Nurturing a Disruptive Technology for Thermodynamic Metrology

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Thermodynamic Metrology

What is Thermodynamic Metrology?

- The Thermodynamic Metrology group realizes, maintains, and disseminates the national measurement standards for temperature, humidity and pressure and vacuum.

- We conduct innovative research aimed at developing novel methods for measurements of temperature, pressure , and humidity.

http://www.nist.gov/pml/div685/grp01/

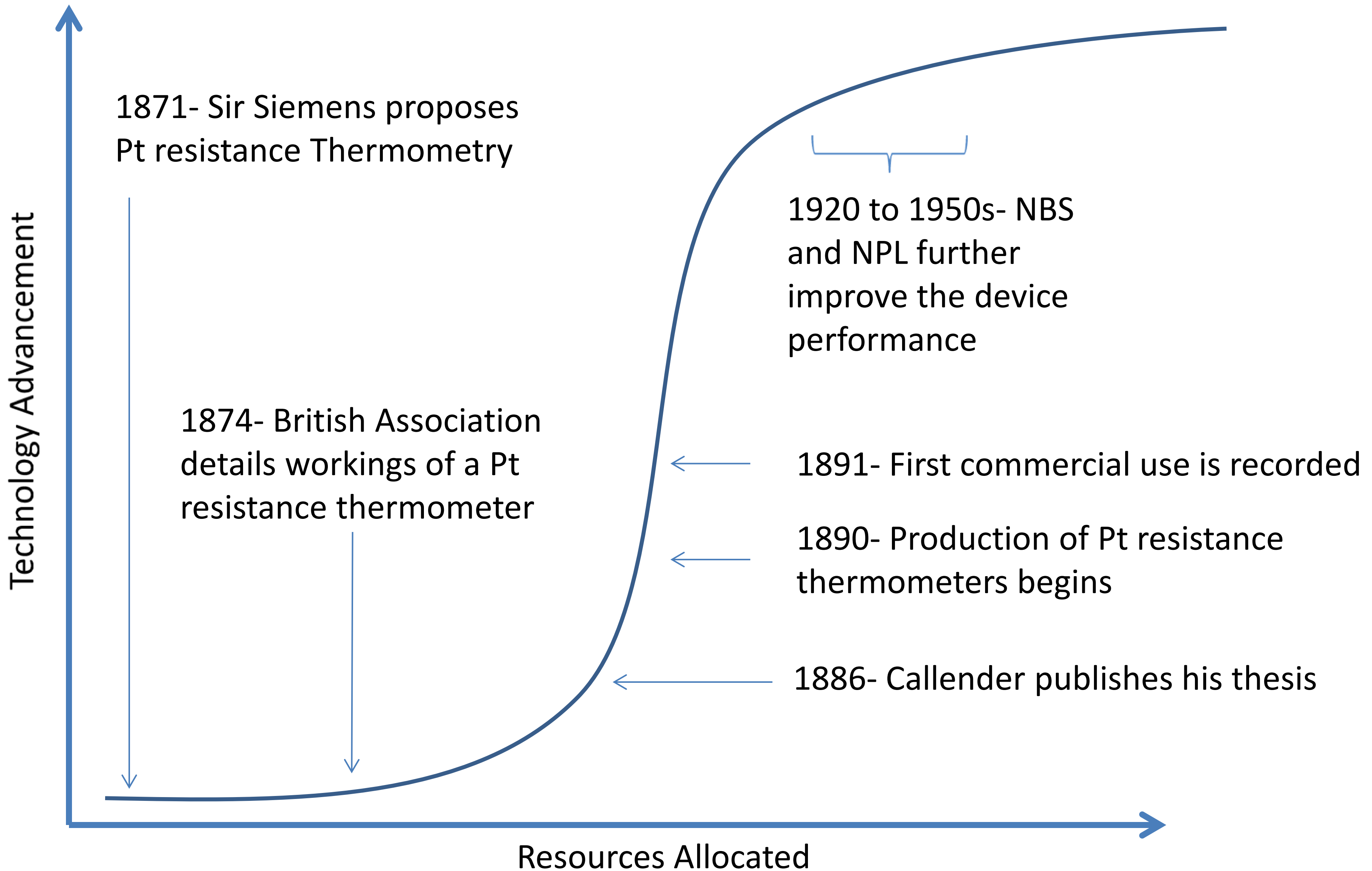
Who Cares About Temperature and Pressure?

- Temperature and Pressure are two of the most widely measured parameters. Measurements of temperature and pressure (and vacuum) are vital to:
  - *Advance manufacturing* (process control)
  - *Biotechnology* (protein expression, glycosylation control)
  - *Regulators* (CMC, GMP)
  - *Armed Services* (temperature/pressure/strain sensing for aircraft and weapons control)

State of Thermodynamic Metrology

- Temperature and pressure measurements rely on voltage measurement devices such as the standard platinum resistance thermometer (SPRT), mercury manometer, and capacitance strain gauges.
- By and large these devices meet or exceed the metrology needs of a vast majority of the market.
- The emerging needs of the markets are focused on dynamic measurements, remote interrogation, and the need to reduce ownership cost.

Current Technology Offers Ever Smaller Bang for the Buck



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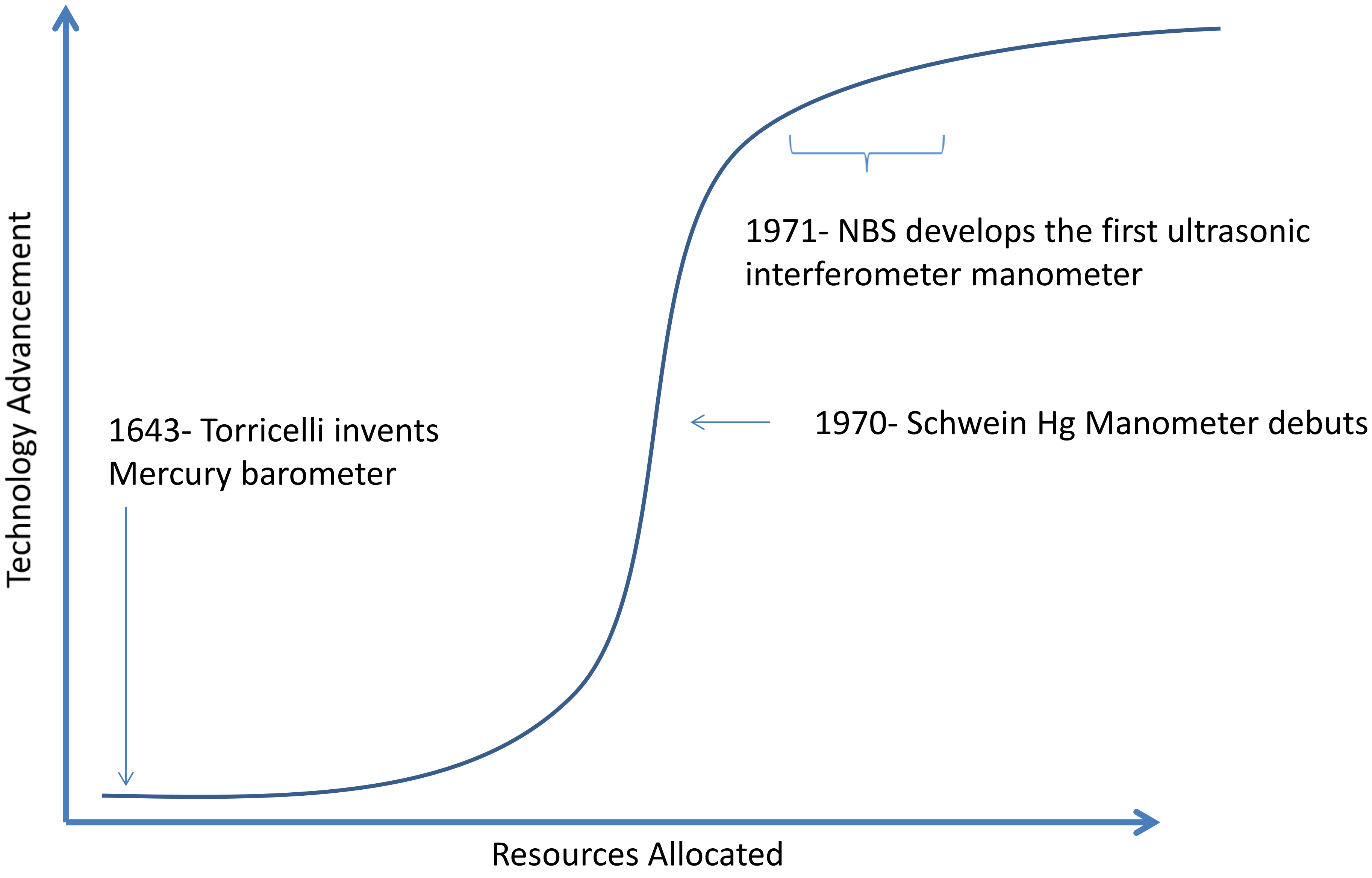


Temperature and Pressure Metrology is Ripe for Disruption

- Photonic sensors, relying on frequency rather that voltage measurement can potentially disrupt the market.

- Main Advantages of photonic sensors are:
  - Free of electromagnetic interference
  - Can tolerate harsh conditions
  - Multiplexing
  - Low cost
  - Low weight
  - Remote interrogation

Photonic Sensing in Thermodynamic Metrology Group

- Recognizing the changing landscape we have proactively initiated research programs that advance photonic measurements of Temperature and Pressure.

