Low-Cost Multi-Channel Fiber Optic Interrogator with Energy Harvesting and Wireless Communication for Power Grid Applications

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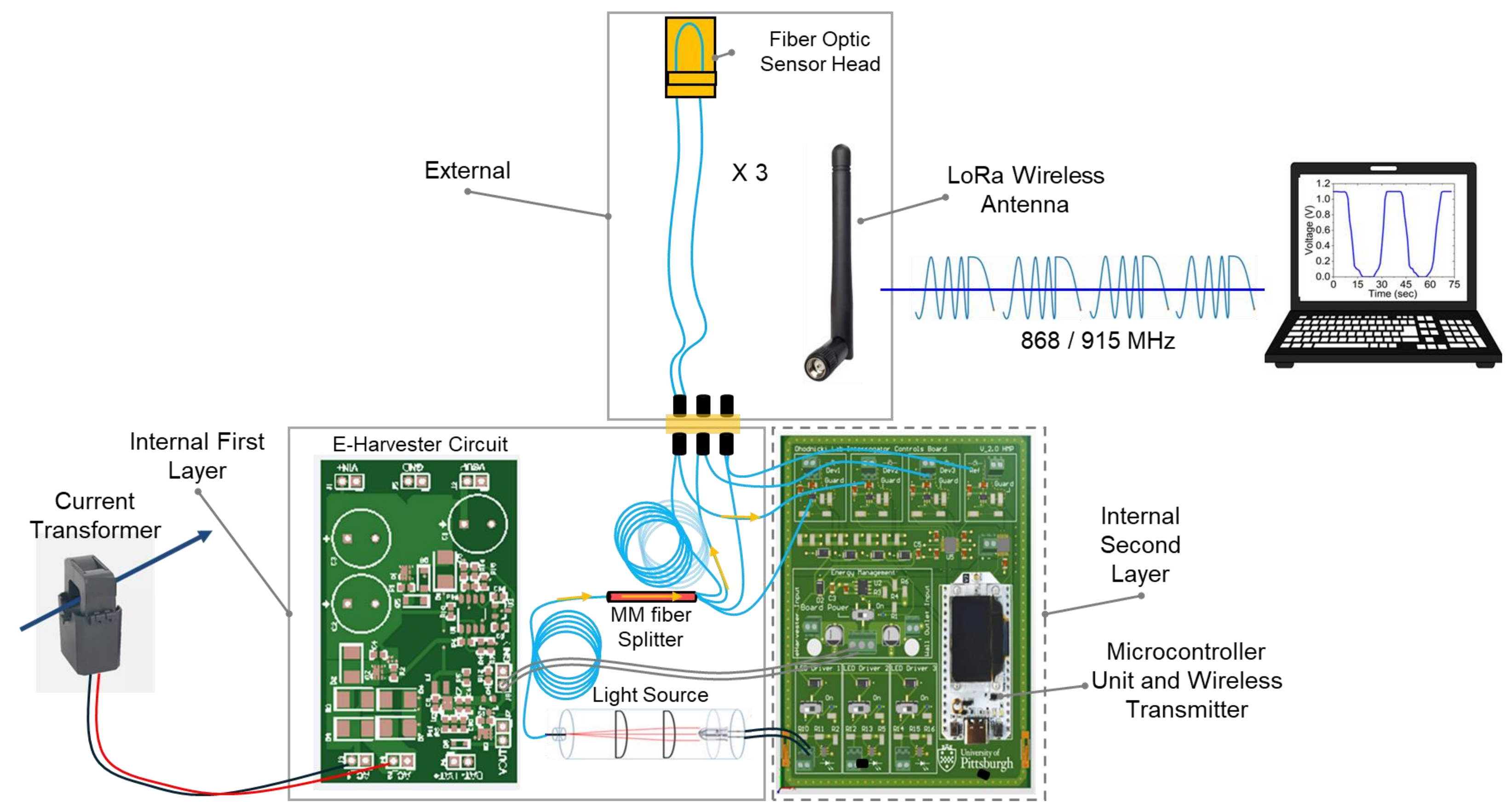
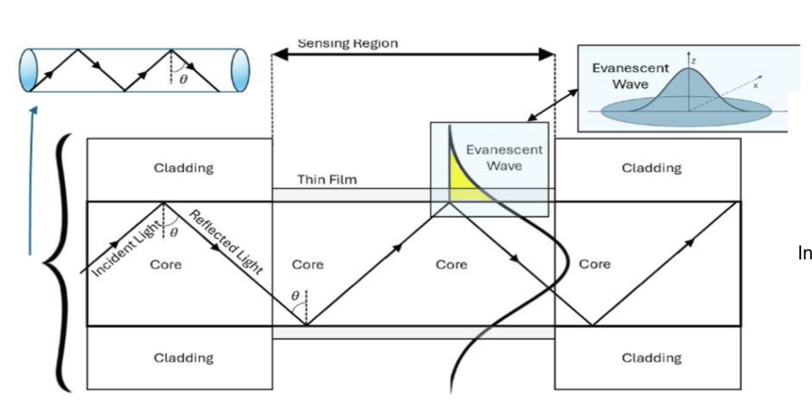
INTRODUCTION & SYSTEM OVERVIEW



