Proximity sensors based on ball-lensed optical fibers

B Guzowski, M Lakomski, M Cywinski
Dept. of Semiconductor and Optoelectronics Devices, Technical University of Lodz, 90-924 Lodz ul. Wolczanska 211/215, Poland

Abstract. In this paper, proximity sensors based on ball-lensed single-mode fibers (SMF) are described. Two types of sensors are presented: (1) Type A with one transmitting and four receiving optical fibers and (2) Type B with one transmitting and eight receiving optical fibers. In both types ball-lensed optical fibers are used as a receiving line. Sensitivity of these sensors is compared to sensitivity of sensors with the same configurations, but involving cleaved optical fibers. All developed sensors were tested at two most popular in SMF wavelengths: 1310 nm and 1550 nm. As a refractive surface the silicon wafer was used.

1. Introduction
There is a great number of types of optical fiber sensors. They can be classified in many ways. Generally intrinsic and extrinsic sensors can be distinguished. In the intrinsic sensors, e.g. reflective sensor, the role of optical fibers is limited to distributing light to and from optical converter. In the extrinsic sensors, such as microbending or interferometric sensors, optical fiber distributes light and at the same time functions as an optical converter. The advantages of fiber optic sensors, such as the resistance to electromagnetic interference, high sensitivity or very small size result in wide range of application [1-5]. Reflective sensors are a group of intensity sensors. Due to high accuracy of processing, low cost and contactless acting they are often used [6-7].

In this type of sensors usually the multi-mode fibers (MMF) and are used. They have bigger core in comparison to single-mode fibers (SMF), therefore MMF can capture more reflected light. However typical wavelengths used in SMF have much lower attenuation than wavelengths transmitted in MMF and in SMF there is no mode dispersion. Therefore in some precision application SMF can be more suitable.

In this paper the results of the tests of four different proximity sensors are shown. To increase amount of reflected light captured by receiving optical fibers, the ball lenses were proposed. Obtained results were compared to the results received during the tests, where cleaved optical fibers were used. As a head of a sensor novel MTP C12405 ferrule was used. This small element allowed us to precisely distribution and adjustment of optical fibers.

2. Theoretical models of sensors

2.1. Cleaved optical fibers
In literature different models of optical fiber reflective sensors are described. In some models the receiving optical fibers are parallel to transmitting optical fibers [8]. There are also models with inclined optical fibers [9,10]. In this paper the theoretical model based on [11] is presented. Kaczmarek in his model assumed that optical fibers are in contact (figure 1a). In our model there is a gap $d$ between optical fibers (figures 1b-1d). To simplify the analysis, it is assumed, that reflective surface reflects all incoming
light and there is no absorption of the light between optical fibers and the surface. To analyze reflective sensor operation, conical shape of the light beam emitted by the transmitting optical fiber and circular cross-section of all optical fibers are assumed. The light intensity of the image of receiving optical fiber is determined. As the analysis method, geometrical optics method was used. It assumes that the intensity of illumination in cross-section of the cone is constant and given by the formula:

\[ I(z) = \frac{P_o}{\pi w^2(z)} \]  

where: \( P_o \) is output power at the tip of transmitting optical fiber, \( w \) – cone radius as a function of \( z \).

**Formula of** \( w(z) \) **function is given below:**

\[ w(z) = z \tan \theta_a = z \frac{w_a}{z_a} = z \frac{w}{l+z_a} \]  

For very small displacements \( l < \frac{dz_a}{2w_a} \) the reflected light is not captured by receiving fibers.

When \( \frac{dz_a}{2w_a} < l < \frac{z_a(w_a+d)}{w_a} \) surface of receiving optical fiber \( S(z) \) is illuminated only partly as shown in figure 2a). For bigger displacements \( l > \frac{z_a(w_a+d)}{w_a} \) surface \( S(z) \) is illuminated fully – figure 2b).

