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Phase-locked fiber interferometer with high frequency, low voltage fiber-stretcher and application to optical field reconstruction

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ABSTRACT

Light carries a great deal of information in the form of amplitude, phase, and polarization, any or most powerfully all, of which may be exploited for the characterization of materials or development of novel technologies. However, extracting the full set of information carried by light becomes increasingly difficult as sample feature sizes shrink and the footprint and cost of detection schemes must decrease as well. Here, a fiber-based interferometric scheme is deployed to extract this information from optical systems which may be assessed three dimensionally down to the nanoscale and/or temporally up to the bandwidth of electronic data acquisition available. The setup utilizes a homemade fiber stretcher to achieve phase-locking of the reference arm and is compatible with heterodyning. More interestingly, a simplified and less expensive approach is demonstrated which employs the fiber stretcher for arbitrarily frequency up-converted (with respect to driving voltage frequency) phase modulation in addition to locking. This improves the detection system's size, weight, power, and cost requirements, eliminating the need for an acousto-optic modulator and reducing the drive power required by orders of magnitude. High performance is maintained as evidenced by imaging amplitude and phase (and inherently polarization state) in micro and nano optical systems such as lensed fibers and focusing waveguide grating couplers previously imaged only for intensity distribution [1].

Keywords: Fiber optics, interferometer, scanning near-field optical microscopy, photonics, imaging

Fiber-based optical systems offer substantial advantages over free-space counterparts for certain applications. For example, they are compact, do not require alignment, avoid bulky optics and optomechanical mounts, can traverse unusual geometries, and have a protected beam path. The wide variety of fiber-based and fiber-coupled components such as laser diodes, polarization controllers, splitters and combiners available inexpensively as commercial off-the-shelf parts further make fiber systems an attractive option, particularly for systems that operate based only on the light's intensity. The fiber format also appears convenient for interferometric systems, given that polarization state may be easily manipulated, and combiners alleviate the hassles of alignment on the photodetector. Unfortunately, even in controlled environments, the extent of random phase drift is remarkable and detrimental to performance. In a homodyne implementation, reference and sample arm signals of particular amplitude interfere on the detector with randomized phase which results in a measured intensity that randomly drifts between that corresponding to sum and difference "rails." It was demonstrated that one may stabilize a fiber interferometer using a so-called fiber-stretcher comprised of fiber wrapped multiple times around a piezoelectric cylinder. Mechanically stretching the fiber results in change in the phase of the light [2]. However, extracting the phase of the sample arm requires rigorous knowledge of the stretcher response over the full range of operation [3]; otherwise the error signal stabilizing the feedback loop is not necessarily representative of the phase. Further, the reference phase should be fully modulated (at least through 2π radians) if an unknown or changing sample amplitude is to be measured.

Figure 1 depicts the arrangement of our initial approach to readily extract the field of the sample arm by a heterodyne approach. Fiber-coupled diode laser light with sufficient coherence length is split into sample (blue) and reference (red) arms. The sample arm generically consists of sample illumination and collection (taking the form of emission from a device and collection by a near-field scanning optical microscope below). The reference arm is further split into two branches, one active and one passive. The active arm is frequency shifted by an acousto-optic modulator (AOM) such that drift in either passive or active reference branches merely phase shifts a sinusoidal signal of constant amplitude, detected at photodiode 2. The phase drift is corrected by a homemade fiber-stretcher (figure 2) following the AOM that is driven by a fast PI controller which receives an error signal corresponding to change in photodiode 2. This renders the reference arm phase-locked such that the signal at photodiode 1 enables easy extraction of amplitude and phase as a function of polarization (reference is rotated to interfere with state of interest) of the sample arm. While this scheme works, it has a number of drawbacks associated with the AOM. First, while it is a fiber coupled component, it is

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fundamentally a free-space device where the light from the input fiber is collimated, frequency shifted in a crystal, and focused into the output fiber. The loss inherent to light leaving and re-entering a single-mode fiber is a drawback for low light applications. The AOM also takes up additional space and requires a 1 W RF driver.

