The Use of Novel Dimension Reduction Optical Fiber Arrays for Hyperspectral Imaging in Flames

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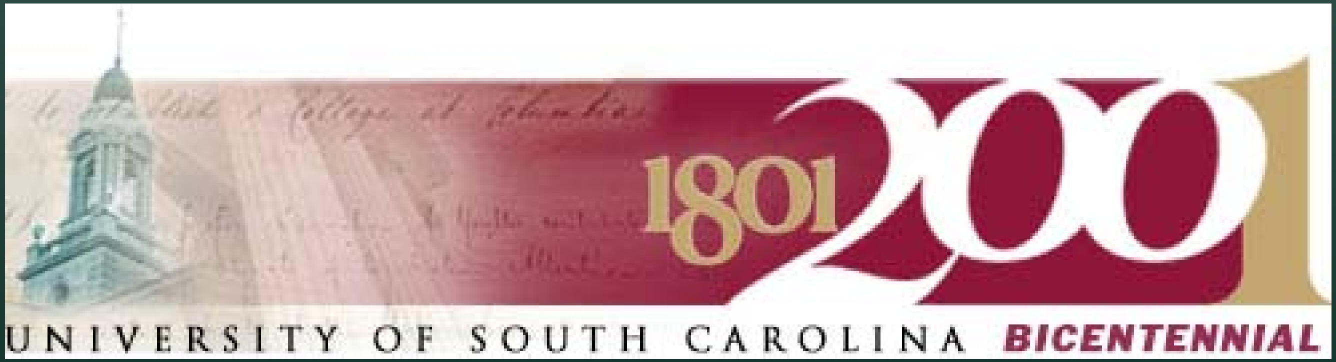


Related Research

- *in-situ* measurement techniques
  - ----LIBS
  - ----REMPI
  - ----Raman imaging
  - ----fluorescence imaging

- applications related to flame characterization

  → introduction of polymer plaques with laser ablation

  → imaging temperature distributions in flame

  → "mapping" chemical (radical) species in flames

Develop Applications That are Generally Applicable to Combustion Measurements

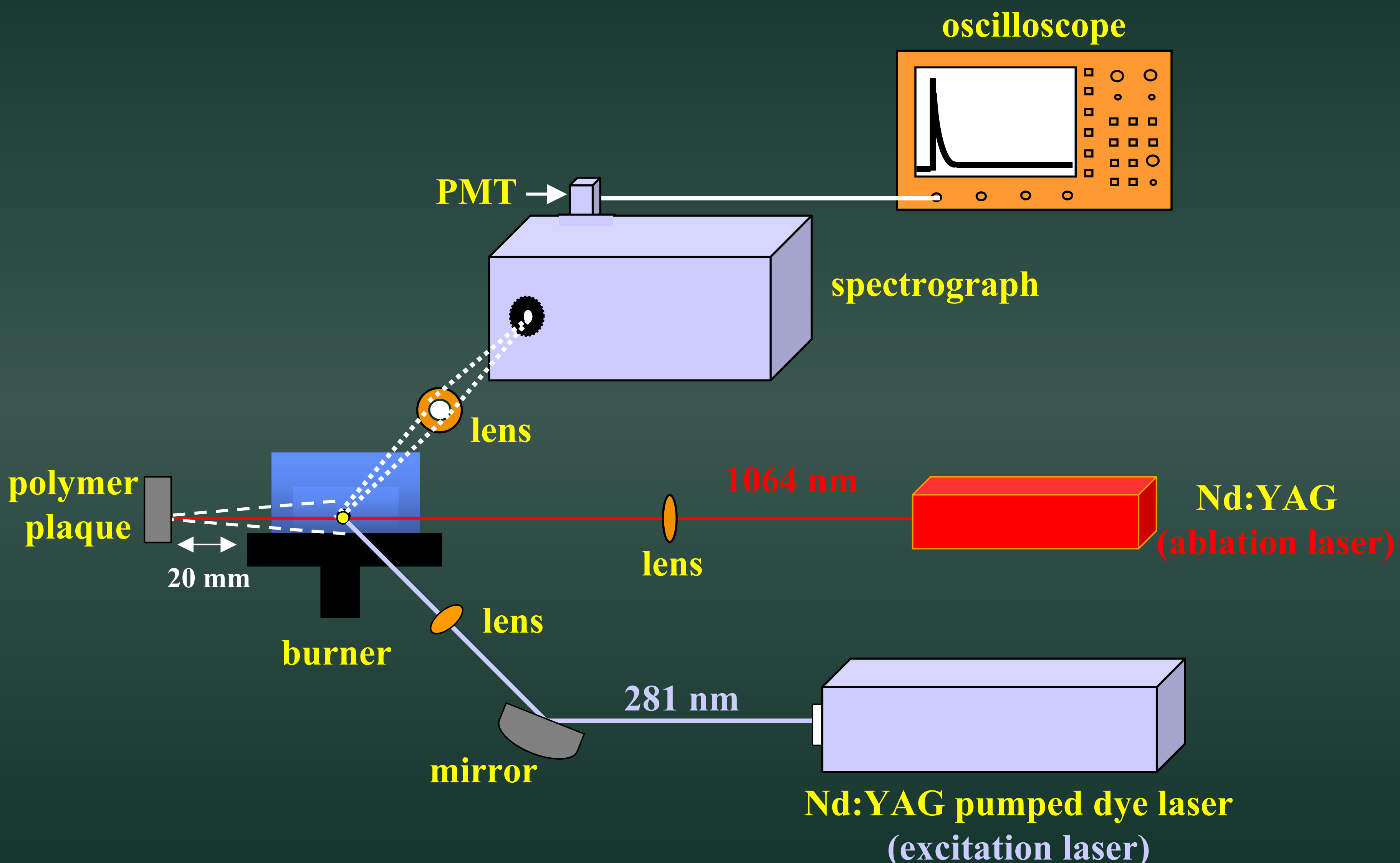
application of these techniques to measure distribution of species and temperature in flame environments

Introduction of Insoluble Polymer Plaques in Flame

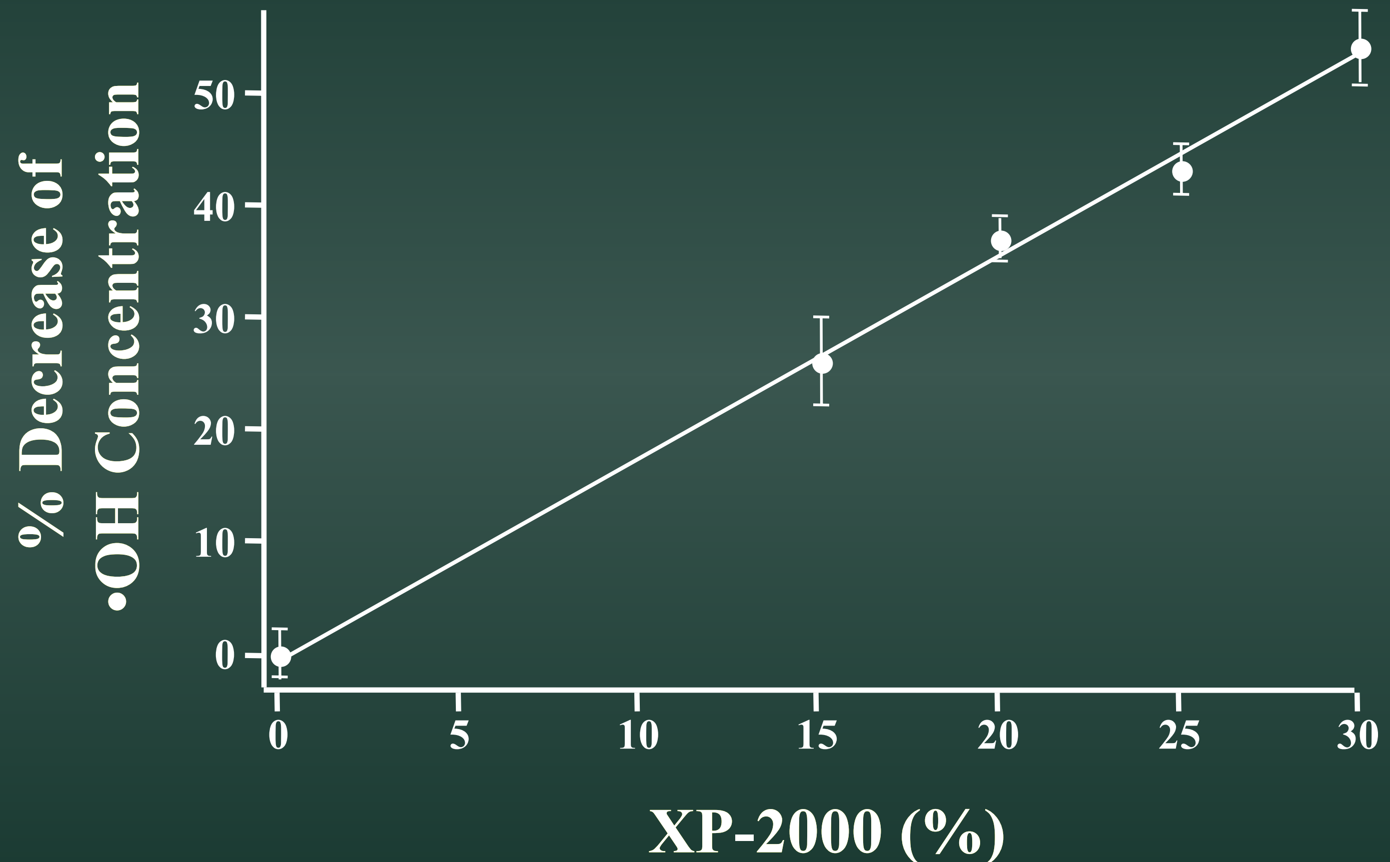
- flame retardants need to be introduced into the flame environment
- difficult for insoluble polymers
- soluble materials can be aspirated in the flame
- many commonly used flame retardants do not appreciably dissolve in most solvents
- use of laser ablation on polymer plaques for sample introduction into the flame

