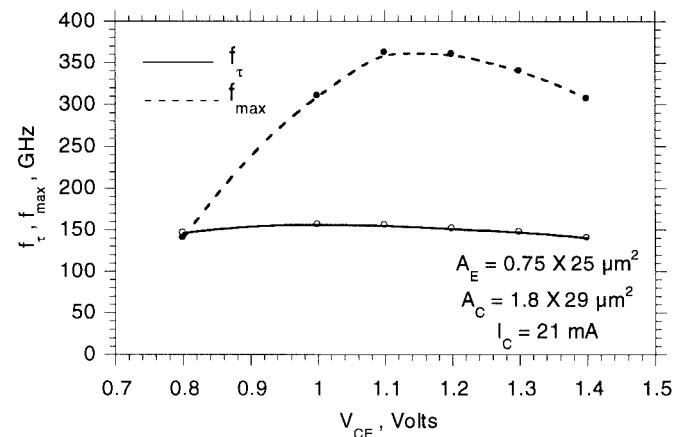


Fig. 5. RF characteristics of transferred-substrate HBT's.

Fig. 6. Variation of f_τ and f_{\max} with emitter current density J_E .Fig. 7. Variation of f_τ and f_{\max} with collector-emitter voltage V_{CE} .

bias conditions are as shown. Extrapolating at -20 dB/decade , $f_{\max} = 370 \text{ GHz}$ and $f_\tau = 160 \text{ GHz}$.

Fig. 6 shows the variation of f_τ and f_{\max} with emitter current density J_E . The peak f_τ is 175 GHz. f_τ increases with current density and saturates at high current densities due to Kirk effect. The Kirk effect threshold is high due to the presence of the pulse-doped layer in the collector, close to the base. Kirk effect influences f_{\max} more strongly than f_τ as is seen from the reduced f_{\max} at high current densities.

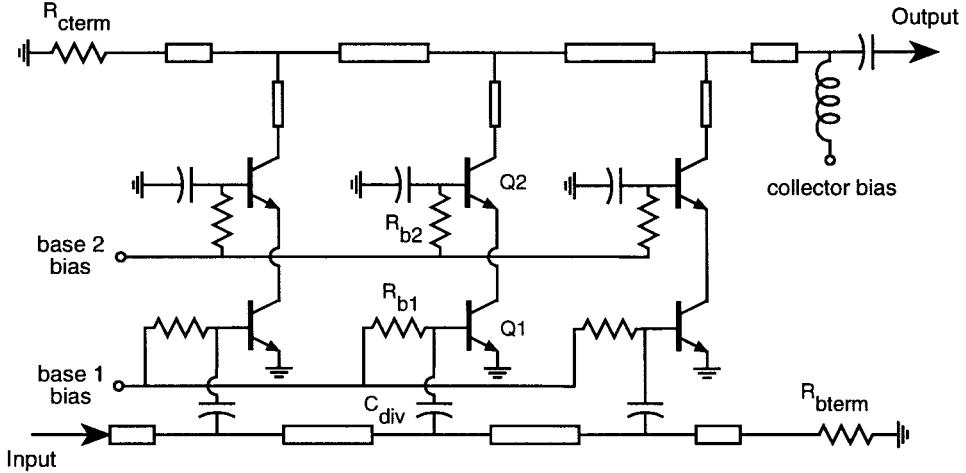


Fig. 8. Schematic circuit diagram of the capacitive-division traveling-wave amplifier.

This is because when the base width increases, the base transit time increases and the collector transit time reduces thus keeping the sum of the two relatively constant. But, the reduced collector thickness increases C_{cb} and degrades f_{\max} . By plotting $1/2\pi f_{\tau}$ versus $1/J_E$, it is determined that the sum of the base and collector transit times ($\tau_b + \tau_c$) is 0.67 ps. Fig. 7 shows the variation of f_{τ} and f_{\max} with collector-emitter voltage, V_{CE} . At low V_{CE} , the collector thickness reduces due to base pushout leading to increased C_{cb} and reduced f_{\max} . At high V_{CE} , f_{τ} and f_{\max} decrease, suggesting a decrease in the collector electron velocity at high electric fields.

Small-signal hybrid- π models of transferred-substrate HBT's were developed from bias-dependent S -parameters. This simple model was used to design and simulate the traveling-wave amplifier, which is presented in the next section.

