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Abstract. A compact, passively *Q*-switched and mode-locked Nd:YAP laser in oscillator-amplifier configuration was designed and constructed. Operation wavelength switching (between 1.34 and 1.08 μm) was achieved with a three-mirror cavity and mechanical shutter. For *Q* switching and mode locking of the 1.34-μm Nd:YAP laser transition, a V^{3+}-doped yttrium aluminum garnet (YAG) saturable absorber was employed. The optimal performance was found after variation of the resonator length (40 to 100 cm) and of the absorber initial transmission (52% to 89%). The duration of a single pulse in a train was around 1 ns. The saturation intensity of the V^{3+}:YAG absorber was determined to be 10 MW/cm^2. A BDN II polymer thin-film saturable absorber was used for *Q* switching the 1.08-μm laser transition. After amplification, the maximum output energy reached was 27 mJ (train of mode-locked pulses at 1.34 μm) or 94 mJ (*Q*-switched pulse at 1.08 μm). The output laser radiation was delivered by means of a hollow glass waveguide coated with cyclic olefin polymer and Ag, with 95% and 80% efficiencies for 1.34 and 1.08 μm, respectively.
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Subject terms: Nd:YAP laser; passive *Q* switch; passive mode locking; V^{3+}:YAG saturable absorber; BDN II saturable absorber.

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1 Introduction

Simultaneous or alternative double-wavelength operation of a single compact laser system has attracted the interest of laser researchers, due to the spectral dependence of the radiation-material interaction during medical treatment and industrial material processing. Nd-host-crystal lasers in general have two main efficient emission bands, around 1- and 1.3-μm wavelengths. The difference of $\approx$0.25 μm corresponds to an increase in radiation absorption in water by about 15 times, which can be significant for some medical procedures. Nd:YAlO$_3$ (Nd:YAP) crystal specifically has been identified as one of the suitable crystals for double-wavelength operation, as it is a more efficient laser crystal than Nd-doped yttrium aluminum garnet (YAG) in the 1.3-μm region, with high efficiency also in the fundamental 1-μm region. Other advantages of this laser-active medium include natural birefringence, which results in linear-polarization purity of the output radiation, and lack of thermally induced birefringence at high output powers. Its wide emission linewidth raises the possibility of shorter pulse duration in a mode-locked operation. Many medical and industrial applications require high-power *Q*-switched or mode-locked laser pulses (mainly in the 1.3-μm band), which are still hardly achievable with diode-pumped lasers, so that flashlamp-driven solid-state lasers are still in use.

The passive resonator *Q*-modulation technique has many advantages over active (e.g., electro-optical) *Q* switching and mode locking, in that it is a compact, inexpensive, and easy-to-operate technology. Solid-state materials with reliable saturable absorption and good chemical and physical properties have been the object of constant interest for researchers. Although several bulk saturable absorbers such as Cr^{4+}:YAG, LiF:F^{2-}, and solid-state dyes have been found suitable for the 1-μm Nd laser channel, they are not effective at the other Nd laser transitions. In the 1.3-μm spectral region, a stable *Q*-switched or mode-locked regime was difficult to reach even with the traditional passive dye absorbers and with a simple optical resonator.[1,2] Passive saturable absorbers based on the V^{3+} active ion in several hosts, such as V^{3+}:LiGaO$_2$ or V^{3+}:YAG, seem to be very promising *Q*-switchers at the 1.3-μm laser wavelength, and some authors have also claimed mode-locked operation in

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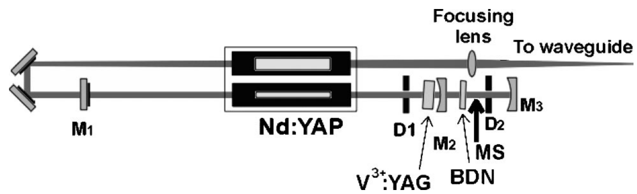