**Figure 1.** The idea of reflective sensor: a) optical fiber are in contact [11], b) out of operating range, c) partially illuminated, d) fully illuminated

**Figure 2.** Reflected surface of the receiving optical fiber: a) partially for \( \frac{dz_a}{2w_a} < l < \frac{z_a(w_a+d)}{w_a} \), b) fully for \( l > \frac{z_a(w_a+d)}{w_a} \).
When \( \frac{dz_a}{2w_a} < l < \frac{z_a(w_a + \frac{d}{2})}{w_a} \) surface \( S(z) \) is described by formula:

\[
S(z) = w^2(z)\alpha_1(z) + w_a^2[\alpha_2(z) - \sin\alpha_2(z)] - w(z)w_a\sin\alpha_1(z)
\] (3)

Thus, the power of light incident on the end of the receiving optical fiber is described by formula:

\[
P(z) = \frac{S(z)}{\pi w^2(z)} P_o
\] (4)

When \( l > \frac{z_a(w_a + \frac{d}{2})}{w_a} \) surface \( S(z) = \pi w_a^2 \) therefore the power \( P(z) \) is described as:

\[
P(z) = \frac{w_a^2}{w^2(z)} P_o
\] (5)

2.2. Theoretical model of ball-lensed optical fibers
To increase the amount of received light and thereby the sensor sensitivity we proposed using ball-lensed optical fiber (BLOF) [12], shown in figure 3, as a receiving optical fiber.

Figure 3. Ball-lensed optical fiber (BLOF), where \( D \) – diameter of ball lens and \( d \) – diameter of input source, \( EFL \) – effective focal length, \( BFL \) – back focal length of ball lens

The \( EFL \) of a ball lens is determined using the equation (6), while the \( BFL \) is represented using the equation (7):

\[
EFL = \frac{nD}{4(n-1)} \quad (6)
\]

\[
BFL = EFL - \frac{D}{2} \quad (7)
\]

where \( n \) is the refractive index of the material.

The numerical aperture \( NA \) of the lens is represented by equation (8):

\[
NA = \frac{2d(n-1)}{nD} \quad (8)
\]

The maximum surface (when \( d = D \)) of the ball lens that can be illuminated is given by the formula \( S(z) = 2\pi r^2 \). In this special case, when we assumed that the ball lens is made of glass \( (n = 1.5) \) the \( NA \) of lens is 0.67. It is five times more than for cleaved SMF. However it must be taken into account that not all of the incoming light will be focused to the core of the optical fiber in this case. Some of the light will be focused to the cladding and will be lost.
3. Construction of the sensor

3.1. Ball-lensed optical fibers
In the Optical Fibers Techniques Laboratory at Lodz University of Technology four types of BLOF were realized. The lenses diameters were in the range of 140 μm to 230 μm.

The process of realization of BLOF was made with the use of Fitel S153 by Furukawa fusion splicer. To realize micro-lens, cleaved optical fiber SMF class G.652 was placed in V-groove, as it is presented on figure 4. The end of the optical fibers was located between the V-groove and two electrodes.

![Figure 4. Schematic of fiber alignment inside the splicer.](image)

The manual mode in optical splicer allow to set some parameters which are responsible for making the lens. The most important of them are shown in the Tab 1. First of all, desired operating parameters of splicer was set and SMF fiber was positioned relative to the two electrodes, according to “Initial length of fiber”. Then the two electrical discharges of electrodes were induced and caused melting of SMF fiber end. In this process ball micro-lens was formed. During these discharges the optical fiber was moved in accordance with the parameter indicated as the " Z push distance".

| Parameter                  | Ball-lensed 140 μm | Ball-lensed 170 μm | Ball-lensed 200 μm | Ball-lensed 230 μm |
|----------------------------|--------------------|--------------------|--------------------|--------------------|
| Diameter of lens (μm)      | 140 ± 4            | 170 ± 3            | 200 ± 4            | 230 ± 4            |
| First arc power (mW)       | 50                 | 100                | 125                | 200                |
| Electrodes discharge time (s) | 3                  | 2                  | 6                  | 3                  |
| Second arc power (mW)      | 80                 | 167                | 167                | 200                |
| Initial length of fiber (μm) | 150                | 200                | 200                | 200                |
| Z push distance (mm)        | 0.02               | 3                  | 16.4               | 32.767             |