III. CIRCUIT DESIGN AND FABRICATION

The theory of traveling-wave amplifiers has been presented in detail elsewhere in this journal [1]. It was shown that capacitive voltage division can be used on the input line to achieve gain-bandwidth products approaching the transistor f_{\max} for any given design bandwidth. To obtain even higher gain-bandwidth products, a cascode transistor cell can be used instead of a single transistor. The theory developed in [1] applies equally well to HBT's. Here, we present only the final result. Using a simplified HBT hybrid- π model with the base resistance r_{bb} , the emitter-base capacitance C_{be} , transconductance g_m , and the division capacitor C_{div} , we obtain for a cascode capacitive-division TWA

$$A_v = -NMg_mZ_o/2 \quad (1)$$

where A_v is the voltage gain, N is the number of TWA cells, M is the capacitive-division ratio ($= C_{div}/(C_{div} + C_{be})$) and Z_o is the characteristic impedance. The number of sections is limited by the input line losses (since output line losses are negligible). The input voltage to the N th stage is attenuated by $e^{-(N-1/2)\alpha_b}$. The maximum number of transistors N_{\max}

for a given desired bandwidth ω_{BW} is given by

$$N_{\max}\omega_{BW}^2 M^2 C_{be}^2 r_{bb} Z_o \simeq 1. \quad (2)$$

Using (1) and (2), the gain-bandwidth product is given by

$$A_v \omega_{BW}^2 = g_m / M C_{be}^2 r_{bb}. \quad (3)$$

If aggressive capacitive-division (smaller M) is used, the number of sections used can be higher and gain-bandwidth improves, but is limited by the maximum available gain of the cascode cell. In the above derivation, the transmission line skin-effect and radiation losses have been neglected. These losses do impact the highest attainable gain-bandwidth in a given technology. If these losses are made negligible, the available power gain from the device can be achieved.

Fig. 8 shows the schematic circuit diagram of the capacitive-division TWA. Cascode-connected HBT's Q1-Q2 are used as explained before. The base and collector lines are composed of 75- Ω microstrip line sections. C_{div} is the division capacitor at the input of the common-emitter transistor Q1. A short length of microstrip is used at the output of the cascode cell to improve velocity matching between the input and output lines. The microstrip lines, together with the division capacitor and the cascode stage synthesize 50 Ω input and output lines. R_{bterm} is the 50 Ω base-line termination resistor. R_{cterm} , the collector-line termination resistor is off-chip to sustain the high collector bias current, and is connected through a microwave probe. R_{b1} is a large resistor to bias the input of Q1. The base of the common-base transistor Q2 is biased through an independent supply. The ac ground at this node is provided by large bypass capacitors. R_{b2} provides decoupling between the multiple cells and prevents oscillations from resonance between the bias probe inductance and the bypass capacitors. The collector bias is through a bias tee at the output of the chip. Amplifiers with three cascode cells were fabricated. The simulated gain is about 7 dB and the designed bandwidth is 90 GHz. Fig. 9 shows a photomicrograph of the fabricated chip. The die size is about 1.4 mm \times 0.6 mm.

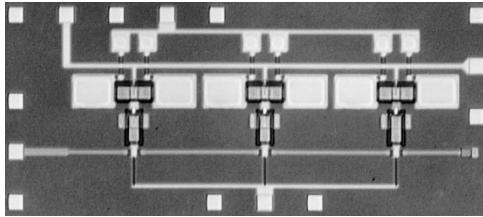


Fig. 9. Photomicrograph of the amplifier IC.

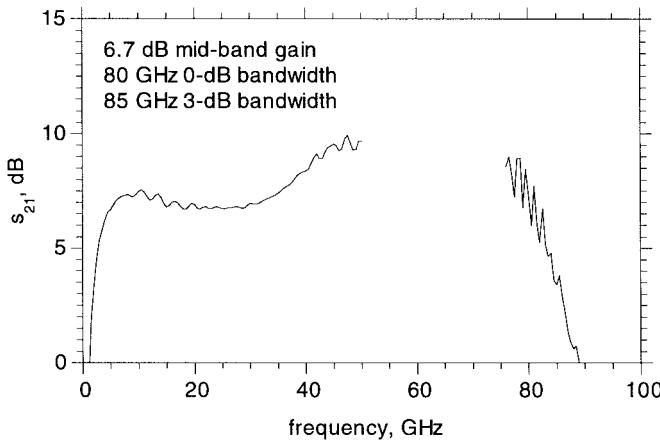


Fig. 10. Measured forward gain s_{21} of the amplifier.