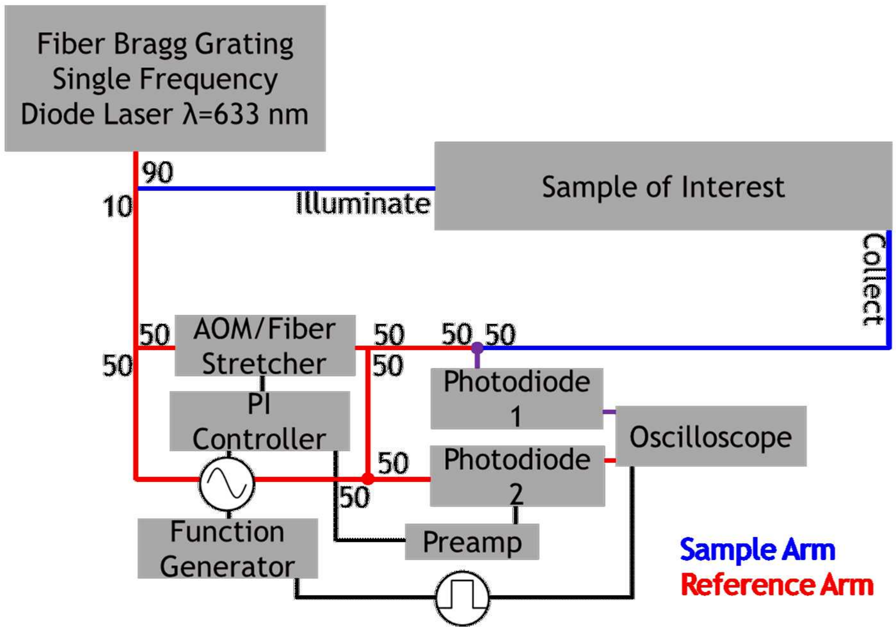

Figure 1: Schematic of the interferometric setup used in this study. Numbers indicate splitter/combiner ratios.

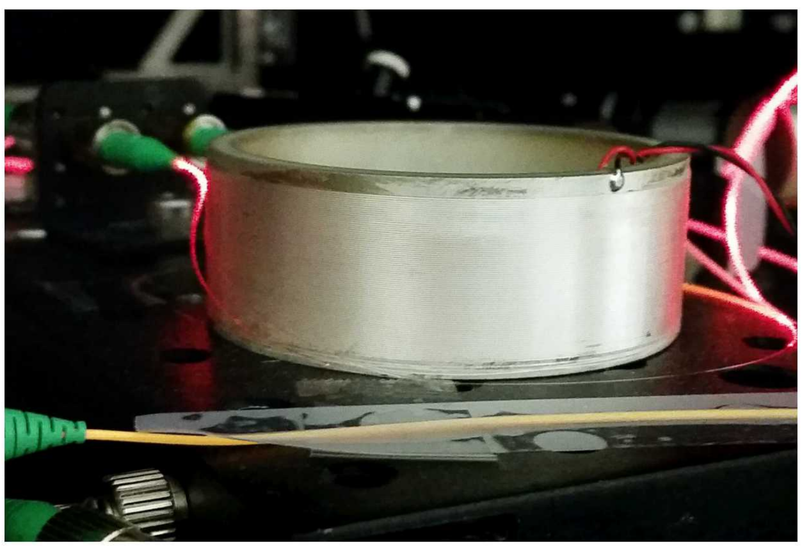

Figure 2: Photograph of the fiber-stretcher fabricated for phase locking the fiber interferometer's reference arm. Piezo cylinder dimensions are 68 mm (OD) x 25 mm (height). The structure has a resonance frequency near 15 kHz. Approximately 18.3 m of SM-600 fiber is coiled around the piezo in a single layer and affixed intermittently using cyanoacrylate adhesive. Fiber leading to and exiting from the unit was spliced to APC-terminated fiber of the same type.

