Passive Q-switching of an Er^{3+}:Yb^{3+} fiber laser with a fiberized liquefying gallium mirror

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Abstract

We report a new technique for passive Q-switching of low-power lasers, which exploits nonlinear reflection from a liquefying gallium mirror. Self-start Q-switching has been achieved in an

Er^{3+}:Yb^{3+} fiber laser for circulating intracavity powers of only a few milliwatts. The laser produced a continuous train of pulses as short as 1 μs at repetition rates of a few tens of kilohertz and with peak powers of 0.5 W. Due to the broadband reflective nature of the nonlinearity of gallium, the technique should be applicable to a wide range of laser systems.

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Passive Q-switching is a powerful technique for the generation of intense laser pulses. It offers considerable simplifications relative to active techniques that require the use of fast intracavity acousto-optic/electro-optic modulators. Passive q-switching is well established in the visible and near infrared regions of the spectrum, where a variety of saturable absorber materials are readily available, such as organic dyes [1], colour centres [2] and more recently materials incorporating the Cr^{4+} ion [3]. However, the choice of suitable materials is considerably reduced as one moves to longer wavelengths. Indeed, there is still a need to develop an efficient passive Q-switch for the 1.55 μm region in which there is significant commercial interest due to the demand for eye-safe lasers in the military, industrial and medical fields. Q-switched erbium doped fibre lasers [4, 5] are an attractive option for use in this wavelength region, as are bulk Er^{3+}:glass lasers for higher pulse energies. Passive Q-switching of Er^{3+}:glass lasers has been demonstrated using saturable absorbers incorporating U^{4+} [6], Er^{3+} ions [7], nonlinear mirrors based on multi-quantum well materials [8] and vanadium dioxide [9].

In this paper we describe a new, simple technique for passive Q-switching of a fiber laser which employs a recently discovered nonlinearity associated with light intensity dependent reflection from a liquefying gallium interface [10 - 12]. Nonlinear mirrors based on liquefying gallium allow for simple integration into fiber laser cavities and can show a considerable nonlinear reflectivity at a very low optical power level. Using such an approach we obtain self start Q-switching at circulating average laser powers of a few milliwatts. Pulse durations of 1 - 2 μs are obtained at repetition rates of a few tens of kilohertz, with peak powers as high as 0.5 W.

The nonlinearity of liquefying gallium manifests itself as a broadband (at least 0.4-1.8 μm), reversible, intensity-dependent reflectivity at temperatures just below the metal's melting point of ~30 °C [11]. The effect is associated with a surface assisted, optically-induced phase transition from the α-gallium phase (which exhibits some polymer and semiconductor properties due the presence of covalent bonding within the structure), to a metastable phase of more metallic nature and correspondingly higher reflectivity. At present this more metallic phase has yet to be uniquely identified, however metastable phases of Ga(III), Ga(II) and β-Ga appear strong candidates.

Our laser cavity is shown in Fig.1a and is of a ring geometry, in which the linear spur section of the cavity provides feedback from the liquefying gallium mirror. The mirror is formed on the tip of a single-mode optical fiber (12 μm mode field diameter) by inserting the freshly cleaved fiber end into a small bead (~1mm diameter) of (initially) molten gallium of 6N purity. The mirror/gallium bead temperature is controlled by a miniature Peltier heat pump to a precision of 0.01 °C in the range -5 to 35 °C. Note, that the temperature we quote for the mirror is actually the temperature recorded on the Peltier cooler surface with which the gallium bead is in direct thermal contact. However, it should be appreciated that the local temperature at the interface could be different depending on the laser operating conditions/optical power absorbed at the interface. Light is coupled to and from the liquefying gallium mirror using a fiberised optical circulator. The optical gain medium within the laser was a 5m section of co-doped erbium:ytterbium fiber, containing 700ppm Er^{3+} and 20000ppm Yb^{3+}. Light is output from the cavity using a 40% output coupler. The total cavity length was ~15 m, corresponding to ~72 ns cavity round-trip time. The laser was pumped with a Nd^{3+}:YLF laser operating at 1047 nm, capable of delivering up to 550 mW of fibre coupled output power.

