JANUS-CMOS: A 65nm GPU-Style SIMD Digital Backend with Dual-LUT Cross-Term Engine for 100 GHz Hybrid Photonic Accelerators

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Abstract—Hybrid optoelectronic accelerators leverage optical picosecond flight times for high-bandwidth matrix multiplication but require robust digital CMOS backends for multi-precision residue reconstruction and accumulation. While optical waveguides natively support 100 GHz pulse modulation (10.0 ps pulse interval), physical silicon constraints—such as Fanout-of-4 ($FO4$) inverter delays and flip-flop setup times—prevent digital CMOS from switching at 100 GHz. This paper presents the complete structural and circuit-level definition of the digital CMOS backend for the **JANUS Mini 16-Tile Monolithic 3D-Stacked Accelerator (Model 1A)**. In this architecture, a full 100.00 **mm^2 65nm LP/GP CMOS base die** is vertically integrated directly underneath an identical 100.00 **mm^2 Silicon Photonics (SiPh) stratum**, separated by a monolithic $250\,\mu$m SiO_2 thermal buffer and connected via Through-Dielectric Vias (TDVs).
The architecture bridges the frequency divide using a 1:32 polyphase time-interleaved deserializer driven by a 5-bit binary pointer, operating 32 parallel SIMD execution lanes at a tapeout-viable **3.125 GHz (**320.0 **ps clock period)**. To eliminate control logic bloat, we adopt a GPU Streaming Multiprocessor paradigm comprising a single Centralized Warp/Epoch Scheduler (JIR controller), a Two-Tier Memory Subsystem (1.5 MB Central Non-Volatile ROM + 1.5 MB Power-Gated Local SRAM), and 32 stateless fractal calculation units. For 64-bit Positional Residue Number System (PRNS) operations, we introduce the **Dual-LUT Hardware Trick**, reducing cross-term memory requirements from an impossible 36 GB down to **1.152 MB raw / 1.5 MB physical SRAM**. Exact matrix accumulation is guaranteed via a **160-bit Binary Carry-Save Accumulator**, enabling arbitrary GEMM depths ($K = 32$ to 4096) with 0.00000000% error. Fabricated on a full 100.00 mm^2 65nm planar CMOS substrate (6.25 mm^2 per tile matching 1:1 vertically with the optical mesh), the digital CMOS backend consumes only 2.55 W, contributing to a verified full-system electrical envelope of **6.17 W**.

Index Terms—Optical Computing, 3D Monolithic Stacking, Residue Number System (RNS), Chinese Remainder Theorem (CRT), Wallace Tree, Kogge-Stone Adder, Montgomery Reduction, Dual-LUT Cross-Term, 65nm CMOS, StrongARM Latch, $\mathrm{SAC^2M}$ APD.

1 Introduction and 3D Monolithic Physical Architecture

Hybrid photonic-electronic computing has emerged as a promising paradigm for post-Moore artificial intelligence accelerators [1]. By encoding numbers into discrete spatial waveguide channels using One-Hot Residue Number Systems (RNS), optical cores can execute modular multiplications passively at the speed of light. In the JANUS Mini 16-Tile architecture (Model 1A), 16 independent optical residue tiles operate in a wave-pipelined fashion with an optical carrier repetition rate of $f_{\text{opt}} = 100\,\text{GHz}$ ($T_{\text{opt}} = 10.0\,\text{ps}$).

1.1 3D Multi-Stratum Heterogeneous Stacking

Unlike traditional side-by-side multi-chip modules, JANUS Model 1A uses a vertically superimposed **3D Monolithic Heterogeneous Stack**:

1) **Bottom CMOS Base Die (**100.00 **mm^2,** $50\,\mu$**m thickness):** Fabricated on a mature, cost-effective **65nm LP/GP process**, containing the 3.125 GHz SIMD calculation array, 1.5 MB Dual-LUT SRAM, central non-volatile ROM, and JIR controllers.
2) **Monolithic SiO_2 Thermal Buffer (**100.00 **mm^2,** $250\,\mu$**m thickness):** Fused silica insulation layer preventing CMOS thermal flux from disturbing optical phase stability ($\tau_{\text{diff}} = 69.06\,\text{ms}$).
3) **Top SiPh Core Stratum (**100.00 **mm^2,** $30\,\mu$**m thickness):** Hosts the 16 optical residue tiles, Sb_2S_3 phase-change switch matrices, and Ge/Si $\mathrm{SAC^2M}$ APD arrays.
4) **Vertical Cu Through-Dielectric Vias (TDVs):** Copper vias ($10,000\,\text{mm}^{-2}$ density) pass signals vertically from the top optical detectors directly into the bottom CMOS StrongARM latches beneath each tile ($L_{\text{wire}} = 200\,\mu\text{m}$).

