Hyper-spectral Imaging Technology Based on Linear Gradient Bandpass Filter for Electricity Power Equipment Status Monitoring Application

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Abstract. Hyperspectral imaging technology has been applied to the status monitoring of power transmission line and equipment as its continuous and narrow-band induction characteristics, which provides a solution for the operation monitoring of lossless large-area power equipment. However, the optical and electronic equipment is complex, and the related products are large and expensive on the market. This paper describes a preparation method of a linear gradient filter that is cost performance and miniaturization, which can be used to realize the prototype hyper-spectral imaging camera. The high precision preparation process and principle make the camera show good spectral performance, which can scan with precision step length of 2nm between 400nm and 1000nm. The feature extraction and classification algorithm can be used to determine the health conditions of power equipment, such as partial discharge, with an accuracy of about 77%. The equipment collocation algorithm can also be used to identify defects in power equipment, which has been proved to be able to distinguish between aging insulators, icing of conductors and heating of wire clips. This method are promising for an entry-level, low-cost hyper-spectral imaging solution for power detection applications.

1. Introduction
The monitoring of power transmission equipment is of great significance, especially for improving power supply quality and power safety. The method that can accurately understand which areas in the line channel need to be monitored can prevent malfunctions such as partial discharge and equipment overheating from evolving into major accidents. Due to the scale of the power transmission line inspection task, this is difficult to be completed by manual inspection or drone inspection. So, the use of new technologies such as lidar, infrared and ultraviolet cameras, multi-spectral and hyper-spectral imaging has been initially solved this problem. It can be seen that hyper-spectral detection has great potential in power system detection applications, especially partial discharge detection of power equipment under different humidity environments [1-3], insulator fault troubleshooting [4] and large-scale power equipment overheating operation monitoring [5] etc. The application of this technology also reduces the training time and experience accumulation required for operators to perform the same inspection tasks.

Partial discharge is a potential hazard to the safety of power transmission systems. X. Jia, et al. (2013) [1] has used reflectance spectroscopy in the visible light (390-770 nm) to near-infrared region (700-1000 nm) to evaluate it. This analysis has determined the health status of equipment samples under different discharge levels under experimental conditions. L. Jin, Z. Tian, J. Ai, et al. (2018) [4] et al. has used spectral analysis to achieve rapid screening of insulator contamination levels, and demonstrated
the use of visible-near-infrared and mid-infrared spectroscopy to distinguish insulators whether flashover was caused by pollution, the classification accuracy was about 90%. Running Gao, et al. (2019) [5] has adopted hyper-spectral nondestructive monitoring methods and used a real-time monitoring system based on visible light and near-infrared reflectance spectroscopy to study on variation of surface pollution content of insulator electrical equipment in strong electric field. Comparing the survey results with the pollution element index determined by laboratory standard instruments, the reliability of the spectral analysis is verified. The previous studies also showed that reflectivity would be a sensitive indicator of chlorophyll concentration at 700 nm. Emadi (2012) [6] et al. showed that linear variable filters (LVF) could be used as a miniaturized optical element to replace diffraction gratings. By citing the advantages of LGF small size and wide scanning range, it only need to move the physical distance of the filter component can achieve multi-target capture in the range of 1000 nm, which is particularly important for the optical path design and effective use of space in optical inspection equipment.

Although the capabilities and potential of the spectral analysis test system seem to be huge, the current multispectral and hyperspectral detection systems are generally expensive that priced is more than $10,000 US dollar. Also, it’s bulky and heavy, which makes it difficult to expand their application scenarios. This paper solves these problems. By using the new linear gradient band-pass filter (LGF) and new material preparation technology, the size and cost of the spectrometer are significantly reduced. The backstage with a unique algorithm has developed a portable hyper-spectral power detection camera (HETC) and make a prototype.

2. Baffle modelling and thickness distribution

In order to obtain the linear space thickness growth distribution and meet the requirements of the filter, a baffle is designed based on the sputtering angle distribution model, and the growth process of the film is controlled, so as to realize the thickness distribution of the film material.

2.1. Magnetic field modelling

The baffle modelling components are relayed to magnetic field, cathode voltage, and gas pressure, while gas pressure and cathode voltage are assumed constant and uniform across the target surface. Magnetic field tangential to target surface, $B_{\text{tan}}$ contributes to electron confinement and plasma generation and as in all magnetrons, and as measured in this example, is highly non-uniform. Goree and Sheridan used a Monto Carlo simulation to show that the ionization efficiency, $\eta$, is approximately linear to $\log \beta$, a dimensionless magnetic field, (eqn.1) prior to saturation [7]. This leads to a sputtering yield dependant on $B_{\text{tan}}$, reflected by the erosion track profile physically.

$$\beta = \sqrt{\frac{e}{2m}} \left( \frac{a}{V_{\text{dis}}^{1/2}} \right) B_{\text{tan}}$$

(1)

Where $e$ and $m$ are electron charge and mass, $a$ is radius at $B_{\text{tan}}$, and $V_{\text{dis}}$ is cathode voltage.

