

# Laser cutting for thick concrete by multi-pass technique

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We demonstrated the measurements of attenuation constant of a multi-mode fiber with 300- $\mu\text{m}$  core diameter and 1-km length at 1070 nm. The observed attenuation constant was below 0.7 dB/km, the laser power of 5 kW was coupled into the 1-km fiber at 1070 nm, and the overall transmittance was 85%, and the first Raman Stokes signal was observed in the transmitted laser spectrum. We demonstrated concrete cutting with a 4-kW fiber laser at 1070 nm. The slab thickness was 100 mm. This technique can be extended to thick concrete slabs more than 1 m without increasing laser power.

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It is certain that one of the biggest issues of nuclear energy policy in this century is the decommissioning of the ceased nuclear power plants. The most commonly used techniques applicable to deep-section cutting of concrete such as biological-shields include diamond-wiring saw, diamond-blade saw, core-boring and abrasive water-jet. Table 1 shows the operation time to be needed for 1-m<sup>2</sup>-area cutting. Except core-boring, these are effective ways in terms of operation time. However, all these techniques create considerable amounts of secondary waste and extremely huge noise, and require operator proximity.

Laser based techniques for deep-section cutting of concrete was proposed<sup>[1-4]</sup>. Laser techniques are superior to others in terms of less amounts of secondary waste and less noise. However, these techniques are not feasible for cutting of concrete with the thickness more than 300 mm because the thickness scaling is owing to laser power. The dross within kerfs plug laser beam pass.

A solution was proposed and has been demonstrated in Japan and UK<sup>[5-7]</sup>. This is hybrid and multi-pass technique. Each pass includes laser beam exposure and dross-removal by mechanical way. In Ref. [7], the scaling of thickness up to 500 mm was presented by this technique with 1-kW laser.

In this paper, the feasibility of remoteness (fiber delivery) was demonstrated by 5-kW fiber laser. 10-kW-power delivery is feasible through a 250-m-long fiber with the core diameter of 150  $\mu\text{m}$ . The cutting of concrete was conducted with 4-kW laser power. The operation time for 1-m<sup>2</sup> cutting was estimated for various scan speeds and compared with the most commonly used techniques mentioned above. The operation time of laser

based technique is as short as the most commonly used techniques.

The experiments were conducted using a 5-kW fiber laser (IPG, YLR-5000) with a 1070-nm wavelength. The output fiber of YLR-5000 has the core diameter of 150  $\mu\text{m}$  and the numerical aperture (NA) of 0.2. The demonstrated 1km-long fiber has the core diameter of 300  $\mu\text{m}$  and the NA of 0.2. The scheme of experiment is shown in Fig. 1.

The output power emitted from the fiber as a function of the input power is shown in Fig. 2. The output power is proportional to the input power, and therefore there is no significant stimulated back-scattering such as stimulated Brillouin scattering (SBS). The spectrum of fiber output at the input power of 5 kW is observed in Fig. 3, in which Raman Stokes signal can be found.

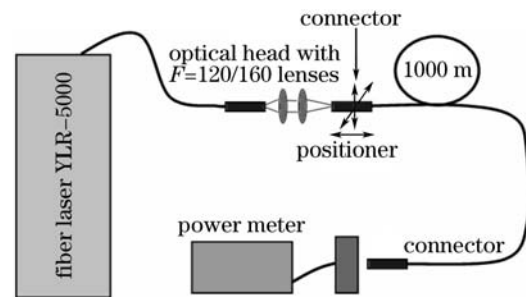


Fig. 1. Scheme of fiber experiment.

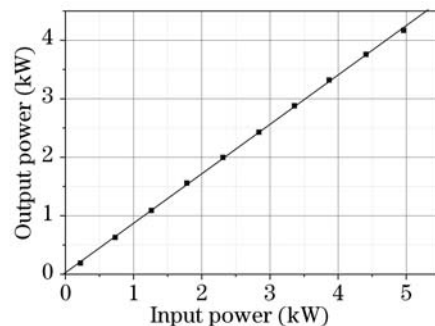


Fig. 2. Optical power transmission through a 1-km fiber with the core diameter of 300  $\mu\text{m}$ . The laser type is a 5-kW high power fiber laser emitting at 1070 nm.

**Table 1. Typical Operation Time for Concrete Demolition by the Most Commonly Used Techniques**

Process	Diamond Wire Saw	Diamond Blade Saw	Core Boring	Abrasive Water Jet
Operation Time (h/m <sup>2</sup> )	1.5-2	2-3	8-15	~1*

\*Calculated from the speed of cutting for 400-mm thickness

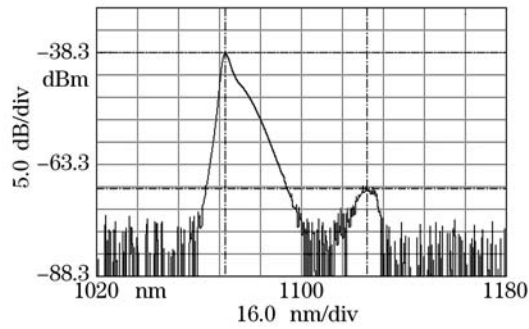


Fig. 3. Spectrum of laser light transmitted through a 1-km fiber spool. The input power is 5 kW.

