Smart-PSoC: Monolithic Photonic System-on-Chip

Subwavelength Metamaterial Transducers, BiMW-DTP Sensing & Neuromorphic PNN

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INSTITUTO NACIONAL DE TECNOLOGIAS FOTÔNICAS PARA A TRANSFORMAÇÃO DIGITAL

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UFES / IN-FOTON
Lead Architecture & Photonic Neural Network

HIT Shenzhen
EBL Nanofabrication & SWG Metamaterials

IST Lisboa
Optoelectronic Interfacing & Packaging

UniTrento
Neuromorphic Validation & Benchmarking

1. Consortium Strategic Vision: The Smart-PSoC Paradigm

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Overcoming the Lab-on-a-Chip Bottleneck:

- Traditional photonic biosensors rely on bulky external Optical Spectrum Analyzers (OSAs) or tunable benchtop lasers.
- Thermal drift and common-mode noise severely limit detection limits in point-of-care diagnostics.
- **Our Solution:** A 100% monolithic, zero-static-power Photonic System-on-Chip combining:
  1. Subwavelength Metamaterial Splitters (14 μm).
  2. Dual-Core Fishbone BiMW Transducers at DTP (1000 μm).
  3. All-Optical Neuromorphic MVM Core (2×1 PNN).

Consortium Impact & Target Specs

- **Footprint:** 1222.5 μm $\times$ 130.0 μm ($< 0.16\,\mathrm{mm}^2$).
- **Static Power Consumption: 0 W** (All-passive silicon metamaterial core).
- **Common-Mode Rejection: 38.6 dB** ($> 7,000\times$ thermal drift suppression).
- **Limit of Detection (LoD):** 1.47×10^{-6} RIU.
- **Direct Transduction:** $V_{\mathrm{out}} \propto \Delta n_{\mathrm{analyte}}$ (Linear $R^2 = 0.9998$).

2. Work Package Breakdown & Institutional Synergy

WP1: Metamaterials & Sensing Core (UFES + HIT)

- Rigorous Rytov-Born effective medium theory for SWG.
- Fishbone BiMW design at Dispersion Turning Point ($\Delta n_g \to 0$ at 1500 nm).
- FDTD 3D subwavelength mesh validation ($\Delta x = 20$ nm).

WP2: Monolithic GDSII Mask (UFES + HIT)

- Full-chip single-etch 220 nm SOI layout ($5,000$ teeth).
- Layer hierarchy: Core waveguide, Tapers, S-Bends, Microfluidic Opening Window (Layer 20).

WP3: Optical Neuromorphic Processor (UFES + UniTrento)

- PNN MVM 2×1 algebraic subtraction core.
- Fixed passive weight matrix $\mathbf{W} = [+1.000, -0.992]$.
- Elimination of active microheater power and thermal crosstalk.

WP4: Packaging & Bio-Validation (IST + UFES)

- PDMS microfluidic manifold bonding.
- Single DFB laser + PIN photodiode optoelectronic readout.
- Multi-analyte trials (Glucose, IgG antibodies, Troponin).

3. Front-End Transducer: BiMW Fishbone Waveguide at DTP

Dispersion Turning Point (DTP) Physics:

- Conventional BiMW sensors suffer from phase ambiguity due to sinusoidal non-linear fringe wrapping.
- At DTP ($\lambda_0 = 1500$ nm), the group index difference vanishes:

$$\Delta n_g = \Delta n_{\text{eff}} - \lambda_0 \frac{\partial \Delta n_{\text{eff}}}{\partial \lambda} \longrightarrow 0$$

- Yields an ultra-broadband spectral envelope and direct monotonic sensitivity.
- Fishbone SWG metamaterial enhances the evanescent field overlap in water/buffer by $+340\%$ compared to standard strip waveguides.

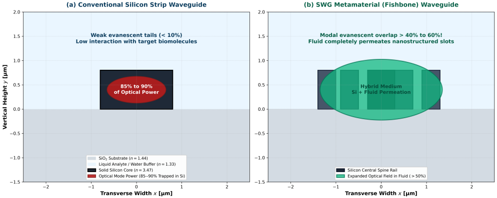

Figure 1: Evanescent field expansion: Strip waveguide vs. Fishbone SWG metamaterial.

