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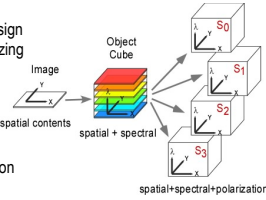
## Summary & Motivation

### Compact Imaging Spectropolarimeter

We propose and model a compact and light spectropolarimeter design that has the potential to improve *stability* and *resolution* while minimizing the size and cost

### Enabling Technology

- Liquid Crystal Polarization Gratings (LCPGs)
- Direct dispersed spectrums allowing higher spectral and polarization sensitivities and resolutions



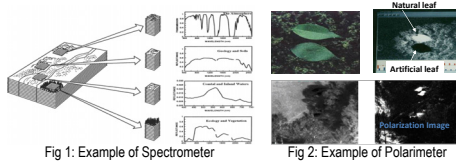
## Motivation and Background

### Imaging Spectropolarimetry

- The technique to extract the spectral and polarimetric information from the 2-D scene
- Analyzing 5D-information ( $\lambda, S_0, S_1, S_2, S_3$ ) from the 2D-scene

### Potential Applications

- Remote Sensing
- Target Detection
- Biomedical Imaging/Diagnosis
- Industrial Inspection



### Previous Works in Spectropolarimetry

- Spectropolarimeter using tunable filters or polarizers<sup>1)</sup>
- Computed Tomography Imaging Spectrometer (CTIS) based on Channelled Spectropolarimetry (CHSP)<sup>2,3)</sup>
- Calibration difficulty, spectral resolution loss, and high computational cost

### How is our Approach Different?

- No moving/tunable part or polarizer – robust and efficient system
- No post processing – no spectral modulation, leading to complexity and reduced sampling resolution
- LCPGs – wide range capability (VIS-NIR), very high diffraction efficiency (~100%)

## Liquid Crystal Polarization Grating

### LCPG Diffractions

Polarization grating with a periodically varying, in-plane uniaxial birefringence has been modeled and compared to analytic expressions

$$\eta_0 = \cos^2\left(\frac{\pi \Delta n d}{\lambda}\right)$$

$$\eta_{\pm 1} = \frac{1}{2}(1 \mp S_1^*) \sin^2\left(\frac{\pi \Delta n d}{\lambda}\right)$$

- only three (0 and  $\pm 1$ ) orders
- ~100% efficiency possible by a thin grating
- polarization selectivity of the first orders

- Diffraction elements → **spectrum analyzer**
- High polarization sensitivity → **polarization detector**
- Bragg properties (only 0,  $\pm 1$  orders) → **high efficiency**

### Full Stokes Spectropolarimeter

The full stokes parameters will be calculated by three series of the polarization gratings as shown below

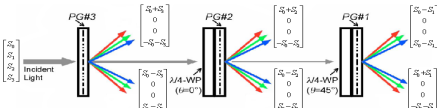


Fig 4: Our proposed implementation with three PGs and quarter wave-plates (QWP)

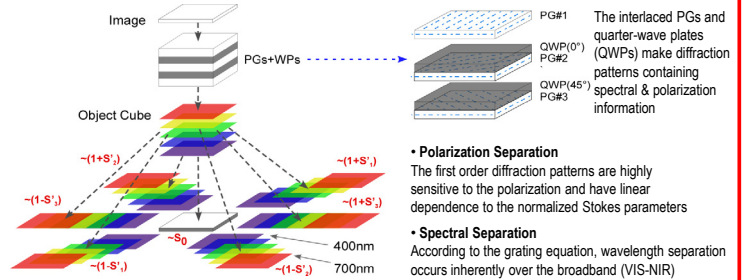
Fig 5: Preliminary experimental setup for PG-based Spectropolarimeter (photograph courtesy of Dr. Escuti)

## Conclusions and Further Works

- We have developed and modeled an imaging spectropolarimeter capable of snapshot detection based on liquid crystal polarization gratings (LCPGs)
- Our design benefits from the spontaneous acquisition of spectral and polarization information with high efficiency (>99%) and sensitivity for each Stokes parameter
- Based on simulation results, our design shows the potential to maximize efficiency in terms of sensitivity and resolution while minimizing cost and size of device
- We will research on the different diffraction patterns which can be made with our PGs and QWPs

