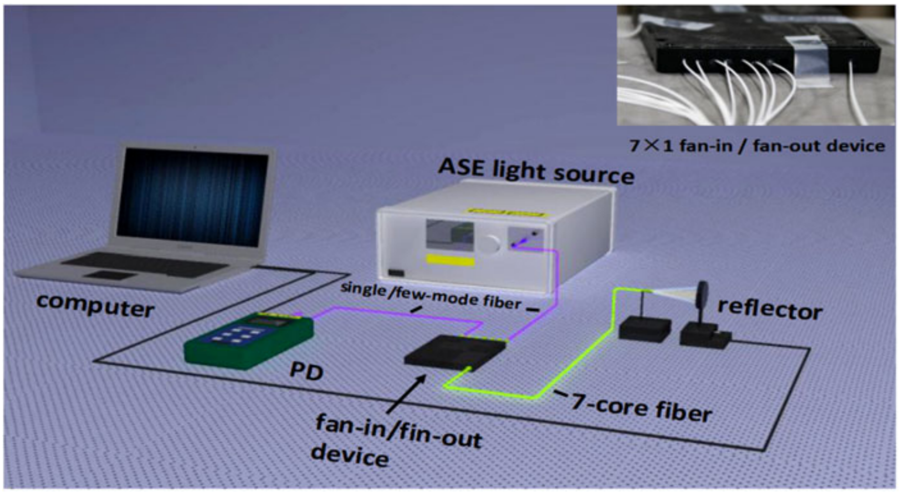
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

Spatial Division Multiplexing-Based Reflective Intensity-Modulated Fiber Optics Displacement Sensor

Volume 10, Number 4, August 2018

Tianye Lan
Cong Zhang
Songnian Fu
Benpeng Zhu
Ming Tang
Weijun Tong



DOI: 10.1109/JPHOT.2018.2848922
1943-0655 © 2018 IEEE

Spatial Division Multiplexing-Based Reflective Intensity-Modulated Fiber Optics Displacement Sensor

Tianye Lan,[1] Cong Zhang,[1] Songnian Fu ,[1] Benpeng Zhu,[1] Ming Tang,[1] and Weijun Tong[2]

[1]Wuhan National Laboratory for Optoelectronics and School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, China
[2]State Key Laboratory of Optical Fiber and Cable Manufacture Technology, Yangtze Optical Fiber and Cable Joint Stock Limited Company, Wuhan 430074, China

DOI:10.1109/JPHOT.2018.2848922
1943-0655 © 2018 IEEE. Translations and content mining are permitted for academic research only. Personal use is also permitted, but republication/redistribution requires IEEE permission. See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.

Manuscript received May 1, 2018; accepted June 13, 2018. Date of publication June 21, 2018; date of current version July 4, 2018. This work was supported in part by the National Natural Science Foundation of China under Grant 61711530043 and in part by the Fundamental Research Funds for the Central Universities under Grant 2016YXZD038. Corresponding author: Songnian Fu (e-mail: songnian@mail.hust.edu.cn).

Abstract: Due to the benefit of multiple parallel channels within single cladding and easy implementation of multi-input multioutput technique, we present the spatial division multiplexing (SDM)-based reflective intensity-modulated fiber optics displacement sensor (RIMFODS). Under the condition of single-input single-output, we experimentally compare the transfer function of RIMFODS by using a pair of standard single-mode fibers (SSMFs), single seven-core-single-mode fiber, and single seven-core-few-mode fiber. In comparison with the conventional SSMF-based RIMFODS, the use of seven-core-few-mode fiber can reduce the dead zone of measurement range from 200 to 100 μm. Meanwhile, the system sensitivity can be enhanced from 0.14 to 12.2 nW/μm. In particular, with the help of two-input-five-output technique, the dead zone can be further reduced to 70 μm, with sensitivity reaching as high as 53.87 nW/μm. Finally, we theoretically investigate the effect of both the core size and the core spacing of multicore fiber on the transfer function of RIMFODS. Such an SDM-based RIMFODS with compact footprint has lots of potential to be exploited.

Index Terms: Fiber optics sensors, detection, multiplexing, optical devices.

