Towards Terahertz MMIC Amplifiers: Present Status and Trends

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Abstract — In this paper, we present an overview of high frequency Monolithic Millimeter-wave Integrated Circuit (MMIC) amplifiers and discuss the state of the art for low noise amplifiers and power amplifiers. We report on the challenges and innovations required to achieve small-signal and power gain above 300 GHz, and present a review of present technology status. The highest frequency MMIC amplifiers ever developed to date will be presented, starting at W-Band (75-110 GHz) and above. Highlights include a MMIC low noise amplifier with gain up to 260 GHz, and a MMIC power amplifier operating up to 190 GHz.

Index Terms — MMICs, terahertz, amplifiers, HEMTs, InP.

I. INTRODUCTION

The growing field of terahertz technology relies on the development of high performance components from the millimeter-wave to the submillimeter-wave regime. Terahertz heterodyne receivers require mixers, multipliers and amplifiers with low noise figure and high output power. This paper addresses some of the issues involved in developing monolithic millimeter-wave integrated circuit (MMIC) amplifiers for applications to terahertz receivers and transmitters.

While most solid state transistor cutoff frequencies are well below the 1 THz range, the use of MMIC amplifiers is growing for terahertz heterodyne applications. In a terahertz receiver, MMIC power amplifiers (PAs) are required for building terahertz or sub-terahertz high power local oscillators. Frequently, MMIC power amplifiers are used as drivers for chains of diode multipliers to increase output power and bandwidth for a local oscillator chain. MMIC low noise amplifiers (LNAs) are increasingly being used as receiver front-ends in the 0.1-0.3 THz range, as transistor cutoff frequencies improve. Traditionally, high electron mobility transistors (HEMTs) built in the GaAs or InP materials system have been the technology to beat in terms of noise performance, bandwidth and output power. Heterojunction bipolar transistors (HBTs) are growing in maturity and applications, and are showing promise for both power and low noise applications as well. We will discuss the state-of-the-art for the highest frequency MMIC power amplifiers and low noise amplifiers to date, in all available device technologies (HEMT, HBT, InP, GaAs) and make some projections about the future trends for solid state transistor amplifiers beyond W-Band (75-110 GHz).

II. APPLICATIONS OF MMIC AMPLIFIERS BEYOND W-BAND

Historically, there have been few commercial applications above W-Band for amplifier chips. The technology drivers for high frequency amplifiers have come from the space and defense industries. Some of these applications include millimeter-wave and submillimeter-wave receivers for astrophysics and earth remote sensing. The GaAs amplifier chips developed in [1] will drive the local-oscillator chains for terahertz mixers on the Herschel Space Observatory’s High Frequency Instrument (HIFI). Herschel is a joint NASA/European Space Agency (ESA) mission to provide imaging and spectroscopy in the 400 GHz-1.9 THz region of the spectrum. [2]. The InP amplifier chips in [3] are being used to provide local oscillator power in submillimeter-wave receivers in the Atacama Large Millimeter Array (ALMA). A similar chip in W-Band [4] is being considered as a local oscillator driver on one of the receivers for the Conical Microwave Imaging Sounder (CMIS), a weather satellite for the NPOESS network. A novel application in the radar area is emerging for G-Band power amplifiers. G-Band Transmit/Receive (T/R) modules are being considered for future planetary entry, descent and landing applications, for highly accurate velocimetry and altimetry measurements with a small antenna size. [5]. A medium power transmitter amplifier in G-Band would enable such an instrument for future planetary landing missions. For most of these applications, having higher power at a higher frequency would enable more measurements, science data, instruments, and possibly space missions.

II. MMIC POWER AMPLIFIERS AT W-BAND AND ABOVE

MMIC power amplifiers in the 100 GHz range are typically Class A amplifiers with power-added efficiencies of the 2-20% depending on the bandwidth of the amplifier. In general, the wider the bandwidth, the lower the overall gain per stage and the lower the efficiency. Most W-Band (or high frequency) PAs are made with HEMTs, although a few HBT results can be found in the literature. While the gate length of a HEMT determines the cutoff frequency, it is the gate width which determines the maximum output power that can be achieved with the device. A wider gate-width, larger periphery device will lead to more overall output power. To date, the highest power MMIC chips utilize gate peripheries of 1.28 mm. These large chips have been limited to W-Band operation due to the very low impedance matching circuits.
required to produce adequate gain in the chips. In Refs [1] and [6], both GaAs and InP HEMT technology are used with 1.28 mm gate peripheries in the output stage of the chips, leading to the highest output power at 94 GHz to date (200-427 mW).

Cutoff frequencies in GaAs are lower than in InP due to the lower electron mobility in GaAs HEMTs, and GaAs HEMTs have been limited to W-Band use. Beyond 120 GHz, the only available technology capable of producing output power greater than a few mW is currently InP. InP amplifier chips beyond W-Band typically run highly compressed in order to achieve output power levels in the tens of milliwatts range.

