Sensors & Transducers, Vol. 245, Issue 6, October 2020, pp. 72-75

Sensors & Transducers
Published by IFSA Publishing, S. L., 2020
http://www.sensorsportal.com

Broadband Multimode Single-channel Optical Rotary Connector

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Received: 19 August 2020 /Accepted: 21 September 2020 /Published: 30 October 2020

Abstract: Optical rotary connectors (ORC) belong to a new generation of newly created optical devices capable of providing continuous optical communication between objects mounted on a common axis of rotation. Due to the wide bandwidth, contactlessness and insensitivity to electromagnetic interference, ORC allow you to reliably transmit various digital and analog signals from rotating objects to stationary ones on broadband fiber-optic communication lines, as well as to take contactless information in optical form from fiber-optic sensors of physical quantities mounted on rotating objects. This brings the telemetry of rotating objects to a qualitatively new much higher level. In this work, we developed a broadband multimode single-channel ORC, built on the basis of ball optical lenses made of optical sapphire. The comprehensive theoretical and experimental studies of this ORC have been conducted. Its design is characterized by high manufacturability, ease of assembly and many times less requirements for the accuracy of size and shape of individual structural components, assemblies and assemblage of such ORC compared to those built on the basis of gradient rod lenses.

Keywords: Fiber optic rotary joint, Fiber optic collimator, Graded-index (GRIN) lenses, Ball lenses.

1. Introduction

In modern control and measurement devices and communication technology between the moving (rotor) and body (stator) parts of rotating objects, there is a problem of transmission of broadband signals from one part of the object to another. The traditional design and circuit solution of this problem due to the use of current-carrying contact rings is limited by a number of significant disadvantages. They include: the insufficient (for transmission of broadband signals) frequency band of electrical signal transmission channels; high level of electrical noise of contacts; insufficient protection against electromagnetic interference; low reliability; short service life, etc.

In addition, with the introduction of fiber-optic sensors of physical quantities and fiber-optic communication lines on rotating objects, additional difficulties arose due to the need to couple physically incompatible electrical interfaces of slip rings with optical interfaces of fiber lines.

In recent years, to solve these problems, fundamentally new devices have been created - the so-called optical rotary connectors (ORC). These devices provide contactless transmission of digital and analog signals from rotating objects in optical form. They adequately meet the task and are compatible with fiber lines. Compared to contact connectors, the contactless ORC have tens of thousands of times wider bandwidth, can operate under the influence of powerful electromagnetic interference (being insensitive to electromagnetic fields), are much more reliable, have a long service life, small size and weight.

Today, dozens of different designs of multi-channel and single-channel facilities, operating on different physical principles, have been created and commercially produced [1-4]. Optical collimator devices based on graded-index rod lenses (GRIN lenses) and C-lenses are widely used in many of these designs [5-7].

The main advantages of GRIN lenses are low chromatic aberration, simple cylindrical shape of lenses with flat end surfaces, convenience for installation in optical devices (easy to assemble due to the plane surfaces). At the same time, the use of GRIN lenses in ORC requires extremely high precision from the structural elements of ORC and its assembly.

For example, the angular beats of the optical axes of the lenses relative to the axis of rotation of 0.1° lead to rotational oscillations of optical losses in the ORC at the level of 1.6 dB [8].

The following work is devoted to the development of broadband multimode single-channel ORC, built on the basis of ball optical lenses. This allowed significantly reduce (compared to devices that use GRIN lenses) the requirements for the accuracy of basic elements of the ORC design and significantly simplify its assembly technology.

2. The Design of ORC, Its Characteristics and Theoretical Analysis

The principle of operation of the device is explained by a simplified optical scheme of the ORC in Fig. 1.

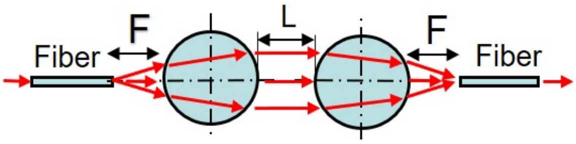

Fig. 1. A simplified optical scheme of the ORC.