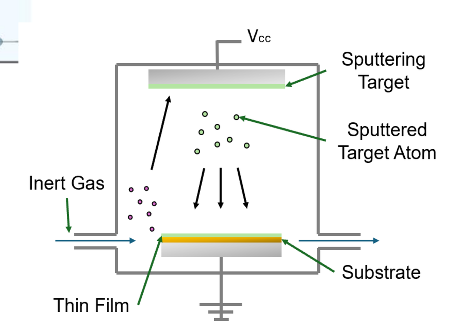
Power transformers benefit from state-of-health (SOH) monitoring. A key challenge in deploying SOH systems is balancing technical difficulty and economic cost. Fiber optic sensors are a good solution because they are compact and enable in-situ measurement with fine-area resolution. This work integrates multiple optical fiber sensors into a compact unit for multi-parameter sensing of critical gas indicators and real-time temperature. Source power is collimated and focused through custom optics, with fluctuation referenced and compensated. The interrogator includes energy harvesting. SPICE simulations validate all circuit models for the interrogator and are compared with output measurements from the final PCB circuit. Optical sensing is performed by measuring the voltage at each detection circuit's output, and wireless sensing capability allows long-distance data transmission via mesh networks using commercial RF hardware. A prototype is demonstrated.

METHODOLOGIES

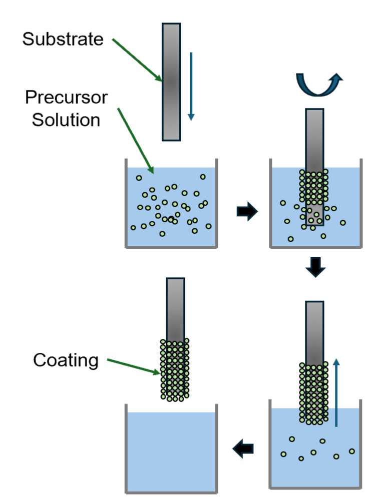
Low-Cost Sensor Design and Fabrication



Evanescent Wave Generation

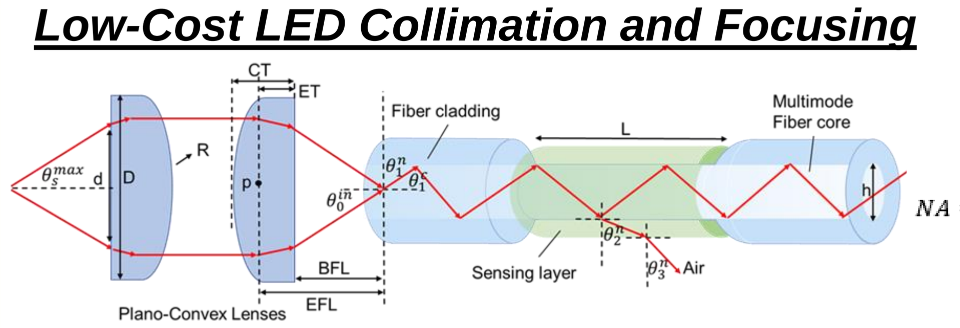


PVD



Dip Coating

Low-Cost LED Collimation and Focusing



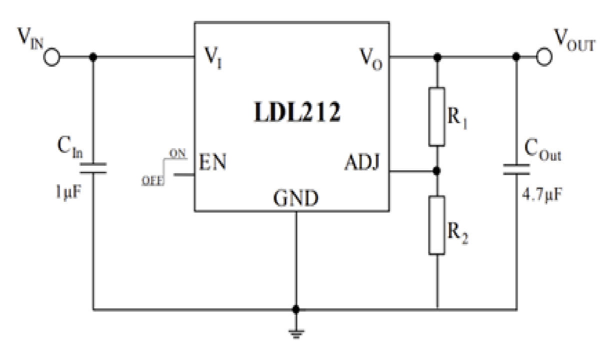
$$EFL = \frac{R}{n_L - 1}$$

$$BFL = EFL - ET$$

$$NA = n_{air} \cdot sin(\theta_s^{max}) = sin\left(arctan\left(\frac{d(n_L-1)}{2R}\right)\right) = \frac{1}{\sqrt{1+\left(\frac{2R}{d(n_L-1)}\right)^2}}$$

