A fiber-diffraction interferometer using a coherent fiber optic taper

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Abstract
We present a fiber-diffraction interferometer using a coherent fiber optic taper (FOT) for optical testing in an uncontrolled environment. We use a coherent FOT and a single-mode fiber (SMF) with a thermally expanded core. Part of the measurement wave coming from a test target is condensed through an FOT and spatially filtered from an SMF to be the reference wave. Vibration of the cavity between the target and the interferometer probe is common to both reference and measurement waves. Thus the interference fringe is stabilized in an optical way. Generation of the reference wave is stable even with the target movement. The focus shift of the input measurement wave is desensitized by a coherent FOT.

Keywords: interferometers

1. Introduction
We describe a new fiber-diffraction interferometer using a coherent fiber optic taper (FOT) for stabilizing interference fringes in an uncontrolled environment. Manufacturing technology of optical components such as lenses and mirrors has evolved from the traditional polishing process to the automated machining process. A diamond turning machine is now able to achieve sub-μm accuracy over a few hundreds of millimeters in diameter, and injection molding technology produces high quality optical components with unprecedented yield rate. Testing those optics depends on optical interferometers due to their fast two-dimensional measurement and quality inspection at the operational wavelength of the test optics, but the interferometer is so vulnerable to external vibration that isolating the test table from the machining bed is essential in most cases. This fact prevents the interferometer system from being united with the machining center as a truly repeatable feedback sensor. Nowadays, research on vibration-insensitive (anti-vibration) interferometers has been spurred on to meet those industrial demands, including large-scale optics used for ignition facility and telescope optics [1]. Several techniques are used for desensitizing the interferometer to external vibration, and these can be categorized into three classes: common-path configuration, vibration feedback control and spatial phase shifting for real-time inspection.

The common-path configuration enables the vibration of test optics common to both reference and measurement waves, whereby the interference fringe between them looks static. The point-diffraction interferometer by Smartt and Steel [2] is an example which generates a reference wave from the focused measurement wave through a pinhole. The lateral shearing interferometer is a common-path interferometer, and optical pick-up lenses in a production line were tested by Cho and Kim [3]. The scatter plate interferometer is also a common-path interferometer with high immunity to external vibration [4].

Another technique for anti-vibration is direct feedback control. Yoshino and Yamaguchi [5] implemented a closed-loop phase-shifting Fizeau interferometer where optical phases are detected by a two-frequency optical heterodyne method. The Twyman–Green interferometer with a single point detector and an electro-optic modulator was also proposed [6].

The last category of the anti-vibration technique is a single-shot interferometer with spatial phase shifting. Phase shifting is necessary to enhance measurement accuracy, and this is accomplished spatially rather than by temporal phase-shifting techniques. Smythe and Moore [7] used polarization beam splitters and waveplates to acquire four phase-shifted fringes. Millerd et al [8] used holographic elements and polarizers to obtain four phase-shifted fringes. A pixelated phase mask can also be used for spatial phase shifting [9]. The spatial carrier phase-shifting technique is widely used due...
to its simple and easy embodiment [10]. By introducing a linear tilt phase term in a reference or test beam, a spatially modulated fringe can be obtained and analyzed with several algorithms, such as sinusoidal fitting [11] and Fourier analysis [12].

The aforementioned anti-vibration interferometers of the common-path configuration, closed-loop feedback control and spatial phase shifting are vying with each other with their relative advantages and disadvantages. Closed-loop feedback cannot control high-frequency vibrations over the bandwidth of a control loop, and the actual implementation is difficult. Spatial phase shifting suffers the same problem with high-frequency vibrations because the detector frame rate and shutter speed are generally limited, and highly repeatable measurement is practically impossible between successive tests, which lowers the system reliability. Common-path interferometers are ideal for stabilizing fringes in principle, but they usually lack real-time capability due to inherent temporal phase-shifting principles.

Combining the common-path configuration with a spatial phase-shifting technique can be a promising solution to anti-vibration interferometry. For example, Kwon [13] made three phase-shifted fringes with a phase grating and a pinhole achieving a common-path real-time interferometer. Millerd et al [14] from 4D Technology Corporation combined a point-diffraction interferometer with their spatial phase-shifting interferometer. Both interferometers use pinholes and their diffracting fields as reference waves. Recently, Kihm et al [15] reported this type of interferometer using a single-mode fiber (SMF), but this suffers from difficulties of focusing an aberrant measurement beam into the small core of an SMF. Defocusing or lateral vibration of the target severely affects the beam intensity coming out of the SMF. Therefore fringe visibility changes when a large vibration is involved. This paper overcomes that weakness and introduces a new type of interferometer.

