Near Field Multi Mode Spectrometers
Further Application of the photonic crystal advanced filtering spectrometer

Adam Saltzman
Biomedical Imaging
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Introduction

A multi mode spectrometer is a spectrometer that can accept and analyze many modes simultaneously. This allows for an average spectrum of large area incoming sources. A traditional spectrometer’s resolution is strictly limited by the size of the input aperture. Because of this input aperture limitation, a multi mode spectrometer can give you a massive increase in your incoming signal strength. Although the idea has been around for decades our new designs provide a graceful solution while still maintaining high efficiency.

The earliest design for multi mode spectrometers used a liner array of filters in front of a detector. This design although very simple is also very inefficient and riddled with problems. If light is only incident on one section of the detector a false reading will be given implying there is no spectral components which would have been detected by the other areas. On top of this each section of the filter blocks the majority of the light. If for example you had a RBG filter, 33% of incoming light gets accepted by 33% of the detector. If your signal is very small in frequency components you will simply throw away most of your signal.

Our designs involve imperfect photonic crystals as a filtering mechanism. These photonic crystals are composed of silica spheres on the order of the wavelength you would like to detect. By a unique fabrication method these photonic crystals have pass bands and stop bands across a large wavelength range. These crystals also have a non uniform structure which allows for a complex spatial spectral pattern on the output of the light. By using these crystals you can allow for a large multi mode input without rejecting light.

In this research I have extended previous work on this concept by implementing a concise near field design. This design bypasses the need for focusing elements as well as tightly coupling the photonic crystal to the detector. These improvements take an interesting idea one step closer to a compact prototype that can be used to read spectral data of real samples in real testing environments.
Non-Uniform Photonic Crystals:

Photonic Crystals are ordered structure of different index sub wavelength particles. These structures traditionally formed by either lithographic or slow settling processes. Lithographic techniques have failed to create three dimensional structures, where settling processes are prohibitively slow and non precise.

Most people are looking for perfect photonic crystals, ordered structures with tight pass and stop bands. Because of the nature of our project we look for the most disarrayed photonic structure possible. (Of course a complete lack of structure, an amorphous crystal, will have no interesting properties.) Ideally we would like to create predictable disorder within a structure; this has so far proved unachievable. As a result we have settled on a unique gravity settling process.

The settling process that has proved most successful involves a traditional gravity settling of silica micro spheres and a nontraditional evaporation process. Traditionally this slow settling process is culminated by an equally slow evaporation process. This evaporation process is very gentle leaving the photonic structure undisturbed. For our photonic crystals the evaporation process is replaced by a non critical vaporization process in which the water is vaporized without boiling. As you would expect this process is stressful forcing domains to crash down and create a unique structure. The final step is this sample is backfilled with a near index matching polymer to optimize spectral diversity and provide stability.

Light incident on this photonic crystal takes a complex path resulting with multiple splits reflections and transmissions of separate wavelengths. Each position in transmission has a pattern formed from multiple wavelengths and multiple positions of incidence. There is little rejection of light just a complex redirection. Of course the thicker the crystal the more redirections it will also have more absorption and reduce your throughput.
**Camera**

The elect rim camera was chosen for its adaptability and price. With this camera I was able to acquire multiple TI TC237B monochrome CCD arrays for a low cost. (See appendix A) Also the accessible nature of this camera allows for quick removal and replacement of the CCD array.

**Previous Designs:**

The previous design was fundamentally a bench top model. Motion of components resulted in a loss of the spectrometer. This poor stability makes tests of actual samples unreliable. Therefore for further development of this spectrometer a more compact and more robust design needed to be implemented. Also my hopes are that a near field spectrometer will allow for more optimal use of a photonic crystal then the past imaging modality. (See appendix B. for diagrams of previous setup)

**Methods**

**Fabrication of Device:**

The photonic crystal must be cut to such a size that allows for mounting on the CCD and within the camera housing. Cutting of photonic crystals of a moderate thickness, less then half a millimeter can be accomplished by treating the photonic crystal like a piece of glass and using score and break techniques. It is important to note that thin crystals will shatter under the pressure of your scribe and thick crystals crumble on the break step. Ideally a water or diamond saw would be used to cut these crystals to a perfect size. I used a score and break technique on a moderately thick sample after sacrificing some crystal to cutting attempts.

