Entangled-Photon Ellipsometry

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ABSTRACT

We present a novel quantum interferometric technique to perform ellipsometric measurements. Classical ellipsometric measurements are limited in their accuracy by virtue of the need for an absolutely calibrated source and detector. Mitigating this limitation requires the use of a well-characterized reference sample. Our technique relies on the use of a non-classical optical source, namely polarization-entangled twin photons generated by spontaneous parametric down-conversion from a nonlinear crystal, in conjunction with a coincidence-detection scheme. We have demonstrated that entangled-photon ellipsometry eliminates the necessity of constructing an interferometer altogether and is thereby self-referencing. The underlying physics that leads to this remarkable result is the presence of fourth-order (coincidence) quantum interference of the photon pairs in conjunction with polarization entanglement.

SUMMARY

A question that arises frequently in metrology is the following: how does one measure reliably the reflection or transmission coefficient of an unknown sample? One optical metrology setting in which high-precision measurements are a necessity is ellipsometry, in which the polarization of light is used to study thin films on substrates, a technique that has been established for more than a hundred years [1,2,3]. Ellipsometers have proven to be an important metrological tool in many arenas ranging from the semiconductor industry to biomedical applications. The outcome of such a measurement depends on the reliability of both the source and the detector used to carry out the measurements. If they are each absolutely calibrated such measurements would be trivial. Since such ideal conditions are seldom met in practice, and since high precision measurements are often required, a myriad of experimental techniques, such as null and interferometric approaches [1,4], have been developed to circumvent the imperfections of the devices involved in these measurements.

In this paper we present a novel technique for obtaining reliable ellipsometric measurements. It is based on the use of entangled two-photon states produced by the process of spontaneous parametric down-conversion [5]. This source has been used effectively in studies of the foundations of quantum mechanics and in applications of quantum information processing, such as quantum cryptography and quantum teleportation. This source has also been utilized in quantum imaging and in the emerging field of "quantum metrology". We now extend the use of this non-classical light source to the field of ellipsometry and demonstrate the advantages of 'entangled-photon ellipsometry' [6,7] over conventional (classical) ellipsometry.

The proposed entangled-photon quantum ellipsometer is illustrated in Fig. 1. An intense ultraviolet laser (pump) beam illuminates a birefringent nonlinear optical crystal (NLC). Quantum mechanics predicts that some of the pump photons disintegrate into pairs, known traditionally as signal (s) and idler (i), which conserve energy (frequency-matching) and momentum (phase-matching) [5]. For our purposes, we choose the SPDC to be in a configuration known as 'type-II non-collinear'. 'Type-II' refers to the fact that the signal and idler photons have orthogonal polarizations (ordinary and extraordinary) in order to satisfy the phase-matching conditions; 'non-collinear' indicates that the signal and idler photons are emitted in two different directions.

The idler beam encounters a linear polarizer A_2 followed by single-photon photodetector D_2. The signal beam reflects off the sample of interest before it encounters a linear polarization analyzer A_1, followed by a single-photon photodetector D_1. The sample is characterized by the parameters ψ and Δ: ψ is the ratio of the magnitudes of the sample reflection coefficients, R_H and R_V for the p- and s-polarized waves, respectively; Δ is the phase shift between them. The detectors are part of a circuit that records the coincidence rate of photon pairs.

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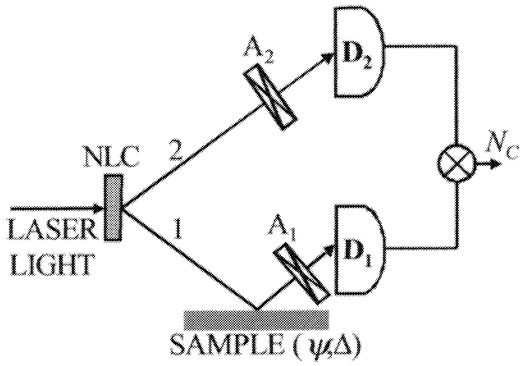

This non-classical source and the optical arrangement shown in Fig. 1 exhibit two features that circumvent the two problems noted earlier: calibration of the source and detector. The first characteristic of this quantum ellipsometer is that the source is a twin-photon source, i.e., we are guaranteed, upon detection of one photon in one of the arms of the setup, that its twin is in the other. The detection of one photon may be used to gate the arrival of its twin in the other arm. This effectively provides us with a calibrated optical source since the efficiency of the 'gating' detector is immaterial. The second characteristic is the polarization entanglement of the source. This feature formally plays the role of an interferometer in our approach, thereby alleviating the need for calibrating the second detector in our coincidence scheme.

Another advantage of this setup over its idealized null ellipsometric counterpart is that the two arms of the ellipsometer are separate and the light beams traverse them independently in different directions. This allows various instrumentation errors of the classical setup to be circumvented. For example, placing optical elements before the sample causes beam deviation errors when the faces of the optical components are not exactly parallel. This leads to an error in the angle of incidence and, consequently, errors in the estimated parameters. In our case no optical components are placed between the source (NLC) and the sample; any desired polarization manipulation may be performed in the other arm of the entangled-photon ellipsometer. Furthermore, one can change the angle of incidence to the sample easily and repeatedly.

We have shown that by employing entangled-photon pairs, generated by type-II SPDC in a non-collinear configuration, absolute ellipsometric data from a reflective sample can be obtained. The underlying physics that permits such ellipsometric measurements resides in the fact that fourth-order (coincidence) quantum interference of the photon pairs, in conjunction with polarization entanglement, emulates an idealized classical ellipsometric setup that utilizes a source and detector that are both calibrated absolutely.

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REFERENCES

[1] P. Drude, "Bestimmung optischer Konstanten der Metalle," Ann. Physik Chemie," **39**, pp. 481-554, 1890.
[2] R. M. A. Azzam and N. M. Bashara, *Ellipsometry and Polarized Light,* North-Holland, Amsterdam, 1977.
[3] A. B. Winterbottom, "Optical methods of studying films on reflecting bases depending on polarisation and interference phenomena," Trans. Faraday Society, **42**, pp. 487-495, 1946.
[4] M. Mansuripur, "Ellipsometry," Opt. & Phot. News, **11(4)**, pp. 52-56, 2000.
[5] D. N. Klyshko, *Photons and Nonlinear Optics*, Gordon and Breach, New York, 1988.
[6] A. F. Abouraddy, K. C. Toussaint, Jr., A. V. Sergienko, B. E. A. Saleh, and M. C. Teich, "Ellipsometric measurements by use of photon pairs generated by spontaneous parametric down conversion," Optics Lett. **26**, pp. 1717-1719, 2001.
[7] A. F. Abouraddy, K. C. Toussaint, Jr., A. V. Sergienko, B. E. A. Saleh, and M. C. Teich, "Entangled-photon ellipsometry," J. Opt. Soc. Am. B **19**, in press, 2002.

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