The main idea of this research is condensing a measurement wave through a coherent FOT and an SMF with a thermally expanded core (TEC) to generate a reference wave. Vibration of the cavity between the target and the interferometer probe is common to both reference and measurement waves; thus the interference fringe is stabilized in an optical way. Generation of the reference wave is stable even with the target movement. The focus shift of the input measurement wave is desensitized by an FOT. The uncertainty of measurement results can be lowered due to highly repeatable performance even with external vibrations. The principles will be explained in section 2, and the experimental results will be detailed in section 3 followed by our conclusions in section 4.

2. Principles

The fiber-diffraction interferometer using an FOT is shown in figure 1. Any type of laser which is linearly polarized and spatially coherent can be used as a light source. Continuous wave lasers like He–Ne lasers or super luminescent diodes (SLD) of short coherence length can be used for general purposes. Pulse lasers could be used for stroboscopic inspection. The laser is filtered through a pinhole and collimated by a lens becoming a well-defined plane wave. A half-wave plate 1 (HWP1) rotates the polarization angle of the measurement wave, which is circularly polarized, is then linearly polarized in the orthogonal direction after the QWP and passes through the PBS1. HWP2 rotates the polarization angle of the measurement wave, and thus controls the split ratio between two arms at PBS2. The reference arm is composed of a focusing lens, an FOT and an SMF with a TEC to make a spatially filtered wavefront. A corner cube (CC) in the measurement arm translates to compensate for the optical path length difference between the two arms. PBS3 combines those two beams and a polarizer (P) with 45° filters in the diagonal direction making interference fringes at the detector.

When phase shifting is required for wavefront analysis, detectors equipped with a spatial phase shifter [8, 9, 15] could be used. Translation of the CC for temporal phase shifting might be adopted in a vibration-isolated environment. In this paper, we focus mainly on the verification of using an FOT in fiber-diffraction interferometry. Also we assume that optical parts comprising the interferometer are fixed as a single body. The relative motion or vibration of the test surface does not...
affect the alignment of the interferometer components. This can be justified in a general optical testing environment where an unstable cavity between the probe and a target is the major contributor lowering repeatability.

Fringe stabilization is possible even with external vibrations by generating a reference wave out of the measurement wave. The shared vibratory phase, which is mainly piston motion, cancels out and the fringes look static. A pinhole has been used for this purpose in point-diffraction interferometry [2, 16]. They use a sidelobe of the focused measurement wave, and tilted fringes are inevitable. Demodulating fringes [11, 12] lowers measurement accuracy, and high-frequency features cannot be recovered. An SMF can be used due to the high-quality wavefront output and easy embodiment [15], but the difficulty of focusing the aberrant measurement wave into the small core of a fiber poses doubt about practical uses. Increasing coupling efficiency of a laser source in an SMF has been a major research activity in optical communication, and thermally expanding the core (TEC) of a fiber is an example [17].

In this research we propose to use an FOT as a beam coupler for interferometric uses. An FOT consists of a large number of optical fibers fused together to form a coherent bundle. The bundle is heat formed, resulting in the variation in its diameter from one end to the other. The magnification of a taper is simply the ratio of the diameter of the end faces, which is generally 2–5×. The light transmission of an FOT is given in terms of the internal transmission of a glass core, Fresnel reflection at the end faces and the ratio of the core area to the total area, termed the packaging fraction (PF). The transmission \( T \) can be expressed as

\[
T = \text{PF} t_f \exp(-\beta \lambda L),
\]

where \( t_f \) is the Fresnel transmission factor, \( \beta \) is the absorption coefficient of the core glass and \( L \) is the length of the taper [18]. Light transmission can be increased by an anti-reflection (AR) coating on the input and output ports of the taper. A pinhole or a coated mask on the small end face blocks unwanted spurious modes [19] and passes only a single mode by point diffraction.

Immunity to the focus shift at the input port is achieved by condensing light through an FOT. The input end face of a taper is placed near the aperture stop of a focusing objective lens. This slightly defocused input beam looks static at the output, even when the vibration of the target changes the direction (tilt) and divergence angle (focus) of the measurement wave. The high numerical aperture (NA) of the FOT, which is 1, captures almost every incoming field from the objective lens. The beam spot size at the output port is reduced according to the reduction ratio of the taper. Multi-mode fields at the output, however, should be filtered into a single mode to be used as the reference wave [20, 21]. A TEC-processed SMF is used to combine individual fibers at the output of the FOT. Then, the reference wave from the SMF is quite stable in its amplitude while carrying vibrant phase motion of the target.

