MEDICAL APPLICATION OF FREE ELECTRON LASER TRANSMITTANCE USING HOLLOW OPTICAL FIBER

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Abstract

Mid-infrared Free Electron Laser (FEL) is expected as new application for biomedical surgery. However, delivery of MIR-FEL into the body is difficult because the common glass optical fibers have strong absorption at MIR region. A good operational and flexible line for FEL is required at medical field. A Hollow optical fiber is developed for IR laser and high-power laser delivery. We evaluated the fiber for FEL transmission line. This fiber is coated with cyclic olefin polymer (COP) and silver thin film on the inside of glass capillary tube. It is 700 μm-bore and 1 m in length. The fiber transmission loss of the measured wavelength region of 5.5 μm to 12 μm is less than 1 dB/m when the fiber is straight and 1.2 dB/m when bent to radius of 20 cm. In additionally, the output beam profile and the pulse structure is not so different form incidence beam. In conclusion, the fiber is suitable for delivery of the FEL energy for applications in medical and laser surgery.

INTRODUCTION

A bio-molecule that constitute of the protein has strong absorption coefficient due to molecule vibration in infrared region. A free electron laser (FEL) is expected as selective and low-invasive treatments because the FEL which is able to tune in a wide wavelength range of infrared region excite molecule vibration selectively.

An atherosclerosis is caused by accumulation of cholesterol ester which is ester bond of cholesterol and fatty acid. We have reported that the wavelength of 5.75 μm corresponding to C=O stretching vibration of ester band resolves only cholesterol ester selectively [1]. The effect was confirmed on the *in-vitro* which used the cholesteryl oleate, the rabbit and the human blood vessel arteriosclerosis part section [2] [3]. Since the technique is the potential a low-invasive laser surgery in blood vessel compared a conventional method, an in-vivo experiment is expected. However, there is no guide line for transmitting infrared FEL. The FEL beam is usually guided by ZnSe lenses and mirrors to target materials but is difficult to deliver to small target in a narrow space and/or in the body. The common medical devices are used articulated manipulator or grass optical fiber for laser transmission. However, the articulated manipulators are unusable *in-vivo* surgery. The common glass optical fibers with IR absorption are also difficult to transmit enough energy. Therefore, the FEL beam transmission line is required good operationally and flexibility at medical field.

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The FEL transmittance loss using chalcogenaide NSEG fiber have been reported by Awazu *et al* [4]. The transmittance could not exceed 70%. The fiber was fabricated with GeAsSeTe glass for the core and GeAsSe glass for the cladding is also harmful to human, thus it is not suitable for medical applications. A Hollow optical fiber which is developed by Miyagi and Matsuura is suitable for delivery IR laser beam and high-power laser such as CO_2 laser and Er:YAG laser which is in practical use [5] [6]. It is a thin tube composed of the air core and the dielectric with high refractive index or metal cladding, and loss in the core is practically nought. Transmission loss of wavelength 6.45 μm FEL at Vanderbilt University has reported by Matsuura *et al* [7]. The 1000 μm bore fiber, 1 m in length, gave transmission loss of 0.46 dB. In addition, the hollow optical fiber is used for some medical application using infrared laser. For example, Shen *et al* [8] reported that the hollow optical fiber is suitable for delivering the IR FEL for intraocular microsurgical procedures.

We have researched various interactions between biomedical tissues and FEL, beside the selective removal of cholesterol (5.75 μm), such as the surface modification of tooth dentin using FEL wavelength 9 μm bands and the ablation of soft tissue using FEL 6.05 μm.

This article reports the FEL transmission loss of wavelength from 5 μm to 12 μm using hollow optical fiber of 700 μm-bore, the guide system in a blood vessel using the hollow optical fiber is discussed.

EXPERIMENT

We tested the FEL power transmission of the hollow optical fibers with 700 μm-bore and 320 μm -bore, respectively. Both the hollow fibers are coated with cyclic olefin polymer (COP) and silver thin film on the inside of glass capillary tube. Figure 1 shows the IR absorption of the fiber measured using Fourier transform infrared spectroscopy (FTIR). The large peak at around 7.0 μm and the broad peak at 7-8 μm are due to absorption of the COP film. However, we need the transmission line which can be broadly covered in a mid infrared region. In addition, 6 μm and 9 μm bands used for our research such as surface modification and/or soft tissue ablation has little absorption.