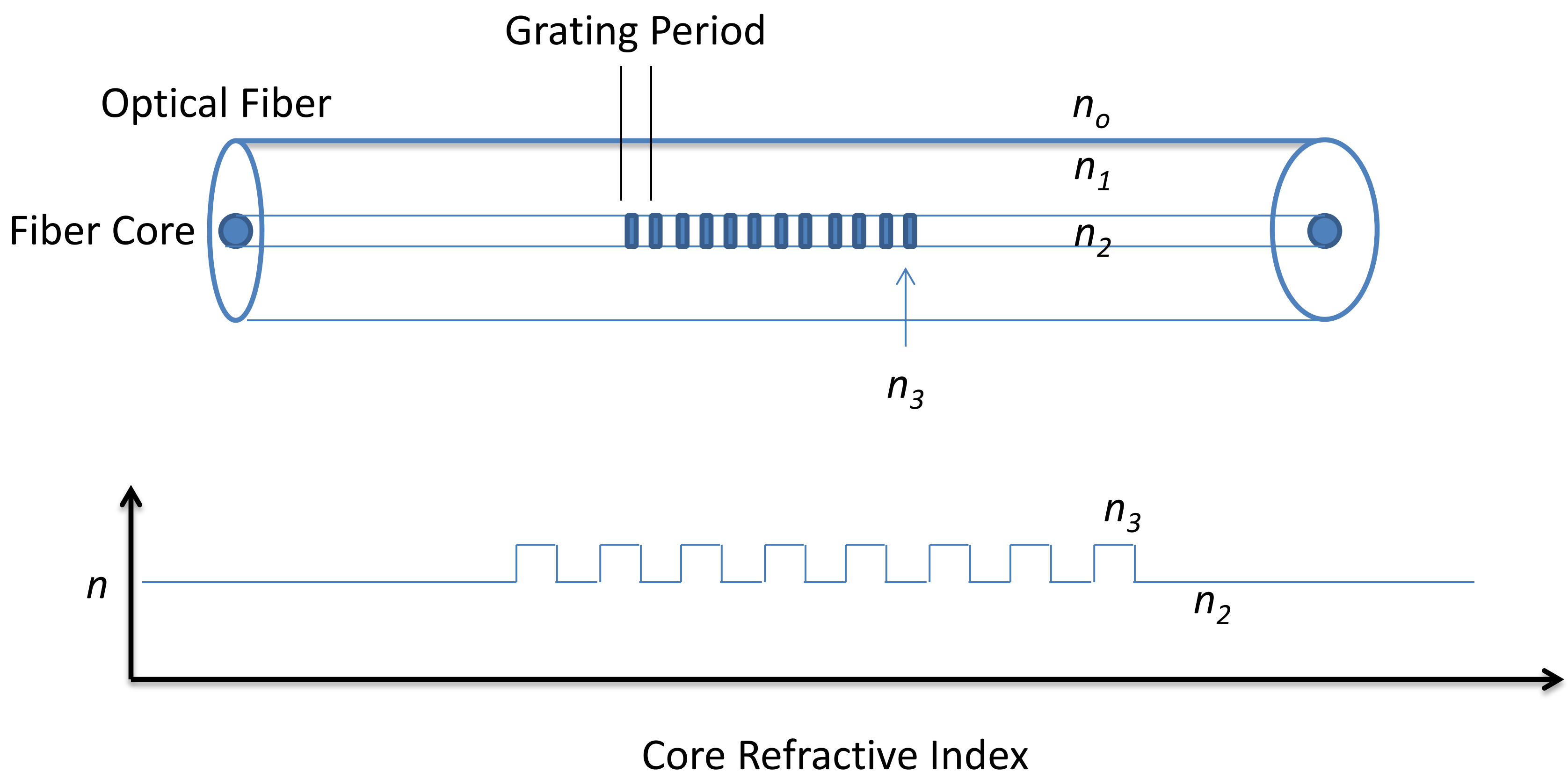
Sensors	Standards
Pressure- Fiber Bragg Grating	XHV- Cold-atom trap
Temperature- Ring Resonator	Temperature- Brownian Motion
Humidity Fiber Bragg Grating	

Such a Complex Problem Demands an Inter-disciplinary Team

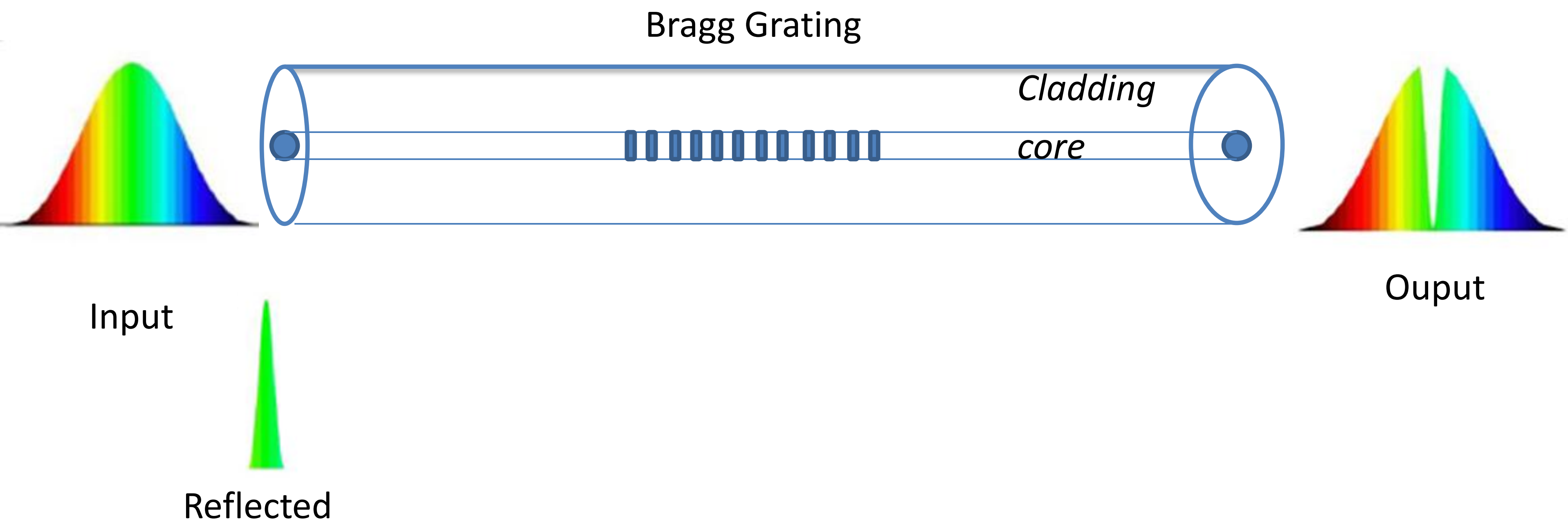
We have assembled an inter-disciplinary team composed of experimentalists (optics, thermometry and pressure) and theoreticians to tackle this challenge:

- Zeeshan Ahmed (685)
- Jake Taylor (684)
- Greg Strouse (685)
- Jay Hendricks (685)
- Doug Olson (685)
- Muhammad Hafezi (684)
- Haitan Xu (UMD-684)
- Jay Fan (684)
- John Quintavalle (182)

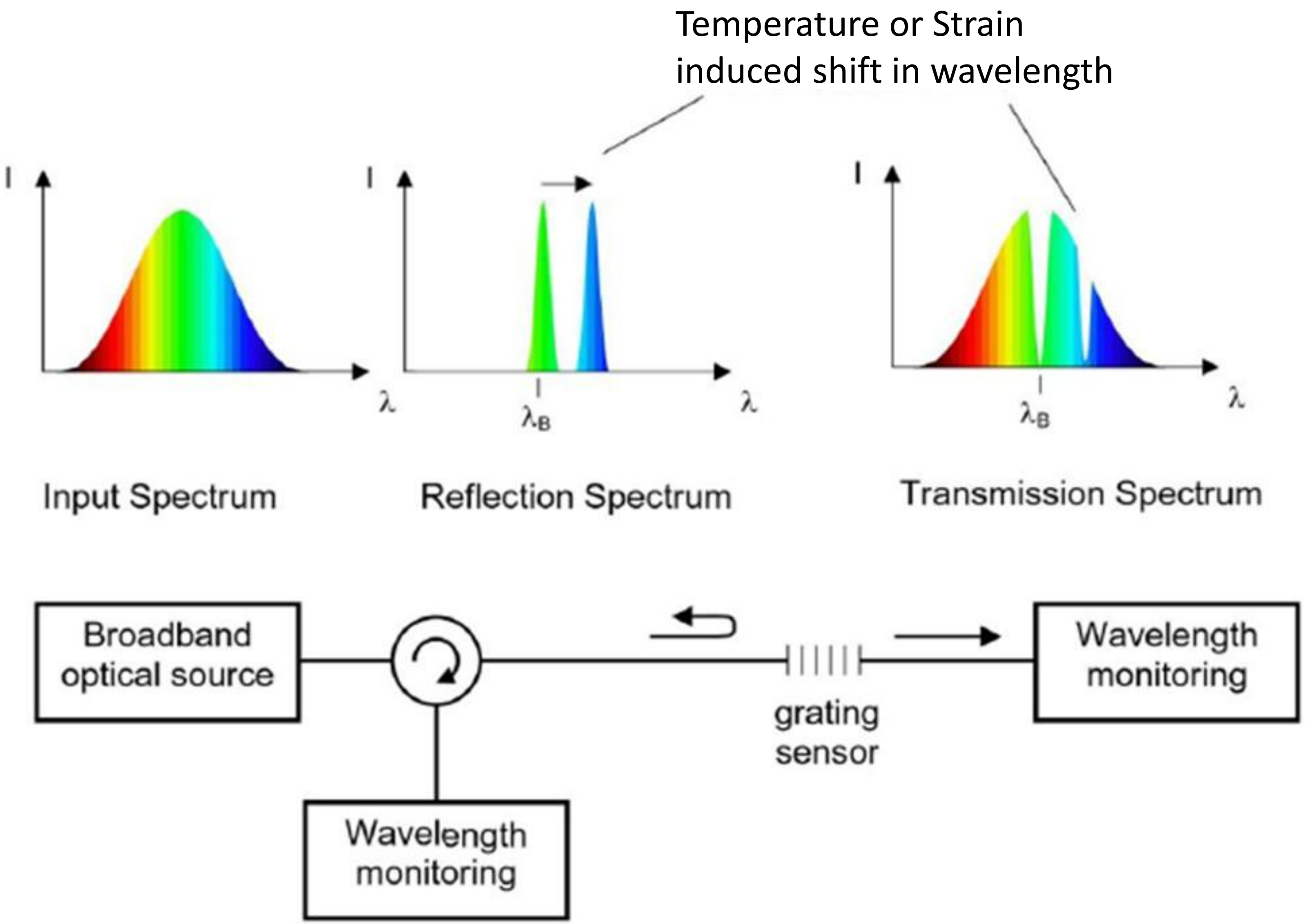
Fiber Bragg Gratings are Standard Telecom Industry Device



FBG act as a Narrow Band Rejection Filter



FBG Rejection Window Drifts with Temperature and Pressure



Stephen J. Mihailov, *Sensors*, 2012, 12, 1898-1918

FBG's Response Arises From Material Property Changes

- Strain and Temperature Dependence derives from material expansion and refractive index changes. The resonance shift is given by:

$$\Delta \lambda = 2 * [(\partial n_{eff}|\partial l) + neff(\partial \Lambda|\partial l)] + 2 * [\Lambda(\partial n_{eff}|\partial T) + neff(\partial l|\partial T)]$$

- FWHM is given by:

$$\Delta \lambda = \lambda_B * S * \sqrt{\left[\frac{\Delta n}{2no}\right]^2 + [1/N]^2}$$

- Assuming there is no cross-talk between strain and temperature

- For strain we can write :

$$\Delta\lambda = \lambda_B\{1 - (n^2|2)[\rho_{12} - \upsilon(\rho_{11} + \rho_{12})]\}\varepsilon_z$$