-----very simple
-----only requires pulsed laser

Diagram of the Laser Ablation Set-up



Laser ablation was used to introduce polymer plaques containing XP-2000 Flame Retardant into a methane flame to measure the FR's effect on •OH concentrations in the Flame



Other Results on •OH Concentration

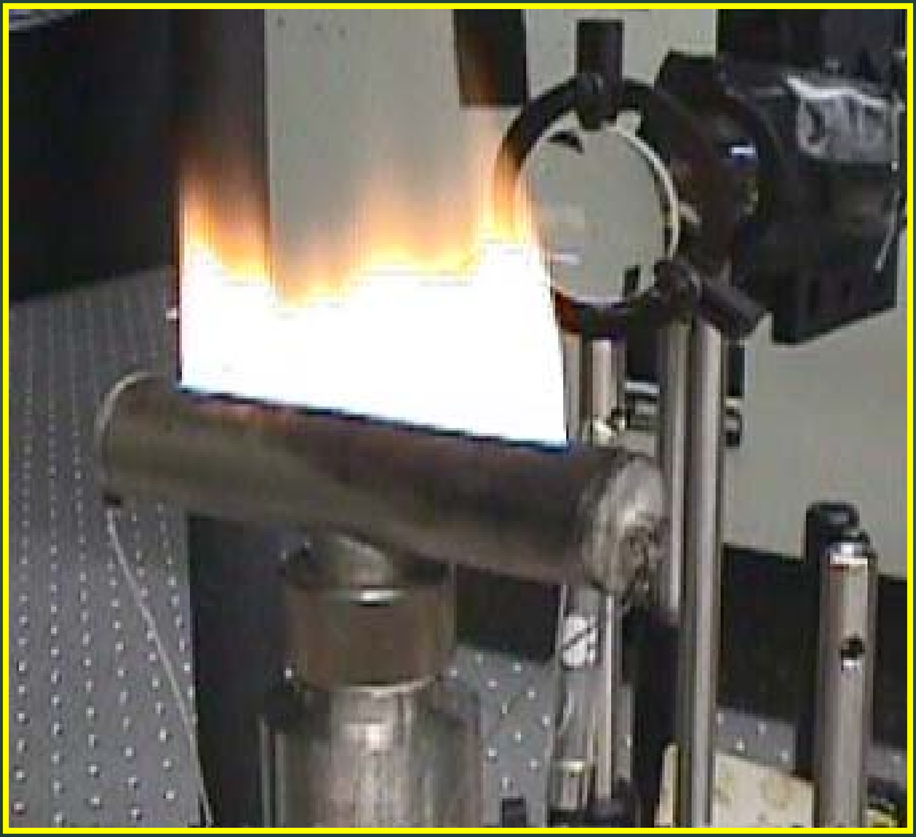
Sample	Decrease of •OH Concentration(%)
12% XP-2000, 88%PC-ABS	18.0 ± 6.6
30% XP-2000, 70% HIPS	12.8 ± 3.2
30% $Et_4P^+Br^-$, 70% ABS	28.7 ± 2.1
30% XP-1000, 70% ABS	29.1 ± 3.4

Recently, we have investigated the use of novel fiber-optic arrays for imaging Chemical Species and Temperature during Combustion Experiments

Purpose

- to test a new technique to measure the spatial distribution of temperature in a flame
- to investigate the ability of flame retardant chemicals to inhibit combustion using this technique

Imaging Sections of a Flame for Temperature Distribution



Introduction to Fiber-Optic Imaging

- imaging using a CCD or ICCD detector provides spatial information

  → single λ technique

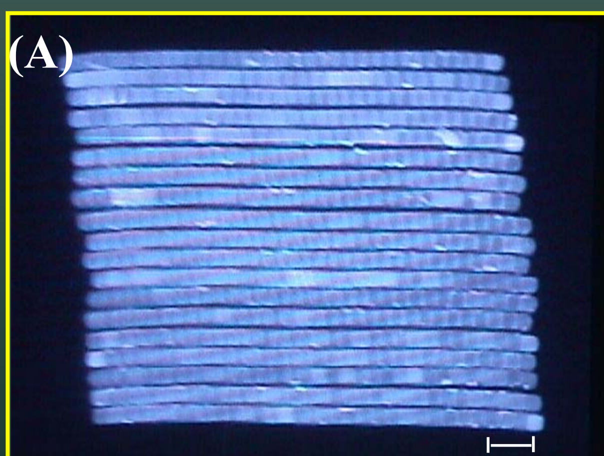
- the use of fiber optic array for simultaneously measuring emission spectra of multiple objects within an image was reported in 1986

  → commonly used for astronomical spectral imaging

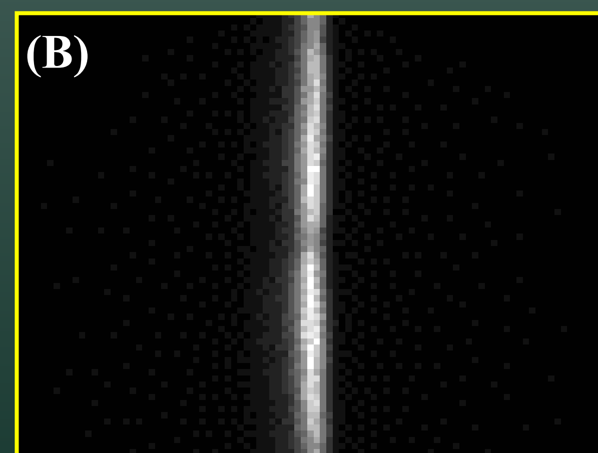
This has been extended for analytical spectral measurements

→ called **dimension reduction**

Full Proximal End Image (A) and Cropped Distal End Image (B) of the Dimension Reduction Fiber Array



Scale = 100 µm



ICCD chip (384 x 576 pixels)

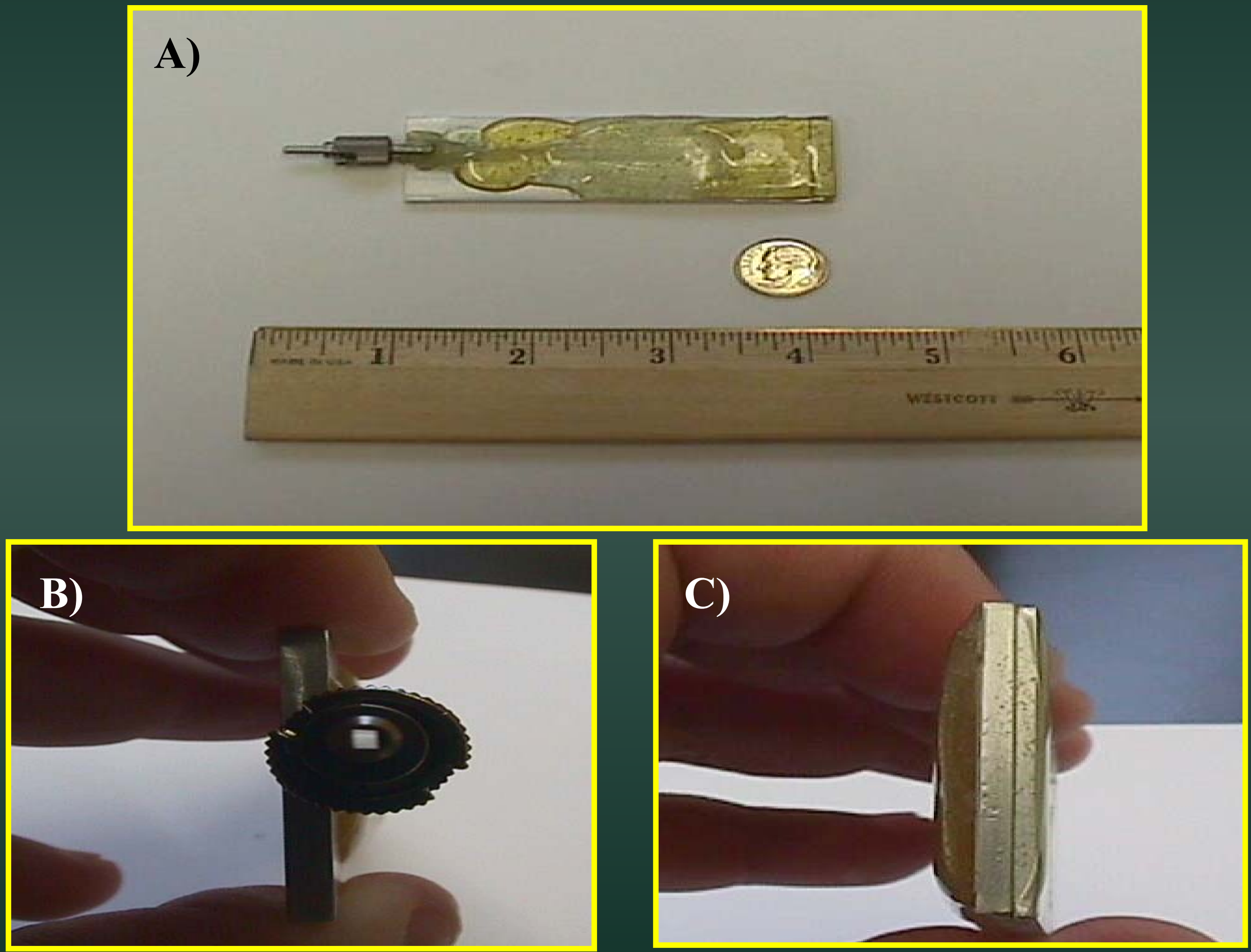
Concept of Multi-Wavelength Single Frame Imaging