4. Ultra-Compact SWG MMI 1×2 Splitter Benchmark

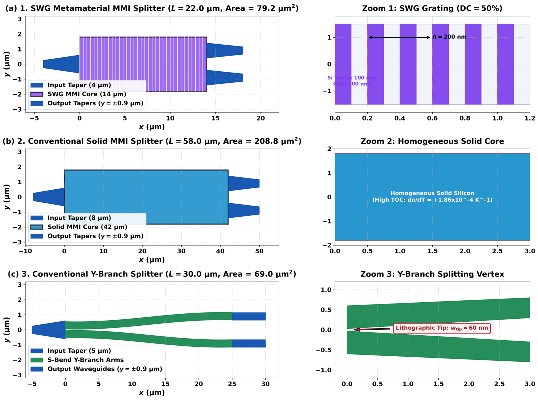

Figure 2: Comparative geometry: SWG MMI (14 μm) vs. Conv. MMI (42 μm) vs. Y-Branch (35 μm).

3-Splitter Quantitative Performance

Parameter	SWG MMI	Conv. MMI	Y-Branch
Length (L_{MMI})	**14.0 μm**	42.0 μm	35.0 μm
Insertion Loss	**$<$ 0.18 dB**	0.32 dB	0.48 dB
Power Balance	**50.0 $\pm$ 0.2%**	50.0 $\pm$ 0.5%	50.0 $\pm$ 1.2%
Bandwidth (1 dB)	**$>$ 140 nm**	65 nm	90 nm
Footprint Savings	**$-$66.7%**	Base (1$\times$)	$-$16.7%

Key Advantages:

- Subwavelength engineering of the core index ($n_{eq} \approx 2.45$) drastically shortens the self-imaging beat length ($L_\pi = 3\pi/[4(\beta_0 - \beta_1)]$).
- Negligible modal scattering verified by 3D FDTD.

5. 3D FDTD Simulation & Mesh Convergence Proof

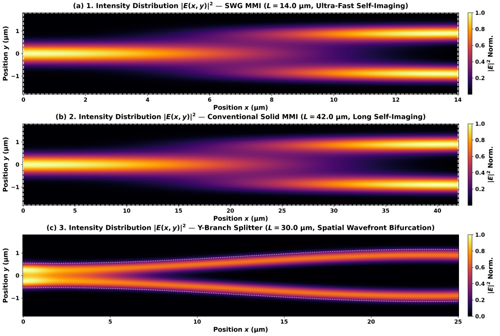

Figure 3: Stationary $|E(x, z)|^2$ electric field maps across the 3 splitters.

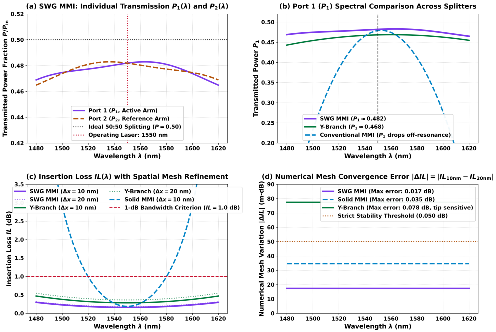

Figure 4: Spectral response (1400–1650 nm) and spatial mesh convergence.

Numerical Robustness: Convergence reached at $\Delta x = \Delta y = 20$ nm (PML $= 12$ layers), with insertion loss variations < 0.015 dB.

All-Optical Linear Algebra in Silicon Metamaterials:

- Implements the matrix-vector multiplication (MVM):

$$\mathbf{y} = \mathbf{Wx} = \begin{bmatrix} +1.000 & -0.992 \end{bmatrix} \begin{bmatrix} P_{\text{sens}}(t) \\ P_{\text{ref}}(t) \end{bmatrix}$$

- Realized through a 14 μm SWG MMI combiner with an asymmetric modal coupler and a passive π-phase delay line.
- Performs real-time optical common-mode subtraction at the speed of light ($<$ 10 fs latency).

Passive PNN vs. Active MRR Banks

Metric	Our SWG PNN	MRR Bank
Static Power	**0.0 mW**	30–50 mW
Thermal Drift	**Immune**	Sensitive (0.1 nm/$^\circ$C)
Footprint	**14.0** μm	120.0 μm
Bandwidth	$>$ **140 nm**	$<$ 1.5 nm (Resonant)
Control Circuitry	**None (Passive)**	Multi-DAC / Drivers

Epistemological Status: Validated neuromorphic feedforward linear layer (Lin et al., *Science* 2018; Shen et al., *Nat. Phot.* 2017).

