Fiber-optic displacement sensor with 4 nm resolution (~ λ/400) at 1550 nm using off-axis interferometer

Zhen Tian[1], Nan-Kuang Chen[1,*], Perry Ping Shum[2], Lina Suo[1], Yicun Yao[1], Liqiang Zhang[1], Kenneth T. V. Grattan[3], B. M. Azizur Rahman[3], and Raman Kashyap[4]

[1]*School of Physics Sciences and Information Technology, Liaocheng University, Liaocheng 252000, Shandong, China*
[2]*Department of Electrical and Electronic Engineering, Southern University of Science and Technology, Shenzhen 518055, China*
[3]*Department of Electrical and Electronic Engineering, City, University of London, London EC1V 0HB, United Kingdom*
[4]*Department of Engineering Physics, Polytechnique Montreal, Montreal H3C 3A7, Canada*
E-mail: nankuang@gmail.com

Abstract: A fiber-optic displacement sensor with ~λ/400 spatial resolution, at an operating wavelength of ~1550 nm, using an off-axis fiber interferometer and achieving the best displacement resolution of 4-nm in the optical domain has been demonstrated.

OCIS codes: (060.2340) Fiber optics components; (260.3160) Interference.

1. Introduction

Fiber-optic interferometry is essential for measuring physical parameters with high precision and many different kinds of interferometric configurations, including Michelson, Fabry-Perot, Mach-Zehnder, Sagnac, Fizeau, Shearing, Rayleigh, and Linnik interferometers are widely used [1-3]. Among them, the Michelson interferometer is especially important due to features such as high accuracy and stability for distance measurement, offering good spatial resolution of a half-wavelength. However, such a half wavelength displacement resolution is normally not likely to be below 100 nm, when considering currently available lasers, which makes the traditional fiber-optic displacement sensor not a strong candidate for the sensing applications in semiconductor photolithography and fabrication needed today. For photolithography, the current narrowest linewidth for the patterns on the mask is ~2 μm and < 3 nm for contact aligners and for steppers, respectively, which means the entire system stability should be carefully controlled. Similarly, the e-beam writer can also achieve a nanometer-scale pattern linewidth and thus nanoscale-resolution translation stages are urgently needed for enlarging the writing area. Moreover, for use in fabrication techniques such as nanoimprinting, wire bonding, and 3D-wafer bonding, the required displacement resolution needed ranges from a few tens of nanometers to <1 μm. Therefore, a displacement sensor with nanoscale resolution is critically needed to allow improvements in system accuracy required for the semiconductor industry. Currently, stepping motors, for example, can offer a nanoscale spatial resolution by using a diffracted LED light mounted on the motorized linear sliding stage to illuminate the optical grating with a pitch of 4 μm. The reflected optical signals are picked up by the photodiode and the detected sinusoidal electronic signals will then be equally divided into 1000 parts by a special decoder integrated circuit (IC), to achieve the required 4 nm resolution.

In contrast in this work, a 4 nm displacement resolution (~ λ/400) in the optical domain can be achieved using an off-axis interferometer (OAI) operating on the C-band wavelengths, without slicing the electronic signals. From Fig. 1(a), it is clear that the OAI is different from the conventional on-axis or paraxial interferometers, where a short segment of hollow core fiber (HOF) is spliced to a standard single mode fiber (SMF) and thus fractional core modes will be converted into cladding modes. The length of the OAI, sample A, is 223.3 μm, as shown in Fig. 1(b). The cladding modes are then deflected by the spherical fiber lens to produce many foci, in accordance with the individual cladding mode and thus many minor peaks can be found in the axial power distribution, as shown in Fig. 1(c). At point A, the mirror is placed at a distance d = 220 μm away from the fiber lens and thus will be in a good position for nanoscale resolution measurements. This is because many of the high order cladding modes are deflected to focus in that region to lead to intensity-spaced interference fringes. This is the mechanism by which an OAI is capable of reducing the displacement resolution limit from λ/2, using on-axis or paraxial interferometers, to down to ~ λ/400 for C-band wavelengths. Consequently, this approach to nanoscale high precision alignment is promising for those applications in photolithography and semiconductor fabrication processes.

2. Experimental set-up, measurements, and discussions

The OAI is extremely sensitive to small vibrations, environment noise, sounds of voices and local airflows. It must be mounted on a 4 nm displacement resolution stepping motor and operated within three-layer thick acrylate boxes, as shown in Fig. 1(d). The joint surface between the box and the optical desk should be filled with PU gasket material to block such small sound perturbations. The Optical Spectrum Analyzer (OSA), Optical Power Meter (OPM), and superluminescent diodes (SLD) spanning 1250-1650 nm are used for all measurements done at the midnight in a clean

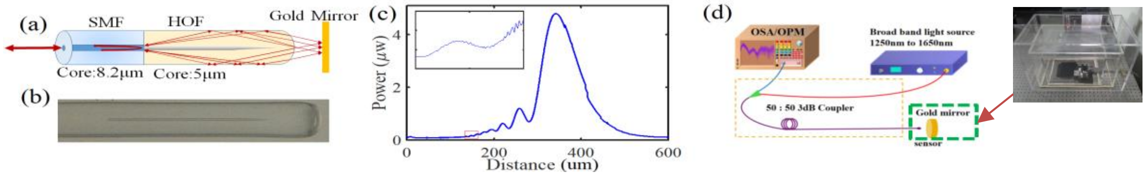

Fig. 1. (a) Device structure of OAI. (b) Microphotograph of OAI, sample A. (c) Axial power distribution, sample A. (d) Experimental set-up.

