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Passive Q-switching of fiber lasers using a broadband liquefying gallium mirror

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Abstract: Using a new type of nonlinear cavity element - a liquefying gallium mirror - we demonstrate stable, self-starting, passive Q-switching of both erbium and ytterbium fiber laser cavities operating at wavelengths of 1550nm and 1030nm respectively. The performance at 1550nm is shown to be equivalent to that achieved with a state-of-the-art semiconductor saturable absorber designed to work at this wavelength. The results highlight the suitability of this tremendously broadband, inexpensive nonlinear medium for a wide range of passive Q-switch applications.

Passive Q-switching provides a convenient way of obtaining intense, nanosecond optical pulses, offering advantages in terms of simplicity, compactness and cost, relative to the more conventional active Q-switching technique. Numerous materials have been used successfully for this purpose including for example organic dyes [1], color centers [2] and the Cr^{4+} ion [3]. Unfortunately, the physical attributes that make these materials useful for Q-switching do not generally extend to wavelengths far beyond 1 μm. For example there are relatively few options for passive Q-switch materials at eye-safe wavelengths around 1550nm. Recently, vanadium-dioxide-coated (VO_2) mirrors have attracted some interest as passive Q-switch devices due to their broad operating wavelength characteristics. Using such mirrors, Q-switching of both Nd:YAG [4] and erbium:glass lasers [5] has been reported. It is also claimed that their use can be extended to the visible regions of the spectrum as well. However, various optimization, longevity and damage problems still remain to be solved within that system. Moreover, the mirror structures themselves are relatively complex since the required response relies on transmission through the nonlinear material.

Recently, we discovered that the reflectivity of a gallium:glass interface becomes strongly nonlinear when its temperature is held close to, but below, the metal's melting point of 29.6 °C. Optical intensities of ~5 - 10 kW/cm^2 were found to be sufficient to cause up to 40 % changes in reflected light intensity, corresponding to ~20% changes in absolute reflectivity [6]. The effect is fully reversible and has been attributed to a surface-assisted, structural phase transition from the common, stable α-gallium phase to an as yet unidentified metastable phase of a more metallic nature. The reflectivity changes can be induced by light over a very broad spectral range, which we believe to extend from ~400nm to ~1800nm. To date we have experimentally confirmed that it extends from 633nm to 1560nm [7]. This level of reflectivity change constitutes an enormous degenerate cubic optical nonlinearity $\chi^{(3)}$ of the order of 10^{-8} V^2/m^2 (~1 in Gaussian units). The nonlinear response is relatively fast, and has been shown to have a turn-on time of less than ~10 ns and a relaxation time between 10 ns and 2 μs, depending on the temperature of the mirror and the excitation conditions. Under typical working conditions the saturation fluence is ~ 10mJ/cm^2.

The above characteristics are attractive for passive Q-switching applications. To prove the viability of the approach we constructed an erbium fiber ring laser incorporating a fiberized gallium mirror, formed on the tip of a single mode fiber. The laser indeed passively Q-switched, generating 1-2 μs pulses of 0.5 W peak powers at 1550 nm [8]. However, due to the length of the cavity used (15m), and lack of means to vary the mode-size on the mirror, the laser was not optimized to give short pulse durations and high peak powers. In this letter we report on passive Q-switch experiments on a more suitable and flexible fiber laser cavity arrangement demonstrating the generation of considerably shorter (~50ns) and more intense (~100W) pulses. Finally, and most significantly, we demonstrate Q-switching of Er^{3+} and Yb^{3+} fiber lasers operating at 1550nm and 1030nm respectively using the same gallium mirror. These results highlight the broadband capability of the technique.

Our experimental set-up is shown in Fig.1. All experiments reported herein were performed with essentially the same Fabry-Perot cavity design, incorporating rareearth doped fiber as the gain medium. In each instance the cavity was defined by a 4% Fresnel reflection from a cleaved fiber end (through which the fiber was pumped), and a nonlinear rear mirror of relatively high reflectivity based on either an (a) liquefying gallium mirror, or (b) a semiconductor saturable absorber. The laser output was separated from the incoming pump beam with a dichroic mirror.

