RESEARCH ARTICLE | JULY 27 2016

X-ray beam transfer between hollow fibers for long-distance transport

Yoshihito Tanaka; Ryuki Matsushita; Ryutaro Shiraishi; Takayuki Hasegawa; Kiyoshi Ishikawa; Kei Sawada; Yoshiki Kohmura; Isao Takahashi

AIP Conf. Proc. 1741, 040029 (2016)
https://doi.org/10.1063/1.4952901

X-Ray Beam Transfer between Hollow Fibers for Long-Distance Transport

Yoshihito Tanaka[1,a)], Ryuki Matsushita[1], Ryutaro Shiraishi[1], Takayuki Hasegawa[1],
Kiyoshi Ishikawa[1], Kei Sawada[2], Yoshiki Kohmura[2] and Isao Takahashi[3]

[1]*Graduate School of Material Science, University of Hyogo, 3-2-1 Kouto, Kamigori-cho, Sayo-gun, Hyogo 678-1297, Japan*
[2]*RIKEN SPring-8 Center, 1-1-1 Kouto, Sayo-cho, Sayo-gun, Hyogo 679-5148, Japan*
[3]*Department of Physics, School of Science and Technology, Kwansei Gakuin University, 2-1 Gakuen, Sanda, Hyogo 669-1337 Japan*

[a)]Corresponding author: tanaka@sci.u-hyogo.ac.jp

Abstract. Fiber optics for controlling the x-ray beam trajectory has been examined at the synchrotron facility of SPring-8. Up to now, we have achieved beam deflection by several tens of milli-radian and axis shift of around 75 mm with a 1.5 m-long flexible hollow glass capillary. The achievable beam deflecting angle, axis shift, and timing delay are, in principle, proportional to the length, the square of length and the cube of length, respectively. Thus, for further applications, requiring larger beam shift and pulse delay, longer fibers are indispensable. In order to achieve long-distance transport using the fiber, we thus examined the connection transferring x-rays between fibers in an experimental hutch. The acceptance angle at the input end and the throughput efficiency of the second fiber is consistent with the consideration of the output beam divergence of the first fiber. The enhancement of the transfer efficiency is also discussed for the cases of a closer joint and the use of a refractive lens as a coupler.

INTRODUCTION

In a hollow glass capillary, an x-ray beam propagates inside the core by way of a number of total reflections. The characteristics have been utilized chiefly for focusing and collimation optics. If a meters-long hollow glass fiber is achievable, it works as fiber optics and can, in principle, connect a light source with a sample at any part, with any angle, and at any distance with arbitrary trajectory. Trajectory control in the x-ray range will open the field to polarization control, jitter-free x-ray pump and probe experiments, real-time x-ray computed tomography, x-ray mapping for fixed samples, and multiple experimental stations with an x-ray source.

We thus began with a 0.7 m-long hollow glass capillary with a bore diameter of 50 μm and an outer diameter of 2 mm [1]. The thick cladding made of borosilicate glass prevents the capillary from abrupt bending and gives the limited curvature satisfying total reflection condition for x-ray beams propagating inside the core. The glass capillary was examined for a well-collimated x-ray beam at a synchrotron facility, realizing the deflection up to 40 mrad with the achieved transmitted power of 0.16 mW at an x-ray photon energy of 12.4 keV. Next, the beam axis shift has been performed by using a 1.5 m-long borosilicate glass capillary with bore and cladding diameters of 20 μm and 1.5 mm, respectively. The observed transmission efficiency was more than 20 % at 12.4 keV. As a demonstration, we reported the two-dimensional scan of an undulator beam to identify the elements for a fixed metal film through its absorption spectra [2]. Although the transmission efficiency is high enough to demonstrate the principle of the trajectory control, higher efficiency is preferable for practical use. Then we examined a fiber made of quartz, and obtained an efficiency of about 70 % which is higher than that of borosilicate. The high efficiency may be due to the stability of centroid and/or the smooth surface of the hollow core. Recently we also examined the

Proceedings of the 12th International Conference on Synchrotron Radiation Instrumentation – SRI2015
AIP Conf. Proc. 1741, 040029-1–040029-4; doi: 10.1063/1.4952901
Published by AIP Publishing. 978-0-7354-1398-6/$30.00

time delay by using the quartz hollow fiber with the same dimensions that of the fiber used for the demonstration of beam axis shift.