At frequencies above 100 GHz, power-combining HEMT devices in large combiner subcircuits becomes problematic. Eight-way device combiners are still possible in W-Band, but become unfeasible in G-Band due to the large relative size of the chip. While scaling of transmission lines is possible to reduce chip size, several other components in the MMIC (the HEMTs themselves and through-substrate vias) have fixed geometrical sizes which cannot be scaled effectively without compromising HEMT performance. The largest power-combining network reported above W-Band utilizes a 4-way combiner.

In Fig. 1, we show the measured MMIC amplifier data for maximum reported output power versus frequency for the best MMIC power amplifiers to date. In the 70-110 GHz range, large periphery InP and GaAs HEMT amplifiers dominate for highest output power, with 200-400 mW possible in GaAs [1] and up to 427 mW reported for InP [6]. Metamorphic HEMTs (InP HEMTs grown on GaAs substrates) also report output power levels in this range [7,8]. Smaller periphery InP medium power amplifiers for wide-band applications covering the full waveguide bands of WR10 (75-110 GHz) [4] and WR8 (90-140 GHz) [3,4] typically power-combine 2 or 4 devices to achieve output power levels in the 20-50 mW range. Several double heterostructure bipolar transistor (DHBT) results in InP have also been reported in W-Band [9,10] under 100 mW. In G-Band (140-220 GHz), results include a medium power InP HEMT MMIC with 15-20 mW from 140-170 GHz [11], a DHBT amplifier with 8 mW at 176 GHz [12], and a recent InP HEMT MMIC with 25 mW from 175-190 GHz [13].

There are several factors limiting high power MMIC amplifiers at G-Band and above. These include the cutoff frequency of the larger periphery transistors, the relatively lower breakdown voltage of InP HEMT devices as compared to GaAs, and the difficulty of increasing power-combining on-chip due to very low-impedance matching required, finite via size, and metal-to-metal spacing lithography constraints.

In Fig. 2, we have plotted many of the results from Fig. 1 as output power versus output periphery for the HEMT devices. HBTs are not included in this graph. Larger periphery devices ( > 0.5 mm) have traditionally been restricted to W-Band operation, while smaller peripheries enable G-Band MMIC PAs. As expected, the smaller periphery devices at higher frequency can achieve output power on the order of 25 mW.

Fig. 1. State of the art for MMIC power amplifiers to date: Maximum output power vs. frequency for various MMIC technologies.

Fig. 2. Approximate relationship between maximum output power and total output stage device periphery for GaAs and InP HEMT MMIC power amplifiers. Between 200-300 W/mm is typically possible for in-phase power combining on a MMIC in W-Band or
higher. W, D, or G refers to W-Band (75-110 GHz), D-Band (110-170 GHz) and G-Band (140-220 GHz).

IV. MMIC LOW NOISE AMPLIFIERS (LNAs)

MMIC LNAs have been in wide use even for G-Band frequencies for several years. The main device technology for high performance LNAs is the InP HEMT. The LNA HEMTs are very similar to those used in power amplifiers, but have much shorter gate widths (typically 20-50 μm peripheries). This results in low current operation near the peak transconductance of the device, hence is suited for low noise. A relative newcomer to the low-noise arena, antimonide HEMTs, also known as Sb-based or “antimonide-based compound semiconductors” (ABCS), are increasing in popularity due to the very low turn-on voltage required for low noise operation, which makes them particularly appealing for array and imaging applications.

In Fig. 3, we plot noise figure vs. frequency for a number of reported LNAs in the literature. The solid line in Fig. 3 is a best fit to measured data as computed by S. Weinreb [14]. Highlights include a 5.5 dB noise figure achieved at 183 GHz [15] in InP and 3.9 dB noise figure at 94 GHz in ABCS technology [16]. While the ABCS results are promising, InP is still the technology to beat.

![Fig. 3. Noise figures vs. frequency for low noise amplifier MMICs using InP and ABCS technology. Black line indicates best-fit measured data [14].](image)

We have summarized the state-of-the-art for MMIC LNAs in Table 1, where we list the frequency, amplifier description, gain, noise figure (if measured) and gain per stage for the data points in Fig. 3. Also included is the gate-length of the HEMT devices. As with power amplifiers, the gate length determines the cutoff frequency and the maximum available/stable gain. While the gain per stage is an important figure of merit, it should be noted that the gain-per-stage for a given chip will depend strongly on the bandwidth of the design. In addition to the low noise figures reported from Fig. 3, some recent results are showing impressive frequency performance. Metamorphic HEMT amplifiers developed at Fraunhofer show gain beyond 220 GHz, with impressive gain-per-stage results[26, 27]. Also included is the highest reported MMIC amplifier to date, with 10 dB gain at 235 GHz from a 3-stage design, and gain up to 260 GHz [28]. Future work will involve measuring the noise figures of these MMICs beyond G-Band.