Two fibers were available for use. The first fiber was 60cm long and was of a large mode area (LMA) design, doped with 1400ppm by weight of Er^{3+}ions [9]. The fiber had a numerical aperture 0.06 and a single mode cut-off wavelength of ~1450nm. Its mode area was ~300μm^2. As previously demonstrated, LMA fibers have improved energy storage characteristics relative to conventional doped fibers, making them particularly attractive for Q-switching applications. The second fiber had a length of 90cm and was of a conventional design with a numerical aperture of 0.21 and a single-mode cut-off wavelength of 940nm. The fiber contained 2300ppm by weight of Yb^{3+} ions.

The liquefying gallium mirror was formed by pressing a thin glass slide onto an initially molten gallium bead that was in direct thermal contact with a temperature stabilized Peltier unit, whose temperature was measured with a thermocouple. This configuration enabled us to control the nominal mirror temperature in the temperature range 10 to 35 °C, with a precision of 0.1 °C, although, the exact mirror temperature at the reflection point might have been somewhat higher due to localized heating by absorbed laser light. Light was coupled onto the mirror surface using a lens pair (L2 and L3), allowing us to change the spot size on the surface by varying the relative focal lengths of the lens combination. For the experiments with the erbium-doped fiber a polarizer was included in the cavity to allow us to align the intra-cavity polarization of the beam with the crystallographic axis of the gallium so as to obtain the maximum nonlinear response [7]. For the experiments with the Yb^{3+} -doped fiber laser a quarter- and a half-wave plate combination was used for the same purpose.

We first investigated passive Q-switching of the erbium-doped fiber cavity. A typical power characteristic is shown in Fig.2. Stable, self-starting passive Q-switching at 1531nm is obtained for incident pump powers above ~900mW. The output pulse energy was ~6 µJ and pulse duration typically ~70ns (see inset Fig.2), although pulse durations as short as 50ns were achieved by careful cavity adjustment. The corresponding pulse peak powers were thus 70 to 100W. The pulse energy was effectively constant with pump power, whereas the pulse repetition rate increased linearly with increasing pump power. For the laser power characteristic shown in Fig.2, the repetition rate is 14 kHz at the self-start threshold, rising to 25kHz at maximum pump power. Q-switching was obtained for a range of spot sizes on the mirror surface, however this was most stable and readily achieved with a relatively tightly focused beam. A spot size of ~30 μm^2 proved optimal for this cavity. Q-switching could be maintained over the entire temperature range between 10 to 25 °C, without any significant changes in the pulse characteristics. Between 25 and 26.5 °C however, Q-switching became unstable and noisy. At even higher temperatures laser pulsing could no longer be maintained. When the temperature was subsequently reduced to below 25 °C Q-switching would again self-start, and could be maintained for hours without any evidence of damage to the mirror.

In separate experiments the gallium mirror was replaced by a state-of-the-art semiconductor saturable absorber mirror (SESAM), designed for Q-switching applications at 1.55μm. These experiments were performed using exactly the same cavity components and length of erbium doped fiber (see Ref. [10] for a full description of the SESAM structure and experiments). In this instance 65 ns pulses with a pulse energy of 4.9 μJ were obtained. The results are almost identical to those reported herein. Clearly, semiconductor technology has the important advantage that parameters such as modulation depth, saturation fluence and recovery time can be tailored during the design process to suit the specific application. However, the benefits of the gallium mirror in terms of simplicity, cost, manufacturability and operational bandwidth should however be evident.

To demonstrate this final point, the very same mirror used in the previously described set-up was used in an ytterbium fiber laser cavity as well. A power characteristic of this cavity is shown in Fig.3. Stable Q-switching self-starts at pump powers above 290 mW and is maintained as long as the pump power does not increase above 520 mW. At higher pump powers, pulsing was unstable, exhibiting excessive noise and timing jitter. The laser operated at 1030 nm and produced ~120 ns pulses, somewhat longer than before, due most probably to the slightly longer fiber in this instance. The pulse energy in this case was ~1 μJ. Note also that the pulse repetition rate was generally higher than before varying with pump power, from 50 to 150 kHz.

In conclusion, the experimental results presented herein demonstrate that a mirror formed at a gallium:glass interface can be used as a new and powerful means to Q-switch a laser cavity. The mirror can be used over a wide range of wavelengths, and the quality of Q-switching can be comparable to that achieved with a state-of-the-art saturable absorber.

