A 0.24pJ/bit, 16Gbps OOK Transmitter Circuit in 45-nm CMOS for Inter and Intra-Chip Wireless Interconnects

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ABSTRACT

Research in recent years has demonstrated that intra and inter-chip wireless interconnects are capable of establishing energy-efficient data communications within as well as between multiple chips. This paper presents a circuit level design of an energy-efficient millimeter wave (mm-wave) on-off keying (OOK) transmitter suitable for such wireless interconnects in 45-nm CMOS process. The transmitter consists of an NMOS cross-coupled VCO, an OOK modulator and a power amplifier. The transmitter is able to achieve maximum modulation data rate of 16Gb/s at 60GHz with the output power of -3dBm consuming a total power of 3.9mW, which translates to a bit-energy efficiency of 0.24pJ/bit.

KEYWORDS

Wireless interconnect, mm-wave, transmitter, VCO, OOK modulator, power amplifier, transformer neutralization

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1 INTRODUCTION

To keep up with the demands in computation and communication of platform based computing devices like micro-servers or embedded systems with multiple multicore chips both on-chip and chip-to-chip communication infrastructures have been evolving at a rapid pace. However, recent trends according to the International Technology Roadmap for Semiconductors (ITRS) predict that the pitch of the I/O interconnects in ICs is not scaling as fast as the gate lengths or pitch of on-chip interconnects. This implies a gap in density and performance of

traditional I/O systems relative to on-chip interconnections [1]. The wiring complexity of both intra and inter-chip interconnects poses design challenges, crosstalk and signal integrity issues. This has led to the exploration of novel interconnect technologies like photonic interconnect [2] and wireless interconnects [3] as an energy efficient solution for inter and intra-chip data communication. Long-range wireless transmitters and receivers (transceivers) operating in the millimeter-wave (mm-wave) frequencies [4] do not require laying out of physical interconnects making them suitable for a variety of application domains such as embedded system platforms, servers, wearable or flexible electronic devices as well as IoT devices. In addition, such mm-wave transceivers and antennas are designed in CMOS-compatible processes, solutions to the wired interconnect problem. Research in recent years has demonstrated that on-chip and off-chip wireless interconnects are capable of establishing radio communications within a chip as well as between multiple chips and are shown to improve system-level energy efficiency and bandwidth of inter and intra-chip data communications by avoiding or eliminating data communication over long multihop wired paths [3].

For computing platforms with multiple chips, an energy efficient, high bandwidth interconnect fabric is desirable. A multi-gigabit wireless channel has the potential to provide such high performance with high energy efficiency [5]. However, the constant need for lower energy expenditure in data transfer between chips motivates newer designs. Moreover, to be compatible for integration with current and future technology nodes the transceivers need to be designed in advanced technology nodes. This poses a problem to the design of power-efficient circuits as advanced technologies operate in low rail

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Figure 1: Proposed block diagram of the OOK

Figure 2: Schematic and component values of the proposed OOK modulator with NMOS cross-coupled

voltages which makes achieving high voltage swings at the output of the transmitter challenging. Therefore in our work we present the circuit design of an ultra-low power CMOS compatible 16Gbps mm-wave transmitter at 60GHz in 45nm technology node for inter and intra-chip wireless communication. We adopt On-Off Keying (OOK) as the modulation mechanism for its simplicity and low power consumption although it has the lowest bandwidth efficiency. The transmitter proposed in this work consists of 60GHz Voltage Controlled Oscillator (VCO), an OOK modulator and a power amplifier (PA) as shown in Fig. 1.

2 RELATED WORK

In [5], a 60GHz OOK transmitter that employed a five stage CS power amplifier have been proposed. Though the transmitter provided high amplification gain, it came with a cost of increased power dissipation and overall noise due to higher number of components. An energy dissipation of 114pJ/bit along with low data rate of 2.5Gbps over a 40mm communication range made the transmitter inefficient for future low power high performance intra and inter-chip communication. A 9.5pJ/bit, 6Gbps ASK transmitter operating at 43GHz was proposed in [6]. However, the use of Si-Ge process makes the integration of this transceiver circuit with a standard CMOS chip challenging. In [7] a data rate of 11Gbps with 10^{-11} Bit Error Rate (BER) was achieved with a cost of 6.4pJ/bit energy efficiency for the transmitter designed in 40nm node. However, the transmitter communication was limited to 14mm and therefore cannot be used for energy efficient chip-to-chip communication. In [8], author proposed OOK transceiver for on-chip communication as the transmitter provides 60GHz OOK modulation at 3.5Gbps maximum data rate. In [9], the author proposed a multi modal transmitter with a highest data rate of 20Gbps for free space communication. As the highest reliable communication distance was limited to 5mm, the transmitter can be used only for on-chip