3.2. Head of the sensor
The most crucial element in proximity sensor is the head of the sensor. It must provide the proper and precise alignment of the optical fibers. Due to this fact this element can be complicated and expensive. In our construction of the sensor as a head of the sensor, the MTP C12405 optical fiber ferrule shown in figure 5 was used. This type of ferrule, developed by US Conec in 2014, allows to place up to 48 optical fibers.
Figure 5. Head of sensor - MTP C12405 optical connector: (a) front view, (b) view from the top [13]

Two different configurations of sensors were designed, called type A and type B. The difference is between receiving optical fibers, respectively 4 and 8 optical fibers. Moreover, for these two types sensors involving also cleaved optical fibers as receiving optical fibers were prepared. All four configurations of the developed proximity sensors are shown in figure 6. In each configuration, the transmitting fiber was always the central fiber (red color in figure 6) and it was always cleaved. All of the used optical fibers were SMF class G.652.

Figure 6. The distribution of receiving optical fibers in sensors: a) Type A sensors with 4 cleaved optical fibers and 4 ball-lensed optical fibers, b) Type B sensors with 8 cleaved optical fibers and 8 ball-lensed optical fibers.

The photos of developed sensor heads, taken by a scanning electron microscope Carl Zeiss model EVO MA10, are shown in figure 7 and figure 8.

Figure 7. Real photo of head of sensors enlarged 88x: a) Type A with 4 receiving optical fibers, b) Type B with 8 receiving optical fibers.
Figure 8. a) Type A sensor with 4 ball-lensed optical fibers enlarged 284x, b) Type B sensor with 8 ball-lensed optical fibers enlarged 170x.

4. Measuring setup
A measuring setup used to carry out all the measurements is presented in figure 9a). Additionally, the Thorlabs MAX373D fiber launch system (5) was used as shown in figure 9b). In this setup the light source FLS-600 by EXFO (1) was connected through SCPC/APC patchcord (2) to transmitting fiber (3). This fiber is the part of the sensor head (4) which was placed on a fixed plate with a holder (6). The reflecting surface was silicon wafer (7) fixed to a moving plate of MAX373D system. The receiving fibers (8) was connected to the optical power meter AF-ORL-3.1 (9).

Figure 9. a) Scheme of the measuring setup b) Measuring setup and head of sensor mounted in front of the reflecting surface.

5. Results
All 4 configurations were tested for two wavelengths: 1310 nm and 1550 nm ± 20 nm. Output characteristics $P_R/P_T = f(h)$ (for constant optical power source) have been designated. Operating range of the sensor was set to 4000 μm with 25 ± 1 μm resolution. In order to eliminate the influence of external light, each configuration was examined five times, in a darkened room at the temperature of 22°C. To remove all possible light from the cladding, the receiving optical fibers were wound five times around a coil with a diameter of 10 mm.

Figure 10 shows the comparison of Type A configuration both for cleaved and ball-lensed optical fibers for both used wavelengths. Similarly results obtained for Type B sensor are shown in figure 11. On the other hand, figure 12 and figure 13 show the characteristics of both wavelengths, 1310 nm and 1550 nm. These figures show the differences between Type A and Type B sensors.
On the basis of the results presented in figure 10 and figure 11, it can be stated that for the distance around 1.45 - 4 mm for both wavelengths (1310 nm and 1550 nm), developed sensors (type A and type B) with BLOF are more sensitive than sensors with cleaved optical fibers. For 1310 nm wavelength (figure 10) sensors with BLOF, received power of reflected light is almost 50% bigger in comparison to sensors with cleaved optical fiber (in distance 1.5–2 mm). For bigger distance using BLOF in sensors results in increased sensors sensitivity up to 33%. For the wavelength 1550nm using ball-lenses increases received power proportionally by c.a. 40% in distance 1.5–2 mm, and for more than 2mm by 20%.

More receiving optical fibers in type B sensors (figure 11) results in increased operating range of sensors. The operating range starts 5mm earlier (in distance 750 µm) compared to type A sensor. Also in this configuration, sensors with ball-lensed optical fibers collect and distribute more (about 30-40 %) reflected light than sensors with cleaved optical fibers.

