Next-Generation Multiparameter Fiber Optic Photonic Nose for Energy Infrastructure Sensing

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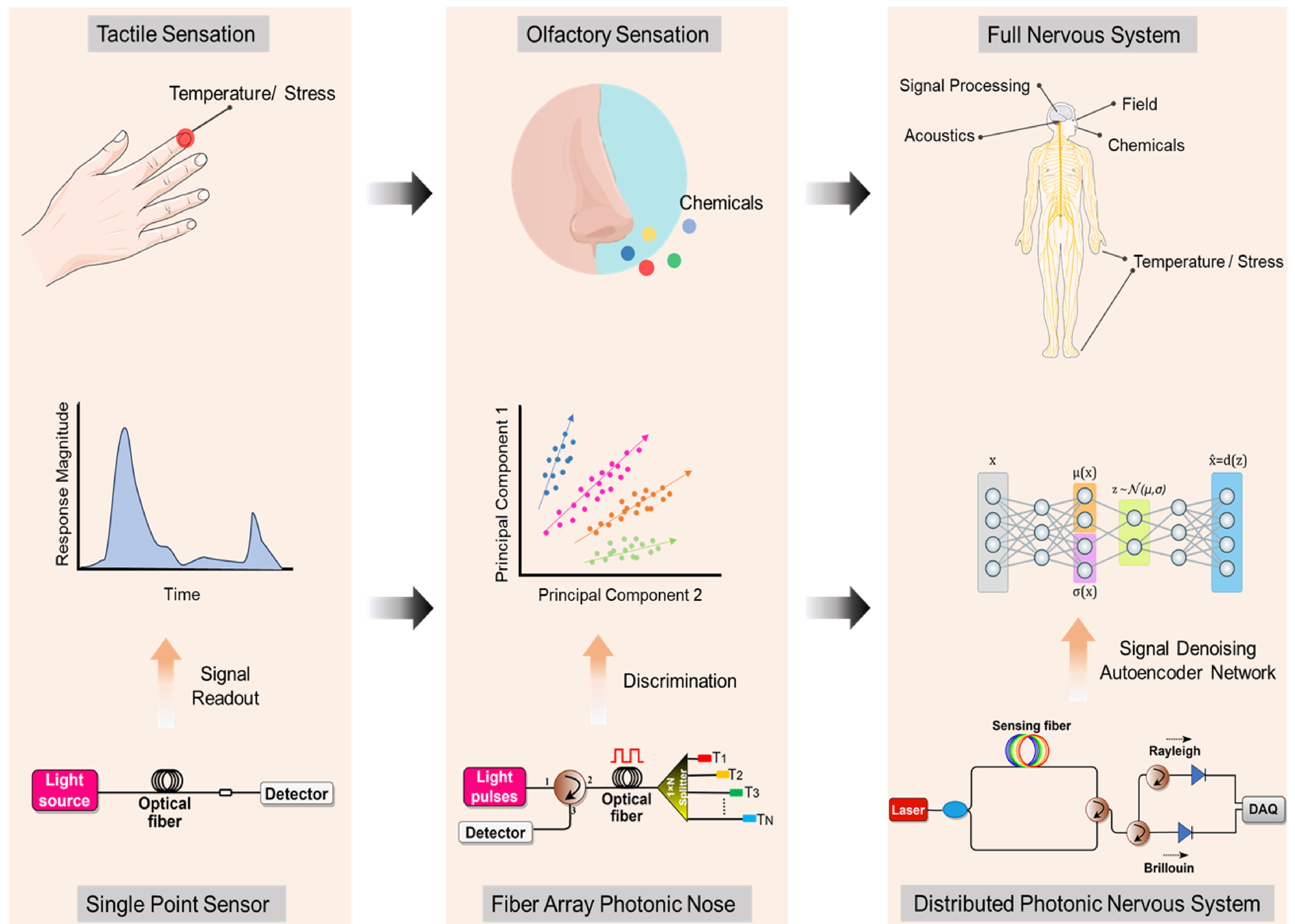
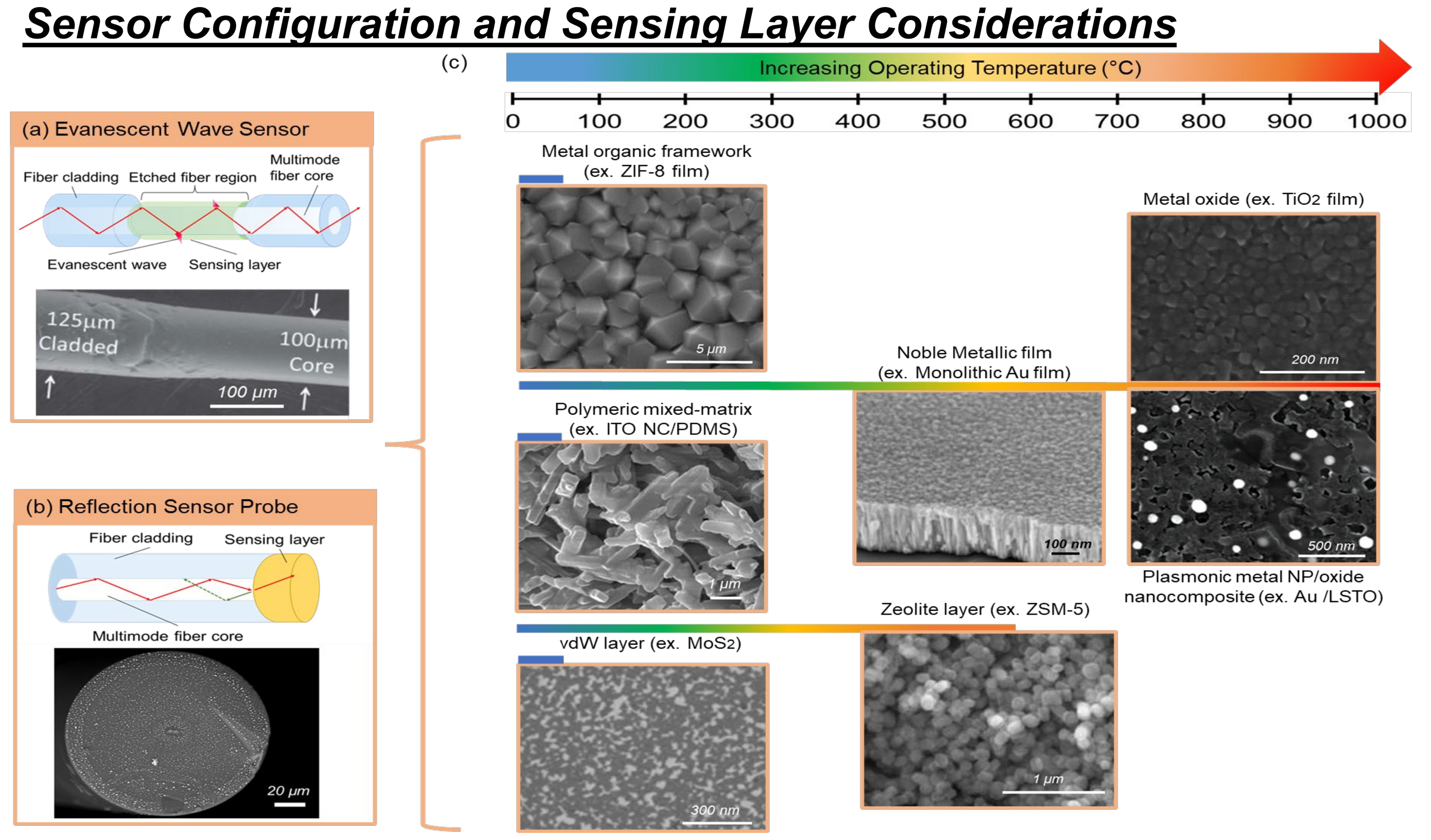
INTRODUCTION & CONCEPT DEVELOPMENT



