Cavity-dumped 2.70 μm erbium laser using optomechanical shutter

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A cavity-dumped 2.70 μm erbium laser with a frustrated total internal reflection (FTIR) shutter was investigated and compared with a *Q*-switched erbium laser using the FTIR shutter. The *Q*-switched and the cavity-dumped 2.70 μm laser outputs were obtained with a dichroic coated mirror with high reflectance at 2.70 μm and high transmittance at 2.79 μm. For the *Q*-switched operation, a maximum peak power of 33.5 kW was achieved, and its pulse width was 1.3 μs. For the cavity-dumped operation, the laser pulse energy was optimized by changing the switching time of the FTIR shutter. When the pulse width is reduced to 210 ns, the peak power increases to 154 kW.
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I. INTRODUCTION

The 2.70 μm erbium laser with short pulse operation is an ideal device for soft-tissue surgery and hard-tissue ablation. It has many applications, such as soft-tissue incision and ablation, corneal transplate, cosmetics, aesthetic surgery, subgingival curettage, scaling of root surfaces, dental drills, osteoplasty, and osteotomy.[1–3] The 2.70 μm erbium laser is suitable for these applications for the following reasons. First, it has high absorption coefficient in tissue water and hydroxyapatite compared to other wavelengths. Second, it allows for pulse width shorter than the thermal relaxation time of the tissue.[4–7] Both conditions are necessary to minimize the thermal damage zone around the target tissue and to enable more accurate surgery of the target tissue. For high hard-tissue ablation, moreover, the pulsed laser should undoubtedly have higher output power than that of a soft-tissue incision.

The Er:Cr:YSGG lasers at 2.79 μm can be *Q*-switched due to the longer lifetime (~1.3 ms) of the upper state ($^4I_{11/2}$) as compared to yttrium aluminum garnet (YAG) (~100 μs). However, their direct application to medical surgeries is limited due to poor transmission at the conventional optic fibers such as the low-hydroxyl-fused-silica fibers.[1,8] The holium YAG lasers of 2.1 μm radiation are not suitable for minimal medical treatment due to broad thermal damage zone of tissue from the laser. The thermal damage zone of the tissue induced with this laser is about 600 μm.[3] For the operation of Er^{3+} lasers at 2.70 μm wavelength under flash-lamp excitation, *Q*-switched CrTmEr:YAG laser with pulse energy of 50 mJ is reported.[9] In recent years, a pulsed pumped Er^{3+}-doped zirconium barium lanthanum aluminum sodium fluoride (ZBLAN) fiber laser with output energy of 1.9 mJ and with pulse width of 200 ns at 2.70 μm is reported.[10]

In this paper, we investigated a cavity-dumped Er:Cr:YSGG laser for less thermal damage to soft tissue and compared this laser with a frustrated total internal reflection (FTIR) optical *Q*-switched laser. The giant short pulse is obtained by an optomechanically *Q*-switching technique using optical switching of the FTIR shutter, and its elastic deformation instead of an electro-optics device such as a Pockels cell.[11–14] For the *Q*-switched operation, the pulse duration of 1.3 μs (full width at half maximum) is obtained. The pulse width can be reduced down to 210 ns under the cavity-dumped operation.

According to the practical necessities for soft-tissue surgery and hard-tissue ablation, the laser system should be operated in *Q*-switched or cavity-dumped operations. The energies and the pulse shapes of the *Q*-switched and the cavity-dumped lasers are measured in these experiments.

II. DESIGN OF THE LASER

Figure 1 shows the structure of the *Q*-switched (A) or the cavity-dumped (B) 2.70 μm erbium lasers. The Er:Cr:YSGG rod (Er 30 at. % and Cr 1.5 at. %) codoping Cr^{3+} ions are used as a laser gain medium with 80 mm in length and 5 mm in diameter. It is pumped by two flash lamps filled with 450 Torr xenon gas. The dichroic dielectric mirror (DDM) made of CaF_2 material is placed at the right end of the system as a rear concave mirror with a 3 m radius of curvature and is coated with reflectance higher than 99.9% at 2.70 μm and less than 10% at 2.79 μm in order to produce an output beam with a wavelength of 2.70 μm. The CaF_2 plane output coupler (OC) with 55% reflectance at 2.70 μm is placed 300 mm away from the end of the DDM. The *Q*-switcher inserted in the cavity consists of two IR-quartz prisms with a gap of about 1 μm. This *Q*-switcher is operated by a piezoelectric transducer (PZT) that adheres to its truncated side. The displacement of PZT is adjusted by a negative control pulse of 350–400 V generated from the secondary power supply, and the switching time from a flash lamp simmer signal can be adjusted by a digital delay generator.