- Sample image projected onto proximal 2-D matrix of optical fibers
- Image waveguided to distal 1-D end
- 1-D end imaged with spectrograph
- Spatial, spectral, and temporal information acquired in a single-frame
- Computer program extracts encoded image

Analytical Applications of the 2-D to 1-D Dimension Reduction Fiber Array

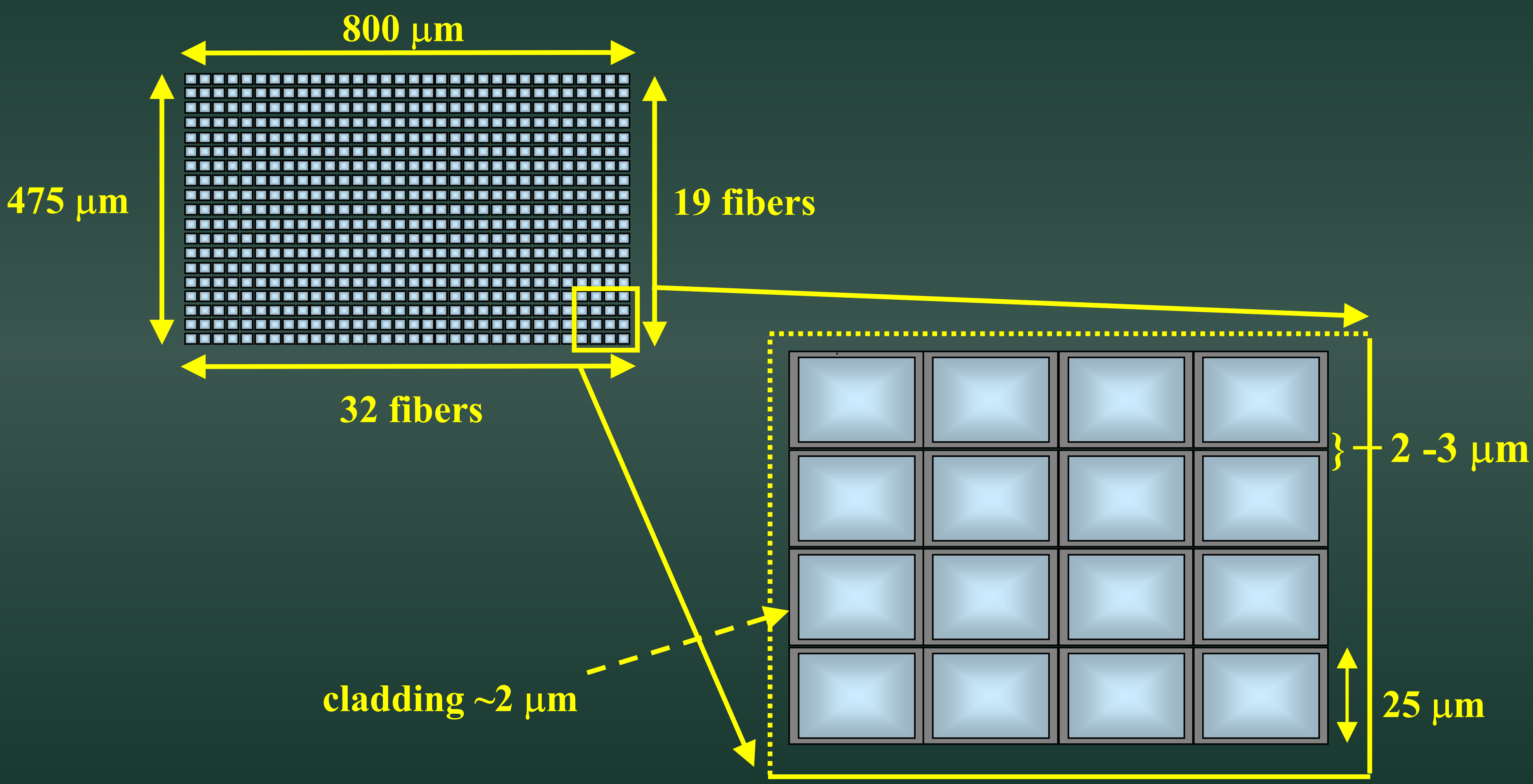
- imaging plasmas generated by laser-induced breakdown spectroscopy (LIBS) on a lead sample
- Raman imaging
- chemical imaging and detection of CO_2/O_2
- imaging of lifetime based sensors

Complete Dimension Reduction Optical Fiber Array Next to a U.S. Quarter for Scale

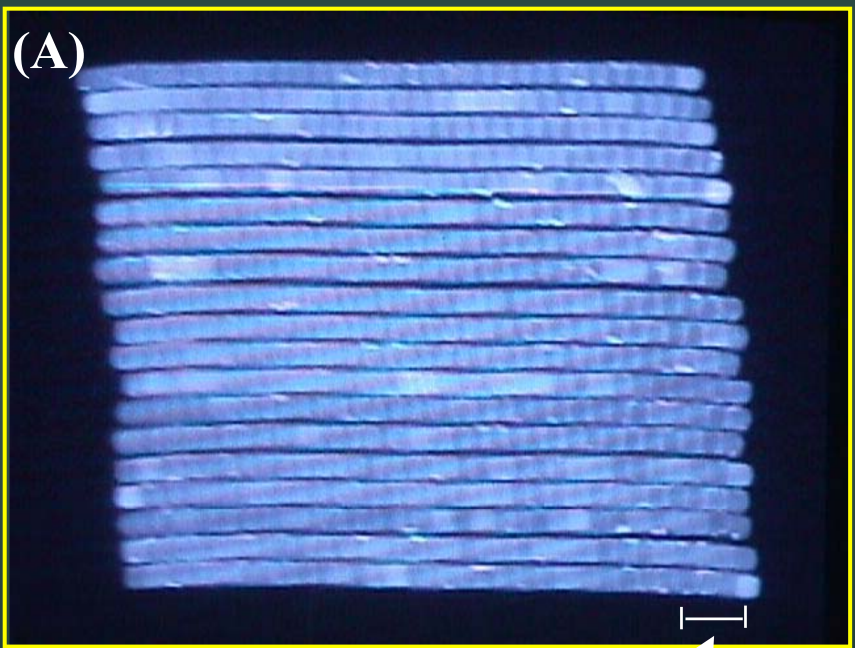


Nelson, M. P. and Myrick, M. L., *Rev. Sci. Instrum.,* 70(6), 2836-2844, **1999.**

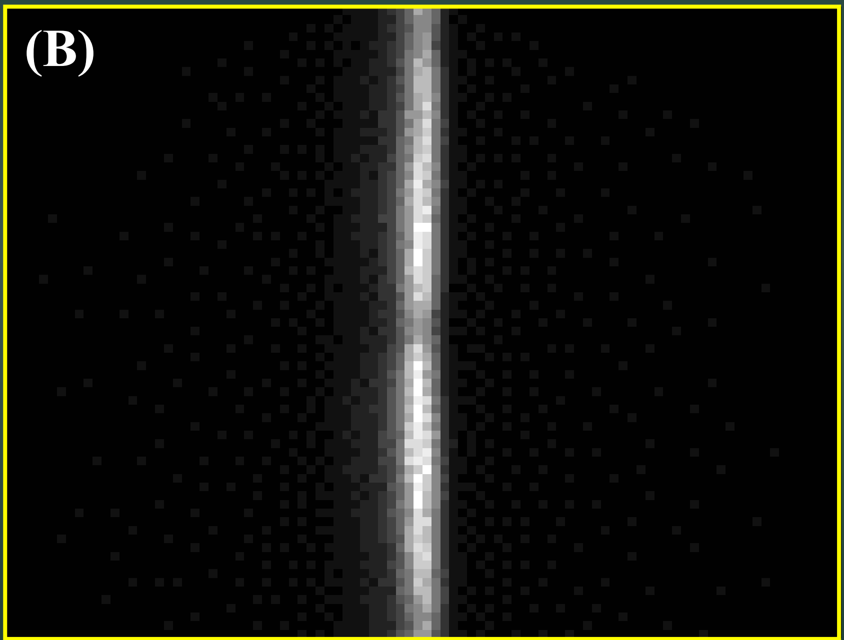
Details of Square-Fiber 2D to 1D Array
(608 total fibers)