$$\theta_0^{in}(i) = arctan\left((d/2(i))/BFL\right)$$

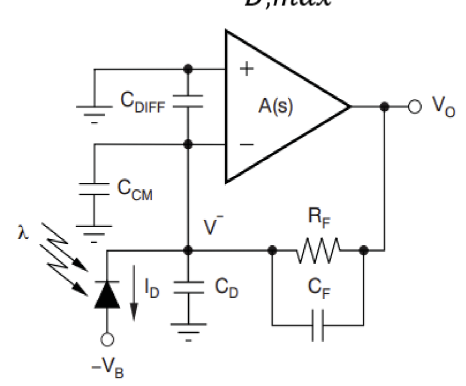
Multi-Channel Transimpedance Amplifier Control Board



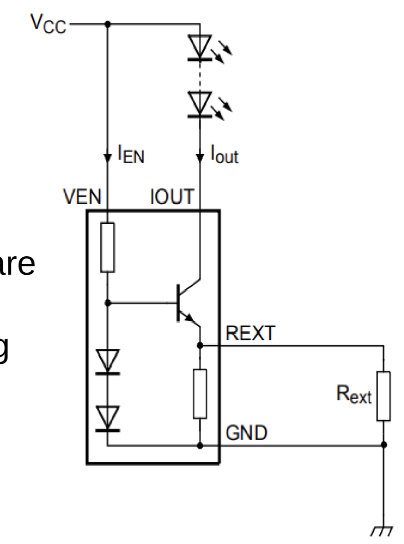
- Energy inserted into the system is regulated via the LDL212 Linear Regulator to provide consistent output power
- Operating voltage range (DC): 3.4V - 18V
- Output voltage for circuit: 5V
- Output current: 1.2A

- Transimpedance Amplifier converts a current source into an output voltage
- Output voltage is linearly correlated with input current and set via feedback gain.
- Stability is provided via external capacitors and virtual ground

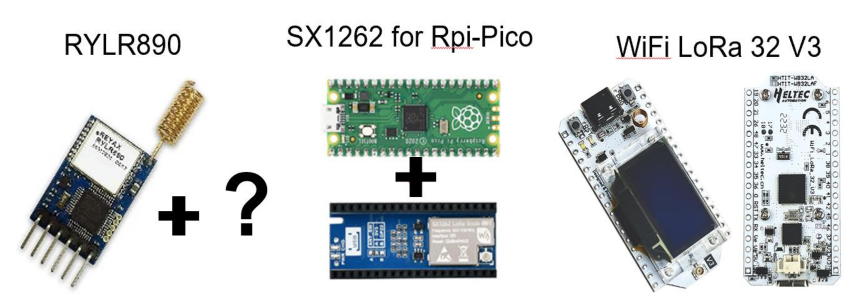
$$R_F = \frac{V_{o,max} - V_{o,min}}{I_{D,max}}$$



- Current sources for TIA are LED Emitters
- LEDs are regulated using the NCR421U Driver
- Configuration of Drivers regulates LED to provide max continuous power

