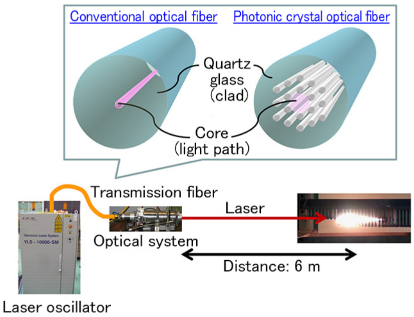
Beam Transmission Technology by Photonic Crystal Fiber to Realizes High-precision and High-efficiency Laser Processing Technology



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Since April 2014, Nippon Telegraph and Telephone Corporation (NTT) and Mitsubishi Heavy Industries, Ltd. (MHI) have applied NTT laboratory's research and development results in the information and communication technology (ICT) field to our energy/environment, traffic/transportation and other social infrastructure products, as well as to domestic and overseas production sites and on-site construction work, and have promoted research and development collaboration with the aim of creating new value. As one of the achievements thereof, we succeeded in transmitting kW-class high-power single-mode laser beam over several tens of meters while maintaining high quality suitable for precision processing by combining photonic crystal fiber (PCF), one of NTT's optical fiber technologies for communication, with our high-power laser processing technology.

1. Introduction

The currently widely-used laser beam is a multi-mode laser beam and can be transmitted over several hundred meters with existing optical fiber (multi-mode optical fiber). However, this multi-mode laser beam has a limit in terms of the beam focusing diameter and is not suitable for applications requiring high processing accuracy. On the other hand, a single-mode laser beam, which is suitable for more precise laser processing due to its high quality and high condensability, can be transmitted only a few meters with existing optical fiber when the single mode is maintained, so it could not be applied to actual processing at production sites or on-site construction work where optical fiber transmission of several tens of meters is required. To realize high-precision and highly-convenient laser processing, it is necessary to efficiently deliver high-quality laser beam output from a high-power single-mode laser oscillator to a processing site while maintaining a level of quality suitable for processing. Optical fiber plays an important role as the transmission medium in this technology. The high power transmission capability of optical fiber can be improved by increasing the effective beam cross-sectional area A_{eff} at the used wavelength. However, as the A_{eff} increases, the number of modes that can propagate in the optical fiber increases, causing the deterioration of the beam quality at the optical fiber output end. For this reason, it is difficult for ordinary single-mode optical fiber (SMF), which forms the core by adding materials, to improve its high-power transmission capability, which is expressed by the product of output light intensity and transmission distance, to 100 kW m or more[(1)].

2. Photonic crystal fiber (PCF)

PCF guides beam by confining it in a region surrounded by multiple holes formed in the propagation direction in pure silica glass. The hole layer operates as an effective cladding region, and the effective refractive index difference with respect to the core region can be flexibly controlled. As such, PCF can realize transmission characteristics that cannot be achieved by ordinary SMF. **Figure 1** illustrates cross-sectional images and the characteristics of ordinary SMF and PCF. PCF with the simplest cross-sectional structure can be realized by periodically arranging

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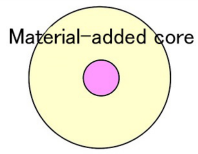
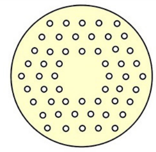
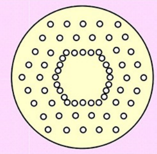
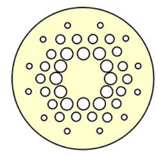
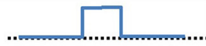
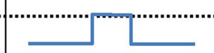
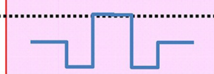
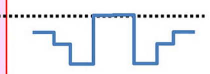
holes with diameter *d* at uniform pitch Λ. The guiding principle of PCF is based on the confinement of beam with total reflection, which is the same as ordinary SMF. However, while the effective refractive index difference between the core and cladding of SMF is about 1%, that of PCF can be very flexibly controlled to be about 0.01% to more than 10%. The transmission characteristics of PCF can be controlled by arbitrarily changing the combination of *d* and Λ. For example, by controlling the ratio *d*/Λ, single-mode transmission at any wavelength can be realized, and therefore can increase A_{eff} significantly. We also devised a quasi-uniform-structure PCF that achieves both A_{eff} controllability and manufacturability. This quasi-uniform-structure PCF is composed of uniform d and realizes a structure in which Λ is effectively changed by increasing the number of holes in a specific layer. Since *d* is constant and there is no need to perform complicated control of the hole diameter during the spinning of the optical fiber, manufacturability equivalent to that of uniform-structure PCF can be maintained. On the other hand, due to the change of occupancy of the holes in the radial direction of PCF, a more complicated equivalent refractive index distribution compared with uniform-structure PCF can be realized.