Fig. 1 Layout of the double-wavelength (1.34 or 1.08 μm) *Q*-switched and mode-locked Nd:YAP laser D_1, D_2: diaphragms; MS: mechanical shutter; BDN: thin polymer film with BDN II dye.

this spectral band, employing tetrahedral V^{3+} saturable transition from the $^3A_2(^3F)$ to the $^3T_2(^3F)$ energy level.[3]

A very common task of laser engineering is the delivery of a laser pulse to its point of interaction with the treated material. At moderate pulse powers in the near infrared (NIR) spectral region, highly developed silica-glass optical fibers can be exploited. However, when the radiation intensity concentrated in the fiber core exceeds the surface or bulk damage threshold, other means of laser pulse delivery must be used. Hollow waveguides rank among the most promising emerging radiation transport devices; they have proved to be suitable for delivering extreme pulsed laser power with high efficiency over a wide spectral region.[4,5]

The goal of this work was to develop a compact, high-power solid-state laser based on Nd-host technology with a possibility of operation wavelength switching and with a reliable flexible radiation transport device. A crystal of V^{3+}:YAG was used as a passive *Q* switch and mode locker at the 1.34-μm Nd:YAP laser transition. The V^{3+}:YAG saturable absorber was characterized, and the laser performance at this wavelength was optimized. Although *Q* switching of V:YAG crystal was reported also at 1.08 μm,[3] in our laser system we employed an additional passive *Q* switch to achieve reliable single *Q*-switched pulse operation. The 1.08-μm laser channel was additionally *Q*-switched by a BDN II dye solution in a polymer thin film. In order to keep the device compact, a single-flashlamp cavity-oscillator–amplifier configuration was utilized. For radiation delivery a hollow glass waveguide coated with cyclic olefin polymer (COP) and silver was used.

2 Experimental Arrangement

Two Nd:YAP 6×120-mm and 7×120-mm crystals (Crytur Turnov, Czech Republic), with ends cut at 2-deg angles, were placed at the outer focus of the double elliptical silver-coated cavity and pumped by one xenon flashlamp placed at the common focus of the two cavity ellipses. The repetition rate of the lamp driver was 3 Hz. The laser oscillator enabled switching between 1.34- and 1.08-μm operation wavelength (see Fig. 1). The 1.34-μm resonator was formed by a mirror M_2 with a curvature $r=10$ m and reflectivities $R=100\%$ and 0.1%, and a flat mirror M_1 with reflectivities 37% and 7%, for $\lambda=1.34$ and 1.08 μm, respectively. For transverse-mode control of this resonator, a diaphragm D_1 was placed close to the saturable absorber. Samples of V^{3+}:YAG crystals with various initial transmissions were used for *Q* switching and mode locking of the 1.34-μm transition. The 1.08-μm resonator was formed by the mirror M_3 with curvature $r=10$ m and 100% reflectivity and the flat output coupler M_1, common to both cavities, with the reflectivities mentioned above. A passive *Q* switcher consisting of BDN II dye in a polymer thin film was used for giant-pulse generation in this lasing branch. The diaphragm D_2 was used for additional transverse-mode control and for tailoring the 1.08-μm resonator gain to the pumping level of the Nd:YAP crystal.

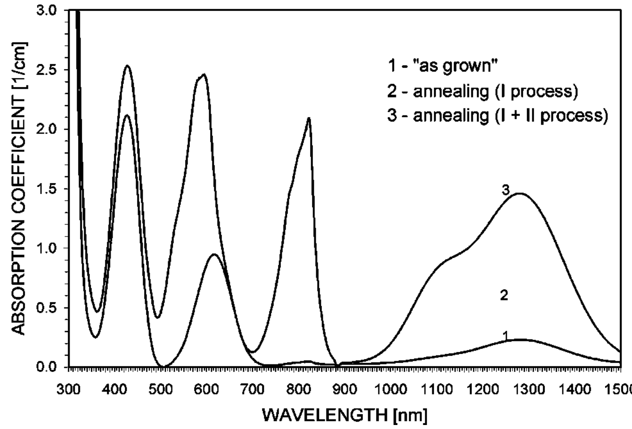

Fig. 2 Low-signal absorption coefficient of a V^{3+}:YAG sample as a function of wavelength. Annealing effectively enhances the absorption coefficient in the active bands.