Due to the high performance of the homemade fiber-stretcher, it is possible to eliminate the AOM altogether and use phase rather than frequency modulation to prevent signal fading. Summing a periodic drive signal with the error signal in the PI controller enables simultaneous modulation and locking of phase in the reference arm. Figure 3 demonstrates the modulation capability of the fiber-stretcher using a standard low power function generator. Shown in light blue is a 14.76 kHz trigger signal for reference. The other traces are collected from the reference arm of the interferometer as the fiber-stretcher is driven near its resonance frequency (14.76 kHz) with a sine wave of amplitude indicated to the right of the waveform. Shown in figure 4 by the plot of 2π phase modulation cycles as a function of drive voltage, the frequency is up-converted such that a nearly arbitrary effective phase modulation frequency may be chosen using a fixed frequency driver. The drive power with respect to the AOM is also dramatically reduced. Operating the fiber-stretcher with a 100 $mV_{pk\text{-}pk}$ drive voltage enables operation with only 563 nW, a reduction of six orders of magnitude. An effective frequency of 3.96 MHz is achieved with 5 $V_{pk\text{-}pk}$ drive voltage, which is at least three orders of magnitude faster (and at lower applied voltage) than demonstrated previously [2-5].

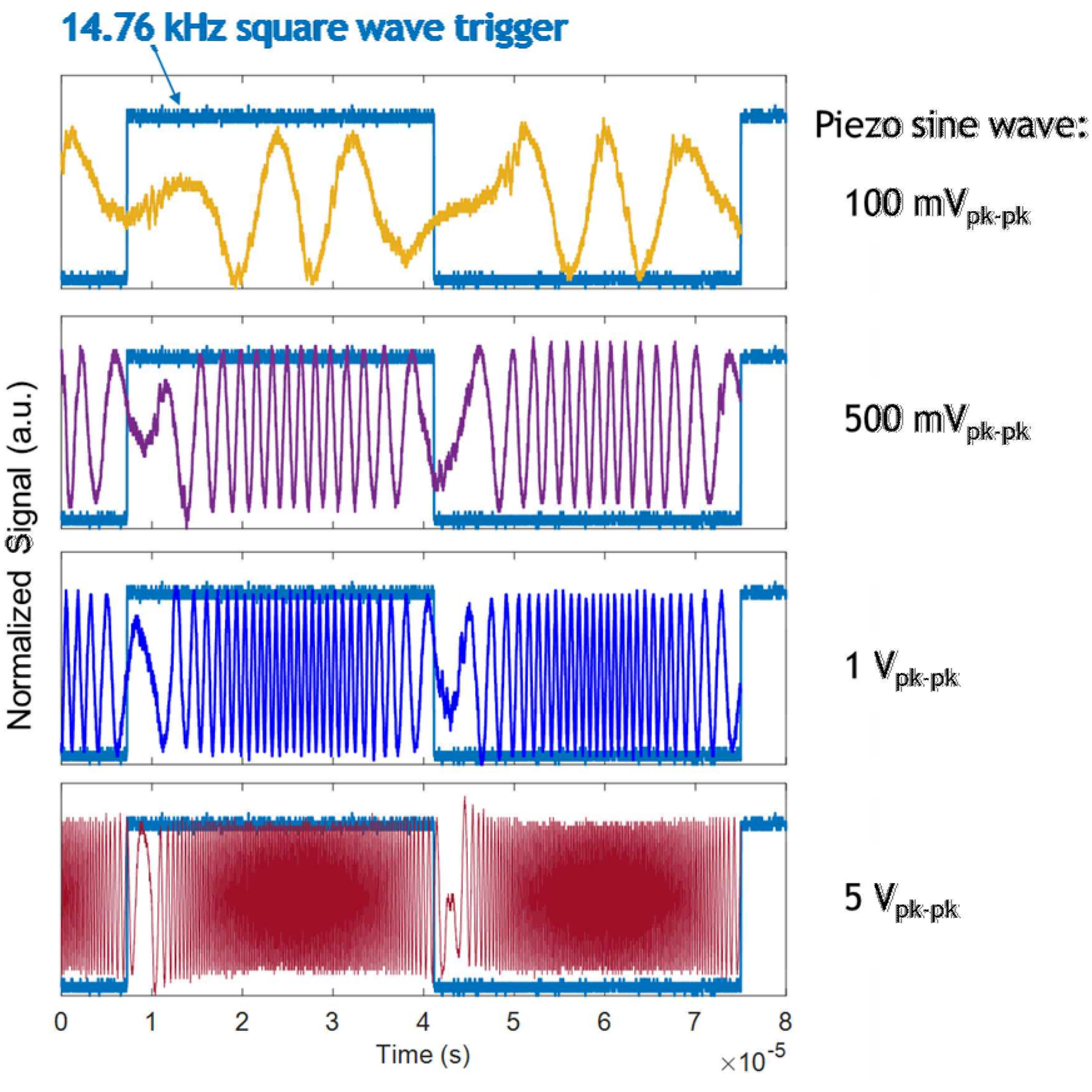

Figure 3: Oscilloscope traces captured for photodiode 2 with the fiber-stretcher providing phase modulation. The light blue square wave at 14.76 kHz is included for reference. A 14.76 kHz sine wave is applied to the fiber-stretcher with amplitude indicated to the right of the waveform.

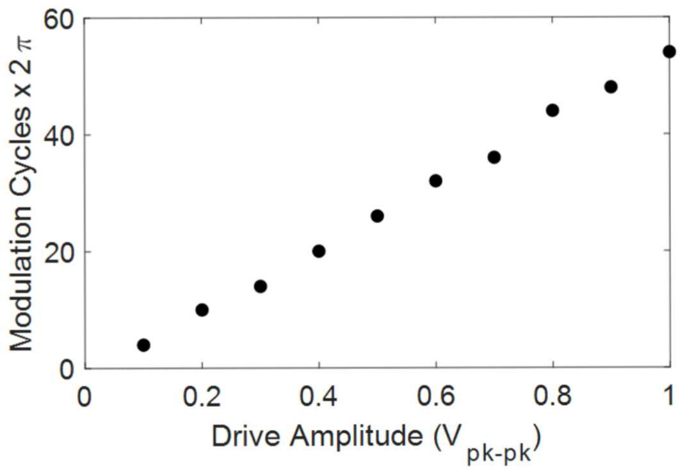

Figure 4: Number of full 2π phase cycles of interferometric signal as a function of piezo drive voltage, per single 14.76 kHz cycle.

The signal from the sample arm takes the form of the reference, however, it exhibits changes in amplitude and shifts in phase according to the sample as a function of space and/or time. Figure 5 shows amplitude and phase images of emission from a lensed single-mode fiber collected with a scanning single mode fiber cleaved flat. The X axis is parallel to that of the lensed fiber. Step size in the X axis is 66 nm. A phase change of 2π is measured in this axis every ten steps (660 nm) which matches the specified laser wavelength to within the resolution of the step size.