1. Introduction

The breakthrough of fiber optics sensor has paved the way for the development of a wide range of physical parameters measurement, such as displacement, pressure, temperature, strain, refractive index, and electric field. In particular, fiber optics displacement sensor (FODS) can be used for several industrial applications of parameter monitoring, including length, bending, vibration, pressure, temperature, and speed. Unlike traditional electromagnetic displacement sensor with electromagnetic interference (EMI) sensitivity [1], FODS has several advantages in terms of high sensitivity, wide dynamic range, light weight, and immunity to environmental EMI, thus leading to a popular choice for practical application. Generally, depending on its operation principle, FODS can be divided into two categories, phase-modulated and intensity-modulated [2]. For the phase-modulated FODS, lots of configurations have been reported so far, by the use of the microfiber couplers [3], Fabry-Perot interferometer [4], and multimode interference [5]. Although the phase modulated

FODS can offer a high sensitivity of 0.1 nm/μm [3], it suffers from extremely high cost and complicated structure, because of the use of wavelength shift monitoring technique. On the contrary, reflective intensity modulated FODS (RIMFODS) has several advantages of simple operation, low cost, compact footprint, and easy implementation in the harsh environment. The most commonly used configuration of RIMFODS is the fiber bundle configuration. The bifurcated fiber bundle structure with seven fibers has been initially proposed for the RIMFODS [6]. Then, a dead zone of around 170 μm arising in the displacement measurement range was experimentally observed for a fiber bundle structure with seven multimode fibers (MMFs) having a core size of 100 μm [7]. Further investigation reveals that, under the condition of a fixed sensor head size, there occurred a trade-off between the dead zone and sensor sensitivity [8]. Generally, system sensitivity is proportional to the core size of fiber, while the dead zone is inversely proportional to the number of fibers and its core diameters. Recently, a sensor head with a configuration of 6x6 MMF has been demonstrated, where 28 MMFs are used to detect the reflected light [9]. Each MMF is a ball-lensed optical fiber, and all MMF are gathered within a ferrule (7 mm $\times$ 8 mm). When the 8 MMFs for the purpose of light transmission are optimized, a dead zone of 50 μm and a sensor sensitivity of 0.024 dB/μm can be obtained simultaneously. It is obvious that such a MMF bundle configuration has a very complicated design of sensor head and a complex signal processing procedure. Meanwhile, we notice that spatial division multiplexing (SDM) technique has attracted worldwide research interests in the area of fiber optical communication during the past few years, due to its potential to solve the capacity crunch of standard single mode fiber (SSMF) [10]. It can enhance the transmission capacity of single fiber with the employment of multicore fiber, few-mode fiber, and few-mode multicore fiber [11]. Recently, due to its capability of spatial dimension manipulation, SDM technique has also stimulated lots of research activities in the area of fiber optic sensor, including mode-division multiplexing for strain and temperature discriminative sensing [12], curvature sensing [13], and multiple parameters monitoring by the use of multicore fiber [14]. Multi-input multi-output (MIMO) technique is inherently matched with the SDM implementation, for its advantage to spatially de-multiplex the signals and dynamically compensate various transmission impairments in the electronic domain [15]. Consequently, it is convenient to explore the use of MIMO technique for the SDM based fiber sensor.

In this submission, we present the SDM based RIMFODS by using seven-core-few-mode fiber and a self-fabricated fan in/fan out device for the ease of coupling between seven input SSMFs and one multicore fiber output [16]. In comparison with conventional RIMFODS using a pair of SSMF, the use of seven-core-few-mode fiber can reduce the dead zone of measurement range from 200 μm to 100 μm. Meanwhile, the system sensitivity can be enhanced from 0.14 nW/μm to 12.2 nW/μm. In particular, with the help of two-input-five-output technique, the dead zone can be further reduced to 70 μm, and sensitivity reaches as high as 53.87 nW/μm. Finally, we theoretically investigate the effect of both the core size and the core spacing of multicore fiber on the FODS performance.

