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Back-focal plane Mueller matrix microscopy: Mueller conoscopy and Mueller diffractometry

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ABSTRACT

The common mode of observation in an imaging Mueller matrix polarimeter is orthoscopic observation, where the front focal plane of the objective is focused onto the camera sensor. Different points on the camera sensor correspond to different points on the sample. But for certain applications, valuable complementary information is obtained when the back focal plane of the objective is focused onto the camera sensor. This observation mode informs about the directions distribution of light so that different points on the camera sensor correspond to different directions of light propagation through the specimen. We distinguish between two types of illumination; the sample can be illuminated with a large numerical aperture, such that what is measured corresponds to usual transmission or specular reflection ellipsometry (Mueller conoscopy), or the sample may be illuminated with collimated light, and what is measured corresponds to scattering or diffraction of light (Mueller diffractometry). A polarimeter suitable for back-focal measurements is described and illustrative examples of Mueller conoscopy and Mueller diffractometry are presented.

1. Introduction

Microscopy can be practiced in two observation modes called orthoscopy and conoscopy [1,2]. In the orthoscopic mode, each point on the camera sensor corresponds to a point on the specimen, and all directions that light takes through the specimen are essentially integrated at each spatial point. In contrast, conoscopic mode maps to each point on the camera sensor a unique direction light takes through the specimen, and all spatial points on the specimen are integrated. In other words, orthoscopy resolves space and integrates directions whereas conoscopy resolves directions and integrates space. Conoscopic microscopy is also referred to as "back-focal plane microscopy" because, in the conoscopic mode, the rear focal plane of the objective is imaged, or "Fourier microscopy" because the images obtained correspond to Fourier space instead of real space. Another suitable and more general name would be "k-space microscopy" because a conoscopic image maps the k-vector distribution of the radiation.

Nearly all modern microscopes use Kohler illumination, where the numerical aperture (NA) of the illumination, and the illumination spot size can be independently controlled. For homogeneous and optically clear specimens, each input direction of light results in a transmitted and a specularly reflected field. For this situation, it is usual to illuminate with a large NA matched to the objective that gathers light after the specimen. However, specimens with strong scattering or diffractive properties (e.g., nanostructures) radiate light in many directions for each illumination direction, i.e., their response is more complex than just transmission or specular reflection [3–6]. To avoid mixing many types of scattered light, it is often more useful to illuminate such specimens with collimated light (small NA). Regardless of the illumination method employed, the ultimate goal of our experimental approach is to achieve an accurate polarization sensitive measurement of the angular distribution of light from a single measurement. Pioneering back focal plane Mueller matrix measurements have been previously reported by researchers at the École Polytechnique [7–9], developing applications in grating metrology. Our approach for Mueller conoscopy is specially simple since it relies on a modified commercial microscope, also capable of orthoscopic Mueller matrix measurements, equipped with Bertrand lens that is insertable into the tube of the microscope and axially displaceable therein.

This work shows how Mueller conoscopy generalizes traditional conoscopic imaging, offering quantitative information for the determination of linear birefringence and optical rotation (also dichroism in case of absorbing samples) that are ultimately related to the optical constants of the material. This concept is illustrated

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with measurements on several different crystalline slabs. We also propose applying this technique as a tool for optical scatterometry or diffractometry, provided that a single measurement with a high NA objective is sufficient to collect different diffraction orders.

2. Experimental setup

A commercial Carl–Zeiss Jenaval microscope has been custom modified in order to allow for Mueller matrix measurements. This series of microscopes was first produced in the 1980s and quickly became a successful instrument with presence in many laboratories worldwide. It is an infinity corrected transmitted light and epi-illumination microscope and its use is mentioned in many scientific papers. The microscope is equipped with a Bertrand lens that is insertable into the tube of the microscope and is displaceable to precisely image the back focal plane of the objective.

As a result of our modifications, the microscope gained a computer controlled polarization state generator (PSG) and a polarization state analyzer (PSA). Our approach for MM imaging (described in detail in [10,11]) is based on the analysis of the images that are continuously captured by aCMOS camera while two rotating film compensators, one at the PSG and the other in the PSA, continuously modulate the polarization of light. The detector has been recently upgraded to a Point Grey Grasshoper3 CMOS camera utilizing a Sony IMX252 sensor, which we usually operate at 50 fps. The compensator in the PSG rotates at approximately 0.0694 Hz, while the compensator in the PSA rotates five times slower, at around 0.0138 Hz. This ratio of angular speeds is not arbitrary, as we showed [10] that it provides the optimum conditions for frequency demodulation. Given these reference frequencies, the images continuously captured by the camera are frequency analyzed by digital demodulation in order to calculate the 16 elements of the Mueller matrix for every camera pixel, following the calculation discussed in Ref. [10].

