High Output Power Ultra-Wideband Distributed Amplifier in InP DHBT Technology Using Diamond Heat Spreader

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Abstract—This work reports on a highly linear and high output power ultra-wideband distributed amplifier with improved thermal properties using a diamond layer for heat spreading. The performances of a circuit with and without the diamond heat spreader are compared. Adding the diamond yields a 4 dB improvement in 1 dB compression point ($P_{\text{sat}}$) and saturated output power ($P_{\text{out}}$). Intermodulation distortion has also been measured and the amplifier achieves 24 dBm $OIP_3$ over a bandwidth larger than 60 GHz. In terms of small-signal characteristics, the circuit shows 12 dB gain and low deviation from linear phase, similarly to the non-diamond version. This amplifier demonstrates highest $P_{\text{sat}}$, $OIP_3$, and PAE values as compared to other technologies with similar or higher bandwidth.

Keywords—distributed amplifier, InP double heterojunction bipolar transistor (DHBT), monolithic microwave integrated circuit (MMIC), travelling wave amplifier.

I. INTRODUCTION

Modern communication systems are undergoing massive changes due to the demand for high data rates, whether in optical wireline technologies, wireless, or RF-over-fibre. Many of such systems require ultra-broadband highly linear amplification with constant group-delay characteristics. Other concurrent applications include broadband spectroscopic and broadband measurement systems which are so far limited by the bandwidth and linearity of the ultra-wideband amplifiers. For all of these applications, ultra-wide bandwidth, low deviation from linear phase, high linearity at the amplifier’s output and finally good efficiency are simultaneously required.

The distributed amplifier, demonstrated as MMIC first in GaAs MESFET technology [1], has been a promising architecture to provide all afore-mentioned merits. With today’s high-speed semiconductor technologies, e.g. CMOS [2], SiGe HBT [3], InP HEMT [4] and InP DHBT [5-9] ultra-wideband amplifiers have been realized up to 235 GHz [9]. However, many of them suffer from low output dynamic range, low saturated output power and low PAE. InP DHBT technology has shown the best combination in terms of bandwidth [9] and output power [8] for operating frequencies beyond 150 GHz. The quest now lies in improving the linearity, for which the 1 dB compression point ($P_{\text{1dB}}$) and the intermodulation products, such as $OIM_3$, are taken as a measure.

This paper reports on a significant improvement in linearity for such an amplifier when using a diamond heat spreading layer. Based on a distributed amplifier with a reported bandwidth of 175 GHz [8], a thin layer of diamond has been applied on top of the wafer to reduce the thermal resistance of the InP DHBT devices and passive circuit elements. This enhances linearity and saturated output power of the amplifier by 4 dB. The $PAE$ remains close to 6% when compared to the non-diamond variant. The thermal vias to the diamond layer, however, introduces an additional parasitic capacitance on the collector of the transistors. Together with the loading of the transmission lines this reduces the overall bandwidth of the amplifier by 25 GHz to 150 GHz.

II. TECHNOLOGY

The distributed amplifier (DA) is manufactured using an InP DHBT MMIC process based on 0.5 μm emitter size. A simplified cross-section of the layer stack is shown in Fig. 1. The InP transistors are transferred to a silicon host substrate by a wafer-level adhesive bond process using benzocyclobutene (BCB), with subsequent wet chemical removal of the InP wafer. In the next step, the interconnections and passive elements of the MMICs are formed. After this, an additional bond process is applied to put a 10 μm thick diamond heat spreader on top of the layer stack, in order to reduce the thermal resistance of transistors.

The InP DHBT devices exhibit $f_{\text{max}}$ values of 390/480 GHz, respectively. The breakdown voltage corresponds to >4 V and facilitates high output power circuit design. Four gold metal layers, G1, G2, G3, and Gd with thickness values of 1.5 μm, 2 μm, 3.5 μm, and 2.5 μm, respectively, serve as interconnect between the circuit components. Additionally, MIM capacitors with a sheet capacitance of 0.3 fF/μm² and NiCr resistor with a sheet resistance of 25 Ω/μm².
are used for matching and DC feed networks. Additional details can be found in [10].

III. MODELING FOR DIAMOND HEAT SPREADER

A. TFMSL Characterization and Modeling

Low-loss thin-film microstrip lines (TFMSL) in the standard transferred substrate InP DHBT technology are formed between the metal layers G2 and Gd (see Fig. 1). Embedding these TFMSL in the diamond heat spreader modifies their propagation properties. To investigate the effect of the diamond heat spreader on the propagation properties of TFMSL, the complex propagation constant, \( \gamma = \alpha + j \beta \), is extracted from measured on-wafer structures using a multi-line TRL calibration strategy [11]. An effective relative dielectric constant is extracted from the complex propagation constant as \( \varepsilon_{\text{eff}} = (\text{Im}(\gamma) c/\omega)^2 \), where \( c \) is the speed of light in vacuum and \( \omega \) is the angular frequency. The characteristic impedance, \( Z_0 \), is estimated from the capacitance per unit length extracted by using the corrected reflection coefficient of a load embedded into a TFMSL structure similar to those used for the multi-line TRL calibration [12]. Fig. 2(a) compares the extracted characteristic impedance for the standard TFMSL to that of a TFMSL embedded in the diamond heat spreader. The effect of the diamond heat spreader is observed to slightly lower the real part of the characteristic impedance. Fig. 2(b) shows a higher effective dielectric constant which could be expected for the embedded TFMSL due to the additional dielectric loading. For simulations a simplified description is created by employing a microstrip model and fitting the dielectric constant of the substrate to provide the same effective dielectric constant as for the TFMSL embedded in the diamond heat spreader given in Fig. 2(b).