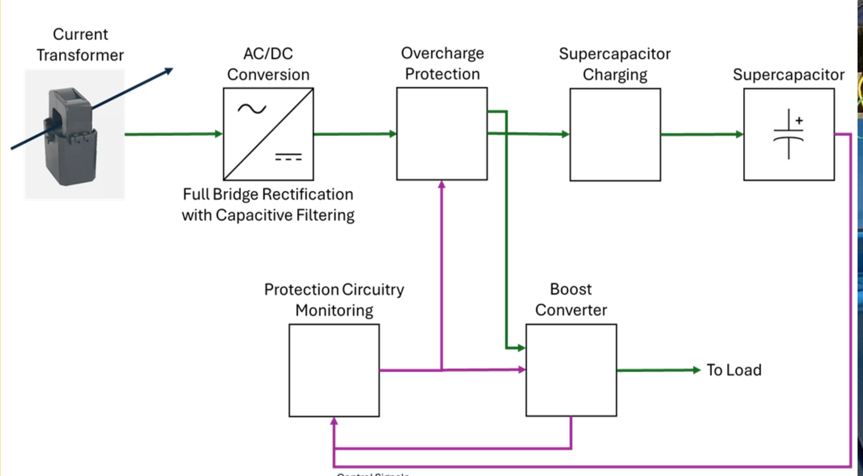


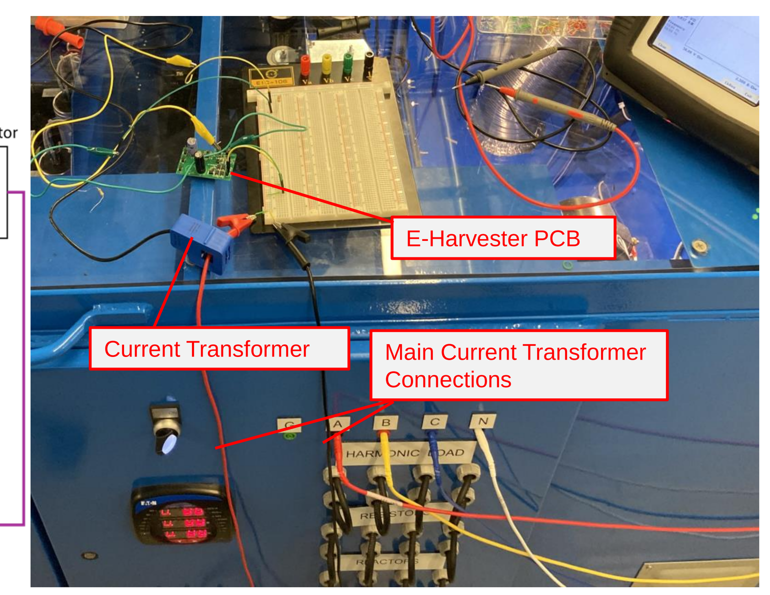
LED Model #	Optical Power Measured	Max Allowed Ratings Set using DC bench supply
LED525L	4.34uW(90%) / 0.3uW(10%)	0.028A / 3.5V
LED545L	13.93uW(90%) / 1 uW(10%)	0.05A / 3.4V
LED595LW	25.63uW(90%) / 3.18uW(10%)	0.15A/2.8V



End node	MCU	Transceiver	LoRaWAN capable?	Features	Cost
RYLR890	n/a*	SX1276	No	AT-commands	17.00
SX1262 for Rpi-Pico	RP4020*	SX1262	Yes	Dual core MCU driver/manager control 18 available GPIO	14.99
WiFi LoRa 32 V3	ESP32	SX1262	Yes	Dual core MCU driver/manager control WiFi BLE TFT screen for rapid prototyping 18 available GPIO	17.90

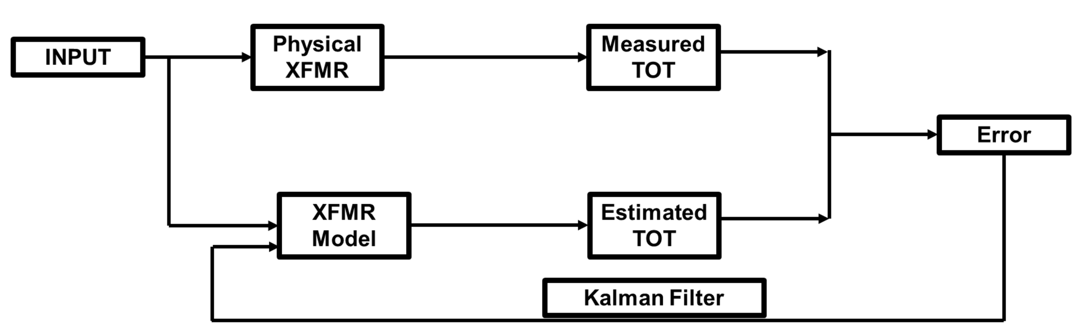
Energy Harvester Circuit for Energy Independence





- The E-Harvester runs via a current transformer
- Small design (~59x36mm)
- Rated for 5 Amps
- Supercapacitor is maintained between ~2.2-2.6V Protection circuits ensure supercapacitor safety
- 4 Volt output at ~1mA

Transformer Health Analytics Based on State Estimation Thermal Model



Input:

1. Ambient temperature
2. Oil thermal time constant
3. Load factor
4. Oil viscosity
5. Rated oil temperature rise
6. RUL

Output:

x_k: state vector

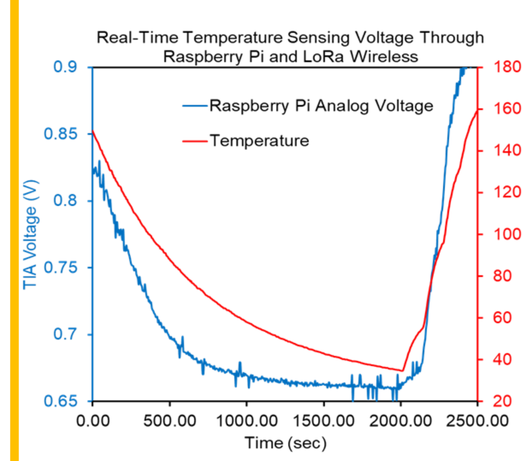
h(x_k): relation equation → h(x_k) = θ_k → predicted TOT