communication. The work proposed in [10] demonstrated a transmitter suitable for a maximum communicating distance of 100mm at 10.7Gbps data rate with 3.45pJ/bit efficiency. However the transmitter design was faced with the challenge of integrating the on-board Yagi-Uda antenna on a non-silicon substrate. An OOK transmitter capable of communicating within a range of 20mm with a BER of 10^{-15} and having an energy efficiency of 1.2pJ/bit and 16Gbps data rate has been proposed in [11] as a solution for on-chip communication. However, its performance for chip-to-chip communication is not evaluated. In this work, we present the design of an OOK transmitter circuit for intra-chip as well as long range inter-chip communication for future high performance multichip computing platforms.

3 OOK TRANSMITTER

The scenario of inter-chip and intra-chip wireless mm-wave links requires extremely low energy consumption to be competitive with high-speed serial I/O and other emerging technologies like photonic interconnects. Therefore, an OOK transmitter is preferred for its energy-efficiency. Fig. 1 shows the block diagram of proposed OOK transmitter consisting of a VCO, modulator and PA. In this section we discuss the design approaches for these components of the 60GHz OOK transmitter.

3.1 Voltage Controlled Oscillator

The VCO is responsible for generating the 60GHz RF carrier wave for the OOK modulator. The maximum single-ended voltage swing with minimum phase noise can be achieved by an NMOS cross-coupled VCO as it has comparatively less phase noise compared to the other oscillators such as ring or LC oscillator [12]. Moreover, it takes less active area compared to Colpitts oscillator. In addition to providing a higher output swing, this design also supports wide tuning range. In the cross coupled NMOS oscillator shown in Fig 2, the positive feedback is given via the M1, M2 transistors and the LC tank circuit. Each of the transistors creates a 180° phase shift at its output. The control voltage i.e. V_{ctrl} is set at 100mV and given to both the capacitors as shown in Fig. 2. Current biasing is used for the VCO and the required current is generated via a simple NMOS current mirror for a reference input of 10uA. The startup time is a critical part in the oscillator design. To avoid the startup time from limiting the data rate we do not use the VCO as a modulator. Therefore, the output of the VCO, the Local Oscillator (LO) signal, is coupled to a separate OOK modulator input via a transformer, X1 with a 1:1 turns ratio to ensure symmetrical swing at the input of the modulator. We adopt transformer matching technique as it reduces overall power consumption by eliminating buffers or coupling capacitors. The two transistors of the VCO, M1 and M2, form a differential pair where only one of them is on at a given time degrading the trans-conductance of the pair. Therefore, we increase the width of the transistors M1 and M2 sufficiently, to provide high trans-conductance and drive the OOK modulator.

Figure 3: Schematic and component values of the proposed power amplifier.

3.2 OOK Modulator

The design of a modulator for high speed inter and intra-chip communication poses a significant challenge on the energy efficiency of the transmitter as power consumption increases with data rate. In the proposed modulator shown in Fig. 2, the modulating M6 NMOS transistor is driven by the Base Band signal (BB). The BB signal turns on and off M6 by charging up the gate terminals above the threshold voltage V_{th} of the NMOS transistor. For logic HIGH at BB, NMOS M6 gets switched on and it passes the LO signal connected to the source of M6 towards its drain and the primary winding of the transformer X2. Effectively, M6 works a pass transistor, passing the carrier signal from its source to drain when the BB signal is logic HIGH and blocking it when the BB signal is logic LOW. When BB signal has a logic LOW value, all charge across primary side of X2 needs to be discharged. This charge gets discharged through NMOS transistor M5. Similar to the transformer X1 coupling the VCO to the modulator, another 1:1.5 transformer, X2 is designed to obtain single ended output from the modulator and for impedance matching of the modulator output with the input of the PA. The primary side of transformer X2 is connected to ground through capacitor C4. Capacitor C4 and C3 cancels the effect of the imaginary part of the impedance due to the inductor coil of the transformer. The body biasing technique is used with NMOS M5 for adjusting the threshold voltage to get symmetrical signal across 0V at the secondary coil of X2.

