Surface Temperature Measurements from a Stator Vane Doublet in a Turbine Engine Afterburner Flame Using an Ultra-Bright Cr-Doped GdAlO$_3$ Thermographic Phosphor

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Background

- Recent laboratory discovery* of exceptional high temperature retention of ultra-bright luminescence by Cr-doped GdAlO$_3$ with orthorhombic perovskite crystal structure: Cr-doped gadolinium aluminum perovskite (Cr:GAP).
- Orders of magnitude stronger luminescence emission above 1000 ºC than previous state-of-the-art rare-earth-doped thermographic phosphors.
- Demonstrated luminescence-decay-based temperature measurements to 1250 ºC.
- Cr:GAP performance promising for turbine engine environment measurements:
  - High-intensity luminescence emission from thin Cr:GAP surface coatings will stand out in presence of strong radiative (flame) environment.
  - Broadband excitation and emission allows flexible choice of excitation and detection wavelengths.

*J. I. Eldridge & M.D. Chambers
Objectives

• Transition to engine environment implementation
  - Measurements of engine component surface in high-velocity, high-temperature radiative (flame) environment.

• Demonstrate temperature measurements from Cr:GAP coated Honeywell stator vane doublet in afterburner flame of UTSI J 85-GE-5 turbojet test stand.

• Challenges:
  - Coating complex component shape.
  - Optical probe design integrating non-intrusive excitation & collection with thermal protection.
  - “See” through flame environment.
  - Remote measurement control from a safe distance.
Basis for High Temperature Ultra-Bright Cr:GAP Luminescence

Cr$^{3+}$ 3$d^3$ energy levels

$^4T_2$ (short-lived but population stabilized by thermal equilibrium with $^2E$ reservoir level)

$^2E$ (long-lived reservoir level)

$^4A_2$

Spin-forbidden R-line emission (long decay)
$^2E \rightarrow ^4A_2$

Spin-allowed broadband emission (short decay)
$^4T_2 \rightarrow ^4A_2$

$\tau_{4T_2} = \tau_{2E} = \tau_{2E}^R \frac{1 + 3e^{-\Delta E/kT}}{1 + \alpha e^{-\Delta E/kT} + \beta e^{-(\Delta E + \Delta\Theta)/kT}}$

Tanabe-Sugano Diagram

Strong crystal field increases $\Delta E$.

For long $\tau$ at high $T$ $\rightarrow$ increase $\Delta E$, $\Delta\Theta$.

Orthorhombic Rare Earth Perovskites
RAIO₃ Meet Criteria
Tightly bonded AlO₆ Octahedra Exhibit Strong Crystal Field High ΔE

Among all RAIO₃ perovskites, GdAlO₃ has highest ΔE among candidates with orthorhombic structure.
Temperature Dependence of Luminescence Emission from Cr(0.2%):GAP Puck
• Nearly single exponential.
• Uniform decay rate over wavelength range.
• Adequate signal for decay time determination at wavelengths as short as 570 nm.
• Collect luminescence decay measurements with bandpass filter @ 593 nm, FWHM = 40 nm to minimize interference from thermal radiation background.
Demonstrating Temperature Sensitivity of Luminescence Decay Curves from Cr:GAP Puck

Bandpass filter: CL = 593 nm; FWHM = 40 nm

Fit to $I = I_1 e^{-t/\tau_1} + I_2 e^{-t/\tau_2}$
Demonstrating Temperature Measurement Capability

Calibration of Decay Time vs. Temperature for GAP:Cr Puck

Two distinct regions

\[200 \, ^\circ\text{C} < T < 750 \, ^\circ\text{C}: \text{less temperature sensitive}\]

\[T > 750 \, ^\circ\text{C}: \text{more temperature sensitive}\]
AFRL VAATE Project
Gas Turbine Engine Sensor and Instrumentation Development
Stepping Stone Approach

NASA GRC High-Heat-Flux Laser Facility
• Proof-of-concept with easy optical access, no radiative background, no probe heating issues.
  Demonstrated to 1360 °C.

Williams International Combustor Burner Rig
• Address probe/TP survivability & ability to “see” through flame.
  Demonstrated to >1400 °C.

AEDC J 85-GE-5
• Probe/translate through afterburner flame.
  • Test integrated excitation/collection probe.
  • Opportunity to test new Cr:GAP thermographic phosphor.