The magnetic field can be calculated and this can be fed into a semi empirical model to calculate the etch profile of the target. The etch profile is calculated taking into account an integration of the ionization efficiency along the approximate ion path. Fig.1(a) shows on the left hand side the magnetic field and on the right hand side the etch profile across a section in the middle of the linear magnetron. Measurements are also shown in Fig.1(b) for comparison.
2.2. Thickness distribution modelling and filter deposition

In order to realize the linear gradient distribution of the film thickness, a baffle is arranged between the sputtering outlet window and the substrate in the direction perpendicular to the outlet of the ion particles. During ion beam etching, the sample moves back and forth at a constant rate. After a certain amount of etching, a motion perpendicular to the sample is obtained. Through the thickness difference in the direction, the designed wedge-shaped spacer layer is finally obtained. Baffle design based on empirical methods is difficult and time-consuming. In order to design a mask that can produce the desired thickness distribution along the axial direction of the substrate more effectively, a simulation program is written. The parts to consider are the substrate on the rotary fixture, the target, and the mask with a predefined shape function, as shown in Figure 2.

3. Results & Discussion

Niobium and silicon are used to deposit high/low refractive index materials for making linear graded filters. The coating characterization is taken by NICOLET6700 spectrometer, which can measure transmission and reflection by using different incidence angle and two different polarization.
3.1. LGF deposition and Results Demonstration

The deposition process of linear gradient filter preparation is produced the first coating performed on the K9 substrate, and the lower film system and the middle cavity layer are plated. Then, the middle layer is etched according to the above method to obtain a certain a wedge-shaped resonant cavity layer with a wedge angle. Finally, bonded with the second coating the preparation of the linear gradient filter can be completed after 32 cycles of repeated cycles.

![Cross-sectional SEM images for LGF film](image1.png)

Figure 3 (a) Cross-sectional SEM images for LGF film (b) The transmittance of several points on LGF has been obtained

The thickness of the film is designed to be 1.6μm at the thickest point, set the deposition working gas parameters as Ar flow rate of 40 sccm (1 sccm = 1 mL/min) and Ar/O2 flow rate of 5/10 sccm. The deposition rates of SiO2 and NB2O5 materials are determined under the two conditions to be 1.33A/s and 3.83 A/s.

3.2. Hyper-spectral imaging system HETC

The design of the HETC detection system uses a high-resolution CMOS sensor as the position of the LGF needs to be considered to correspond to the corresponding detection wavelength. A stepper motor with a custom-designed rack and pinion was introduced to achieve linear gradient filter (LGF) translation and accurate positioning in the camera system. This creates discrete vertical bands at linearly spaced wavelengths in each image. Figure 4 shows the basic schematic diagram of the HETC imaging system.

![Basic components and LGF in HETC system set up](image2.png)

Figure 4. (a) Basic components and LGF in HETC system set up (b) Prototype HETC assembly with internals exposed

HETC developed for the electricity transmission line monitoring is a low-cost hyper-spectral imaging system based on LGF. As part of the hardware development of the project, HETC is calibrated based on the technical standards of high-end push-broom hyper-spectral systems.
3.3. **Classification of Insulator Contamination**

By referring to the electric power standard, the on-site insulators are classified into different pollution levels after pollution value detection, and divided into 84 training sets and 36 test sets. The hyperspectral images of the training set samples are collected, and the characteristic bands are extracted after black and white correction and fitting smoothing to reduce redundant information. At the same time, the HSI algorithm is used to extract image features, and the S (color saturation) component that is most relevant to the pollution level is selected to identify the pollution level of the insulator samples in the test set. Then, based on the pollution level classification model and HSI test results, this study realized the level classification and visualization of the insulator surface pollution.

![Visualized image of insulator surface contamination obtained by HETC system](image)

Figure 5. Visualized image of insulator surface contamination obtained by HETC system

Figure 5 shows the pollution level distribution at different positions on the surface of the on-site insulator string. The gradual colors represent different pollution levels in the picture. Darker color means lower pollution content, and lighter color means higher pollution content. As shown in the figure, contamination on the upper surface of the insulating sheet accumulates more than that on the lower surface, and contamination accumulates in multiple directions on the pillars. The analysis result is basically consistent with the pollution distribution on the surface of the on-site insulation string, which further verifies the feasibility and accuracy of the pollution grade classification model based on the on-site insulator map information to visualize the pollution grade distribution.

4. **Conclusions**

This paper describes the design and development process of a customized special baffle and provide a linear graded band-pass filter LGF with low cost and wide detection range covering visible and near-infrared wavelengths. The simulation model ensures that LGF with controlled thickness distribution can be mass-produced. Low-cost LGF combined with appropriate detector systems can reduce the cost, weight, and size of the detection equipment. Compared to high-priced multi-lens scanning hyperspectral imaging systems with similar technical specifications, the hyper-spectral prototype camera has similar performance and the cost save about 85%. The algorithm of the HETC system shows good feature extraction and classification in the process of similar insulator and metal fault judgment, and achieves about 88% accuracy in differentiating the flash-over and aging degree of insulators. These results have broad implications for the future applications of low-cost HETC in power detection and the potential of remote sensing.

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