Optical signals are transmitted from one optical fiber to another by means of optical lenses through a small air space between the lenses. The lenses with optical fiber segments are mounted on a common axis of rotation at a certain distance L from each other. The ends of the transmitting and receiving optical fibers are installed at the focal points of the respective lenses at distances F from the edge of the lens.

The collective drawing of ORC is given in Fig. 2. The basic units of ORC are cases 1 and 2; inserts 3 and 4 with a lens; lenses 5 and 6; double row ball bearing 7; standard threaded FC-type connectors 8 and 9.

Most commercial products use fiber-optic pigtails glued to the ORC body on both sides to connect the ORC to the fiber. In the developed design of ORC (Fig. 2) pigtails are not used. Fiber optic cables are connected to the bodies 1 and 2 via standard FC-type threaded connectors.

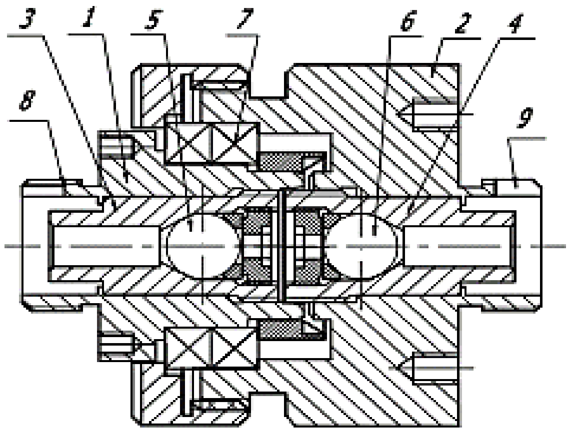

Fig. 2. Collective drawing of ORC with ball lenses.

Although this has some negative effects on the optical characteristics of the device, but such a circuit solution allows the use of ORC with different types of fiber cables and gives the product certain advantages in the possibility of wider application. In addition, this approach greatly simplifies and reduces the cost of design.

From Fig. 2 it is easy to see that the coefficient of optical communication between the optical fibers installed on different parts of the ORC depends on the physical and geometrical parameters of the lenses and the design factors that affect the course of the rays between the optical fibers.

To ensure the ORC maximum manufacturability, its theoretical analysis was performed in terms of accuracy. According to the analysis, the necessary requirements for the accuracy of manufacturing of individual structural elements and their assembly in housings were determined. This allowed to optimally form the requirements for tolerances and landings of individual parts and assembly units, which were the basis of design documentation.

To conduct a theoretical analysis of ORC with spherical lenses, a physical and mathematical model of ORC in the framework of geometric optics was built and a computer program for computer simulation of ORC in the software environment of the Matlab package was created.

The course of rays between the ends of optical fibers is calculated by methods of analytical geometry.

The model is based on the division of the radiating end of the optical fiber into elementary planes. In each of them there is a set of rays with their geometric characteristics and intensity (taking into account the radiation pattern of the radiation source).

When creating such a model, it is important to choose a coordinate system convenient for determining in this coordinate system the guiding cosines of the rays emanating from the end of the fiber. For the optical circuit shown in Fig. 3, a rectangular coordinate system is selected with the beginning at the end of the optical fiber, conventionally divided into elementary round areas (see Fig. 3).

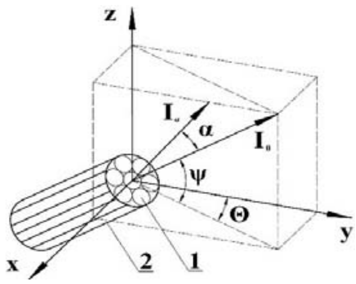

Fig. 3. The scheme of the rays at the output of the end of the fiber in a rectangular coordinate system.
1 - elementary plane at the end of the fiber, from which the rays emanate; 2 - light guide; I_0 is a ray propagating along the output axis of a fiber with a beveled end. I_α is the ray describing the light cone around the ray I_0.