room on ground floor, far away from the main roads. The whole set of experiments must be placed on the smart table (Newport®: RS 2000™) to guarantee high measurement accuracy. The above criteria should be strictly satisfied to achieve 4 nm displacement resolution, which must be stable for typically four hours, otherwise the interference spectra seen on the OSA will not be stable and will be reflected immediately. The multiple high order cladding modes are excited from the splicing point between the SMF and HOF due to core size mismatch. The wavelength beating ascribed to multi-beam interference can be found in the spectral responses, using sample B, shown in Fig. 2(a), when d is 200 μm. The beating phenomenon changes with varying d, shown in Fig. 2(b) using sample B. Obviously, the frequency of the beating envelope increases with increasing d, since more high order cladding modes are involved in the interference effect. In Fig. 2(b), the beating disappears when d approaches >300 μm since most of the high order cladding modes survive well only when d is <300 μm. To move to the position A in Fig. 1(c) using sample A, the mirror is carried by a high precision stepping motor with 4 nm displacement resolution and placed at d = 200 μm. The mirror is moved away, with an increment Δd = 4 nm and the corresponding spectral responses are shown in Fig. 2(c), (with an optical resolution of 0.05 nm). The wavelength shift linearly changes with Δd and a linear fit to the slope yields 0.03018 nm/nm. With a linear relationship between the wavelength shift and displacement, a 1 nm displacement can be estimated by the interpolation method, when a wavelength shift of 0.03018 nm is measured using the OSA. Figs. 2(e) and 2(f) shows similar results when the mirror is moved to d = 220 μm, using sample A. This simple OAI is a very powerful demonstration of ~4 nm displacement resolution in the optical domain, with 1nm demonstrable from interpolation, emphasizing its importance for fiber OAIs employed in the semiconductor industry.

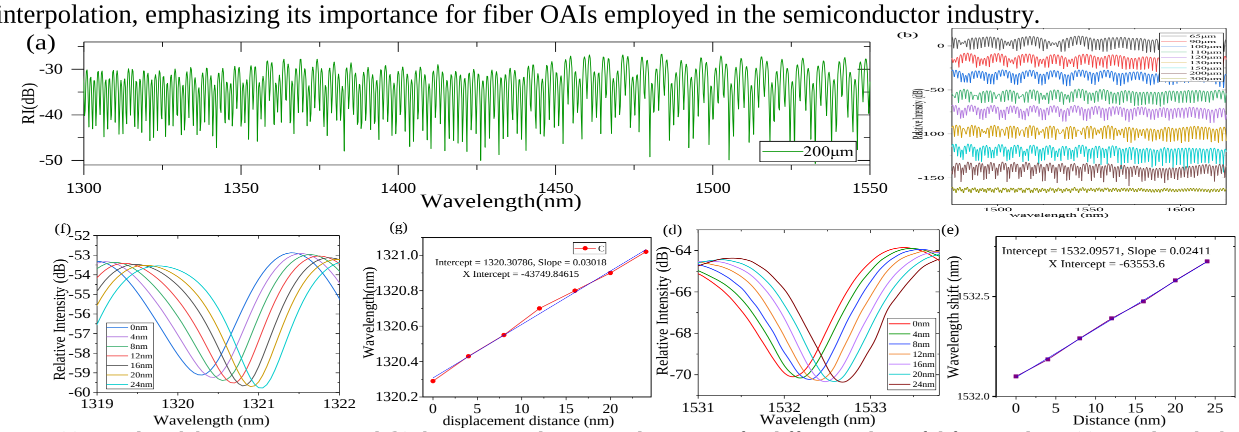

Fig. 2. (a) Wavelength beating spectrum and (b) the corresponding spectral responses for different values of d for sample B. (c) Wavelength shift versus displacement when d = 200 μm and Δd = 4 nm and (d) linear fit for sample A. (e) Wavelength shift versus displacement when d = 220 μm and Δd = 4 nm and (f) linear fit for sample A.

3. Conclusion

A fiber-optic displacement sensor with 4 nm in measurement and 1 nm by interpolation estimation, using an off-axis interferometer on the C-band wavelengths, has been demonstrated. The displacement resolution can be significantly improved from $\lambda/2$, conventional on-axis or paraxial interferometers, to reach ~$\lambda/400$ in the optical domain, based on this off-axis interferometry approach. In principle, optical signals can be further divided into 1000 parts by a decoder IC to achieve 1 – 4 pm displacement resolution, similarly to a commercial optical ruler. This OAI is clearly important to the development of advanced equipment for semiconductor photolithography and future fabrication processes.

4. References

[1] Y. E. Korchev, J. Gorelik, M. J. Lab, E. V. Sviderskaya, C. L. Johnston, C. R. Coombes, I. Vodyanoy, and C. R. Edwards, "Cell volume measurement using scanning ion conductance microscopy," Biophys J. **78**, 451 (2000).

[2] Q. Chai, H. W. Lee, S. G. Hong, Y. S. Lee, J. B. Park, J. Z. Zhang, and K. H. Oh, "Nanoliter liquid refractive index sensing using a silica V-groove fiber interferometer," Photon. Res. **7**, 792(2019).

[3] C. K. Yao, N. K. Chen, H. C. Chui, C. N. Liu, K. T. V. Grattan, B M A Rahman, "Real-time microanalysis on evaporation rate for cellular subpicoliter liquid droplet using off-axis fiber interferometer," **CLEO 2020** conference, San Jose, USA, May 11-15, 2020. paper no. SM4M.7.