Displacement Interferometry with Fiber-Coupled Delivery

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Abstract:

Heterodyne interferometry is a widely applied technique for length and displacement measurements in precision systems. Free-space optical beam delivery couples the source directly to the interferometer location. Conversely, fiber delivery is desired to decouple the source and interferometer. Drawbacks to using fibers are either time consuming alignment (PM fiber) or time varying polarization output (MM fiber). Jones matrices were used to analyze Joo-type interferometers to simulate the effects of using MM fiber inputs. The results showed loss of interference at some instances from the rotating polarization states. Measurements with a MM fiber coupled interferometer showed minimal polarization rotation and no interference loss.

Introduction and Motivation

Heterodyne displacement measuring interferometry is a widely applied technique which uses two beams at slightly different optical frequencies to measure displacements by measuring the optical path length change between reference and measurement arms. It is known for its high dynamic range, high signal-to-noise ratio, and direct traceability to length standards [1]. Primary applications for such a system can be found in calibration of other measurement tools such as capacitive sensors, inductive sensors, and optical encoders. Sub-nanometer level measurements must be achieved to satisfy industrial demands on performance [2]. The main error sources that limit the performance are the laser frequency stability [1], refractive index fluctuations in non-common optical paths [3], and periodic nonlinearity [4-5] in the measured phase due to frequency mixing, polarization mixing and a combination of polarization-frequency mixing [6]. Causes of mixing can be found in non-ideal optical alignment and manufacturing tolerances (i.e. leakage, ghosting).

Previously, we demonstrated three different Joo-type interferometer configurations which had no detectable periodic nonlinearity when employing free-space delivery [7-9]. Recently, we have also reported the Generalized Joo-type interferometer can be fiber delivered with two polarization maintaining fibers (PM fibers) while eliminating the fiber-induced Doppler shifts and maintaining a periodic error free measurement [9].

The Joo-type interferometer is characterized by two spatially separated source beams with a known frequency offset, which are held separate until a final interference surface. Periodic nonlinearity is significantly reduced by postponing beam overlap until the final interference surface [10-13].

When applying fiber delivery, a number of potential error sources are introduced. Fiber induced Doppler shifts due to stretch of the fiber can be mitigated by generating an optical reference after the fibers, one of the advantages of this design. Stress induced birefringence will however distort the source beam's original wave front and polarization state. Most fiber delivered systems will show a decrease in polarization state [14]. For a system where optical fibers are employed, this is often the largest source for polarization degradation. Polarization clean-up can be applied after fiber outcoupling [15, 16] using a polarizer, but this reduces the available optical power. Employing PM fibers reduces this effect but also increases the complexity and required robustness of the optical coupling between fiber and source.

In this proceeding, we discuss the possibilities and limitations with using MM fibers instead of PM fibers for Joo-type interferometer fiber delivery. We employ a Jones Matrix model of the Joo Retroreflector Interferometer including the time varying polarization effects in MM fibers.

The Joo Retroreflector Interferometer

The fiber-coupled Joo Retroreflector Interferometer, Figure 1, is the simplest form of the Joo-type interferometer configurations with fiber input coupling. Two optical beams with slightly different frequencies are delivered via two fibers. After delivery, a beamsplitter (BS) is used to split the spatially separated incoming beams into measurement and reference arms. The reference arms reflect via a vertical right angle prism (RAP) while the measurement arms reflect off a retroreflector (RR) attached to the target. The irradiance signals detected by PD_1 and PD_2 are of the form

$$I_1 \propto \cos\left(2\pi f_s t + \theta_1 - \theta_2 - \theta_r\right) \text{ and} \tag{1}$$

$$I_2 \propto \cos\left(2\pi f_s t + \theta_1 - \theta_2 + \theta_r\right) \tag{2}$$

where f_s is the heterodyne split frequency, θ_1 is the fiber Doppler shift of beam *1*, θ_2 is the fiber Doppler shift of beam 2, and θ_r is the phase change due to retroreflector motions. The measured phase change, θ_r, is the difference between the phases of I_1 and I_2 or $\left|(\theta_1-\theta_2-\theta_r)-(\theta_1-\theta_2+\theta_r)\right|=2\theta_r$, where the fiber Doppler shifts cancel. The measured phase is related to the retroreflector displacement by $\theta_r=\frac{2\pi Nnz}{\lambda}$, where N is the interferometer fold constant (N = 4), n is the refractive index, z is the optical path length difference, and λ is the optical wavelength.

