PTL. 553

Integrated Q-switched multiple-cavity glass waveguide laser

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Abstract

A novel Q-switching scheme, using rapid variation of the path difference between the cavities of a multiple-cavity resonator, is demonstrated. A thermo-optic phase modulator was used to switch the cavity loss of a Y-junction glass waveguide laser between high and low states. Q-switched pulses with durations of 5μs and peak powers of 70mW were obtained.

553

Introduction

Optical amplification has been reported in planar optical waveguides in a variety of rare-earth doped crystals and glasses[1]. Recently two devices demonstrating the potential of planar technology have been reported: An FM mode-locked waveguide laser in neodymium-doped lithium niobate with an integral modulator[2] and a Y-branch waveguide laser in neodymium-doped silicate glass[3]. Q-switching of planar waveguide lasers has been achieved by using a bulk modulator in an extended-cavity configuration[4]. Such configurations, however, are unattractive for integrated optics applications because coupling between guided and bulk devices is difficult to achieve without unwanted reflections, and the optical circuit is no longer as robust. Monolithic integration of cavity elements offers robust devices which can be printed photolithographically and packaged at lower cost.

In this Letter, we report the demonstration of a Q-switched glass waveguide laser suitable for monolithic integration. The device uses an integrated thermo-optic phase modulator to switch the Q-value of a multiple-cavity resonator. Q-switched pulses of 5μs duration and 70mW peak power were obtained. Extension of this technique to electro-optic material systems will allow shorter pulses to be obtained.

Operation

The laser configuration employed was a waveguide Y-junction with mirror terminations on each of its externally-available ports 1,2, and 3 as shown in Fig. 1. The device has two cavities of optical lengths l_{13} and l_{23} between ports 1 and 3, and ports 2 and 3 respectively. The mutual resonance frequencies of the coupled-cavity are defined by

$$\beta l_{13} = n\pi \qquad \text{and} \qquad \beta l_{23} = m\pi \tag{1}$$

where $\beta = 2\pi/\lambda$ is the propagation coefficient, n, m are integers and λ is the operating wavelength.

The optical path length of one cavity may be varied by applying a voltage to the thermo-optic phase modulator. At wavelengths where both cavities are in resonance, laser radiation recombines in phase at the Y-junction on reflection from mirrors 1 and 2, resulting in a low-loss combined cavity response. At other wavelengths light is radiated into the substrate at the junction. In devices with small path difference, the free spectral range between mutual resonances is large compared with the gain bandwidth of the material. The phase modulator may then be employed to move a single peak in the combined cavity transmission in and out of the gain band, thereby modulating the Q-value of the system at wavelengths where oscillation may occur, and generating Q-switched pulses. It should be noted that in devices with small path difference, a peak in the envelope of the combined cavity transmission contains multiple individual peaks corresponding approximately to the Fabry-Perot modes of the individual cavities.

Experimental

The Y-junction waveguide was fabricated by potassium ion-exchange in BK-7 glass doped with 1.5 wt.% neodymium oxide using a process similar to that previously documented for straight channel waveguide lasers[5]. The aluminium diffusion mask openings were $3\mu m$ and the junction angle was 1.1°. An exchange time of 7 hours in molten potassium nitrate at 390°C was used. The waveguides supported a single transverse mode at the pump wavelength of 810nm, and at the signal wavelength around 1060nm.

A second photolithographic step was used to define a thermo-optic phase modulator in the form of an aluminium electrode next to one branch of the waveguide. Its dimensions were $5\mu m \times 0.2\mu m \times 10mm$ and it had a resistance of approximately 200 Ohms. The nearest edge of the electrode was separated from the stripe opening through which the waveguide was made by $3\mu m$, to reduce excess loss in the waveguide due to absorption and scattering by the aluminium film.