Full Proximal End Image (A) and Cropped Distal End Image (B) of the Dimension Reduction Fiber Array

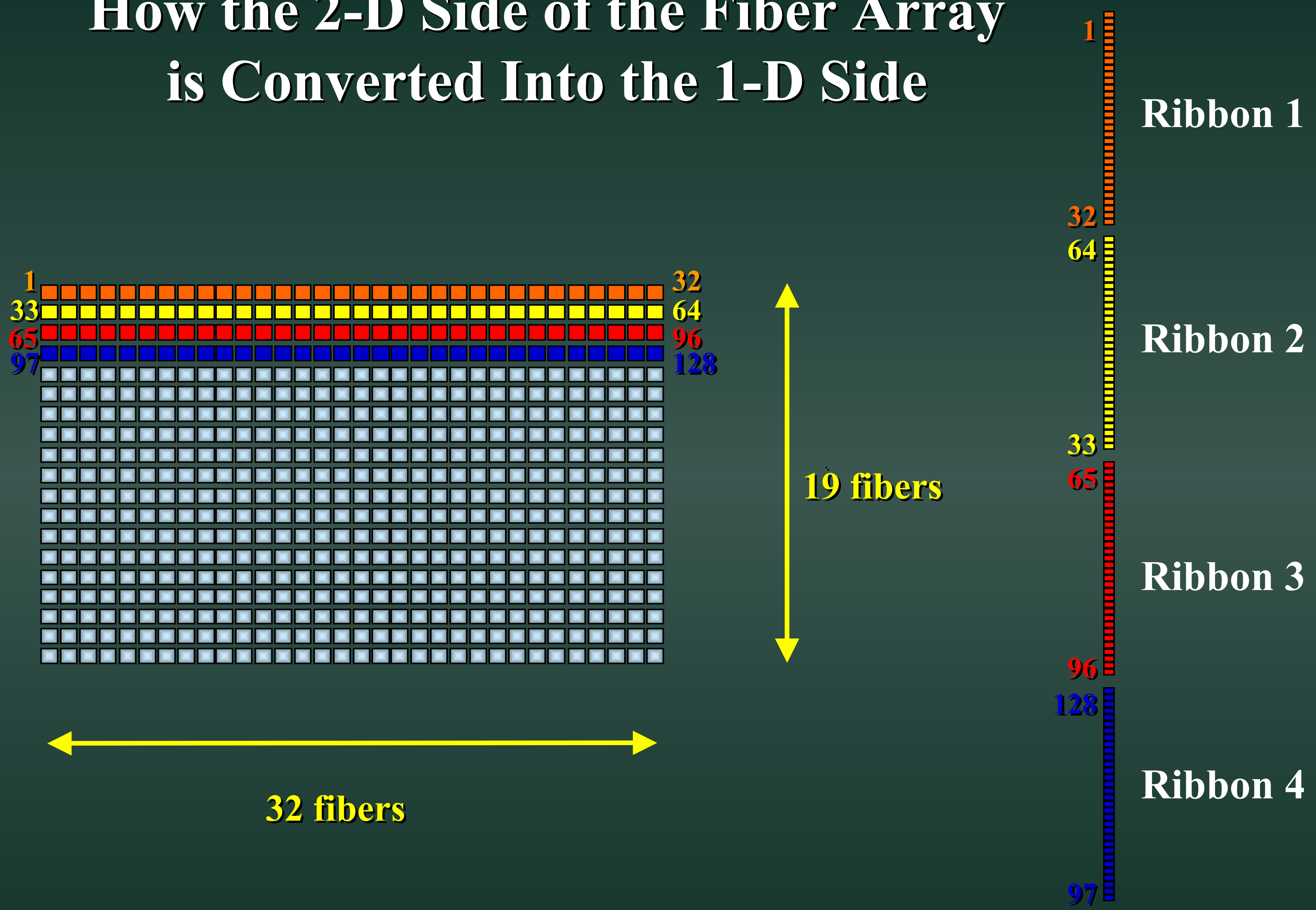


Scale = 100 μm



ICCD chip (384 x 576 pixels)

How the 2-D Side of the Fiber Array is Converted Into the 1-D Side



and so on ....

Dimension Reduction

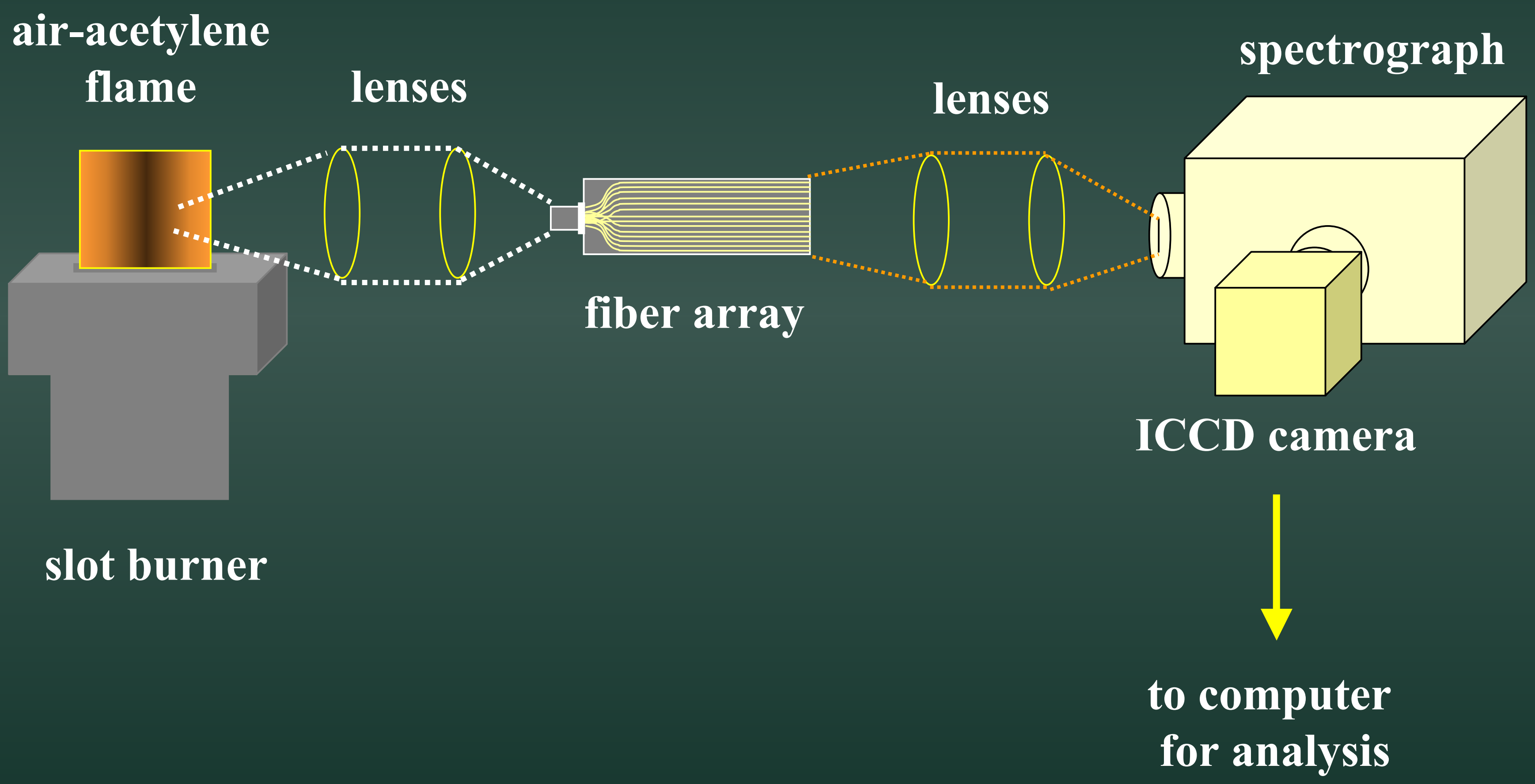
Advantages

- high spectral resolution
- simultaneous imaging at many different λ's
- direct measurement of the development of the chemical concentration gradients, *in-situ*