The higher transmission efficiency allows us to use the longer fiber for trajectory control, and to get the high flexibility in beam handling. As shown in the following section, the beam deflection, axis shift, and timing delay are in principle proportional to the length, the square of length and the cube of length, respectively. In this paper, we estimate the achievable parameters as a function of the fiber length using the relations, in order to show the importance of the connection of the fibers for extension of the total transport distance. We then show the transfer efficiency at the connection without additional coupling devices through the demonstration using two 1.5 m-long hollow glass fibers, and discuss how to enhance the transfer efficiency.

DESIGN OF X-RAY FIBER OPTICS

In a hollow fiber, an x-ray beam is reflected at the core-cladding interface under the total reflection condition. The dimensions were thus designed on the basis of the optical parameters in the hard x-ray region, where the refractive index is slightly smaller than a unity, which is expressed as $n=1-\delta+i\beta$ $(1>>\delta > 0)$. As the curvature of the fiber is limited due to the small critical angle, $\theta_c \approx \sqrt{2\delta}$, the available curvature radius, R, is given as,

$$R \geq \frac{2d}{\theta_c^2}, \tag{1}$$

where d is the bore diameter. The relation of (1) gives the achievable beam deflection by θ, the beam axis shift, x, and the time delay, t, satisfying,

$$\theta \leq \frac{l\theta_c^2}{2d}, \qquad x \leq \frac{l^2\theta_c^2}{8d}, \qquad t \leq \frac{l^3\theta_c^4}{144cd^2}, \tag{2}$$

where l and c are the length of the fiber and the speed of light, respectively. From eq. (2), the beam deflection, axis shift, and timing delay are proportional to ld^{-1}, l^2d^{-1}, and l^3d^{-2}, respectively. Figure 1 shows the length dependences for a borosilicate fiber, which has θ_c~2.3 mrad for a 12.4 keV x-ray beam. The graphs are drawn for the cases of d=20 μm and 50 μm. In fact, the experimental result we reported [1] that the deflection of up to ~40 mrad (2.3°) was achieved by an x-ray fiber with d=50 μm, and l=0.7 m, is consistent with the estimation shown in Fig. 1(a). For the beam axis shift, where the fiber is bent as shown in the upper part of Fig. 1(b), we made the demonstration using the fiber with d=20 μm, and$l$ =1.5 m[2], in which the experimental result is also consistent with the estimation.

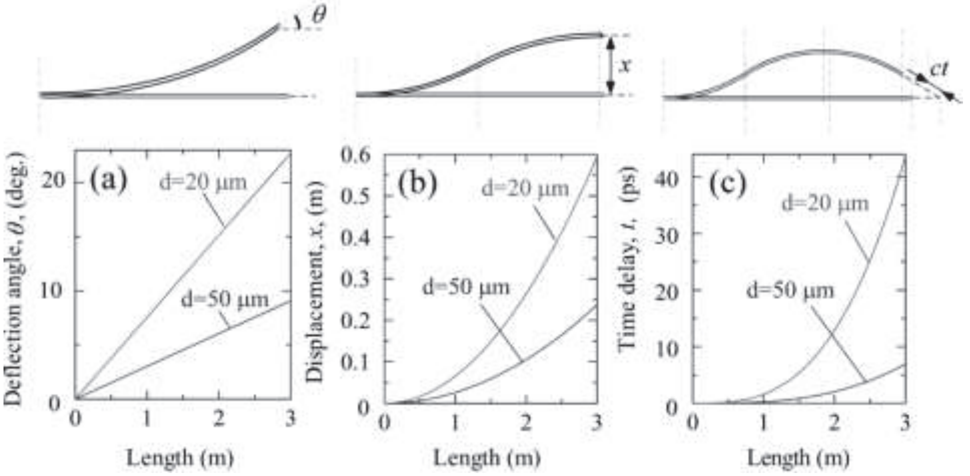

FIGURE 1. Calculations of the achievable (a) beam deflecting angle, (b) beam axis shift, and (c) time-delay by curved x-ray fibers with bore diameters of 20 μm and 50 μm, using eq. (2).

The above observation indicates that the total length, l, as well as the bore diameter, d, are important parameters to obtain the high flexibility with the beam trajectory control, especially for the beam axis shift and timing control. However, the limited curvature requires the connection of the fibers in order to obtain the long fiber with l>>1 m. We thus examined the connection with the same fiber that was used in the previous experiment for the beam axis shift. If the two fibers can be connected, the total length will be over 3.0 m, and the axis shift by ~600 mm can, in principle, be achievable with the 20 μm-core fiber according to Fig. 1(b).