The gallium mirror was temporarily removed from the cavity and its performance characterized with pump - probe measurements. In Fig.2 (inset) we plot the change in reflectivity of the nonlinear mirror used in our experiments induced by exposure to a square wave modulated optical signal of peak intensity 7 kW/cm^2 at a wavelength of 1536 nm. The reflectivity change was measured with a low power 100 W/cm^2 continuous wave probe at 1549 nm. As much as 30% change in reflected light intensity is seen for optical powers of a few milliwatts, corresponding to field intensities of just a few kW/cm^2 (see Fig.2). The absolute reflectivity of solid gallium is approximately 50% and therefore the corresponding change in absolute reflectivity is ~15%. It should be appreciated that the cubic optical nonlinearity associated with the effect is huge. It can be estimated from the difference between the α-Ga dielectric coefficient ε_α and the metastable gallium dielectric coefficient ε_m, which we assume to be close to that of a free-electron metal, as $\chi^{(3)} \approx |\varepsilon_\alpha - \varepsilon_m|/4\pi E^2 \approx 1$ esu, where E^2 is the electric field of the light wave used in our experiment and $|\varepsilon_\alpha - \varepsilon_m| \approx 180$.

The strength of the nonlinear response of the gallium mirror is a function of temperature, increasing rapidly as the temperature is increased towards the melting point. The nonlinearity disappears completely once the mirror undergoes bulk melting. Pump-probe measurements with pump pulses of variable duration in the range 10 - 100 ns showed that the turn-on time of the nonlinearity is reasonably fast (of the order of 1 ns), whilst its recovery time is highly temperature dependent increasing critically as the bulk melting point is approached from below; it ranges from a few tens of nanoseconds at temperatures 5 - 10 °C below the melting point to a few microseconds at temperatures just below the melting point. These measurements showed that the saturation fluence of the reflectivity change is ~5 mJ/cm^2.

The laser performance was characterized for a broad range of mirror temperatures and pump powers. Stable, self-starting passive Q-switching could be obtained for a wide range of pump powers for mirror temperatures in the range 0 °C up to the bulk melting point of gallium. In Fig.3 we plot a typical laser input/output characteristic. At low pump powers (region A) the laser operated continuous wave, however at a well defined, temperature dependent pump level (270 mW in this instance) the laser entered a stable, self-start Q-switch mode regime (region B). At a further well defined, temperature dependent power level (410 mW in this instance) the pulsing became unstable (region C) exhibiting either pulse repetition rate doubling behavior or irregular pulsing, as well as considerable pulse amplitude instability.

Q-switch operation within the operating regime B was both highly stable and reproducible. In Fig.4 we plot a typical pulse trace of a Q-switch output train as measured with a detector and sampling scope of 200 MHz overall bandwidth. The pump power to the system was 300 mW and average output power 13 mW. The pulse duration is ~1.75 μs at a repetition rate of ~20 kHz. As the pump power to the laser was increased (decreased) the pulse repetition rate increased (decreased), the pulse duration and peak power remaining approximately constant over most of the stable operating range (see Fig.5). Pulse to pulse jitter was minimal in the stable operating regime. The minimum pulse duration achieved was ~1 μs and did not vary greatly over the full operating temperature range, although the corresponding pulse peak power was highly dependent on the mirror temperature. This rather long pulse duration was due to the ~15 m cavity length. In more recent experiments employing a shorter cavity (~1 m), pulses as short as 50 ns have been obtained. These experiments will be reported elsewhere.

In Fig.5 we plot the Q-switched laser pulse peak power, and repetition frequency, as a function of optical pump power for two gallium bead temperatures, 5 and 17 °C. The pulse peak power at 5 °C was ~450 mW, around three times higher than that at 17 °C. This is commensurate with the nonlinearity being weaker at temperatures further removed from the gallium melting point.

To demonstrate laser tunability we incorporated a tunable 1 nm bandpass filter within the cavity. Q-switching was obtained over the range 1532 - 1560 nm limited only by the gain bandwidth of the laser and the tuning range of the filter. A typical spectrum of the laser emission is shown inset in Fig.4 where the optical bandwidth of the pulses is seen to be ~0.2 nm, this bandwidth was maintained over the full laser tuning range.