Note: I acquired a photonic crystal pre polished, the surface needs to be polished in order for light not to simply scatter off the surface.
Once the crystal has been prepared it is necessary to remove the face plate from the CCD and attach the photonic crystal directly on the silica face. This must be accomplished with the greatest care in order to avoid scratching the surface. The photonic crystal needs to be attached without getting adhesive on either the used center of the photonic crystal or the CCD. I chose Norland index matching adhesive. The index matching was an added protection against mistakes. The adhesive is UV cured so it is quick to solidify and relatively easy to remove if the sample needs to be reclaimed.

This construction although initially delicate is actually quite simple, compact and robust when constructed. Once the crystal is affixed and a glass window placed on the camera it is as durable as any camera. It can be shuffled about moved with little effort and affixed to a new computer with little concern.

**Calibration:**

For calibration a monochromatic light source needs to be coupled into the camera. For this light source I used a Jarell Ash monospec 18 (See Appendix C.) with a oriel light source coupled into it. The coupling was done with a condenser lens setup and although it is close the f# does not match exactly and coupling could be better. From this monochromatic I output into a tube assembly containing a short focal length lens that images on a diffuser and then passes through an aperture. This assembly is connected to the electrom camera threw the use of another tube assembly. Doing everything inside tube assembly makes the calibration process isolated from room conditions. (See Diagram 1)

Once the assembly for calibration is built labview code was written to interface the camera and the monochromator together. The labview code advances the monochromator a set step and takes a picture at every location. The drivers to take the picture were purchased with the camera but the code to run the monochromator and the interface between them was in house. (See Adendix D.)

Once the apparatus for calibration has been built and the code to run it written a background needs to be taken. The intensity of light exiting the monochromator due to a the blackbody curve as well as the efficiency of the grating is not constant. On top of this the response of the CCD across a hundred nanometer range is not constant. The only
difficulty with this process is the poor dynamic range of the electrim camera. Because of this fact the exposure time should be different for each wavelength and recorded so those times can be used to normalize the data. It is unclear if I have taken the correct approach to removing this background and acquiring proper variance some more thought needs to be put into this in order to make sure the response is calculated from a flat intensity profile.

After the background is taken it is a simple process to take the pictures using the same exposure times selected for the background measurements at each wavelength. Multiple exposures and an averaging process will result in the best data. This data is consequently loaded into matlab and a spectral variance calculated in order to asses the quality of the data. (See Appendix E)

The method of liner least squares inversion is used to calculate the transfer function of this photonic crystal. (See Appendix F) This is the result of the simple matrix concept that

\[ \text{input} \times \text{transfer} = \text{output} \]

\[ \therefore \text{transfer} = \text{output} \times \text{input}^{-1} \]

It should be noted that to know exactly the output of the monochromator at each output the spectrum of our monochromator is taken using the ocean optics usb2000. (See Appendix G) This spectrum is used in our inversion process as the wavelength of the input.

**Inversion:**

Once the transfer function is known any unknown source can be calculated from its output threw the photonic crystal. I took pictures of a neon sample in order to try and reconstruct the source. Unfortunately just from my spectral variance data I could see that I would be unable to do a reconstruction with any sort of accuracy. The code is provided and ready to form a reconstruction regardless (See Appendix H)
Results

As I stated previously the results achieved for this first test were not optimal. My initial data sets were not up to snuff and my background compensation leaves a great deal to be desired. The spectral variance of the data has a net zero value. Although this data is not optimal the work has given me ideas on how to make the data optimal and shown me that creation of a near field spectrometer is possible and ideal.

The devices is prototyped and all the code is created to make this spectrometer work. I have two additional CCD arrays in order to test new samples and can acquire more from the same source at a moderate cost.

Improvements

In order to compensate for the dynamic range problems it is necessary for me to subdivide my wavelength regions and use different exposure times for different wavelengths. Also perhaps playing with the optics I use for calibration will result in a more complete data and less overexposing underexposing issues. The more diffuse the source is and the further back the camera is from the slit the more uniform the light will be and the smaller the chance for saturation.

Different photonic crystals, thick photonic crystals and photonic crystals in different ranges would be useful for optimization and study of this breed of spectrometer. Thicker crystals will naturally produce a greater spectral variance and maybe push the resolution of this spectrometer into a competitive zone.

