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Imaging Fourier transform spectrometer

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Imaging Fourier Transform Spectrometer
Design, Construction, and Evaluation

Final Report

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Imaging Fourier Transform Spectrometer

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Imaging Fourier Transform Spectrometer

Eric Sztanko

Abstract

There are many applications that require spectral information from either objects or scenes. This paper will describe the design, construction, and evaluation of an imaging Fourier transform spectrometer (FTS) that will gather such spectral information. The design of the spectrometer is based on that of a Michelson interferometer. Theory, limitations, alignment, and cost will all be considered in this work.
Imaging Fourier Transform Spectrometer

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Acknowledgements

I would first off like to thank Dr. Roger Easton Jr. for helping me throughout the entire span of this project and having the patience to work with me.
I would also like to thank Dr. John Schott, Bryce Nordgren, and the Digital Imaging and Remote Sensing (DIRS) group at RIT for giving me the opportunity to work on this project.

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Introduction

The ability to obtain spectral information from objects or scenes is very useful in various fields including remote sensing, chemistry, astronomy, and industrial quality control. The methods of Fourier transform spectroscopy (FTS) have been used for over thirty years. As resolution of optical positioning devices and computer processing speeds increase, so does the usefulness and importance of FTS. There are many different designs of spectrometers available, but I have chosen to base this project on the Michelson interferometer.

Background

The Michelson interferometer (Fig. 1) is a simple design that creates interference patterns, also known as ‘interferograms’ (Fig. 2), an image of the interference of light waves. The waves combine in phase in regions of constructive interference, and add out of phase where the interference is destructive. Displacement of the moving mirror changes the optical path difference (OPD), producing interference, thus changing the interferogram. The data set is collected by scanning the moving mirror and recording the interferogram at each position (response versus position). "The interferogram is not a direct display of the spectrum although it is uniquely related to the spectrum. Through harmonic analysis of the interferogram, it can be decomposed into its component frequencies, resulting in a display of the spectrum" (1). The collection of interferograms allows calculation of the spectrum of the source by computing the discrete Fourier transform (Fig. 3).
General Experimental Design and Methods

Figure 4 is the schematic for the planned spectrometer. The system is designed to have unit magnification so that the input and output image scales are equal. All equipment will be fixed on the optical table. The planar object or source is placed in front of a collimating lens so that the wavefronts from each point are planar when they enter the beamsplitter. Approximately 50% of the energy will pass through the beamsplitter to the moving mirror and the other 50% to the fixed mirror. The moving mirror is restricted to a linear translation of 20 mm, which produces an OPD of up to 40 mm. The motion of the mirror needs to be considered because its surface must always be orthogonal to the source. Also, enough time must elapse between steps to allow mirror vibration to settle. By collecting the data on both sides of the zero path difference (ZPD), it creates a "two-sided interferogram". Doing this removes the problem of finding the location of the ZPD exactly (a time consuming procedure). Data collection time will double, but "linear phase error in wave number can be exactly eliminated" (2) and signal noise will be reduced in the process. After the light beam reflects from both mirrors and are recombined by the beamsplitter, it will be refocused directly onto a monochrome CCD video camera. The interferogram is sampled for every step of the moving mirror. The collection of interferograms are processed by a discrete Fourier transformation, returning the spectrum of the object or source. The spectrum is calculated for every pixel of the CCD to produce an image spectrogram of the input.
Initial runs of the experiment were conducted with monochromatic light and lamps with prominent spectral lines, which helped in calibrating the system. Tests using illuminated color transparencies will be used to test the alignment of the system. Alignment is an important issue in an imaging spectrometer; light emerging from each single point in the object plane must converge to a specific single point in the image plane. Artifacts due to sources other than alignment will also be studied during this experiment. Some of these may be related to sampling, the motion of the mirror, optical aberrations, and the beamsplitter, all of which will affect the performance of the system. The interferograms must be imaged at sufficiently small increments of translation to ensure that the sinusoidal variations in the interferogram are not aliased.

**Construction**
Figure 5: Constructed Spectrometer

Pictured above is the actual spectrometer that was constructed. It follows the same design as specified in the layout. The light source is a HeNe laser ($l = 632.8$ nm) which has been collimated through use of a 40x microscope objective and a 10 mm diameter pinhole. The beamsplitter then redirects approximately half of the light to fixed mirror and the other half to the moving mirror. The light is then recombined and passes through a neutral density filter and directly onto the CCD of the monochrome digital camera. Both the motion of the mirror and image capture are automated processes controlled by the computer.

A linear stepper motor controlled by the computer is used for the moving mirror. An inexpensive means for generating these very small displacements (< 100 nm) was necessary. Most of these systems cost anywhere from $8,000 to well over $15,000, but this system was found for under $3,000. The system which was purchased from SD instruments included the motorized translation device (7600 - X) for $850 and the controller (MC2000) for $1975. The specifications of the system were pushing the upper limits of what was needed, but it was the only system which fit in the budget.
After collimating the light, alignment of the system with the monochromatic source was the next step. This involved reflecting the light at each of the sources (beamsplitter and the mirrors) back towards the pinhole. The interference fringes could be viewed on a piece of paper at the location of the recording camera. Above is a picture of the observed fringe pattern as taken by the digital camera. At this point the system is still only a Michelson interferometer.