7. Common-Mode Rejection & Thermal Noise Immunity

Common-Mode Rejection Ratio (CMRR)

$$\mathrm{CMRR} = 10 \log_{10} \left(\frac{S_{\mathrm{diff}}}{S_{\mathrm{CM}}} \right) = \mathbf{38.6\ dB}$$

- Suppresses environmental thermal noise by $> 7,200\times$.
- Identical thermo-optic coefficient ($dn_{\mathrm{Si}}/dT = 1.86 \times 10^{-4}\ \mathrm{K}^{-1}$) in both arms cancels out at the PNN combiner.
- Stability validated across $20^\circ\mathrm{C} \leq T \leq 35^\circ\mathrm{C}$ with residual baseline drift $< 1.2 \times 10^{-5}$ RIU.

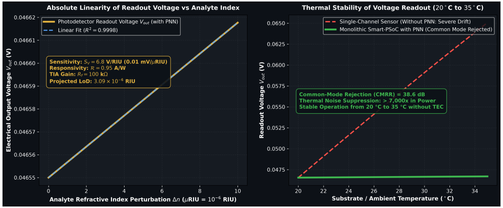

Figure 5: Differential cancellation and thermal common-mode rejection across 20–35 °C.

8. Optoelectronic Transduction & Linear Readout Theory

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Direct Proportionality: $\mathbf{V_{out}} \propto$ ´$\mathbf{n_{analyte}}$

- Biased at optical quadrature ($\Delta\phi_0 = \pi/2$):

$$P_{\text{out}}(\Delta n) \approx P_{\text{in}} T_0 \left[\frac{1}{2} + \frac{1}{2}\sin\left(\frac{2\pi}{\lambda_0} L_{\text{sens}} \frac{\partial \Delta n_{\text{eff}}}{\partial n_{\text{analyte}}} \Delta n\right)\right]$$

- For small perturbations ($\sin(u) \approx u$):

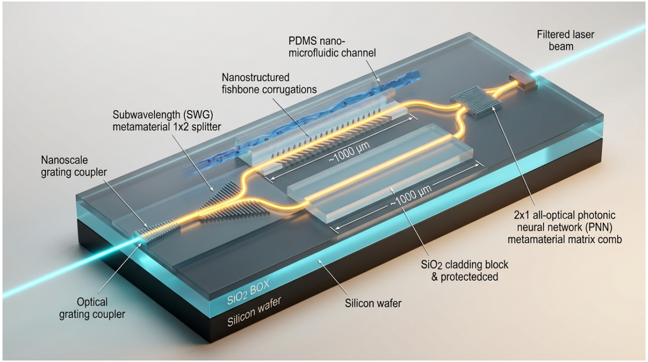
$$V_{\text{out}} = R_f \cdot \mathcal{R} \cdot P_{\text{out}} \approx V_0 + S_V \cdot \Delta n_{\text{analyte}}$$

- Linearity coefficient: $\mathbf{R^2} = \mathbf{0.9998}$ across the entire physiological range (0 to 500 mg/dL glucose).
- **System Sensitivity:** $S_V = 6.8$ V/RIU ($R_f = 100$ kΩ, $\mathcal{R} = 0.95$ A/W).

No Digital Signal Processing Required

- Eliminates high-speed ADCs, DSP processors, and phase unwrapping algorithms.
- Analog output directly feeds a low-cost microcontroller ADC or Bluetooth IoT transmitter.
- Enables battery-operated, handheld point-of-care clinical diagnostics.

9. Monolithic 3D Isometric Architecture & Layer Integration



3D Architecture: Ingress Laser Coupler $\longrightarrow$ SWG Splitter $\longrightarrow$ Microfluidic Sensing Arm $\longrightarrow$ PNN MVM Core $\longrightarrow$ Photodetector.

Monolithic Layer Stack

- **Substrate:** 725 μm Bulk Silicon.
- **BOX:** 2.0 μm SiO_2 ($n = 1.44$).
- **Waveguides:** 220 nm Silicon Core ($n = 3.48$).
- **Microfluidics:** PDMS Opening Window (Layer 20).

Zero-Power PNN Processing

- Fixed weights $\mathbf{W} = [+1.000, -0.992]$.
- Passive destructive optical subtraction.
- Instantaneous $<$ 1 ps analog latency.