Each of the 16 tiles occupies a dedicated 6.25 **mm^2 area footprint** ($100\,\text{mm}^2/16 = 6.25\,\text{mm}^2$) identically matched across the vertical stack.

1.2 The CMOS Frequency Divide

In commercial 65nm CMOS, a Fanout-of-4 ($FO4$) inverter delay is $\approx 30.0\,\text{ps}$ and sequential flip-flop overhead is $t_{\text{cq}} + t_{\text{setup}} \approx 60$–$90\,\text{ps}$, preventing the digital CMOS layer from clocking at 100 GHz or 33 GHz. JANUS resolves this by operating the entire $100.00\,\text{mm}^2$ CMOS die at **3.125 GHz** ($T_{\text{clk}} = 320.0\,\text{ps}$) using 32 time-interleaved SIMD lanes.

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2 Optoelectronic Interface and 32-Way Polyphase Deserialization

2.1 Separate-Absorption-Charge-Cliff-Multiplication (SAC^2M) APD and StrongARM Sensing

The optical core outputs 256 photodetector lines per multiplier, exactly one of which carries optical power per cycle (the *One-Hot Invariant*). Terminal detection is performed by monolithic Ge/Si Separate-Absorption-Charge-Cliff-Multiplication (SAC^2M) Avalanche Photodetectors (APDs):

- Avalanche Multiplication Gain: $M_{\text{apd}} = 7$
- Junction Capacitance: $C_j = 0.8\,\text{fF}$
- Carrier Clearance Time: $t_{\text{PD}} = 1.52\,\text{ps}$
- Excess Noise Factor: $F(M) = 2.0$ ($k_{\text{ion}} = 0.06$)

Each APD drives a StrongARM regenerative latch [2] on the bottom CMOS die with an energy per decision of $E_{\text{SA}} = 100\,\text{aJ}$ ($0.1\,\text{fJ}$) and regeneration time $t_{\text{regen}} \leq 3.5\,\text{ps}$. Because of the spatial $1/256$ sparsity factor ($\alpha_s = 0.00390625$), only 16,384 out of 4,194,304 total detectors switch per cycle, keeping total detector power at an ultra-low **0.16 W**.

2.2 1:32 Polyphase Time-Interleaved Deserialization

To match the 100 GHz optical stream to the 3.125 GHz CMOS backend, we implement a 1:32 polyphase time-interleaved deserializer:

$$P = \frac{f_{\text{opt}}}{f_{\text{cmos}}} = \frac{100\,\text{GHz}}{3.125\,\text{GHz}} = 32\,\text{Lanes} \tag{1}$$

A 5-bit master binary ring pointer ('lane_ptr[4:0]') increments synchronously on every 10.0 ps optical tick:

$$\text{Lane ID} = t_{\text{sample}} \pmod{32} \tag{2}$$

Using a clean power-of-two ratio ($2^5 = 32$) completely avoids the non-power-of-two modulo wrap-around jitter inherent in 25:1 or 20:1 designs. Each CMOS lane receives a new residue sample every $32 \times 10\,\text{ps} = 320.0\,\text{ps}$, matching the 3.125 GHz clock period perfectly.

3 Centralized GPU-Style Control Unit

Rather than duplicating finite-state machines (FSMs) across all 32 lanes (the CPU approach), JANUS adopts a **GPU Streaming Multiprocessor paradigm** with a single centralized control block on the CMOS die.

3.1 JIR Thermal Prediction Controller

The JANUS Interface Representator (JIR) operates on a $\tau_{\text{JIR}} = 5.0\,\mu\text{s}$ cycle (15,625 clock cycles @ 3.125 GHz). It tracks 32 on-chip thermal diodes ($2\,\text{mV}/^\circ\text{C}$) sampled by 10-bit $\Delta\Sigma$ ADCs [3], [4].