The laser cavity was formed by bonding dielectric mirrors, on thin glass slides, with epoxy resin onto polished ends of the waveguides. The reflectivities of the mirrors at 1060nm were $R_1 = R_2 = 99.9\%$ and $R_3 = 90\%$, and their transmission at the pump wavelength was typically 90%. The pump source was a Ti:sapphire laser tuned to 810nm. The lasing characteristic shown in Fig. 2 was obtained by pumping the device from port 1 and taking the laser output at port 3, with no voltage applied across the electrode. Lasing commenced when the launched pump power was approximately 35mW with a slope efficiency of 15%. A typical lasing spectrum of the device with no voltage applied to the modulator is shown in Fig. 3. It had a bandwidth of 1.2nm around 1056.5nm. Single-longitudinal-mode operation was not realised because there was insufficient path difference between the cavities[3].

The response of the laser to thermo-optic modulation was investigated by applying a square wave of 100Hz to the phase modulator while maintaining a constant pumping level. The temperature of the waveguide adjacent to the electrode rises after the application of a voltage and the optical path length of the corresponding cavity increases to a new value. Fig. 4 shows the modulation and laser output waveforms when the applied voltage was varied between 0 and 3.3 volts. The laser output increased when the modulation voltage was applied due to reduction in laser threshold as the Q-value of the resonator was increased.

When the amplitude of the modulation voltage was increased, pulses appeared in the laser output. Fig. 5 shows the modulation voltage and laser output power as a function of time. The amplitude of the applied voltage had been adjusted to 10.4 volts to select only one short pulse in the modulation cycle. A pulse of 5μs duration (FWHM) and 70mW peak power was observed shortly after the falling edge of the modulation waveform. The continuous wave lasing power at the same pumping level was 4mW with no voltage applied to the modulator.

The formation of these pulses is explained as follows: Immediately before the input voltage falls, one cavity is at an elevated steady state temperature. In this condition, the cavities are not mutually resonant, so that the combined cavities have low Q, and lasing is suppressed as there is insufficient gain to overcome the high cavity loss. Population inversion builds up beyond the steady state lasing level in this part of the modulation cycle. When the modulation voltage is removed, the temperature of the heated waveguide falls rapidly, and its optical path length passes through that required for mutual cavity resonance. The combined cavities then have a high Q-value and the device emits a Q-switched pulse. Immediately before the falling edge, the cavities are only slightly off-resonance, so that the pulse occurs immediately after the falling edge. The device passes through other resonances in the remainder of the modulation cycle; however, at these times the rate of change of temperature, and thus of cavity length, is too slow to generate sharp pulses.

The Q-switched pulses were long because of the slow response of the thermo-optic modulator. This could be remedied by using faster acousto-optic or electro-optic overlays, for example.

Thermo-optic tuning of the coupled-cavity transmission spectrum within the gain band of the Nd:glass system may also be used to tune the laser output wavelength. Work is in progress to investigate the spectral characteristics of the laser output as a function of the applied voltage, and to develop single-longitudinal-mode devices.

Conclusions

We have demonstrated Q-switched operation of a multiple-cavity planar waveguide laser driven by an on-chip thermo-optic modulator. The configuration used is suitable for monolithic integration, and may be enhanced in material systems allowing faster switching speeds.