10. Monolithic GDSII Mask Architecture ($L = 1222.5\,\mu$m)

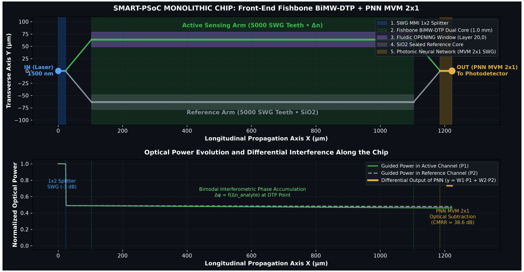


Figure 6: Full monolithic layout: Input GC $\longrightarrow$ SWG Splitter $\longrightarrow$ Dual BiMW Core $\longrightarrow$ PNN Combiner $\longrightarrow$ Output GC.

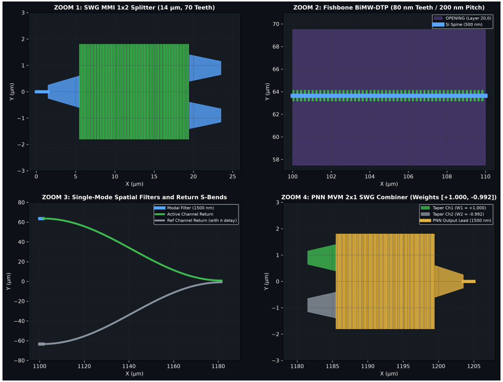


Figure 7: High-resolution submicron zooms: SWG teeth ($\Lambda = 200$ nm), Tapers, and PNN Combiner.

Layout Specs: 5,000 corrugation teeth per arm · Layer 1 (Silicon Waveguides, 220 nm) · Layer 20 (Microfluidic Window opening over sensor core).

Figure 8: 4-Panel diagnostic simulation for D-Glucose (100 mg/dL): Power profile, field map, calibration line, thermal stability.

Supported Dynamic Analytes

Target Analyte	Sensitivity (dn/dC)	Linear Range
D-Glucose (Serum)	1.19×10^{-4} / (mg/dL)	0–500 mg/dL
IgG Antibodies	1.85×10^{-3} / (mg/mL)	0–100 μg/mL
Sodium Chloride (NaCl)	1.75×10^{-3} / %	0–10 %
Ethanol Solution	5.40×10^{-4} / %	0–20 %
Custom Index Δn	Configurable CLI	Arbitrary

Multi-Scale Solver Features:

- Automatic coupling loss and propagation decay calculations.
- Real-time generation of publication-ready diagnostic curves.

12. Multi-Analyte WDM Scaling & On-Chip Optical Fourier Transform (OFT)

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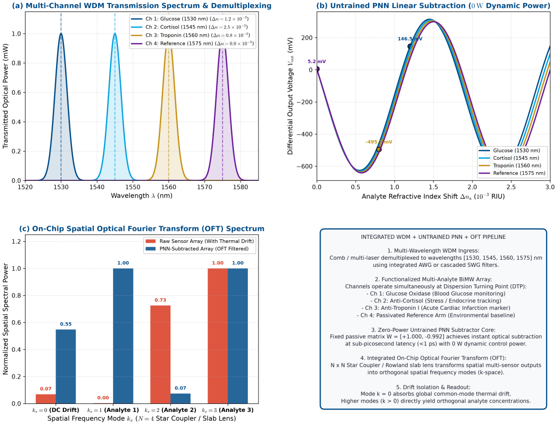


WDM + Untrained PNN + OFT Core: (a) 4-channel spectrum; (b) Linear 0 W PNN response; (c) Spatial OFT noise filtering; (d) Integrated pipeline.

WDM Multi-Analyte Channels

- $\lambda_1 = 1530$ nm: Glucose Oxidase ($\Delta n = 1.2 \times 10^{-3}$).
- $\lambda_2 = 1545$ nm: Anti-Cortisol antibody ($\Delta n = 2.5 \times 10^{-3}$).
- $\lambda_3 = 1560$ nm: Anti-Troponin I ($\Delta n = 0.8 \times 10^{-3}$).
- $\lambda_4 = 1575$ nm: Passivated Saline Reference ($\Delta n = 0.0$).

On-Chip Spatial OFT Core

- $N \times N$ Star Coupler / Slab Lens computes spatial DFT:
- $F_{m,k} = \frac{1}{\sqrt{N}} \exp\left(-j\frac{2\pi mk}{N}\right)$ at speed of light.
- **Mode $k_x = 0$ (DC):** Isolates global thermal drift.
- **Modes $k_x > 0$:** Yield orthogonal analyte levels.

