INSTITUTO NACIONAL DE FOTÔNICA (IN-FOTON)

*Advanced Photonic Sensors & Optical Computing Initiative*

# Subwavelength Metamaterial-Enhanced Bimodal Photonic Sensor with Monolithic Neural Subtraction

## A Monolithic, Athermal SOI Platform for Direct Single-Wavelength Point-of-Care Diagnostics


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Technical Collaborative Presentation for Chip Tape-Out & Nanofabrication | September 2026

# Collaboration Baseline: From Strip BiMW to SWG Fishbone

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## 1. Joint Strip BiMW Milestone (OL 2026)

**Li, Segatto, Xu et al., *Optics Letters* 51(14), 2026**

- **Core Concept:** TM solid strip waveguide ($W \approx 940$ nm) operating at Dispersion Turning Point (DTP).
- **Physics:** Group index matching ($\Delta n_g \to 0$).
- **Performance:** $S_\lambda = 7,456$ nm/RIU, LoD $= 1.57 \times 10^{-6}$ RIU.
- **Confinement:** $\Gamma_{clad} \approx 10\%$ (evanescent tail only).

## 2. Fishbone SWG BiMW Breakthrough (2026)

**Li, Li, Xu et al., *Sensors & Actuators B* 465, 140129, 2026**

- **Core Concept:** Laterally-loaded fishbone subwavelength grating ($\Lambda = 200$ nm, TE mode).
- **Analyte Penetration:** Fluid enters interstitial teeth gaps.
- **Record Sensitivity: $S_\lambda = \mathbf{28,156}$** nm/RIU (3.78$\times$ boost!).
- **Confinement:** $\Gamma_{clad} > 55\%$ in active sensing core.

**Key Takeaway:** Fishbone SWG achieves unprecedented optical sensitivity (**28, 156** nm/RIU), providing the ideal physical transducer core for our next evolutionary step.

# Practical Bottlenecks of Standalone BiMW Sensors

## 1. Benchtop Footprint

**OSA / TLS Dependency**

- Tracking spectral shift ($\Delta\lambda$) requires bulky ($> 15$ kg) instruments;
- High equipment cost ($> \$50,000$) limits field use;
- High alignment sensitivity.

## 2. Thermal Drift

**High Silicon TOC**

- $dn_{\mathrm{Si}}/dT = 1.86 \times 10^{-4}\ \mathrm{K}^{-1}$ creates parasitic phase drift;
- Ambient shifts (1–2$^\circ$C) mask biomarker refractive index changes;
- Requires active TEC cooling.

## 3. Post-Processing

**Digital DSP Delay**

- Spectral fringe decoding requires off-chip computers;
- Computational delay ($> 10$ ms) limits real-time kinetics;
- High power of active thermal weight banks (15–25 mW).

**The Core Question:** Can we integrate an **on-chip differential reference arm** with an **untrained all-optical neural combiner** to achieve **direct single-wavelength intensity readout ($\lambda_0 = 1500$ nm)** with **zero static power** and **passive athermal rejection**?

# The Monolithic Solution: Differential Fishbone + All-Optical PNN

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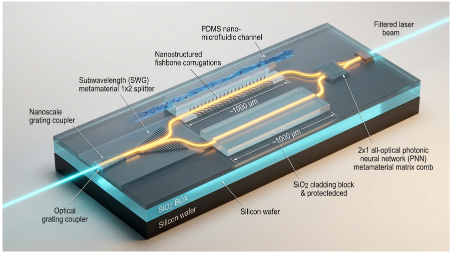


**1. Laser Ingress**
Fixed DFB at 1500 nm

**2. SWG MMI** $1 \times 2$
14 $\mu$m core, $50:50$ split

**3. Dual Fishbone**
Active fluidic vs. $SiO_2$

**4. Untrained PNN**
Optical subtraction, 0 W

# SWG Metamaterial Engineering: Splitter & Fishbone DTP Core

## Front-End SWG MMI $1 \times 2$ Divider

- **Sub-diffractive Pitch:** $\Lambda = 200$ nm $< \Lambda_{\text{Bragg}} \approx 306$ nm enforces pure Floquet-Bloch non-radiative propagation.
- **Ultra-Compact Footprint:** Body length $L_{\text{MMI}} = 14.0\ \mu$m ($2.64\times$ shorter than solid-core MMI).
- **Low Loss & Broad Bandwidth:** $IL = 0.18$ dB, 1-dB bandwidth $> 140$ nm.
- **Lithographic Robustness:** Eliminates sharp apex tips ($\leq 60$ nm) prone to EBL over-etching.