Find a replacement for liner least square inversion, the liner least squares inversion of this data is slow and possibly inaccurate. Looking into new methods of inversion, perhaps finding some constraint that allows for higher order inversion would be a drastic improvement.
Appendix A

**ELECTRIM EDC-2000 SERIES PCI BUS COMPUTER CAMERAS**

Electrim PCI bus computer cameras are compact, digitally controlled/digital output television-like image acquisition systems designed and built in the United States specifically for computer use. An Electrim camera can be an inexpensive alternative to a video camera attached to a frame-grabber board. The result is a cost effective way to put image data into a computer. The cameras operate under computer control, and have features not available from conventional cameras. For example, Electrim cameras provide software control of CCD (charge coupled device) clock signals. Custom software and hardware design is available. No additional equipment is required other than a PC and a lens (or other optics). All Electrim cameras use full-frame or frame transfer CCD detectors.

**FEATURES:**

- Up to 10 bits per pixel gray scale (1024 levels), or more with signal averaging or color images
- Data rate of 1.5-6 megapixels per second per camera head
- Multiple camera heads per interface card (optional EDC-2000N and EDC-2000E)
- Sub-array scanning with software control (EDC-2000N)
- Interfaces directly to PCI bus (interface card is included)
- All power is derived from the computer bus, no external power is required
- Software control of anti-blooming
- Fixed pixels (direct correspondence between pixels and memory data)
- Pixels have 85-100% fill factor
- High quantum efficiency (up to 75 percent) and low noise (down to 20 e⁻ r.m.s.)
- Spectral range from 0.4 microns to 1.1 microns (for monochrome cameras)

**APPLICATIONS:**

- Science
- Microscopy
- Machine Vision
- Biomedical
- Factory Automation
- Industrial Inspection
- Quality Assurance
- Pattern Recognition
- Security and Surveillance
- Inspection
- Education
- Astronomy

*Providing low cost imaging solutions for science and technology*
SPECIFICATIONS:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Image Size (Sensing area)</td>
<td>2.64×2.64 mm</td>
<td>8.00×8.00 mm</td>
<td>4.84×3.67 mm</td>
<td>4.84×3.67 mm</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>192(H)×165(V)</td>
<td>1000(H)×1000(V)</td>
<td>652(H)×494(V)</td>
<td>652(H)×494(V)</td>
</tr>
<tr>
<td>Pixel Well Size</td>
<td>13.75×16 μ</td>
<td>8.0×8.0 μ</td>
<td>7.4×7.4 μ</td>
<td>7.4×7.4 μ</td>
</tr>
<tr>
<td>Pixel Well Capacity (saturation signal)</td>
<td>100,000 e⁻</td>
<td>32,000 e⁻</td>
<td>30,000 e⁻</td>
<td>30,000 e⁻</td>
</tr>
<tr>
<td>R.M.S. Readout Noise (electrons/pixel)</td>
<td>90 e⁻</td>
<td>40 e⁻</td>
<td>20 e⁻</td>
<td>20 e⁻</td>
</tr>
<tr>
<td>Peak Quantum Efficiency</td>
<td>60% @0.73μ</td>
<td>60% @0.55μ</td>
<td>75% @0.65μ</td>
<td>N/A</td>
</tr>
<tr>
<td>Sensor Type</td>
<td>TITM TC211 monochrome</td>
<td>TITC261 monochrome</td>
<td>TITC237B monochrome</td>
<td>TITC236P color</td>
</tr>
<tr>
<td>Exposure Time (S/W controlled)</td>
<td>&lt;1 msec to &gt;5 sec</td>
<td>&lt;1 msec to &gt;5 sec</td>
<td>&lt;1 msec to &gt;5 sec</td>
<td>&lt;1 msec to &gt;5 sec</td>
</tr>
</tbody>
</table>


All of the EDC-2000 series cameras feature software control of parameters including gain, bias (offset), exposure time, and anti-blooming. Camera system power is derived from the computer PCI bus. No external power is required. All timing and video signals as well as power are carried on a single multiplexer cable which connects the camera head (or heads) to the computer. The computer controls exposure time and allows for a wide range of light levels. Multiple frame acquisition (signal averaging) can be used for lower light level (higher SNR) imaging and thus provides a dynamic range greater than 10 bits per pixel.