The results reported within this paper are covered by a patent application [11]. The authors would like to thank F. Morier-Genoud and R. Paschotta from ETH Zürich (group of Prof. Keller) for the loan of a SESAM, and for assistance in the experiments performed with this device. Also, the contributions of Goodfellow Cambridge Ltd. for the free supply of high-purity gallium samples, and the Royal Society, London for financial support are gratefully acknowledged.

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Figure captions

Fig.1 Schematic of the passively Q-switched fiber laser cavities, consisting of either 60 cm of LMA erbium-doped fiber or 90 cm of conventional ytterbium-doped fiber. The nonlinear element is a liquefying gallium mirror (a), the performance of which, for the case of the erbium fiber laser, is compared to that of a SESAM (b).

Fig.2 Output power laser characteristic of the erbium fiber laser with a liquefying gallium mirror, showing the regime for stable Q-switching, and a typical output pulse obtained at a pump power of 1.09 W (inset).

Fig.3 Output power laser characteristic of the ytterbium fiber laser with a liquefying gallium mirror, showing the region of stable Q-switching, and a typical output pulse obtained at a pump power of 420 mW (inset).

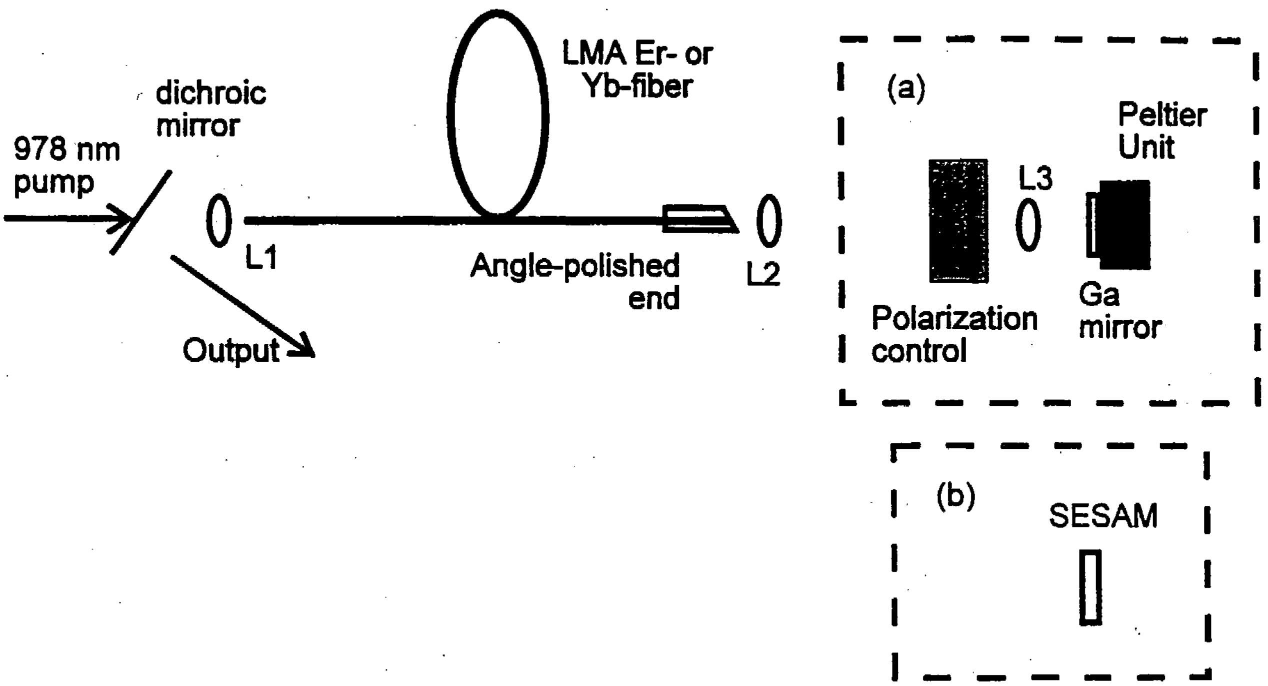
978 nm
pump
dichroic
mirror
L1
Output
LMA Er- or
Yb-fiber
Angle-polished
end
L2
(a)
Peltier
Unit
L3
Polarization
control
Ga
mirror
(b)
SESAM