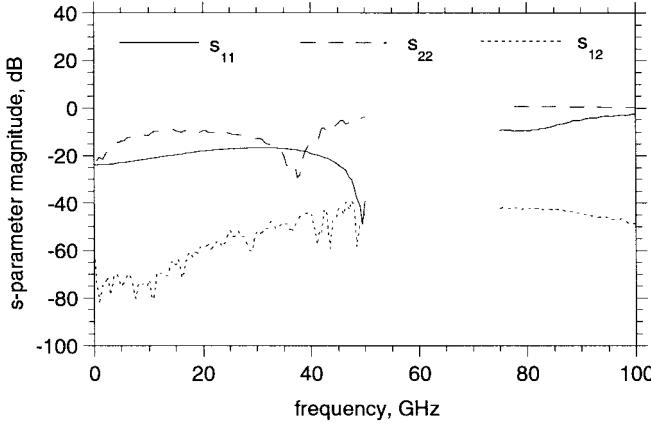


Fig. 11. Measured input return loss s_{11} , output return loss s_{22} , and reverse isolation s_{12} of the amplifier.

IV. MEASUREMENTS

The amplifiers were tested on-wafer using commercial network analyzers from 0.045 to 50 GHz and 75 to 110 GHz. Fig. 10 shows the forward gain of the amplifier. The midband gain is about 6.7 dB. The 0-dB bandwidth (where the gain goes below the mid-band gain) is 80 GHz. The 3-dB bandwidth is 85 GHz.

From this curve, we can also observe gain peaking at high frequencies. The gain-frequency response of TWA's is strongly impacted by device f_{\max} and the designed Bragg frequency. During design, a conservative HBT model with a 200-GHz f_{\max} was assumed. HBT's on the current wafer have 370-GHz f_{\max} which results in the observed gain peaking. Given the 370-GHz f_{\max} , redesigning the amplifier would

permit bandwidths greater than 80–90 GHz. The low frequency cutoff is about 2 GHz and is determined by the transistor f_{τ}/β . Fig. 11 shows the input and output return losses and the reverse isolation. The amplifier output return loss s_{22} is poor at high frequencies because of the off-chip collector-line termination. The chip consumes about 250 mW of power.

V. CONCLUSION

We have designed and fabricated distributed amplifiers with 6.7-dB gain, 80-GHz 0-dB bandwidth, and 85-GHz 3-dB bandwidth. These amplifiers have the highest gain-bandwidth product reported for a distributed HBT amplifier. The IC's demonstrate the potential of transferred-substrate HBT's for producing very high-speed integrated circuits. Further improvements in the design of the amplifier, as well as in the intrinsic device technology will lead to wider bandwidth circuits.

REFERENCES

- [1] B. Agarwal, A. E. Schmitz, J. J. Brown, M. Le, M. Lui, and M. J. W. Rodwell, "A 1–157 GHz InP HEMT traveling-wave amplifier," this issue, pp. XXXX–XXXX.
- [2] S. Kimura, Y. Imai, and T. Enoki, "0–90 GHz InAlAs/InGaAs/InP HEMT distributed baseband amplifier IC," *Electron. Lett.*, vol. 31, pp. 1430–1431, 1995.
- [3] K. W. Kobayashi, J. Cowles, L. T. Tran, A. Gutierrez-Aitken, T. R. Block, A. K. Oki, and D. C. Streit, "A 50-MHz-55-GHz multidecade InP-based HBT distributed amplifier," *IEEE Microwave Guided Wave Lett.*, vol. 7, pp. 353–355, 1997.
- [4] H. Suzuki, K. Watanabe, K. Ishikawa, H. Masuda, K. Ouchi, T. Tanoue, and R. Takeyari, "InP/InGaAs HBT IC's for 40 Gbit/s optical transmission systems," in *GaAs IC Symp. Tech. Dig.*, 1997, pp. 215–218.
- [5] Q. Lee, B. Agarwal, D. Mensa, R. Pullela, J. Guthrie, L. Samoska, and M. J. W. Rodwell, "A >400 GHz f_{\max} transferred-substrate heterojunction bipolar transistor IC technology," *IEEE Electron Device Lett.*, vol. 19, pp. 77–79, 1998.
- [6] B. Agarwal, D. Mensa, Q. Lee, R. Pullela, J. Guthrie, L. Samoska, and M. J. W. Rodwell, "A 50 GHz feedback amplifier with AlInAs/GaInAs transferred-substrate HBT," in *Int. Electron Devices Meeting Tech. Dig.*, 1997, pp. 743–746.
- [7] Y. Ayasli, S. W. Miller, R. Mozzi, and L. K. Hanes, "Capacitively coupled traveling-wave power amplifier," *IEEE Trans. Electron Devices*, vol. 31, pp. 1937–1942, 1984.