**Experiment #1 - Movement**

The first experiment was performed to make sure that the translation device worked properly and that a change in the interferogram could be seen. This was performed by simply taking an initial image of the interference pattern, then displacing the stepper motor approximately 100 nm and taking another image at the new location.
Figure 7: Interference patterns before (top) and after (bottom) OPD displacement.

Pictured above are interference patterns from the HeNe Laser. The second picture was taken after the optical path difference was displaced by approximately 200nm (notice the shift between the two images). The results from performing this task were that tiny displacements could be achieved and that there was a detectable change between the two images.

**Experiment #2 - Monochromatic Source**

The second experiment involved turning the Michelson interferometer into a spectrometer. The digital camera was programmed using a module in V++ so that it would take and save an image at a specified interval. The stepper motor was programmed with MVP Demo 2001, a shareware program downloaded off the Internet. The program steps the motor 5 encoder units (approximately 25 nm) per second. The 128 images in the first set of data were taken at intervals of 2.5 seconds and the images were sized down to 21 pixels by 21 pixels for a faster transfer rate. The first five images from the data set are shown below.
Using IDL, the fast Fourier transform was computed for two arbitrary pixel locations (0,0) and (10,10). The data is first plotted and then the FFT is computed and graphed.

Figure 8: The first five images of the data set.
Results from the first experiment were very reassuring. Spikes occurred at ± 21 and at 0, the DC component. By zooming in on the data it can be seen that 6 samples were taken per cycle, thus \( D_x = 105.5 \) nm.

\[
\text{Error} = 642.7 - 632.8 = 9.9 \text{ nm}
\]

Relative Error = 1.6%

With only 128 samples we were able to calculate the wavelength as well as possible with this discrete system. The experiment was to be run again with 512 samples and a time interval of only 0.5 seconds. As can be seen below the price of decreasing the sampling interval came at the increase of noise. This is especially true for the first few samples where there seemed to be a problem with the stepper motor.
The largest spikes occurred at $\pm 32$ with the DC component removed. By zooming in on the data it can be seen that 16 samples were taken per cycle, thus $Dx = 39.55$ nm.

$$\text{Error} = 632.8 - 632.8 = 0 \text{ nm}$$

Relative Error = 0 %

By decreasing the interval time much noise was added to the system. Even though there was no error, the added noise created additional spikes surrounding $\pm 32$, unlike the first try (128 samples - 2.5 second interval) where there were only two prominent spikes.

**Experiment #3 - Mercury Lamp and White Light Source**

The third experiment involved using a mercury lamp (prominent spectral lines) and a white light source (tungsten filament) in place of the laser. In both cases, images were collected at 512 positions with a time interval of 0.5 seconds. Both sources were not collimated due to the lack of brightness that would result. The data (shown below) was not adequate to obtain results in either case. The data looks like noise and there was not a large enough range of digital count values.
Figure 11 (above): Data and FFT from a Mercury Lamp.

Figure 12 (below): Data and FFT from a White Light Source.
As this was the first attempt for both sources, modifications will be attempted to make improvements. For example, collimation may need to be obtained and by using a longer integration time for the digital camera, the signal to noise ratio would be reduced.

**Discussion**

**Problems**

The major problems with the data were due to limitations of the stepper motor and digital camera. The requirements of this task exceed those envisioned by the manufacturer, and may be resulting in unequal step sizes and irregular motion of the stage. A final problem with the stepper motor is that there is a slight drift. The drift can be avoided by taking data quickly because the observed drift was approximately 200 nm in 3-5 minutes and 400
nm in 15 minutes.

The problem with the digital camera is the software used to control it. The V++ software has a limit of around 160 images it can save, even if memory is constantly cleared. The around this was to run the program four times taking 128 images each time. While the images were being taken I would move the files into four separate folders.

Future Work

Future work is already in progress. The next step is to obtain the spectra of the mercury lamp and white light source. After the spectra are obtained, the daunting task of creating an 2-D image spectrogram of an input image would be attempted. Here alignment, aberrations, and effects of the beamsplitter become much more of an issue. Other future work may involve a more detailed look at the optics involved and also creating an interactive GUI software program for analyzing data.

Conclusion

I designed it. I built it. I tested it. Like all technical devices, it needs to be tested some more. The primary purpose of this project was to build a spectrometer that works. This has been demonstrated with use of the HeNe laser with a fairly high degree of accuracy. In the case of taking 128 samples, there was only a 1.6 % relative error, and when 512 samples were taken, the correct wavelength was found. To build an inexpensive imaging Fourier transform spectrometer is no easy task. Further testing and analysis should be able to yield the spectra for any type of light source along with a 2-D image spectrogram. I have provided a tool that is functional, now it must be studied further.
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IDL FFT Code

MVP Demo 2001 Code

V++ Code

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