AOI2 Wireless High-Temperature Sensor Network for Smart Boiler Systems

Project No.: DE-FE0031895

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Outline

- Project objective
- Background
- Methods
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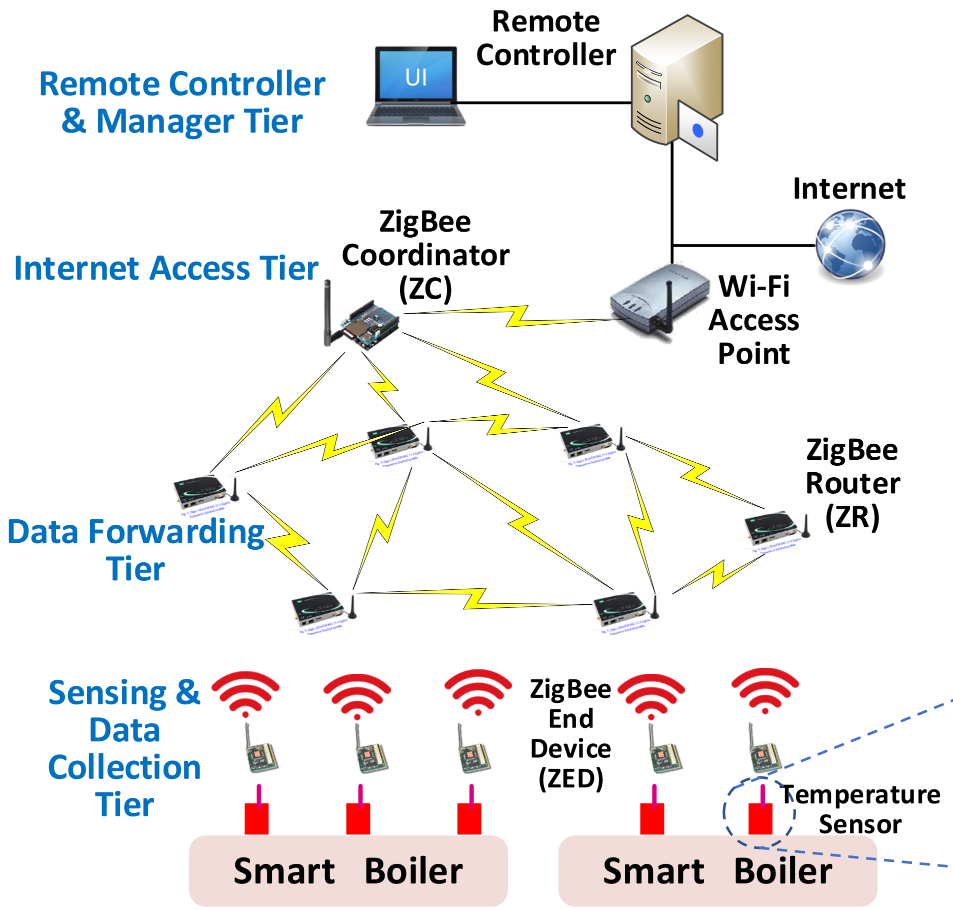
- Team members

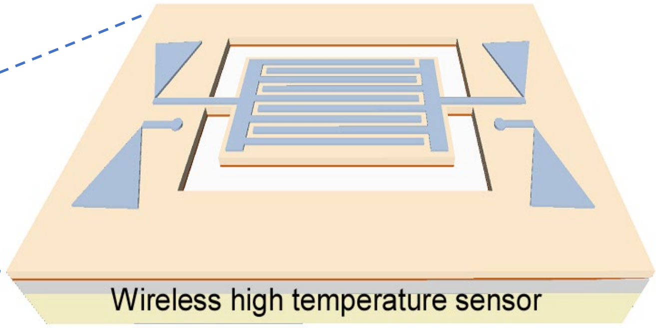
Project objective

Develop a new wireless high-temperature sensor network for real-time continuous boiler condition monitoring in harsh environments



Schematic architecture of the smart boiler wireless sensor network

- High-temperature sensors with integrated antennas
- Coupled with a ZigBee end device (ZED)
- Collect and route boiler temperature data in real-time



Background

The needs

- Boilers and furnaces are extensively used virtually everywhere
- These systems consume the most significant amount of energy
- Optimizing the operation of the systems can lead not only to huge energy savings and bring tremendous benefits to our environment

Estimated impacts

- 1% efficiency improvement provides energy savings of around 30 billion kilowatt-hours (kW·h)
- ~ 300 billion cubic feet of natural gas
- ~ 17 million tons of carbon emission reduction

Methods

High-temperature piezoelectric materials

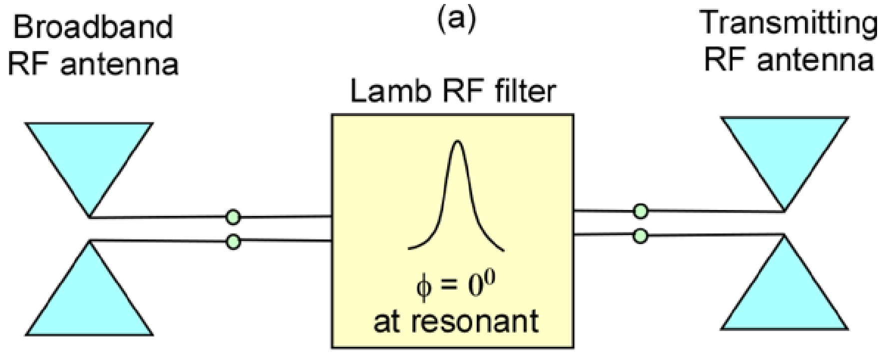
Values	4H SiC	AlN	ZnO	$LiNbO_3$	PZT
Melting temperature (°C)	2,800	1,800	1,975	1,250	1,350
Electrical stability at high temperature	High	High	High	Not high	Not high
Chemical resistance	High	React > 600 °C	High	High	High
Curie Point (°C)	N/A	2,000	N/A	1,140	200
CTE (10^{-6} /°C)	4.0	$\alpha_{\parallel}$: 4.2 $\alpha_{\perp}$: 5.3	47.7	$\alpha_{\parallel}$: 4.0 $\alpha_{\perp}$: 16	4.0
Surface Wave Velocity (m/s)	6,832	5,790	4,355	3,488	4,160
Piezoelectric constant (C/m^2)[5]	e_{15}= 0.08 e_{33} = 0.20	e_{31} = −0.58 e_{33} = 1.55	e_{31} = −0.57 e_{33} = 1.32	e_{31} = 0.23 e_{33} = 1.33	e_{31} = −6.5 e_{33} = 23.3