- And for temperature:

$$\Delta\lambda = \lambda_B\{\alpha_\Lambda + \alpha_n\}\Delta T$$

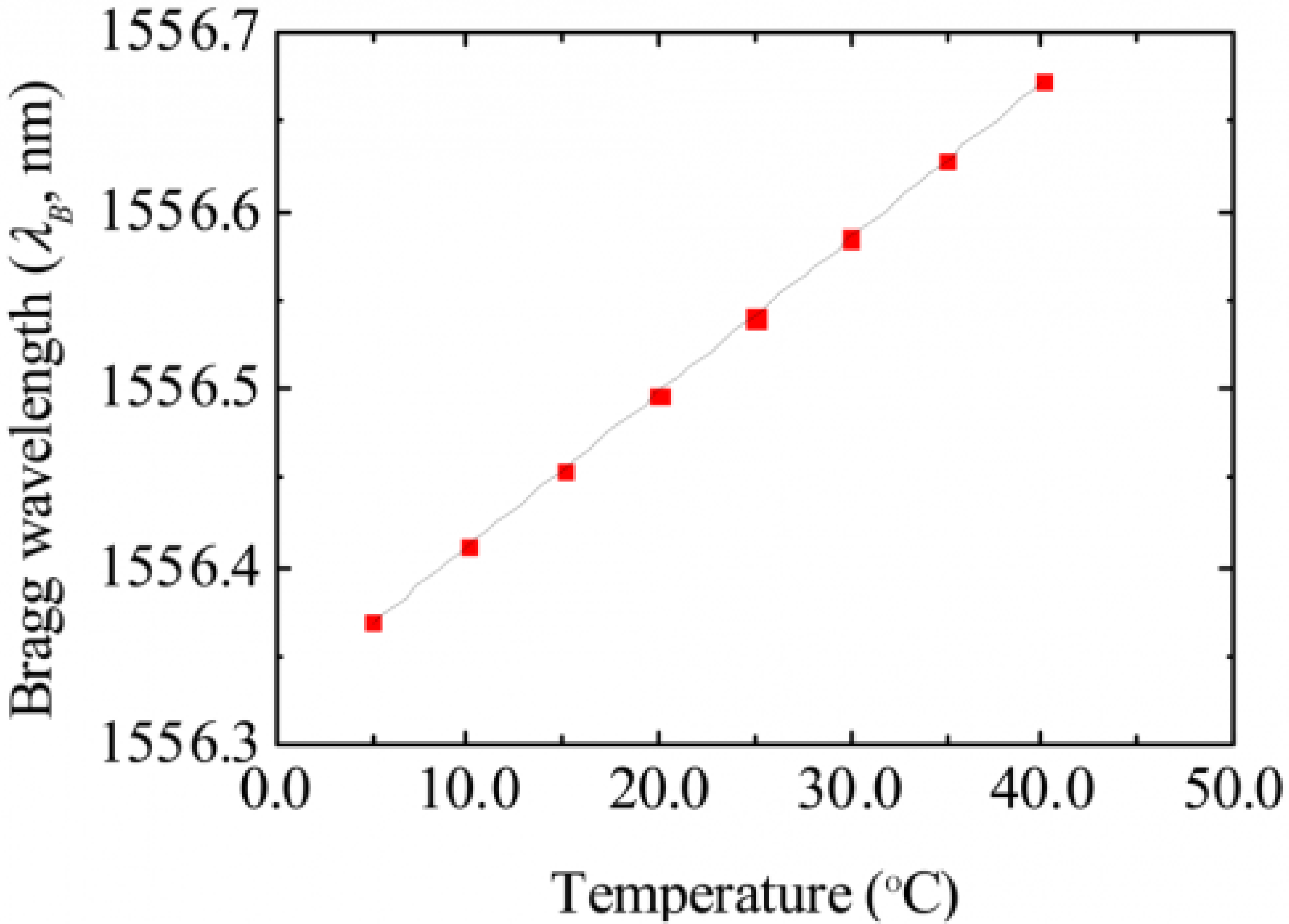
D. A Krohn, Fiber Optic Sensors Fundamentals and Applications, third edition

Thermo-Optic Effect Dominates FBG's Response

- For Temperature sensing the thermo-optic effect [$\alpha = (1|n)(\partial n|\partial T)$] dominates the FBG response

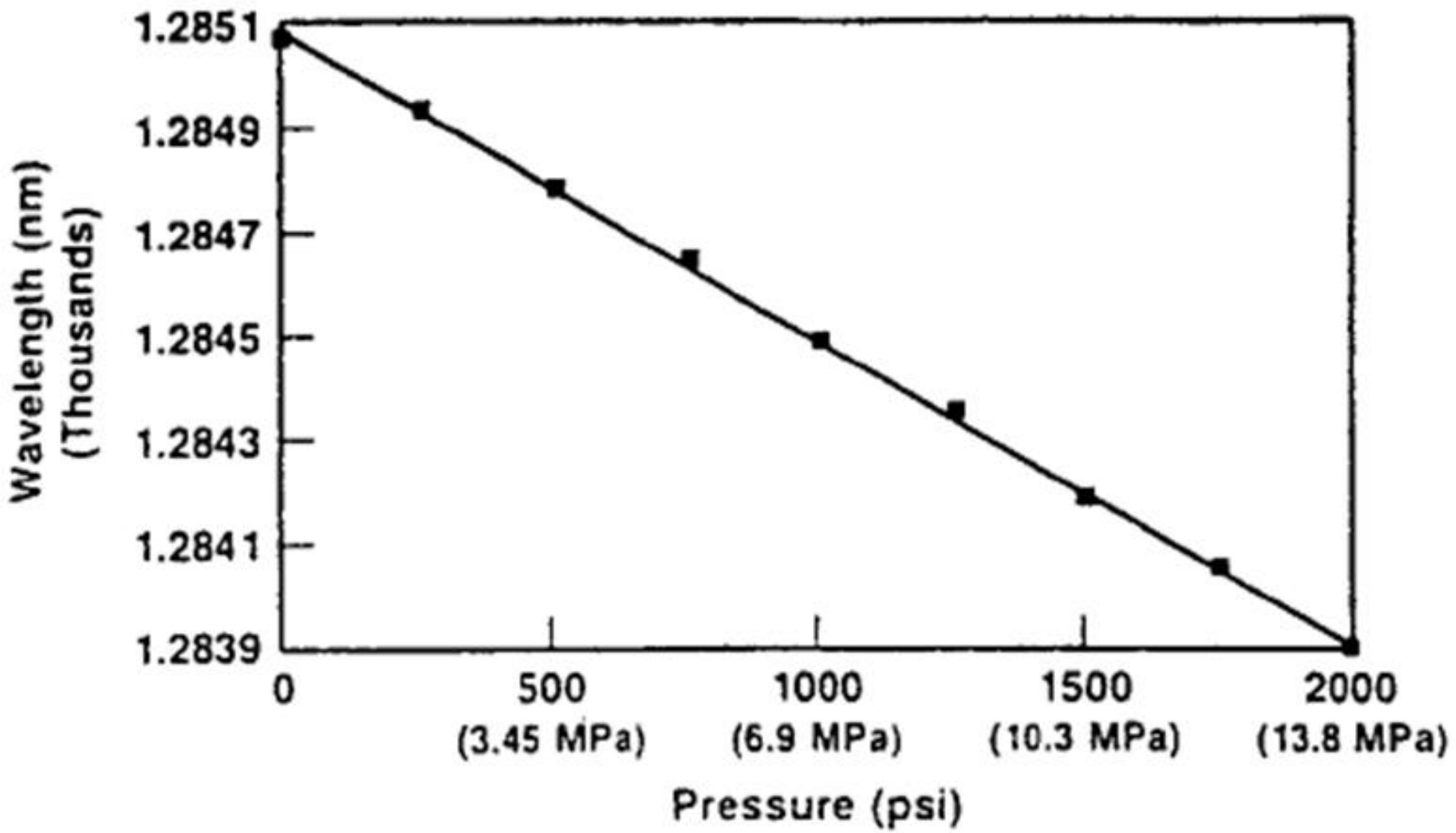
- For silica fibers, at 1550 nm
  - thermal response is approximately 10-15 pm/˚C
  - Strain response is approximately 1p m/μ ε