Goal: Demonstrate thermographic phosphor based temperature measurements to 1300 °C on TBC-coated HPT stator on Honeywell TECH7000 demonstrator engine.
Cr:GAP Coatings for Surface Temperature Measurements

Electron Beam Physical Vapor Deposition Challenges

- Deposition of Cr:GAP by EB-PVD at Penn State proved to be challenging.
  - Top of Cr:GAP ingot explodes under electron beam heating.
  - Ingot fractures due to thermal shock.

- Successful Resolution: Top section of ingot removed & then use extremely gentle electron beam heating.
Superb signal-to-noise from thin 25 µm thick coating confirms retention of ultra-bright luminescence at high temperatures.
Demonstrating EB-PVD Cr:GAP Temperature Measurement Capability

Decay Time vs. Temperature for 25 µm Thick EB-PVD Cr:GAP Coating

Decay time ($\tau_2$) vs. temperature dependence for thin EB-PVD Cr:GAP coating follows same calibration curve as Cr:GAP puck.
Cr:GAP-Coated Stator Vane Doublet
EB-PVD at Penn State

15 µm Cr:GAP
200 µm YSZ
 NiPtAl (Howmet)
  Vane

EB-PVD
Probe Design for Vane Measurements

Constraints for probe design
- Do not protrude into gas flow.
- Limited space: integrated excitation & collection.
- End of probe exposed to gas flow temperatures.
- Temperature-sensitive optical components require cooling.

Final probe design by Rob Flori, Honeywell.
Optical Probe Setup

Vane

Laser spot

Probe
Cooling Fixture for Mounting in Afterburner Flame at UTSI J 85 Test Stand
High-Velocity Exhaust Gas up to 1760 °C

J 85-GE-5 Turbojet Test Stand

Mounted vane doublet

Air-purge cooling

Water-cooling
J 85-GE-5 Engine Test at UTSI

Engine Aft View

Overhead View of Vane in Afterburner Flame

Afterburner Flame at Night
Initial J 85 Test Runs Reveal Unintended Probe Cooling Effect!*

PLA (power lever angle) # = throttle setting

Probe cooling air cools target area! Highly perturbing temperature measurement!

*Directed probe cooling effect will be considerably smaller inside engine where combustion gas cross-flow will be much greater.
Reduce Probe Cooling Air Pressure to Minimize Unintended Probe Cooling Effect

PLA (power lever angle) # = throttle setting

Reduced pressure greatly reduces but does not completely eliminate probe cooling effect. Less measurement time before probe overheats.
**Temperature Determination from Luminescence Decay Curves**

**J 85 Engine Tests at Different Afterburner Settings**

**Luminescence Decay Curves**
- PLA # = throttle setting
  - 98
  - 100
  - 102
  - 104

- $\tau = 80.0 \, \mu s$
- $\tau = 20.3 \, \mu s$
- $\tau = 7.7 \, \mu s$

**Calibration**
- PLA # = throttle setting
  - PLA 90
  - PLA 96
  - PLA 98
  - PLA 100

- 830 °C
- 911 °C
- 969 °C
- 1027 °C

Fit to bi-exponential:

$$I = I_1 e^{-t/\tau_1} + I_2 e^{-t/\tau_2}; \tau_2 > \tau_1$$

Determine $T$ from $\tau$ vs. $T$ calibration

$$\tau_2 = \tau_{2E} \frac{1 + 3e^{-\Delta E/kT}}{1 + ae^{-\Delta E/kT} + be^{-(\Delta E_q + \Delta E)/kT}}$$
Temperature Determination Summary for Cr:GAP-Coated Vane During J85 Engine Test Sequences

PLA # = throttle setting

Higher temperatures not obtained due to unintended probe cooling effect.
Summary

• Successfully demonstrated temperature measurements from Cr:GAP coated Honeywell stator vane doublet in afterburner flame of UTSI J 85-GE-5 turbojet test stand.
  - Successful coating deposition onto complex stator doublet shape by EB-PVD.
  - Excellent emission intensity and temperature sensitivity from 25 µm thick surface coating.
  - Wide temperature range 549 ºC to 1027 ºC measured over range of afterburner conditions.
  - Engine-compatible probe design demonstrated
    - Integrated excitation and collection. ✓
    - Thermal protection of probe. ✓
    - Unintended cooling of measurement surface to be corrected in future. ✗

• Future Plans
  - Cr:GAP downselected as one of two thermographic phosphors for upcoming AFRL VAATE temperature measurements of high-pressure turbine stator in Honeywell TECH7000 demonstrator engine.
  - Cr:GAP downselected as one of three thermographic phosphors for upcoming NASA VIPR temperature measurements of rotating blade surfaces in Pratt & Whitney F117 engine.
  - 2D surface temperature mapping by gated imaging underway at NASA GRC.
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