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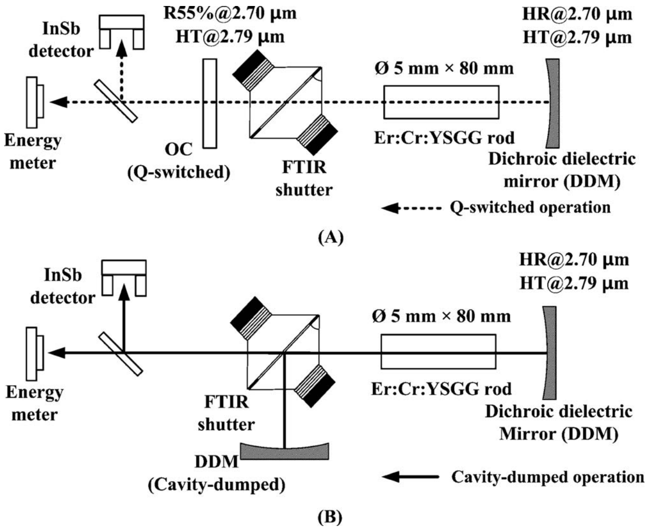

FIG. 1. Schematic of (a) the *Q*-switched and (b) the cavity-dumped Er:Cr:YSGG laser systems.

This laser system operates at both *Q*-switched operation and cavity-dumped operation. At the *Q*-switched operation, the OC coated 55% reflectance at 2.70 μm is placed at the left end of the system. At the cavity-dumped operation, the *Q*-switcher is still in the cavity and the OC is replaced by a DDM identical to the one of the rear mirror.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Experimental results of *Q*-switched operation

Figure 2 shows the temporal pulse shapes for laser operation. The signals are the flash lamp current signal, its simmer signal, the output pulse shape at the free-running operation, and the switching signal determining the switching time of the FTIR optical shutter at the *Q*-switched operation. All temporal shapes are measured simultaneously. The switching time from the simmer signal can be tuned from 0 to 200 μs. The laser pulse with a wavelength of 2.70 μm is detected by an InSb detector (EOS, IS-001/HS, rise time $<2-5$ ns) operating at 77 K and a digital storage oscilloscope with a 500 MHz bandwidth. The output energy is measured by a pyroelectric energy meter (Oriel, 70273). The *Q*-switched laser pulse repetition rate is limited from 1 to 50 Hz due to the

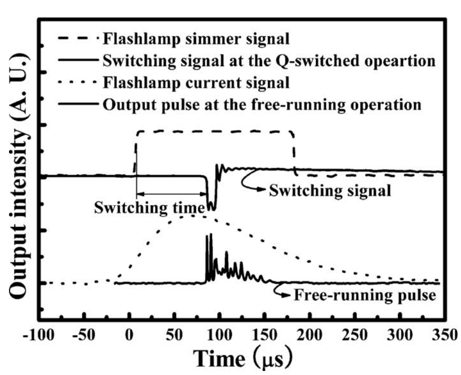

FIG. 2. Temporal pulse shapes: flash lamp simmer signal, switching signal at the *Q*-switched operation, flash lamp current signal, and output pulse shape in the free-running operation.

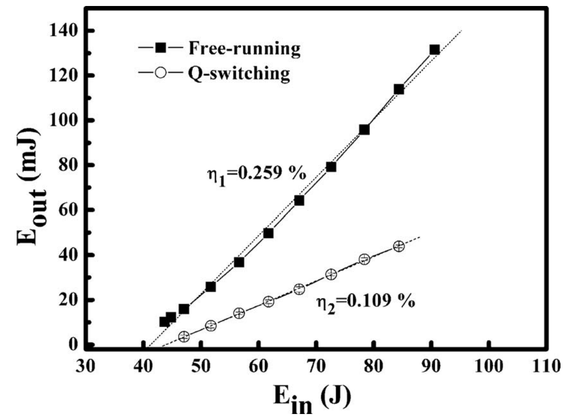

FIG. 3. Free-running output and *Q*-switched output (output coupler with 55% reflectance at 2.70 μm and a switching time of 140 μs) at the repetition rate of 1 Hz.

limitation of the relaxation time of mechanical vibrations caused by the shock excitation of the shutter prism. At a repetition rate of 1 Hz, the *Q*-switched result is shown in Fig. 3. When the pulse width is 1.3 μs (Fig. 6), the maximum peak power of 33.5 kW has been achieved at a switching time of 140 μs and at an electrical input energy (E_{in}) of 84.4 J. At the free-running operation, the output energy is measured without losing of the FTIR prism. At the *Q*-switched operation, when the inserted FTIR *Q*-switch is opened, the threshold of the *Q*-switched operation is the same as that of the free-running operation.