2. Operation Principle and Simulation

Generally, the RIMFODS configuration can be divided into three parts: light source, sensor head, and signal processing unit. The light source is transmitted through one SSMF to an object to be reflected. When the displacement between the sensor head and the object occurs, the corresponding reflected power is captured by another SSMF. Finally, the received power is processed by the signal processing unit, so that the transfer function can be achieved and the displacement value can be monitored. Fig. 1(a) shows the scheme of RIMFODS using a pair of SSMF. The transfer function of RIMFODS is generally defined as:

$$M = \frac{P_{\mathrm{r}}}{P_{\mathrm{t}}} = F\left(R_t, R_r, S, d\right) \tag{1}$$

where Pr and Pt are the received and transmitted light powers, respectively. Rt and Rr are core radii of the transmitted and received fibers, respectively. S is the core spacing of two SSMFs, and d is the displacement to be monitored. Based on the theoretical results [17], we derive an analytical

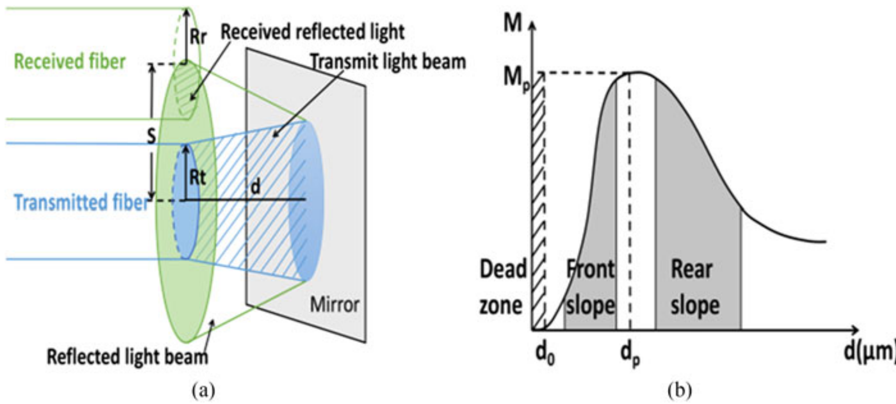


Fig. 1. (a) Schematic of fiber bundle based RIMFODS, (b) its typical transfer function.

transfer function, as shown in Eq. (2),

$$M(d') = \begin{cases} 0 & w(d') \le S - R_r \\ \frac{4\delta}{(1-e^{-2})\pi w^2(d')} \int_{S-R_r}^{w(d')} e^{-2r^2/w^2(d')} \cos^{-1}\left(\frac{S^2+r^2-R_r^2}{2S_r}\right) r dr & S - R_r \le w(d') \le S + R_r \\ \frac{4\delta}{(1-e^{-2})\pi w^2(d')} \int_{S-R_r}^{S+R_r} e^{-2r^2/w^2(d')} \cos^{-1}\left(\frac{S^2+r^2-R_r^2}{2S_r}\right) r dr & w(d') \ge S + R_r \end{cases} \quad (2)$$

where δ is the reflectivity of object surface, w(d') is waist radius of the reflected light at the sensor head plane, and can be defined as:

$$w(\mathrm{d}') = R_t \left[1 + a\left(\frac{2d}{R_t}\right)^b \tan(\arcsin NA)\right] \quad (3)$$

where a and b are dimensionless constants related to light source, and NA is numerical aperture of the transmitted fiber. According to Eq. (2), a qualitative transfer function of RIMFODS using a pair of SSMF is shown in Fig. 1(b), where both Rt and Rr are 4 μm, S is 125 μm, NA is 0.2, and the two dimensionless constants a and b are set as 2 and 0.7. The transfer function can be divided into three regions including the dead zone where the received power is zero, the front slope where the received power sharply increases with the growing displacement, and the rear slope where the received power slowly decrease with the increments of displacement. Generally, the gradient of front slope is treated as the sensitivity of RIMOFDS [2]. From Eq. (2), we can find that, a larger core radius Rr of the received fiber, small core spacing S, and larger waist radius w(d') are helpful to reduce the dead zone. Meanwhile, increasing the number of both transmitted fiber and received fiber and making a specific arrangement can also reduce the dead zone. However, both a complicate sensor head design and complex signal processing occur. In the following part, we mainly focus on the optimization of both dead zone and front slope gradient for the SDM based RIMFODS.

