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Studies of melting ice using CO_2 laser for ice drilling

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ABSTRACT

A CO_2 laser can be used to melt ice. Here we use a CO_2 laser at 10.6 μm, a wavelength at which ice strongly absorbs, to drill (via melting) through ice. The resulting drilling speed is measured at several irradiation intensities, ice-snow densities, and beam angles relative to the horizontal axis. The speed increases nearly in proportion to the laser intensity. For an intensity of about 50 W/cm^2, for instance, the melting speed is 4 mm/s for snow of density 153 kg/m^3 and 0.8 mm/s for solid ice. Results also show that for downward beam angles, melt-water accumulates in the hole, reducing the drilling speed. Nevertheless, we also consider other laser mediums and argue that an optical-fiber-coupled laser drilling system could be used for drilling on glaciers and ice sheets.

1. Introduction

Ever since Erich von Drygalski drilled the first ice core in 1892–1893, ice-drilling technologies have been developed to investigate ice temperatures, ice-dynamics and structure, and the Earth's past climate changes (Lüdecke, 1992). Recently, researchers have drilled into some of the deepest polar ice, as well as into subglacial lakes and rivers located beneath ice sheets to obtain valuable information. Indeed, the deepest drilled hole in ice was mechanically bored at Vostok station, East Antarctica, to a depth of 3769.3 m (Kotlyakov et al., 2013). However, the thickest of Antarctic ice, at Terre Adélie (69° 54′S, 135° 12′ E), is 4776 m (Riffenburgh, 2007). Therefore, the deepest polar ice has yet to be drilled.

A faster method to drill to the bedrock of Antarctica is the hot-water drill, originally developed by M. Calciati. With the original method, the drilling speed varies between 1.1 and 2.8 mm/s (Nizery, 1951). But current hot-water drilling systems can drill much faster up to 36.7 mm/s (Benson et al., 2014). Recently, this method was used to drill to Lake Whillans, beneath the Whillans Ice Stream in West Antarctica (Christner et al., 2014), which revealed a microbial ecosystem. Persisting microbial contamination can be reduced by using ultraviolet radiation on the drilling water (Priscu et al., 2013). The hot-water drill was also used to study subglacial water at the grounding line of the Antarctic Langhovde Glacier, which revealed a living crustacean on the sea floor and phytoplankton in the sea water (Sugiyama et al., 2014).

Thermal drill (melting-probe) technology is another possible ice drilling method, not only for polar ice on Earth, but also for future planetary missions to other planets, including Mars and Jupiter's moon, Europa (Biele et al., 2011; Di Pippo et al., 1999; Kaufmann et al., 2009; Treffer et al., 2006; Weiss et al., 2008).

Lasers may provide another method. High-power lasers exceeding 10 kW have been developed and widely used for industry (Gapontsev et al., 2009; Richardson et al., 2010; Fujita et al., 2010). For example, a recent laboratory test using a 1.6-kW pulsed Nd:YAG 1.064 μm wavelength laser beam determined the energy required to spall, melt, and vaporize several rock samples for oil and gas well drilling. The required energy (specific energy) depends on the absorption properties of each rock sample as well as the reflective properties of the rock surface (Gahan and Parker, 2001; Xu et al., 2003). A new laser-mechanical bit for laser spallation of rock to give an optimum drilling mechanism was found to reduce rig time and increase drilling efficiency (Pooniwala, 2006). More recently, a 20-kW laser was delivered through a 1500-m-long fiber-optical cable and shown to be able to efficiently drill oil and gas wells (Hecht, 2012). Finally, in the project VALKYRIE, ice was drilled by a self-contained "intelligent ice penetrator", a 5-kW laser at 1070 nm wavelength (Siegel et al., 2013)(Stone et al., 2014). Test of VALKYRIE between 2010 and 2013 used high-power optical energy transfer over kilometer-scale distances and tested the feasibility of a vehicle deployed optical waveguide. Thus, a laser-drill system may

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be useful for ice-sheet applications, including the search for life in extreme environmental conditions here on Earth as well as outer planets.

With continual improvements, laser drilling may develop advantages over other methods for ice. We investigate here the behavior of laser melting of ice and snow with an infrared laser for the potential use as a drill. We use a CO_2 laser, which is a relatively inexpensive common infrared gas laser (Patel, 1964) with fundamental lines from 9.2 to 10.8 μm and used in both pulse and continuous wave (CW) mode. For ice, an earlier study demonstrated the potential of CO_2 laser irradiation to help breakup nautical sea-ice (Clark et al., 1973), but the laser has apparently not previously been used for snow and ice drilling.

2. Theory/calculation

2.1. Characteristics of light absorbance in ice

The absorption of light in ice depends on the complex refractive index of ice. In particular, the linear absorption coefficient α of ice is related to the extinction coefficient κ, defined as the imaginary part of the complex refractive index, from the relation $\alpha = \frac{4\pi\kappa}{\lambda}$, where λ is the wavelength of the light. According to data in a previous study (Warren and Brandt, 2008), the absorption coefficient of ice significantly increases from the near- to mid-infrared region, reaching a value of about 628.3 cm^{-1} at the CO_2 laser wavelength of 10.6 μm. At the ground- and second harmonics of a Nd:YAG (neodymium doped yttrium aluminum garnet crystal) laser wavelengths of 1.064 and 0.532 μm, the absorption coefficients are much less, at 2.4 and 0.004 cm^{-1} (Table 1). Ice absorbs almost 100% of the light intensity at 10.6 and 1.064 μm within a penetration distance of 0.01 and 2 cm, respectively (Fig. 1). Evidently, absorption at the CO_2 laser wavelength is much stronger than that at the Nd:YAG laser wavelength. As this absorbed energy effectively melts the ice, we chose the CO_2 laser for the ice melting experiments presented below.