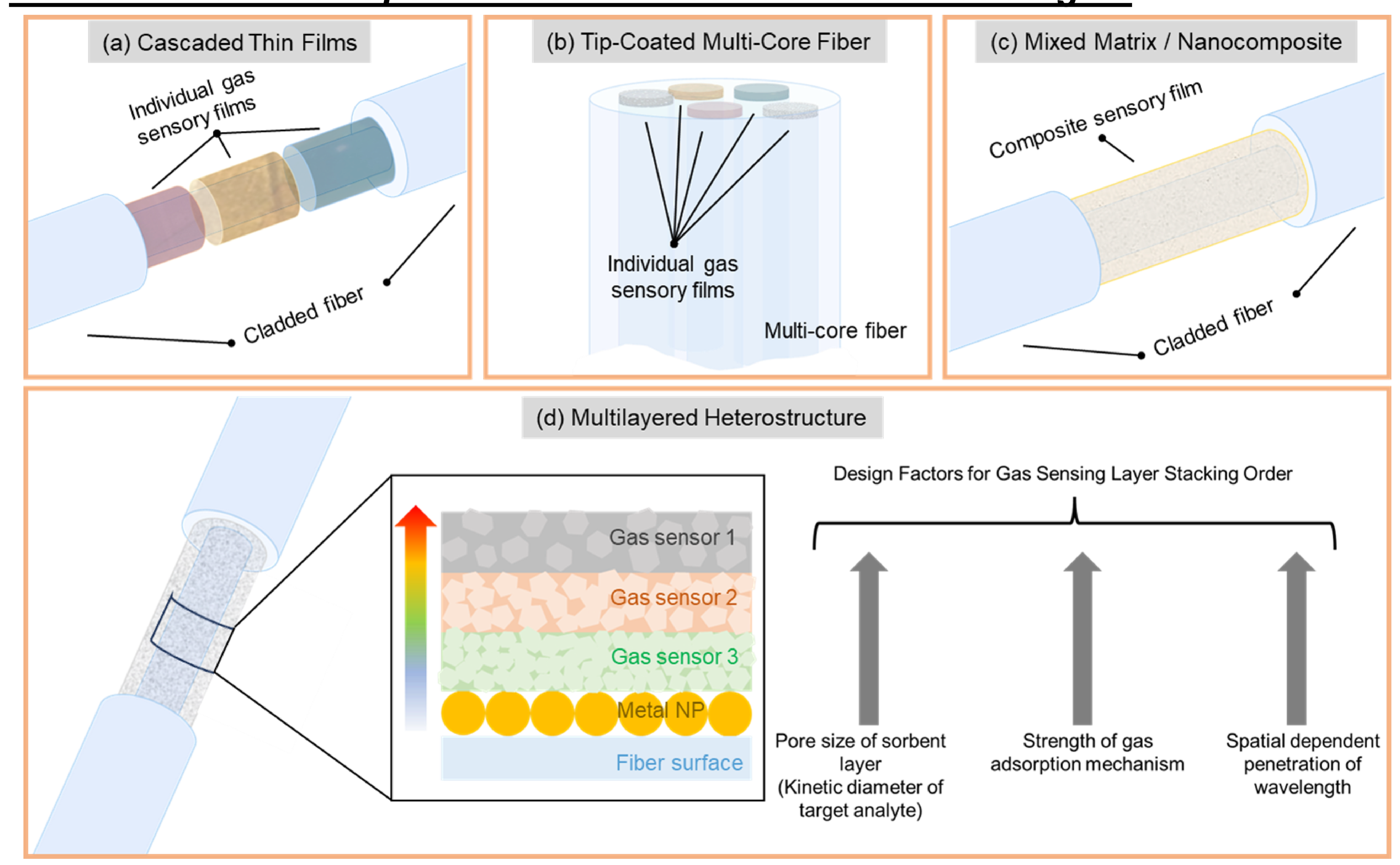
The concept of an optical fiber based "photonic nose" via multiple interrogation wavelengths and/or sensor nodes offers a compelling platform technology to realize multiparameter speciation of chemical analytes within complex gas mixtures. We further generalize the notion of multiparameter sensing through the novel "photonic nervous system" concept based upon low-cost, functionalized optical fiber sensor probes monitoring a variety of distinct analyte classes (physical, chemical, electromagnetic, etc.) simultaneously to provide broad situational awareness via integrated sensors. (Y-D Su et al., APL Photonics, Under Review)