Methods

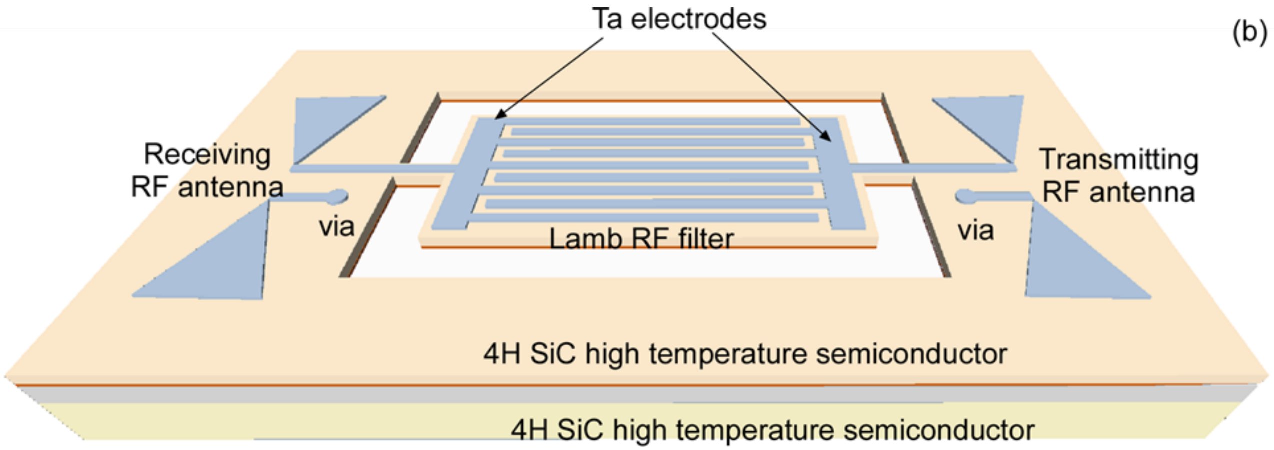
High-temperature metal

Values	Ta	Pt	Au	W	Cu
Melting temperature (°C)	3,017	1,768	1,064	3,422	1,085
Chemical resistance	High	High	High	Oxidization	Oxidization
Conductivity (10^7 S/m)	0.77	1.06	4.11	1.79	5.96

High-temperature wireless sensor



(a) Equivalent circuit



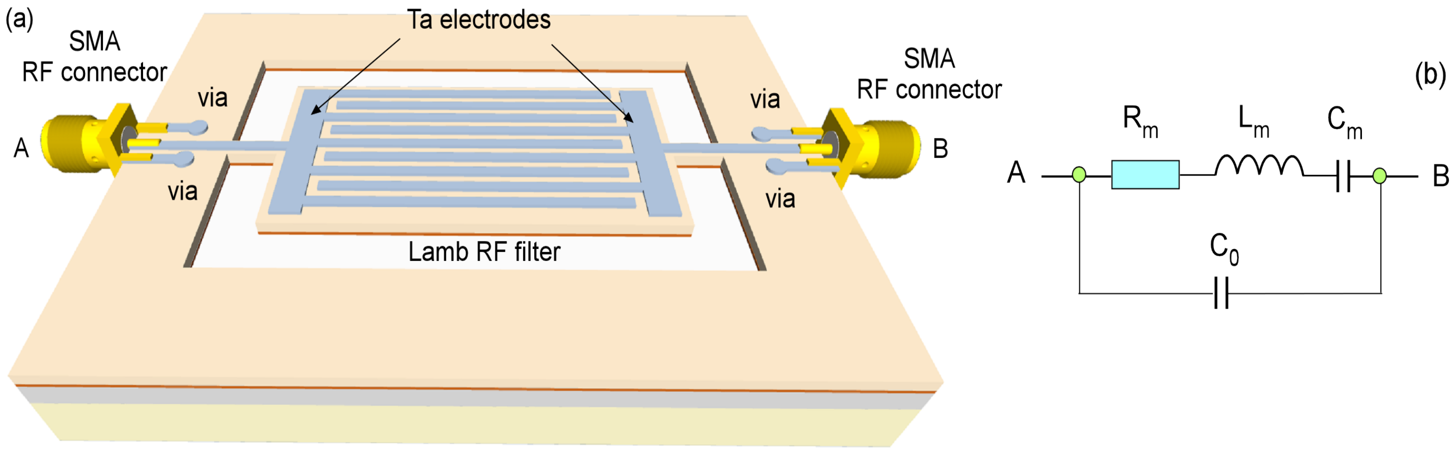
(b) 3D schematic structure

- A Lamb filter[1] sensing structure
- The high-temperature sensor and the bow-tie transmission and receiving antennas are all on the 4H SiC piezoelectric substrate.
- The Lamb filter provides sharp transmission spectrum and a 0^0 degree phase shift at the resonant frequency
- Enables strong coupling of the integrated antennas.
- The resonant frequency shifts with the temperature, allowing temperature measurement through the transmission and receiving and the coupling properties of the antennas

