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Method of producing tapered optical fiber

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A novel method for fabricating a subwavelength-diameter optical fiber that can be coupled with optical microresonators is proposed. This method is characterized by the ability to produce a fiber with the specified characteristics required for reliable coupling owing to the possibility of correction of the fiber pulling parameters during fiber production by using sensors to monitor the tension and heating temperature. The main characteristics of the obtained samples of the subwavelength-diameter optical fiber are determined.

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1. INTRODUCTION

Optical dielectric resonators are widely used in photonics owing to their unique properties. The quality factor of microresonators (McRs) with whispering gallery modes can reach the order of 10^{11} [1]; moreover, they have small dimensions—from tens of micrometers to several millimeters. The increased interest in the use of these devices in various areas was confirmed by review articles [2,3]. McRs are fabricated using various materials in the form of microspheres, disks, rings, and toroids. Such devices are promising for the creation of different types of photonic filters in spectroscopy [4], including tunable filters [5]; they can be used as sensors with high sensitivity [6] for biodetection and the detection of small concentrations of nanoparticles. Lasing in microdisk resonators is also possible [7].

To use the McRs, it is necessary to excite high-quality-factor whispering gallery modes inside their volume, i.e., to achieve coupling with the McRs. Maintaining effective coupling is an important task during the operation of such devices. The monograph [8] describes various methods of coupling with the use of optical fibers (OFs) and prisms and coupling via separate scattering centers and surface inhomogeneities. Most effective methods of coupling are based on the effect of frustration of total internal reflection, where coupling is performed via an evanescent field. One such method is coupling using a subwavelength-diameter OF (SDOF), wherein the interaction with McRs occurs through the core of a single-mode optical fiber. Such a mechanism of inputting radiation can achieve small losses [9] and allows the creation of a high-quality fiber resonator system. The advantage of this system of input/output of radiation, apart from small losses, is the compactness and ease of switching using standard optical connectors. The alignment of such a system is simpler than that of a prism-based communication system. Therefore, systems with elongated fibers allow the creation of modern photonic devices with good characteristics and minimal form factor. In order to achieve reliable coupling with the McR, it is necessary to maintain a gap between the SDOF and the McR of the order of the wavelength. This gap seriously affects the energy exchange owing to the energy losses of the radiation in the coupling element. Therefore, it is important to maintain the mechanical strength of the region with a subwavelength-diameter waist.

The purpose of this work was the development of a technique for producing SDOF characterized by the shortest waist length with an adiabatic taper and high transmittance.

2. SETUP

In this paper, we describe a technique for manufacturing an SDOF for the system of input/output of optical radiation into an optical disk-type McR using the experimental setup illustrated in Fig. 1.

A known method for the manufacture of SDOFs is the heating of the OF workpiece with subsequent longitudinal pulling. In the literature, one can find a description of the machines for pulling OFs [11–13]. As a rule, the length of the waist of SDOFs obtained from these machines exceeds 3 mm. The best results of pulling OFs with a diameter of 530 nm and transmittance of the optical radiation of 99.95% were obtained in [11], which used an expensive noise-canceling system and a system for monitoring for the parameters of an elongated OF, including a microscope. Similar results were obtained in [13,14]. In contrast, the proposed setup uses sensors for monitoring the fiber tension and flame temperature, which enables monitoring of the pulling parameters. The readings of the sensors facilitate timely changes to the pulling process, ensuring

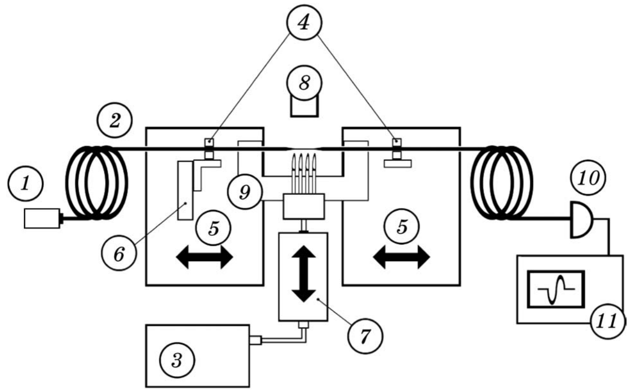

Fig. 1. Layout of the experimental setup. *1*—semiconductor laser with a VitaWave ECDL10620R external resonator [10], *2*—OF, *3*—LIGA 02S electrolyzer, *4*—Stenda 7FA1 fiber clamp with adjustable force of compression, *5*—HPS80-50X-M5 motorized stage, *6*—cantilever load cell CAS BCL-1 strain sensor, *7*—burner positioning system, *8*—pyroelectric sensor, *9*—fork drive positioning system for gluing the OF, *10*—DET20C/M photodetector, *11*—Tektronix TDS 2012C oscilloscope.

