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Measuring the focal length of a tapered fiber: experiment and modeling in the approximation of geometric optics

A.S. Pankov ✉, D.P. Sokolchik, L.O. Zhukov, A.I. Shmyrova, R.S. Ponomarev

Perm State University, Perm, Russia
✉ lab.photon.psu@gmail.com

Abstract. To connect a fiber light guide with a waveguide of a photonic integrated circuit fiber lenses are usually used. The parameters of these lenses must be certified. This paper describes a technique for fiber lens focal length measuring method of longitudinal displacement of a lensed fiber from which light comes out and a flat tipped fiber, which is a radiation receiver. The measurement results received by this method were compared with the results received using the Fabry-Perot interferometer. Additionally, light propagation in the system under study was modeled in the approximation of geometric optics.

Keywords: tapered fiber, focal length, Fabry-Perot interferometer method, longitudinal displacement method

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Измерение фокусного расстояния линзованного оптического волокна: эксперимент и моделирование в приближении геометрической оптики

А.С. Паньков ✉, Д.П. Сокольчик, Л.О. Жуков, А.И. Шмырова, Р.С. Пономарев

Пермский государственный национальный исследовательский университет, г. Пермь, Россия
✉ lab.photon.psu@gmail.com

Аннотация. В настоящей работе описана техника измерения фокусного расстояния волоконной линзы методом продольного смещения линзованного волокна, из которого выходит свет и волокна с плоским сколом, являющегося приемником излучения. Результаты измерений, полученные данным способом, сравнивались с результатами, полученными с помощью интерферометра Фабри-Перо.

Ключевые слова: линзованный волоконный световод, фокусное расстояние, метод интерферометра Фабри-Перо, метод продольного смещения

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Introduction

One of the problems of integrated optics is the question of the indissoluble connection of fiber light guides (FLG) and waveguides of a photonic integrated circuit, which have a characteristic diameter several times smaller than the core of a standard single-mode optical fiber. The use of tapered fiber (TF) is an effective solution to the problem of minimizing optical losses when joining these optical elements – optical components that represent a fiber light guide, on the end of which a microlens is formed (Fig. 1) [1, 2]. The light is focused at a finite distance, gathering into a beam at the output of the TF unlike flat tip FLG, which have at the output a divergent beam of light [3]. The possibility of varying the focal length enables the use of a TF for matching the mode fields between the laser and fiber in laser modules, as well as, for example, for detecting the interface of liquids in chemistry, or obtaining images from an endoscope and supplying radiation in medical procedures [4].

The focal length of the lens is defined by geometry, which depends of the method of production. Currently, such manufacturing methods as thermal methods, chemical etching and mechanical polishing can be distinguished. Each of these methods for making fiber lenses, as well as their combinations, has its own advantages and disadvantages. These methods make possible to produce fiber lenses with a focal length in the range from 4 to 40 μm with a minimum diameter of the mode field up to 2 μm [5]. But lenses produced by any of these methods require accurate measurement of their parameters for correct use in the assembly of photonic devices. The precise determination of the focal length of the fiber lens allows it to be used correctly as an element to decrease optical losses during the input and output of radiation.

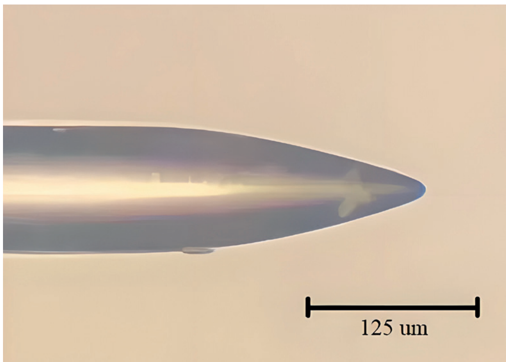

Fig. 1. The investigated tapered fiber

In this article two methods of measuring the focal length are considered: the longitudinal shift method and the Fabry-Perot interferometer method. A fiber lens produced by electric arc melting is also investigated. However, the described measurement methods can also be used for FLG formed by etching or polishing.

Measuring the focal length of fiber lenses

The emission outgoing from a flat tipped FLG is a Gaussian beam. It has a minimum diameter in the constriction located on the plane of the fiber end, as well as a certain divergence angle determined by the refractive index of the core, its diameter and the numerical aperture (NA) of the fiber.

The lens at the FLG tip converts the Gaussian beam into a convergent one, as a result of which the beam constriction can be observed at a certain finite distance, depending on the geometry of the TF. This focal length can be determined, for example, by measuring the power of emission incoming the axisymmetric receiver fiber at its distance from the source fiber (Fig. 2, *a*). The distance increase from the source fiber to the receiver fiber is performed using the three-axis micropositioner with a step of 1 μm. At each step the optical power value is recorded. Then the dependency graph of the distance between the fiber-source and the fiber-receiver on the reduced intensity of optical radiation is plotted. In the dependency graph of the power derived by the receiver, a peak will be observed at the focal length (Fig. 2, *b*).