FBG Can be Used for Temperature Sensing



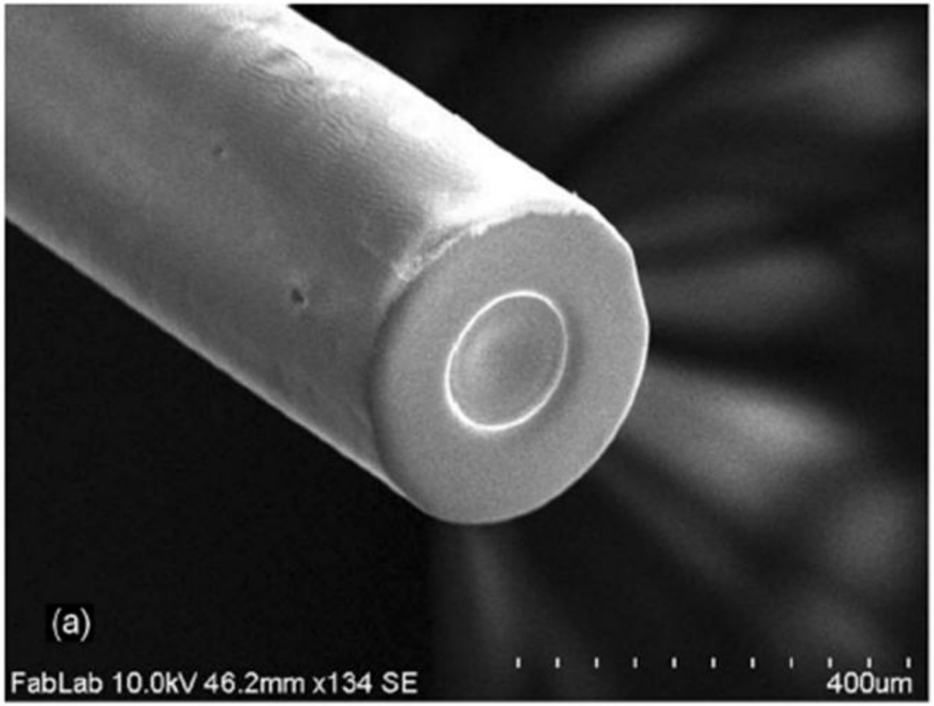
Sensors **2012**, *12*(7), 8847-8860

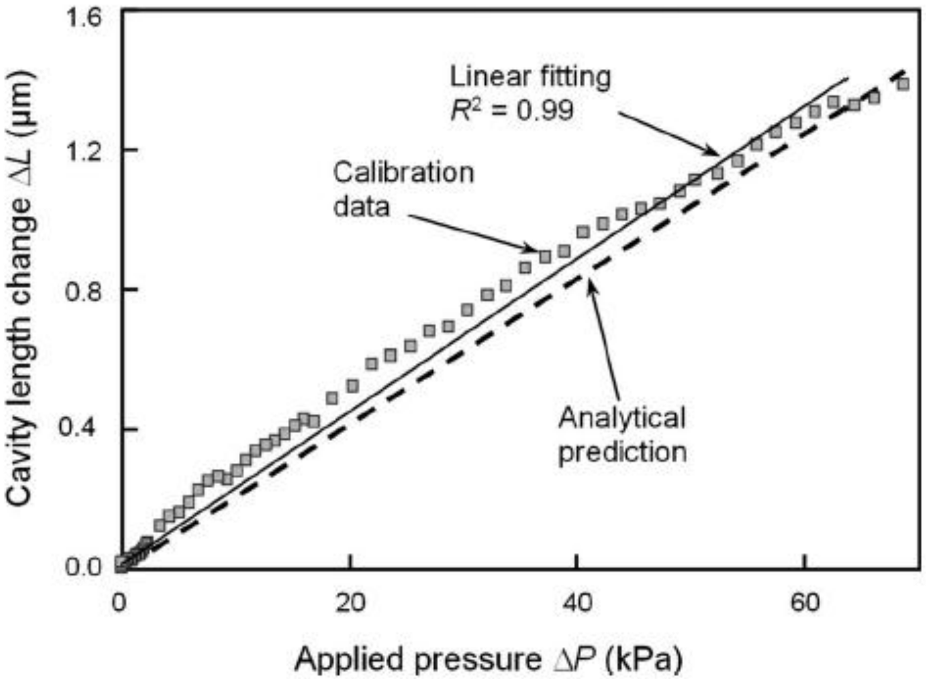
Bare Fibers May be Useful for Sensing at High Pressures



J. Lightwave Tech, **1997**, *15, 1263-1275*

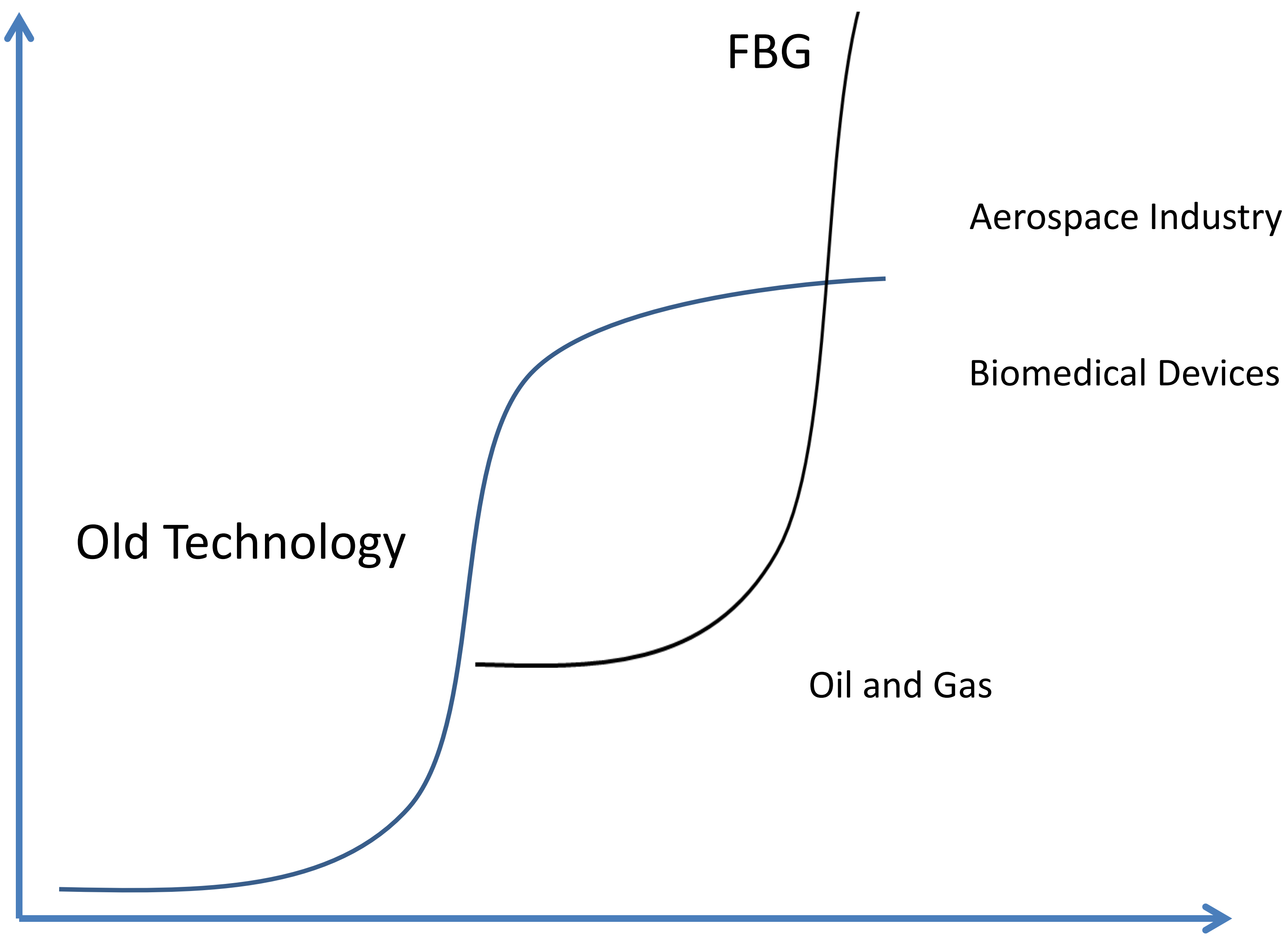
FP-FBG Pressure Sensing Devices May be Useful In Biomedical Applications





Nesson *et al.*, *Journal of Biomedical Optics*, 2008, 13, 044040-044040-1

In the Tech Cycle, FBG Metrology has Established a Beach head and is Looking Upstream



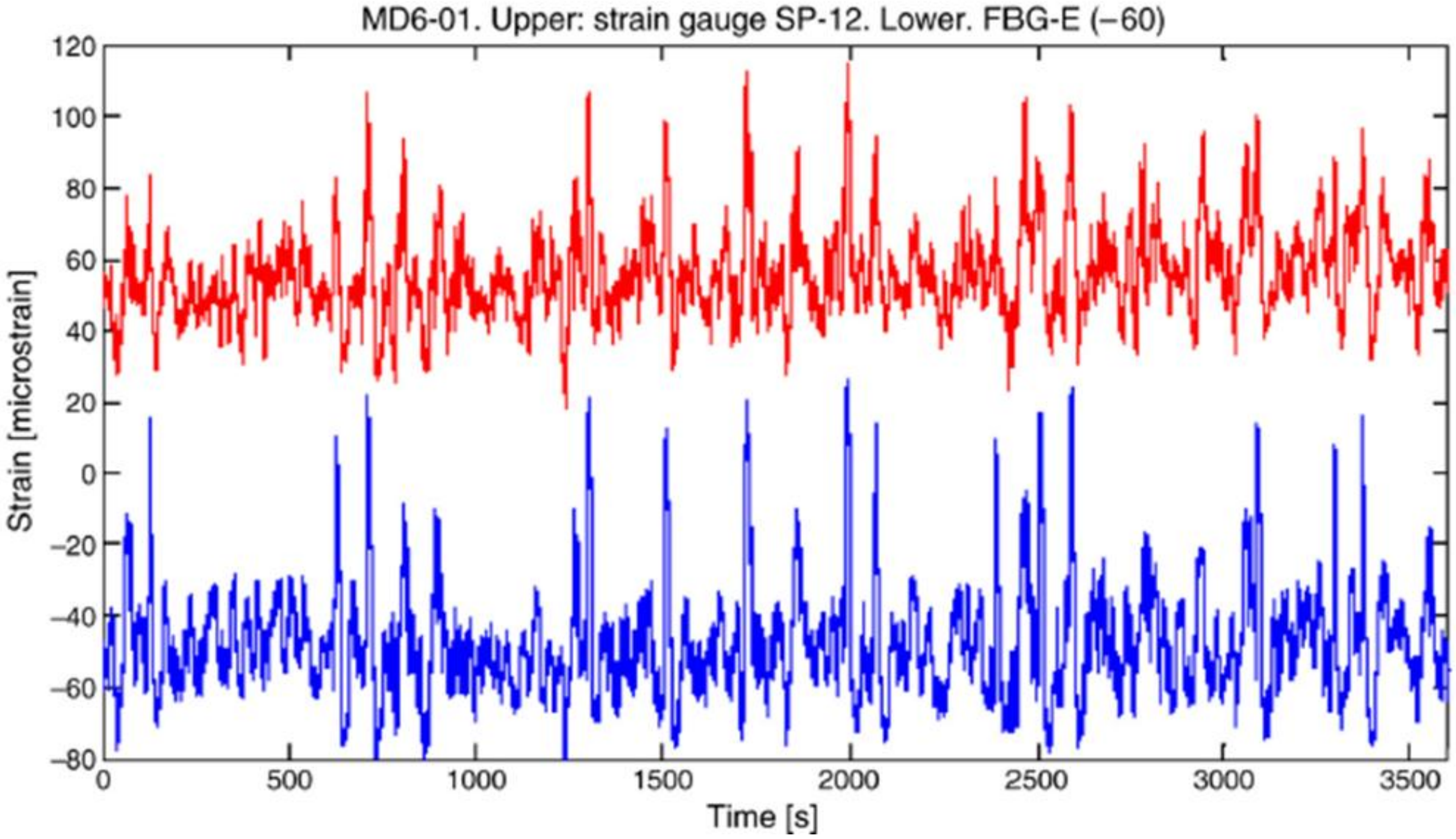
FBG has the Potential to Significantly Impact Infrastructure Monitoring

- At the present inspection of infrastructure such bridges, roads and buildings require the inspector to physically interact the structure, either by climbing the structure with mountaineering gear or using a crane; either way puts the inspectors in physical danger.

- Recent demonstration projects such as the Tsing Ma bridge project[1] have demonstrated that Fiber Bragg gratings can be embedded into structures and later utilized for monitoring the health of the structure.