the reproducibility of the SDOF parameters. The tension sensor facilitates the determination of slippage of the OF in the clamping mounts and the moment when the fiber begins to soften and thus facilitates the selection of the optimal size and position of the flame. The temperature sensor, in turn, performs additional monitoring of the zone subjected to heating. Moreover, this experimental setup favorably differs from its analogs owing to the simplified design, which reduces the cost of manufacture of SDOF and maintenance of the experimental setup as a whole (Fig. 2).

As a source of heating, an oxygen-hydrogen mixture from an electrolyzer cell is used, which facilitates the production of a combustible mixture in a stoichiometric proportion. Consequently, the necessity of using additional precision regulators of the gas flow to select the optimal mixture composition is eliminated. The flame is formed by the nozzles fabricated from the needles of disposable medical syringes placed along a straight line, which allows the maintenance of uniform heating at a fixed length. The use of the nozzles to create different widths of the flame produces variations in the length of the elongated region, which may be necessary for its coupling with McRs of different sizes and shapes. For example, the diameter of the McR produced using the thermal method is tens of micrometers, while the diameter of the McR obtained using machining can exceed 5 mm. The use of the electrolyzer as a source of the combustible mixture has the following distinguishing feature: as the combustible mixture is delivered to the burner in the mixed form, it is necessary to maintain the flow velocity inside the nozzle above a certain limit. If the flow rate decreases, the flame may penetrate into the nozzle. A flow meter is installed at the outlet of the electrolyzer cell to monitor the flow of the prepared mixture of the burner. The reactive gas jet produced by the flame can deform the pulled fiber when the fiber becomes quite thin.

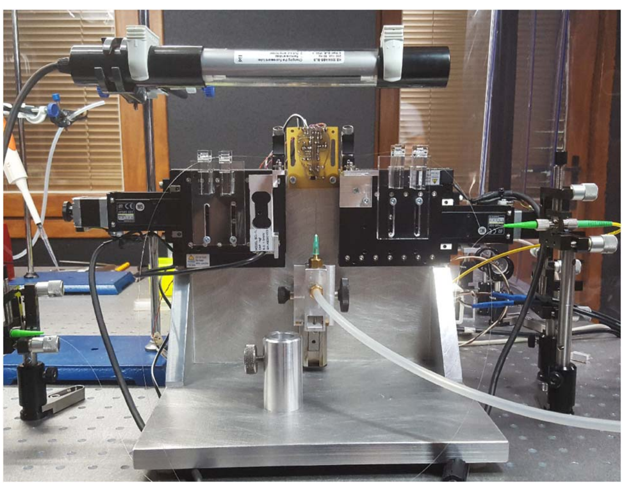

Fig. 2. Exterior view of the experimental setup.

Notably, this drawback associated with possible fiber breakage can be eliminated by using an electric heater instead of a burner. In this case, the heating process is more uniform [15,16]. However, the electric heater has a shortcoming associated with the evaporation of the heating material on the heating element, which can reduce the quality of the surface of the heated fiber unless special measures are undertaken.

The tension sensor used in the experimental setup is a strain sensor of the cantilever load cell type. Such sensors are used in electronic scales as sensitive elements. The load limit of the cell is 1 kg. At one end, the sensor is attached to the massive body of the experimental setup. At the other end of the sensor, a platform containing a fiber clamp in a hanging position is mounted. Thus, any force applied to the fiber clamp along the fiber direction will be detected. The temperature sensor is an infrared sensor fixed near the OF and directed toward the heating region. This solution does not provide accurate information about the flame temperature but allows the estimation of the temperature of the fiber surface, which is required for the proper selection of the processing conditions.