[1] *Lin, C.-M. et al. Thermally compensated aluminum nitride Lamb wave resonators for high temperature applications. Applied Physics Letters 97, 083501, doi:10.1063/1.3481361 (2010)*

Methods

Lamb-filter temperature shift



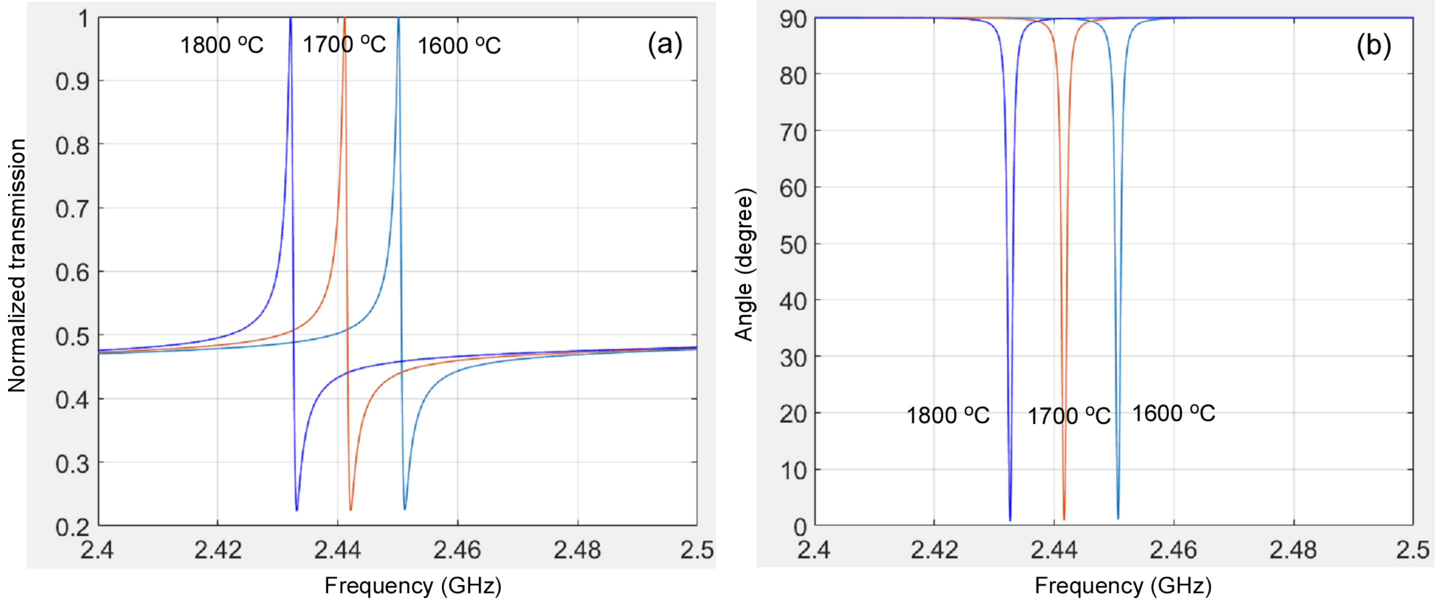
$$Y = \frac{1}{R_m + j\omega L_m + \frac{1}{j\omega C_m}} + j\omega C_0$$

$$= \frac{1 + \frac{C_0}{C_m} - \omega^2 C_m L_m + j\omega C_0 R_m}{R_m + j\omega L_m + \frac{1}{j\omega C_m}}$$

$$\Gamma = \frac{F}{V} = e_{31} \cdot l \qquad C_m = \frac{\Gamma^2}{k_{eq}},$$

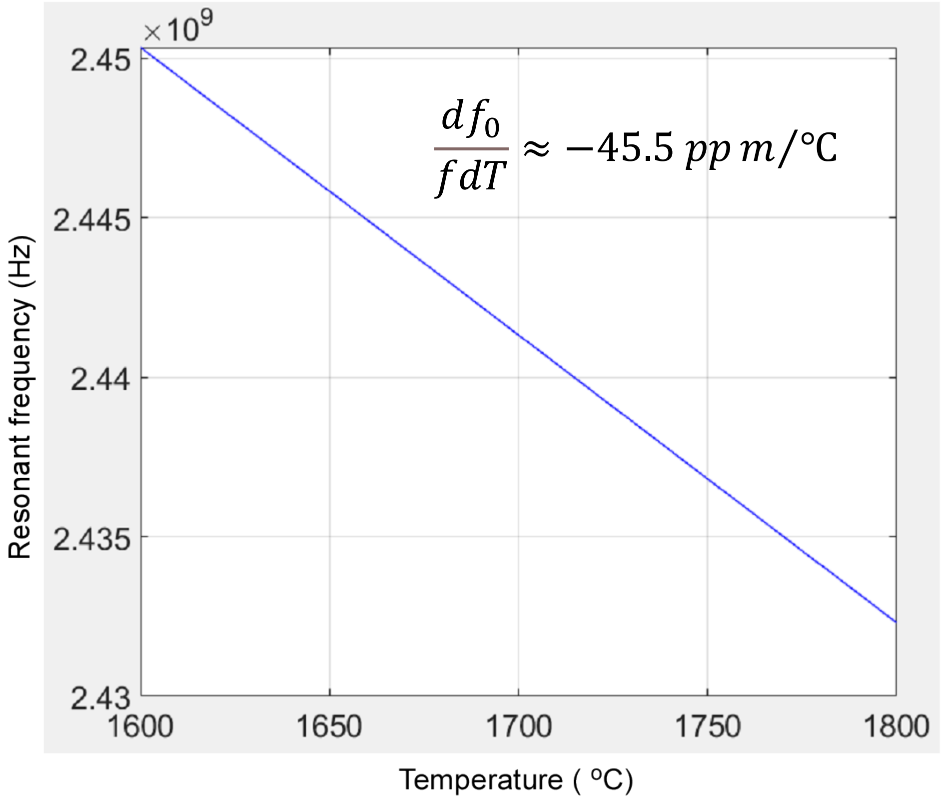
$$L_m = \frac{m_{eq}}{\Gamma^2} \qquad C_0 = \frac{\varepsilon_r \varepsilon_0}{t} wl$$

$$k_{eq} = \frac{Elt}{2w} \qquad R_m = \frac{\sqrt{L_m/C_m}}{Q}$$



Lin, C.-M. et al. Thermally compensated aluminum nitride Lamb wave resonators for high temperature applications. Applied Physics Letters 97, 083501, doi:10.1063/1.3481361 (2010)