Figure 4: Simulated Y_{12} for PA versus coupling factor,

Figure 5: Simulated VCO gain.

3.3 Two Stage PA

In the transmitter, power amplifier is one of the power-hungry blocks that affects the overall efficiency of the transmitter. Cascode structures, which are commonly used to obtain high gains at lower frequencies, are not suitable for high frequency applications as the parasitic capacitances become dominant and the stacking of transistors reduces the voltage headroom in advanced technology nodes operating at low rail voltages [13]. Therefore, in our design, a two-stage Common Source (CS) topology is used as shown in Fig. 3 as it provides high frequency response and larger voltage swing compared to cascode designs. At high frequency of operation, degradation in the performance of power amplifier is caused by the drain-to-gate parasitic capacitor C_{gd} , which introduces a direct signal path between output and input. This drain-to-gate feedback degrades reverse isolation and can directly lead to instability of the amplifier. Moreover, as any change in output impedance affects the input impedance through C_{gd} , it significantly affects frequency response and output impedance matching of the transmitter. The two-stage PA proposed in this work uses a CS topology with drain-to-gate transformer-feedback neutralization technique which creates an additional signal path that neutralizes the current flow through C_{gd} [11]. The transformers are formed using inductors at the gate and drain terminals of M1 (L_{g1} & L_{d1}) and M2 (L_{g2} & L_{d2}) as shown in Fig. 3 with coupling factors, k_1 and k_2 respectively. The values of the coupling factors are chosen such that they minimize the reverse transformation of the two stages of the amplifier, $Y_{12} = \frac{I_{gs}}{V_{ds}} \big|_{V_{in} = 0}$. Fig. 4 plots the Y_{12} for the two CS stages of the PA and shows that the optimal values of the coupling factors, k_1 and k_2 are 0.088 and 0.128 respectively. The inductors L_{d1} and L_{d2} at the drain of the transistors M1 and M2 resonate with the drain capacitances. This increases the overall gain and bandwidth at the center frequency. Transistor M1 and M2 are biased using a voltage divider based biasing circuit. To complete the biasing, the DC blocking capacitor C1 and C2 are placed to prevent the upsetting of the gate to source bias of M1 and M2. The value of C1 is chosen to be 1pF. C2 and C3 cancels imaginary impedance effect of drain inductors L_{d1} and L_{d2} on the output side of both stages. Hence, it has negligible reactance at the center frequency. The output of the power amplifier is matched with 50 Ohms by using L match impedance matching technique.

Figure 6: Simulated phase noise of VCO.

4 RESULTS AND SIMULATION

The proposed transmitter is designed in 45nm CMOS technology and the simulation is carried out using Cadence Virtuoso Analog Design Environment (ADE). In this section we present the characterization of the VCO, the modulator, the PA and the overall OOK transmitter.

4.1 Characterization of the VCO

In this section, we characterize the VCO for frequency response and phase noise. We consider the frequency range from 45GHz to 75GHz for the characterization of the VCO. Fig. 5 shows the frequency response of the VCO. From the figure, it can be observed that a peak-gain of 17dB is achieved for the VCO centered at 60GHz signifying a carrier frequency of 60GHz. Since the oscillator needs to be triggered initially for its proper functionality in the simulation environment, one of the tank capacitors was initialized with 1nV.

The frequency stability is an important concern for the VCO and ideally, it should be immune to the random frequency fluctuations. The measure of these fluctuations is characterized by the phase noise. Phase noise is defined as the ratio of power in one phase modulation sideband per Hz bandwidth, at an offset of f Hz away from the carrier, to the total signal power. The

Figure 7: Simulated On-Off gain of the OOK

phase noise evaluated at an offset of 10MHz is -101.4dBc/Hz as shown in Fig. 6. The VCO consumes a maximum steady-state current of 1.1mA from a 1V supply.

4.2 Characterization of the OOK Modulator

An ideal OOK modulator should not have any output power in the off-state (when the BB input is logic LOW). However, due to non-ideal effects such as leakage, the output power is not completely zero in the off-state. Therefore, a high on-off gain is desirable for reliable detection at an OOK receiver. Here, we characterize our OOK modulator in terms of the on-off steady-state gain. The on-off steady-state gain can be defined as the difference between the steady-state gains of the modulator for the two valid logic levels of the BB input. At 60GHz the modulator has an “on” and “off” state gain of -3.6dB and -81.6dB respectively as shown in Fig. 7. Therefore, the on-off steady state gain is above 78dB for the frequency ranges from 45GHz to 75GHz. With this gain the valid logic levels can be detected with a transmitter output power penalty of less than 1dB [11].