3. METHOD

The utilized technique involves manual operations sequentially performed by the operator. As a raw pulling material, a quartz single-mode OF of the 980 HP brand manufactured by Thorlabs for wavelengths ranging from 980 to 1600 nm was used. The nominal diameter of the core is $d_1 = 3.6$ μm, and that of the cladding is $d_2 = (125 \pm 15)$ μm. The selection of this particular OF is attributed to the use of laser radiations with wavelengths of 1.06 and 1.5 μm for coupling with optical McRs in many experiments. The losses inside the McRs fabricated using the fused quartz are extremely small at these wavelengths, which facilitates the achievement of high values of the *Q*-factor.

1. Before pulling, the protective polymer coating should be removed, and the heated surface must be thoroughly cleaned. Subsequently, the OF workpiece is mounted between the force-adjustable fiber clamps. The ends of the OF are connected to the laser and the photodetector. Subsequently, the pre-tension of the OF is manually set, and the absence

of slippage is monitored by the force sensor. When slippage of the OF occurs, the force inside the fiber clamp increases.

2. The flame is gradually moved to the OF; consequently, the viscosity of the quartz begins to decrease owing to heating, which causes a decrease in the fiber tension. Subsequently, the temperature in the melting zone is monitored. The quality of SDOFs significantly depends on the flame temperature of the burner. When the optimal temperature is exceeded, the quartz evaporates, which degrades the quality of the surface, and at an insufficient temperature, the required viscosity of the OF is not reached, which leads to either its breakage or significant heterogeneity of the fiber thickness. In order to adjust the temperature in the heating zone, the position of the burner nozzle and height of the flame are varied. If the tension and temperature parameters correspond to the selected processing regime for this type of OF, the following step of the procedure is performed.

3. The motorized stages are turned on. The speed of the stages is controlled using a computer. Pulling was performed at a constant speed of 0.9 mm/min. The constancy of the pulling speed potentially minimizes the beat intensity of the signal in the fiber. These results are consistent with the results of [11,13,14]. Figure 3 illustrates the change in the transmittance and tension of the OF after the motorized stages are turned on; the fiber enters a multimode regime, resulting in a characteristic pattern of the mode interference.

4. A necessary step in this method is the gradual removal of the flame of the burner downwards by 5–10 mm at the onset of beating of the intensity of the transmission signal when the waist has already started to form. This reduces the deformation of the thinned OF; at this position of the flame, the amount of heat is still sufficient for maintaining the viscosity of the OF. Upon further thinning of the fiber, the intensity beating gradually decreases, and a single-mode transmission mode is observed.

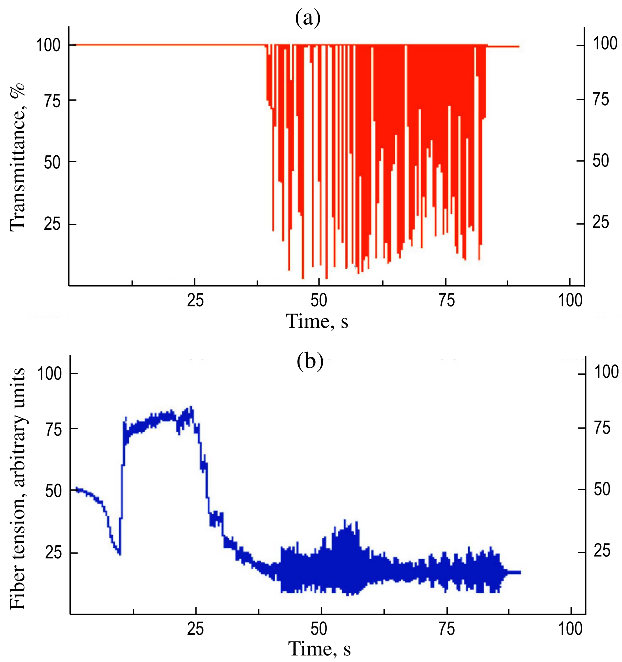

Fig. 3. Diagram of the dependence of (a) transmittance and (b) fiber tension on the pulling time.

5. The pulling is discontinued at the moment when the intensity beating of the transmission signal becomes minimal.

6. Furthermore, after completing the pulling and turning off the heating source, it is necessary to prevent sagging of the fiber under its own weight; accordingly, it should be tightened before being mounted on the fork. The fiber is tightened manually by a small movement of one of the stages. The force applied to the fiber is monitored using the tension sensor. Notably, the presence of impurities that represent optical inhomogeneities and lead to the scattering of light into the environment or its reflection back into the fiber (which in turn reduces the transmittance) is not allowed on the SDOF surface.