Lam-filter temperature shift



Simulated resonant frequency shift with temperature

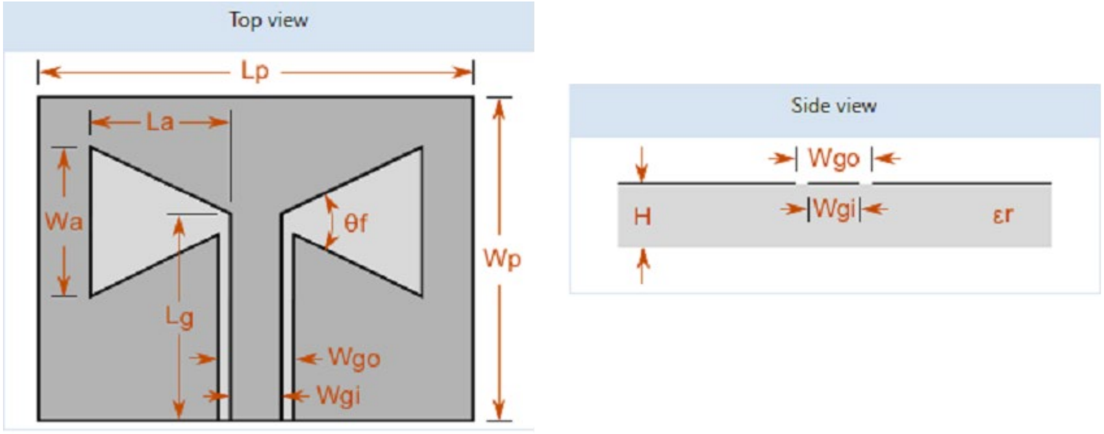
Temperature coefficient of Young's modulus

$$\kappa = \frac{de}{dT} \approx -0.02\ GPa/°C \qquad \Gamma = \frac{F}{V} = e_{31} \cdot l$$

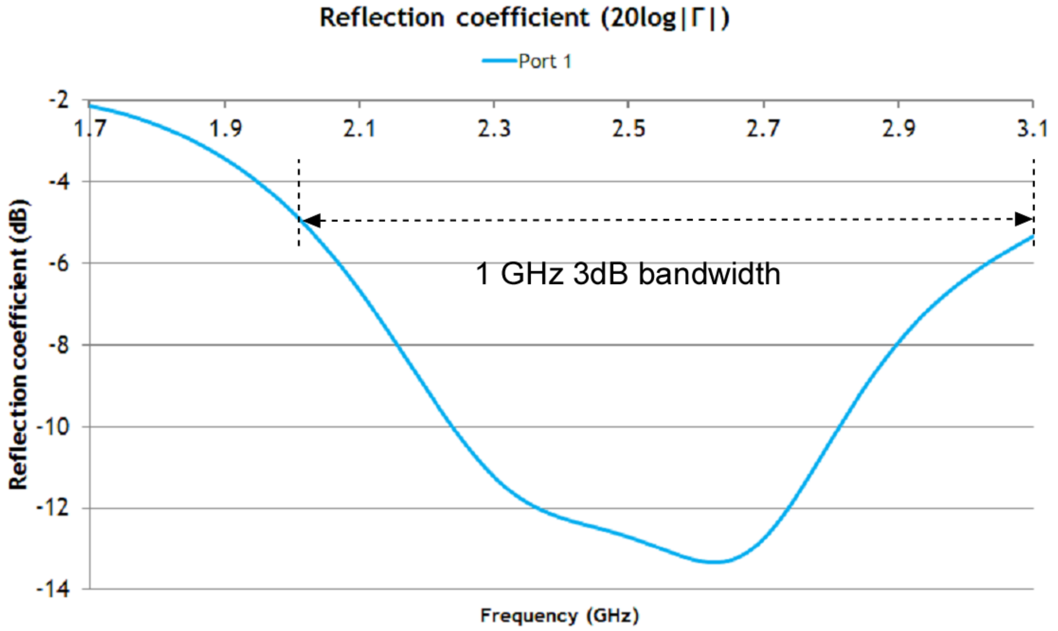
CTE $\alpha \approx 2.2ppm/°C.$

Methods

Broadband antenna



Antenna design parameters using Antenna Magus and CST Microwave Studio®.