X-RAY BEAM TRANSFER BETWEEN FIBERS

The demonstration of x-ray transfer between fibers was conducted at undulator beamlines of BL19LXU and BL29XU in the SPring-8 synchrotron radiation facility. The experimental station has a size of 5 m in the beam direction, which is sufficient for the test experiment to connect two 1.5 m-long x-ray fibers. First, the upstream fiber (fiber 1) was installed in the experimental hutch. The alignment of the input end of fiber 1 was done as follows: A fiber holder was adjusted with respect to the x-ray beam by monitoring the shadow of the holder by a flat panel detector, whose area and the pixel size are 100 mm by 100 mm and a pixel size of 50 μm, respectively. Then, a fiber 0 with l =0.7 m, d=50 μm was set on the holder, and the angle and the position of fiber holder were tuned to get throughput beam on the flat panel. Then, the fiber was replaced with the fiber 1 (l =1.5 m, d=20 μm), and the holder was again finely adjusted to optimize the output beam intensity. After the alignment for fiber 1 was completed, another fiber with the same dimension, fiber 2 was also installed downstream of fiber 1 in the same manner as stated above.

The important parameters for transfer efficiency at the connection are the output beam divergence of fiber 1 and the distance between the output end of fiber 1 and the input end of fiber 2. Figure 2 (a) shows the dimensions of fibers and the interval at the connection. The interval was 200 mm, which was chosen in order to allow placement of a photodetector for the measurement of output intensity at the experiment. The throughput intensity dependent on the holder position for the input of fiber 2 is shown in Fig. (b). From the widths of 0.24 mm in FWHM, the divergence angle is roughly estimated to be 1.2 mrad, which is approximately the same magnitude in the previous report (1.1 mrad) [2]. The angle dependence of the throughput intensity of fiber 2 was also measured and is about 2.5 to 3.0 mrad in FWHM in Fig. 2(c). The tuning range in the angle is larger than that for the fiber 1 (~1.6 mrad [2]), which may be attributed to the output beam divergence. Note that the alignment of the input holder for fiber 2 is easily achievable by way of the rough estimation of the position- and angle-dependences of throughput intensity, although the dependences do not directly give the beam size and the divergence. The fact that the angle tuning range for fiber 1 is much larger than the transferred beam divergence, indicates that the bulk of the beam reaching the core of fiber 2 propagates in the fiber. Thus, the ratio of the input intensity of fiber 2 to the output of fiber 1 can be estimated by using the ratio of the area at the input end of fiber 2, as $d^2/{d_2}^2 \sim (20\ \mu\mathrm{m})^2/(240\ \mu\mathrm{m})^2 = 6.9 \times 10^{-3}$, where d_2 is the diameter of beam size at the input of fiber 2. According to this estimation, an x-ray beam with $\sim 7 \times 10^6$ photons/s is transferred to fiber 2 when 10^9 photons /s is output from fiber 1.

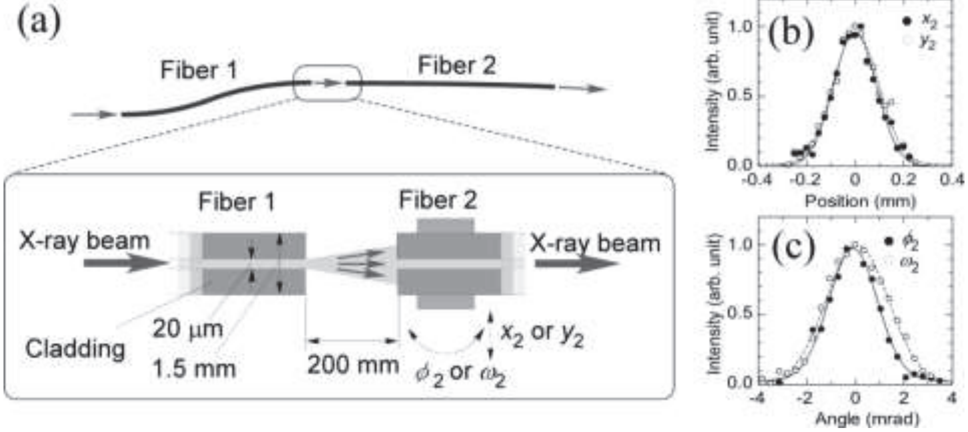

FIGURE 2. (a) A schematic illustration of the fiber connection. A support table for the input-end of the second fiber was also equipped with the 4 axes stages as set for the first fiber. (b) The position dependence of the throughput intensity at the input end of the fiber 2. (c) The input-end angle dependence of the throughput intensity for the fiber 2.