Multiple camera heads may be attached to a single EDC-2000 series interface card, depending on model. For the EDC-2000N or EDC-2000E, two camera heads may be used to acquire two monochrome or two color images simultaneously. Please consult with Electrim Corporation before ordering systems with multiple camera heads. Other custom configurations are possible. The EDC-2000 series camera architecture supports up to four parallel 8-bit image acquisition channels or three 10-bit image acquisition channels.

In addition, custom modifications to the EDC-2000 series cameras—and to all Electrim camera products—are available both to O.E.M. customers and to individual end users. Examples of custom solutions include: hardware pixel binning, miniature camera head design, long cables, external signal connections. Please enquire how we may meet your needs.

<table>
<thead>
<tr>
<th>Camera Model</th>
<th>Special Resolution</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDC-2000</td>
<td>192 × 165</td>
<td>$900</td>
</tr>
<tr>
<td>EDC-2000S</td>
<td>1000 × 1000</td>
<td>$1,950</td>
</tr>
<tr>
<td>EDC-2000N</td>
<td>652 × 494</td>
<td>$1,390</td>
</tr>
<tr>
<td>EDC-2000E</td>
<td>652 × 494</td>
<td>$1,490</td>
</tr>
</tbody>
</table>

All Electrim Camera Systems consist of:

- Camera Head(s)
- Interface Card
- Cable
- Software
- Owner's Manual
- 1 Year Warranty
SOFTWARE:

The software furnished with EDC-2000 series cameras provides image acquisition and display, and contains features (varying with camera model) such as anti-blooming, false color display, histogram based contrast enhancement, asynchronous triggering, flatfielding (pixel gain correction), and sub-array scanning. Not all models are supported on all platforms. Please see the above table for operating system compatibility. Consult with Electrim for most current compatibility information.

One or more operating system specific Software Development Kits (SDK’s) are provided with the cameras, depending on model. These SDK’s include DLL functions or linkable routines for setting camera parameters, and acquiring and displaying camera images. Sample programs with C source code and documentation are provided.

Support for additional operating systems, such as QNX, may be available on a custom basis.

The EDC-2000 series SDK’s are provided on a royalty-free basis. There are no “per-unit” licensing fees or other charges.

ADDITIONAL SOFTWARE PACKAGES:

**EDC-2000E Photoshop® Plug-in:**

Electrim provides an Adobe Photoshop Plug-in which acquires images under Adobe Photoshop or compatible applications. This plug-in allows users to apply any of Photoshop’s many features of image analysis, processing, printing, saving, or format conversion on the acquired images. A possibly unique feature of this plug-in is the allowance for both live and still imaging within Photoshop. The EDC-2000E Photoshop Plug-in is priced at $95.

**LabVIEW® Drivers:**

Electrim also provides software for acquiring images from an Electrim camera and displaying images in both live and still mode within a National Instruments LabVIEW environment. The LabVIEW software, including DLL and Sample C program for Windows 95/98 (EDC-2000, EDC-2000N, EDC-2000E), or for Windows NT (EDC-2000S), is priced at $195 for any one specific camera.

**Customized Software and Hardware Design:**

Electrim can often provide changes in software, linkable routines, and hardware design to meet customers’ specifications at reasonable cost. Please contact us regarding your requirements.

Updates of standard software supplied with cameras are available on request at no charge.
SYSTEM REQUIREMENTS:
Electrim EDC-2000 series cameras require a Pentium III or higher CPU and a free PCI slot. Models EDC-2000 and EDC-2000E require DOS or Windows 95/98. The model EDC-2000N requires DOS, Windows 95/98, or Linux. For the model EDC-2000S, Windows NT is required. A video display supporting true color (16 million colors) is strongly recommended, though not required.

