A Simultaneous Tri-band On-Chip RF-Interconnect for Future Network-on-Chip

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Abstract

A simultaneous tri-band on-chip RF-interconnect for future network on-chip is demonstrated. Two RF bands in mm-wave frequencies, 30GHz and 50GHz, are modulated using amplitude-shift keying, while the base-band utilizes the low swing capacitive coupling technique. Each RF-Band and base-band carries 4Gbps and 2Gbps respectively. Three different bands, up to 10Gbps, are transmitted simultaneously across a shared 5mm on-chip differential transmission line. The energy per bit is 0.125pJ/b/mm in base-band, while RF-band is 0.09pJ/b/mm.

Keywords: Amplitude-shift keying, Chip Multi-Processor, Multi-band, mm-Wave, Network-On-Chip, RF-Interconnect

Introduction

On-chip interconnects, especially in future chip multi-processor (CMP) and network-on-chip (NoC), have been projected as the limiting factor in terms of bandwidth, power and latency [1,2]. Although the low-swing interconnect technique [3,4,5] has been able to reduce the power and latency, on-chip interconnect still remains non-scalable and non-reconfigurable. To mitigate this impact, we propose the use of multiband RF-interconnect (RF-I) that can simultaneously communicate through multiple bands (including the traditional baseband) to offer a scalable, reconfigurable, high aggregate data rate, low latency and low energy per bit interconnect.

Architecture and Circuit Design of the RF-I

The proposed tri-band RF-I has 2 concurrent RF-bands in mm-wave frequencies, 30GHz and 50GHz, and 1 base-band (BB) to serve as one of the multiple parallel communication links in future on-chip NoC, as shown in Fig. 1. The modulation scheme of each RF band is amplitude-shift keying (ASK) in which a pair of on-off switches directly modulates the RF carrier. Unlike other modulation schemes such as BPSK, the receiver of the ASK system only detects the changes in amplitude and not in phase or frequency variations. Therefore, it can operate asynchronously without a power hungry PLL. It also eliminates the need of carrier re-generation at the receiver. Consequently, the RF-I does not suffer from process-induced carrier variations between the Tx and Rx. The RF-I can also operate properly with conventional digital logic circuits placed directly under its passive structure, which gives better area utilization.

For each RF band, the design uses a minimal configuration that includes a VCO and an ASK switch on the transmitter side, and a self-mixer and baseband amplifiers on the receiver side. As shown in Fig. 2, the VCO generates the RF-carrier and acts as a push-pull amplifier. The RF-carrier from the VCO is first inductively coupled to the ASK modulator through a 2:1 ratio transformer. After that the input data stream modulates the RF carrier via a pair of ASK switches. In order to maximize the modulation depth of the ASK signal, the size of switch is chosen to provide a optimal balance between the on state loss and the off state feed through. After the ASK modulation, the differential ASK signal is inductively coupled to the transmission line (TL) through the second frequency selective transformer. The impedance matching requirement is greatly relaxed because the reflected wave is attenuated significantly in the on-chip TL after reflection. By choosing the RF-carrier in mm-wave frequencies, the higher carrier to data rate ratio further minimizes the dispersion of the signal and removes the need for a power hungry equalization circuit. The receiver architecture in each RF band, as shown in Fig. 3b, the self-mixer acts as an envelope detector and demodulates the mm-wave frequency ASK signal into baseband signal, where it is further amplified to full swing digital signal.

The BB utilizes a low-swing interconnect technique using capacitive coupling [3]. As shown in Fig. 4, the baseband data is transmitted and received using the common mode of the differential TL. At low frequency, the transformer becomes a short circuit, and a pair of low-swing capacitive coupling buffers transmits and receives the baseband data at the center tap of the transformer.

The transmitter and the receiver are connected by an on-chip 5mm differential TL, as shown in Fig. 3a. In order to support simultaneous multi-band RF-I on a shared TL, RF and BB are transmitted in differential mode and common mode respectively. These two propagation modes are naturally orthogonal to each other and suppress the inter-channel interference (ICI) between RF and BB. Even with finite coupling between the differential mode (RF) and the common mode (BB), the low-pass characteristic of the BB receiver and the band-pass characteristic of the RF receiver can provide further rejection of this ICI. The remaining challenge is the ICI between the different RF channels. In the transmitter, the frequency selectivity of the second transformer in each RF band reduces the risk of ICI due to signal leakage to the adjacent RF band's ASK modulator. In the receiver of the RF bands, the transformer at the input of the self-mixer acts as a band-pass filter.