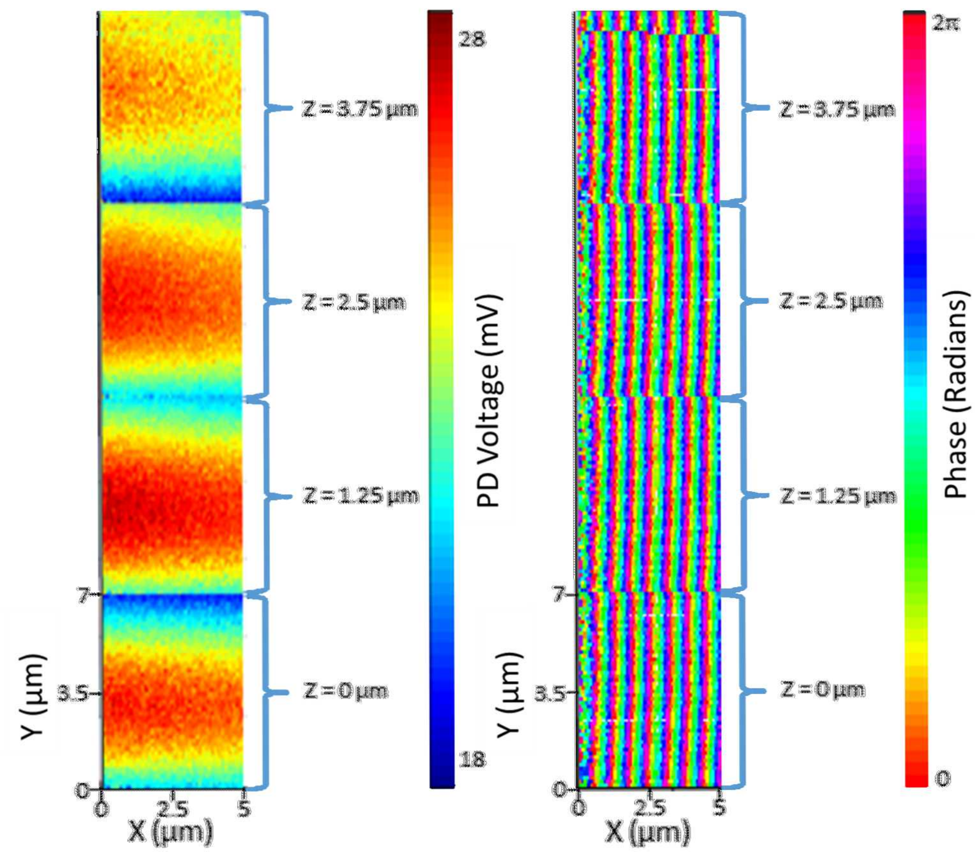

Figure 5: Photodetector voltage (proportional to E^2) and relative phase of light emitted from lensed fiber. Collection was performed with a single mode fiber cleaved flat and scanned through the beam (Z axis). Pixel resolution in each of the four planes is 66 nm x 140 nm.

Given correct reconstruction yielding the laser wavelength, a more complicated structure was considered. Focusing waveguide grating couplers are important elements for coupling light to and from integrated photonic structures [6]. Figure 6 shows amplitude and phase images collected at various heights above the surface of a focusing waveguide grating coupler analyzed previously only in terms of intensity of emission [1]. A fiber probe with a nanoaperture was used in a scanning near-field optical microscope apparatus to collect the images. The probe was affixed to a quartz tuning fork to facilitate Z axis positioning with respect to the position of the sample surface. A lensed fiber like that imaged in figure 5 was used to couple into the waveguide. The evolution of the amplitude profile and phase fronts moving away from the surface are consistent with finite difference time domain (FDTD) simulations including the inversion of the phase fronts from concave to convex profiles (left to right).