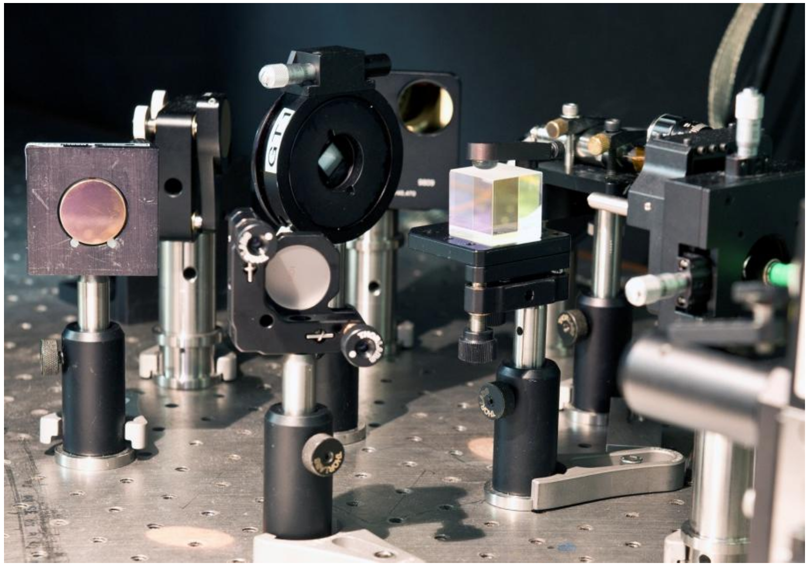
1- T.H. T. Chan *et al.*, *Engineering Structures*, 2006, 28, 648-659

Demonstration Projects Such as the Tsing Ma Bridge Project Showcase the Potential of FBG Technology



T.H. T. Chan *et al.*, *Engineering Structures*, 2006, 28, 648-659

Where Do We Stand on FBG?



- We have initiated a research program that seeks to quantitatively measure the temperature and strain response of FBGs at various wavelengths in the 1550 nm region
- Our goal is to quantify the various sources of uncertainty and determine the noise floor on FBG based measurements of temperature and pressure.

Optical Thermometry for Industrial Manufacturing

- To meet market demands for industrial applications we need a device that can achieve 10 mK accuracy.

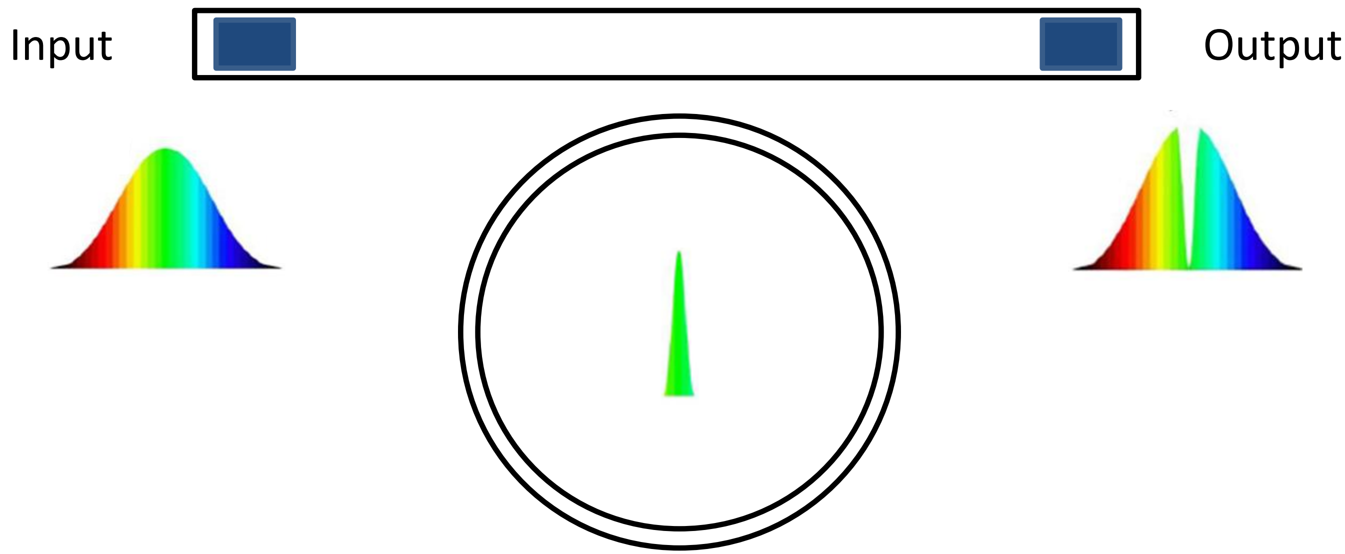
- To this end we are developing an optical ring resonator based thermometer

Origins of Optical Thermometry Project

- This project originated from an IMS proposal by Jake Taylor and collaborators.

- PML has generously provided funds to develop optical thermometry in support of the NIST-on-a-Chip initiative

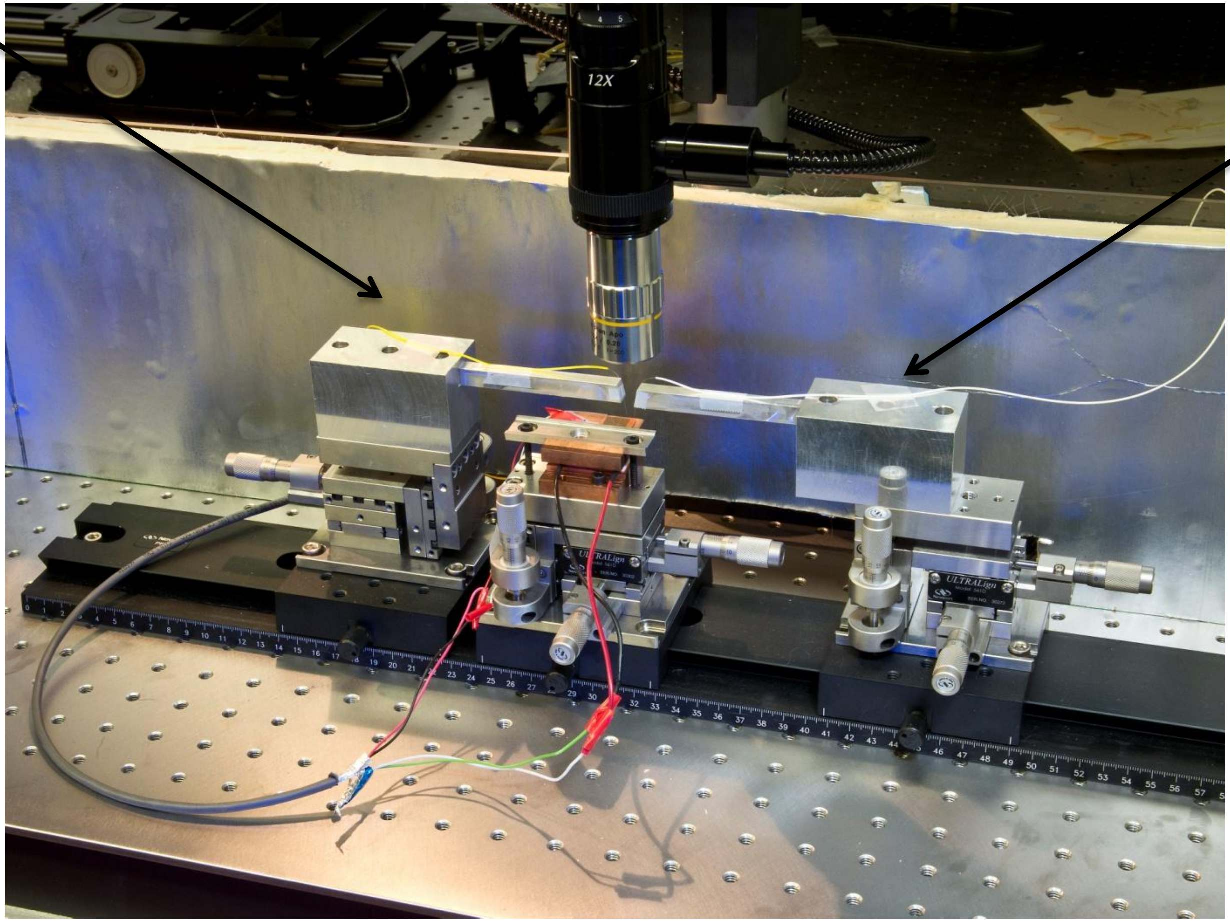
Optical Ring Resonator Acts as a Periodic Notch Filter



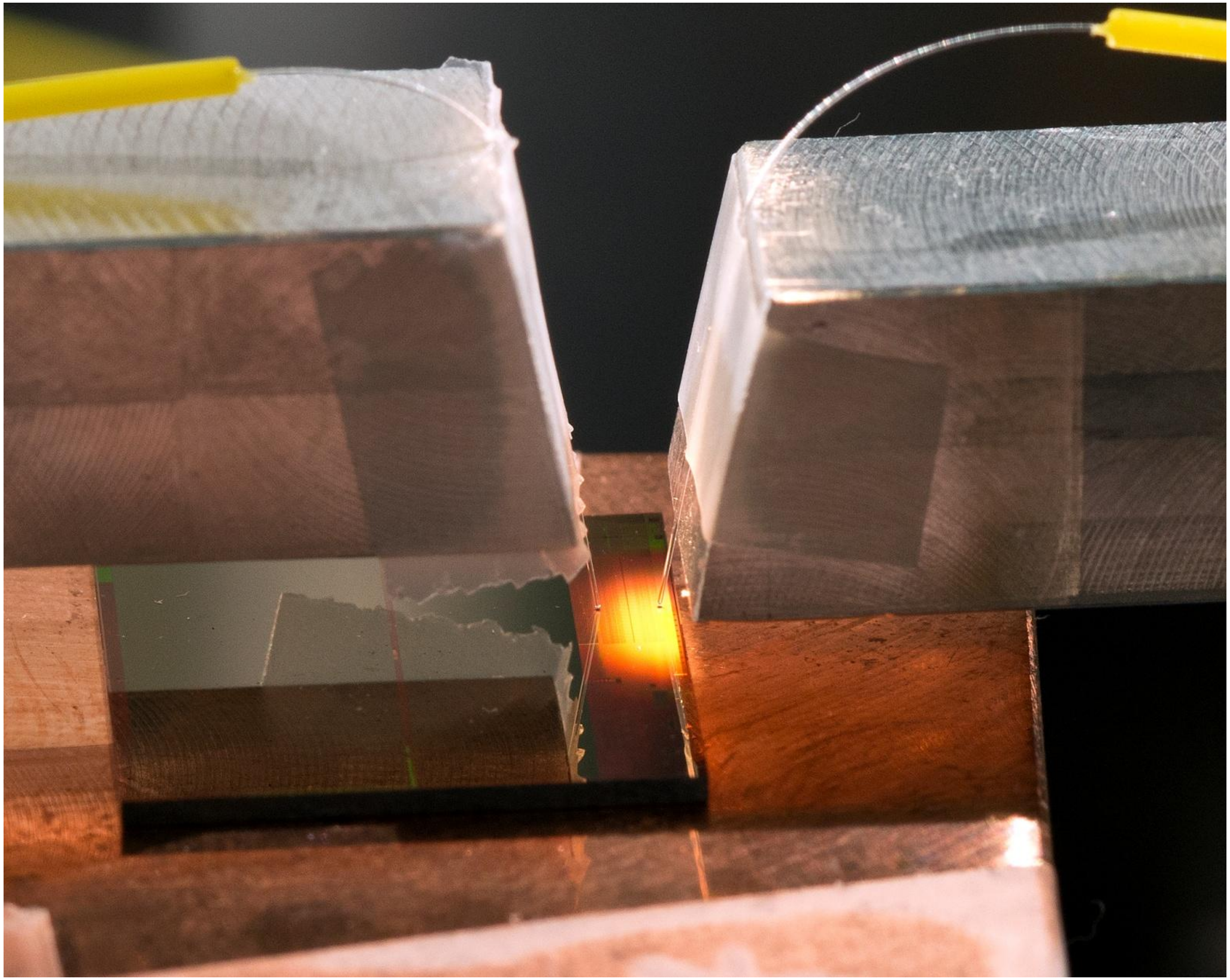
- Optical ring resonators exhibit a periodic notch-filter like response where the resonant wavelength shows a temperature-dependent shift in frequency