	Ordinary SMF	Uniform-structure PCF	Quasi-uniform-structure PCF (proposed structure)	Nonuniform-structure PCF
Hole diameter: *d* Hole interval: Λ	No hole	*d*: Constant Λ: Constant	*d*: Constant Λ: Two types or more	*d*: Two types or more Λ: Two types or more
Example cross-sectional structure				
Equivalent refractive index distribution				
Design flexibility (core extensibility)	×	○	◎	◎
Productivity	◎	○	○	×

×: Low ○: Medium high ◎: High

Figure 1 Images and characteristics of ordinary SMF and PCF

The relationship between the hole diameter *d* and the pitch Λ that simultaneously satisfies the requirements of the hole structure of PCF, where the number of allowable propagation modes (beam quality M^2) is 3 or less, the minimum allowable bending radius is 500 mm and the high power transmission capability is 300 kWm or more, was examined. **Figure 2** depicts the relationship between Λ and *d*/Λ. The left part of Figure 2 shows the calculation results for uniform-structure PCF, and the right part the examination for the quasi-uniform-structure PCF. The solid, dashed and dotted lines in the figure represent the structural boundaries for the requirements of the number of modes, bending radius and high-power transmission capability, respectively, and all the requirements can be met simultaneously in the shaded area in the figure. Figure 2 indicates that the quasi-uniform-structure PCF devised this time can be designed under conditions less restrictive than those of uniform-structure PCF. **Table 1** compares the calculation results of A_{eff} and high-power transmission capability at the design centers indicated by the two red circles in Figure 2 with the example reported in the literature (1). Table 1 shows that PCF can achieve A_{eff} of 2000 μm^2 or more and can be expected to have a high power transmission capability four times or more higher than that of the existing SMF.

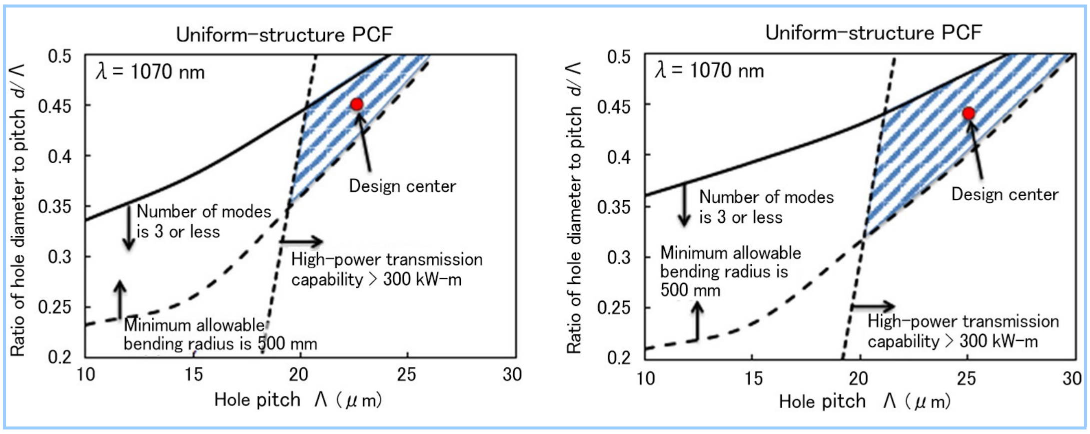


Figure 2 Design requirements of uniform-structure PCF and quasi-uniform-structure PCF for achieving desired transmission characteristics