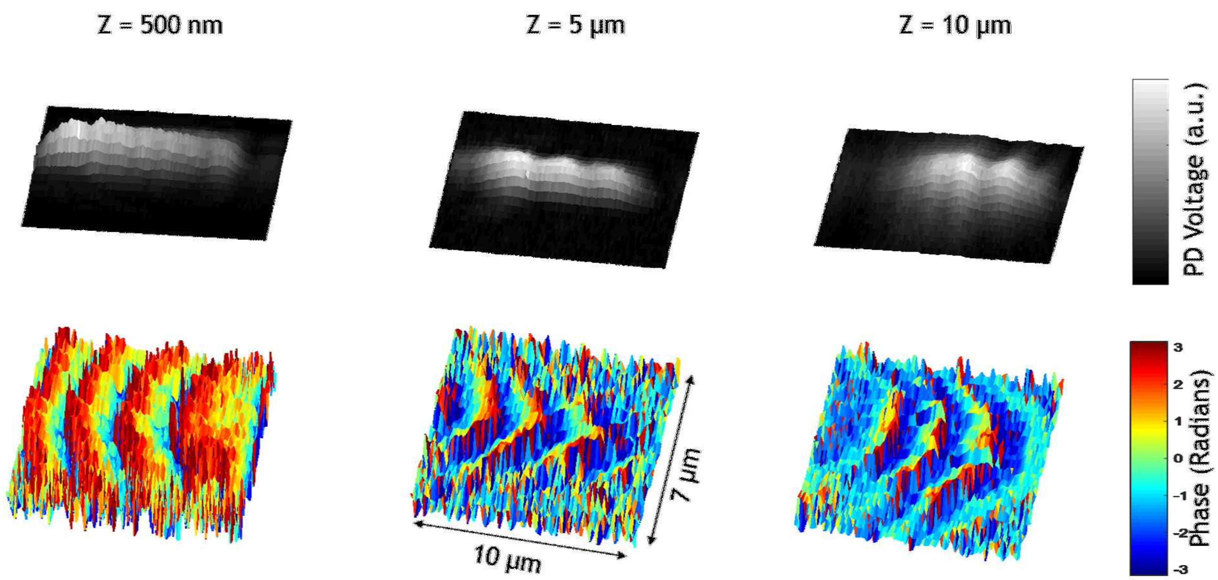

Figure 6: Amplitude (photodetector voltage proportional to E^2) and phase profiles for a focusing waveguide grating coupler previously imaged for intensity profile only in reference 1. Z position corresponds to height above sample surface. Pixel resolution for images left to right: 80 nm x 280 nm, 100 nm x 280 nm, and 100 nm x 280 nm.

An example of simulated compared to measured amplitude and phase profiles is provided in figure 7 for the plane Z = 10 µm above the sample surface. The measured profiles show strong resemblance to those predicted by simulation. All images in figures 6 and 7 correspond to electric field polarization parallel to the teeth of the grating.

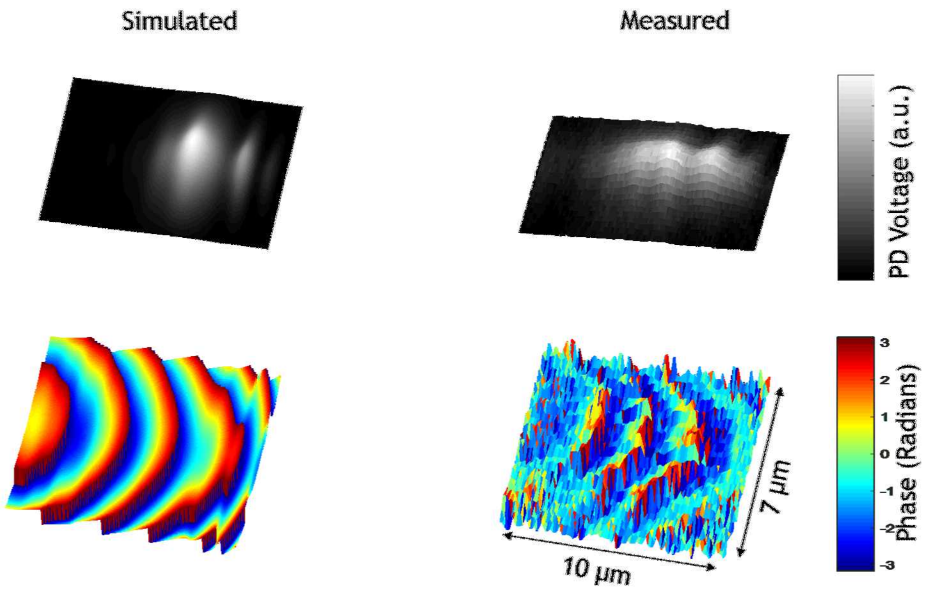

Figure 7: Amplitude and phase profiles simulated via FDTD method (left) and those measured (right) for Z = 10 μm above the focusing waveguide grating coupler surface.

In imaging, the reference arm remains locked for durations longer than required to obtain scanned probe images. Improved image quality will result from reducing drift in the sample arm (for example by reducing fiber length) and/or improving the speed of waveform transfer from the oscilloscope per pixel.

An inexpensive yet high-performance fiber stretcher has been fabricated and characterized. It shows high frequency operation with relatively low power and low voltage drive requirements. The ability to both phase modulate and lock the reference arm of a fiber interferometer was demonstrated. As a testament to performance of the interferometer and stability of the phase-locking, it was used to determine amplitude, phase, and polarization of micro and integrated photonic structures where a near-field scanning optical microscope setup collected emission three dimensionally. This arrangement may also be applied to temporal monitoring of the sample arm up to the bandwidth of the detection electronics.

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