$$\Delta\lambda = \{\alpha_{W(n_{eff}|n_g)} + (\partial neff|\partial T)(1|n_g)\}\lambda\Delta T$$

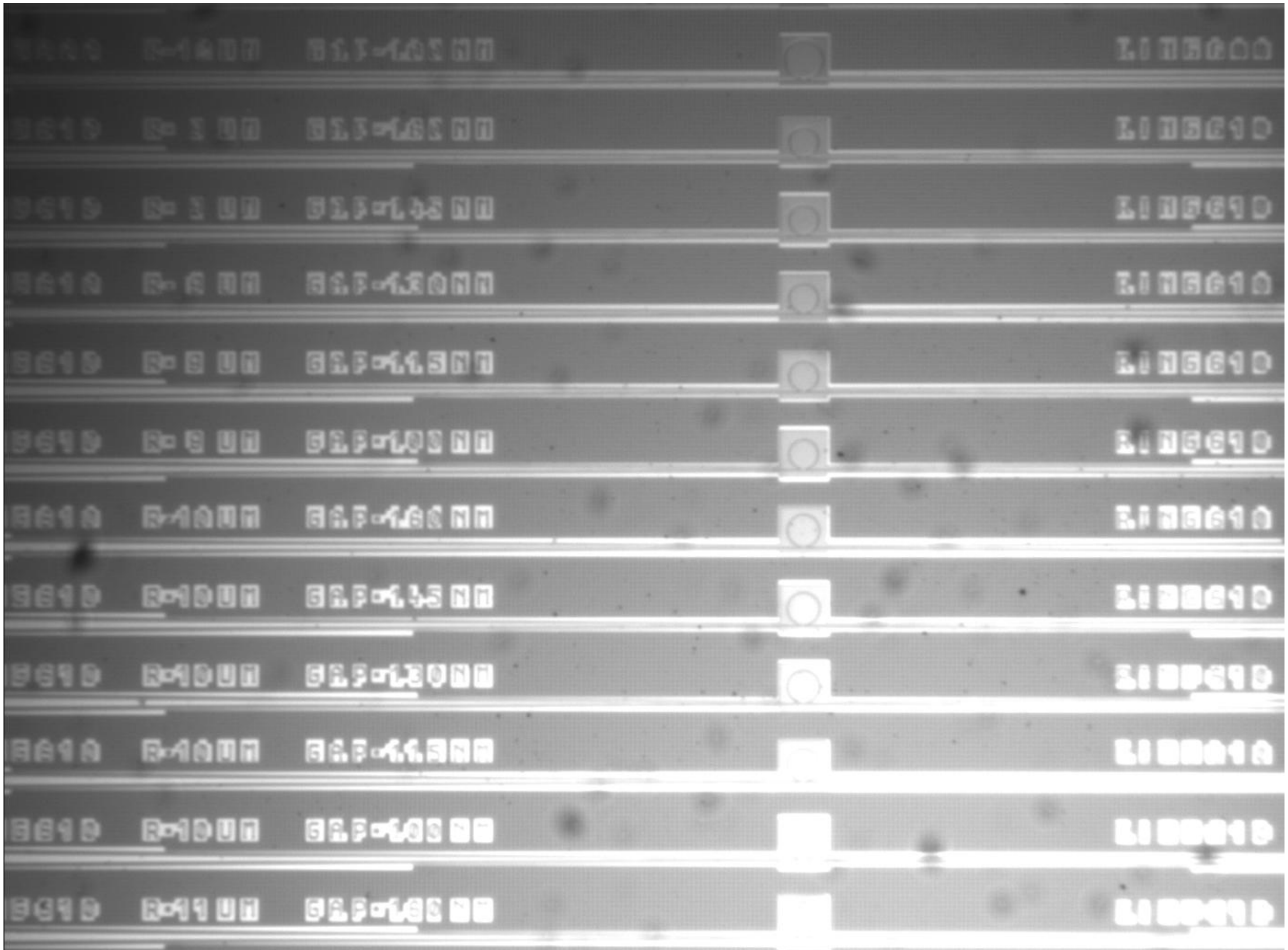
Experimental Setup For Interrogating Ring Resonators