Bipul Agarwal was born in Cuttack, India, in 1970. He received the undergraduate degree in electronics and communications engineering from the Indian Institute of Technology, Madras, in 1992, and the M.S. and Ph.D. degrees in electrical engineering (solid state) from the University of California, Santa Barbara, in 1995 and 1998, respectively. His Ph.D. dissertation dealt with high-speed InP HBT circuits for fiber-optic communication.

He is currently employed as a Design Engineer at Rockwell Semiconductor Systems in Newport Beach, CA. At Rockwell, he is involved with design of RF circuits for wireless communications.



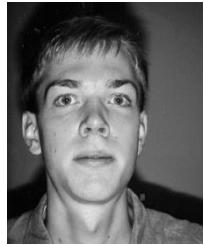
Dino Mensa was born in Ventura, CA, in 1973. He received the B.S. degree in physics and the M.S. degree in electrical engineering from the University of California at Santa Barbara, in 1995 and 1997, respectively, and is currently working toward the Ph.D. degree in electrical engineering at UCSB.

His research projects are the MBE growth and device design of InP HBT's, as well as high-frequency analog and digital design in the transferred-substrate pr.



Raja Pullela was born on August 14, 1972, in Chirala, India. He obtained the B.Tech. degree in electronics and communication engineering from the Indian Institute of Technology, Mumbai, and the Ph.D. degree from the University of California, Santa Barbara, in 1993 and 1998, respectively.

He is currently a member of Technical Staff at Bell Laboratories, Lucent Technologies. His current research involves high-speed devices and IC's for fiber communication systems.



James Guthrie received the B.S. degree in engineering science and the M.S. degree in electrical engineering from the University of Toronto, Toronto, ON, Canada, in 1992 and 1994, respectively, and since 1994, he has been working toward the Ph.D. degree in the ECE Department of the University of California at Santa Barbara.

His current research interests include millimeter-wave circuit design and novel HBT MMIC process technologies.



Mark J. W. Rodwell was born in Altrincham, U.K., in 1960. He received the B.S. degree in electrical engineering from the University of Tennessee, Knoxville, in 1980, and the M.S. and Ph.D. degrees in electrical engineering from Stanford University, Stanford, CA, in 1982 and 1988, respectively.

From 1982 through 1984, he worked at AT&T Bell Laboratories, developing optical transmission systems. He was a Research Associate at Stanford University from January to September 1988. In September 1988, he joined the Department of Electrical and Computer Engineering, at the University of California, Santa Barbara, where he is currently a Professor and Director of the Compound Semiconductor Research Laboratories. His current research involves submicron scaling of millimeter-wave heterojunction bipolar transistors (HBT's) and development of HBT integrated circuits for microwave mixed-signal IC's and fiber-optic transmission systems. His group has developed deep micrometer Schottky-collector resonant-tunnel diodes with terahertz bandwidths, and has developed monolithic submillimeter-wave oscillators with these devices. His group has worked extensively in the area of GaAs Schottky-diode integrated circuits for subpicosecond pulse generation, signal sampling at submillimeter-wave bandwidths, and millimeter-wave instrumentation.

Dr. Rodwell was the recipient of a 1989 National Science Foundation Presidential Young Investigators Award, and his work on submillimeter-wave diode IC's was awarded the 1997 IEEE Microwave Prize.