The experimental setup of the SDM based RIMFODS is schematically shown in Fig. 2(a). An amplified spontaneous emission (ASE) source (AIS-CL-20-B-FA, Amonics) with a power fluctuation of less than 0.02 dB over 8 hours and a wavelength range from 1500 nm to 1600 nm is used as light source, instead of laser diode, in order to avoid the interference effect. Its output is introduced to the sensor head through a SSMF, and reflected by a mirror (BB1-E04, Thorlabs) mounted on a computer controlled motion stage, for the emulation of object moving. When the stage moves, the corresponding reflected light power is collected by another SSMF and detected by a photodetector (PD, PMSII-B, AccelLink). According to the fiber we used, the sensor head configuration will be changed accordingly. Firstly, we use the SSMF pair, as shown in Fig. 2(b). One is connected to the ASE light source for the light transmission, and the other one is used to collect the reflected light to the PD. Secondly, we replace the SSMF pair with two kinds of multicore fiber, including single

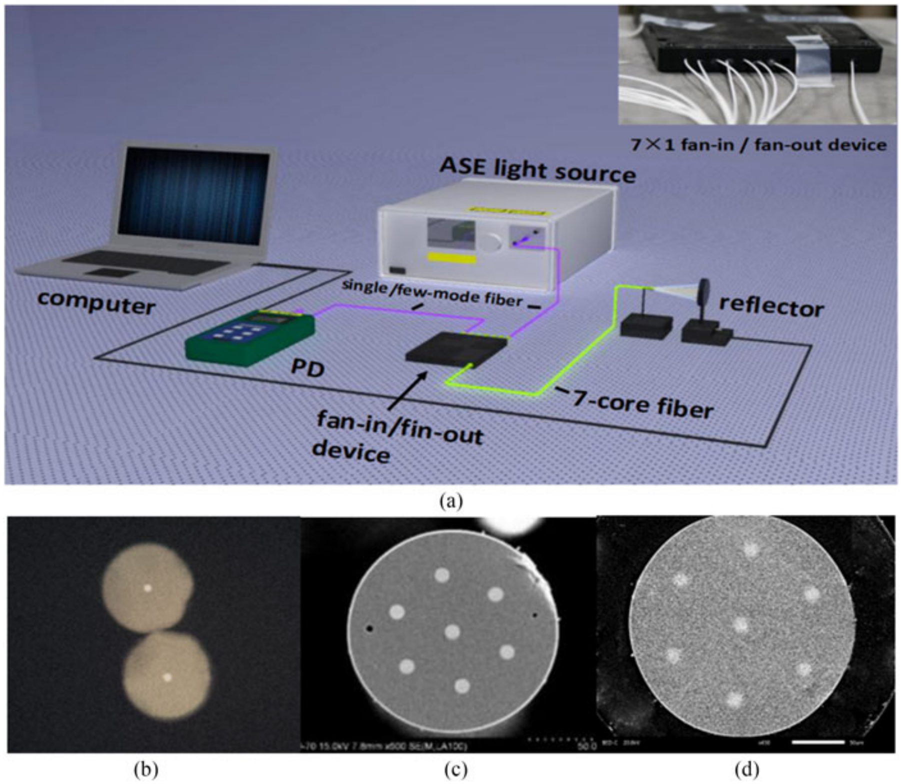


Fig. 2. (a) Experimental setup of RIMFODS and the inset is 7 × 1 fan-in/fan-out device. SEM of (b) SSMF pair, (c) seven-core-single-mode fiber, (d) seven-core-few-mode fiber.

seven-core-single-mode fiber, as shown in Fig. 2(c), and single seven-core-few-mode fiber, as shown in Fig. 2(d), to act as sensor head. The transmission loss of both seven-core fibers is around 0.22 dB/km at 1550 nm. Meanwhile, two kinds of 7 × 1 fan-in/fan-out devices made by chemical etching method are used to offer a low insertion loss of 2.95 dB and reliable connections between seven input fibers and one multicore fiber. As shown in the inset of Fig. 2(a), when the output fiber is seven-core single-mode fiber, the inputs of fan-in/fan-out device are 7 SSMFs. However, for the case of seven-core few-mode fiber, the inputs are 7 few-mode fibers. Consequently, the light can be easily introduced into individual cores of seven-core fiber by connecting the corresponding fiber to the ASE light. After the reflection by the moving object, the light is collected by the rest cores of multicore fiber. Finally, the transfer function of SDM based RIMFODS can be obtained after the optical-to-electronic conversion and signal processing.