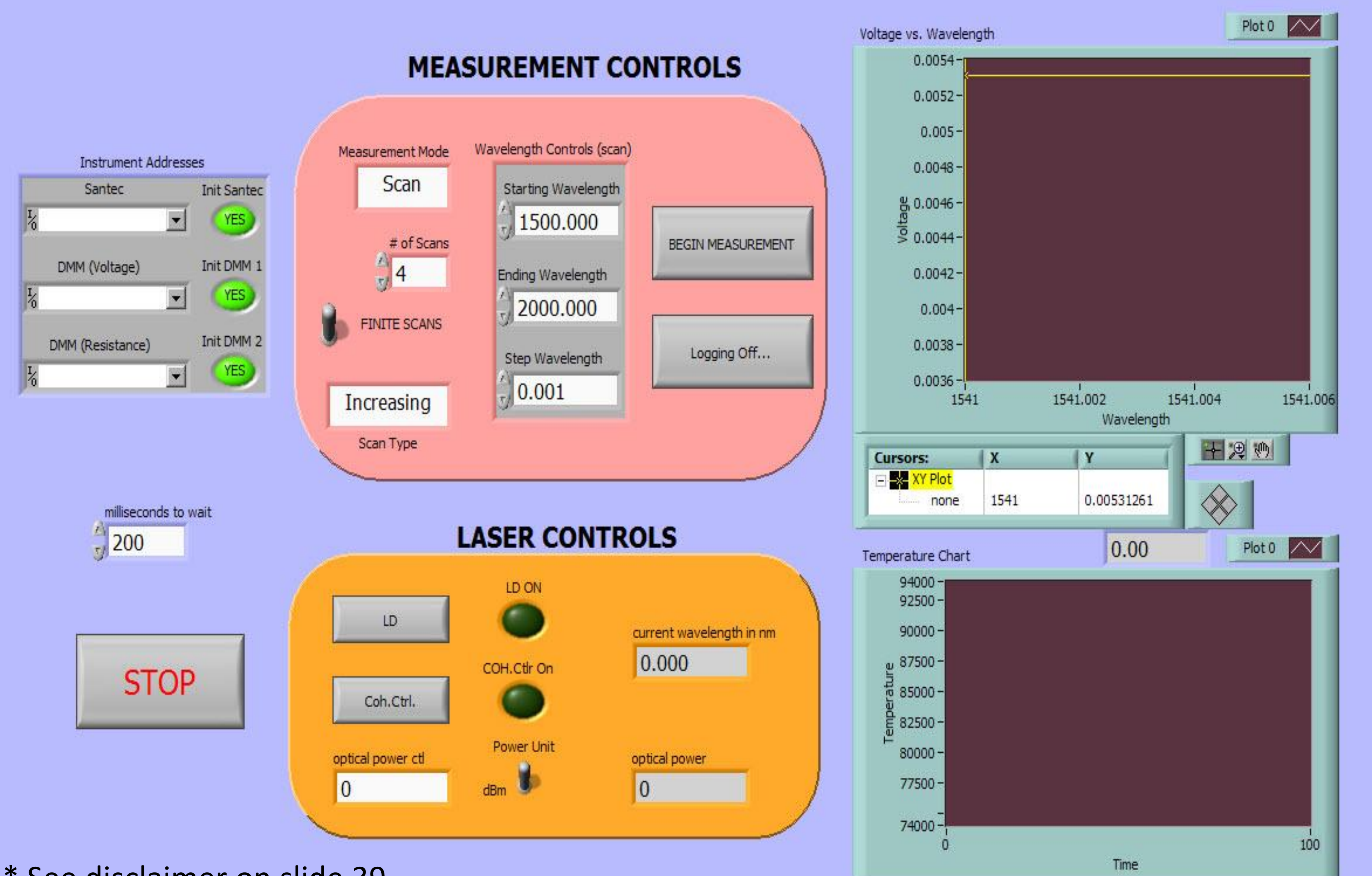
Interrogating an Optical Ring Resonator



We Have Ring Resonators of Different Radii and Gap Sizes on the Chip

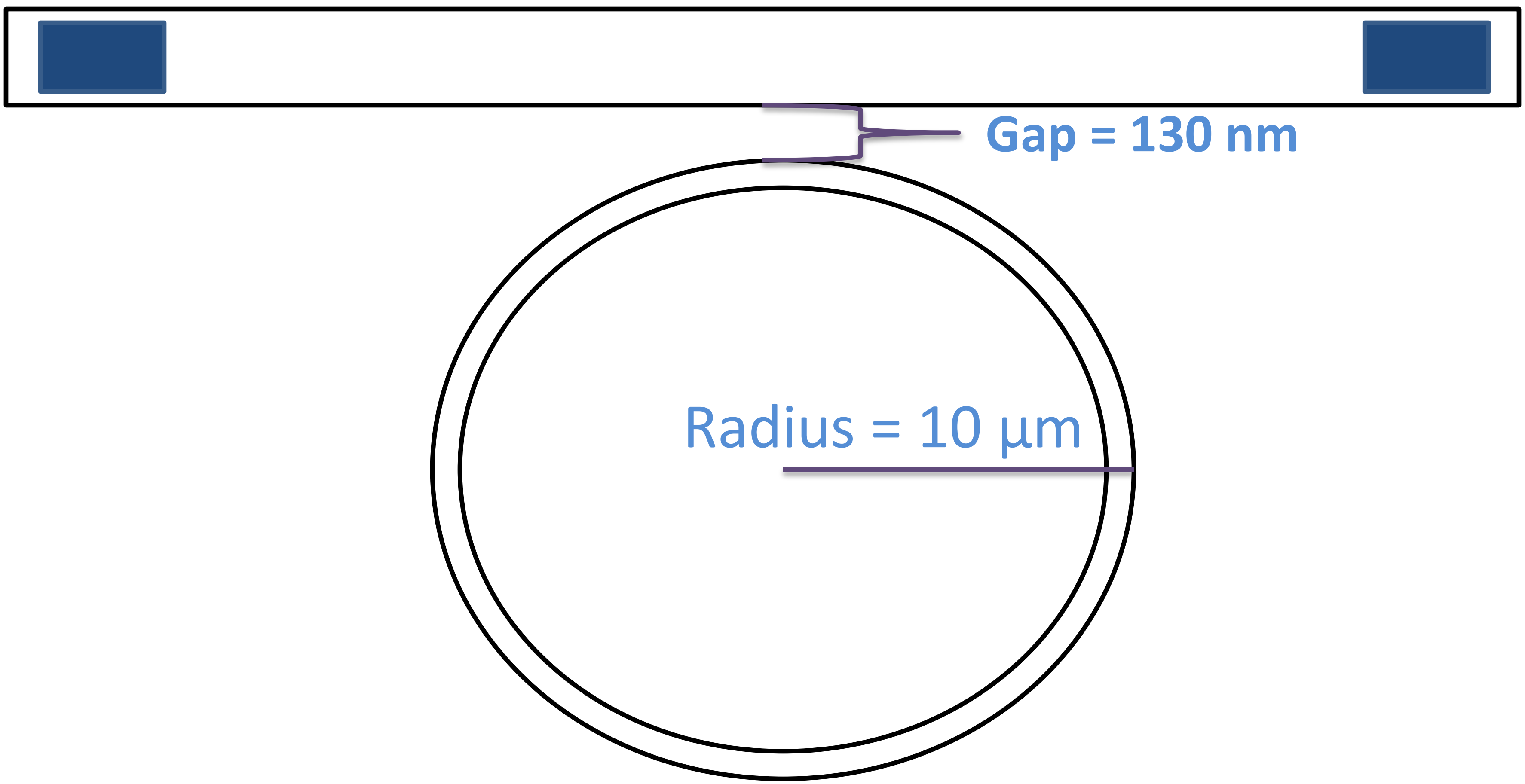


LabView* Based Program is Used to Acquire Data

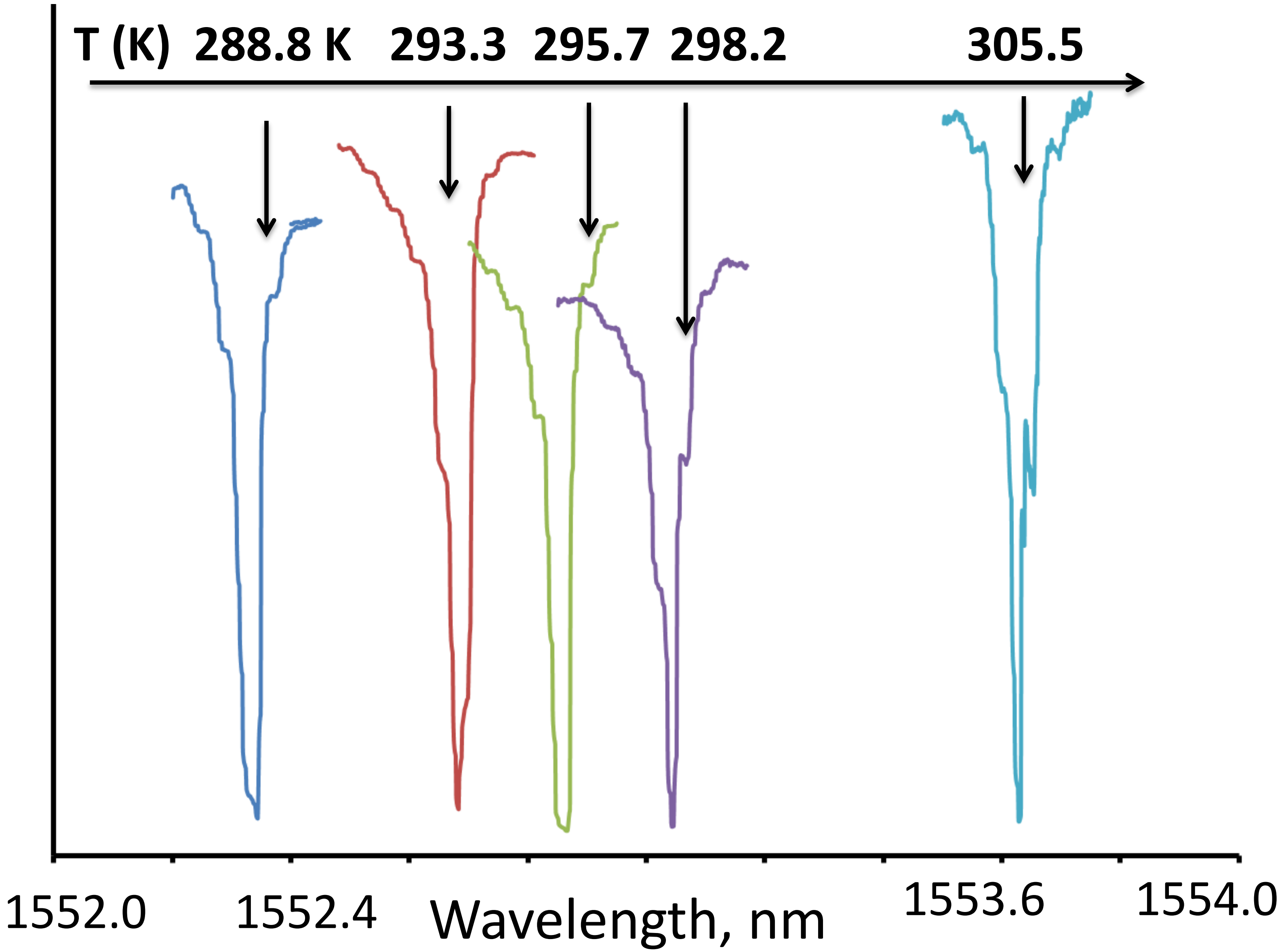


* See disclaimer on slide 39

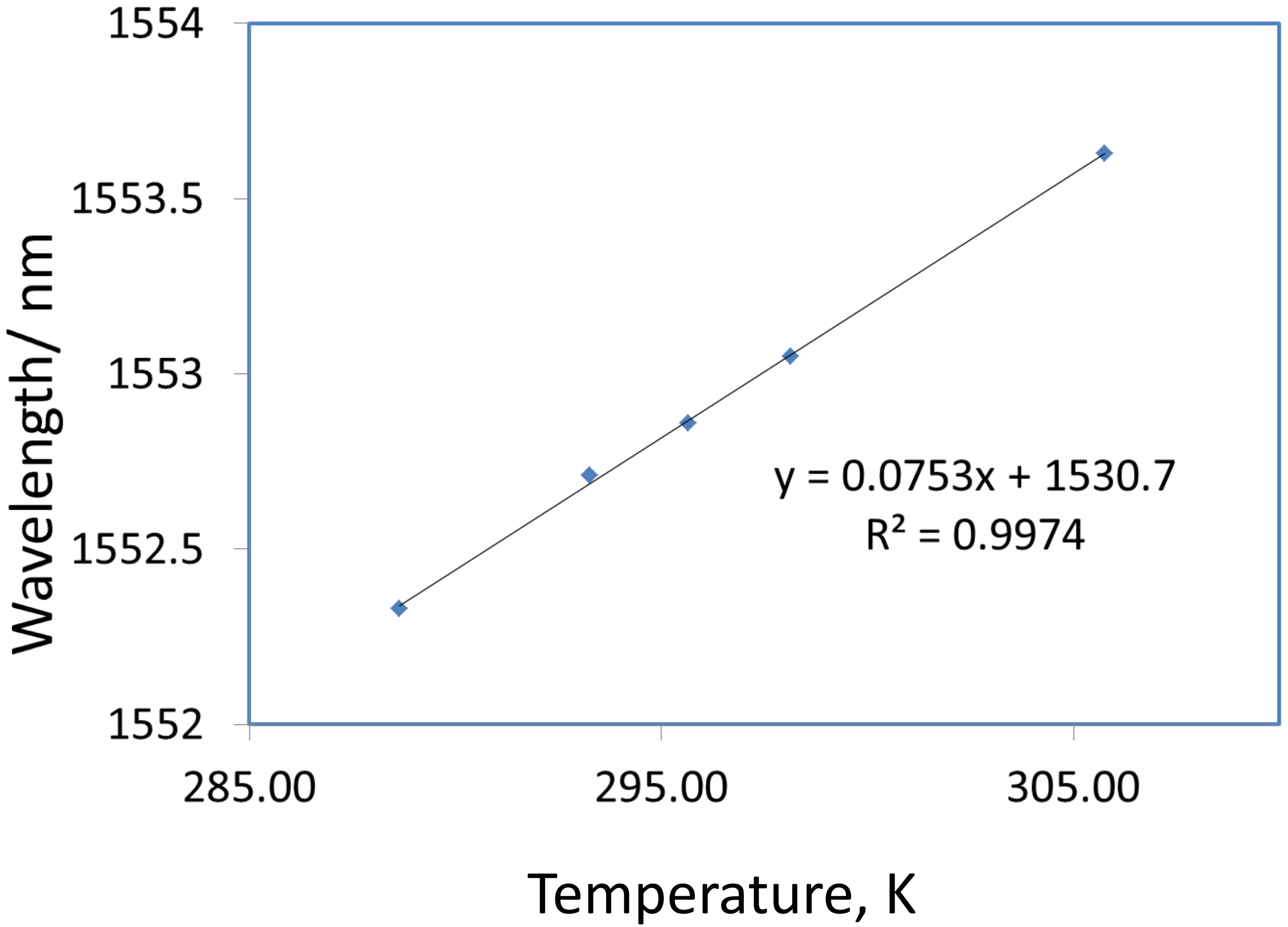
Characterizing the Temperature Dependence of a Ring Resonator Structure