Fig.1

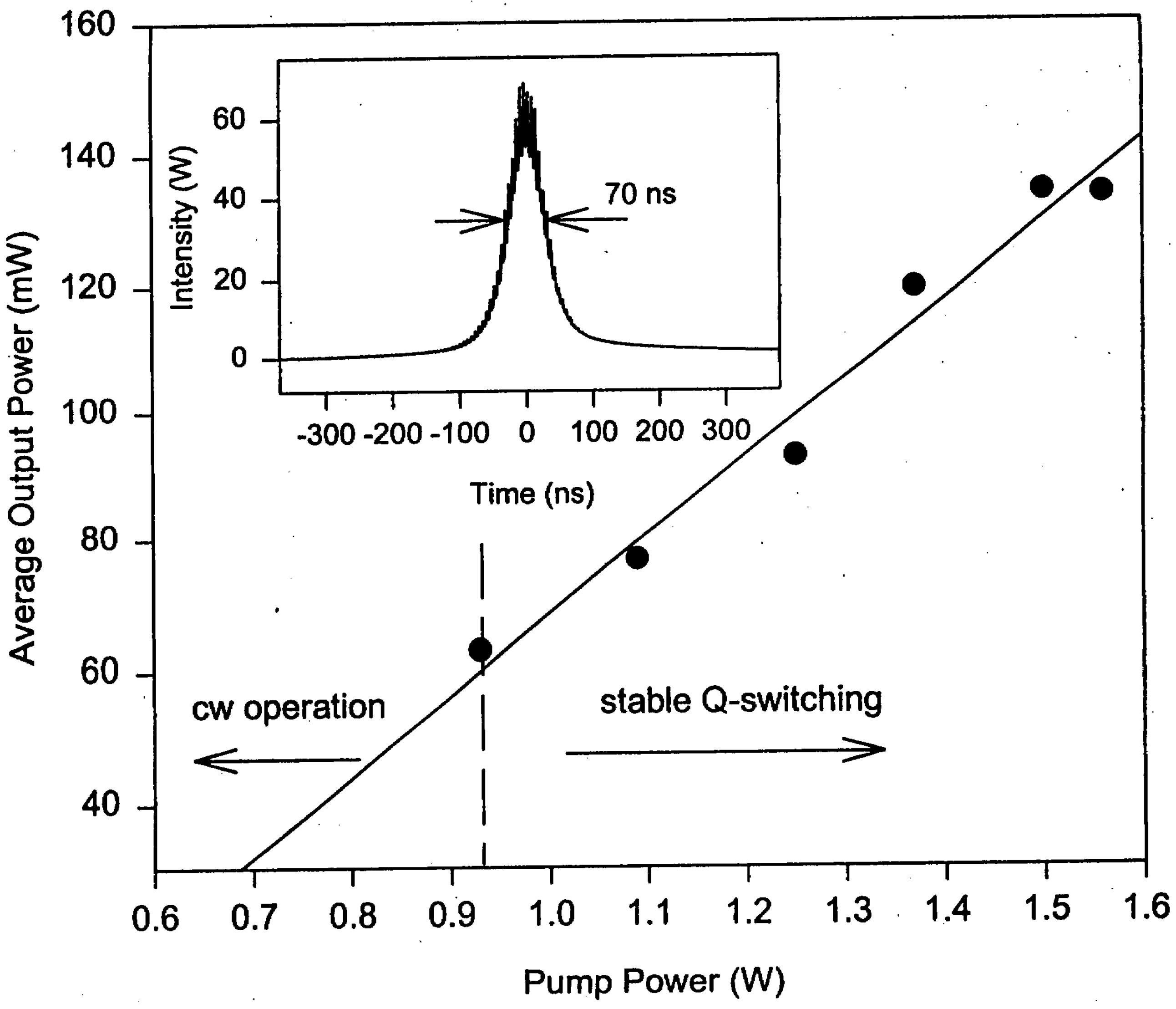
Average Output Power (mW)
160
140
120
100
80
60
40
Pump Power (W)
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
cw operation
stable Q-switching
Intensity (W)
60
40
20
0
70 ns
-300
-200
-100
0
100
200
300
Time (ns)