3. Experiment Results and Discussions

Under the scenario of single-input-single-output, the transfer function using the SSMF pair is compared with that using single seven-core-single-mode fiber, as shown in Fig. 3. When the input power of ASE source is set as 8.93 mW, the RIMFODS using the SSMF pair possesses a wide measurement range of about 900 μm, due to the large core spacing of 125 μm for the ease of power collection. However, the large core spacing and small core diameter of 8 μm lead to a low sensor sensitivity of about 0.14 nW/μm and large dead zone of about 200 μm. Meanwhile, when we fix the input power of ASE source, the light is launched into the central core of seven-core-single-mode fiber, with the help of 7 × 1 fan-in/fan-out device. The use of seven-core-single-mode fiber with compact footprint can reduce the core spacing to 42.3 μm, leading to significant improvement of the system sensitivity to 1.08 nW/μm, which is 7 times higher

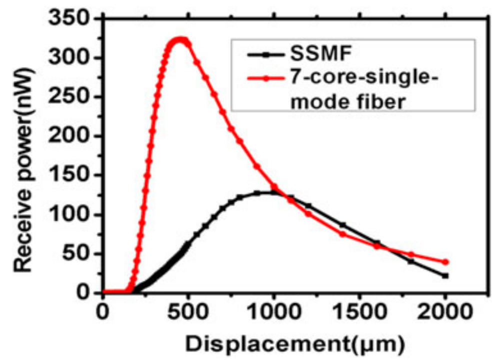


Fig. 3. Transfer function comparison between the use of SSMF pair and the use of seven-core-single-mode fiber.

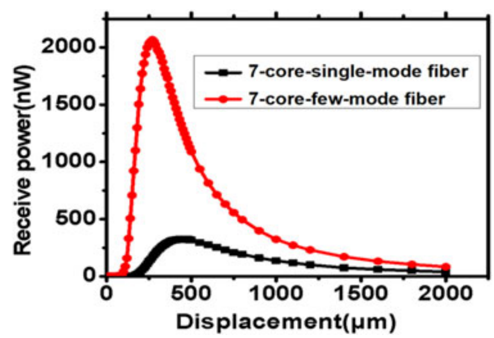


Fig. 4. Transfer function comparison between the use of seven-core-single-mode fiber and the use of seven-core-few-mode fiber.

than that of the SSMF pair. At the same time, the dead zone is reduced by 20% to 160 μm. The results indicate that the seven-core-single-mode fiber based FODS has a performance promotion.

Next, we replace the seven-core-single-mode fiber with a seven-core-few-mode fiber and a corresponding 7×1 fan-in/fan-out device. After the input power of ASE source is fixed and the light is also launched to the central core of seven-core-few-mode, the comparison of transfer function is preformed between the use of seven-core-few-mode fiber and seven-core-single-mode fiber, as shown in Fig. 4. Since the core diameter of seven-core-few-mode fiber is 24 μm, further improvement of system sensitivity is observed with 12.2 nW/μm, which is 10 times higher than that of seven-core-single-mode fiber. Since the increase of transmitted fiber core radius Rt results in a larger w(d'), the dead zone range can be reduced to 100 μm, according to Eq. (2) and (3).

In the previous experiments, actually we do not fully take the advantage of multicore fiber and 7×1 fan-in/fan-out device, as only two cores are chosen to launch and collect the light power, and the rest cores are not take into consideration. Here, in order to further improve the performance of RIMFODS, we start to exploit the MIMO technique. Firstly, we compare the different transfer functions when either single-input-single-output or single-input-multiple-output is in use, as shown in Fig. 5(a). The central core is chosen to introduce the ASE output to the moving object and the other six cores are used to collect the reflected power. Meanwhile, the input power is fixed to 8.93 mW. For each displacement variation, we record the individual power of the remaining cores and sum up all six power values. In comparison with single channel output, multiple-channel outputs possess an extremely high sensitivity of about 60.5 nW/μm, while the dead zone and measurement range remain unchanged. Secondly, as for the situation of multiple-input-multiple-output, ASE source outputs are introduced to the central core and one surrounding core through a 50:50 optical coupler, respectively. Meanwhile, single PD is used to detect the individual output power from the remaining cores. Please note that the total input power of two ASE light sources is still 8.93 mW. Then, the rest