3. Material and methods

3.1. Experimental setup for melting studies of ice and snow by CO_2 laser

Fig. 2 shows the experimental setup used in the present study. The CO_2 laser (model ULR-25, Universal Laser Systems), generates CW light at 10.6 μm. The beam size ϕ in the near field is about 4 ± 1 mm and the beam divergence θ is about 5 ± 1 mrad. We use a beam-expander (IN-BXZ-10.6-2-8X, Wavelength Technology Singapore) with variable magnification to control the beam divergence and focus it on ice samples located at several distances from the laser oscillator output. The laser beam focal-spot size on the samples is about ϕ4 mm. To characterize the attenuation of the system, we measured the laser power using a power meter (PM10, Coherent). The maximum power just after the oscillator is 26.5 W. The total power attenuation loss after the mirrors, beam expander, and atmospheric scattering/turbulence between the system and the ice samples is about 26%. (The power attenuation loss from beam transit through a humid atmosphere is negligible.) Thus, the maximum power on the sample is 19.6 W, and for a diameter of ϕ 4 mm, the maximum laser intensity on the sample is about 160 ± 8 W/cm^2. We checked the linearity of the laser power output after the mirrors and the beam expander, and found no dependence of attenuation loss on laser output power. Air cooling of the laser system is recommended at ambient temperatures above 10 °C.

Table 1
Absorption coefficients of ice at four characteristic wavelengths corresponding to three laser mediums. Calculated from Warren and Brandt (2008).

Laser medium	Wavelength	Absorption coefficient
	μm	cm^{-1}
CO_2	10.6	628.3
Nd:YAG(ω)	1.064	2.4
Nd:YAG(2ω)	0.532	0.004
Er:YAG	2.9	>10,000

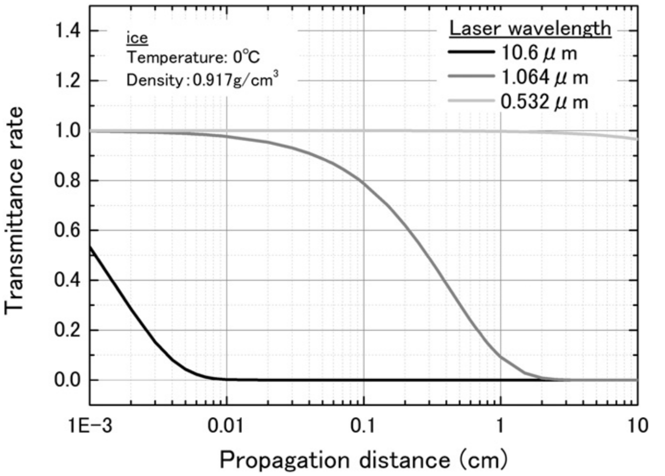

Fig. 1. Light transmittance rate through solid ice (917 kg/m^3). The 10.6-μm wavelength corresponds to CO_2, the 1.064 μm to Nd:YAG (ω), and the 0.532 μm to Nd:YAG (2ω).

We tested also the laser operation at an open-air site at a temperature just below zero and at room temperature in an indoor laboratory (at ~25 °C), and confirmed that the laser worked without any problems in both cases. The distance between the ice and CO_2 laser oscillator is fixed in each experiment. The requirements for operating voltage and current of the CO_2 laser in the CW regime with an integrated fan for air cooling are 48 V and 10 A. During the field experiments, we used an electrical generator with 100 V and 20 A for maximum output voltage and current (EF2000iS, Yamaha Motor) as a power supply. In the laboratory experiments, ice blocks are preserved in an insulated box and taken out just before the measurements. Before using a block, we check that the ice surface is melting to ensure that the ice blocks are just slightly below 0 °C. In the measurements, we measured the times at 1-cm melting penetration depth increments by viewing an incremented scale next to the hole. We purchased common consumer-standard bubble-free ice blocks for food use of dimensions 25 × 13 × 6 cm^3. Fig. 3 shows one example of a hole made with the laser. For snow measurements, we used a 100-cm^3 square-type snow sampler (Climate Engineering) for snow sampling. The natural snow densities used in this study were 153, 340, 415, and 610 kg/m^3 with uncertainty ±20 kg/m^3 (the highest density is technically firn). We measured the penetration times of the laser beam through the samples with thicknesses of about 5.0–5.5 cm for snow and 13 cm for ice blocks.

4. Results and discussion

4.1. Melting studies of ice and snow by CO_2 laser

In general, the melting speed increases with increasing laser intensity and with decreasing ice density (Fig. 4). The melting speed ratio between ice (917 kg/m^3) and the lowest-density snow (153 kg/m^3) is 4–5, slightly less than the value of ~6 expected from the density ratio. The reason for this discrepancy could be explained by the snow having a greater reflectivity than solid ice. Unfortunately, it is difficult to measure the amount of melt-water accurately. The melting speed decreases with increasing snow density. Because the pores may promote melt-water removal away from the irradiant laser spot, this decrease is likely due to the decrease in pore space at higher densities.