Table 1 Calculation results of A_{eff} and high-power transmission capability at design centers (red circles) indicated in Figure 2 (λ = 1070 nm)

	Reported SMF example(1)	Uniform-structure PCF	Quasi-uniform-structure PCF
Effective core area Aeff (μm2)	600	2,100	2,500
High-power transmission capability (kW-m)	100	350	420

3. Prototyping and transmission experiment

Based on the design requirements described in Chapter 2, we prototyped a quasi-uniform-structure PCF wire and made a 30-m long optical cable equipped with a connector for high-power connection. The developed high-power PCF has a small fiber core diameter, so an optical coupling system that can accurately align the incident beam to the fiber end face is required to efficiently transmit the beam emitted from the laser oscillator. However, the high power causes a temperature increase in the lens used in the optical coupling system, which leads to a change in the refractive index, resulting in fluctuation in the beam position. Therefore, we used synthetic quartz and CaF_2, the refractive index change characteristics of which are contrary to each other with respect to temperature, as the lens material, and determined and applied the best arrangement through simulation (**Figure 3**). **Figure 4** presents the experimental results of the input and output characteristics obtained in a transmission experiment using a high-power single-mode laser oscillator. This shows that the output beam intensity increases linearly with the input beam intensity. With 10 kW input power, which was the maximum output of the available device, the output power was 9.1 kW, so the propagation efficiency including the coupling loss was 91%. The value of the beam quality M^2 was 2.5. The above results verified that the actual optical fiber cable with connector including the quasi-uniform-structure PCF had the high-power transmission capability of 270 kWm or more.

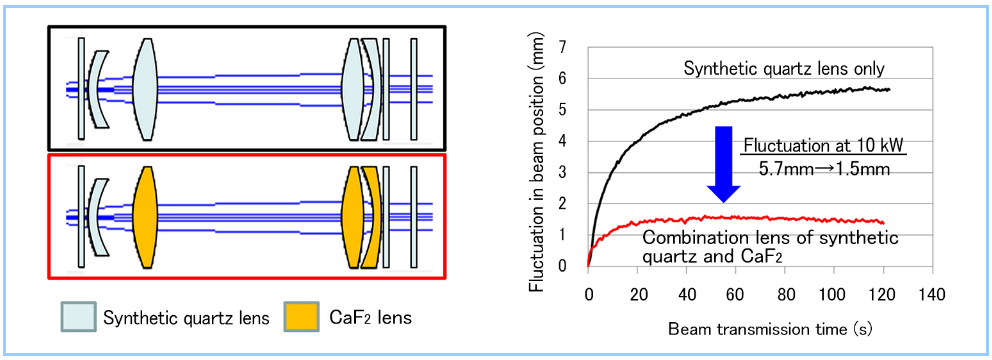
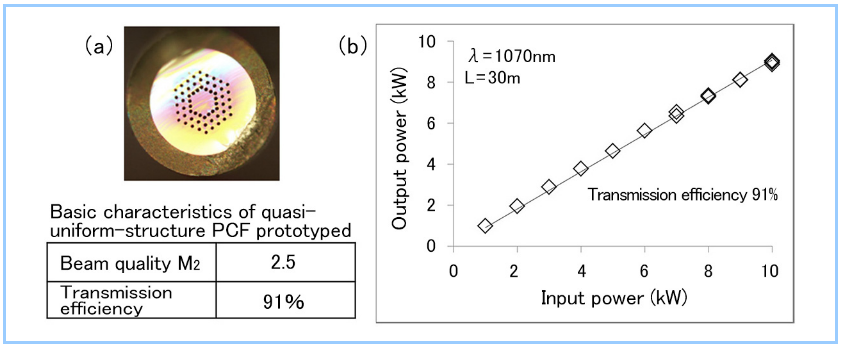


Figure 3 High-power optical coupling system with reduced beam position fluctuation



Basic characteristics of quasi-uniform-structure PCF prototyped

Beam quality M2	2.5
Transmission efficiency	91%

Figure 4 Prototyping and transmission experiment results
(a) Cross-sectional photograph and basic characteristics of quasi-uniform-structure PCF prototyped
(b) Input and output characteristics of high-quality single-mode laser beam

4. Application of laser processing using single-mode optical fiber

This technology is expected to be applied to ultra-low heat input and high-quality welding of heat-resistant alloys for gas turbine high-temperature parts and engine parts, laser cutting using long-distance beam irradiation in the demolition of decommissioned nuclear reactors, and cutting and drilling of CFRP aircraft parts (main wing and soundproof cover) without heat effect. **Figure 5 to Figure 7** give processing examples.