Expressing the direction of the beam I_0 through the angles θ and ψ of the beam to the plane XOY and YOZ, and the direction of the beam I_α through the angle α between the beam I_α and the beam I_0 and through the azimuthal angle φ of rotation of the beam I_α around the beam I_0, we can find guide cosines l, m and n of the beam at the output of the fiber:

$$m = 1 \tag{1}$$

$$l = (\cos\psi \cdot \sin\Theta + \tan\alpha \cdot \sin\phi \cdot \cos\Theta - \tan\alpha \cdot \cos\phi \cdot \sin\psi \cdot \sin\Theta) \; / \; (\cos\psi \cdot \cos\Theta - \tan\alpha \cdot \sin\phi \cdot \sin\Theta - \tan\alpha \cdot \cos\phi \cdot \sin\psi \cdot \cos\Theta) \tag{2}$$

$$n = (\tan\alpha \cdot \cos\phi \cdot \cos\psi + \sin\psi) / (\cos\psi \cdot \cos\Theta - \tan\alpha \cdot \sin\phi \cdot \sin\Theta - \tan\alpha \cdot \cos\phi \cdot \sin\psi \cdot \cos\Theta) \tag{3}$$

Using these equations for the guiding cosines of the rays and taking into account the intensity of each ray obtained from the radiation pattern of the laser or LED radiation source, the course of the rays between the radiating and receiving ends of the fibers and the total intensity of the radiation incident on the surface of the end face of the receiving fiber in a given range of angles of incidence were subsequently calculated by methods of analytical geometry. The optical coupling coefficient was calculated as the ratio of the total intensity of the emitted rays to the intensity of the rays introduced into the fiber cable, taking into account its numerical aperture.

Some of the most important of the results of the computer analysis are shown in Fig. 4 - Fig. 6. From these figures it is seen that the greatest influence on the magnitude of optical losses in the ORC have errors associated with the transverse displacement and inclination of the axes of the optical fibers relative to the optical axis of the lens. These results take into account the optical Fresnel losses on the optical surfaces of the lenses, which are about 26 %.

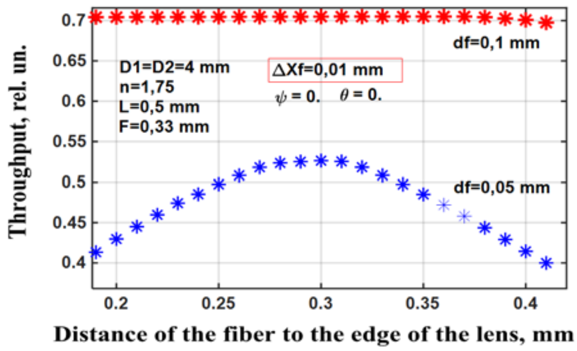

Fig. 4. Influence of the longitudinal displacement of the end of the optical fiber relative to the focus of the lens on optical losses in ORC.

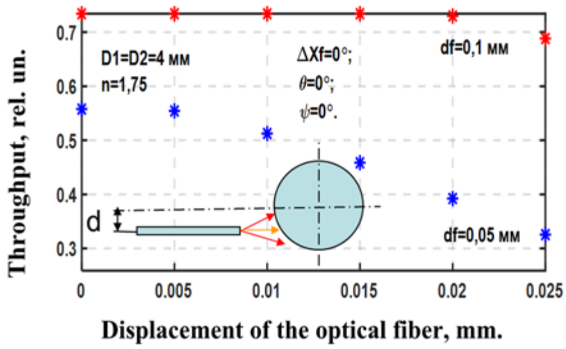

Fig. 5. Influence of transverse displacement of the end of a light guide concerning an axis of rotation on optical losses in ORC.

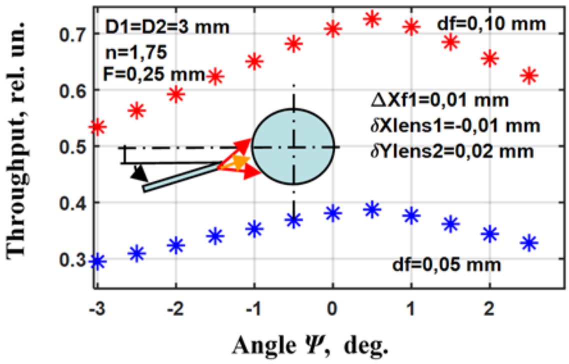

Fig. 6. Influence of an angle of inclination of a light guide to an axis of rotation on optical losses in ORC.