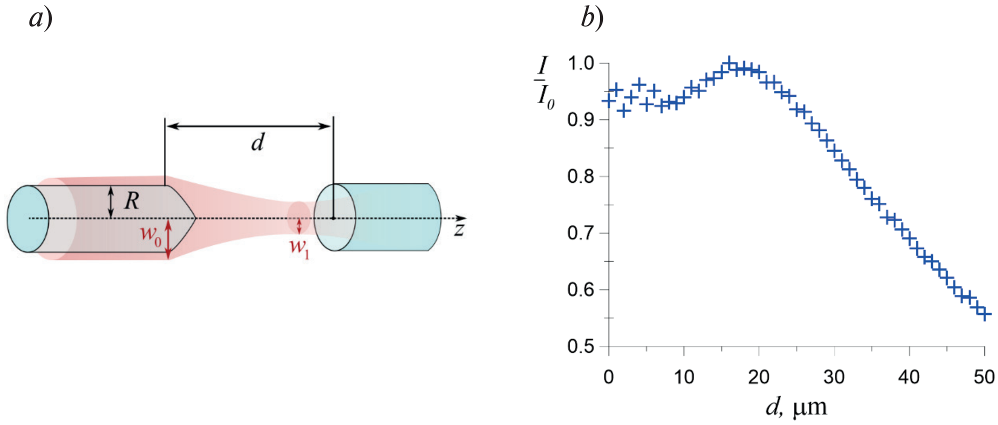

Fig. 2. The measurement of the focal length by the longitudinal shift method: the model of the method in the approximation of Gaussian beams optics (*a*); the reduced intensity distribution (*b*)

The second focal length determination method of the TF is associated with the use of a Fabry-Perot interferometer, in which outgoing beam of light is reflected from a mirror and comeback into the fiber, while experiencing interference [6]. Emission from a laser source with a wavelength of 1550 nm passed through an optical circulator and transformed by a TF. Then the emission directed to the mirror surface, reflected from it, returned back to the fiber. At the same time, interference occurred between the rays reflected from the internal surface of the TF and the rays that passed the “fiber-mirror-fiber” path. The returned power depended on the length of the Fabry-Perot cavity, i.e. the distance between the fiber lens and the mirror, the change of which was varied using a piezo positioner equipped with a controller.

The emission outgoing of the fiber is a Gaussian beam. Its generatrix is a hyperbola, the asymptote of which is inclined to the axis at an angle θ. To simplify the task, we will conduct modeling within the framework of geometric optics (Fig. 3, *a*), making a number of assumptions: we will assume that the rays come from a point source immersed deep into the fiber to a depth of $x = \theta_0 / r_0$, where θ_0 is determined by the fiber parameters: $\sin \theta_0 = \mathrm{NA} / n$, where NA – numerical aperture, and n is the refractive index of the core material. After the transformation by the lens, which we will consider thin, the rays are focused at a distance F. In fact, this distance cannot be called focal, because the depth of occurrence the source is not infinite, and the beam of rays should be considered divergent before passing the lens. However, this ray vanishing point coinside to the surface of the Gaussian beam, and therefore, within the framework of this article, we will call this distance focal. Thus, it is assumed that all emission outgoing from the fiber is enclosed within rigid limits, while in reality the limits of the Gaussian beam are blurred, and only 86% of the emission is enclosed inside them. The intensity distribution of the beam also depends on the distance from the axis according to the exponential law. However, within the framework of such a simplified model, it is possible to describe the process quite correctly.

Considering the Fabry-Perot interference, we suppose that after leaving the fiber, a beam of optical emission is repeatedly reflected between a fiber tip (with a reflection coefficient r and transmittance $t = 1–r$) and a mirror reflecting all the radiation incident on it.

In our model the outgoing laser beam is a set of rays coming from a single point. Consider one of these rays which is a wave with an amplitude of E_0. Part of this wave is reflected from the inner surface of TF, returning a wave with an amplitude of $E_1 = rE_0$ inside the fiber, and part passes through the lens with an amplitude of tE_0. After passing through the refractive surface, the TF beam is repeatedly reflected between the fiber surfaces and the mirror, returning t% of