In order to confirm that the Q-switching obtained was due to the presence of the liquefying gallium mirror, and not due to some other mechanism, e.g. self driven relaxation oscillations in the gain medium we performed a number of additional experiments with the gallium mirror replaced with a 'conventional' reflector of controllable and variable linear reflectivity (see Fig.1b). We investigated the laser performance over the effective mirror reflectivity range from 20 to 99.9%, which encompasses the full range of gallium mirror reflectivities from 47% (solid) to 87%

(liquid). No evidence of Q-switching was observed confirming the critical role of the liquefying gallium mirror within the Q-switch laser cavity.

In conclusion, we have introduced a new passive Q-switching mechanism based on intensity dependent reflection from liquefying gallium mirrors that can operate at very low levels of intracavity laser power. We have demonstrated and characterized passive Q-switching of an erbium fiber laser using this new mechanism, obtaining μJ energy pulses of μs duration. With optimization considerably shorter pulse durations and increased peak powers can be obtained. Although detailed long term studies of the mirror performance under Q-switch operation have yet to be made, no degradation or damage has been observed to date. Finally, we wish to point out that this nonlinearity is extremely broadband and therefore appropriate for use in a wide range of laser types, wavelength regimes and cavity designs.

Acknowledgments

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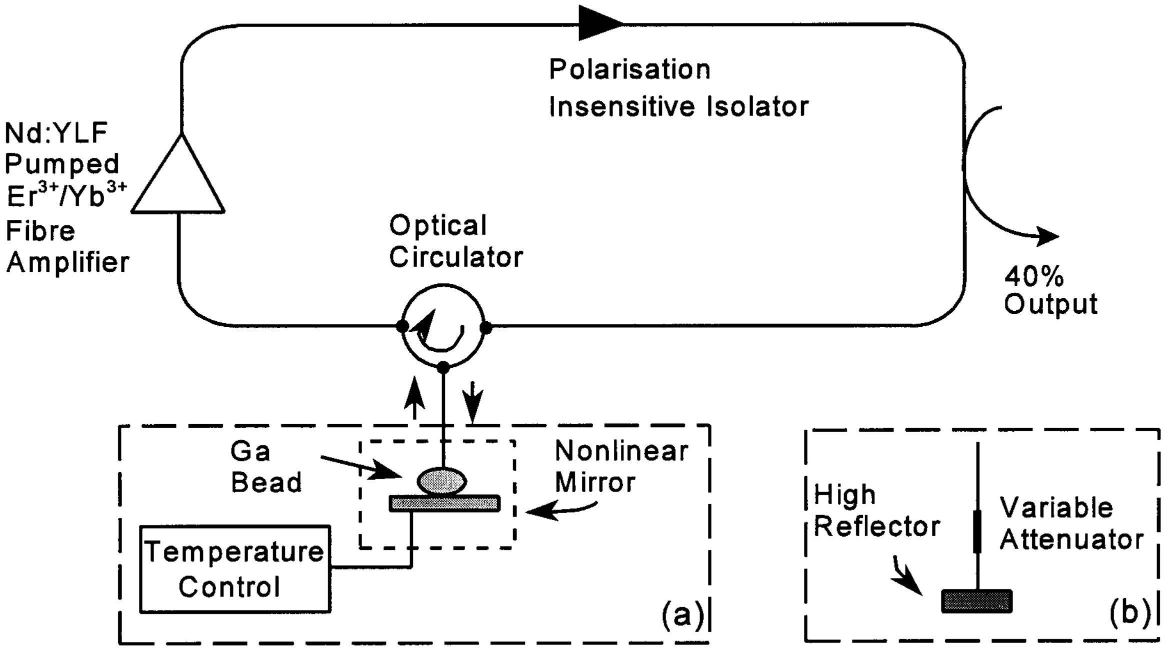

Fig.1 Passively Q-switched Er^{3+}:Yb^{3+} fiber laser cavity incorporating the liquefying gallium mirror (a). For the test experiments the mirror was replaced with a variable reflector (b) to confirm the critical role of the gallium mirror in the Q-switching process.