DIMENSIONS:

<table>
<thead>
<tr>
<th>Model</th>
<th>Width</th>
<th>Height</th>
<th>Depth</th>
<th>Weight (w/o lens)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDC-2000 size/weight</td>
<td>1.95 in.</td>
<td>1.95 in.</td>
<td>1.20 in.</td>
<td>4 oz.</td>
</tr>
<tr>
<td>EDC-2000N/E/S size/weight</td>
<td>2.50 in.</td>
<td>2.29 in.</td>
<td>1.35 in.</td>
<td>7 oz.</td>
</tr>
</tbody>
</table>

Lens mount: C or CS (CCTV Standard)  
Cable length: 10 ft. supplied (longer cables can be used)

Electrim Corporation
356 Wall Street
Princeton, NJ 08540, USA
Voice: (800)683 5546 or (609)683 5546
Fax: (609)683 5882
info@electrim.com
http://electrim.com

Ordering information:
Units may be purchased directly from Electrim. New Jersey residents add 6% sales tax. Prices and specifications are subject to change without notice (04/05/2002).
Appendix B

original spectrometer design

Calibration setup for original setup
Appendix C

MonoSpec 18 Monochromator / Spectrograph

<table>
<thead>
<tr>
<th>Specifications</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal Length</td>
<td>156 mm</td>
</tr>
<tr>
<td>Aperture</td>
<td>f/3.8</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.6 nm with 1200 g/mm grating</td>
</tr>
<tr>
<td>Reciprocal Linear Disp.</td>
<td>4.5 nm/mm with 1200 g/mm grating</td>
</tr>
<tr>
<td>Stray Light</td>
<td>0.0015%</td>
</tr>
</tbody>
</table>

The MonoSpec 18 Monochromator/Spectrograph is the ultimate in high quality compact instruments. Only 6.5 x 6.5 x 5 inches, it features much greater user flexibility than any instrument on the market today. The MonoSpec 18's 90° optical configuration lends itself to easy adaptability in OEM system design.

Because its kinematic grating is easily interchanged, the MonoSpec 18 has a wavelength range that extends from 190 nm - 40μm. There are many gratings available to suit a variety of requirements for resolution and dispersion. Plus ... scattered light is at a minimum due to the Crossed Czerny-Turner optical design, which also virtually eliminates re-entry spectra.

By a simple change in the exit flange, the MonoSpec 18 is converted from a monochromator to a spectrograph. The MonoSpec 18 Model 82-479 Spectrograph is configured to provide an expanded focal plane at the exit port when the spectrograph flanges are in place. This unique feature allows the user to interface the MonoSpec 18 with a variety of multielement detectors including CCD, or photodiode systems.

Monochromators are passive optical devices that can be used to present one wavelength of light at a time. They include an optical configuration of lenses and mirrors, a separating element (commonly a diffraction grating), and an optomechanical means for selecting the wavelength of light displayed.
Appendix E (Matlab Code)

% load the crystal data from the picture files average it to create numpic
% images then normalise with the background and take the variance of the
% numpic images. This should give you a general spectral response of the
% crystal.

% it is very important to change the rootdir, numpic numavg, and the area in which it is
% using to normalise out the background of the crystal. The regions in which
% the crystal area change according to the positioning in initial measurements.

clear all

rootdir='C:\temp\electrim\'; % set directory which you working with easy to map
% network drives and redefine

Sx = 1:494; % define the size of the matrix with which were working with
Sy = 1:652;

numpic=50; % defines the total number of averaged pictures that you took
numavg=1; % defines the sample size were using to averaging

directory = [rootdir 'crystal\'];

directory = [rootdir 'background\'];

% some function needs to be used to average the change in intensity from a
% changing intensity when wavelength changes.

% background intensity compensation make sure you find the blued out
% regions in the corners, its very possible that this is the upper corner
% rather then the lower corner its important to keep track of this
% normalising with the photonic crystal region itself is quite dangerous

% this original idea for normalising is frankly rediculous the camera
% saturates one area and therefore underexposes another unless your dynamic
% range is frankly amazing you have to take a separate picture at each
% wavelength and subtract off the difference which is what i did in this case.

directory = [rootdir 'background\'];
% read raw data into a 3D matrix S
for k = 1:numpic
k;
    A = zeros(length(Sx),length(Sy));
    for i = 1:numavg
        filename = num2str(498+2*k);
        data=load([directory filename]);
        A = A + double(data(Sx,Sy));
    end
    bkg(:,:,k) = A/numavg;
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%
for k = 1:numpic
    back = mean2(S(100:200,300:450,k));
    S(:,:,k) = S(:,:,k)/back;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%
%S=S-bkg;

%becouse subtracting off the background in this fashion leads to negative
%values of my ccd output its nessesary to normalise the data taking the
%lowest value to zero and everything else positive

