Visibility in magnetostrictive fiber-optic interferometric sensors and its dependence on the input SOP

Changhai Shi (施长海), Jianping Chen (陈建平), Xinwan Li (李新碗), Ailun Ye (叶爱伦),
Junhe Zhou (周俊鹤), Yi Zhang (张 翼), Qing Xue (薛 青), and Lin Hong (洪 琳)

The State Key Laboratory on Fiber-Optic Local Area Network and Advanced Optical Communication Systems,
Shanghai Jiao Tong University, Shanghai 200030

Received April 7, 2005

The visibility in magnetostrictive fiber-optic interferometric sensors using a Gaussian laser beam is analyzed. It is shown that the conventional Gaussian laser beam has little influence on the visibility. The visibility depends strongly on the input state of polarization (SOP). We implement a cylindrical transducer and build a measurement setup with a polarization controller. The visibility dependent on the SOP of input light is measured. The estimated values are similar to the experiment results, which verifies the analysis.

OCIS codes: 060.2370, 060.2430, 120.3180, 120.6710.

Fiber-optic interferometric sensors have the unique advantages of high sensitivity and good linearity over wide dynamic range[1]. They have been investigated for sensing a variety of environmental parameters such as current[2], magnetic field[3,4], acoustic pressure[5], and temperature[6]. Especially, magnetostrictive fiber-optic sensors based on Mach-Zehnder (M-Z) interferometer have extremely high sensitivity and can be used to detect ultra weak magnetic field[7−9]. In such sensors, a fundamental parameter that decides the system sensitivity is the output fringe visibility of interferometer. A lot of work has been carried out to explore the visibility of the M-Z interferometer[10−12], which is determined by parameters including the length and optical intensity differences between sensing arm and reference arm, the linewidth of light source, and the state of polarization (SOP) of light for interferometers made of conventional single-mode optical fiber and couplers. Usually Lorentzian spectral lines were employed to analyze the system performance theoretically. In practical applications, Gaussian laser beams are frequently used in magnetostrictive fiber-optic interferometric sensors, therefore it is useful to carry out related analysis on the visibility performance.

In this paper, the visibility in magnetostrictive fiber-optic interferometric sensors using a Gaussian laser beam is analyzed. It is shown that the conventional Gaussian laser beam has little influence on the visibility. The visibility depends strongly on the input SOP. A cylindrical transducer, which has been proved to have the best magnetic field response[13], was implemented and tested in the experiments with a polarization controller (Agilent 11896A[14]). The visibility performance was analyzed. The estimated values are similar to the experiment results.

In magnetostrictive fiber-optic interferometric sensors, the phase shift sensitivity is proportional to the output fringe visibility of interferometer, which can be expressed as $V = V_0 \cdot \cos\eta$[11], where V_0 represents the optimum visibility of M-Z interferometer and is given by

$$V_0 = \frac{2[\alpha_{\mathrm{r}}\alpha_{\mathrm{s}}k_1k_2(1-k_1)(1-k_2)]^{1/2}}{\alpha_{\mathrm{r}}k_1k_2+\alpha_{\mathrm{s}}(1-k_1)(1-k_2)} \cdot \gamma(\tau), \tag{1}$$

where α_{r} and α_{s} are the optical loss in the reference and sensing arms, respectively, k_1 and k_2 are the power coupling coefficients of the two fiber couplers, $\gamma(\tau)$ is the normalized self coherence function of the light source. $\cos\eta$ is the normalized visibility defined as

$$\cos\eta = \{1-\sin^2\theta\sin^2(\Omega_{\mathrm{r-s}}/2)\}^{1/2}, \tag{2}$$

where $\Omega_{\mathrm{r-s}}$ is the rotation magnitude of general elliptic retarder $\Re_{\mathrm{r-s}}$, i.e. the net birefringence between two arms, θ is the angle between the input SOP and the azimuth of eigenmodes of the interferometer, on Poincaré sphere[11].

In practical applications, Gaussian laser beams are used frequently. The self coherence function of a Gaussian laser beam is given by[15]

$$r(\tau) = \exp\left[-\left(\frac{\pi\Delta\nu}{2\sqrt{\ln 2}}\tau\right)^2\right], \tag{3}$$

where $\Delta\nu$ is the half spectral width, $|\Delta\nu| = c\cdot\Delta\lambda/\lambda^2$, c is the velocity of light, and $\Delta\lambda$ is the linewidth; τ is the differential time delay of the interfering beams propagating in two arms of interferometer, $\tau = \Delta L/c$, ΔL is the length difference of two arms.