B. InP DHBT Modeling with Diamond Heat Spreader

The influence of the diamond heat spreader on the InP DHBTs is evaluated using an electromagnetic (EM) extraction procedure as reported in [13]. The transferred-substrate technology is well compatible to InP DHBT devices in the common-emitter configuration. For the tricode-based unit cells, however, as used for the distributed amplifier, three-terminal InP DHBT devices must be used. This requires an opening of the ground plane (Gd metallization) around the active part of the device with an increase in terminal inductances as a result. A 3D EM simulation model implemented in HFSS allows the investigation of the EM effect of the thermal via (formed by the V3 and G3 layers) connected to the collector on device performance. A rather large collector capacitance of ~9 fF is found which should be compared to ~3.5 fF extracted from a similar structure without the thermal via. To model the effect of the diamond heat spreader the existing large-signal model for the transferred-substrate InP DHBT described in [8] is modified according to the extracted extrinsic parasitic network. Furthermore, the existing large-signal model is modified to take into account a slight increase in the access resistances associated with the active part of the InP DHBT.

IV. BENCHMARK CIRCUIT DESIGN

To correctly compare the performance improvement by a diamond heat spreader, a stable benchmark circuit is needed. A distributed amplifier circuit is compared before and after the diamond processing. The basic circuit design is similar to [7, 8]. In this work, a thin layer of 10 µm diamond is added on top and the circuit is compared to the version without diamond in Fig. 3. The only change in layout is the inclusion of modified input stub to have a better match of \( S_{11} \) in diamond.

Some modifications to the layer stack are necessary for the version with thermal heat spreader. This comprises a via, V3, connecting the top metal layer, G3, to the diamond heat spreader to form a good thermal connection as well as adding a G3 metal layer on top of the diamond to realize DC and RF pads for probing.

V. MEASUREMENTS AND DISCUSSIONS

A. Small-Signal Measurements

First, the small-signal performance was characterized using on-wafer probing and multiline TRL calibration. The S-parameters were measured in two bands, namely, DC-110 GHz and 140-220 GHz using 100 µm and 50 µm probes, respectively.

Fig. 4(a) presents the results for the S-parameters (solid line) and the comparison to simulations (dotted lines). The forward gain, \( S_{21} \), has an average value of 12 dB and matches well with the simulation. The output reflection coefficient, \( S_{22} \), is below -10 dB within the range DC-150 GHz except for the small bands 50-75 GHz and 125-150 GHz. The input reflection remains below -10 dB throughout the bandwidth of 150 GHz. When compared with a non-diamond version of the
products are plotted versus input power in Fig. 6. The fundamental and third-order intermodulation products are obtained using low power sweep and path loss compensation. The fundamental and third-order intermodulation products are directly taken from the PNA-X, separated by a frequency of 1 MHz, and fundamental intermodulation products at 5-65 GHz using a PNA-X network analyzer using the cold-source method. To calibrate, the noise figure (NF) is directly measured by means of a Keysight PNA-X vector network analyzer using the cold-source method. A Keysight 346CK01 50 GHz noise source was used. The noise figure of DA with and without diamond is shown in Fig. 4(a). The group delay is flat up to around 150 GHz, which can be seen also from the very low deviation in linear phase, which stays within ±15º up to 150 GHz.

B. Noise Figure Measurements

Fig. 5(a) Noise figure of DA with and without diamond. (b) Noise figure measurement setup for the frequency range up to 50 GHz.

Fig. 5(b) illustrates the noise figure measurement setup for the frequency range up to 50 GHz. The noise figure (NF) is directly measured by means of a Keysight PNA-X vector network analyzer using the cold-source method. To calibrate, a Keysight 346CK01 50 GHz noise source was used. The noise level of the circuit with diamond heat spreader is found to be very similar to the previous report on NF of 8.5 dB except for the low frequency part as shown in Fig. 5(a). This is due to the lower $S_{21}$ at low frequencies when compared with the non-diamond circuit [8]. Between 20-50 GHz, identical NF values around 8.5 dB are measured. This confirms that the DA delivers the same NF even though DC bias currents are identical for the frequency range up to 50 GHz.