%S=S-min(min(min(S)));

%compute the variance from picture to picture in order to get some feel of
%spectral responce
spectralvar = zeros(length(Sx),length(Sy));
for i = 1:length(Sx)
    for j = 1:length(Sy)
        spectralvar(i,j) = var(S(i,j,:));
    end
end

eval(['save ', rootdir, 'labdata S bkg spectralvar Sx Sy rootdir numpic numavg'])
Appendix F

% load the spectral data for each picture into the computer and begin to % analyse it. This code is reinterpreted and understood by Adam Saltzman

clear all

load 'C:\temp\electrim\labdata.m'

% pick the region(s) where the spatiotemporal diversities are significant
% use pixel reads of those region(s) to estimate transfer functions H

% these points are picked out by hand from the spectral variance plots and
% are the regions of high spectral diversity. 3 is nearly a resonable
% starting point for data analysis

% first idea use a signifigantly larger area of the crystal then i first did like insted of
% this small subdivision we cut things up

Sy1=200:520;
Sx1=300:400;

Sy2=200:520;
Sx2=400:500;

Sy3=200:520;
Sx3=500:650;

channel = 200;       % # of spectral channels this is the subdivision
start = 500;        % of your wavelength range the larger channel the more precise the
finish = 600;       % division
delta = (finish-start)/channel;

% forming the training matrix T
load(fullfile('wavelength.mat'));
block = wavelength>=start & wavelength<=finish; % choose relevant spectral range, this acts as a bandpass
range = wavelength(block); % uses the bandpass filter
directory = fullfile('spec/');
clear T;

% loads and concatenates the relevant spectral data, the spec files that go along with the pictures
for k = 1:numpic
    filename = sprintf('refspec%d.oos', (498 + 2*k));
    load(fullfile(directory, filename));
    baseline = mean(specdata(wavelength>=700 & wavelength<=900));
    specdata = specdata(block);
    specdata = specdata-baseline; % eliminate baseline
    specdata = specdata/sum(specdata); % normalize to unit area
    for i = 1:channel
        T(i,k) = mean(specdata(range>=start+(i-1)*delta & range<=start+i*delta));
    end
end
T = T.*(T>=0); % set negative to zero

%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Estimate transfer function H
%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear M; clear H;
for i = 1:numpic
    M(:,i) = [reshape(S(Sx1,Sy1,i),[],1);reshape(S(Sx2,Sy2,i),[],1);reshape(S(Sx3,Sy3,i),[],1)];
    % redefines the matrixes as vectors so they can be worked with
end
H = M/T;

eval(['save ', fullfile('H H T Sx1 Sy1 Sx2 Sy2 Sx3 Sy3 channel start finish delta block range')])
Appendix G

USB2000 Fiber Optic Spectrometer

The USB2000 Miniature Fiber Optic Spectrometer, starting at just $2,199, is a small-footprint (about the size of a deck of cards), plug-and-play version of Ocean Optics' revolutionary S2000 Miniature Fiber Optic Spectrometer. The S2000, however, must communicate with a PC via an external A/D converter, which can be problematic if a PC is connected to several devices. In an effort to fill a need among our users -- hassle-free instrument-to-PC interfacing -- we created a plug-and-play spectrometer.

Detector Specifications

| Detector:  | 2048-element linear silicon CCD array |
| Effective range: | 200-1100 nm |
| Dynamic range: | $2 \times 10^8$ |
| Sensitivity (estimate): | 8.6 photons/count; also, $2.9 \times 10^{-17}$ joule/count; $2.9 \times 10^{-17}$ watts/count (for 1-second integration) |
| Signal-to-noise: | 250:1 (at full signal) |
| Dark noise: | 2:5-4.0 (RMS) |

Optics Specifications

| Gratings: | Multiple grating choices, optimized for UV, VIS or Shortwave NIR |
| Slits: | 5, 10, 25, 50, 100, 200 μm widths (slit height is 1000 μm); no slit option also available (optical fiber is entrance aperture) |
| Focal length: | 42 mm (input); 68 mm (output) |
| Order-sorting: | Single-piece, multi-bandpass detector coatings for applications from ~ 200-850 nm (available only with 600-line gratings) or 350-1000 nm (Grating #2, #3 or #4 only); Schott glass longpass filters (installed or loose) also available |
| Resolution: | ~ 0.3 nm-10.0 nm FWHM (depends on groove density of grating and diameter of fiber or width of slit) |
| Stray light: | < 0.05% at 600 nm; < 0.10% at 435 nm; <0.10% at 250 nm |
| Fiber optic connector: | SMA 905 to single-strand optical fiber (0.22 NA) |
Appendix H