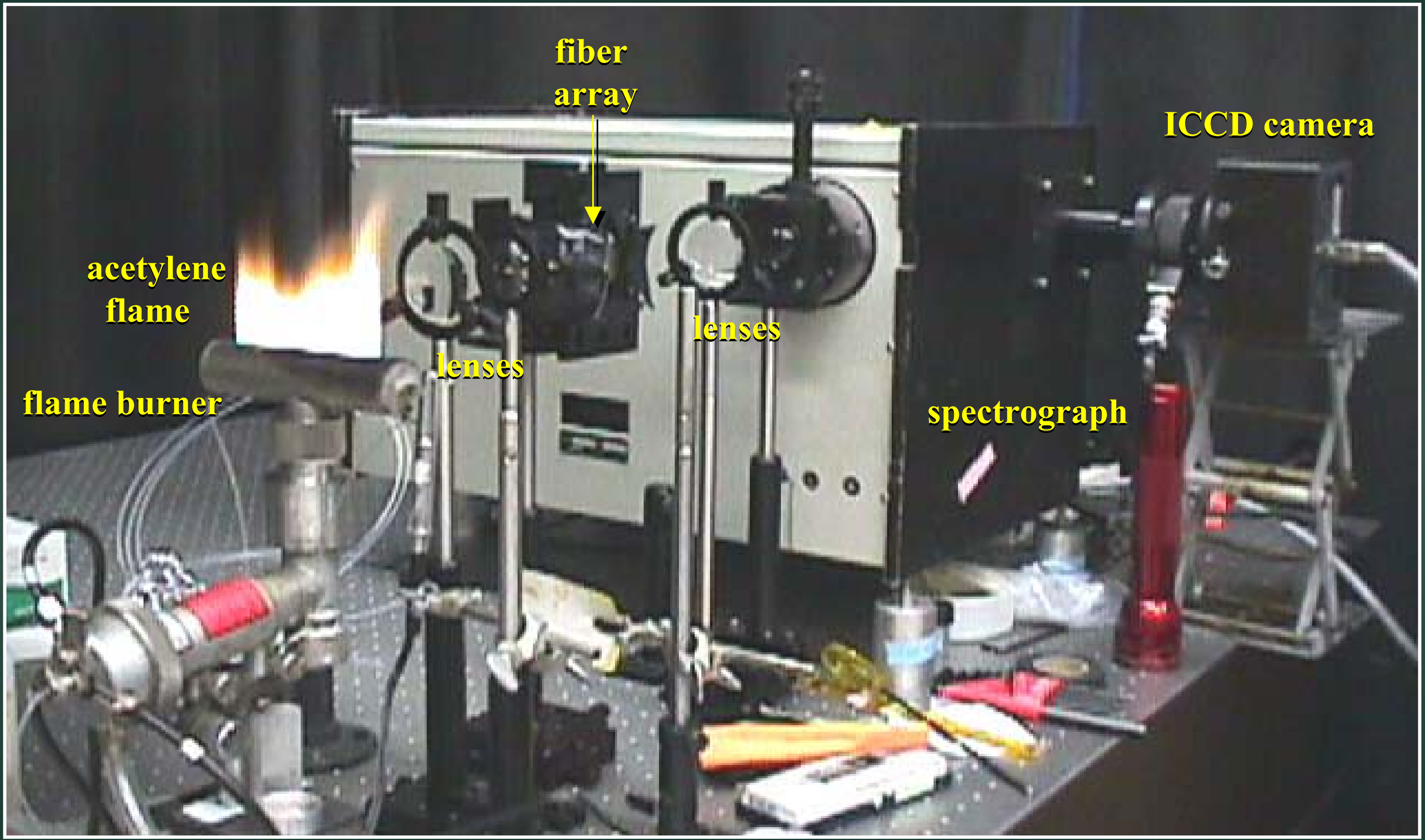
Disadvantages

- increased complexity of system
- some loss of spatial resolution determined by the number of vertical pixel of the detector

Experimental Set-up



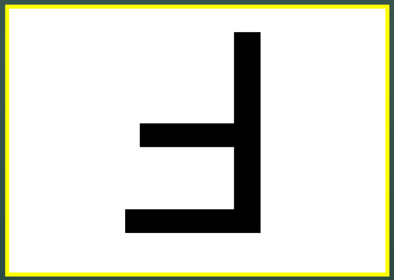
Flame Set-up with the Fiber Array

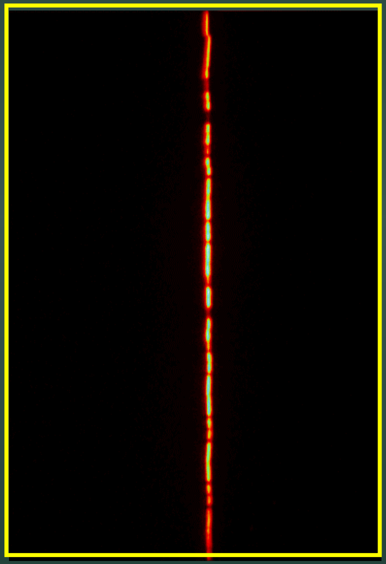


Reconstructed Image of the Letter "F"

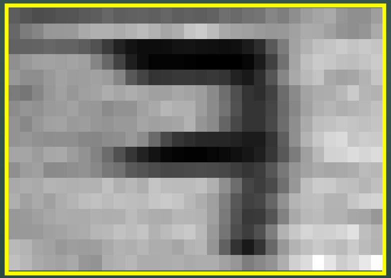
Zero order of letter image
through the array

Image of letter



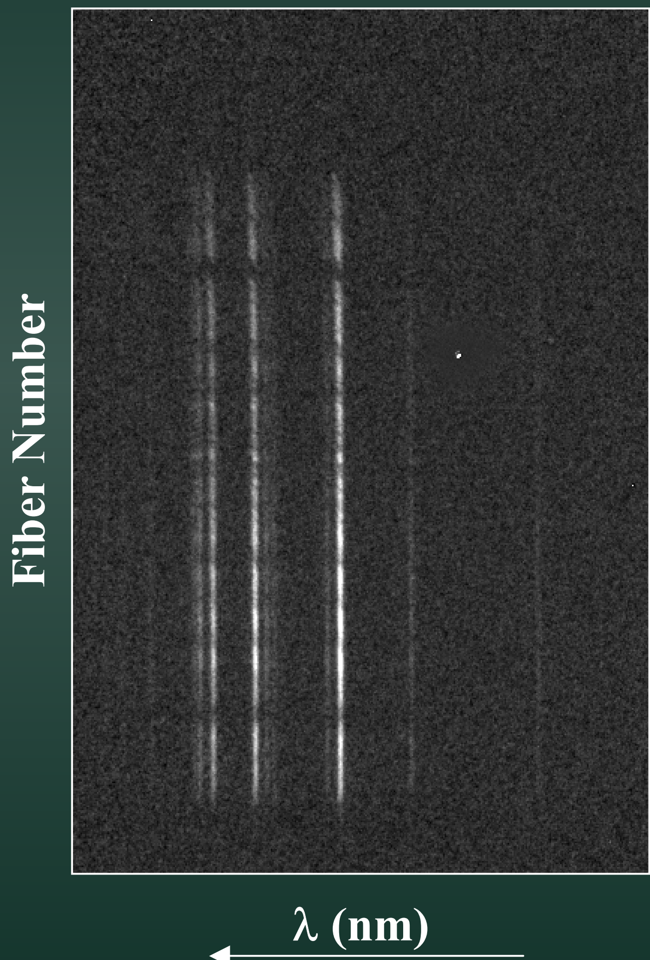


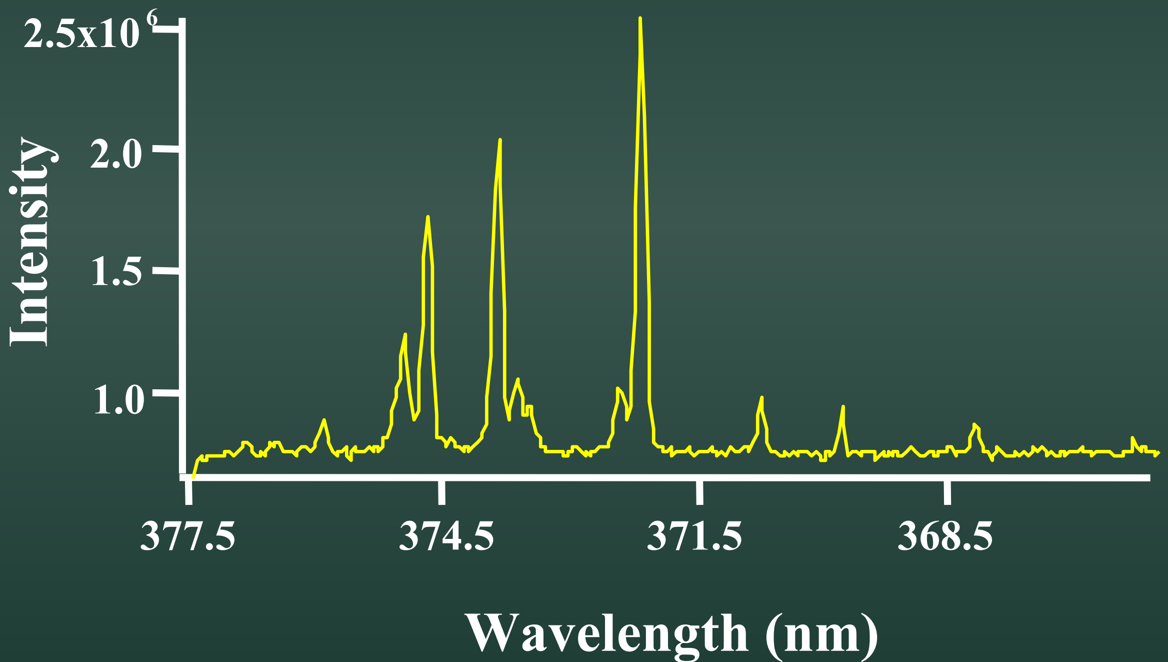
Reconstructed letter



ICCD Chip 384 x 576 pixels

Typical Spectral Image from ICCD Camera with Corresponding Fe Spectrum





Calculating Temperature using Emission Lines

- five images of Fe emission were taken for each sample type
- temperature was calculated by performing a Boltzmann Plot using the equation:

$$\ln(I_{kj}\lambda_{kj}/g_k A_{kj}) = -E_k/k_b T + \ln(N(T)/u(T))$$

- temperature was determined three different ways:
  ---using spectra integrated over entire image
  ---using spectra integrated from each of the ribbons on the 1-D side
  ---reconstructing 2-D images at each wavelength