4. RESULTS AND CONCLUSION

The obtained SDOF samples were examined using a Leica DCM 3D interference microscope with a magnification of 50× and a numerical aperture of 0.90. The results of measurements of the SDOF profile are shown in Fig. 4.

As shown by the measurements, a tapered fiber profile is formed during pulling, whose diameter decreases following nearly exponential behavior, which ensures the matching of the modes and less reflection from the elongated region as a consequence. In the described pulling regime performed by an experienced operator, the smallest obtained diameter of the waist of this SDOF is 3.3 μm. The variation of the waist diameter length from one SDOF sample to another is ±0.1 μm. This spread is acceptable for using SDOFs in the infrared wavelength range. When manufacturing SDOFs for the visible range, such a spread may increase the amount of rejection.

It is important to emphasize that, for stable coupling with McRs, the elongated part of the fiber must have a short length (of the order of 3–5 mm) to maintain sufficient rigidity. The required length is achieved, as a rule, by replacing the nozzles and changing the drawing speed (the minimum length is provided by a nozzle fabricated from a single needle). The main results presented above are obtained using a single nozzle.

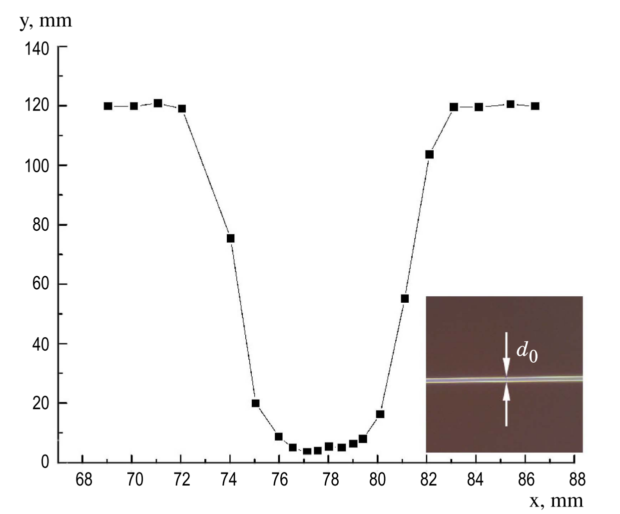

Fig. 4. Profile of the elongated part of the fiber. The diameter of the fiber is plotted along the *y*-axis. The inset shows the image of the waist of the elongated part of the fiber, $d_0 = 3.4$ μm.

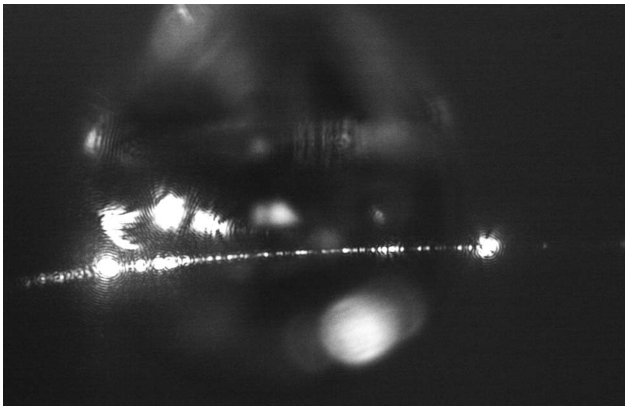

Fig. 5. Excitation of the whispering gallery modes of the microsphere using SDOFs

The described technique allows the fabrication of SDOFs with a working length range between 3 and 15 mm; it provides a smooth transition between the waist diameters and transmittance of the order of 98%. The highest transmittance obtained using the aforementioned procedure is 98.5%. The obtained geometry of the SDOF exhibits sufficient rigidity that allows the minimization of the influence of electric charge accumulated on the coupling elements of the fiber resonator, thereby providing a stable coupling with the McR. Figure 5 shows a sphere of fused quartz with a diameter of 550 μm. The excitation of the whispering gallery modes occurs at a wavelength of 1.06 μm.

The originality of this technique arises from the use of simple, commercially available tension and temperature sensors for monitoring the process of SDOF pulling, which will allow the complete automation of the process of manufacturing SDOF in the future.

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