% modified by adam saltzman 7/25/03
% spectral inversion using nonnegative least squares optimization
% using gas lamp as an unknown source (neon source)
% use the spectra from the spectrometer to form the training matrix T,
% to have a better approximation to reality.

clear all; load 'c:\temp\electrim\labdata.mat'; load 'c:\temp\electrim\H.mat'; %load the files created by spec4 and wave.
result = [];
spectrum = [];

sourceNo =1
linOptimize = 0;            % '0' using nonnegative least squares optimization, '1' using linear least squares

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Quantum efficiency compensation
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
lambda = start+delta/2:delta:finish-delta/2;
QE = -0.825/616*(lambda'-200)+0.825;   % quantum efficiency of the ccd

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% measurement data preparation
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear measurement;

%load unknown source
    CCD = zeros(length(Sy),length(Sx));
    for i = 1:numavg
        %     filename = sprintf('500%d.mat',i);
        filename =imread('neon.tif')
        load([rootdir filename]);
        CCD = CCD + double(data(Sy,Sx));
    end
    CCD = CCD/16;

%reshape the data into vectors for analysis
measurement = [reshape(CCD(Sx1,Sy1),[],1);reshape(CCD(Sx2,Sy2),[],1);reshape(CCD(Sx3,Sy3),[],1)];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Spectral inversion
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
options = optimset('TolX',[],'MaxIter',100);
edge = ones(channel,1); edge(1:2)=0; edge(channel-1:channel)=0; % eliminate edge effect
if linOptimize == 1                                             % linear inversion
    s_estimate1 = ((H\measurement).*edge)./QE;
    s_estimate1 = s_estimate1.*(s_estimate1>=0);
    s_estimate2 = ((meanCenter(H)\meanCenter(measurement)).*edge)./QE;
    s_estimate2 = s_estimate2.*(s_estimate2>=0);
elseif linOptimize == 0                                         % nonlinear optimization
    s_estimate1 = ((lsqnonneg(H,measurement,[],options)).*edge)./QE;
    s_estimate2 = ((lsqnonneg(meanCenter(H),meanCenter(measurement),[],options)).*edge)./QE;
end

result = [result s_estimate1 s_estimate2];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% plot
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%load in the x axis's to make some sort of reasonable display
load([rootdir 'wavelength.mat']);

    filename = 'src.mat';
    load([rootdir filename]);
    baseline = mean(specdata(wavelength>=700 & wavelength<=900));
    specdata = specdata(block);
    specdata = specdata-baseline;                         % eliminate baseline

spectrum = [spectrum specdata specdata];

figure;
subplot(2,1,1);
bar(lambda,s_estimate1/max(s_estimate1),1);
colormap(cool);
hold on;
h=plot(range,specdata/max(specdata),'r');
set(h,'linewidth',2); hold off;
legend('true','estimate');
xlabel('Wavelength \lambda (nm)','FontSize',14,'FontWeight','bold');
ylabel('Intensity (Arbitrary Unit)','FontSize',14, 'FontWeight','bold');

if sourceNo ~= 0
    title(['Spectral inversion (not mean-centered) -- unknown source No. ' num2str(sourceNo)]);
end
axis([500 600 0 1.1]);
grid on;

subplot(2,1,2);
bar(lambda,s_estimate2/max(s_estimate2),1);
colormap(cool);
hold on;
h=plot(range,specdata/max(specdata),'r');
set(h,'linewidth',2); hold off;
legend('true','estimate');
xlabel(['Wavelength \lambda (nm)']);
ylabel('Intensity (Arbitrary Unit)');

if sourceNo ~= 0
    title(['Spectral inversion (mean-centered) -- unknown source No. ' num2str(sourceNo)]);
end
axis([500 600 0 1.1]);
grid on;

filename = sprintf('result%d',channel);
save(filename,'result','spectrum','lambda','range');