Calculations were performed for cases of signal transmission on multimode fiber-optic cables with a core diameter 50 μm and numerical aperture NA = 0.16, lenses diameters D = 3 and 4 mm, lens refractive index n = 1.75. The displacement of the axes of the optical fibers relative to the optical axis of the lens is indicated in the figures by the parameters ΔXf1 and ΔXf2, the displacement of the centers of the lenses relative to the axis of rotation are denoted as δXlens1 and δXlens2.

The results of these studies show that the greatest influence on the magnitude of optical losses in the ORC have errors associated with the transverse displacement and inclination of the axes of the optical fibers relative to the optical axis of lenses located in the inserts 3 and 4 (Fig. 2). The transverse displacement of the latter should not exceed 3 µm, and the angular slope of 0.3°. The permissible deviation of the longitudinal position of the end of the fiber from the focal point of the lens is ±5 µm.

The calculated coupling loss against rotational angle is shown in Fig. 7.

Fig. 8 shows the experimental characteristic of the transmission of an optical signal when the rotor rotates.

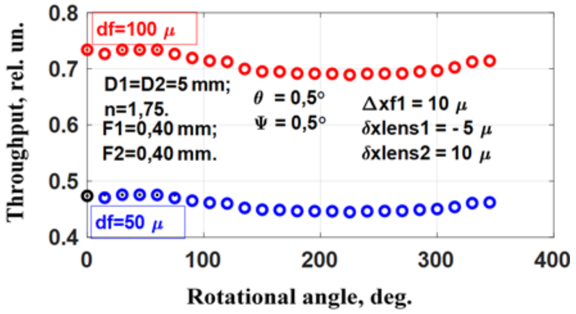

Fig. 7. The variation of optical throughput with rotational position.

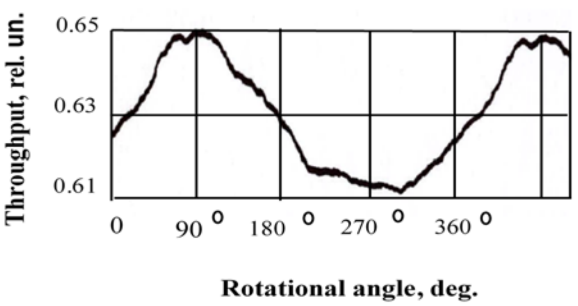

Fig. 8. The variation of optical throughput with rotational position in ORC. Experimental characteristics.

3. Conclusions

1. Optical rotating connectors built on the basis of ball lenses meet the requirements of modern multimode fiber-optic communication lines, both in terms of optical losses and the amount of rotational oscillations of the optical signal. The device can be used with bidirectional data links and at wide wave range (lengths of the 850-1550 nm).

In our experimental samples of ORC optical losses were 3.0 dB when operating ORC in the composition of standard fiber-optic cables with a core diameter of 50 µm and 1.5-1.7 dB when using cables with a core of 100 µm. The variation of insertion loss caused by device rotation was less than 0.25 dB.

2. The main optical losses in the device are due to Fresnel losses on the optical surfaces of the lenses, if you do not use coated optics. In the case of the use of optical sapphire lenses with a refractive index of $n = 1.75$, Fresnel losses exceed 26 %. Fresnel optical losses can be reduced by using lenses with a lower refractive index, such as lenses made of optical glass K8 ($n = 0.547$), or use lenses with coated surfaces resistant to environmental influences, which significantly increases the cost of the device.

3. There are no high standards for the accuracy of the ORC mechanism. Permissible radial beats of the rotating part of the ORC relative to the stator are at the level of 40 µm. Accordingly, particularly precise expensive bearings are not required to create a high-quality device with high optical characteristics.

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