Generation of *Q*-switched Er:YAG laser pulses using evanescent wave absorption in ethanol

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We report on a technique of passively Q switching an Er:YAG laser operating at 2.94 μm. The Q switch consists of a high refractive index prism having one total internal reflection surface in contact with an absorbing liquid. The initial losses were achieved via attenuated total reflection. Using the above Q switch, pulses with up to 85 mJ having 130–140 ns pulse width were generated. The output was linearly polarized and the spacial beam profile was near TEM_{00}. The laser was operated at 2 Hz repetition rate. © *1998 American Institute of Physics.* [S0003-6951(98)01418-1]

Erbium based solid state infrared lasers (e.g., Er:YAG, Er:YSGG, Er:YLF) operating near 3 μm are the most long-wave crystalline lasers in practical use. They are relatively simple to design and operate with high efficiency. Due to the strong absorption in OH-containing media near 3 μm, these lasers have a promising future in medical and dental applications[1,2] as tissue generally consists of 70%–80% water. In addition, the output from these lasers is also desirable in pumping a number of non-linear optical materials (e.g., $ZnGeP_2$, GaSe, CdSe) to generate tunable mid-IR radiation.[3,4]

While in some cases of medical and dental applications it is sufficient to use erbium laser in the free-running mode ($\tau = 150-200\ \mu s$), in most applications the much shorter Q-switched pulses ($\tau = 50-150$ ns) are preferred since the shorter pulses significantly reduce the thermal damage resulting from laser ablation.[1] The Q-switched operation with high energies (>30 mJ) in the fundamental TEM_{00} mode is also desired when pumping nonlinear optical materials where high peak powers are needed to achieve the threshold for conversion to longer waves.

Since the discovery of the Er:YAG laser in the mid-1970's[5] many different techniques of active and passive Q switching this laser have been reported. Some of the active Q-switching techniques include using a rotary mirror,[6] electro-optical and acoustooptical,[4,7–11] PZT-controlled frustrated total internal reflection (FTIR).[12–14] Passive Q-switching techniques include using thin layers of water or ethanol,[15] InAs epilayers,[16] graphite foils,[17] and even soap films.[18] While means to achieve Q-switched outputs of 50–100 mJ per pulse have been reported,[7,8,14,19] reproducible outputs in the TEM_{00} have been limited to 20–30 mJ.[4,9,10] The generation of higher pulse energies has been limited due to lack of availability of high damage threshold Q-switched material and the optical coatings near 3 μm.

In this letter we describe a simple design of passive Q switching of an Er:YAG laser using a bleachable absorption of the evanescent EM wave at the interface between the reflecting surface of a high refractive index prism and strongly absorbing liquid, in this case ethanol. This technique permits the generation of 85 mJ pulses in a near TEM_{00} with high degree of reproducibility. The key element comprising the Q switch is a prism made using undoped YAG. YAG has a quite high damage threshold ($>100\ MW/cm^2$) as is demonstrated by its use as host material in a great variety of high peak power solid state lasers.

Due to the OH resonance near 3 μm, hydroxyl-containing liquids with hydrogen bonds such as water, ethanol, and methanol have a strong absorption peak near 3 μm absorption coefficient $>10^3\ cm^{-1}$. The effect of bleaching in OH-containing liquids under intense 3 μm laser irradiation while first reported in 1982[15] was not studied in detail until the early 1990's.[20,21] These studies revealed that the bleaching effect (on the time scale >1 ns) predominantly results from a blueshift of the absorption peak due to superheating. The implications of the effects of water bleaching on laser–tissue interaction were investigated in detail later.[22]

Because of the high absorption in OH-containing liquids, any attempts to use liquids as passive Q switches dictate that the liquid layers be very thin ($\leqslant 1\ \mu m$).[15] Apart from technological difficulties associated with fabrication of cuvettes with such small spacing, operation of a laser using such a device for a prolonged time may cause irreversible change(s) in the liquid with bubble formation being the extreme case.

The total internal reflection of light at the interface between the high refractive index medium and air is attenuated by placing a strongly absorbing medium (e.g., liquid) in contact with the reflecting surface, which is the essence of internal reflection spectroscopy.[23] The interaction of the evanescent wave in a total internal reflection geometry with the absorbing rarer medium is expressed by Fresnel equations where the complex refractive index for the absorbing medium is expressed as $\hat{n} = n - i\kappa$. The strength of the interaction (i.e., reflection loss) increases as the angle of incidence decreases (and approaches the critical angle).

