A 294 GHz 0.47mW Caterpillar Amplifier Based Transmitter in 65nm CMOS For THz Data-Links

Adrian Tang[1] and Mau-Chung Frank Chang[2]

[1]Jet Propulsion Laboratory, California Institute of Technology, [2] University of California, Los Angeles

***Abstract*—A fully integrated CMOS THz transmitter for short range data-links is presented which provides 0.47mW of output power at 294 GHz. The output frequency is derived from a 147 GHz on-chip LO and fully differential caterpillar power amplifier combined with a transformer coupled frequency doubler. The transmitter is integrated with an on-chip dipole antenna for use in THz communication systems and consumes a total of 258 mW.**

I. INTRODUCTION

Communication at THz frequencies has recently gained interest for emerging short range applications which demand Gb/s data-rates such as kiosk and wireless high-definition video links. While the available channel bandwidth of a data-link will increase linearly with carrier frequency, (assuming a fixed fractional bandwidth), the omni-directional free space losses will increase with the square of the carrier frequency. Further to this, transmitted powers in CMOS technology tend to decrease [1] as the carrier frequency is increased. With these issues considered, the overall SNR of a data-link operating in the sub-mm-wave regime is expected to be less than that of a lower frequency wireless or mm-wave link. This lower SNR has strong implications on the type of modulation that is best suited for a THz or sub-mm-wave data link. In regular wireless systems, constellation based modulation schemes such as 64QAM and 16 QAM are often employed to provide high data-rates though added constellation complexity, which in turn sets higher SNR requirements for correct detection with reasonable bit error rates (BERs). One major motivation for these high complexity constellations is that they offer much higher spectral efficiency than that of simpler keying schemes (ASK, BPSK). This spectral efficiency is critical as the total bandwidth is limited and links must often provide multiple channels for multiple users.

The short range nature of THz communication systems ensures that the number of users will be low and so spectral efficiency becomes much less critical. Additionally at THz frequencies, the available bandwidth is almost unlimited and relaxes the need to have tightly packed channels. Also as the SNR of a THz link is typically much lower than a conventional wireless link, simple keying schemes like ASK become more attractive as the SNR required for detection is far lower than constellation based signaling.

A second major challenge related to modulation complexity is that of transceiver linearity. High order constellations like 64QAM demand extremely linear data transceivers, often with error-vector magnitude (EVM) levels in the -30 dBc range. That high linearity is often achieved through the use of complex digital pre-distortion in the transmitter, digital equalization of the receiver and use of many other circuit, block and architecture level linearization techniques [1].

THz transmitters are typically implemented as multiplier chains in which frequency multipliers are employed to double or triple incoming frequencies to provide THz range operation. Most frequency doublers or triplers employ techniques which boost and then isolate the harmonics of an incoming signal while simultaneously suppressing the fundamental. While this technique is relatively simple is has the property of being truly non-linear as the output signal is completely derived from a harmonic of the input. For example if we send a QPSK constellation through a frequency doubler as shown in Fig. 1a, we will actually destroy the constellation information as the doubling operation removes the sign of the I and Q components and reduces the constellation from 4 symbols down to 2 ambiguous points.

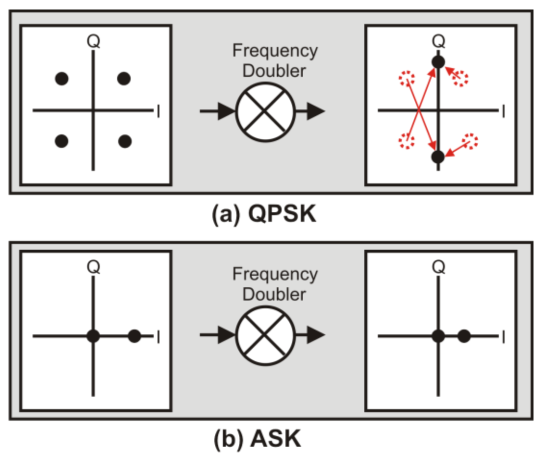

Fig. 1(a). Effects of a frequency doubler on a QPSK signal constellation.
(b) Effects of a frequency doubler on an ASK signal constellation.

