Three-Beam Interferometry for Dynamic and Low-Signal Measurements

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Abstract: We present an interferometer for the characterization of dynamic optical materials and metasurfaces. A three-beam method provides robust measurements despite unavoidable drift. Measurements are demonstrated with a phase-change material, ultra-thin materials, and a dielectric metasurface.

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1. Introduction

The development of novel optical materials and metamaterials often benefits from the measurement of transmitted or reflected phase. This measurement, while straight-forward in theory, is difficult to implement in practice. For measurements in the visible/near-infrared range, 1 degree of phase shift corresponds to only several nanometers of optical path length variation. Practical sources of noise and drift such as passing cars, a door opening, building climate control cycles, and thermal or temporal variation of optical components can have a major impact on the measurement. Here we demonstrate a three-beam variation of a Mach-Zehnder interferometer, showing sensitive measurement largely unaffected by extrinsic sources of noise and drift. The setup is highly reconfigurable and continuously referenced, allowing samples to be measured under dynamic conditions such as temperature variation. Although not shown here, this design is compatible with spectrally and spatially resolved interferometry (SSRI) techniques [1].

2. Interferometer Design

The interferometer presented here is a three-beam variation of a Mach-Zehnder interferometer (Fig. 1a). The sample arm employs a birefringent beam displacer to produce two parallel, closely spaced beams. One of these beams (sample beam) is directed through the sample of interest while the other (reference beam) is directed through an adjacent area of exposed substrate. At the plane of measurement, both sample and reference beams interfere with a third beam (interfering beam) that has passed through a second arm of the interferometer. This method allows for continuous referencing of the sample measurement. As the sample and reference beam traverse nearly identical optical paths, most sources of noise and drift effect both equally and are excluded from the measurement. This allows for highly accurate, highly stable phase measurement over long periods of time (Fig. 1c). The measurement in Fig. 1c was taken with reference and sample beams passing through the same glass substrate, with no additional sample. The blue data represents the referenced phase shift measurement, while red and yellow correspond to the raw sample and reference phase values. Over the course of 16 hours, the phase shift data has a standard deviation of 2.8 degrees, compared to 41.6 degrees for the sample phase. Over a 10-minute averaging time, the phase shift noise has standard deviation of 0.56 degrees and the sample phase 6.9 degrees. This demonstrates significant stabilization of both drift and noise. The two arms are aligned at a slight relative angle to produce a series of fringes (Fig. 1b).

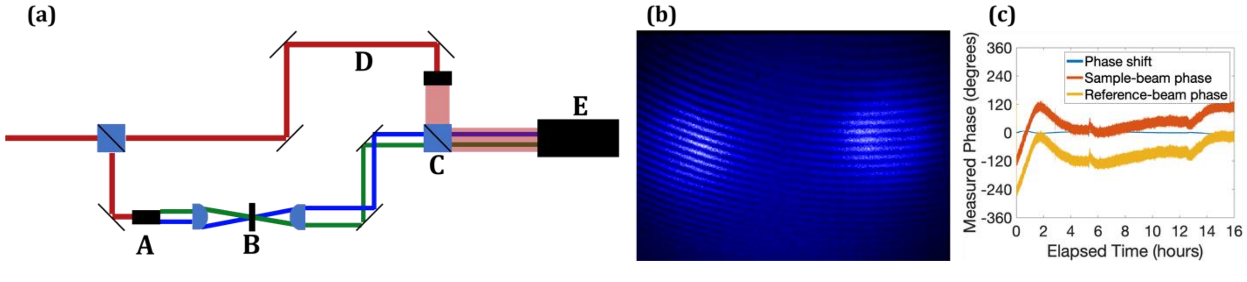

Fig. 2. (a) Schematic diagram of interferometer. Birefringent beam splitter, A, creates sample (green) and reference (blue) beams. An objective lens focuses the two beams to the sample plane, B, with an imaging lens immediately following. A micrometer-controlled path delay, D, allows for adjustment of the interfering path length to maintain coherence. A beam splitter, C, recombines the three beams, allowing them to interfere at the camera plane, E, at a small angle. (b) Interference fringes produced between interfering beam (large spot) and sample (left) and reference (right) beams. (c) Demonstration of enhanced stability and precision due to the three-beam method.

Phase measurement is made by observing the shift of the fringe pattern by taking a 2D Fourier transform (FT), isolating the peak corresponding to the fringes, and extracting the phase from the complex FT. Observation of fringe shift rather than amplitude allows for simultaneous measurement of sample transmittance and phase. Transmittance is calculated by comparison of fringe contrast. For the purposes of alignment with small samples, a microscope is built into the design, along with optics to focus the sample and reference beams to small spot sizes. The set-up is highly reconfigurable. Samples may be mounted on stages, like the temperature control stage demonstrated below.