The original polarizer placed in the bottom part of the microscope was replaced by the PSG that consists of polarizer (polaroid film, Edmund optics) a rotating retarder ($\lambda/4$ polymer retarding film, Edmund optics). Similarly, the polarizer placed in the upper part of the microscope was replaced by a PSA with the optical characteristics of the PSG. These changes were made without modifying the optical layout of the microscope so that all original optical components (lenses, condensers, objectives, iris, etc.) remain in their original place and are fully operational. The PSG and PSA motors are belt-driven and they were custom designed to minimize their effective thickness so that they could fit in the microscope. This was one of the main challenges of the microscope construction, since the vertical free space available in our microscope is quite reduced. Arduino controllers with custom made software are used for motor control. The use of film polarizing elements has two main advantages: (1) allows for a very low profile PSG and PSA that can fit in the microscope and, (2) prevents the image precession related to the compensator rotation that could appear if thicker compensator were used. The nominal thickness of the polymer retarding films is 75 μm, so small misalignments with respect to the optical path are negligible. The retardance of the compensators for every wavelength of measurement (close to $\lambda/4$ but not perfect) is determined during the calibration process, as detailed in [10].

The original Halogen lamp of the microscope has been replaced by a more stable Metaphase white LED source and band-pass filters are used to select the wavelength of light for each measurement. In the future, we plan to add a monochromator after the light source to be able to do fully spectroscopic measurements. All objectives, condensers and lenses are the original ones supplied with this polarization microscope and hence, they are strain free and do not exhibit any significant amount of birefringence. For conoscopic measurements we typically use objectives with larger NA (two Planachromat 50×, one with 0.89 NA, and another with 0.95 NA). Note that the NA of the objective determines the angle of incidence on the sample which, because of refraction, is different from the internal propagation angle unless methods based on the immersion with index-matching fluids are used.

As seen in the photo of Fig. 1, the whole instrument keeps a very compact size and can easily fit any conventional laboratory table, although orthoscopic imaging at high magnification requires a vibration free environment.

3. Examples of conoscopic measurements in thin crystal slabs

In this section we overview a collection of experimental Mueller conoscopic images obtained from several different crystal slabs. All of them are made with an objective of 0.89 NA. Our purpose is to discuss qualitatively the information offered by Mueller conoscopy in terms of crystal's symmetry, orientation, and optical constants. In conoscopic mode every pixel captured by the camera is better described with polar coordinates, given by a radius, r, and azimuth angle α. The radius is related to the angle of incidence (θ) of light by $r = \sin(\theta)$, while α is directly the azimuth orientation of the ray projected onto the back focal plane.

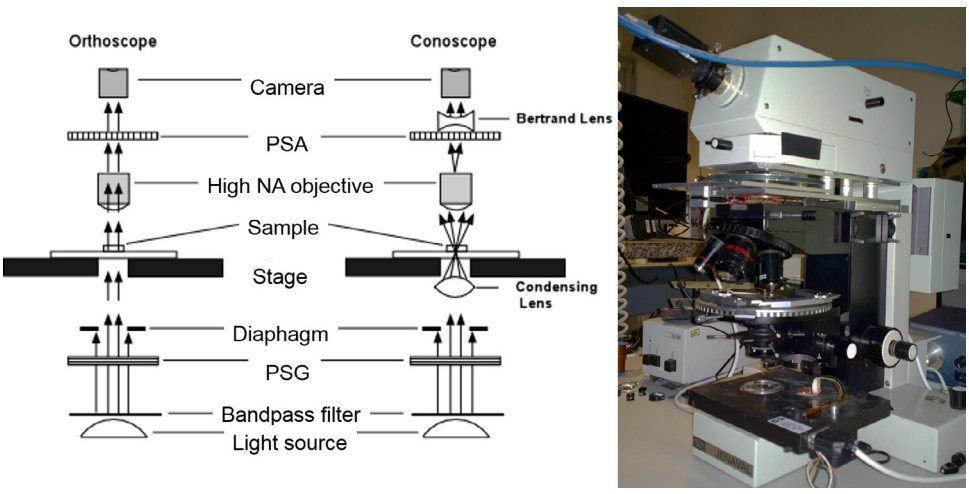

Fig. 1. Scheme of the basic differences between orthoscopic and conoscopic illumination (adapted from [1]) and photo of our modified Carl–Zeiss Jenaval microscope.

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