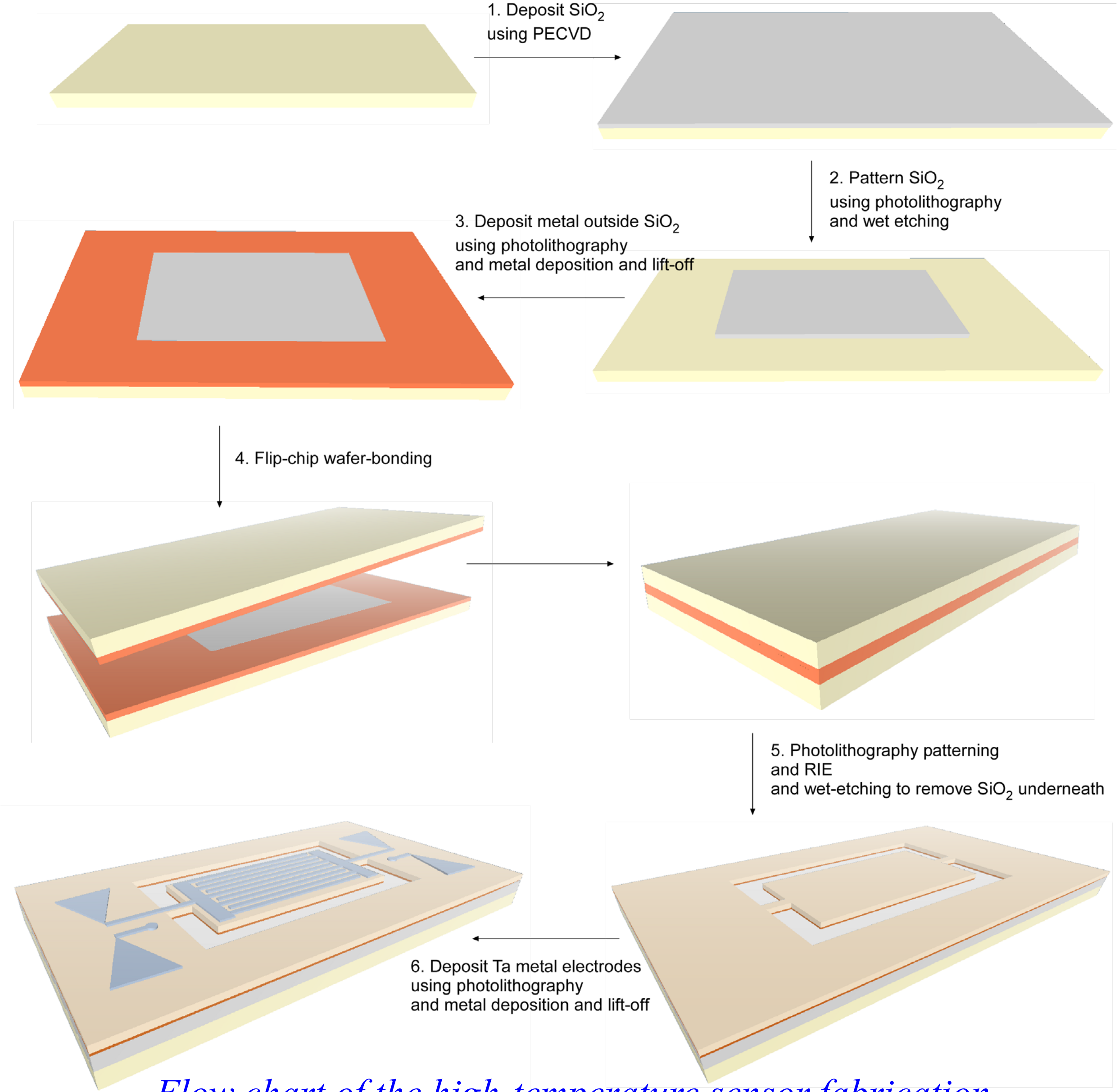


Simulated 3dB bandwidth. A broadband operation of 400 MHz can be achieved

- Antenna coupling

$$S_{11} = \frac{Z_L - Z_0}{Z_L + Z_0} \qquad Z_L = Z_0 \frac{1 + \Gamma e^{-j\beta L}}{1 - \Gamma e^{-j\beta L}} \qquad \Gamma = \left(\frac{Z_{filter} Z_{antenna}}{Z_{filter} + Z_{antenna}} - Z_0\right) \Big/ \left(\frac{Z_{filter} Z_{antenna}}{Z_{filter} + Z_{antenna}} + Z_0\right)$$

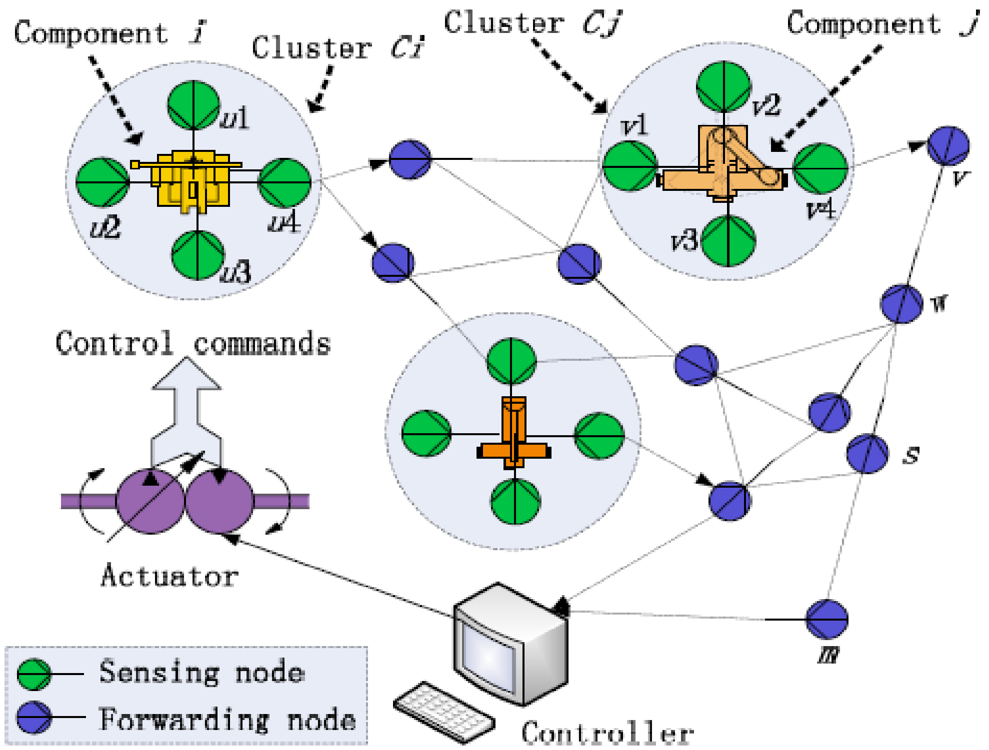
Wireless high-temperature sensor fabrication