V. FUTURE TRENDS

Projections for MMIC HEMT amplifiers with gate lengths shorter than 0.07 μm indicate that over 6 dB gain per stage is predicted at 300 GHz, for a gate length of 35 nm [13]. The move to shorter gate lengths, compact dry-etched thru-substrate vias, and substrate thickness of 1 mil (25 μm) will greatly improve device cutoff frequencies and gain per stage, enabling submillimeter-wave amplifiers for the first time.

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REFERENCES


TABLE I
SUMMARY OF LNA MMIC AMPLIFIER DATA

<table>
<thead>
<tr>
<th>Frequency [GHz]</th>
<th>Technology</th>
<th>LNA Description</th>
<th>Noise Figure</th>
<th>Gain</th>
<th>Gain per Stage</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>77-105</td>
<td>0.1μm InP, 1999</td>
<td>4 stage (NGST/JPL)</td>
<td>3.0 dB</td>
<td>20 dB</td>
<td>5 dB</td>
<td>[16]</td>
</tr>
<tr>
<td>91-97</td>
<td>0.1μm InP 2000</td>
<td>1-stage (NGST)</td>
<td>2.2 dB</td>
<td>8 dB</td>
<td>8 dB</td>
<td>[13]</td>
</tr>
<tr>
<td>94</td>
<td>Sb-based, 2005</td>
<td>5-stage (RWSC)</td>
<td>3.9 dB</td>
<td>20 dB</td>
<td>4 dB</td>
<td>[17]</td>
</tr>
<tr>
<td>94</td>
<td>Sb-based, 2005</td>
<td>3-stage (NGST)</td>
<td>5.4 dB</td>
<td>11 dB</td>
<td>3.7 dB</td>
<td>[18]</td>
</tr>
<tr>
<td>85-119</td>
<td>0.1μm InP, 2000</td>
<td>4-stage (HRL)</td>
<td>3.7 dB</td>
<td>20 dB</td>
<td>5 dB</td>
<td>[19]</td>
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<tr>
<td>155</td>
<td>0.1μm InP, 1997</td>
<td>3-stage (NGST)</td>
<td>5.1 dB</td>
<td>10 dB</td>
<td>3 dB</td>
<td>[20]</td>
</tr>
<tr>
<td>150-215</td>
<td>0.1μm InP, 1999</td>
<td>6-stage (JPL/NGST)</td>
<td>8.1 dB</td>
<td>15-27 dB</td>
<td>3-4 dB</td>
<td>[21]</td>
</tr>
<tr>
<td>150-205</td>
<td>0.1μm InP, 1999</td>
<td>8-stage (HRL/JPL)</td>
<td>N/A</td>
<td>17 dB</td>
<td>2 dB</td>
<td>[22]</td>
</tr>
<tr>
<td>160-200</td>
<td>0.07μm InP, 2000</td>
<td>2-stage (NGST)</td>
<td>5.0 dB</td>
<td>15 dB</td>
<td>7 dB</td>
<td>[15]</td>
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<td>180-205</td>
<td>0.1μm InP, 2001</td>
<td>3-stage (CSIRO/NGST)</td>
<td>12 ± 4 dB</td>
<td>15 dB</td>
<td>4 dB</td>
<td>[23]</td>
</tr>
<tr>
<td>150-215</td>
<td>0.07μm InP, 2005</td>
<td>3-stage (NGST)</td>
<td>N/A</td>
<td>12 dB</td>
<td>4 dB</td>
<td>[24]</td>
</tr>
<tr>
<td>175</td>
<td>InP HBT, 2003</td>
<td>1-stage (UCSB)</td>
<td>N/A</td>
<td>6 dB</td>
<td>6 dB</td>
<td>[25]</td>
</tr>
<tr>
<td>220</td>
<td>InP MHEMT, 2004</td>
<td>4-stage (Fraunhofer)</td>
<td>N/A</td>
<td>20 dB</td>
<td>5 dB</td>
<td>[26]</td>
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<tr>
<td>220</td>
<td>InP MHEMT, 2005</td>
<td>1 Cascade Stage (Fraunhofer)</td>
<td>N/A</td>
<td>10 dB</td>
<td>5 dB</td>
<td>[27]</td>
</tr>
<tr>
<td>235</td>
<td>0.07μm InP, 2005</td>
<td>3 stage (JL/NGST)</td>
<td>N/A</td>
<td>10 dB</td>
<td>3.5 dB</td>
<td>[28]</td>
</tr>
</tbody>
</table>