Fig.1

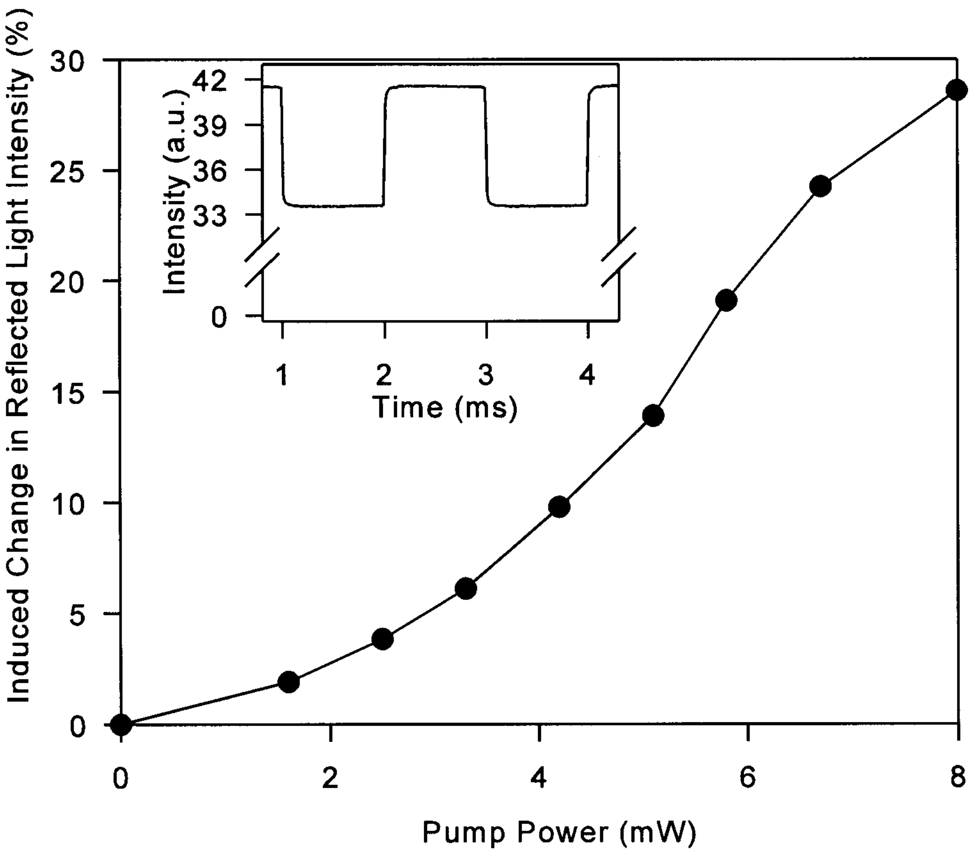

Fig.2 Induced change in reflected light intensity as a function of peak power for a nonlinear mirror temperature of 27 °C, i.e. ~3 °C below gallium's melting point. Inset is a plot of the temporal dynamics of the reflectivity change induced by square pulses of 200 ns rise/fall times and peak intensity of 6.7 mW.