C. Large-Signal Measurements

The large-signal measurements were carried out in two steps. First, linearity of the amplifier was characterized by IM3 measurements between 5-65 GHz using a PNA-X network analyzer and its integrated two signal tones. The two tones are directly taken from the PNA-X, separated by a frequency of 1 MHz, and fundamental intermodulation products are obtained using low power sweep and path loss compensation. The fundamental and third-order intermodulation products are plotted versus input power in Fig. 6. Fig. 6(a) shows the plot at 50 GHz with a 3rd order output intercept point of 25 dBm. Fig. 6(b) presents the output third-order intercept point (OIP3) from 5-65 GHz with a frequency span of 5 GHz. Very constant OIP3 values of ~24 dBm are observed for the amplifier which confirms its highly linear characteristics over the entire bandwidth.

To further analyse the circuit, the 1-dB output compression point and the saturated output power performance is studied, measuring the circuit with an Hewlett-Packard power meter in 5 GHz steps between 75 to 110 GHz. Fig. 7(a) shows the 1-dB compression point, $P_{1dB}$ saturated output power, $P_{sat}$ and power added efficiency, $PAE$ versus input power at 110 GHz. A high value $P_{1dB} = 13$ dBm was observed. Fig. 7(b) presents the $P_{1dB}$, $P_{sat}$ and maximum $PAE$ vs frequency. In comparison to the previously reported version without diamond heat spreader [7, 8], a significant improvement of approximately 4 dB with regard to $P_{1dB}$ and $P_{sat}$ is achieved over this frequency range. This is mainly due to the heat spreading feature of diamond, which allows higher bias current for the transistors. Even though the DC consumption now is 340 mW and thus higher than the non-diamond circuit with 180 mW, the maximum $PAE$ value around 5-6% is maintained, because output RF power has increased accordingly.

The comparison to the state of the art of ultra-wideband amplifiers with bandwidths of more than 100 GHz is shown in Table 1. The circuit surpasses the state of the art in several regards. Firstly, this work has the highest $P_{1dB}$ of 13 dBm at 110 GHz together with a very high $PAE$. Secondly, the high dynamic range is relatively constant throughout the range of 5-110 GHz as confirmed by the OIP3 measurements between 5-65 GHz and the power sweeps between 75-110 GHz. This is much unlike previous reports which show a decreasing linearity and saturated output power with increasing frequency. In
addition, with regard to small-signal behaviour, the circuit exhibits constant group delay up to 150 GHz. While generating high output power with good linearity, this circuit features a NF of 8.5 dB. It, therefore, stands unique in terms of integrating the most relevant state-of-the-art features in a single component.

VI. CONCLUSIONS

This work reports an ultra-wideband DA with enhanced linearity performance using a diamond heat spreader. With a 3-dB bandwidth of 150 GHz, the circuit achieves a $P_{1dB}$ value of 13 dBm up to 110 GHz, the highest reported for this class of circuits. What is unique to the circuit is the combination of low noise, linear phase and high value of PAE combined with high output power over a significant portion of the bandwidth. Therefore, it is ideally suited to be integrated into broadband measurement systems, optical modulators and demodulators for communication systems beyond 100 Gbps. With a saturated output power of ~14 dBm in W-band, this circuit establishes distributed amplifiers as potential alternatives to conventional medium power amplifiers, with the added benefit of ultra-wide bandwidth.

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REFERENCES


Table 1. Ultra-wideband DAs with bandwidth larger than 100 GHz.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>BW* (GHz)</th>
<th>Gain (dB)</th>
<th>Technology</th>
<th>Circuit Topology</th>
<th>GBP (GHz)</th>
<th>$P_{DC}$ (mW)</th>
<th>$P_{1dB}$ (dBm) @ Freq (GHz)</th>
<th>Max_PAE (%)</th>
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<tbody>
<tr>
<td>[14]</td>
<td>110</td>
<td>11</td>
<td>50 nm InGaAs mHEMT</td>
<td>Cascode</td>
<td>390</td>
<td>450</td>
<td>7@5/75</td>
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<td>&gt;110</td>
<td>13</td>
<td>500 nm InP DHBT</td>
<td>Cascode</td>
<td>&gt;491</td>
<td>129</td>
<td>10@5-5/110</td>
<td>8</td>
</tr>
<tr>
<td>[15]</td>
<td>120</td>
<td>7.3</td>
<td>40 nm GaN DHFET</td>
<td>Cascode</td>
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<td>448</td>
<td>15.5@20</td>
<td>6.5</td>
</tr>
<tr>
<td>This work</td>
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<td>12</td>
<td>500 nm InP DHBT*</td>
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<td>597</td>
<td>340</td>
<td>13@110</td>
<td>7</td>
</tr>
<tr>
<td>[3]</td>
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<td>10</td>
<td>130 nm SiGe HBT</td>
<td>Tricode</td>
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<td>108</td>
<td>7.5@50</td>
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</tr>
<tr>
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<td>12</td>
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<td>Tricode</td>
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<td>180</td>
<td>8.4@150/6.2@165</td>
<td>6/4</td>
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<td>13.5</td>
<td>250 nm DHBT</td>
<td>Tricode</td>
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<td>210</td>
<td>3@100, 1@195</td>
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<td>250 nm DHBT</td>
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<td>117</td>
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<td>NA</td>
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*Table is arranged in order of increasing BW, with diamond, without diamond