4.3 Characterization of the PA

In this section, we characterize the PA in the OOK transmitter in terms of S-parameters, and Power Added Efficiency (PAE). First, we extract the S-parameter of the PA. At high frequencies i.e.

Table 1: Performance Comparison of mm-wave OOK Transmitter

References	This Work	[11] *	[7] *	[6] *	[10] *	[5] *	[8] *
Technology node	45-nm CMOS	65-nm CMOS	40-nm CMOS	180-nm SiGe	90-nm CMOS	90nm CMOS	90nm CMOS
Carrier Frequency	60GHz	60GHz	57GHz	43GHz	60GHz	60GHz	60GHz
Modulation	OOK	OOK	ASK	ASK	OOK	OOK	OOK
Maximum Data Rate	16Gb/s	16Gb/s	11Gb/s	6Gb/s	10.7Gb/s	2.5Gb/s	3.5Gb/s
Power Consumption	3.9mW	19mW	29mW	57mW	31.mW	183mW	156mW
Supply Voltage	1V	1V	1.1V	1.6V	0.8/1.8V	1.2V	N/A
RF output P1dB	-3dBm	1.5dBm	-2dBm	-1.5dBm	5.1dBm	5dBm	2dBm
Bit-Energy Efficiency	0.24pJ/bit	1.2pJ/bit	2.6pJ/bit	9.5pJ/bit	2.9pJ/bit	73.2pJ/bit	44.6pJ/bit
Active-Foot Print	N/A	0.077mm ²	0.06mm ²	0.25mm ²	0.15mm ²	0.43mm ²	N/A
FoM	2.055	1.19	0.24	0.07	1.12	0.04	0.04

Figure 8: Simulated S-parameters of PA.

60GHz, it is important to consider the S-parameters of the circuit as it describes the input-output relationship between the terminals of the circuit. A two-port network is setup for the S-parameter extraction. Both the input and output ports are matched to 50Ohm impedance to extract the S-parameters. Fig. 8 shows the S_{11} , S_{22} , and S_{21} for the proposed PA. The S_{11} is the ratio of reflected power to the incident power at the input port and is known as reflection coefficient or return loss. For the proposed PA design the value of reflection coefficient, S_{11} is found to be -30.15dB at 60GHz. Therefore, we conclude that the input is matched well with the 50Ohm antenna impedance and hence we find negligible reflections at the input at 60GHz. Similarly, S_{22} is the ratio of reflected power to the incident power on the output port and it is found to be -15.42dB at 60GHz. S_{21} is the ratio of output power to the input power and represents the power gain for a well-matched PA. From Fig. 8 S_{21} is found to be 14.48dB .

The power added efficiency (PAE) is defined as the percentage ratio of difference between output and input power over total DC power. Hence it signifies the amplification factor of the PA. Fig. 9 shows the simulated PAE versus input power of the PA at 60GHz. It shows the output power at 1dB compression point is -3dBm . Maximum simulated PAE is found to be 17% at -3dBm of output power. Overall, the PA draws 2.2mA from a 1V supply.

4.4 Characterization of the Overall Transmitter

Here, we characterize whole OOK transmitter in terms of data rate, total DC power consumption and transmitted power and bit

Figure 9: Simulated gain, output power and PAE of the PA versus input power at 60 GHz.

energy-efficiency. To characterize the OOK transmitter the input and output impedances of PA are matched with the output impedance of OOK modulator and that of a standard antenna impedance of 50Ohms respectively.