However, Raman signal has lower order of magnitude, which is 0.1% of the pump magnitude. The critical power of forward SRS is expressed as

$$P_{\text{critical}} = \frac{16A}{gL}, \quad (1)$$

where  $A$  is the mode area,  $g = 1 \times 10^{-13}$  m/W is Raman gain, and  $L$  is the interaction length. The critical power corresponding to the experimental condition (core diameter and fiber length) is 11.3 kW, which is twice higher than the experimental condition of 5 kW.

In order to cut a concrete slab with the thickness of 1 m, it is required to maintain the laser beam diameter through the kerf depth of 1 m. To maintain the diameter of 10 mm within a tolerance of 10%,  $M^2 = 44$  is required at the wavelength of 1070 nm. The beam quality is obtained from a fiber which has the diameter of 150  $\mu\text{m}$  and the NA of 0.2. Table 2 shows the critical condition, which corresponds to the critical power of 11.3 kW. Therefore, 250-m fiber delivery is feasible for the remote cutting of 1-m-thick concrete. Assuming the laser power within the range of 1–10 kW, the laser power density enough to cut concrete can be generated to make the area have the diameter around 10 mm. In Ref. [7], the beam diameter was chosen within the range of 8–16 mm.

The experiments were performed as shown in Fig. 4. The laser power was 4.0–4.5 kW. The scanning speed

Table 2. Predicted Critical Power of Stimulated Raman Scattering

	Core Diameter ( $\mu\text{m}$ )	Fiber Length (m)	Critical Power (kW)
Case 1	300	1000	11.3
Case 2	150	250	11.3

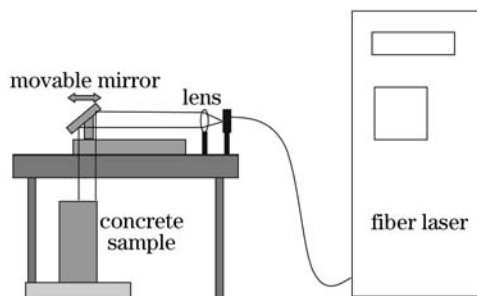


Fig. 4. Scheme of concrete cutting experiment.

was changed within the range of 5–80 mm/s. The beam diameters of 10 and 5 mm were chosen. Here the concrete blocks of 400×300×100 (mm) were used as work pieces. The kerf depth was measured after removal using a small chipping tool. All data in Fig. 5 lie on a curve though these are scattering results. Beam diameter and air blowing do not affect kerf depth. It is clear that kerf depth is greatly affected by the scanning speed. The estimated operation times for 1-m<sup>2</sup> cutting are shown in Table 3 and Fig. 6.

A concrete block of 100×100×300 (mm) was used in this experiment. The laser power was 4.5 kW at the wavelength of 1070 nm. The beam diameter was 10 mm. The scanning speed was 5 mm/s. The vitrified dross was removed after each laser scan. The tool for dross removal (Nitto Kohki, AJC-16) simply consists of three jouncing metal sticks. After 10 scans, a 10-mm-thick section remained in cut. According to single scanning experiments, these experimental conditions allow us a 10-mm-kerf depth for each scan. It means that the results in Table 3 are over-estimated in terms of the removal rate. The reason is that a square-well is assumed as a shape of kerf instead of a V-shape.

Table 3. Operation Time (for 1-m<sup>2</sup> Cutting) and Removal Rate Predicted from Single Scanning at 4 kW

Scanning Speed (mm/s)	Kerf Depth (mm)	Operation Time (h)	Removal Rate (cm <sup>3</sup> /kW·h)
5	10	5.6	450
10	5	5.6	450
80	1.5	2.3	1100

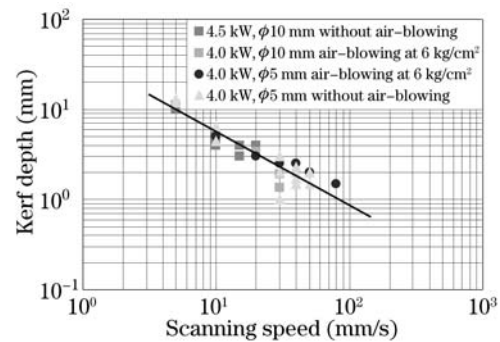


Fig. 5. Kerf depth as a function of scanning speed with 4-kW laser output.

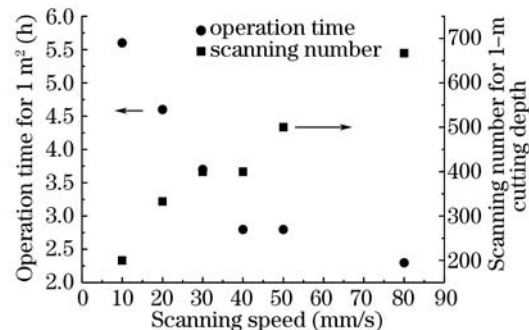


Fig. 6. Predicted operation time and scanning number for 1-m cutting depth.

The feasibility of remoteness of laser-based concrete cutting technique was demonstrated by 5-kW fiber laser. It is found that 10-kW-power delivery is feasible through a 250-m-long fiber with the core diameter of 150  $\mu\text{m}$ . The physical phenomenon which restricts the transmitted power is SRS. The demonstrated concrete cutting technique is a multi-scan technique which includes fiber laser exposure and dross removal in each scan. This technique has the operation time of 1-m<sup>2</sup> cutting which is as short as the most commonly used techniques. The operation time for 1-m<sup>2</sup> area cutting with 5-kW laser power was estimated within the range of 2–6 hours.

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