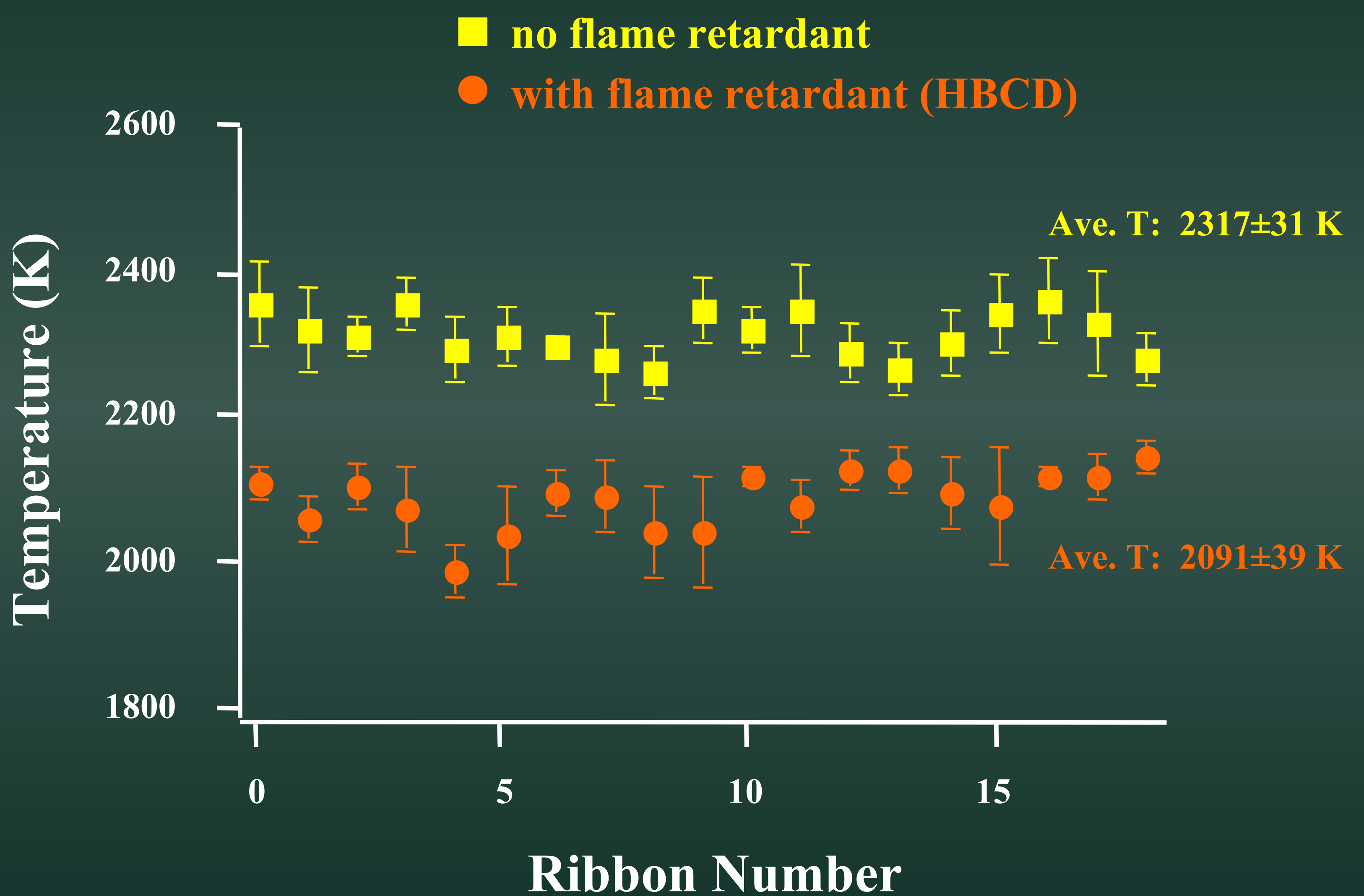
Temperature Calculated after Binning the Entire Image

with flame retardant (HBCD)		without flame retardant	
Trial 1	2087 K	Trial 1	2334 K
Trial 2	2099 K	Trial 2	2306 K
Trial 3	2102 K	Trial 3	2346 K
Trial 4	2099 K	Trial 4	2279 K
Trial 5	2016 K	Trial 5	2299 K

Average: 2081 ± 37 K
%RSD: 1.8

Average: 2299 ± 47 K
%RSD: 2.0

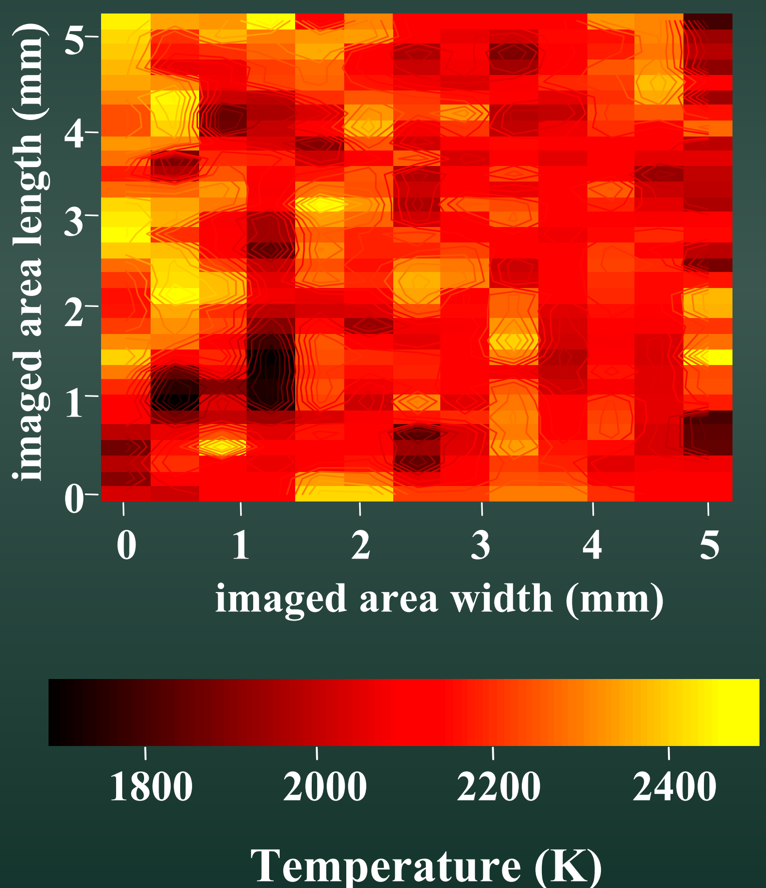
Comparison of Temperatures Calculated After Binning Each Fiber Ribbon Individually on the 1-D Side of the Fiber Array



2-D Temperature Maps of the Acetylene Flame

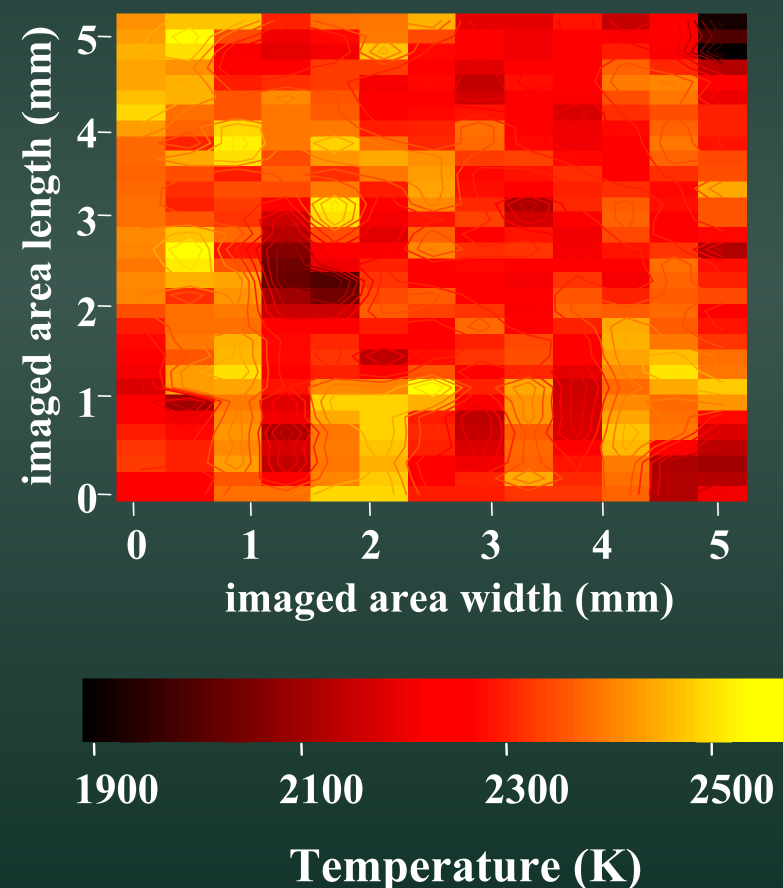
With Flame Retardant (HBCD)