Fig.2

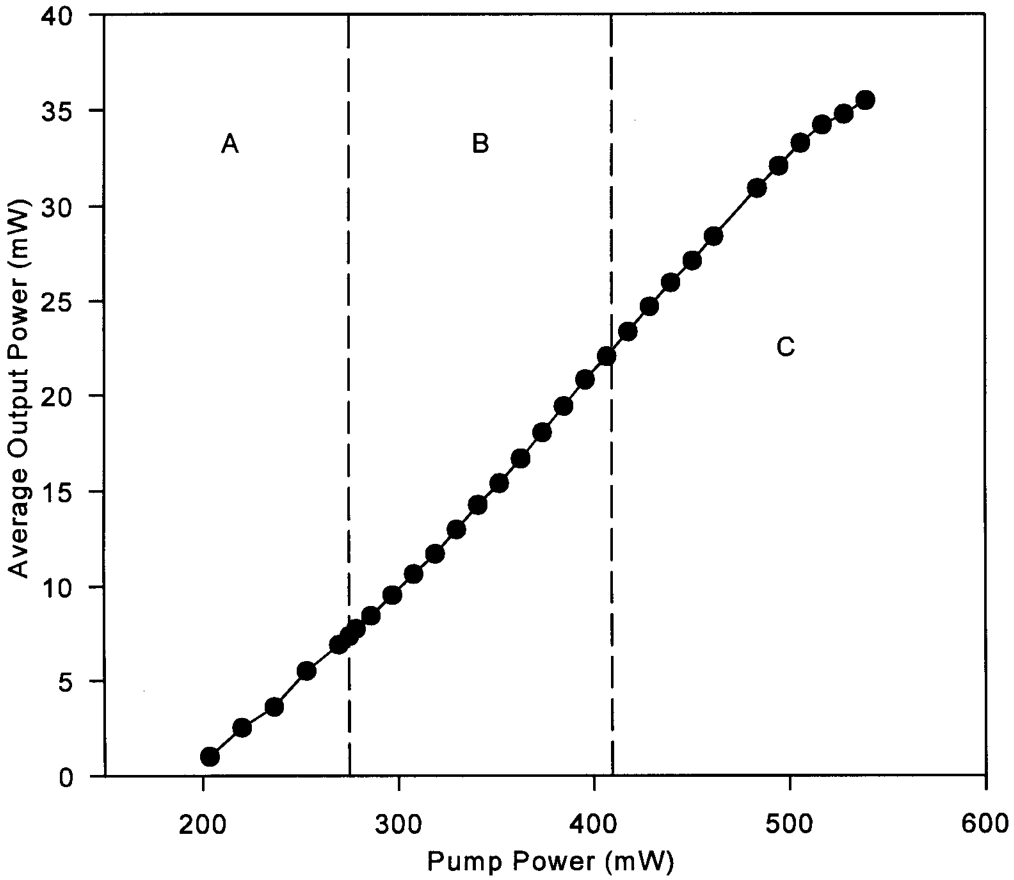

Fig.3 Laser input/output power characteristic obtained for a mirror temperature of 17 °C, indicating the various operating regimes: A) Continuous wave output, B) stable Q-switching, C) unstable Q-switching. The laser threshold is ~200 mW and quantum slope efficiency ~16.5%.