METHODOLOGIES

Sensor Configuration and Sensing Layer Considerations

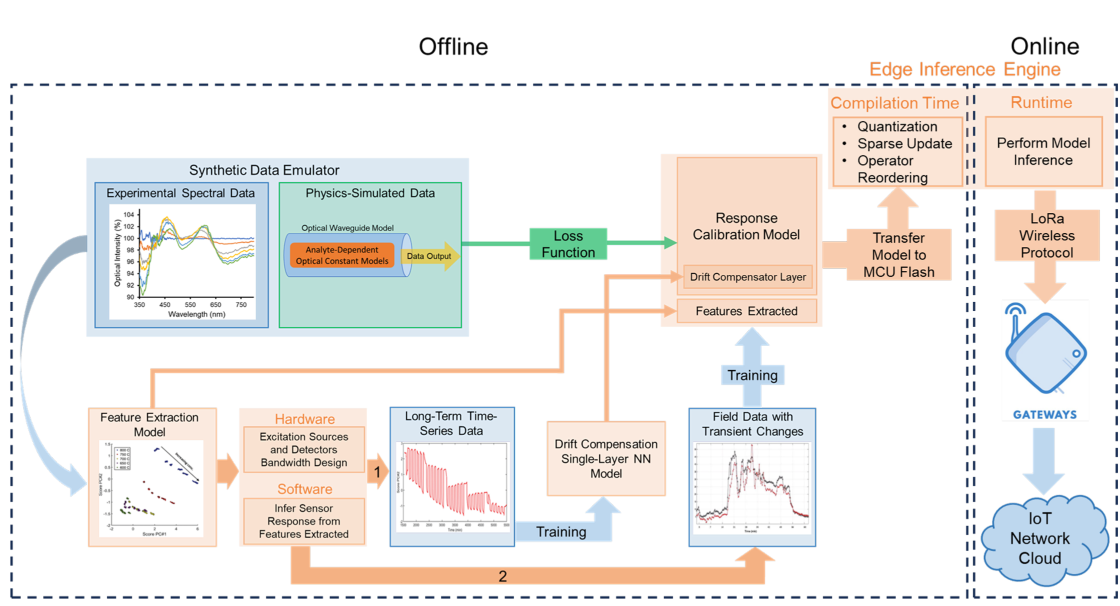


Device-Level Fiber Optic Photonic Nose Fabrication Strategies



Combined with multivariate analytics, various multiparameter approaches can be demonstrated at the sensing layer device level. One unique way to introduce spectral dependences and selective responses of each contributing layer is to leverage the multilayered structure itself, imposing a leaky engineered waveguide. By leveraging the nature of optical penetration depth difference between light at different wavelengths within each layer, a particular bandwidth for each sensing layer can be sensitized and detected, thus presenting a potential wavelength multiplexing scheme using multi-sensing layer structure. (Y-D Su et al., APL Photonics, Under Review)