Alternatively if we transmit an ASK signal through a frequency doubler as shown in Fig. 1b, we see that although the amplitude changes the overall constellation shape is preserved. A similar behavior can be observed if other multiplication factors are considered. Overall, when data-link SNR, number of users, communication channel requirements, available transceiver bandwidth, and transceiver linearity are considered, ASK based modulation appears to be the best selection for short range THz data-links.

While THz systems have been dominated by III-V technologies, CMOS remains of particular interest because of its high level of integration, lower power consumption and overall lower cost. While much work has been done on CMOS based THz receivers [2,3] only few solutions have been proposed for THz signal sources and transmitters [4,5]. While these sources offer high operating frequencies, they also suffer from limited radiated output power in the 10uW range, and some must even be driven with an external LO source to provide useful output power.

II. THZ TRANSMITTER DESIGN

In this paper we demonstrate a compact CMOS transmitter chip for THz communication operating at 294 GHz based on a caterpillar power amplifier. The transmitter contains a VCO and requires no external RF or mm-wave frequency sources to operate. Fig. 2 shows the block diagram of the proposed transmitter. An mm-wave VCO generates the 146-148 GHz carrier that is then amplified by a 4-stage caterpillar power amplifier and applied to an active frequency doubling circuit. Two versions of the transmitter chip are implemented; one has the output coupled to a probe output for power measurement, while the other has an on-chip dipole antenna for actual use.

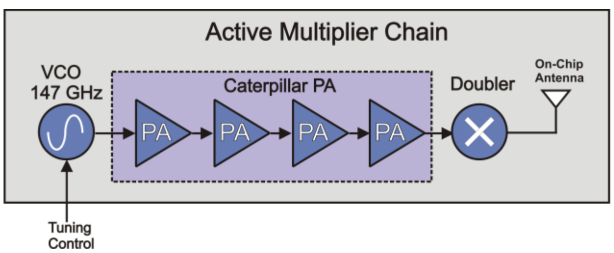

Fig. 2. Block diagram of the proposed THz transmitter.

The detailed schematic of the 147 GHz VCO and buffer stage is shown in Fig 3. The VCO is implemented as a simple cross-coupled VCO with a single inductor driving a single-stage amplifier which is transformer coupled into the caterpillar amplifier.

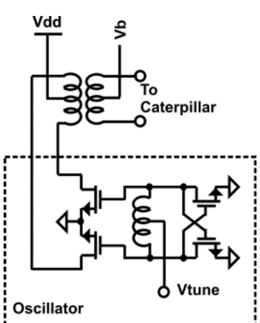

Fig. 3. Schematic diagram of 147 GHz mm-wave VCO and transformer coupled output stage.

As the quality factor of varactors are extremely low in this frequency range and offer very limited frequency tuning, we instead trim the supply voltage of the VCO to adjust the free-running frequency.

III. CATERPILLAR AMPLIFIER

The four-stage caterpillar amplifier schematic is shown in Fig. 4. Unlike most CMOS power amplifiers, this PA is fully differential and transformer coupled at every stage. Since the transmitter is intended for ASK communication, and the output signal will eventually enter a frequency doubler, the PA linearity is not critical as strong harmonics will be generated later anyways. The bias and drain voltage for each stage is connected at the center tap of each transformer winding allowing for a compact design. Although, designing all stages to be identical does cost some power added efficiency, the approach still delivers reasonable overall efficiency as the power amplifier can be operated in a saturated condition for ASK signaling, unlike regular complex constellation communications where some power back-off is required for linearity purposes. The successive transformer coupling of the caterpillar PA leads to a layout shape, which resembles the insect.