Another correlation was noticed on the basis of the research presented in figure 12 and figure 13. Type B sensor with 8 receiving optical fibers, called B2, is the most sensitive sensor in the whole tested range and both wavelengths. For bigger distance (2.2 - 2.5 mm and more) sensor with 4 BLOF as
receiving fibers (type A2) collect more light than sensor B1 with 8 cleaved optical fiber. These result clearly show the better effectiveness of the sensors with ball-lensed optical fibers.

Figure 12. Comparison of two configurations in both type of sensors – wavelength 1310 nm.

Figure 13. Comparison of two configurations in both type of sensors – wavelength 1550 nm.

6. Conclusions
In this paper, two configurations of proximity sensors using BLOF were presented and compared with similar sensors using cleaved optical fibers. As a head of a sensor novel MTP C12405 ferrule was used, which allowed us to precisely distribution of optical fibers. Based on our study, we show that using BLOF as a receiving optical fibers, significantly increase the amount of collected light. Type A sensor with 4 BLOF (A2 sensor) for the distance bigger than 2.4 - 2.5 mm collects more light than 8 cleaved optical fibers (B1 sensor). Moreover the operating range of the sensors with BLOF is wider due to increased collecting surface. Number of receiving optical fibers placed in the sensors also change the sensitivity of proximity sensor. Both types of sensors: A and B with 8 receiving optical fibers are more sensitive than sensors with 4 receiving optical fibers.

The obtained results may contain small errors due to unequal positioning ± 5 μm of the cleaved fibers into the MTP connector, or due to the lenses being of different sizes ± 4 μm. Those errors have been found to be within the range of 2 - 3 μm, which certainly does not affect how the proximity sensor works or the results obtained from the measurements. To make the theoretical model more precisely the Beer–Lambert law must be taken in account, as well as the absorption of the light by the reflective surface.
7. References

[1] Walker S Loewke K et al 2007 An optical fiber proximity sensor for haptic exploration with a robotic finger (IEEE Robotics and Automation) pp 473-478
[2] Sasaki M Ando T et al 2001 Lens fabrication on optical fiber end using photolithography pp 258-259
[3] Nabeel R A et al 2006 Harsh environments minimally invasive optical sensor using free-space targeted single-crystal silicon carbide (IEEE Sensors Journal 6(3)) pp 672-685
[4] Quero G et al 2013 Two-dimensional hybrid metallo-dielectric nanostructures directly realized on the tip of optical fibers for sensing applications (Proceedings of the SPIE 8774 id. 877402) pp 1-10
[5] Consales M Ricciardi A et al 2012 Lab-on-Fiber Technology: Toward Multifunctional Optical Nanoprobes (ACS Nano 6(4)) pp 3163-3170
[6] Yuan J et al 2014 A Fresnel reflection-based optical fiber sensor system for remote refractive index measurement using an OTDR (Photonic Sensors, Vol 4, Issue 1) pp 48-52
[7] Chen C et al 2012 Reflective Optical Fiber Sensors Based on Tilted Fiber Bragg Gratings Fabricated With Femtosecond Laser, (Journal of Lightwave Technology Vol 31, Issue 3) pp 455-460
[8] Wanninayake B Indika 2015 Modeling and Optimizing Output Characteristics of Intensity Modulated Optical Fiber-Based Displacement Sensors, (IEEE Transactions on Instrumentation and Measurement Vol 64, Issue 3) pp 758-767
[9] Woo-Seong C et al 2011 An intensity function for inclined multimode optical fiber sensors, (10th International Workshop on Electronics, Control, Measurement and Signals ECMS) pp 1-6
[10] Puangmali P et al 2010 Mathematical Modeling of Intensity-Modulated Bent-Tip Optical Fiber Displacement Sensors, (IEEE Transactions on Instrumentation and Measurement Vol 59, Issue 2) pp 283-291
[11] Kaczmarek Z 2006 Światłowodowe czujniki i przetworniki pomiarowe, ISBN 83-87982-07-5 pp 105-111
[12] Kato D 1973 Light coupling from a stripe-geometry GaAs diode laser into an optical fiber with spherical end (Journal of Applied Physics 44) pp 2756-2758
[13] Yount M 2009 Customer Drawing http://www.usconec.com/images/drawings/C12405.pdf

Acknowledgment

The authors would like to thank the US Conect company for sharing with us the MTP ferrules.