Using Eqs. (1) and (3), the optimum visibility V_0 as a function of the linewidth $\Delta\lambda$ of Gaussian laser beams is shown in Fig. 1. It is shown that as long as the linewidth is less than 1 nm, the optimum visibility is always larger than 0.8 when $\Delta L = 0.45$ mm. This is easy to be realized for a conventional Gaussian laser beam. For the M-Z interferometers employing conventional single-mode optical fiber and couplers made of it, factors affecting the visibility, such as the length and optical intensity differences between two arms, can be well controlled. The SOP of light remains to be a major source that influencing

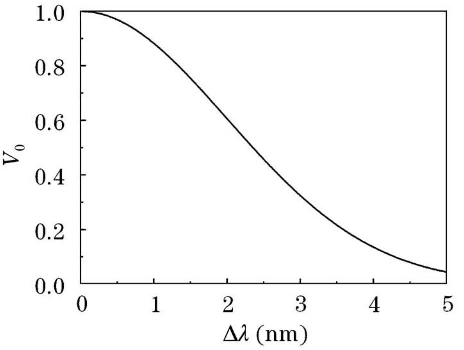

Fig. 1. Optimum visibility V_0 as a function of the linewidth $\Delta\lambda$ of Gaussian laser beams. $\alpha_r = 0.99$, $\alpha_s = 0.91$, $k_1 = 0.506$, $k_2 = 0.494$, $\Delta L = 0.45$ mm, $\lambda = 1550$ nm.

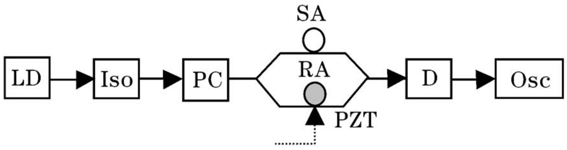

Fig. 2. Diagram of measurement setup. LD: laser diode, Iso: isolator; PC: polarization controller, SA: sensing arm; PZT: piezoelectric transducer; RA: reference arm; Osc: oscilloscope; D: optical detectors.

the visibility and stability. If the net birefringence between the two arms keeps unchanged, the input SOP may not only lower the visibility but also bring instability, i.e., visibility fluctuation between $V_{\max} = V_0$ and $V_{\min} = V_0 \cdot \cos(\Omega_{\text{r}-\text{s}}/2)$.

The measurement setup is shown in Fig. 2. The input SOP is altered by a polarization controller (Agilent 11896A). The complete and continuous polarization adjustability is achieved by independently adjusting each loop as a quarter-wave retarder over an angular range of 180°[14]. The angle between the input SOP and the azimuth of eigenmodes of the interferometer, θ, is given by

$$\theta = \varphi - \phi_0, \qquad (4)$$

where ϕ_0 is the azimuth of retarder $\Re_{\text{r}-\text{s}}$, φ is the azimuth of input light at the first coupler of the M-Z interferometer. $\varphi = \tan^{-1}(|Y_{\text{out}}|/|X_{\text{out}}|)$, where X_{out} and Y_{out} are the two orthogonal polarization output components of the polarization controller and are related to the input polarization components, X_{in} and Y_{in}, by the Jones matrix as

$$\begin{bmatrix} X_{\text{out}} \\ Y_{\text{out}} \end{bmatrix} = \prod_{i=1}^{4} \frac{1}{\sqrt{2}} \begin{bmatrix} 1 + i\cos 2\psi_i & i\sin 2\psi_i \\ i\sin 2\psi_i & 1 - i\cos 2\psi_i \end{bmatrix} \cdot \begin{bmatrix} X_{\text{in}} \\ Y_{\text{in}} \end{bmatrix}, \qquad (5)$$

where ψ_i is the azimuth of the ith retarder of the polarization controller.

We fabricated a cylindrical transducer. The fiber is Corning SMF-28 single-mode fiber and the length difference between the two arms is measured by Michelson precision reflectometer (HP8504A) as $\Delta L = 0.45$ mm. The sensing fiber was wound on a magnetostrictive material adhered to cylinder configuration. The reference fiber was wound around a cylindrical piezoelectric transducer (PZT) and was placed in the paunch of the cylinder configuration to form a compact structure for test and application convenience. Before the measurement, we tested the stabilization of the laser source for about 3 hours. It is shown that the dither of optical power is about 1 μW compared with the total power of 157 μW. Then we tested the stabilization of our measurement setup by an X-Y recorder for about 1 hour. The direct current (DC) voltage is 0.45 V, the dither is not more than 2 mV. The measurement setup is also shown to be extremely stable in laboratory environment.

The laser source used is of Gaussian shape with linewidth of 0.18 nm at wavelength of 1550 nm. Other parameters are $\alpha_r = 0.99$, $\alpha_s = 0.91$, $k_1 = 0.506$, and $k_2 = 0.494$. The output fringe visibilities were measured for various SOPs. Figures 3 and 4 show the comparison between experimental results and estimated results, where C is defined as $|Y_{\text{in}}|/|X_{\text{in}}|$. The discrepancy between the measured results may result from the possible slight difference in the exact azimuth of the adjusted quarter-wave retarder. As can be seen from the figures, the visibility is influenced greatly by the input SOP. The experimental result of the optimum visibility is 0.932, which