3. Demonstration of Dynamic Measurements

Robust interferometry is especially critical for dynamic measurements in which some stimulus, such as sample temperature, is variable in time. For the measurement to be accurate, the measured phase at different times must be co-referenced to isolate the effect of the varying stimulus from systemic drift. If the transmittance of the sample depends on the dynamic variable, this effect too must be separated from the phase measurement. To demonstrate these capabilities, measurements were made on a thin film of vanadium dioxide (VO_2), which undergoes an insulator-to-metal transition (Fig. 2a) [2]. The insulator-metal phase transition can be seen around 65°C, and the expected hysteresis loop is clearly visible.

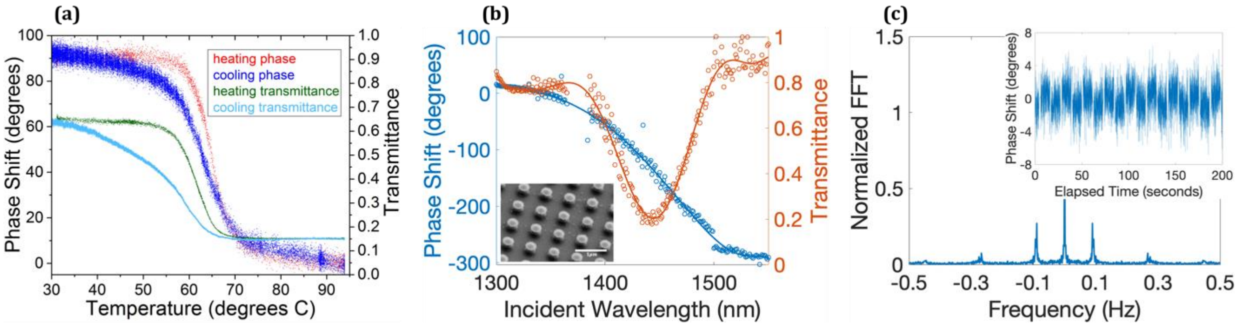

Fig. 2. (a) Phase shift and transmittance measurements, made simultaneously, of a 170nm VO_2 film grown using pulsed laser deposition. (b) Raw data and polynomial fit of spectral phase and transmittance measurement of a dielectric Huygens metasurface. Insert shows SEM of similar metasurface consisting of a-Si nanoantennas on a glass substrate and exposed to air. (c) Normalized FFT of phase measurement of few-atomic-layer MoS_2 film (inset). The amplitude of the square wave can be calculated using the amplitude of the harmonic peaks, and corresponds to a phase shift of 1.45 degrees, notably smaller than the ambient noise.

Spectral measurement, too, is broadly useful, particularly for the characterization of metasurfaces with strongly resonant features (Fig. 2b). This measurement is performed by sweeping the incident wavelength by way of white light source and monochrometer. The high temporal stability of the three-beam measurement allows for the use of filtering techniques to enhance the sensitivity. For samples expected to produce a very small phase shift, of similar magnitude to noise and drift, a square-wave Fourier transform (FT) method is employed. The sample is mounted on a motorized micrometer stage, which shifts the sample beam on and off the sample at a constant rate creating a square wave signal (Fig. 2c, inset). A FT filter is applied to the signal, extracting the amplitude of the square wave (Fig. 2c). The moderate frequency of the square wave allows both noise and drift to be filtered accurately. A natural application of this method is the measurement of ultra-thin few-layer materials. We demonstrate this measurement with few-atomic-layer MoS_2 (Fig. 2c), measuring a phase shift of 1.45 degrees against a background noise with standard deviation of 1.63 degrees and drift contributing a further standard deviation of ~0.8 degrees across the measurement. While isolated noise can be filtered by standard averaging, drift, or a combination of the two, cannot.

3. Conclusion

We have designed and tested a three-beam modified Mach-Zehnder interferometer. Continuous referencing leads to a significant decrease in both noise (93% decrease) and drift (92% decrease) of the measurement. Simultaneous phase and transmittance measurement enables rapid characterization of materials. Measurements are demonstrated with the phase change material VO_2 as well as a dielectric metasurface. A FT-based method for further reducing noise and drift for low-signal applications is demonstrated with a few-layer MoS_2 film.

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5. References

[1] Kevin O'Brian, *et al., Optics Letters*, 37, 19 (2012)
[2] Ryan Briggs, *et al., Optics Express,* 18.11, (2010)