Output laser radiation at both wavelengths was focused by a lens of focal length $f=50$ cm (measured in the visible spectral range). The radiation was coupled into a COP- and Ag-coated hollow glass waveguide using a special translation stage. Because during the adjustment the input waveguide surface could be damaged by the high-power radiation, the waveguide input was protected by a hollow brass cylinder (see also Ref. 5) with an inner diameter equal to that of the waveguide. The time characteristics were measured by a fast vacuum photodiode (developed at the Czech Technical University) with an S3 photocathode (used at 1.34 μm), HP 4207 *pin* photodiode (1.08 μm), Tektronix TDS 3032 oscilloscope (400 MHz), and S7-19 oscilloscope (7 GHz). A computer-operated two-channel Molectron JD 2000 joulemeter with two thermal detectors (Gentec ED-100A, Molectron J25) was used to measure the energy. The spectrum of the generated radiation was investigated with an IR wavelength meter (StellarNet EPP2000).

3 Characterization of the V^{3+}:YAG Saturable Absorber

The V^{3+}:YAG samples were grown by the Czochralski method at the Institute of Electronic Materials Technology, Warsaw, Poland, and except for the low-signal transmission (see Fig. 2), no crystal parameters were known. After the growing and cutting of the V^{3+}:YAG samples, several laser annealing processes were applied to enhance the active absorption bands, as can be seen in Fig. 2. The tetrahedral V^{3+} saturable $^3A_2(^3F)\rightarrow{}^3T_2(^3F)$ transition[3,6] is responsible for the absorption band with peak at 1280 nm. This channel can be used for *Q* modulation in the 1- to 1.4-μm spectral region.

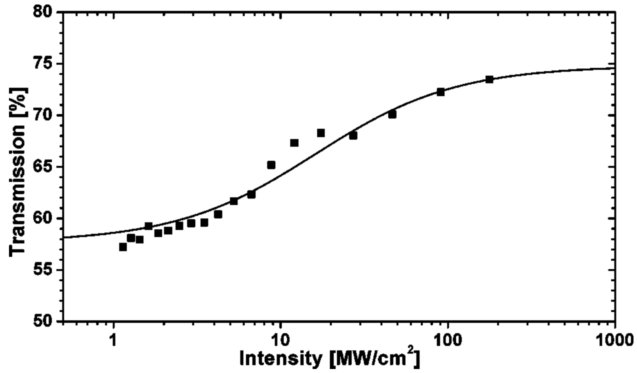

Fig. 3 Transmission of the V^{3+}:YAG sample as a function of 1.34-μm probe-beam intensity. Data were fitted according to Eq. (1), and the resulting value of the saturation intensity was 10 ±1 MW/cm^2.

In order to characterize the samples and to compare their parameters with values published earlier, the saturation intensity of the V^{3+}:YAG sample was measured. The saturation intensity I_S can be defined by the following expression:

$$I_S=\frac{h\nu}{2\sigma\tau}, \tag{1}$$

where τ is the recovery time of excited absorber, σ is the absorption cross section, h is Planck's constant, and ν is the laser frequency.