Fig. 2

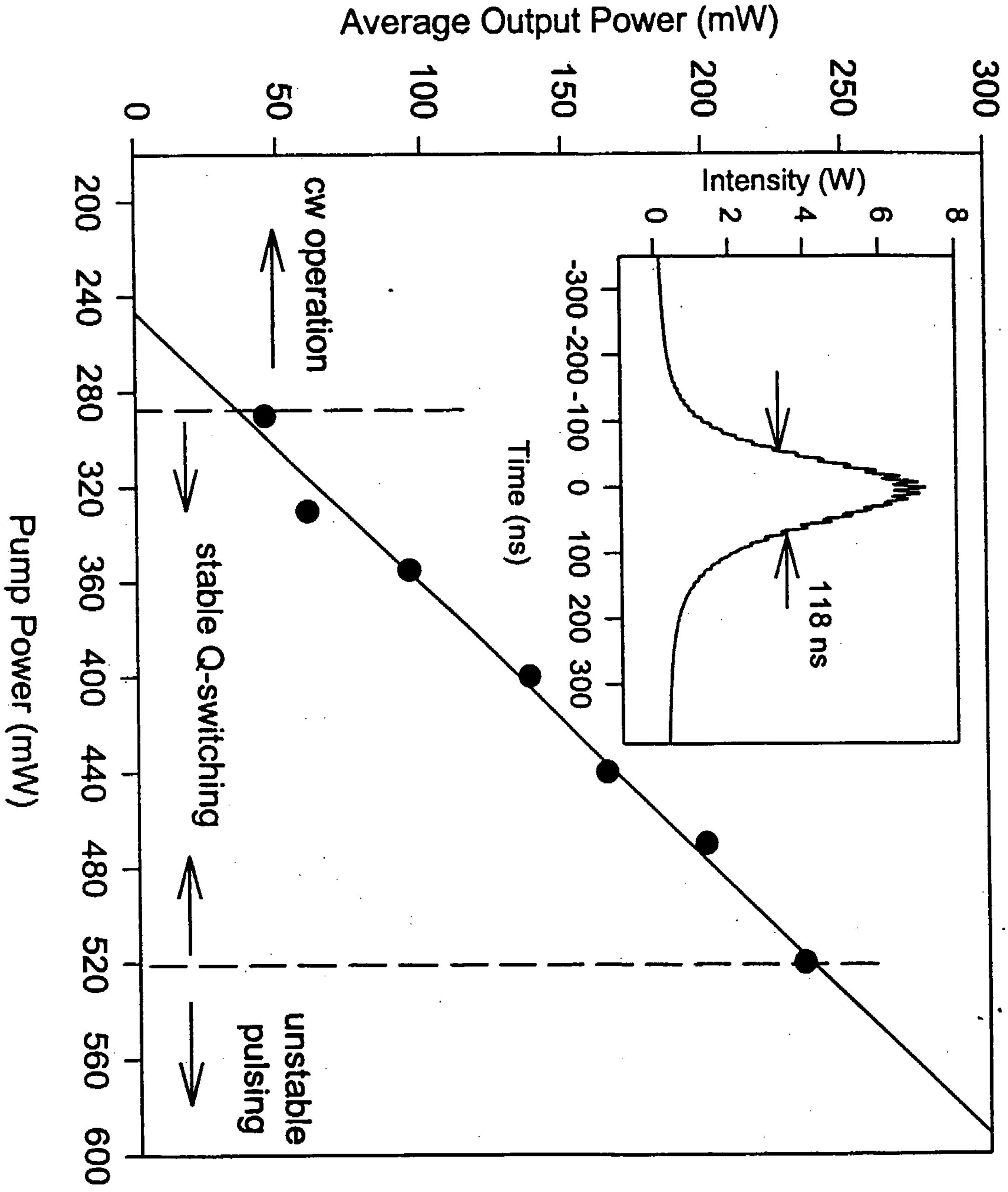
Average Output Power (mW)
0
50
100
150
200
250
300
Pump Power (mW)
200
240
280
320
360
400
440
480
520
560
600
cw operation
stable Q-switching
unstable pulsing
Intensity (W)
0
2
4
6
8
Time (ns)
-300
-200
-100
0
100
200
300
118 ns

Fig. 3