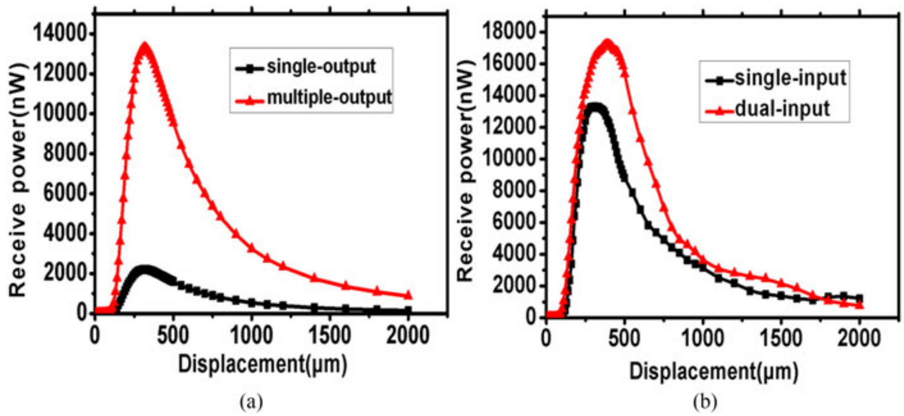


Fig. 5. MIMO implementation for the performance promotion, (a) multiple-output, (b) dual-input.

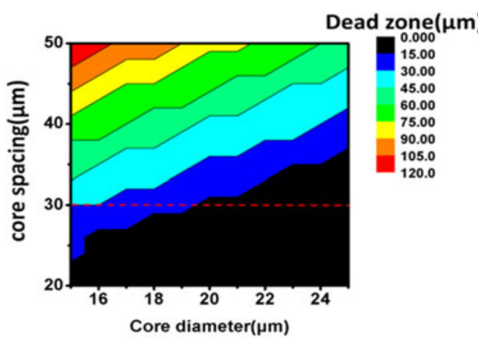


Fig. 6. Dead zone range calculation using weakly or strongly-coupled multicore fiber.

of five cores are used to collect the reflected power. As shown in Fig. 5(b), dual-input-five-output has a performance promotion in dead zone reduction and measurement range enlargement. The dead zone is now about 70 μm, and the measurement range is about 320 μm, together with a high sensitivity of 53.87 nW/μm. Besides, when more cores are acted as the input channel, the optical power of each core is decreased, due to the fixed input power. Therefore, only dual-input-five-out experiment is conducted.

Actually, such two kinds of multicore fibers have a core spacing of 42.3 μm and 41.77 μm, respectively. Thus, they belong to the weakly-coupled multicore fiber with a crosstalk of less than -30 dB per 100 km, for the ease of SDM transmission. We notice that there also exist a strongly-coupled multicore fiber with a smaller core spacing of 30 μm [18], leading to a typical crosstalk of -10 dB per 100 km. Since the length of used multicore fiber in the sensor head is around 2 m, crosstalk is not an issue. Moreover, since the performance of RIMFODS is determined by the core spacing, we believe the strongly coupled multicore fiber may be a better choice.

Here, we theoretically investigate the relationship between the dead zone range and multicore fiber parameters, under the condition of single-input-single-output, as shown in Fig. 6. According to Eq. (2), when the waist radius of light at the fiber end is equal to the difference of core spacing and core radii for the used fiber, the value of d in Eq. (3) can be treated as the dead zone range. The area above the dot line in Fig. 6 belongs to the weakly-coupled multicore fiber. We can clearly observe that the core spacing plays an important role in the reduction of dead zone. When the weakly-coupled multicore fiber possesses a large core diameter and small core spacing, dead zone can even disappear. For the area below the dot line, which belongs to the strongly-coupled multicore fiber, dead zone is very small. In particular, when the core spacing is below 25 μm and the core diameter is larger than 16 μm, the dead zone vanishes. However, the use of strongly-coupled multicore fiber with small core spacing will bring a lot of challenges during the fabrication of corresponding fan-in/fan-out device.

4. Conclusion

In conclusion, with the help of SDM technique, we successfully demonstrate a multicore fiber based RIMFODS, which possesses a very simple and integrated sensor head. The use of MIMO technique can bring great reduction of the dead zone to 70 μm, together with a high sensitivity of 53.87 nW/μm, which is competitive with the existing fiber bundle structure. Moreover, we theoretically investigate the possible use of strongly-coupled multicore fiber with potential for total elimination of dead zone, which is promising for the RIMFODS applications.