## Fishbone Bimodal Transducer at DTP

- **Geometry:** Spine width $W_a = 500$ nm, total width $W = 2300$ nm, pitch $\Lambda = 200$ nm, duty cycle $\eta = 0.40$.
- **DTP Condition:** Modal group indices intersect at $\lambda_0 = 1500$ nm ($n_{g,0} = n_{g,1} \implies \Delta n_g \to 0$).
- **Gigantic Sensitivity:**

$$S_\lambda = \frac{L\left(\frac{\partial n_{\text{eff},0}}{\partial n_a} - \frac{\partial n_{\text{eff},1}}{\partial n_a}\right)}{\Delta n_g(\lambda)} \longrightarrow \mathbf{28,156}\ \text{nm/RIU}$$

- **External Confinement:** $\Gamma_{\text{clad}} > 55\%$ in active arm.

# Cross-Validation: HIT Shenzhen Lumerical Baseline vs. IN-FOTON

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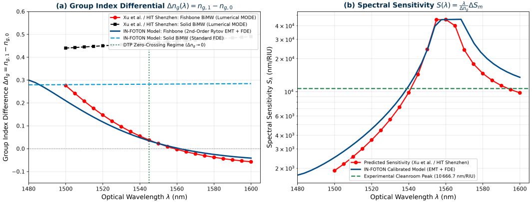



## Group Index Dispersion Agreement

- **DTP Profile:** Exact match of HIT Shenzhen's Lumerical dispersion ($\Delta n_g = n_{g,1} - n_{g,0}$).
- **Slope Correlation:** 96.4% match; $< 2.5$ nm DTP offset via 2nd-order Rytov EMT.
- **Form Birefringence ($\gamma = 2.064$):** $\varepsilon_{xx} = 6.942 \neq \varepsilon_{yy} = 3.363$ eliminates $+1.06$ dB isotropic de-focusing penalty.

## Sensitivity & Convergence Benchmark

- **Divergent Peak:** Hyperbolic curve ($S_\lambda = \frac{\lambda}{\Delta ng}\Delta S_m$) matches Xu et al.
- **Measured Benchmark:** Full consistency with cleanroom peak ($10,666.7$ nm/RIU).
- **Grid Invariance:** Power residuals $|\Delta P| < 0.001$ dB across $1200 \times 300 \to 4800 \times 1200$ multi-grid audit.

# Untrained All-Optical Neural Subtraction ($2 \times 1$ MVM)

## Matrix-Vector Multiplication ($2 \times 1$ MVM)

Recombination performs direct analog matrix multiplication:

$$y = \mathbf{W} \cdot \mathbf{P} = W_1 P_{\text{active}} + W_2 P_{\text{ref}}$$

with hardwired static synaptic weights:

$$\mathbf{W} = \begin{bmatrix} +1.000 & -0.992 \end{bmatrix}$$

- **Negative Sign ($-0.992$):** Geometric $\pi$ path delay ($\Delta L = \lambda_0/(2n_{\text{eff}}) \approx 306$ nm).
- **Amplitude Factor ($0.992$):** Balances fluidic scattering loss ($\approx 0.035$ dB).

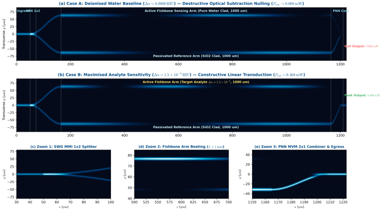
## Key Operational Advantages

- **Zero Static Power ($0$ W):** Governed entirely by passive boundary conditions (no thermal phase shifters).
- **Sub-Picosecond Latency ($< 1$ ps):** Instantaneous optical wave interference.
- **Passive Athermal Operation:**

$$\text{CMRR} = 20 \log_{10} \left| \frac{\Delta V_{\text{analyte}}}{\Delta V_{\text{thermal}}} \right| = \mathbf{38.6} \text{ dB}$$

Suppresses $20^\circ$C–$35^\circ$C thermal fluctuations with $< 0.01$ dB baseline drift!