Flow chart of the high-temperature sensor fabrication

Methods

Sensor network simulation

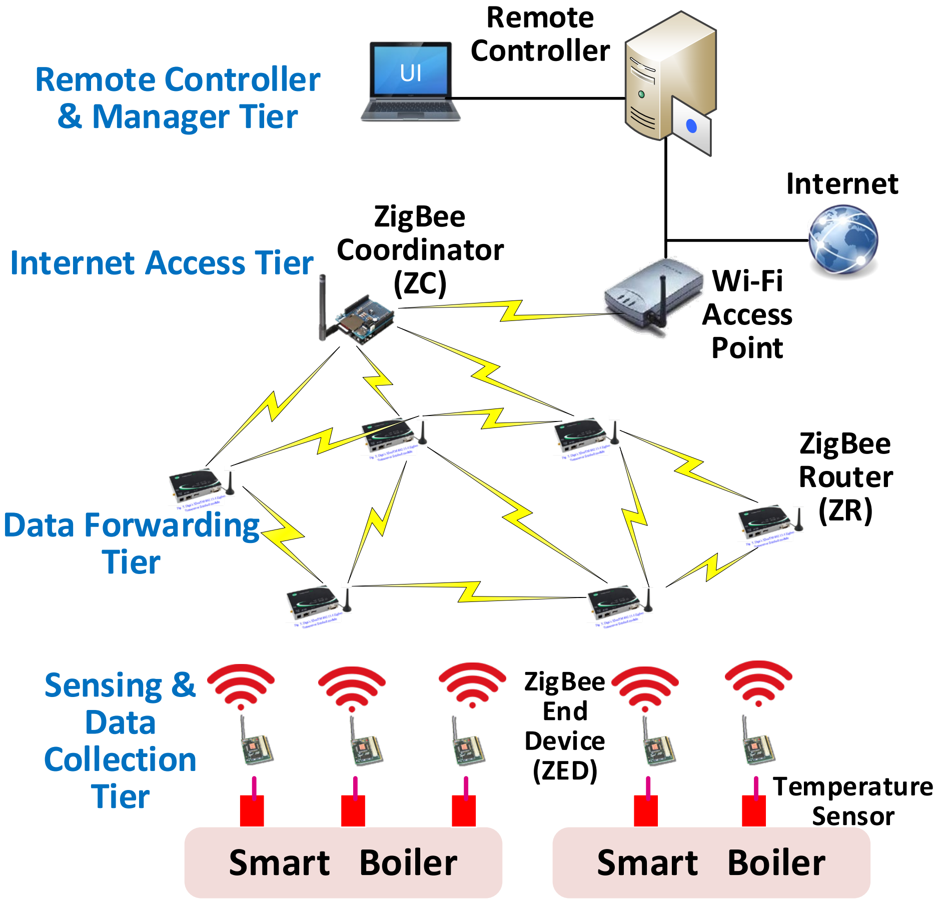


Sensor Network for data collection (With permission of Prof. X. Fu)

- Network simulator (NS)
- Configuration of arbitrary number of network nodes and the properties
- Different types of networks, including Wireless Sensor Networks (WSN), Wireless LAN, Personal Area Network (PAN), and TCP/IP

Methods

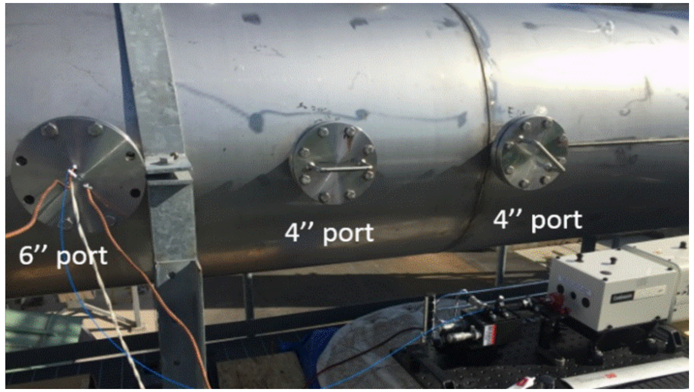
Set up the wireless high-temperature sensor network testbed

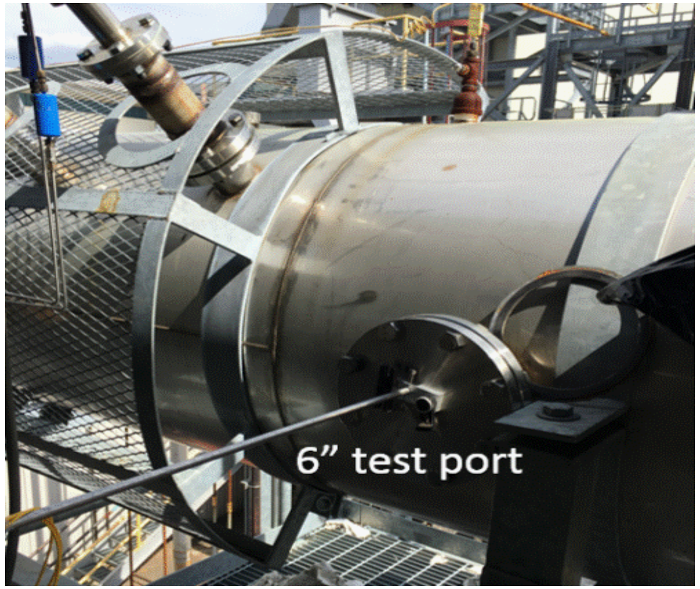


High-temperature WSN testbed

- Include Different ZigBee PRO devices (ZigBee End Device (ZED), ZigBee Router (ZR), and ZigBee Coordinator (ZC)).
- Implement several augmented routing protocol candidates (e.g., ARTO-AODV, EA-AODV, AODV-FL) in the Ad-hoc On-demand Distance Vector (AODV) routing protocol family
- Evaluate and compare both non-beacon-enabled and beacon-enabled modes at the MAC layer
- Validate the most energy-efficient channel access mechanism with low/tolerable transmission latency