Average Temperature: 2148±149 K



Without Flame Retardant (no HBCD)

Average Temperature: 2315±107 K



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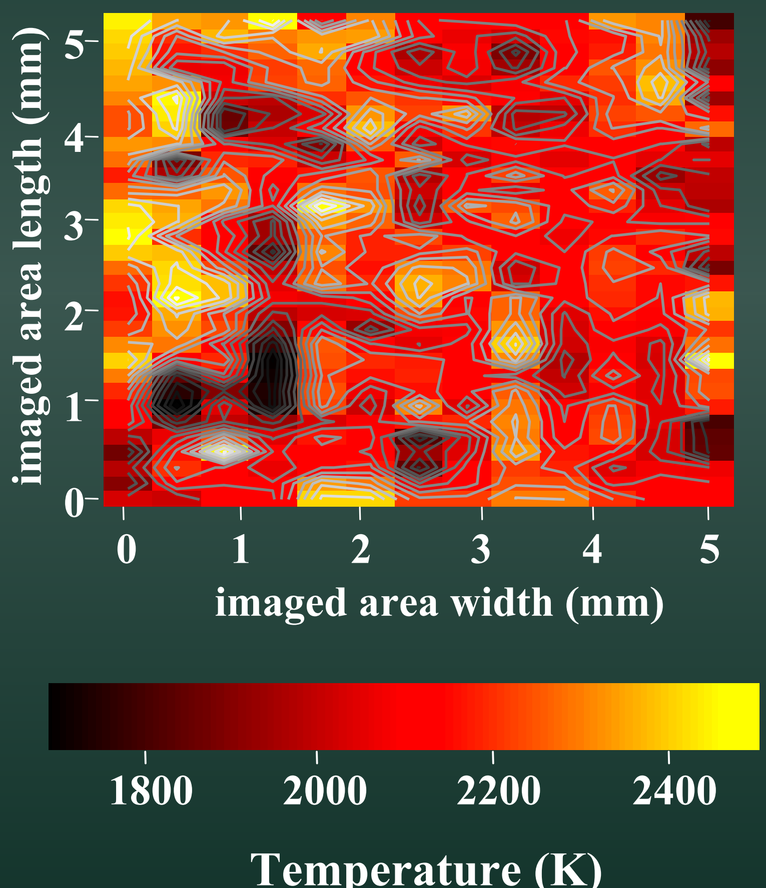

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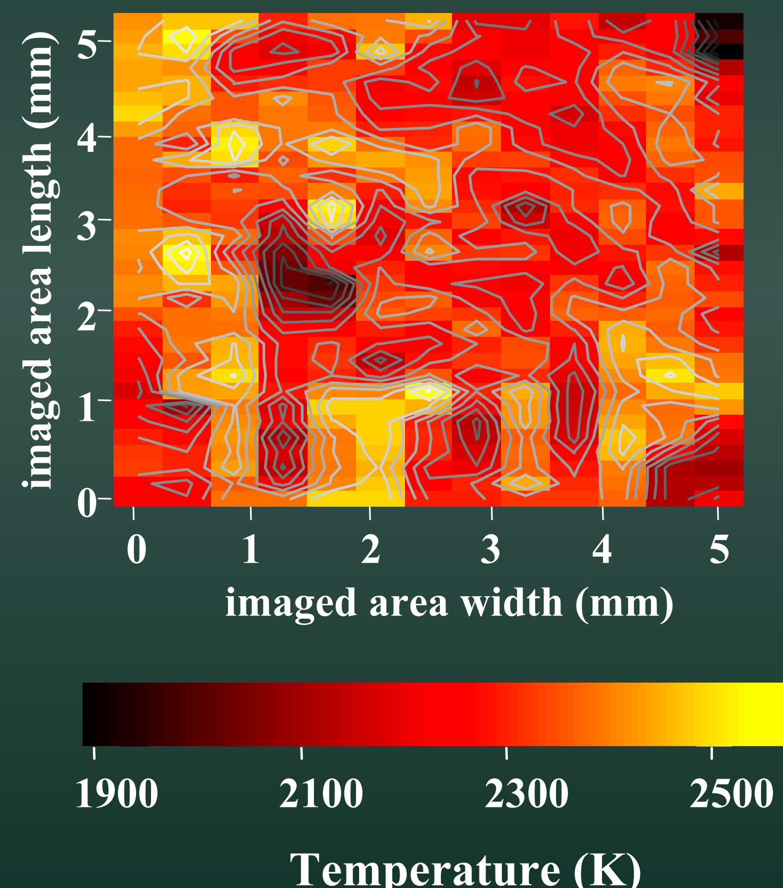
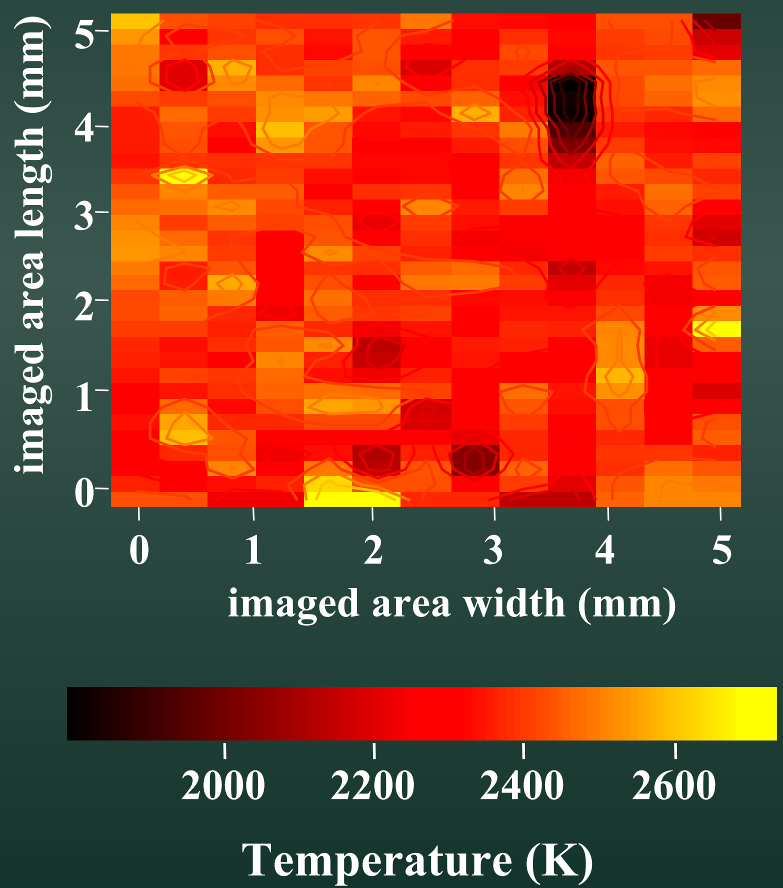