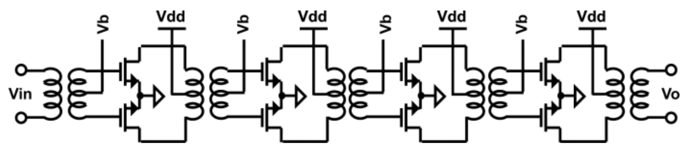

Fig. 4. Schematic diagram of 147 GHz transformer-coupled caterpillar PA.

IV. FREQUENCY DOUBLER

The frequency doubler is responsible for converting the power amplifier's 146-148 GHz output to the 292 to 296 GHz frequency range. Minimizing the conversion loss of the frequency doubler is critical as the output frequency is above f_{max}, (the frequency where device power gain decays to unity) making it impossible to increase power by cascading additional amplification stages to the transmitter.

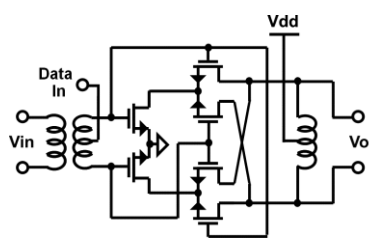

Fig. 5. Schematic diagram of 147 GHz to 296 GHz transformer-coupled frequency doubler stage.

Fig. 5 shows the schematic of frequency doubler used at the output of the transmitter chain. The doubler is transformer coupled differentially, similar to the 147 GHz power amplifier. The output is impedance matched to 50 ohm using a differential shunt inductor. The doubler itself is also a fully differential structure based on an active Gilbert cell. As the voltage swing at the PA output is quite large there is no need to separate the two input ports (IF and LO) of the multiplying Gilbert cell with different bias voltages, so instead they are connected directly together. The transmitter applies the ASK modulation signal directly at the transformer center-tap of the frequency doublers input. This way the doubler is essentially switched on and off by applying and removing its input bias based on the ASK signal to be transmitted.

V. MEASUREMENTS

In order to test the performance of the caterpillar THz transmitter, two versions were implemented, one with an antenna and one with a probe output. Fig. 6 shows the output frequency of the transmitter as the VCO supply is adjusted from 0.8 to 1.3 volts when measured with a WR3.4 waveguide probe connected to a WR3.4 harmonic mixer from VDI. Below this range the oscillator swing is quite limited and increasing the supply beyond this range creates device reliability problems with the transistors inside the oscillator.

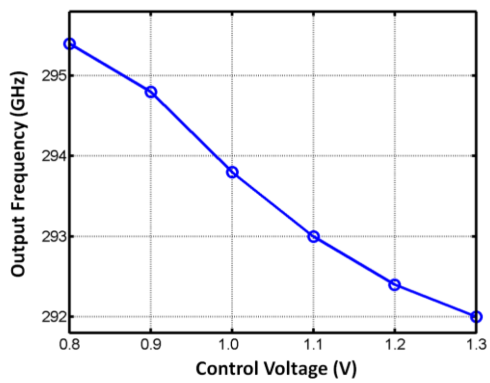

Fig. 6. Tuning range of the caterpillar THz transmitter when measured with a WR4.3 waveguide probe.

Next, the power across the output band was measured using a WR3.4 waveguide probe combined with a PM4 power meter. Losses of the probe setup were calibrated out using a symmetric setup and VDI 300 GHz source with the procedure shown in Fig 7.

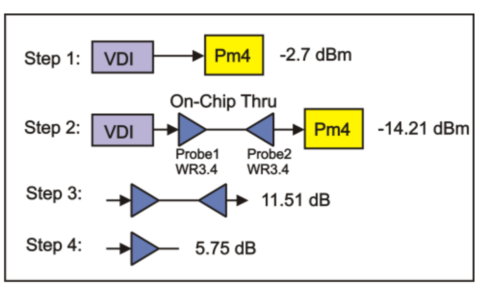

Fig. 7. Procedure for calibrating out probe losses based on a symmetric setup.