Acknowledgements

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Figure captions

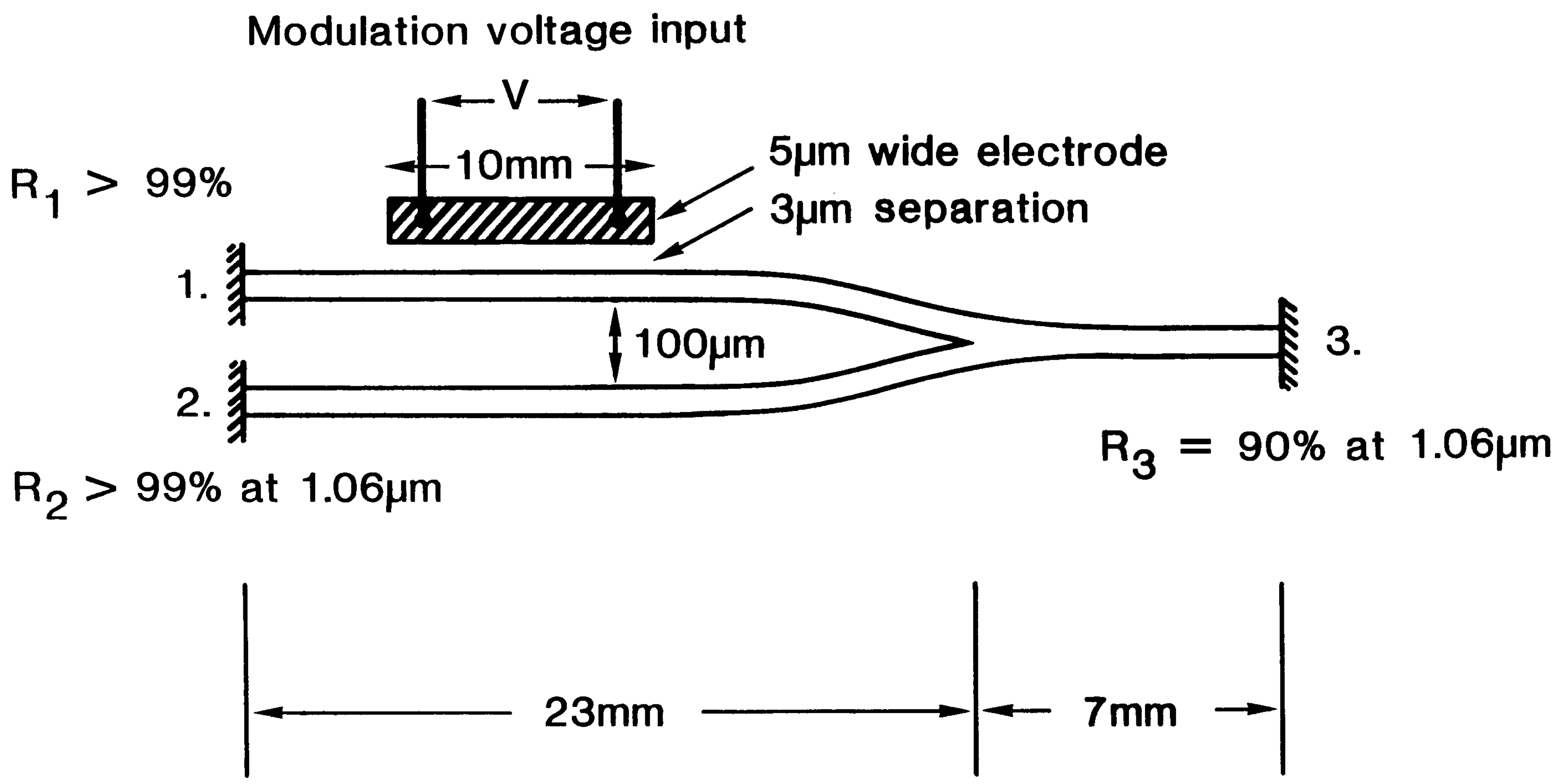
Figure 1. Layout of the device

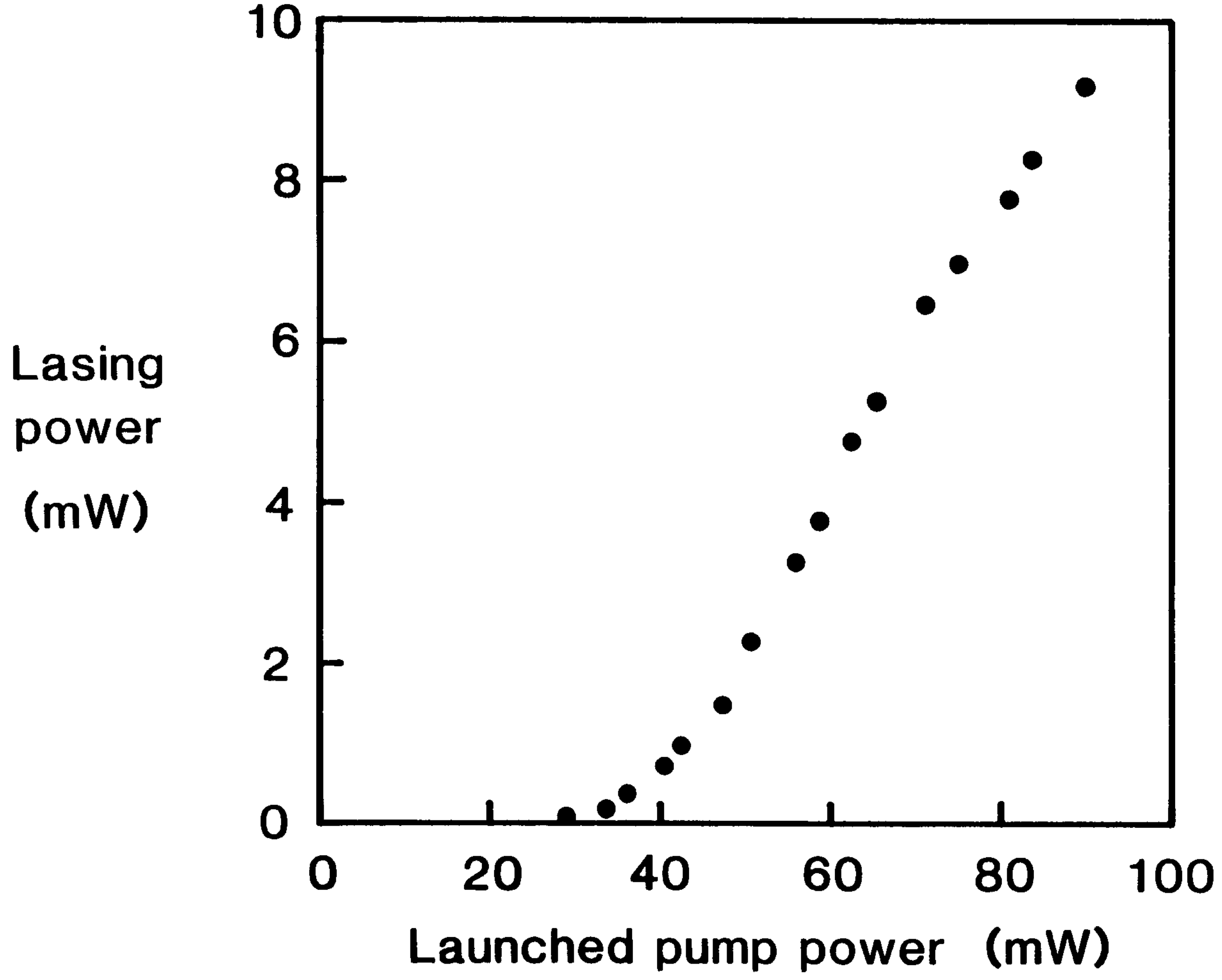