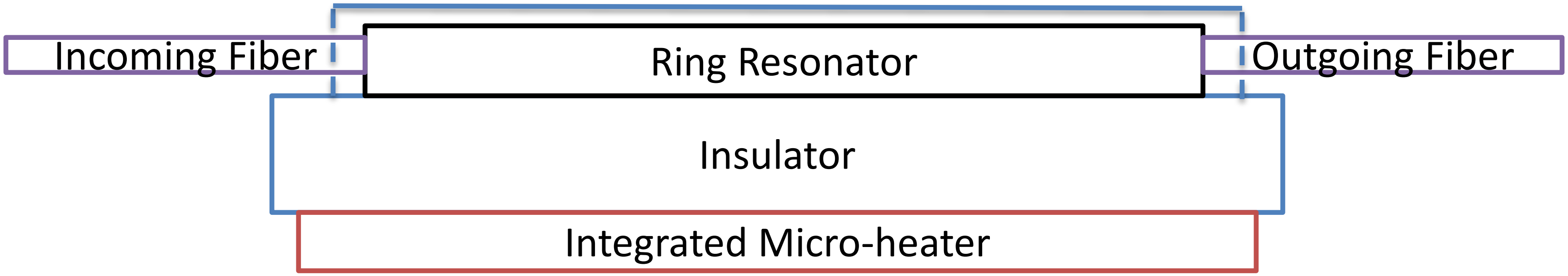
Temperature Dependent Response of a Ring Resonator



Temperature Resolution of 13 mK or Better is Achievable



Future Plans: Self Diagnosing Photonic Sensors



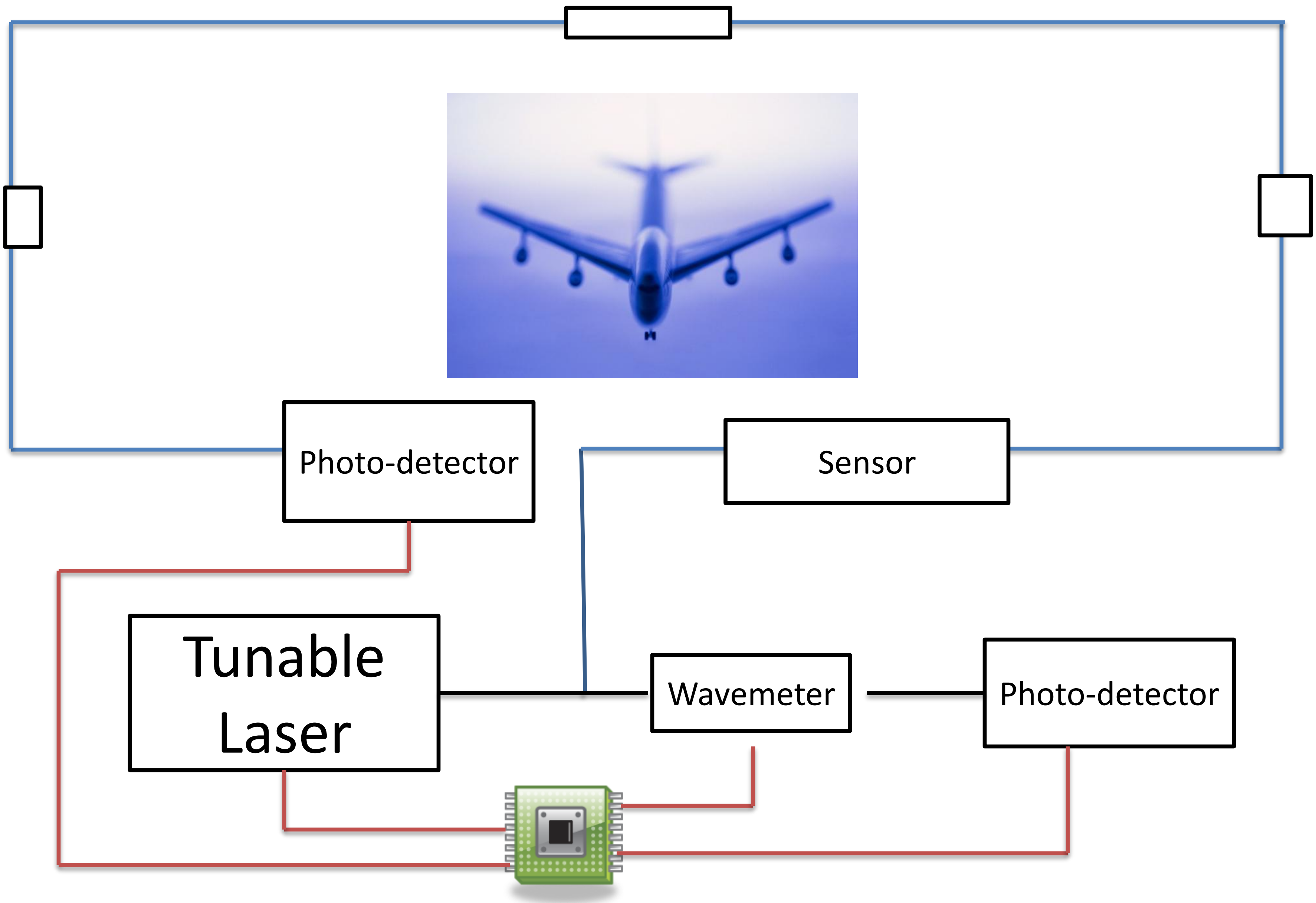
- We will utilize an integrated micro-heater for remote interrogation of the ring resonator.
- In this scheme the micro-heater is used to deposit a known heat load into the chip. We then optically interrogate the ring resonator to determine if its resonance shift corresponds to the expected value for the deposited heat load.
- This mechanism will allow us to remotely evaluate the performance of buried devices.

Future Plans: Self Calibrating Photonic Sensors

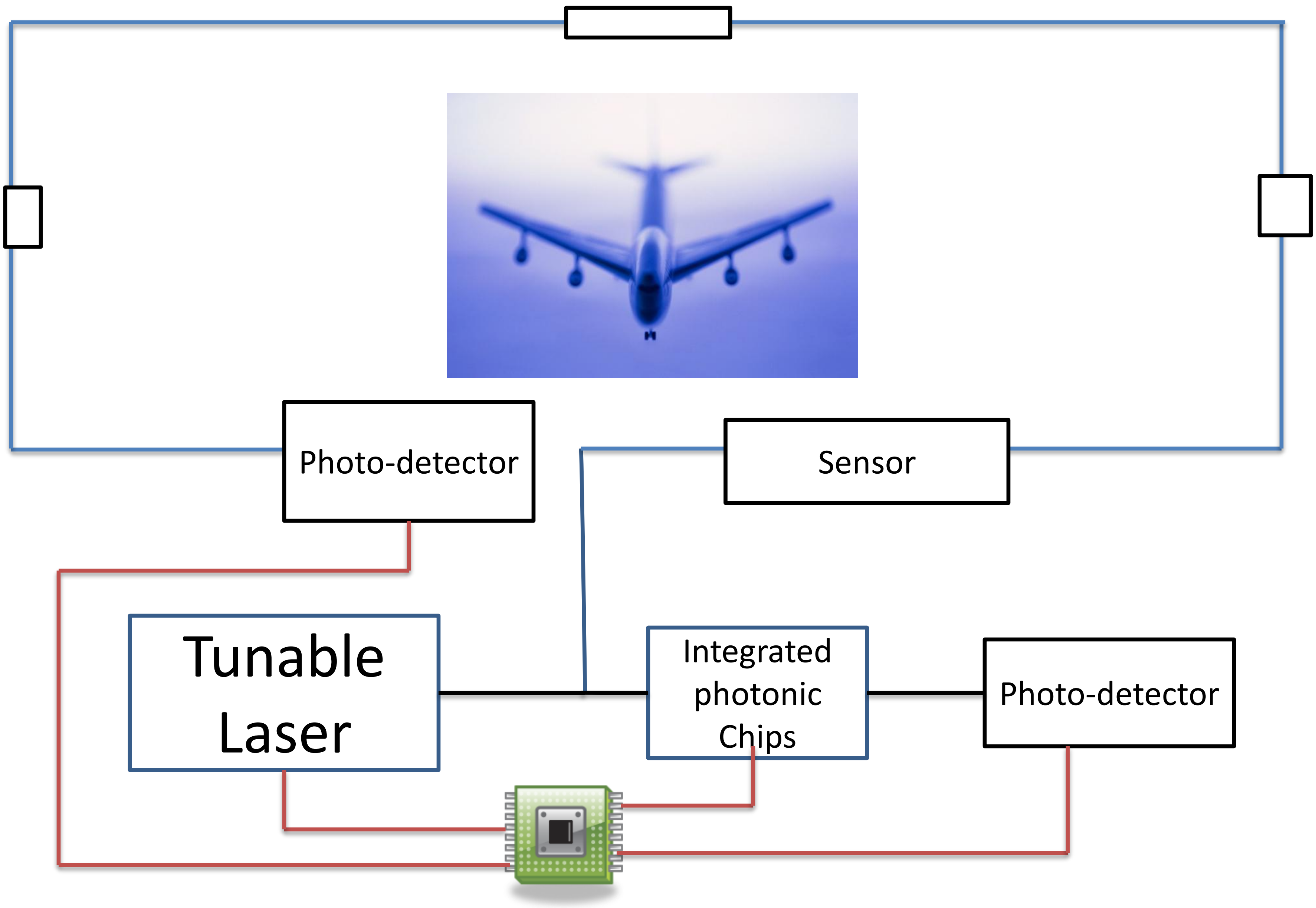
- In the long term, we will focus on developing self-calibrating photonic sensors.

- One exciting pathway is to utilize laser cooling methods to map the resonator phonon energy occupation to its Brownian motion. Temperature dependence of the resonator's Brownian motion can then be mapped on to thermo-optic shift of the resonator at higher temperatures to provide full coverage over the ITS-90 temperature scale.

Ultra lightweight Self-Calibrating Sensor Network



Photonic Chips May be Used *in lieu* of a Wavemeter for Frequency Calibrations

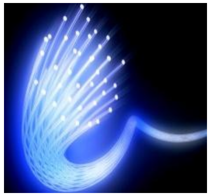


A Million Here and a Million There…

- An Arleigh-Burke class guided missile destroyer has over forty thousand sensors

- Self-calibrating Temperature and Pressure sensors will result in estimated savings of **$450 million** for Arleigh-Burke DDG fleet alone.

- Over a 30 year life span of the fleet this is equivalent to the acquisition cost of **7+ ships**.



Conclusions

- Photonic sensing is opening up an entire new landscape for metrology
- We have initiated research programs that will build in-house expertise in photonic sensor metrology.
- Rather than waiting for this technology to take over the field, we are proactively developing novel techniques to maintain NIST's role as a leader of metrology and science research

Acknowledgments

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Disclaimer

Certain equipment or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available. .