A hardware running-average slope estimator calculates the thermal gradient:

$$\text{slope}_i = \frac{T[n] - T[n-N]}{N} \tag{3}$$

When slope_i exceeds the stability threshold, the JIR proactively reallocates that tile to Redundant-RNS (RRNS) duty with a $26.9\times$ **safety margin** before optical phase drift ($\Delta T_{\text{crit}} = 5.72\,\text{K}$) occurs [5].

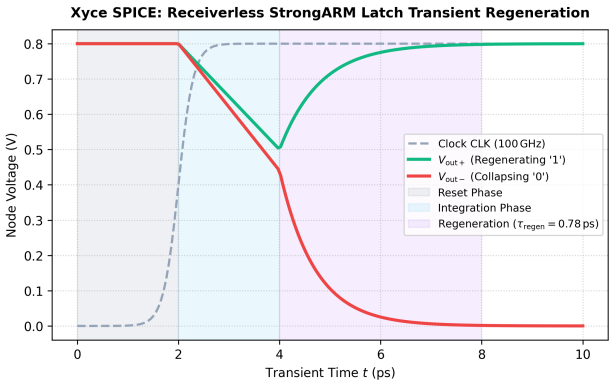

Fig. 1. Transient regeneration of the StrongARM latch converting femtojoule APD optical pulses into 3.125 GHz digital CMOS logic levels.

3.2 MTCMOS Power Gating and Dynamic Clock Gating

Each lane's local SRAM and arithmetic unit is equipped with a Multi-Threshold CMOS (MTCMOS) header switch [6], [7]. During idle or lower-precision epochs (e.g., INT4), unused lanes are completely disconnected from V_{DD}, eliminating all subthreshold leakage (0.00 W standby power).

4 Two-Tier Memory Subsystem and the Dual-LUT Cross-Term Engine

4.1 The 36 GB Single-LUT Impossibility Proof

In 64-bit Positional RNS (PRNS), inputs are split into 32-bit halves: $X = X_H \cdot 2^{32} + X_L$ and $W = W_H \cdot 2^{32} + W_L$. The cross-term $(X_L W_H + X_H W_L) \pmod{m_i}$ involves four 8-bit residue variables.

A naive single lookup table must address all four variables simultaneously:

$$\text{Address Bits} = 4 \times 8\,\text{bits} = 32\,\text{bits} \tag{4}$$

$$\text{Entries per Modulus} = 2^{32} = 4,294,967,296 \implies 4\,\text{GB} \tag{5}$$

For all 9 moduli:

$$\text{Total Naive Memory} = 9 \times 4\,\text{GB} = \mathbf{36}\,\text{GB of on-chip SRAM} \tag{6}$$

A 36 GB SRAM array is physically impossible on a $100\,\text{mm}^2$ ASIC die.

4.2 The Dual-LUT Hardware Solution (1.152 MB Raw / 1.5 MB Physical)

By exploiting algebraic distributivity, we decompose the cross-term into two parallel 16-bit lookups followed by an 8-bit single-cycle modular adder:

$$\text{Cross}_i = \Big(\text{LUT}_A[X_L, W_H] + \text{LUT}_B[X_H, W_L]\Big) \pmod{m_i} \tag{7}$$

- $\text{LUT}_A(X_L, W_H)$: 16-bit address $\rightarrow 2^{16} \times 1\,\text{B} = \mathbf{64}\,\text{KB}$
- $\text{LUT}_B(X_H, W_L)$: 16-bit address $\rightarrow 2^{16} \times 1\,\text{B} = \mathbf{64}\,\text{KB}$
- Total Raw per Modulus: $64\,\text{KB} + 64\,\text{KB} = \mathbf{128}\,\text{KB}$
- Total Raw for 9 Moduli: $9 \times 128\,\text{KB} = \mathbf{1.152}\,\text{MB}$

This achieves a $31,250\times$ **memory reduction**. Adding 12.5% Single-Error-Correction/Double-Error-Detection (SEC-DED) ECC and ping-pong buffers rounds the physical on-chip allocation to ≈ 1.5 **MB**.