The waveform shown in Fig. 10 (a) shows the amplified OOK modulated signal at the output of PA with a pseudo-random sequence of logic 0s and 1s at baseband signal input. As demonstrated 10 bits (1110101001) are modulated between 1ns and 1.625ns indicating a data rate of 16Gbps. From Fig. 10(a) the output waveform indicates a 450mVpp which translates to -3dBm output power and is achieved with a total DC power consumption of 3.9mW. This implies a bit energy efficiency of 0.24pJ/bit at 16Gbps. The designed OOK transmitter is compared with other existing designs in comparable technology nodes. For a comprehensive comparison, we use Figure-of-Merit (FoM), which is given by

$$FoM(mW \cdot \frac{\text{bit}}{\text{pJ}}) = \frac{\text{Data Rate (Gbps)} \cdot OP_{1dB}(mW)}{P_{DC}(mW)} \quad (1)$$

Where P_{DC} is the power consumption and OP_{1dB} is the 1-dB compression point at the output of the transmitter. In Table 1 we compare our OOK transmitter with other transmitters designed for similar applications with respect to important performance metrics. While our design outperforms all the existing works it is to be noted that all the other works are post-layout or post-fabrication results while ours is circuit-level characterization.

4.5 Corner Analysis

The corner analysis is performed to obtain the performance of the transmitter over different operating voltages and temperatures. The analysis is performed for SS, TT, FF corners over 0.9, 1, 1.1 V and 125, 25, 0°C operation voltages and temperatures respectively. The

Figure 10: BB signal and PA output for (a) pseudo-random sequence and (b) lone pulse analysis.

Table 2: Performance of Transmitter at different corners

Corners	Voltage (V)	Temp.(C)	Speed (Gbps)	Power (mW)	R _{OOK} (dB)
SS	0.9	125	16	1.399	15.24
TT	1	25	16	2.064	16.54
FF	1.1	0	16	2.903	18.15

characterization of OOK transmitter at the various corner cases is shown in Table 2 with respect to total power consumption and on-off ratio of the overall OOK transmitter, R_{OOK} while operating at a data rate of 16Gbps.

4.6 Link Budget Analysis

In [11] the path loss for a 20mm intra-chip link is shown to be around 26dB. In [3] it is shown that the longest distance for an inter-chip link is 59mm resulting in a path loss of about 35dB. Here, we evaluate the BER corresponding to typical intra and inter-chip communication distances. The received signal power is

$$P_R = P_T - PL. \quad (2)$$

Here, P_R and P_T are the received and transmitted power respectively and PL is the path loss. We assume a non-coherent OOK receiver as these are most power efficient. LNAs used in typical non-coherent OOK receivers have a noise figure, NF of 10dB or less [11]. The Noise Floor, N_{Floor} of such a receiver is,

$$N_{Floor} = 10 \log(kT) + 10 \log(BW) + NF. \quad (3)$$

Where, k is the Boltzmann constant, T is the absolute temperature and BW is the bandwidth. Therefore, from (3) the N_{Floor} of the receiver is -67.8dBm at 300K for a BW of 16GHz. However, in addition to thermal AWGN, Inter-symbol Interference (ISI) due to bandwidth limitation of the transmitter can add interference noise. As can be seen from the lone-pulse analysis in Fig. 10(b) the transmitter output is 450mVpp and 67mVpp when it is transmitting a '1' and a '0' respectively when measured at the center of the pulses. Therefore, the on-off ratio of overall OOK transmitter, R_{OOK} is 16.54dB. The value of ISI noise, N_{ISI} is dependent on path loss and is given by,

$$N_{ISI} = P_T - R_{OOK} - PL. \quad (4)$$

The received Signal to Interference and Noise Ratio (SINR) is,

$$SINR = P_R - N_{Floor} - N_{ISI}. \quad (5)$$

For non-coherent OOK demodulation, the BER is given by,

$$BER_{OOK} = \frac{1}{2} \exp\left(-\frac{1}{2} SINR\right) + \frac{1}{4} \operatorname{erfc}\left(\sqrt{\frac{1}{2} SINR}\right). \quad (6)$$

Where, $\operatorname{erfc}(\cdot)$ is the complimentary error function. Fig. 11 shows the BER achieved with this transmitter for various values of path loss with and without ISI (for comparison). For a path loss of 35dB corresponding to a 59mm inter-chip link [3], the BER is dominated by the ISI and is around 10^{-10} .

5 CONCLUSIONS

In this paper we present the circuit-level design of a 60GHz mm-wave OOK transmitter for inter and intra-chip communications. A bit energy-efficiency of 0.24pJ/bit at 16Gbps is obtained at a low BER of 10^{-10} for typical transmission distances. This energy-efficiency

Figure 11: Variation of BER with Path Loss.

makes the mm-wave wireless interconnect competitive with other emerging technologies such as photonic interconnects.

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