Measurement Results and Comparison

The tri-band on-chip RF-I is implemented in the IBM 90nm digital CMOS process, and the die size is 1mm×2mm, as shown in Fig. 5. Fig. 6 and 7 show the recovered data waveform and eye-diagram of the 3 bands: 30GHz, 50GHz and BB. The maximum data rate for each RF band and BB are 4Gbps and 2Gbps respectively. The total aggregate data rate is 10Gbps. The measured BER across all channels is $< 1\times10^{-9}$. As the RF-I approaching to the maximum data rate, BER of RF bands starts to degrade while BB remains unchanged. In future RF-I, a design with better supply noise rejection in the self-mixer and faster frequency response of the buffer in RF channel will reduce the BER in the RF bands. A structure with TX and TL only (without Rx) was also implemented for measuring the spectrum of the tri-band RF-I signals. A 67-GS Cascade Micro-Probe (only differential mode can be measured) directly probes the on-chip differential TL. Fig. 8a shows the free running VCO spectrum with no input data modulation on both RF channels at 28.8GHz and 49.5GHz. When the two uncorrelated 4Gbps random data streams are applied to both RF bands, as shown in Fig. 8b, the spectrum of each band broadens and spreads over 10GHz of bandwidth. Compared with BB low-swing interconnects [3,4,5], as shown in Table 1, the tri-band RF-I achieves superior aggregate data rate (10Gbps), latency (6ps/mm) and energy per bit (0.09pJ/bit/mm and 0.125 pJ/bit/mm, for RF & baseband, respectively). As the CMOS technology scales, with higher of f_T, date rate of RF-I will be able to scale by simply expanding to more carrier bands. Moreover, reconfigurable and fault-tolerant NoC/CMP [6] can also be achieved by simply adaptively selecting/combining multiple RF bands in RF-I to meet dynamic routing and data throughput requirements.

References

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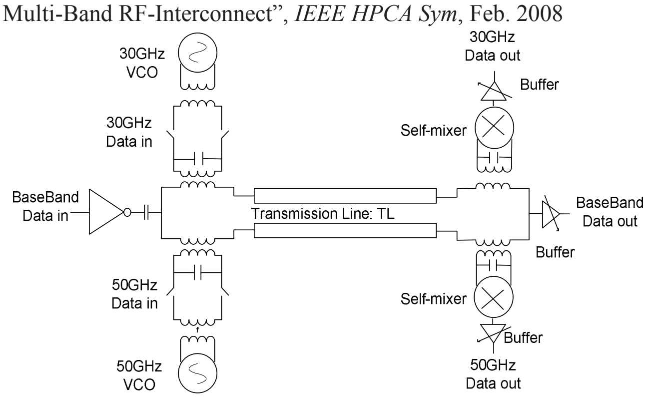