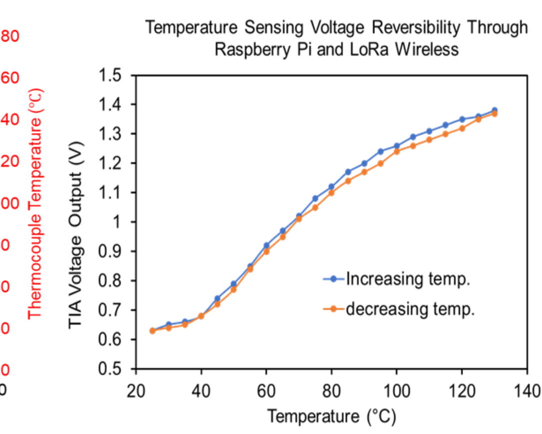
Error to feedback to model: $\varepsilon_k = z_k - h(x_k) - r_{k-1}$

$$\theta_k = \theta_{k-1} + \delta_t\left(\frac{1+RK^2}{1+R} * \left(\frac{\Delta\theta_{oil,r}}{\tau_{oil,r}}\right) - \left(\frac{(\theta_{k-1} - \theta_{amb})^{1+n}}{\Delta\theta^n_{oil,r} * \mu_{pu} * \tau_{oil}}\right)\right)$$

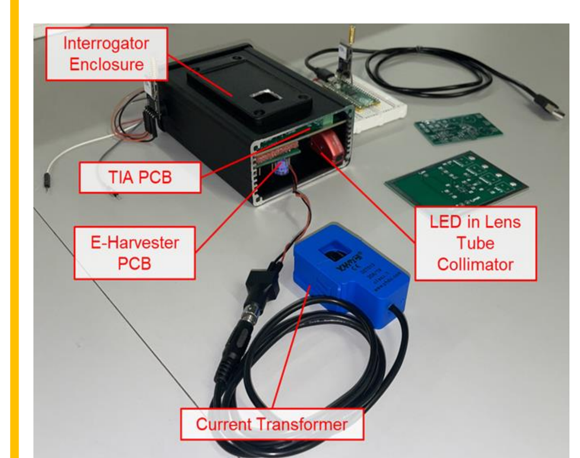
RESULTS & DISCUSSION

Temperature Sensing Data Through Wireless Transmission





Wireless Interrogator Signal Tested Metrics	
Resolution at 86 dB gain	10 mV
Temp. LOD	1.1 ℃



Cost-Benefit Analysis for a 2500 kVA Power Transformer

Stage	Lab-scale Research/ Development				
		Pilot-scale			
				Full-scale Industrial Production	
Number of Fiber Sensor Channels	1 (temperature)	1 (temperature) – cost reduction starts factoring in	4 (temperature, H_2, CH4, C_2H_2)	6 (temperature, H_2, CH4, C_2H_2, C_2H_4, CO)	≥ 8 (temperature, H_2, CH_4, C_2H_2, C_2H_4, CO, CO_2, C_2H_6 and Moisture)
Fiber Optic Photonic Nose Suite Projected Sales Price	$ 830	$ 580	$ 830	$ 1000	$ 1200
Reduced Cost in New Transformer Purchase (R_{Pr})[a]	$ 67.2k		$ 98k	$ 112k	$ 137.2k
Saved Downtime Cost (D_{Sv})[b] Over Lifetime	$ 3743.1		$ 5989	$ 6737.6	$ 7478.7
Avoided Catastrophe Cost (C_{Av})[c] Over Lifetime	$ 687.7k		$ 1.1M	$ 1.2M	$ 1.4M
Note	[a] $R_{Pr} = p_{Ex} \cdot T_c$, where p_{Ex} is stage dependent. [b] $D_{Sv} = p_{Sv} \cdot t_{avg} \cdot R_{kWh} \cdot P_{avg}$, where p_{Sv} is stage dependent. [c] $C_{Av} = q_c \cdot q_d \cdot C_c$, where q_d is stage dependent.				

Hypothetical value streams are justified, with the reduced cost in new transformer purchase and avoided failure cost being the most compelling due to the possible lifetime extension and the daunting cost of one single catastrophic failure given the historical examples referenced. (*Y-D, Su. et al., APL Photonics, under review*).

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