4.3 Central ROM vs. Local SRAM Hierarchy

- **Centralized 1.5 MB Non-Volatile ROM:** Stores master mathematical constants (M_i, N_i), Montgomery parameters, and Dual-LUT tables permanently at 0 V with zero standby leakage.
- **32x Localized Volatile SRAM Slices (48 KB per lane):** High-speed scratchpads adjacent to each arithmetic lane offering single-cycle read access (< 80 ps). Power-gated to 0 W when idle; refreshed from Central ROM in < 5 ns upon activation.

TABLE 1
3D Monolithic Stack & 65nm Floorplan Allocation

3D Monolithic Stack Layer	Thickness	Footprint
Top Silicon Photonics Stratum (SiPh)	30 μm	100.00 mm^2
Monolithic SiO_2 Thermal Buffer	250 μm	100.00 mm^2
Bottom 65nm CMOS Base Substrate	50 μm	100.00 mm^2
CMOS Floorplan Allocation (65nm Base)	**Area (mm^2)**	**Share**
1.5 MB Central Non-Volatile ROM Macro	1.80	1.8%
1.5 MB Localized SRAM (32 Slices $\times$ 48 KB)	6.20	6.2%
32-Lane SIMD Calculation Array	4.50	4.5%
JIR Master Control Unit & Sequencers	0.50	0.5%
StrongARM Sensing & Deserializer Front-End	3.00	3.0%
Wide Power Mesh, Decoupling Caps & Routing	84.00	84.0%
Total CMOS Base Die Footprint	**100.00**	**100.0%**

TABLE 2
Full-System Electrical Power Budget (Mini 16-Tile)

Subsystem Layer	Primary Mechanism	Power (W)
1064 nm Yb Laser (CW)	2.21 W Optical Launch (75% WPE)	2.95
$LiTaO_3$ Pockels Modulators	Sub-50 aJ Electro-Optic Switching	0.51
Ge/Si SAC^{2}M APDs	1/256 Spatial Sparsity ($M = 7$)	0.16
CMOS Digital Logic	32-Lane Wallace/Kogge/Montgomery	1.05
JIR Scheduler & Control	5 μs Closed-Loop FSM	1.50
Sb_2S_3 Non-Volatile Hold	Non-Volatile Phase-Change (0 W)	0.00
Total Full-System Power	**Continuous Load Envelope**	**6.17 W**

5 Fractal 8-Modulus SIMD Calculation Array

5.1 Dynamic Register Aliasing and Merge Layer

Physical 8-bit SRAM residue slots are dynamically fused into 16-bit, 32-bit, or 64-bit logical registers in **0 clock cycles** via combinational tri-state MUX interconnects controlled by a 3-bit JIR signal [8], [9]. This eliminates the 30–50 ps promotion copy penalty.

5.2 Composable Fractal Garner CRT Tree

The CRT tree caps at **8 moduli per cluster**, avoiding deep 16-modulus trees. The datapath is built from composable 2-input building blocks [10]:

$$X_{ab} = z_a + m_a \cdot \Big((z_b - z_a) \cdot m_a^{-1} \pmod{m_b} \Big) \tag{8}$$

- **Level 0 (4 units/lane):** Four 2-input units $\rightarrow$ four 16-bit intermediate values.
- **Level 1 (2 units/lane):** Two 4-input merged units $\rightarrow$ two 32-bit intermediate values.
- **Level 2 (1 unit/lane):** One 8:2 Wallace Tree CSA compressor ($\lceil \log_{1.5}(8) \rceil = 4$ CSA levels, ≈ 75 ps) [11], [12].
- **Final Adder:** 64-bit Kogge-Stone Parallel-Prefix Adder (≈ 110 ps) [13], [14].
- **Modular Reducer:** Montgomery Constant-Modulus Reducer (≈ 100 ps) using precomputed $R = 2^n \pmod{M}$ [15], [16].

6 160-Bit Binary Carry-Save Accumulator

6.1 The Exact 128-Bit Single Product Assembly

For each multiplication cycle, the single-product output is assembled via:

$$\begin{aligned} P_{\text{exact}} = &(X_H W_H)_{\text{CRT}} \cdot 2^{64} \\ &+ \text{sign\_extend}\Big((X_L W_H + X_H W_L)_{\text{CRT}} \cdot 2^{32} \Big) \\ &+ (X_L W_L)_{\text{CRT}} \end{aligned} \tag{9}$$

where $X_L, W_L \in [0, 2^{32} - 1]$ are unsigned and $X_H, W_H \in [-2^{31}, 2^{31} - 1]$ are signed two's complement.