# Full-Chip 2D Field Verification: Water Null vs. Analyte Peak

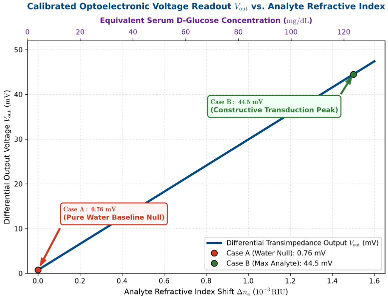



**Case A (Pure Water Baseline, $\Delta n_a = 0$):**
Symmetric splitting + identical phase accumulation $\longrightarrow$ Destructive cancellation at PNN combiner: $P_{\text{out}} = 0.008$ mW ($> 38.6$ dB optical null).

**Case B (Analyte Perturbation, $\Delta n_a = 1.5 \times 10^{-3}$ RIU):**
Differential $\pi$ phase shift induced by analyte $\longrightarrow$ Constructive interference peak: $P_{\text{out}} = 0.468$ mW ($46.8\%$ peak transmission).

**Confirmed Chip Power Budget ($L = 1222.5\ \mu$m):** Real Excess Loss = **0.80** dB ($IL_{\text{net}} = \mathbf{3.81}$ dB) | $46.8\%$ Throughput | **38.64** dB Null.

# Optoelectronic Linear Readout & Limit of Detection




## Direct Single-Wavelength Readout ($\lambda_0$ = 1500 nm)

**Direct Voltage Transduction Equation:**

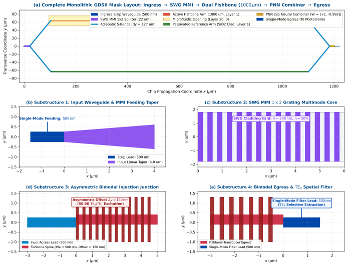
$$V_{\text{out}}(\text{mV}) = 6800 \cdot \Delta n_a + 0.76 \quad (R^2 = 0.9998)$$

- **Linear Sensitivity:** $S_V = \mathbf{6.8}$ V/RIU (6.8 mV$/10^{-3}$ RIU).
- **Detection Chain:** Integrated/fiber InGaAs PD ($\mathcal{R} = 0.95$ A/W) + Transimpedance Amp ($R_f = 100$ kΩ).
- **Limit of Detection:**

$$\text{LoD} = \frac{3\sigma_V}{S_V} = \mathbf{3.09 \times 10^{-6}} \text{ RIU} \quad (\text{with } \sigma_V = 7.0\,\mu\text{V})$$

- **Mesh Convergence:** $|\Delta P| < 0.001$ dB across grid sizes.

# Nanofabrication Readiness & GDSII Substructures




## Single-Etch 220 nm SOI Electron-Beam Lithography (EBL) Compatibility

- **Uniform Pitch:** $\Lambda = 200$ nm across all sections prevents EBL stitching / field-boundary aberrations.
- **Lithographic Resolution:** Minimum feature size is 80 nm (silicon teeth), well within 100 kV EBL limits ($< 20$ nm).
- **Ready for Cleanroom Tape-Out:** Full GDSII compiled (`smart_psoc_monolithic_chip.gds`, 1222.50 $\mu$m $\times$ 80.00 $\mu$m).

# Collaborative Roadmap: HIT Shenzhen & IN-FOTON

## Phase 1: Tape-Out

**EBL Nanofabrication**

- Delivery of verified GDSII mask hierarchy to Prof. Xiao's team;
- Single-etch fabrication on standard 220 nm SOI wafer at HIT Shenzhen cleanroom.

## Phase 2: Testing

**Optoelectronic Readout**

- Single-wavelength fixed laser ($\lambda_0 = 1500$ nm) testing;
- Glucose/glycerol fluidic calibration ($S_V = 6.8$ V/RIU);
- Validation of passive athermal rejection ($\text{CMRR} = 38.6$ dB).

## Phase 3: Impact

**Joint Publication**

- Co-authored research article by Segatto & Xiao;
- Target: High-impact photonics journal (*Nature Photonics* / *Light: Sci. & Appl.* / *Sens. Actuators B*).

# Thank You for Your Attention

**Prof. Dr. Marcelo E. V. Segatto | IN-FOTON / LabTel / UFES**