Figure 2. Lasing characteristics

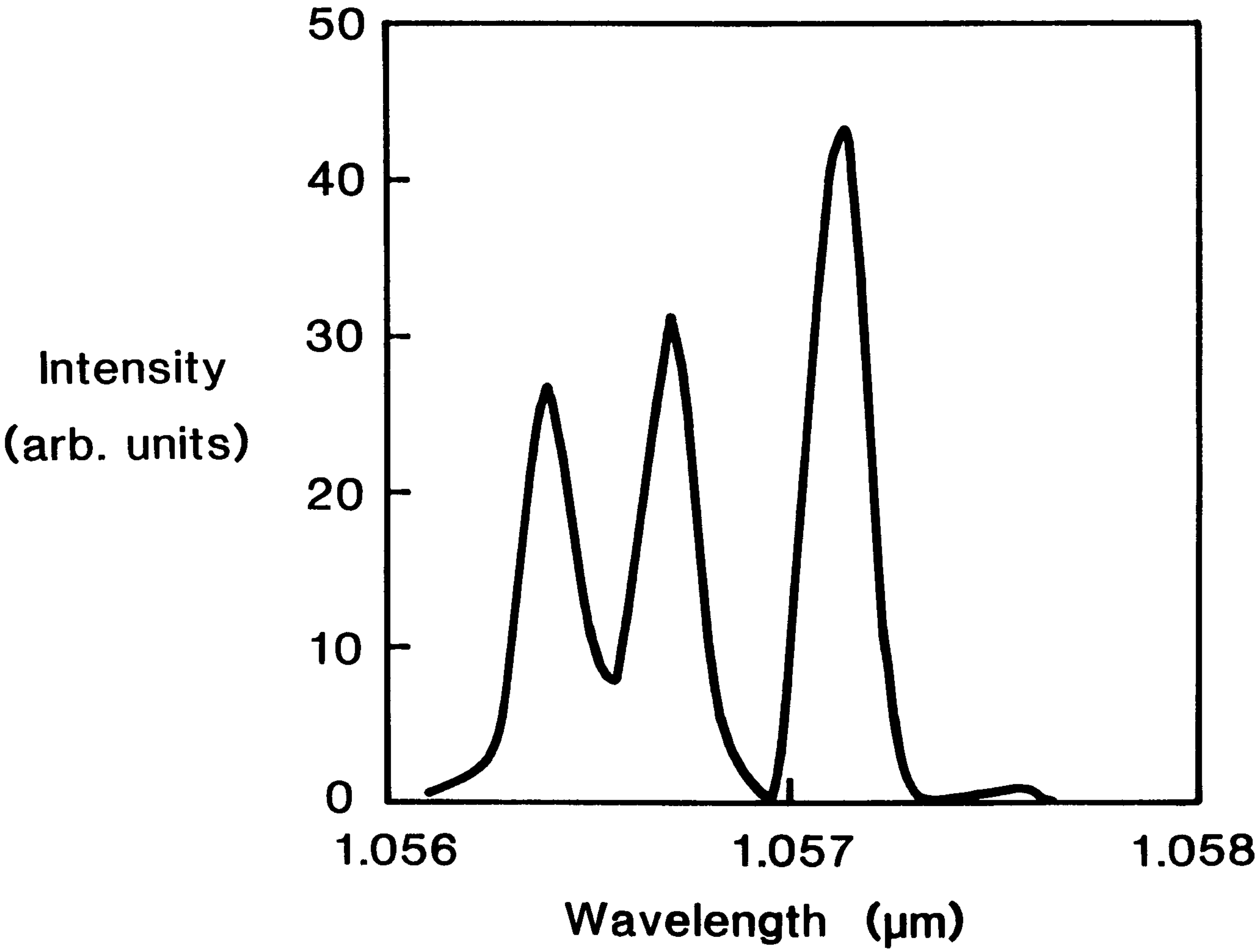
Figure 3. Lasing spectrum

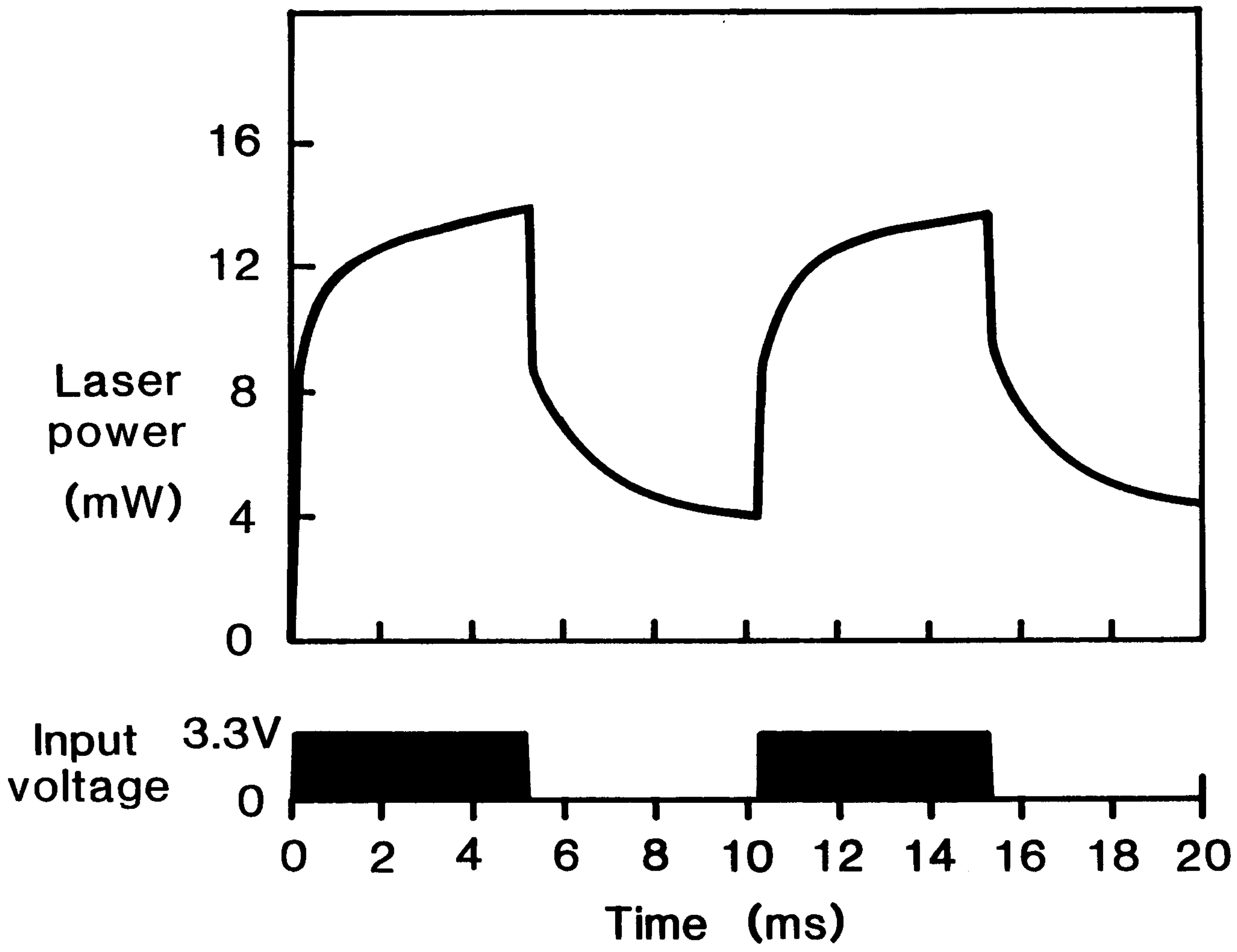
Figure 4. Modulated operation