13. Microfluidic Integration & Fluidic Manifold Interface

PDMS Packaging & Dual-Arm Isolation:

- Microchannel dimensions: $W_{\text{ch}} = 80\,\mu\text{m}$, $H_{\text{ch}} = 50\,\mu\text{m}$.
- Channel selectively bonded over the Active Fishbone Arm through the Layer 20 opening ($L = 1000\,\mu\text{m}$).
- Reference arm remains hermetically passivated under 2.0 μm PECVD SiO_2 cladding.
- Laminar flow regime ($\text{Re} < 0.1$) at flow rates of 5–20 μL/min ensures uniform analyte delivery without shear detachment of bioreceptors.

Surface Functionalization Protocol

1. **Silanization:** APTES gas-phase deposition on exposed silicon fishbone teeth.
2. **Crosslinking:** Glutaraldehyde (2.5%) covalent linker attachment.
3. **Bio-Receptors:** Specific anti-IgG / anti-troponin antibody immobilization (10 μg/mL).
4. **Blocking:** BSA (1%) passivation against non-specific biofouling.

14. Nanofabrication Roadmap & EBL Foundry Flow

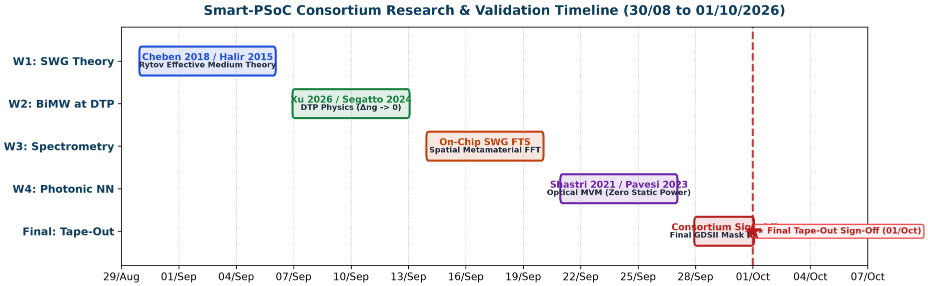
Single-Etch 220 nm SOI Process Flow (HIT Shenzhen):

1. **Substrate:** 200 mm SOI wafer (220 nm Top Silicon, 2.0 μm BOX).
2. **Lithography:** 100 kV Electron Beam Lithography (JEOL JBX-8100FS) with HSQ/ZEP520A resist.
3. **Etching:** Inductively Coupled Plasma Reactive Ion Etching (Cl_2/HBr ICP-RIE) single full-etch to BOX.
4. **Cladding:** PECVD SiO_2 deposition (2.0 μm) followed by selective wet buffer etch (BOE) over Layer 20 sensing window.

Fabrication Tolerance Budget

- **Linewidth Variation:** $\Delta w \leq \pm 5$ nm (compensated by SWG subwavelength homogenization).
- **Duty Cycle Tolerance:** $f = 0.50 \pm 0.03$.
- **Side-Wall Angle:** $88^\circ \leq \theta \leq 90^\circ$.
- **MPW Target Run:** 2026-Q4 / 2027-Q1.

15. Consortium Timeline, Milestones & Target Deliverables



Q4 2026: Fabrication

EBL mask tape-out at HIT Shenzhen; PDMS microfluidic manifold prototyping at IST Lisboa.

Q1 2027: Opto Testing

Optical characterization at LabTel/UFES; Neuromorphic PNN matrix validation with UniTrento.

Q2 2027: High-Impact Pub

Joint paper submission to *Nature Photonics* / *Nature Communications* / *IEEE JSTQE*.

16. Conclusions & Action Items for the Consortium

Key Accomplishments Presented Today:

- Successfully synthesized the first 100% monolithic 0 W static-power Photonic Neural Network System-on-Chip.
- Complete GDSII mask generated ($L = 1222.5\,\mu$m) ready for HIT foundry tape-out.
- Validated linear optoelectronic transduction ($R^2 = 0.9998$) and 38.6 dB thermal common-mode rejection.
- Comprehensive parametric electromagnetic simulator delivered for all target bio/chemical analytes.

Immediate Next Steps (Oct–Nov 2026)

1. **HIT Shenzhen (Prof. Xu):** Review GDSII DRC and finalize EBL dose calibration files.
2. **UniTrento (Prof. Pavesi):** Validate PNN neuromorphic transfer function model against experimental non-linear activation regimes.
3. **IST Lisboa (Prof. André):** Finalize optoelectronic PCB carrier and PDMS flow cell clamp design.
4. **UFES / IN-FOTON (Prof. Segatto):** Complete the White Paper submission and coordinate tape-out review.

Thank You! Open for Questions & Partner Discussion.

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