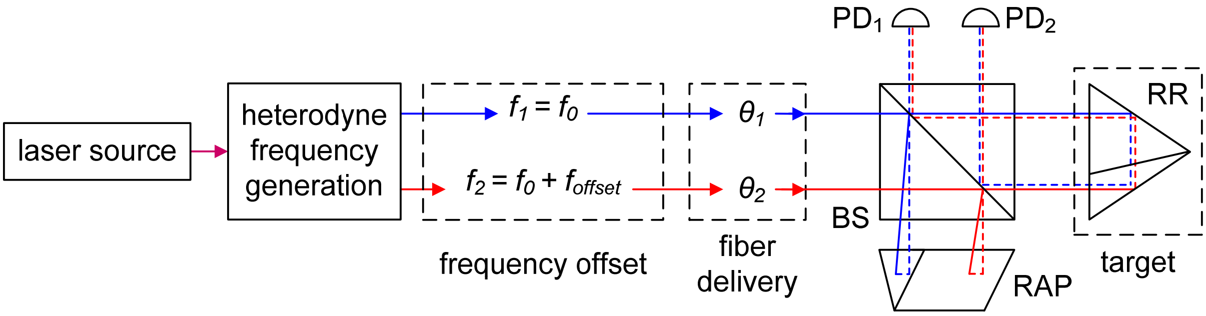

Fig. 1: Schematic the fiber coupled Joo Retroreflector Interferometer. Generation of the heterodyne source beams, with a frequency offset between them at the left, fiber-coupled delivery in the middle and the Joo Retroreflector Interferometer at the right.

Previous research

One of the concerns with the fiber delivery is limiting the polarization leakage of the unwanted polarization state into the system. Because a PM fiber has two different stress states (anisotropic core) and no coupling is ever perfect, some light will pass through the unwanted polarization state. Stress in the fiber should largely be common mode between the two polarizations states but the different stress levels can result in a minor difference, potentially leading to periodic nonlinearity.

In practice, this effect can be minimized with proper alignment techniques. The fiber delivery induced Doppler shifts do cause attenuation in vibration peaks in the Fourier domain. Figure 2 shows the error amplitude in the fringe domain for forwards and backwards traces for both fiber-delivered and free-space delivered Generalized Joo Interferometer [9], with a stage traveling at ±100 μm/s. The shifts between forwards and backwards motions are attributed to stage induced vibrations which change based on the Doppler direction. In the free-space measurements, the peaks at 0.8 and 1.2 Fringe Orders are sharp compared to their respective fiber delivered measurements.

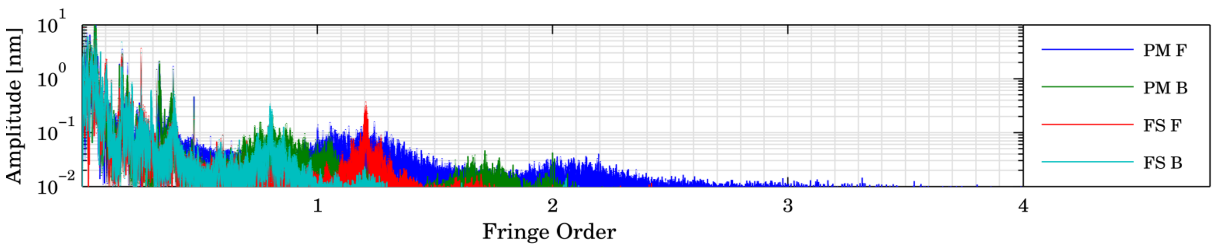

Fig. 2: Error amplitude for 100 µm/s linear forwards and backwards traces using the Generalized Joo Interferometer [9]. The fiber-coupled setup shows broadening of Fringe Orders, possible due to fiber dispersion [17]. (PM: polarization maintaining, FS: free-space, F: forwards trace, B: backwards trace).

Multimode Fibers and Polarization Rotation

Employing polarization maintaining fibers requires tight tolerances on the input beam alignment, both in space and polarization. Conversely multimode fibers can be used with only minor tolerances but will cause a random polarization state to be launched from the fiber into the system. The equivalence of a multimode fiber can be simulated by a uniform element possessing both linear and circular birefringence (i.e. a retarder/rotator pair [17]) built using Jones matrices [18]. With a horizontal fast axis for the retarder as

$$J_{mm}(\theta_i) = \prod_{i=1}^{M} P_i \cdot R_i = \begin{bmatrix} e^{j\Delta\tau_i/2} & 0 \\ 0 & e^{-j\Delta\tau_i/2} \end{bmatrix} \begin{bmatrix} \cos(\theta_i) & \sin(\theta_i) \\ -\sin(\theta_i) & \cos(\theta_i) \end{bmatrix} \quad (3)$$