In this experiment an undoped YAG prism ($n = 1.787$ at 2.94 μm[24]) was designed in such a way that the angle of internal reflection was 68° (Fig. 1). To eliminate the need for

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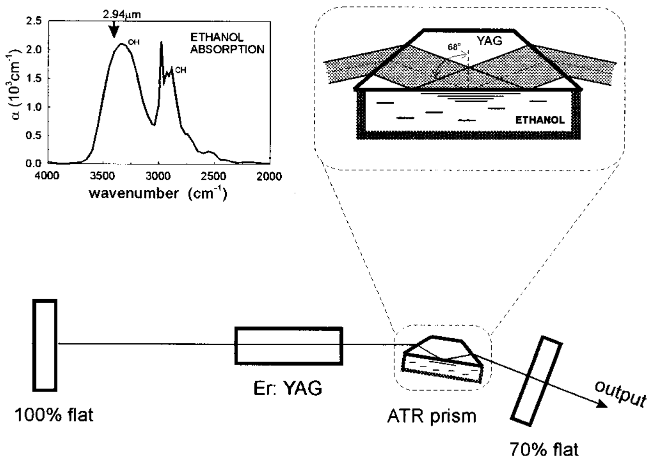

FIG. 1. Schematic diagram of a passively Q-switched Er:YAG laser. Insets show ethanol linear absorption spectra near 3 μm and an ATR prism design.

antireflection coating and to polarize the resonating beam, the input and output faces of the prism were cut at Brewster angle.

The experimentally measured reflection loss of the attenuated total reflection (ATR) prism with ethanol as the rarer absorbing medium was 18%±2% for the p-polarized beam at 2.94 μm. This result is in good agreement with the theoretical attenuation value of 17% which was found using the $n=1.36$ and $\kappa=0.045$[25] for ethanol. The reflection loss thus corresponds to an equivalent ethanol thickness $d_{\text{eff}} \approx 1.1$ μm (in the transmission measurement).

The Er:YAG laser resonator had a flat-flat mirror configuration with the output coupler having a 70% reflectivity. An Er:YAG laser rod with plane-parallel faces was flash lamp-pumped at 2 Hz. The ATR prism was located close to the output coupler and the total resonator length was approximately 75 cm. The layout used is depicted in Fig. 1.

While the lasing threshold with a ''dry'' prism reflecting surface was 56 J, when ethanol was placed in contact with the prism, the lasing threshold increased to 89 J. When the pumping level reached 120 J, stable Q-switched pulses were observed with each pulse containing approximately 80–85 mJ in a 130–140 ns pulse [Fig. 2(a)]. The output was linearly polarized and the spacial beam profile was near TEM_{00}. At higher pump energies, multiple Q-switched pulses were observed with approximately 50–80 mJ per pulse and typically spaced by 20–30 μs.

In the current experiment, the bleaching mechanism is believed to be the same as that described in Ref. 20, namely due to superheating of the ultrathin ($\sim\lambda$) liquid layer near the reflecting interface, followed by weakening of the H bonds and the subsequent blueshift of the absorption peak. When methanol was used as an absorbing liquid, similar results were obtained since ethanol and methanol have very close absorption characteristics. However, when water was used as an absorbing medium, no Q-switching effect was observed. This may be caused by the initial loss at the ATR prism being too high (50%–60%)—due to the much higher absorption coefficient of water at 2.94 μm ($\alpha=1.28 \times 10^4$ cm^{-1}).[24]

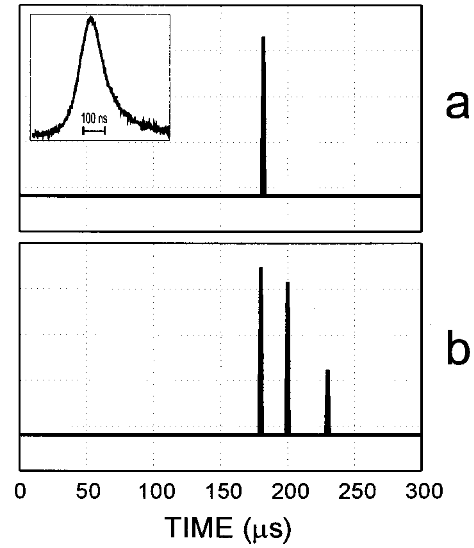

FIG. 2. Oscillograms of the laser output, corresponding to: (a) a single giant pulse and (b) multiple pulses at elevated pump. Inset shows time-resolved Q-switched pulse shape.

In conclusion, we demonstrated a relatively simple means of passive Q switching of an Er:YAG laser using a total internal reflection prism with ethanol placed in contact at its reflecting surface. The laser produced linearly polarized, near TEM_{00} Q-switched pulses with energies up to 85 mJ and no signs of degradation in any of the optical elements.

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[25] We found the imaginary part of the refractive index $\kappa = \alpha\lambda/4\pi$ from our experimentally measured ($\lambda = 2.94\ \mu$m) absorption coefficient in ethanol: $\alpha = 2\times10^3$ cm^{-1}.

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