The output power was measured as the VCO was set to provide specific frequencies across the same frequency range as Fig. 6 and a peak output power of 0.47mW was obtained at 294 GHz as shown in Fig 8. Radiated power was also measured using a WR3.4 horn antenna placed directly on the PM4 meter. The horn was placed on top of the bonded transmitter chip and the peak power measured was 57uW also at 294 GHz. As setup losses were not considered the true radiated power may be higher.

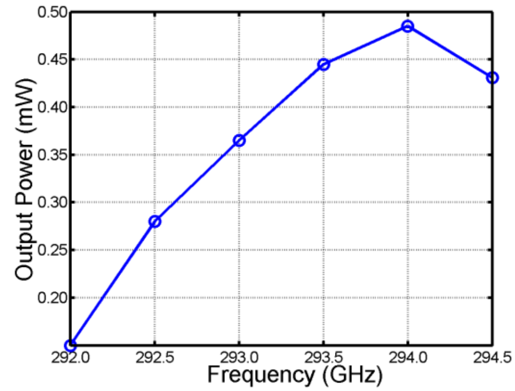

Fig. 8. Power response of the caterpillar THz transmitter when measured with a calibrated WR4.3 waveguide probe.

VI. SUMMARY

The proposed caterpillar active multiplying chain source was implemented in 65nm CMOS technology and shown to provide 470 uW of peak power at 294 GHz. The total power consumption was 258 mW which can be used to determine the peak power added efficiency (PAE) of 0.19%. The die photo with dimensions is shown in Fig. 9 where the caterpillar-like shape of the power amplifier is clearly visible.

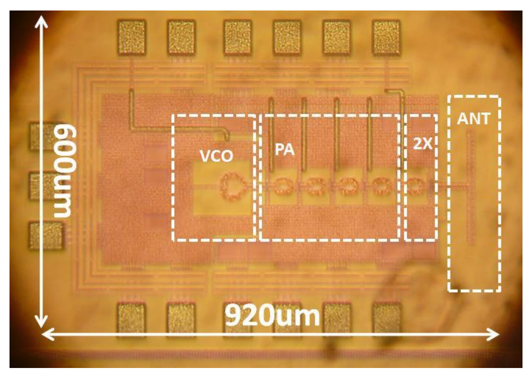

Fig.9. Die photo of the caterpillar THz transmitter in 65nm CMOS.

VII. ACKNOWLEDGEMENTS

Authors are grateful to TSMC for 65nm foundry support. Part of this work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

[1] A. Tang, D. Murphy, F. Hsiao, Q. Gu, Z. Xu, G. Virbila, Y.H. Wang, H. Wu, L. Nan, Y. Wu, and F. Chang, "A CMOS 135-150 GHz 0.4 dBm EIRP TX with 5.1dB P1dB Extension Using Envelope Feed-Forward Compensation" IEEE IMS 2012.

[2] A. Tang, Q. Gu, Z. Xu, G. Virbila, M.F. Chang "A 349 GHz 18.2mW/Pixel CMOS Tri-Color Inter-modulated Regenerative Receiver for Color mm-Wave Imaging" IEEE IMS 2012.

[3] Q. J. Gu, Z. Xu, H.-Y. Jian, and M.-C. F. Chang, "A CMOS Fully Differential W-Band Passive Imager with <2 K NETD," IEEE RFIC 2011

[4] K. Sengupta, A. Hajimiri, "Distributed Active Radation for THz Signal Generation" IEEE ISSCC, Vol. 54, pp 288-289, Feb 2011

[5] O Momeni and E. Afshari, "A 220-to-275 GHz Traveling-Wave Frequency Doubler with -6.6dBm Power at 244 GHz in 65nm CMOS, IEEE ISSCC, Vol. 54, pp 286-287, Feb 2011