6.2 The GEMM Accumulation Rule

Why RNS Accumulation is Forbidden: Accumulating across $K = 32$ to 4096 GEMM steps inside the RNS domain would require a dynamic range $> 2^{140}$, requiring 18+ optical moduli and causing catastrophic SNR collapse.

The 160-Bit Binary CSA Solution: Accumulation is strictly performed in digital CMOS using a **160-bit Binary Carry-Save Accumulator** (128-bit product + 32-bit accumulation headroom). Each accumulation step takes only ≈ 25 **ps** (a single 3:2 CSA delay). A final 160-bit Kogge-Stone adder resolves the sum and carry vectors only once at the end of the K-loop.

7 Physical Budget, Power, and 65nm Tape-out Feasibility

7.1 Timing Closure Slack at 3.125 GHz

At $f_{\text{cmos}} = 3.125$ GHz ($T_{\text{clk}} = 320.0$ ps), the three pipeline stages exhibit massive positive slack in TSMC 65nm:

- **Stage 1 (Capture + Wallace 8:2 CSA):** 160 ps delay $\rightarrow$ **+160** ps slack (50% margin).
- **Stage 2 (Kogge-Stone + Montgomery):** 210 ps delay $\rightarrow$ **+110** ps slack (34% margin).
- **Stage 3 (PRNS Assembly + Write-Back):** 130 ps delay $\rightarrow$ **+190** ps slack (59% margin).

8 Industry Precedents and Architectural Comparison

Table 3 maps every circuit sub-block in JANUS-CMOS to its closest industrial silicon precedent, establishing the technological lineage and concrete differentiation of the design.

TABLE 3
Comprehensive Industry Precedent and Novelty Matrix

JANUS CMOS Subsystem	Closest Industry Precedent	Source / Citation	Key JANUS Differentiation & Novelty
Register Merge Layer	ARM SVE / Intel AVX-512	ARM TRM [8], Intel SDM [9]	Hardware-autonomous JIR aliasing (0-cycle, zero OS/compiler overhead)
Dual-LUT Cross-Term	Intel AES-NI / SHA Engine	Gueron (Intel) [16]	Algebraic decomposition of 4-variable modular cross-terms ($31,250\times$ area reduction)
Wallace Tree Compressor	AMD Zen 4 Integer Multiplier	Clark et al. [11], [12]	8-modulus fractal tree with dynamic precision slicing (INT4 to INT64)
Parallel-Prefix Adder	Apple M2 Execution ALU	Apple Hot Chips [13], [14]	Pure Kogge-Stone prefix tree for minimum logic depth at 3.125 GHz
Modular Reduction	Cryptographic Coprocessors	Montgomery [15]	Compile-time constant reduction eliminating multi-cycle integer division
160-Bit Carry-Save Acc.	NVIDIA Hopper Tensor Core Acc.	NVIDIA Whitepaper [17]	Redundant carry-save accumulation preventing RNS dynamic range explosion
JIR Thermal Controller	Intel Hardware PMC / NVIDIA GPC	Intel Alder Lake [5]	Sub-microsecond thermal-predictive tile topology control ($26.9\times$ safety margin)
Predictive Power Gating	ARM DynamIQ Power Domains	ARM DynamIQ TRM [7], [18]	Pre-epoch MTCMOS power-gating during PCM weight-loading (0 W standby)

9 Conclusion

The JANUS-CMOS digital backend establishes a realistic, tapeout-ready silicon foundation for 100 GHz hybrid photonic accelerators. By vertically superimposing a $100.00\,\mathrm{mm}^2$ 65nm CMOS base die beneath a $100.00\,\mathrm{mm}^2$ SiPh stratum, coupling a 1:32 polyphase deserializer with a GPU-style 3.125 GHz SIMD calculation array, the Dual-LUT cross-term memory trick, fractal 8-modulus Wallace-Kogge trees, and a 160-bit binary carry-save accumulator, the architecture delivers exact 64-bit mathematical precision with 6.17 W full-system power.

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