B. Experimental results of cavity-dumped operation

In cavity-dumped operation, the pulse width is measured at the cavity length of 30 cm, which is equal to that of *Q*-switched operation. The buildup time is adjusted by changing the switching time of the FTIR optical shutter and the electrical input energy. The experimental results are shown in Figs. 4 and 5. These results show the output energies as a function of the switching time and the electrical input at the cavity-dumped operation and the *Q*-switched operation. In Fig. 4, the output energy is measured at the low electrical input energy of 61.7 J to avoid optical damage at the surface of DDM. The buildup time at the cavity-dumped operation is shorter than that at the *Q*-switched operation. In Fig. 5, the maximum peak power is obtained at 140 μs after the flash lamp simmer signal with an electrical input energy

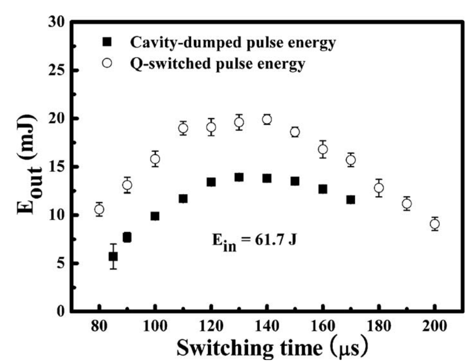

FIG. 4. Output energies as a function of the switching time in the *Q*-switched operation and cavity-dumped operation at E_{in}=61.7 J.

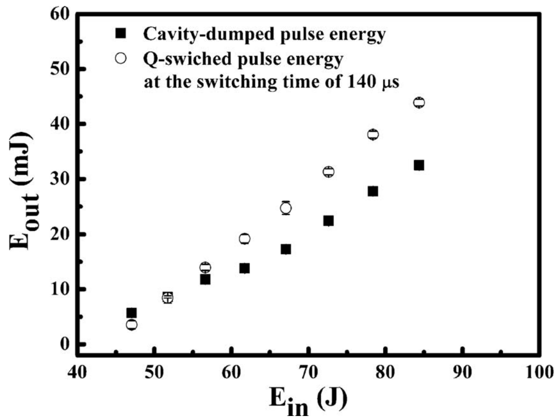

FIG. 5. Output energies as a function of the electrical input energy for the Q-switched operation (output coupler with 55% reflectance at 2.70 μm) and for the cavity-dumped operation at a switching time of 140 μs.

of 84.4 J. Although the pulse energy is reduced at the cavity-dumped operation, the peak power is further increased with the pulse width reduction. When the pulse width is 210 ns, the maximum peak power of 154 kW was achieved for the cavity-dumped operation. The cavity-dumped pulse waveform is compared with the Q-switched pulse shape, as shown in Fig. 6. The duration of the cavity-dumped laser is narrower than that of the Q-switched laser.

In conclusion, in this work, the cavity-dumped 2.70 μm

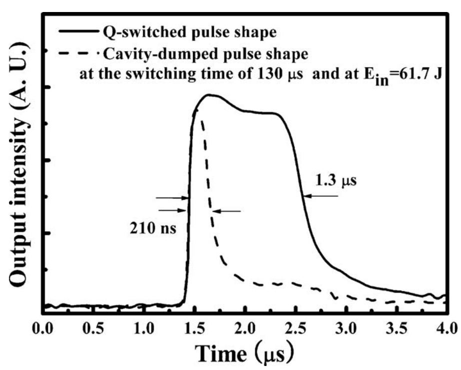

FIG. 6. Q-switched and cavity-dumped pulse waveform at a switching time of 130 μs and at E_{in}=61.7 J.

erbium laser was demonstrated using a FTIR shutter and compared with the Q-switched erbium laser using the FTIR. For the Q-switched operation, the pulse width is 1.3 μs, and a maximum peak power of 33.5 kW was achieved. For the cavity-dumped operation, the pulse width is reduced to 210 ns, and a maximum peak power of 154 kW was obtained. The peak power of the cavity-dumped laser output is five times higher than that of the Q-switched laser output. The main advantage of the cavity-dumped laser is higher peak power than that of a Q-switched operation. The short pulse output from this cavity-dumped technology enables precise operation of soft tissue and hard tissue without damaging the adjacent tissues. These advantage leads to medical applications such as soft-tissue incision, hard-tissue ablation, and other medical surgeries.

ACKNOWLEDGMENTS

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