Fig.3

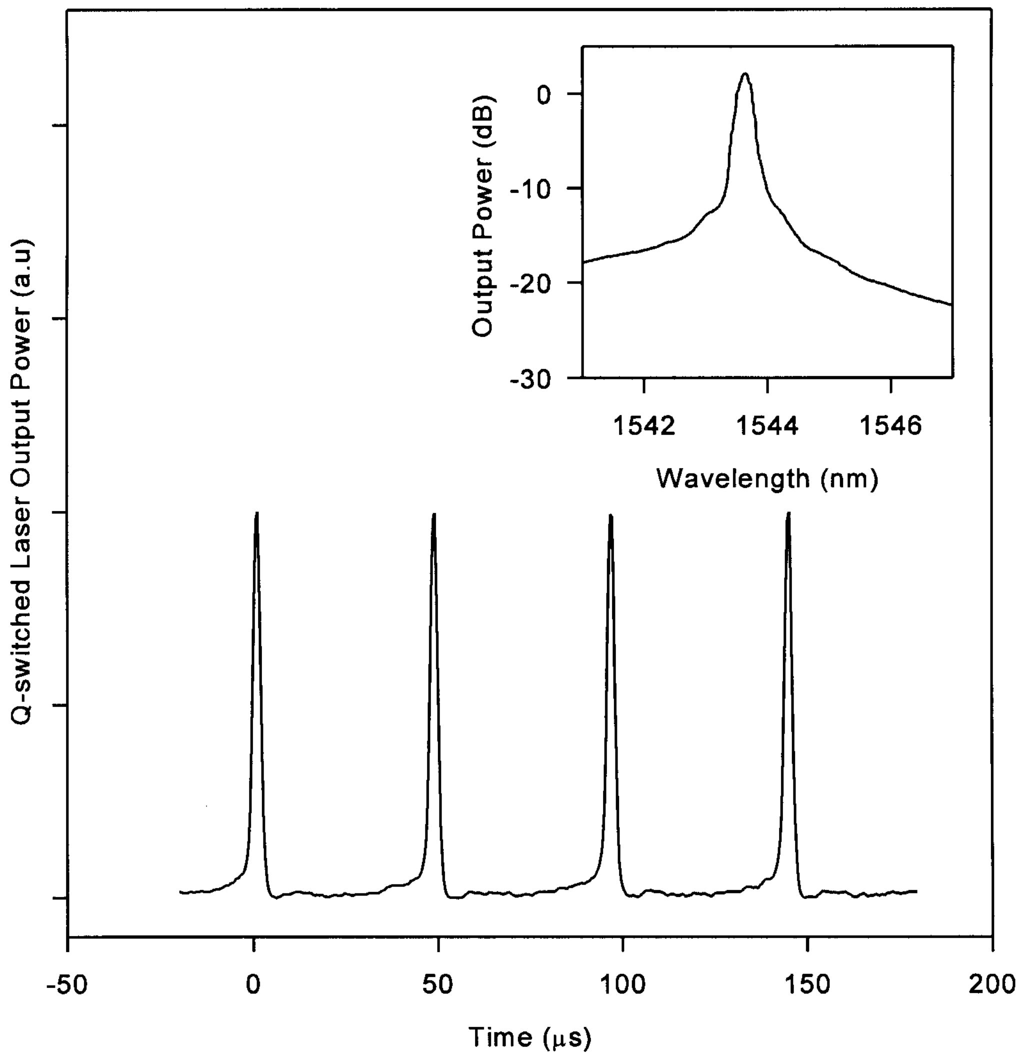

Fig.4 Typical Q-switch pulse train and its corresponding spectrum (inset) obtained at a mirror temperature of 17 °C. The pulse duration is 1.75 μs, repetition rate ~20 kHz, optical bandwidth ~0.2 nm and pulse peak power 100 mW.

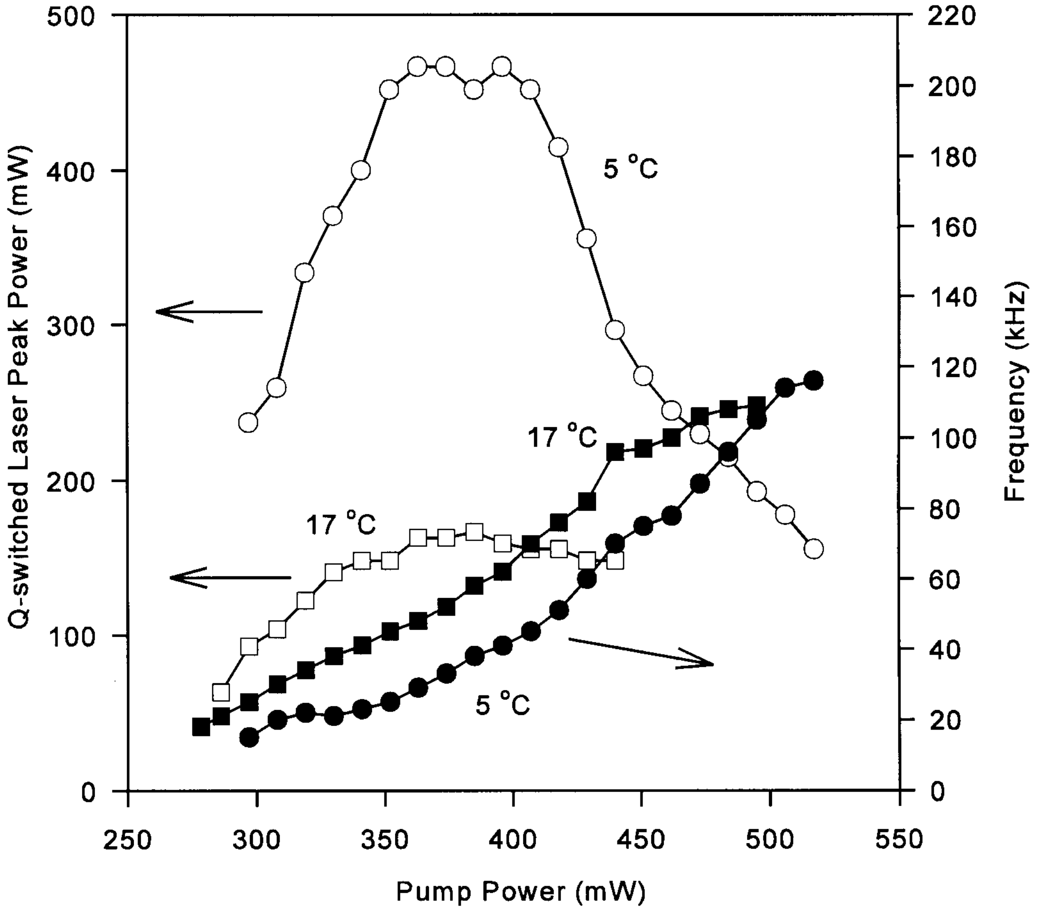

Fig.5 Variation of pulse repetition rate and Q-switched laser peak power with pump power for two mirror temperatures (a) 17 °C; (b) 5 °C.

Fig.5