Figure 2. Coupling efficiency test with respect to the input focus shift: (a) single-mode fiber (SMF) only, (b) thermally expanded core (TEC) fiber only, (c) fiber-optic taper (FOT) and SMF, (d) FOT and TEC fiber; PD: photo-detector.

Considering the power of available lasers and the sensitivity of detectors, transmission loss through an FOT and a TEC-processed SMF is not a problem in interferometric applications [22]. The following section explains the actual implementation and verifies the use of an FOT in fiber-diffraction interferometry.

3. Experimental results and discussion

The reference wave is generated by fiber diffraction from the end face of an SMF. Focusing the aberrant measurement wave into the small core of an SMF is difficult when the test optic has vibrational motion. Axial motion makes the beam defocused at the input port. Lateral or tilt motion shifts the beam focus and lowers the coupling efficiency more severely. When large vibration is involved at the cavity between the test optic and the interferometer probe, the amplitude of the reference wave fluctuates accordingly. Thus we cannot get enough stable fringes for practical phase measurement. The objective of this research is to get stable fringes immune to the focus shift of the measurement wave.

We verified the improvement of using an FOT by comparative experiments shown in figure 2. The laser is focused into an SMF, and a photo-detector (PD) captures the output intensity to examine the coupling efficiency. The laser is rotated to simulate tilt motions of the measurement wave. We tested with four different set-ups: using (a) an SMF, (b) a TEC fiber, (c) an FOT and an SMF, and (d) an FOT and a TEC fiber. Figure 2(a) shows a conventional method using an SMF in fiber-diffraction interferometry. The TEC fiber in figure 2(b) has a longitudinal variation of the core diameter. The mode-field diameter of the input end becomes 10 \( \mu \text{m} \) from 4 \( \mu \text{m} \) after the TEC process. This makes the coupling less sensitive to the beam focus. We used an FOT from Schott (see footnote 1). The diameter of the large end is

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1 SCHOTT North America, Inc., 555 Taxter Road, Elmsford, NY 10523, USA. http://www.us.schott.com/lightingimaging/english/ (accessed on July 2010).
The magnification is 3.1:1, which is the ratio of end face diameters. The element size of each fiber at the large end side is 6 μm, and the ratio of the core and the cladding area is 1:1. The PF in equation (1) is lower than 50% due to extramural absorption (EMA), which eliminates stray light through the cladding [23]. The refractive index of the core is 1.810 and the NA of the fiber at the end face is 1 from the manufacturer’s specification (see footnote 1).

The output is a convolution process between the focused laser and the input modal field of the fibers and the FOT. The NA of the SMF and the TEC fiber is 0.12, while the NA of the FOT is 1. The mode-field diameters of the SMF and the TEC fiber are 4 μm and 10 μm, respectively. In the case of (c) and (d) in figure 2, the mode-field diameter depends on the magnifications of the lens and the FOT. We used a lens with 1× magnification and an FOT with 3.1× magnification. The input mode-field diameters of figures 2(c) and (d) are 12 μm and 31 μm, respectively.

Figure 3 shows the experimental results from the set-up shown in figure 2. The coupled intensity output from the PD is normalized in each case. Immunity to the focus shift can be compared by their relative output profiles, not their maximum values. If the plot is steep in a small input variation, the sensitivity to the focus shift is high. The SMF is the most sensitive, as shown in figure 3(a). The TEC fiber in figure 3(b) is relatively insensitive to the focus shift due to the enlarged mode-field diameter. The FOT has a large NA, accepting almost every incoming field, but the EMA makes the beam fluctuate, as shown in figure 3(c). This problem can be minimized by using a TEC fiber, as in figure 3(d). The FOT’s large NA makes the output robust to the focus shift, and the TEC fiber’s large mode-field diameter mitigates the EMA effect. About five times improvement is observed in terms of the acceptance angle when we compare the 1/e² intensity outputs of figures 3(a) and (d).

Figure 4 shows an experimental set-up of the fiber-diffraction interferometer using an FOT and a TEC SMF. Optical components are arranged similar to the layout of figure 1 except for the test surface. We used a flat mirror instead of a spherical mirror. A flat mirror is suitable for evaluating immunity to the focus shift due to tilt motion. The TEC SMF is bent 90° to filter out unwanted multi-modes effectively within a short optical path. Figure 5(a) shows an interferogram when the test surface has a tilt angle of 0.02°. The noisy background is due to the speckles coming from optical surfaces comprising the interferometer. This coherent noise can be minimized when we put imaging optics with a spatial filter in front of the camera and image the test optics. Figure 5(b) was obtained when the test surface was rotated by 0.2°. The fringe visibility is comparable to that of figure 5(a). This is expected in figure 3(d), where the coupled intensity output is over 80% of its maximum value at an angle 0.2°.