The setup for the FEL power transmission experiments is shown Figure 2. The length of both the fibers is 1m. A FEL at Institute of FEL (iFEL), Osaka University in JAPAN, is tunable from 5 μm to 22 μm in mid-infrared (MIR) region, which is high peak power and short pulse

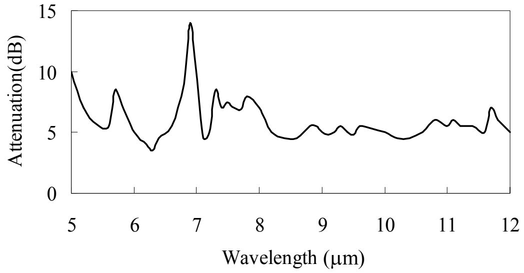

Figure1: Typical absorption spectrum of hollow optical fiber.

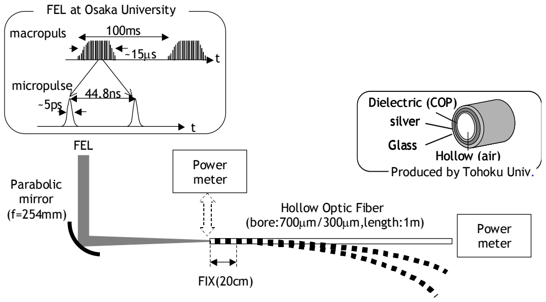

Figure 2: Experiment setup for the power transmission of the FEL.

operation. The FEL has a unique double pulse structure; the structure consists of a train of macropulses, and each macropulses contains train 300-400 ultrashort micropulses. The width of the macropulses is about 15 μs and repetition rate is 10 Hz. The width of micropulses is shorter than 10 ps and the separation between micropulses is 44.8 ns. The FEL beam focused using parabolic mirror (f = 254 mm) and enter an input end of hollow optical fiber. The mirror with a long focus reduces the coupling loss. The diameter of a beam is small enough to the input end of the fibers, and the input end of the fiber is not damage.

We measured the FEL average power at input end and output end of the fiber using the power meter (LaserStar 2A-SH, OPHIR) and calculate the power loss.

TRANSMISSION CHARACTERISTICS

Transmittance loss

The FEL transmission loss of wavelength from 5.5 μm to 12.0 μm in each fiber is shown in Figure 3. The transmission loss is not dependent on wavelength and is not influenced by IR absorption of COP. In the 700 μm -bore fiber, the transmittance loss at 5.5-12.2 μm is less than 1.2dB/m, which corresponds to over 80 % power transmission. The result shows that the 700 μm -bore hollow optical fiber is low loss and is enough as the guide line of FEL. In contrast, the 320 μm -bore fiber have the large loss exceeding 3dB/m, which corresponds to 50 % power transmission, because the diameter of FEL beam is no focus attention on less than 320 μm.

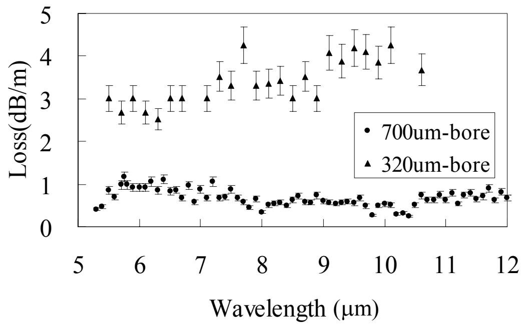

Figure3: Transmittance loss as a function of wavelength. The bore diameter is 700 mm and 320 mm, respectively and each fibers length is 1m.

Bending loss

Figure 4 shows the bending loss of FEL wavelength 5.75, 6.0, 9.4 10.6 and 12.0 μm, which are effective in bio-molecular such as ester band [1][2], phosphoric group and amide bond. The bending loss was increased from straight state (0 m^{-1}). The max bending loss in curvature 4.5 m^{-1} is 1.2 dB/m. The hollow optical fiber has losses sufficiently low for MIR-FEL transmittance.

Output beam profile

FEL beam spectrum and pulse structure after transmission are estimated. Figure 6 (a), (b), (c) shows beam profile of points which is distant from output end 2, 5, 10 mm, respectively. The estimated divergence angle is 2-3 degree. The form of these output beams are the same Gaussian as an input beam form. The distributed of light in Figure 6 (c) may be due to propagation mode but it is no problem because fiber come in contact with treated area in a blood vessel.