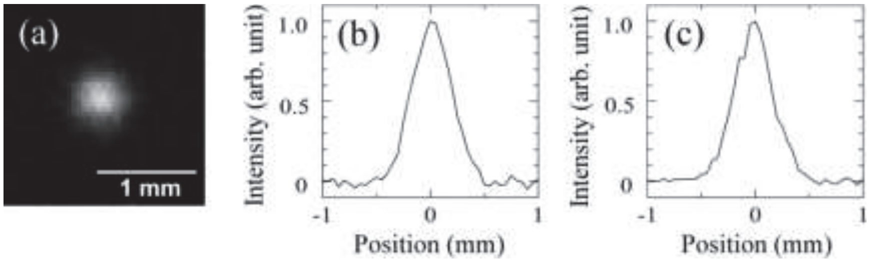

FIGURE 3. (a) 2-dimensional, (b) horizontal, and (c) vertical x-ray beam profiles through the fiber 2 observed at 200 mm downstream from the output end.

The transmitted x-ray beam pattern was observed with a flat panel detector located at 200 mm downstream from the output end of fiber 2, the 2-dimensional profile of which is shown in Fig. 3(a) together with the horizontal and the vertical profiles in Fig. 3(b) and 3(c), respectively. The output divergence is estimated to be ~2.0 mrad, which is larger than that of fiber 1 by ~2. This may be due to the divergence of input beam. The integrated intensity on the flat panel was also measured with a PIN photodiode. The ratio between with and without the fiber 2 was measured to be 6.3×10^{-4}. The ratio is composed of the geometrical loss at the interval between the fibers as stated above and the transmission efficiency of the fiber 2, which are 0.69 % and 9 %, respectively. The transmission efficiency is slightly smaller than the single 1.5 meter-long fiber (~20 %) by a factor of ~2, which may be also due to the input beam divergence. The fact that the transmission efficiency is still of the same order promises a practical joint by a closer interval.

SUMMARY AND PERSPECTIVE

An x-ray fiber with a flexible hollow capillary will be a powerful tool for controlling the beam trajectory when the length can be extended to meters. As the joint is indispensable to extend the length, the beam transfer between fibers has been examined. The transfer efficiency is consistent with a geometrical loss and the divergence of the output beam. As the loss in the transfer efficiency is mostly attributed to the interval between the fibers, the transfer efficiency will be up to ~20 % by minimizing the interval to a few mm with miniature components for the fiber holders in practical use. In the future, a direct joint will also be effective as used for optical fiber.

Another way to enhance the transfer efficiency is to collect the diverged beam onto the input of fiber 2 using a refractive lens. We also examined to use a compound refractive lens (made by KIT) with a focal length of ~1 m for the x-ray beam with a photon energy of 12.4 keV, and an acceptance diameter of 380 μm. The throughput was ~30 times higher, which corresponds to ~20 % transfer efficiency. The efficiency is equivalent to an interval of ~5 mm without the lens. For the joint, the lens with a shorter focusing length with a smaller acceptance diameter is useful to save the space between the fibers and to reduce the absorption by the compound lens.

Toward the practical application, development of reproducible and smooth shape control of the fibers is essential in accordance with the longer transport of the x-ray beam. A simple mechanism which is composed of cams and rods is under construction, according to the concept of easy- and simple-handling.

ACKNOWLEDGMENTS

The authors would like to thank Dr K. Ito, Ms H. Sato, Dr A. Nisawa, Mr S. Yamamoto, and Mr M. Shirai for technical help. The synchrotron radiation experiments were performed at BL19LXU andBL29XU at SPring-8 with the approval of RIKEN (proposal Nos. 20120058 and 20130050). This work was supported by A-STEP, Japan Science and Technology Agency and JSPSKAKENHI grant No. 24651109, and 25286092.

REFERENCES

1. Y. Tanaka, K. Ito, Y. Matsushita, Y. Oji, T. Nakatani, K. Sawada, I. Takahashi, X-ray beam deflection control with a flexible capillary, J. Phys. Conf. Ser. **425**, 052017 (2013).
2. Y. Tanaka, T. Nakatani, R. Onitsuka, K. Sawada, I. Takahashi, Controlling X-ray beam trajectory with a flexible hollow glass fibre, J. Synchrotron Rad. **21**, 61 (2014).