The fiber-diffraction interferometer using an SMF [15] cannot obtain fringes like figure 5(b). As evident in figure 3(a), the coupled intensity output from an SMF is almost zero at an angle 0.2°. This result proves the improvement in performance with the use of an FOT in fiber-diffraction interferometry.

4. Conclusions

We have proposed a new fiber-diffraction interferometer using a coherent FOT for stabilizing fringes in a vibrational optical testing environment. A reference wave is generated by condensing the measurement wave through a coherent optical fiber and an SMF with a thermally expanded core. Experimental comparison proved the superior coupling efficiency of the
proposed method. Combining this technique with a spatial phase shifter increases measurement repeatability as well as freezing vibrations, whereby an ideal vibration-insensitive interferometer could be realized. Cascading multiple FOTs to study coupling efficiency and comparing with the state-of-the-art commercial interferometers will be the subject of future work.

References

[1] Wyant J C 2003 Dynamic interferometry Opt. Photon. News 14 36–41
[2] Smartt R N and Steel W H 1975 Theory and application of point-diffraction interferometers Japan. J. Appl. Phys. 14 (Suppl. 14) 351–6
[3] Cho W-J and Kim S-W 1997 Stable lateral-shearing interferometer for production-line inspection of lenses Opt. Eng. 36 896–900
[4] North-Morris M B, VanDelden J and Wyant J C 2002 Phase-shifting birefringent scatterplate interferometer Appl. Opt. 41 668–77
[5] Yoshino T and Yamaguchi H 1998 Closed-loop phase-shifting interferometry with a laser diode Opt. Lett. 23 1576–8
[6] Yamaguchi I, Liu J-Y and Kato J I 1996 Active phase-shifting interferometers for shape and deformation measurements Opt. Eng. 35 2930–7
[7] Smythe R and Moore R 1984 Instantaneous phase measuring interferometry Opt. Eng. 23 361–4
[8] Miller J E and Brock N J 2001 Methods and apparatus for splitting, imaging and measuring wavefronts in interferometry US Patent 6,304,330
[9] Miller J E, Brock N J, Hayes J B, North-Morris M B, Novak M and Wyant J C 2004 Pixelated phase-mask dynamic interferometer Proc. SPIE 5531 304–14
[10] Melozzi M, Pezzati L and Mazzoni A 1995 Vibration-insensitive interferometer for on-line measurements Appl. Opt. 34 5595–601
[11] Ransom P L and Kokal J V 1986 Interferogram analysis by a modified sinusoid fitting technique Appl. Opt. 25 8199–204
[12] Takeda M, Ina H and Kobayashi S 1982 Fourier-transform method of fringe-pattern analysis for computer-based topography and interferometry J. Opt. Soc. Am. 72 156–60
[13] Kwon O Y 1984 Multichannel phase-shifted interferometer Opt. Lett. 9 59–61
[14] Miller J E, Brock N J, Hayes J B and Wyant J C 2004 Instantaneous phase-shift point-diffraction interferometer Proc. SPIE 5531 264–72
[15] Kihm H and Kim S-W 2005 Fiber-diffraction interferometer for vibration desensitization Opt. Lett. 30 2059–61
[16] Medecki H, Tejnil E, Goldberg K A and Bokor J 1996 Phase-shifting point diffraction interferometer Opt. Lett. 21 1526–8
[17] Hanafusa H, Horiguchi M and Noda J 1991 Thermally-diffused expanded core fibers for low-loss and inexpensive photonic components Electron. Lett. 27 1968–9
[18] Peli E and Siegmund W P 1995 Fiber-optic reading magnifiers for the visually impaired J. Opt. Soc. Am. A 12 2274–85
[19] Shi K, Omenetto F G and Liu Z 2006 Supercontinuum generation in an imaging fiber taper Opt. Express 14 12359–64
[20] Li Y-F and Lit J W Y 1985 Transmission properties of a multimode optical-fiber taper J. Opt. Soc. Am. A 2 462–8
[21] Leon-Saval S G, Birks T A, Bland-Hawthorn J and Enslund M 2005 Multimode fiber devices with single-mode performance Opt. Lett. 30 2545–7
[22] Kosterin A, Temyanko V, Fallahi M and Mansuripur M 2004 Tapered fiber bundles for combining high-power diode lasers Appl. Opt. 43 3893–900
[23] Siegmund W P 1966 Fiber optical image transfer device having a multiplicity of light absorbing elements US Patent 3,247,756