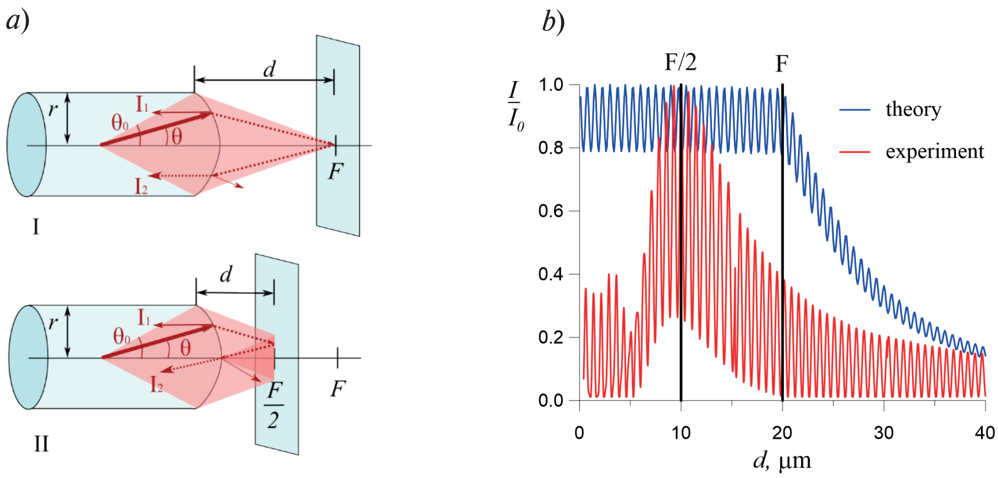

Fig. 3. Focal length measurement by the Fabry-Perot method: the model of the method in the approximation of geometric optics (a); the reduced intensity distribution (b)

each subsequent beam back to the fiber. Accordingly, each subsequent re-reflection returns to the fiber a wave with a geometrically decreasing amplitude $E_0 t^2 e^{ik\Delta}$, where $\Delta = 2L\cos\theta$ is the phase difference of the interfering rays.

Summing all the rays returned to the fiber allows us to get the total intensity of all rays that hit the fiber after re-reflection of one beam:

$$E_\theta = E_0\left(r + \frac{t^2 e^{ik\Delta}}{1 - t^2 e^{ik\Delta}}\right), \tag{1}$$

and the entire returned signal can be defined as an integral of this expression over all possible angles θ.

$$E = 2\pi \int_0^{\theta max} E_\theta d\theta \tag{2}$$

where $\theta_{max} = \text{arctg}\,(r_0 F/(2L_x – xF))$ – the maximum angle at which the emission enters back into the waveguide. It should be noted that with the length of the cavity less than the focal length, in the model under consideration, any rays will return to the waveguide, reflected from the mirror: $\theta_{max} = \theta_0$.

The intensity of the returned emission can be defined as the square of the electric field strength:

$$I = EE^* \tag{3}$$

The result of the modeling is that the distribution of optical power from the distance between the lens and the mirror (the blue curve in Fig. 3, b, which corresponds to the upper figure in Fig. 3, a) is an interference pattern, the envelope of which is determined by the length of the Fabry-Perot cavity d, and the local extremes depend on the phase difference of the interfering rays Δ. The horizontal plateau is clearly visible on the graph when the length of the cavity is less than the focal length. Then the envelope of the returned intensity decreases exponentially with the distance increasing.

The intensity distribution received experimentally in the Fabry-Perot method has a peak at a distance of half the focal length of the lens, which falls in the middle of the plateau of the theoretical graph (the lower figure on Fig. 3, a). Despite the fact that the image of the radiation source focuses on the end of the fiber at a gap length equal to half the focal length, the rigid beam boundaries in the geometric optics model ensure that all radiation enters the waveguide at a gap length less than the focus. In reality, the edges of the beam are blurred, and the shape of the intensity distribution depends on the coordinate along the z axis. Thus, the percentage of radiation that did not get into the fiber is lower the closer the detection coordinate is to the beam constriction: at the moment when the plane of the fiber end coincides with the plane of the constriction, a maximum is observed in the envelope of the interference pattern.

The interference patterns received experimentally and theoretically by Fabry-Perot have a common asymptotic behavior at large distances between the lens and the mirror, as well as a high similarity of the interference signal periods.

Comparing the two focal length measuring methods of a fiber lens, the longitudinal displacement and Fabry-Perot methods, it can be seen that both intensity distribution graphs have a maximum. However, in the Fabry-Perot method, when light passes the distance between the fiber and the mirror twice, this maximum is at a distance twice smaller than in the longitudinal displacement method. Both methods can be used to measure the focal length of a fiber lens. The longitudinal shear method is easier to implement and process. The Fabry-Perot method has a steeper peak, which may be easier to detect.

Conclusion

In this paper, such focal length measuring methods as longitudinal shift methods and the Fabry-Perot method are considered. Using these focal length measuring methods allows to verify the accuracy of the measurement results received: the received values of the focal length coincide. The modeling of the process of fiber lens focal length measuring in the approximation of geometric optics is performed. In future work, it is planned to model the outgoing beam taking into account its Gaussian nature.

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THE AUTHORS

PANKOV Anatoliy S.
lab.photon.psu@gmail.com

SOKOLCHIK Darya P.
dsokolchik@rambler.ru

ZHUKOV Leonid O.
leonidgp@bk.ru

SHMYROVA Anastasia I.
shmyrova@psu.ru
ORCID: 0000-0001-9199-2487

PONOMAREV Roman S.
rsponomarev@gmail.com
ORCID: 0000-0001-9729-628X

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