Wireless high-temperature sensor network test





Boilers at GE

- Characterize the high-temperature sensor and create the temperature mapping
- Antenna attenuation through the chamber
- Antenna bandwidth at different temperature ranges
- The directional gains and the 3D profiles
- Transmission and reflection characteristics and effective working distances

Tasks

Task 1: Obtain optimal designs of the wireless high temperature sensor network.

Task 2: Fabricate the wireless high-temperature sensor and build the wireless sensor network.

Task 3: Characterize the wireless high-temperature sensor and evaluate the performance of the wireless high-temperature sensor.

Task 4: Determine the system stability and reliability.

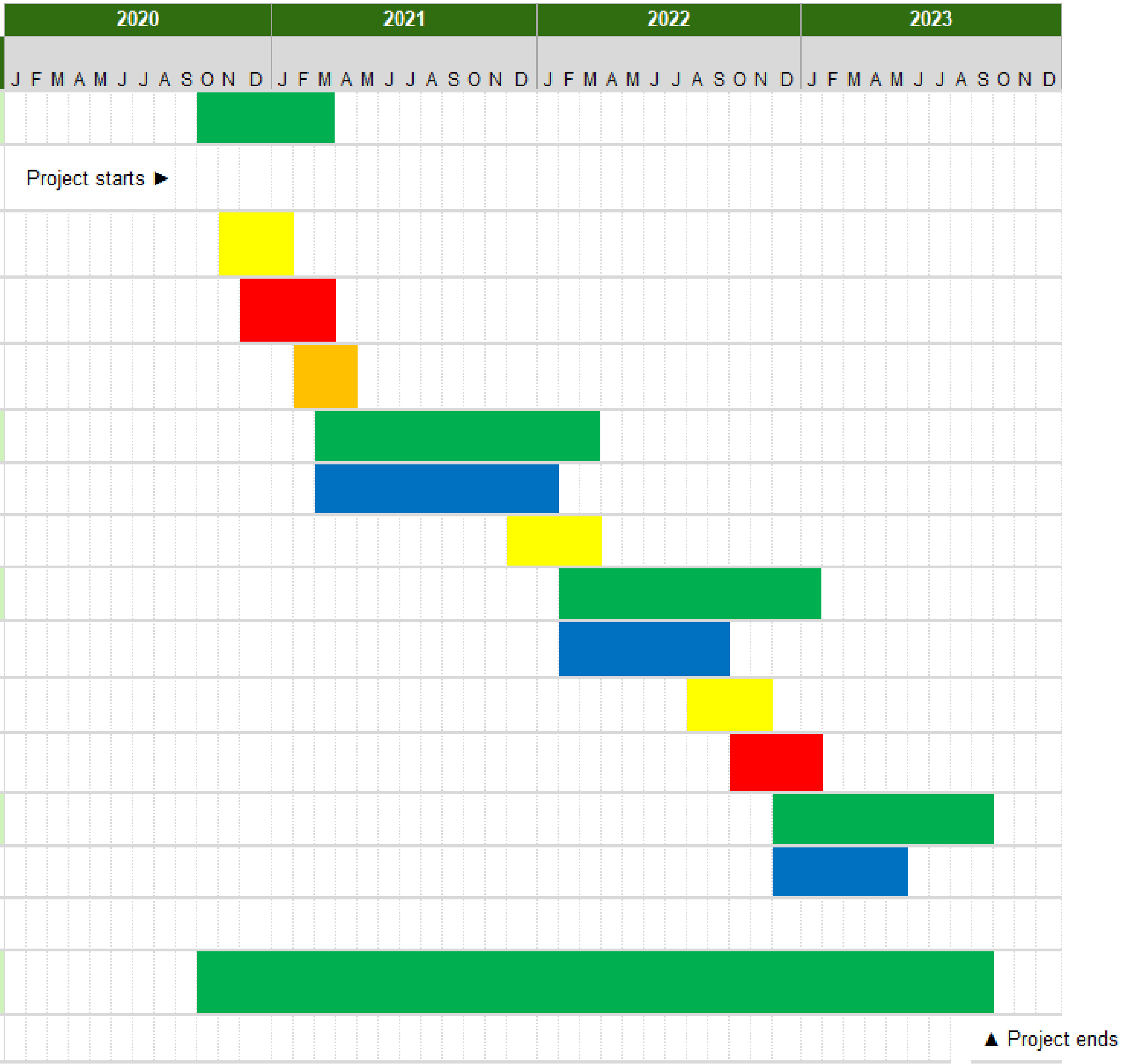
Task 5: Report.