2-D Temperature Maps of the Acetylene Flame

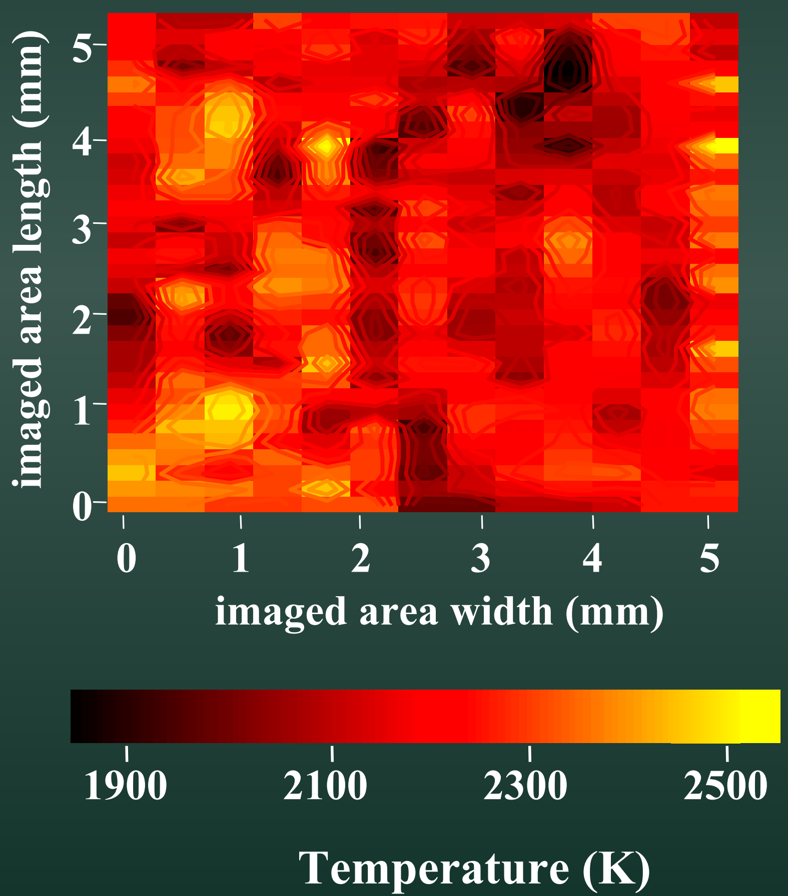
Fuel-Rich Flame

Average Temperature: 2284±30 K



Lean Flame

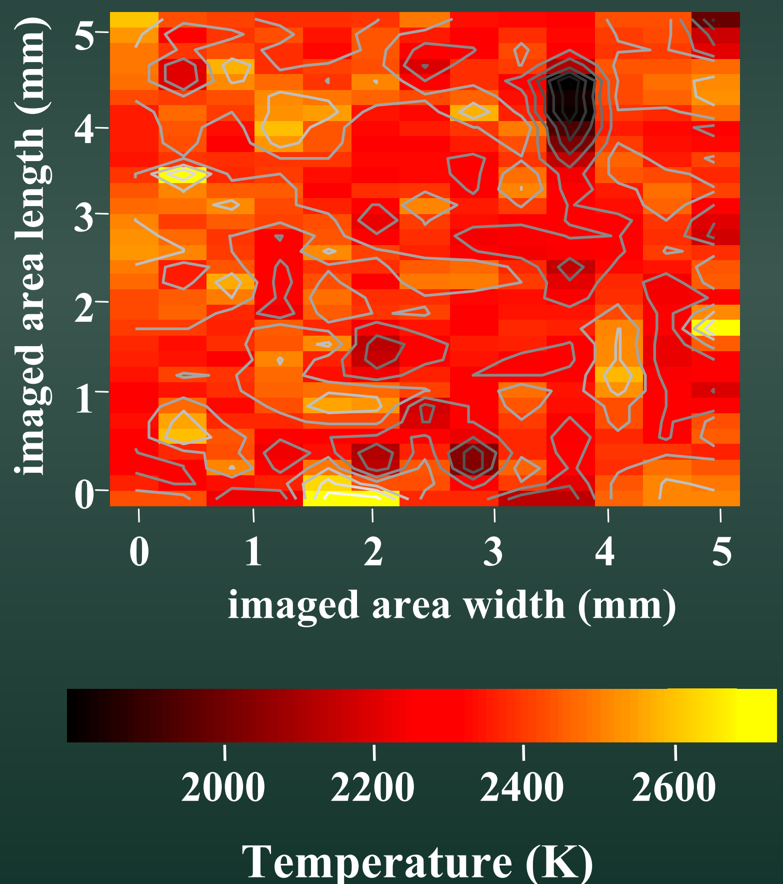
Average Temperature: 2035±26 K



2-D Temperature Maps of the Acetylene Flame

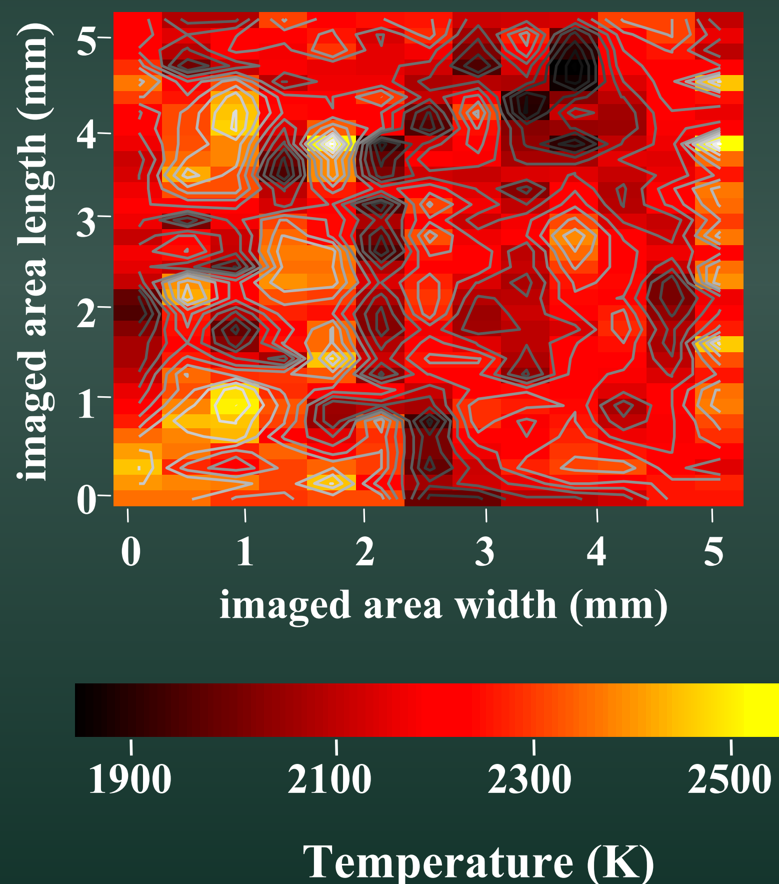
Fuel-Rich Flame

Average Temperature: 2369±30 K



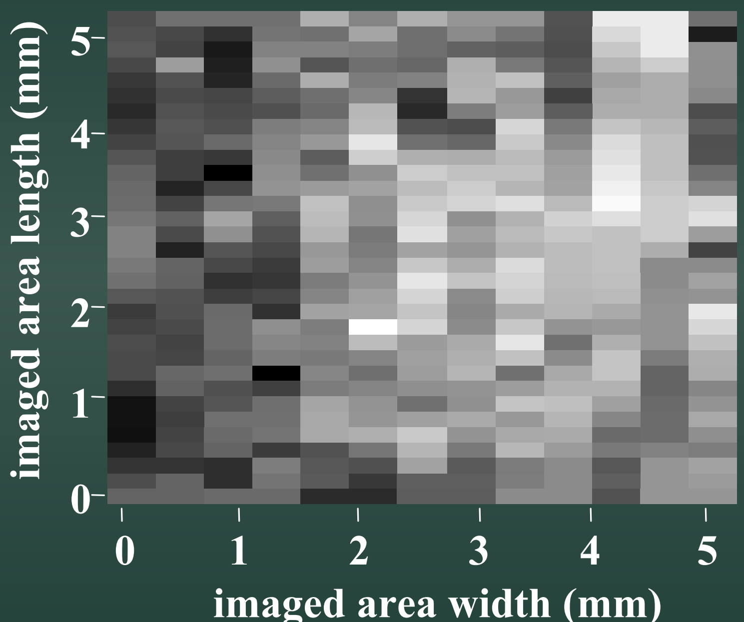
Lean Flame

Average Temperature: 2203±26 K

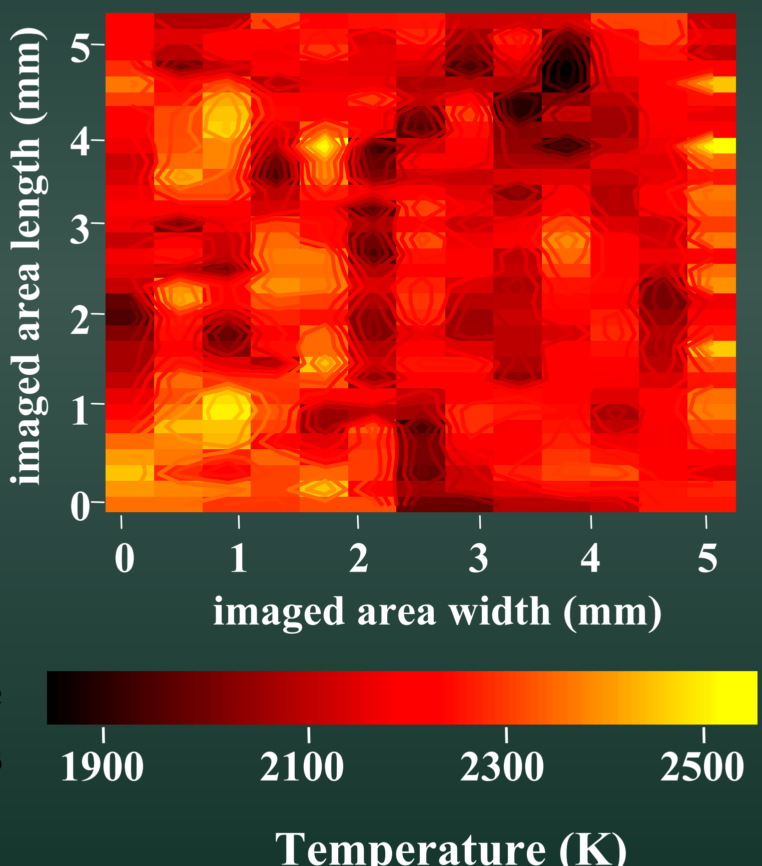


Comparison of the Wavelength Reconstruction to the Temperature Map

Single λ Reconstruction (374.83 nm)



2-D Temp Map of the Flame



Spectral imaging of many λ's can provide more insight and accurate measurements than imaging one λ

Conclusions

- showed that laser ablation is useful for introduction of polymer plaques into a flame
- showed the ability to make temperature "maps" of a flame, simultaneously measuring all points in the imaged area of the flame
- The fiber-array is generally applicable to any spectral imaging technique

Future Work

- determine temperatures of other flame environments

- extend this to measure the lifetimes and concentrations of •OH, •CH and/or other radical species present in flame environments

Acknowledgments

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Dr. M.L. Myrick