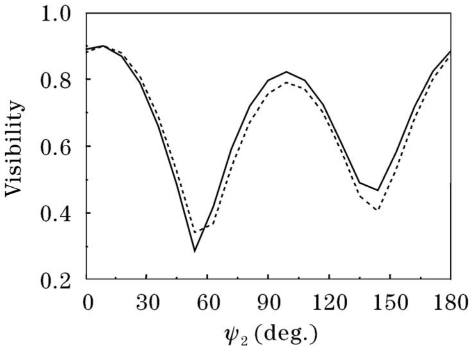

Fig. 3. Dependence of visibility on the input SOP. The abscissa is the relative variety of the azimuth of the second loop of Agilent 11896A. The solid curve shows the experimental results, the dashed curve is the estimated results with $\psi_1 = 0.11\pi$, $\psi_3 = 0.05\pi$, $\psi_4 = 0.63\pi$, $\phi_0 = 0.43\pi$, $\Omega = 0.9\pi$, $C = 0.8$.

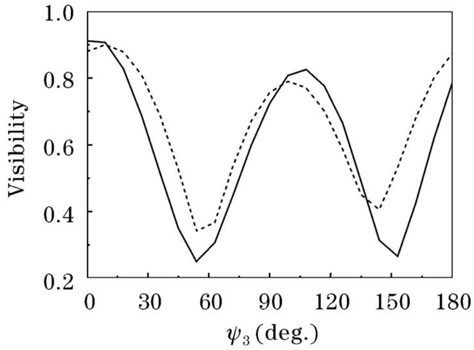

Fig. 4. Dependence of visibility on the input SOP. The abscissa is the relative variety of the azimuth of the third loop of Agilent 11896A. The solid curve shows the experimental results, the dashed curve is the estimated results with $\psi_1 = 0.1\pi$, $\psi_2 = 0.05\pi$, $\psi_4 = 0.7\pi$, $\phi_0 = 0.42\pi$, $\Omega = \pi$, $C = 0.8$.

shows that the conventional laser has little influence on the performance.

In conclusion, a quantitative analysis of the visibility in magnetostrictive fiber-optic sensors employing a Gaussian laser beam is presented. An experimental setup was established with a fabricated cylindrical transducer and a polarization controller, the visibility dependent on the input SOP was analyzed. Experiment results show that the conventional Gaussian laser beam has little influence on the visibility. We should pay more attention to the polarization-induced fading than the linewidth of Gaussian laser beams in the design of magnetostrictive fiber-optic interferometric sensors.

This work was supported by the National Natural Science Foundation of China (No. 90204006 and 60377013), the Ministry of Education, China (No. 20030248035), and the Science and Technology Committee of Shanghai Municipality (No. 036105009). C. Shi's e-mail address is shichanghai@sjtu.edu.cn, J. Chen's e-mail address is jpchen62@sjtu.edu.cn.

References

1. B. Culshaw, J. Lightwave Technol. **22,** 39 (2004).
2. T. Wang, Q. Guo, M. Tang, Q. Zhou, Z. Shi, and S. Zheng, J. Optoelectonics·Laser (in Chinese) **13,** 923 (2002).
3. D. M. Dagenais, F. Bucholtz, K. P. Koo, and A. Dandridge, Electron. Lett. **24,** 1422 (1988).
4. F. Bucholz, D. M. Dagenais, and K. P. Koo, Electron. Lett. **25,** 1719 (1989).
5. T. Y. Kim, K. S. Suh, J. H. Nam, and T. Takada, IEEE Trans. Dielectrics and Electrical Insulation **10,** 266 (2003).
6. M. S. Rao, M. V. N. Rao, and R. Renuka, in *Aerospace and Electronics Conference, NAECON, Proceeding of the IEEE 1992* **3,** 1104 (1992).
7. A. D. Kerseye and A. Dandridge, in *LEOS'90 Conference Proceedings* 180 (1990).
8. F. Bucholtz, C. A. Villarruel, C. K. Kirkendall, D. M. Dagenais, J. A. McVicker, A. R. Davis, S. S. Patrick, K. P. Koo, K. G. Wathen, A. Dandridge, G. Wang, T. Lund, and H. Valo, Electron. Lett. **29,** 1032 (1993).
9. A. D. Kersey and A. Dandridge, IEEE Trans. Components, Hybrids, and Manufacturing Technology **13,** 137 (1990).
10. D. W. Stowe, D. R. Moore, and R. G. Priest, IEEE J. Quantum Electron. **18,** 1644 (1982).
11. A. D. Kersey, M. J. Marrone, A. Dandridge, and A. B. Tveten, J. Lightwave Technol. **6,** 1599 (1988).
12. A. D. Kersey, M. J. Marrone, and A. Dandridge, J. Lightwave Technol. **8,** 838 (1990).
13. L. L. Picon, V. M. Bright, and E. S. Kolesar, in *Aerospace and Electronics Conference, NAECON, Proceedings of the IEEE 1994* **2,** 1034 (1994).
14. Agilent, "User, Programming and Service Guide 11896A Polarization Controller" http://www.agilent.com.
15. J. Zhao, *Advanced Optics* (in Chinese) (National Defence Industry Press, Beijing, 2002) pp.128—131.