References

[1] A. Zikmund and P. Ripka, “A magnetic distance sensor with high precision,” *Sens. Actuat. A, Phys.*, vol. 186, no. 4, pp. 137–142, 2012.
[2] H. Huang and U. Tata, “Simulation, implementation, and analysis of an optical fiber bundle distant sensor with single mode illumination,” *Appl. Opt.*, vol. 47, no. 9, pp. 1302–1309, 2008.
[3] Y. Chen, S. C. Yan, X. Zheng, F. Xu, and Y. Q. Lu, “A miniature reflective micro-force sensor based on a microfiber coupler,” *Opt. Exp.*, vol. 22, no. 3, pp. 2443–2450, 2014.
[4] Q. Sun, N. Chen, Y. Ding, Z. Chen, and T. Wang, “Distance detection with optical fiber extrinsic Fabry-Perot interference ultrasonic sensor,” in *Proc. IET Int. Commun. Conf. Wireless Mobile Comput.*, 2009, pp. 441–443.
[5] A. Mehta, W. Mohammed, and E. G. Johnson, “Multimode interference-based fiber-optic displacement sensor,” *IEEE Photon. Technol. Lett.*, vol. 15, no. 8, pp. 1129–1131, Aug. 2003.
[6] R. O. Cook and C. W. Hamm, “fiber optic lever displacement transducer,” *Appl. Opt.*, vol. 18, no. 19, pp. 3230–3241, 1979.
[7] G. He and F. W. Cuomo, “Displacement response, detection limit,and dynamic range of fiber-optic lever sensors,” *J. Lightw. Technol.*, vol. 9, no. 11, pp. 1618–1625, Nov. 1991.
[8] A. Shimamoto and K. Tanaka, “Geometrical analysis of an optical fiber bundle displacement sensor,” *Appl. Opt.*, vol. 35, no. 34, pp. 6767–6774, 1996.
[9] B. Guzowski and M. Lakomski, “Realization of fiber optic displacement sensors,” *Opt. Fiber Technol.*, vol. 41, pp. 34–39, 2018.
[10] P. J. Winzer, “Making spatial multiplexing a reality,” *Nature Photon.*, vol. 8, no. 5, pp. 345–348, 2014.
[11] D. J. Richardson, J. M. Fini, and L. E. Nelson, “Space-division multiplexing in optical fibers,” *Nature Photon.*, vol. 7, no. 5, pp. 354–362, 2013.
[12] Y. Weng, E. Ip, Z. Pan, and T. Wang, “Single-end simultaneous temperature and strain sensing techniques based on Brillouin optical time domain relectometry in few-mode fibers,” *Opt. Exp.*, vol. 23, no. 7, pp. 9024–9039, 2015.
[13] H. Wu *et al.*, “Few-mode fiber based distributed curvature sensor through quasi-single-mode Brillouin frequency shift,” *Opt. Lett.*, vol. 41, no. 7, pp. 1514–1517, 2016.
[14] A. V. Newkirk, L. E. Antonio, D. G. Salceda, M. U. Piracha, C. R. Amezcua, and A. Schulzgen, “Multicore fiber sensors for simultaneous measurement of force and temperature,” *Photon. Technol. Lett.*, vol. 27, no. 14, pp. 1523–1526, 2015.
[15] S. Randel *et al.*, “6x56-Gb/s mode-division multiplexed transmission over 33-km few-mode fiber enabled by 6x6 MIMO equalization,” *Opt. Exp.*, vol. 19, no. 17, pp. 16697–16707, 2011.
[16] B. R. Li *et al.*, “Experimental demonstration of large capacity WSDM optical access network with multicore fibers and advanced modulation formats,” *Opt. Exp.*, vol. 23, no. 9, pp. 10997–11006, 2015.
[17] H. Cao, Y. Chen, Z. Zhou, and G. Zhang, “General models of optical-fiber bundle displacement sensors,” *Microw. Opt. Technol. Lett.*, vol. 47, no. 5, pp. 494–497, 2005.
[18] K. Saitoh and S. Matsuo, “Multicore fiber technology,” *J. Lightw. Technol.*, vol. 34, no. 1, pp. 55–66, Jan. 2016.