Fig. 1 Schematic of the On-chip Tri-band ASK RF-I

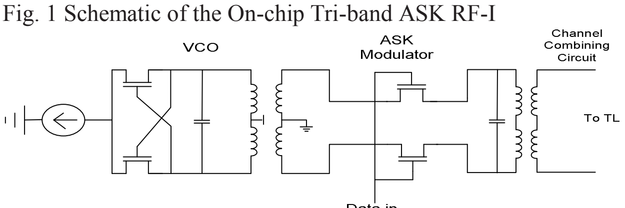

Fig. 2 Schematic of the transmitter of the RF band

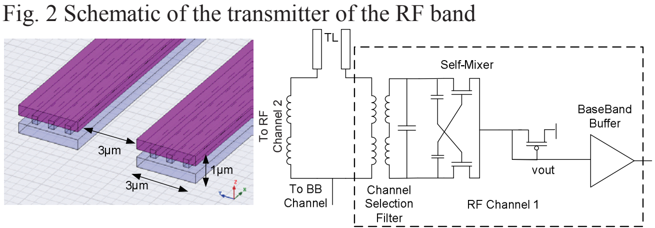

Fig. 3(a) On-Chip differential TL (b) Schematics of the RF receiver

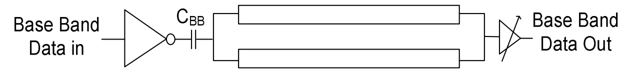

Fig. 4 Equivalent circuit of the Base Band in common mode

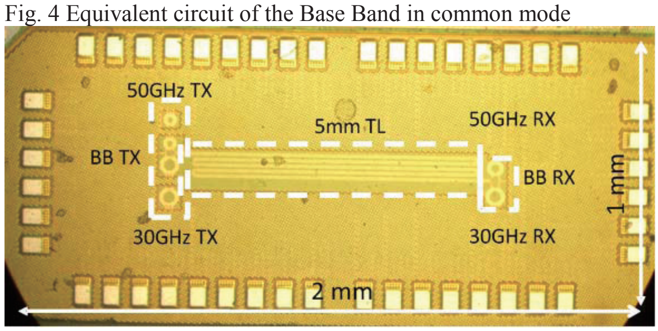

Fig. 5 Die Photograph

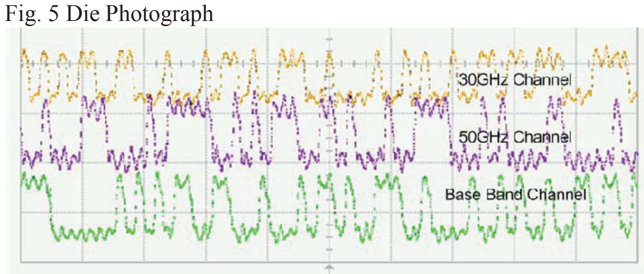

Fig.6 Data output of the tri-band waveform 30GHz, 50GHz and BB

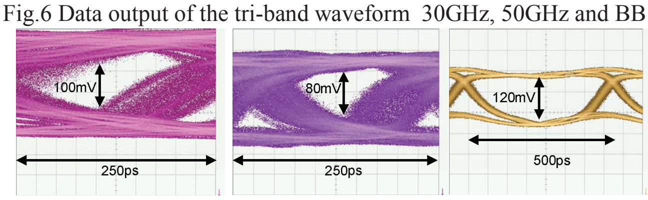

Fig. 7 Eye diagram of the 30GHz band, 50GHz band and BB

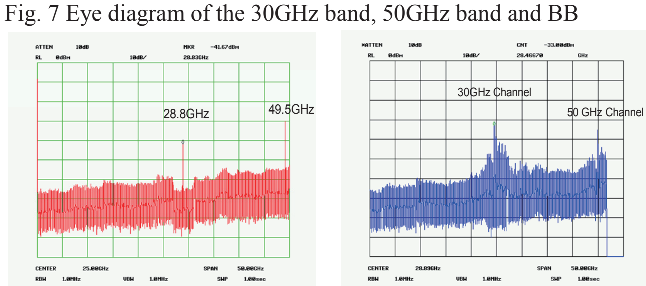

Fig. 8 Spectrum on the differential mode RF-I signal with (a) no data input (b) with 4Gbps data input in each band

	This Work	[3]	[4], [5]
Interconnect Technique	RF-I	Low-Swing Capacitive Coupling	Low-Swing CML
Channels	30GHz, 50GHz, Base-Band	Base-Band	Base-Band
Data Rate in RF Channel (Gbps)	4	NA	NA/NA
Data Rate in BB Channel (Gbps)	2	1	8, 3
Total Aggregate Data Rate (Gpbs)	10	1	8, 3
Latency (ps/mm)	6	55	30, 6.5
Energy Per Bit (RF) pJ/bit/mm	0.09*	NA	NA
Energy Per Bit (BB) pJ/bit/mm	0.125	0.28	0.18, 0.14

Table 1 Comparison with prior works in BB low swing interconnect
*VCO power (5mW) can be shared by all (many tens) parallel RF-I links in NOC and does not burden individual link significantly.