where i is the fiber segment, M is the number of fiber segments (usually >100), P_i is the relative polarization delay matrix, R_i is rotation matrix, j is $\sqrt{-1}$, τ_i is the time delay, θ_i is the instantaneous angle of rotation, and φ_i is the instantaneous phase of the incoming wave. Because the fibers in this research are short (<10 m), the relative polarization delay between orthogonal polarization states is negligible [18]. However, the outcoming polarization can be anywhere between 0 and 2π. This presents a problem because two fibers are used to launch light into the interferometer, which means there will always be a situation where the outcoming polarizations states can be orthogonal, eliminating interference. The complete MM, fiber-coupled Joo retroreflector interferometer can be using Jones matrices since little depolarization occurs (where Mueller matrices would be better suited). The modeled irradiance at the detector is

$$I = \Re\left[\left(J_{bs} J_{rap} J_{bs} J_{mm,1} E_1\right) \bullet \left(J_{bs} J_{rr} J_{bs} J_{mm,2} E_2\right)\right] \quad (4)$$

where I is modeled irradiance; J_{bs}, J_{rap}, and J_{rr} are the Jones matrices for the beamsplitter, right angle prism, and retroreflector, respectively; $J_{mm,1}$ and $J_{mm,2}$ are the MM fiber matrices, and E_1 and E_2 are the two input electric field vectors. In this case, we only model one irradiance value at the detector because the polarization states are the same at both detectors. If the output rotations of $J_{mm,1}$ and $J_{mm,2}$ are varied at different rates, the normalized irradiance at the detector has specific instances where it loses the heterodyne signal, Figure 3. One potential solution to the interference loss problem is to use multimode-polarization maintaing fiber which has a larger core for easier coupling but maintains some fixed polarization output [19].

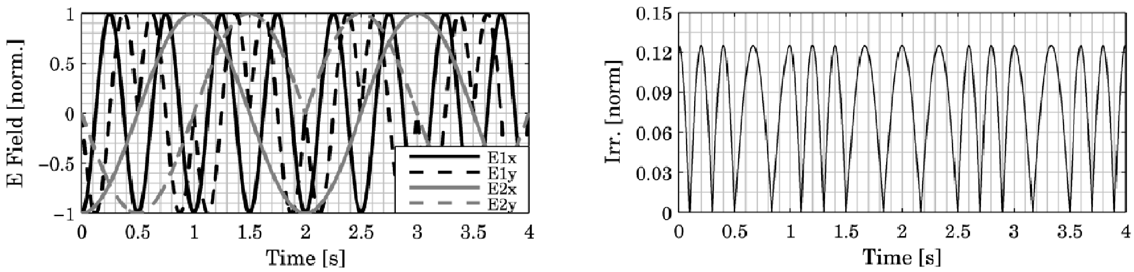

Fig. 3: (left) Simulated electric field amplitude changes for the assessing the fiber output polarization. (right) Detected irradiance as the input fibers continuously change orientation, causing signal loss when the signals are orthogonal.

Multimode and Polarization Maintaining Fiber Measurements

A general Joo Interferometer has been tested using both MM and PM fibers, Figure 4. Since the polarization state from MM fibers did not lose interference, sufficient signal was obtained to measure similar stage motions as with the PM fiber configuration. However, further experiments are needed to characterize the MM fiber effects for this purpose.

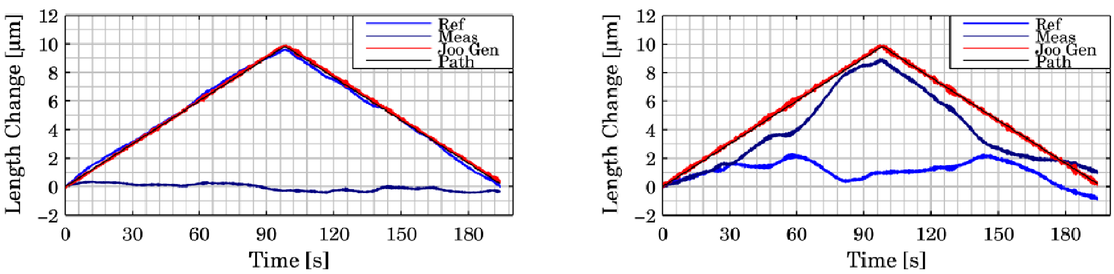

Fig. 4: Forward and backward scans of an air bearing stage measured with a Generalized Joo Interferometer using MM fibers (left) and PM fibers (right). The fluctuations of the measurements in blue are from fiber induced Doppler shifts.

Conclusions

The effect of a time varying polarization state analysis for a fiber coupled Joo Retroreflector Interferometer using Jones matrices has been described. The analysis shows when heterodyne source beams are assumed to be linearly polarized and rotate independently over time, there will be an instance that the interference signal is lost due to perpendicular polarization states. Measurements in which multimode fibers were employed showed no loss of signal during minor fiber disturbances. During fiber transport, the ideal linear polarization states will be altered, which is more present in MM fibers than in PM fibers. Further research is needed on the relationship between output polarizations in MM fibers relative to the applied stress on the fibers.

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