## Design of Imaging Spectropolarimeter

### PG-Based Imaging Spectropolarimeter



The interlaced PGs and quarter-wave plates (QWPs) make diffraction patterns containing spectral & polarization information

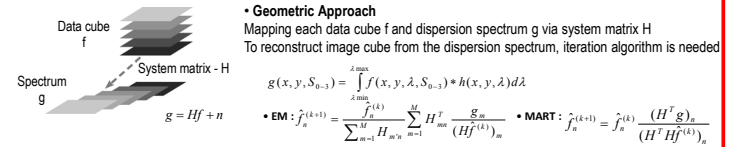
### Polarization Separation

The first order diffraction patterns are highly sensitive to the polarization and have linear dependence to the normalized Stokes parameters

### Spectral Separation

According to the grating equation, wavelength separation occurs inherently over the broadband (VIS-NIR)

### Computed Tomography Algorithm



### Geometric Approach

Mapping each data cube  $f$  and dispersion spectrum  $g$  via system matrix  $H$

To reconstruct image cube from the dispersion spectrum, iteration algorithm is needed

$$g(x, y, S_{0..3}) = \int_{\lambda_{min}}^{\lambda_{max}} f(x, y, \lambda, S_{0..3}) * h(x, y, \lambda) d\lambda$$

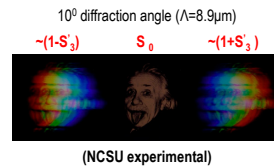
$$g = Hf + n$$

$$\bullet \text{EM: } \hat{f}_n^{(k+1)} = \frac{\sum_{m=1}^M H_{nm}^T \frac{g_n}{(Hf^{(k)})_n}}{\sum_{m=1}^M H_{nm}^T \frac{g_n}{(Hf^{(k)})_n}}$$

$$\bullet \text{MART: } \hat{f}_n^{(k+1)} = \hat{f}_n^{(k)} \frac{(H^T g)_n}{(H^T Hf^{(k)})_n}$$

## Simulation & Results

### Diffraction Spectrum with Single PG



(NCSU experimental)

- The dispersion of PG causes the separation of spectral information of image according to the grating equation
- Diffraction angle:  $\theta_m = \sin^{-1}(m\lambda / \Lambda)$ ,  $m = \pm 1$  orders
- $\lambda$ : applied light wavelength (VIS: 400-700nm)
- $\Lambda$ : grating period of PGs
- $\pm 1$ st orders are dependent on the polarization states

### Dispersion Pattern and Reconstruction Simulation

#### Test Image: Tiger

- To simulate spectrally non-uniform data, slightly different tiger images are used – each face indicates each wavelength image
- Each tiger image contains polarization sensitive parts (ex:  $S_1$  sensitive nose,  $S_2$  sensitive tongue,  $S_3$  sensitive background)
- To test a reconstruction of polarization (full Stokes parameters), each image is manipulated manually for giving different polarization states (most parts are partially polarized)

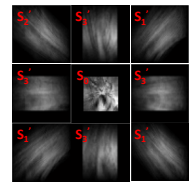


Fig 6: Dispersion Pattern from the interlaced 4 PGs and wave-plates

#### Reconstruction Images

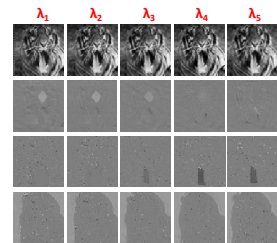


Fig 7: Reconstructed images which are related to each wavelength and each polarization state

### Error Rate Test Simulation

Test Image	Image Information	Error rate (RMS)
Narrowband Point source	Point source containing Gaussian profile	< 5%
Uniform	Spatially and spectrally uniform image	< 5%
Broadband Point source	Point source over the broadband	< 10%
NCSU Logo	Spatially and spectrally non-uniform image	< 20%
Tiger (real)	Captured image having polarization information	~30%

### References

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