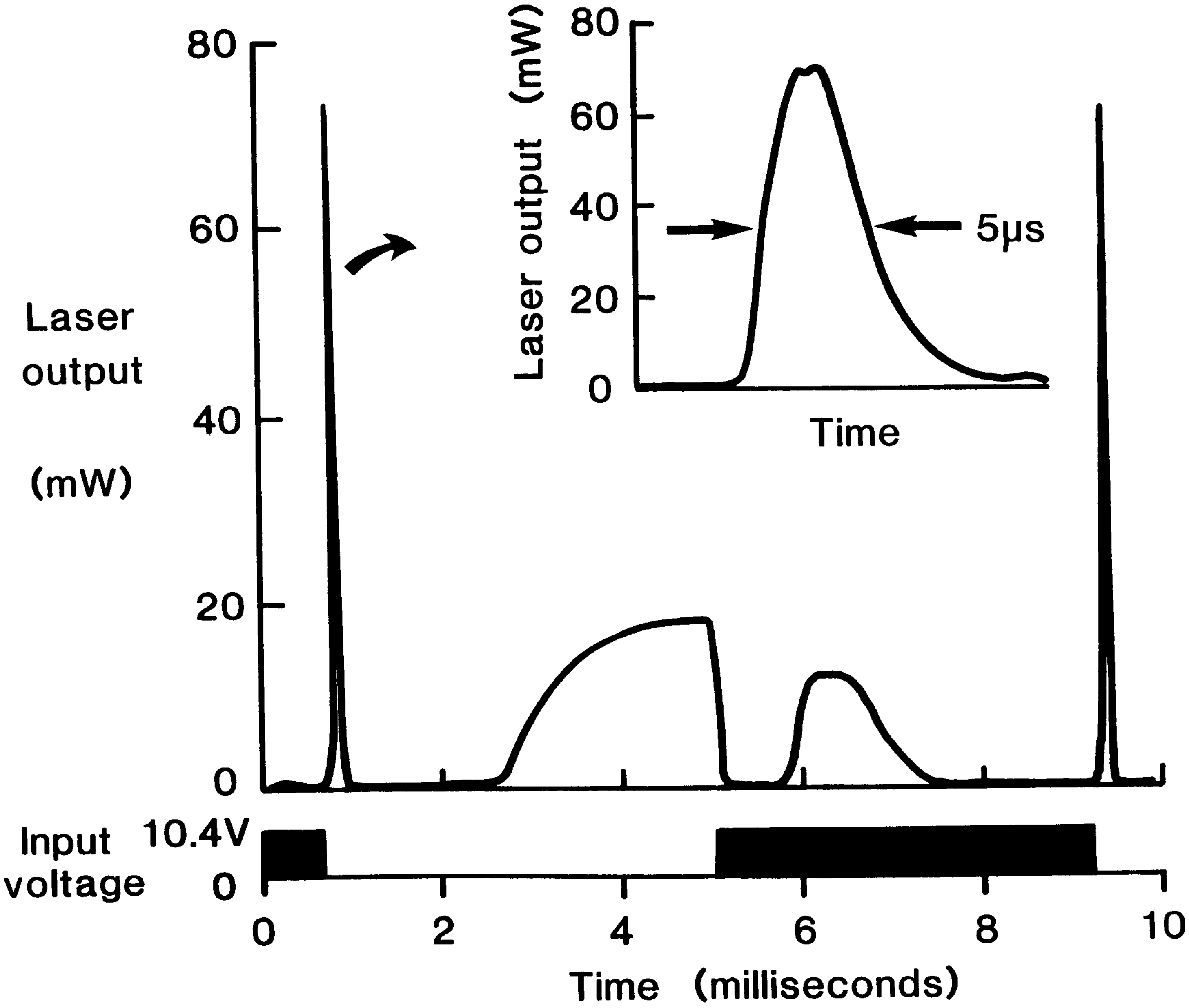
Figure 5. Q-switched operation


Modulation voltage input
V
10mm
5μm wide electrode
3μm separation
R1 > 99%
1.
2.
100μm
3.
R2 > 99% at 1.06μm
R3 = 90% at 1.06μm
23mm
7mm


Lasing
power
(mW)
10
8
6
4
2
0
0
20
40
60
80
100
Launched pump power (mW)


Intensity
(arb. units)
50
40
30
20
10
0
1.056
1.057
1.058
Wavelength (μm)


16
12
8
4
0
Laser
power
(mW)
Input
voltage
3.3V
0
0
2
4
6
8
10
12
14
16
18
20
Time (ms)


Laser output (mW)
80
60
40
20
0
Input voltage
10.4V
0
0
2
4
6
8
10
Time (milliseconds)
Laser output (mW)
80
60
40
20
0
5µs
Time