Physics-Informed Sensor Response Calibration and Edge -Inference Analytics

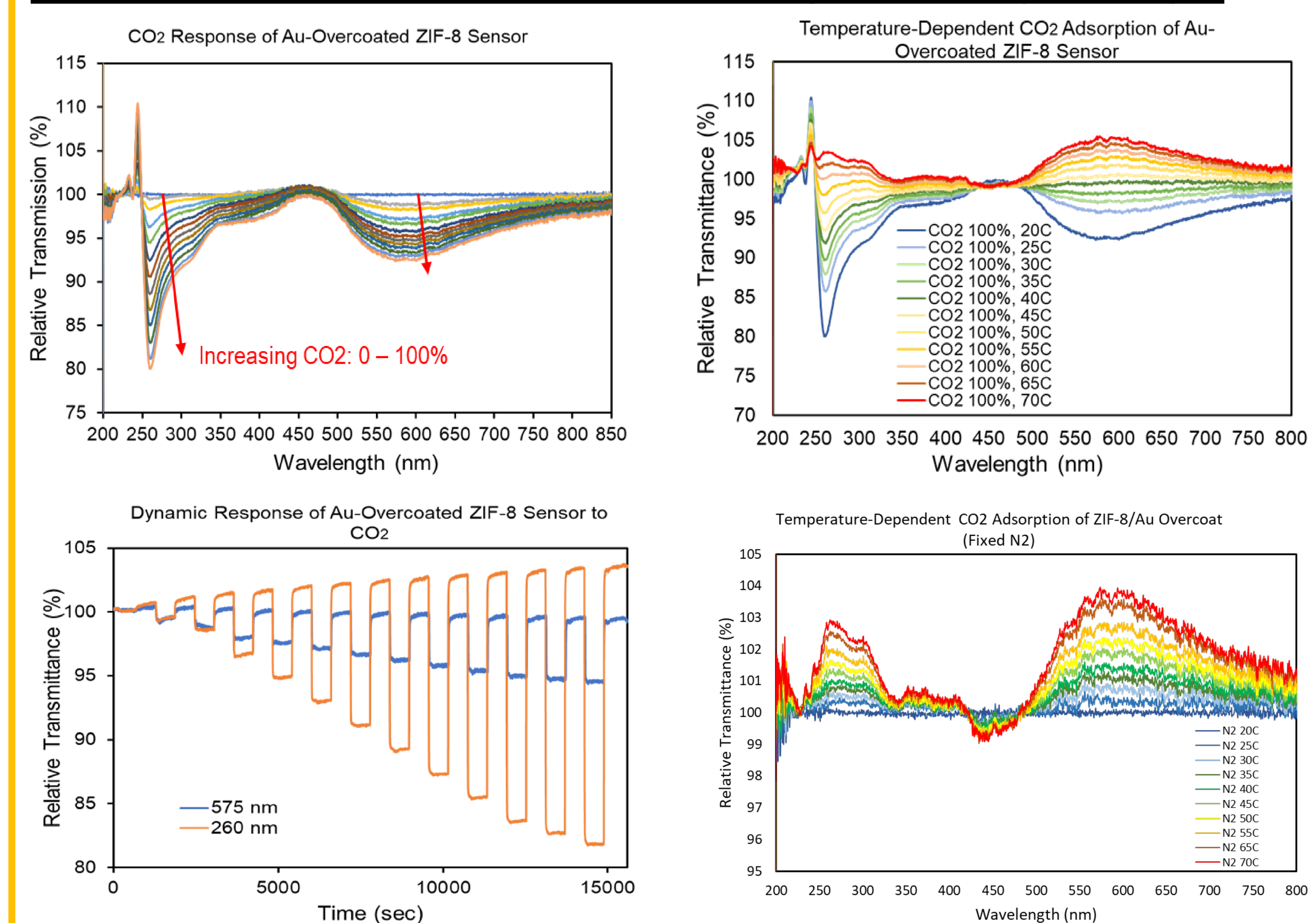


Category	Description	Equation	Application
Example Free Carrier Behaviors	Electron-electron (ω_{ce}) and electron-phonon (ω_{cp}) scattering of plasmonic metals	$\omega_{ce}(T) = \frac{1}{6}\pi^4 \frac{G\Delta}{h E_F}\left[(k_B T)^2 + (\frac{h\omega}{4\pi^2})^2\right]$; $\omega_{cp}(T) = \omega^0\left[\frac{2}{5} + 4\left(\frac{T}{T_D}\right)^5 \int_0^{T_D/T} \frac{z^4\,dz}{e^z - 1}\right]$	Temperature response modeling
	Defect chemistry equilibrium of metal oxide layers (ex. LSTO)	$O_O \rightleftarrows V_O^{\cdot\cdot} + 2e + \frac{1}{2}O_{2(g)}$, $K_o(T) = [V_O^{\cdot\cdot}] \cdot \rho^2 \cdot \sqrt{pO_2}$, $Sr_{Sr} + O_O \rightleftarrows V_{Sr}'' + V_O^{\cdot\cdot} + (SrO)$, $K_S(T) = [V_O^{\cdot\cdot}] \cdot [V_{Sr}^{\cdot\cdot}]$, $2[V_O^{\cdot\cdot}] + [La^{\cdot}] - 2[V_{Sr}''] - \rho = 0$	High temperature gas sensing response dominated by equilibration mechanism
	1-D approximation of Poisson-Boltzmann equation for infinite interface	$\frac{d^2\phi}{dx^2} = \frac{e}{\varepsilon_s}\left(N_d - N_e(\infty)\exp\left[\frac{e}{k_B T}\phi(x)\right] - 2N_v(\infty)\exp\left[\frac{2e}{k_B T}\phi(x)\right]\right)$	Sensing response due to electronic exchange at metal NP - oxide interface
	pH-dependent surface charge density (σ_0) from modified Gouy-Chapman theory	$\sigma_0(pH) = \frac{D_M}{1+10^{pK_a}[H^+]_s} e + D_0$, $[H^+]_s = 10^{-pH}\exp\left(-\frac{e\phi_0}{k_b T}\right)$	pH sensing response based on surface refractive index change
Optical Waveguide Models	Mode propagation model for step-index multimode fibers	$\frac{\partial^2 P(\theta,z)}{\partial\theta^2} + \frac{1}{\theta}\frac{\partial P(\theta,z)}{\partial\theta} - \frac{1}{C_0(\Delta\theta)^2}\frac{\partial P(\theta,z)}{\partial z} - \frac{\alpha(\theta)}{C_0(\Delta\theta)^2}P(\theta,z) = 0$	Ray tracing of propagating θ-modes through cladded lead fibers
	Matrix formulation for layered media	$\begin{pmatrix} A_0 \\ B_0 \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}\begin{pmatrix} A_s' \\ B_s' \end{pmatrix}$, $\begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = D_0^{-1}\left[\prod_{l=1}^{N} D_l P_l D_l^{-1}\right]D_s$, $R_{film} = \frac{1}{2}\left(\left\|\frac{M_{21}}{M_{11}}\right\|_s^2 + \left\|\frac{M_{21}}{M_{11}}\right\|_p^2\right)$, $T_{film} = \frac{n_s \cos\theta_s}{n_0 \cos\theta_0}\frac{1}{2}\left(\left\|\frac{1}{M_{11}}\right\|_s^2 + \left\|\frac{1}{M_{11}}\right\|_p^2\right)$	Deriving total transmittance / reflectance of isotropic sensing (multi)layers