Figure 7 shows the pulse structure of before entering fiber and after transmission using MCT detector (R005, Vigo System). There is not much difference between before and after entering fiber.

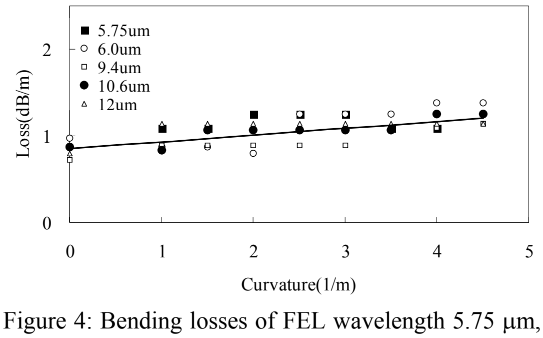

Figure 4: Bending losses of FEL wavelength 5.75 μm, 6.0 μm, 9.4 μm, 10.6 μm and 12 μm.

DISCUSSION AND CONCLUSIONS

We verified the hollow optical fiber as guiding line for transmitting FEL. The transmission efficiency achieved

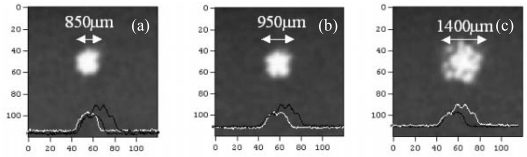

Figure 6: Beam profile of output end. Each point is distant fram output end (a) 2 mm, (b) 5 mm, (c)10 mm.

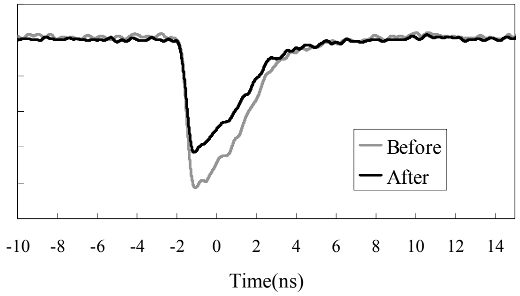

Figure 7: Pulse form of before entering fiber and after transmission using MCT detector

over 80 % in the case of bore diameter of 700 μm. The form and profile of beam passed in the fiber is like incident beam. These results confirmed that the fiber which developed CO_2 laser is applicable to the FEL with a unique pulse structure.

We have proposed the medical treatment in a blood vessel of atherosclerosis using the hollow optical fiber. In a previous report, we showed that the optimal power density which removes cholesterol ester selectively is 16 W/cm^2 [3]. Figure 8 shows the relation of the FEL average power to the diameter of beam required in order to give the power density of 16W/cm. When using the fiber of 700 μm-bore, the FEL average power exceeding 60mW is needed, but in iFEL, it is less than 50 mW. The scale factor of the fiber of 320 μm-bore to 700 μm-bore is 4.7, thus the fiber of 300 μm-bore obtains a necessary requirement for removes cholesterol ester by 15 mW average power. However, the loss of 320 μm-bore fiber is not the optimal in order to exceed 3dB by coupling loss (see Figure 3). In addition, the guide of the light in a blood vessel has a problem about the structure of the hollow optical fiber. Since the core of the fiber is an air hole, the blood flows in the fiber and blocks transmission of laser beam. We are developing the fiber cap like lens. The material of lens cap uses a diamond which has little absorption at MIR region and is harmless to humans.

In the future we are going to evaluate about the fiber with lens cap and to apply to clinical. Establishment of the technique is only the guiding light in blood vessel, but is also possible to transmit at region which it is not possible to focus by lens and/or mirror such as vacuum region, is useful to the FEL application.

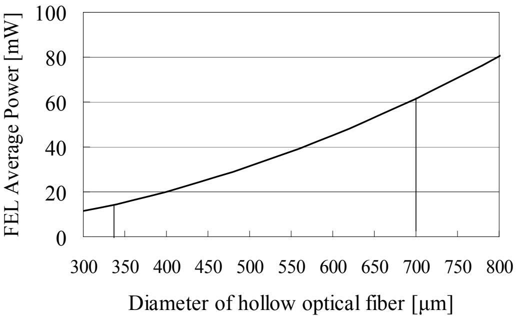

Figure 8: the relation of the FEL average power to the diameter of beam required in order to give the power density for removes cholesterol ester (16W/cm).

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