Milestones

DOE Project Schedule

University of Massachusetts Lowell

TASK DESCRIPTION	PLAN START	PLAN END
Task 1 Obtain optimal designs of the wireless sensor network	10/1/2020	3/31/2021
1. Design the high-temperature sensor	10/01/202	12/31/2020
2. Design the broadband antenna	11/1/2020	1/31/2021
3. Antenna coupling through the Lamb filter	12/1/2020	3/30/2021
4. Design the sensor network and perform network simulation	2/2/2021	4/30/2021
Task 2 Fabricate the wireless sensor network	3/1/2021	3/30/2022
1. Fabricate the wireless high-temperature sensor	3/1/2021	1/31/2022
2. Set up the wireless high-temperature sensor network	12/1/2021	3/30/2022
Task 3 Characterize the wireless high-temperature sensor network	2/2/2022	1/31/2023
1. Characterize the high-temperature sensor	2/2/2022	9/30/2022
2. Characterize the RF performance of the antenna	8/1/2022	11/30/2022
3. Characterize the wireless sensor network	10/1/2022	1/31/2023
Task 4 Determine the system stability and reliability	12/1/2022	9/3/2023
1. Characterize the high-temperature sensor reliability	12/1/2022	5/31/2023
2. Characterize the reliability of the senor network	4/1/2023	9/3/2020
Task 5 Report	10/1/2020	9/3/2023



Team members

- Dr. Xuejun Lu, US Citizen
  - ❑ Ph.D. in Electrical Engineering, University of Texas Austin 2001
  - ❑ 20 years research experience in EO IR and optoelectronic devices

Selected Publications of Dr. Lu

1. T. Kemsri, G. Gu, C. Schnitzer, M. Sullivan, B. Xiang, A. GhafaryAghdam, L. Li and **X. Lu**, "Study of frequency-dependent plasmonic enhancement of a circular disk nano-optical antenna array using a femtosecond laser frequency comb," *J. Phys. D: Appl. Phys.* 52 385104 (2019)
2. L. Li, T. Kemsri, Y. Zhang, B. Xiang, A. GhafaryAghdam, G. Gu and **X. Lu**, "Surface current confinement in circular ring optical antennas and its enhancement effect to the photoresponse of longwave infrared photodetectors," *J. Phys. D: Appl. Phys.* 52 095103 (2018)
3. Y. Zhai, G. Gu, and **X. Lu**, "Voltage-Tunable Mid- and Long-Wavelength Dual-Band Infrared Photodetector Based on Hybrid Self-Assembled and Sub-Monolayer Quantum Dots", *Micromachines* 2019, 10(1), 4.
4. **X. Lu**, N. Mojaverian, L. Li, G. Gu, Y. Zhang and T. Kemsri "A backside configured pointed dipole plasmonic optical antenna array enhanced quantum dot infrared photodetector," *Semicond. Sci. Technol.* 32 pp. 125017 (2017)
5. **X. Lu**, J. Vaillancourt, and G. Gu "A plasmonic perfect absorber enhanced longwave infrared quantum dot infrared photodetector with high quantum efficiency," *J. Phys. D: Appl. Phys.* 50 135101 (2017).

Team members

- Dr. Xingwei Wang, US Citizen
  - ❑ Ph.D. in Electrical Engineering, Virginia Tech 2006
  - ❑ Research experience in optical fiber sensors and high temperature sensors

Selected Publications of Dr. Wang

1. Jingcheng Zhou, Xu Guo, Cong Du, Xinsheng Lou, Chengyu Cao, Xingwei Wang, "A Fiber Optic Acoustic Pyrometer for Temperature Monitoring in an Exhaust Pipe of a Boiler" IEEE Photonics Technology Letters, 31 (19), 1580-1583 (2019).
2. Jingcheng Zhou, Xu Guo, Cong Du, Chengyu Cao, and Xingwei Wang, "A Fiber Optic Ultrasonic Sensing System for High Temperature Monitoring Using Optically Generated Ultrasonic Waves" Sensors, 19 (2), 404 (2019).
3. Xu Guo, Jingcheng Zhou, Cong Du, and Xingwei Wang, "Highly Sensitive Miniature All-Silica Fiber Tip Fabry-Perot Pressure Sensor", IEEE Photonics Technology Letters, 2019.
4. Jingcheng Zhou, Xu Guo, Cong Du, and Xingwei Wang, "Ultrasound beam steering using a fiber optic ultrasound phased array", Optics Letters, 44(21), 5390-5393 (2019).
5. Xu Guo, Nan Wu, Jingcheng Zhou, Cong Du and Xingwei Wang (2020). Validation of an ultrasound transducer's generation and receiving function on one single-mode fiber. Optics and Lasers in Engineering, 127, 105962.

Team members

- Dr. Tricia Chigan, US Permanent Resident (subject to DOE's approval)
  - Ph.D. in Electrical Engineering, State University of New York at Stony Brook 2002
  - 18 years research experience in wireless networking

Selected Publications of Dr. Chigan

1. L. Li, C. Chigan, "An Energy-Efficient Privacy Preserving Security-oriented DSA with Low Latency," *IEEE Transactions on Vehicular Technology*, Vol. 68 (11), pp. 11283-11294, Nov., 2019.
2. S.Yuan, L. Li, C. Chigan, "On MMD-based Secure Fusion Strategy for Robust Cooperative Spectrum Sensing," *IEEE Transactions on Cognitive Communications and Networking*, Vol. 5 (3), pp. 504-516, Sept., 2019.
3. L. Li, S.Yuan, C. Chigan, "A Relay Selection based Bidirectional Full-Duplex Communication Scheme," *in Proceedings of IEEE ICC 2018 Workshop - 3rd Workshop on Full-Duplex Communications for Future Wireless Networks*, May, 2018.
4. S.Yuan, L. Li, C. Chigan, H. Zhu, "Stochastic Game Approach for Long-term Fairness-aware Radio Resource Allocation," *in Proceedings of IEEE Global Communications Conference (Globecom 2017)*, Dec. 2017.
5. C. Zou, C. Chigan, "Dynamic Spectrum Access based Cryptosystem for Cognitive Radio Networks," *Wiley Journal of Security and Communication Networks*, Oct. 2016.

Thank you!