To address the challenges in (1) acquiring calibration data in "beyond lab" conditions and (2) avoiding overfitting model to the bias of a subset of calibration data, we incorporate the concepts in recent trends of synthetic training dataset that combines simulated data with empirical data, and physics-informed learning method. The importance, of integrating data analytic algorithms with edge-compatible hardware/firmware for grid-tied energy applications, necessitates the approaches of compile-time and runtime separation and model quantization that make edge inference or even training possible. (Y-D Su et al., APL Photonics, Under Review)

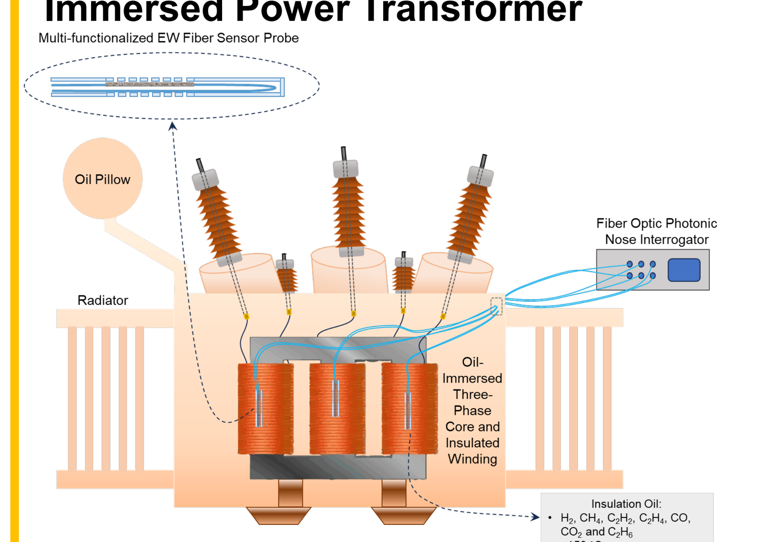
PRELIMINARY RESULTS & PERSPECTIVES

Simultaneous CO2 and Temperature Sensing Possible by Multilayer

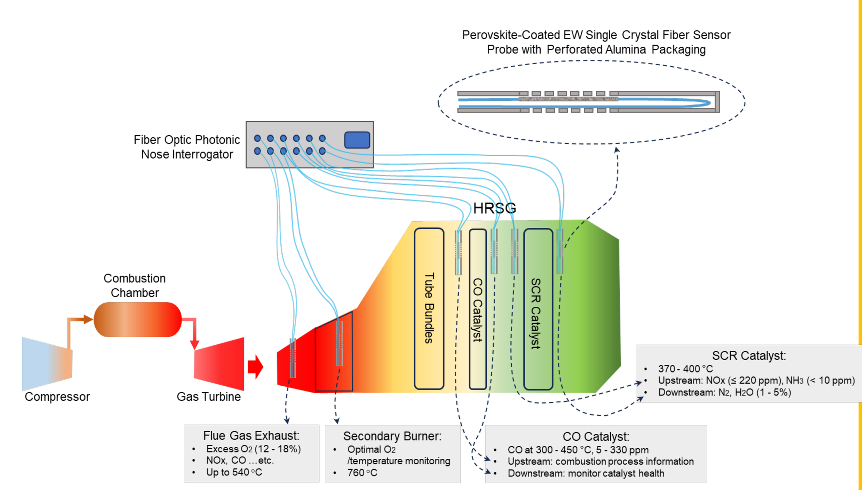


Potential Applications

Near-Ambient Conditions: Oil-Immersed Power Transformer



Extreme Conditions: Catalysis and Combustion Process in a Power Plant



Critical gas species exist in both oil-type power transformers and harsh environment such as combined-cycle power plants, indicating informative health status and process control parameters. (Y-D Su et al., APL Photonics, Under Review)

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