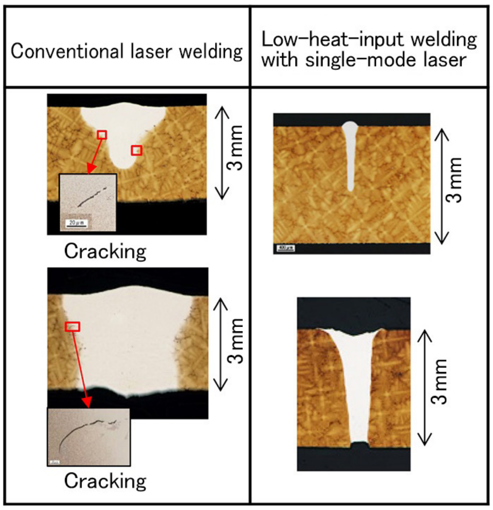


Figure 5 High-quality welding of heat-resistant nickel alloys

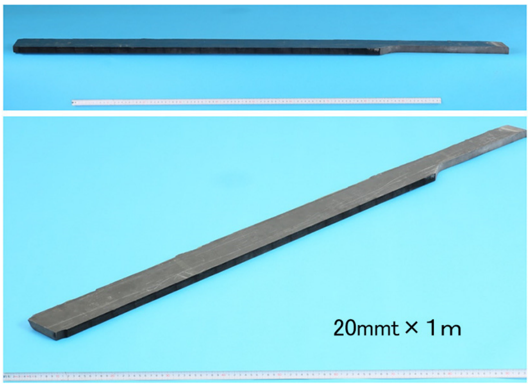


Figure 7 High-quality and high-efficiency laser cutting of CFRP

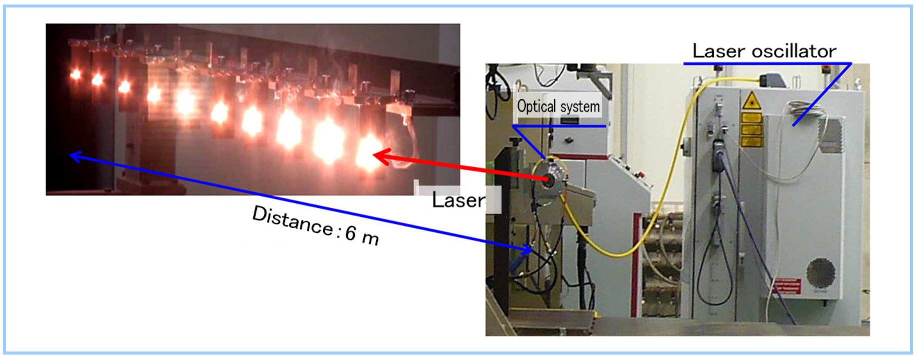


Figure 6 Laser cutting with long-distance beam irradiation

5. Conclusion

In collaboration with NTT, we developed the world's first technology that enables the long-distance transmission of high-power and high-quality laser beam. This technology enables a high-power single-mode laser beam to be transmitted over a long distance while maintaining quality suitable for precision processing and it is expected to accelerate the expansion of the application of laser processing technology and lead to a revolution in manufacturing. Moving forward, we will proceed with the verification of application to actual equipment, aiming to apply this technology to the cutting of composite materials for aircraft, etc., remote high-efficiency dismantling methods for the demolition of decommissioned nuclear reactors and laser processing systems to be sold outside our company.

References

(1) Uchiyama et al., High Power Single Mode Fiber Laser and Processing Application, 60th Lightwave Sensing Technology Professional Group（2017-12）p.133～139