Assuming that τ is equal to 5 ns,[3] the use of a "fast" absorber model[7] is satisfactory, and the saturation intensity could be derived from the following equation[8]:

$$\frac{I}{I_S}=\frac{1}{T_S-T(I)}\ln\left(\frac{T(I)}{T_0}\right), \tag{2}$$

where $T(I)$ is the transmission of the V^{3+}:YAG sample corresponding to radiation intensity I, and T_0 is the initial and T_S the saturated transmission of the absorber sample under investigation. By introducing variable bleached transmission ($T_S\leqslant 1$), nonsaturable losses of the V^{3+}:YAG crystal sample are taken into account. Measurements of the saturation intensity I_S were performed by the z-scan method[9] with an actively Q-switched (by a $LiNbO_3$ Pockels cell) Nd:YAP 1.34-μm laser used as a probe-beam source. The duration of the probe-beam pulse was 25 ns, and the pulse energy was set to 10 mJ. Probe-beam propagation parameters were determined by the knife-edge method.[10] The V^{3+}:YAG transmission curve obtained in dependence on the probe-beam intensity can be seen in Fig. 3. The resulting saturation intensity value was calculated to be $I_S=10\pm 1$ MW/cm^2, giving the ground-state absorption cross section $\sigma_{GSA}=1.5\times 10^{-18}$ cm^2. This result is in good agreement with the value published earlier.[11]

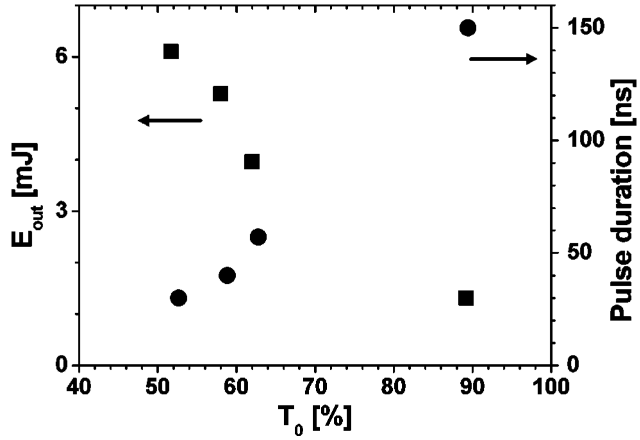

Fig. 4 Dependence of the 1.34-μm output energy (■) and of the pulse-train duration (●) on the initial transmission of the V^{3+}:YAG saturable absorber (2-mm diaphragm).

4 Laser Performance at 1.34 μm

4.1 *Dependence on the Initial Transmission of the* V^{3+}:YAG *Saturable Absorber*

In order to maximize output energy and to obtain the best pulse stability, several V^{3+}:YAG samples were investigated. The initial transmissions (at 1.34 μm) of available samples were $T_0=89\%$, 84%, and 58%. Combining two of them, we obtained $T_0=52\%$. The lamp driving power was chosen for just-above-threshold operation in order to generate a single Q-switched mode-locked pulse train. The resonator physical length was 40 cm during all the measurements. Inside the resonator, a 2-mm diaphragm was placed to suppress the higher transverse modes. The resulting dependence of the output energy and of the mode-locked pulse-train duration on the initial transmission of the V^{3+}:YAG saturable absorber is shown in Fig. 4. Full modulation was observed with all samples of initial transmission between 50% and 70%. For sample pulses corresponding to $T_0=58\%$ and 89% see Fig. 5.

The highest energy and shortest train of the generated pulses was reached with the initial V^{3+}:YAG transmission $T_0=52\%$. The output oscillator energy was 10.2 mJ in near-to-TEM_{00} mode ($M^2=1.4$). The corresponding pulse-train duration was 30 ns (see Fig. 4). However, in this configuration the laser oscillator was very sensitive to any operating-condition instability, such as slight increases of the laser-rod cooling-water temperature or room temperature, and the lamp driver had to be operated at the maximum power. Thus, a sample with the 58% initial transmission, exhibiting stable performance, was chosen for further investigation.

4.2 *Dependence on the Optical-Resonator Length*

In these measurements the output pulse-train duration and energy were evaluated against the optical-resonator length, which was varied from 40 to 100 cm. As a saturable absorber V^{3+}:YAG with initial transmission $T_0=58\%$ was used, and the 1.8-mm diaphragm was placed inside the resonator. The resulting dependences are shown in Fig. 6.

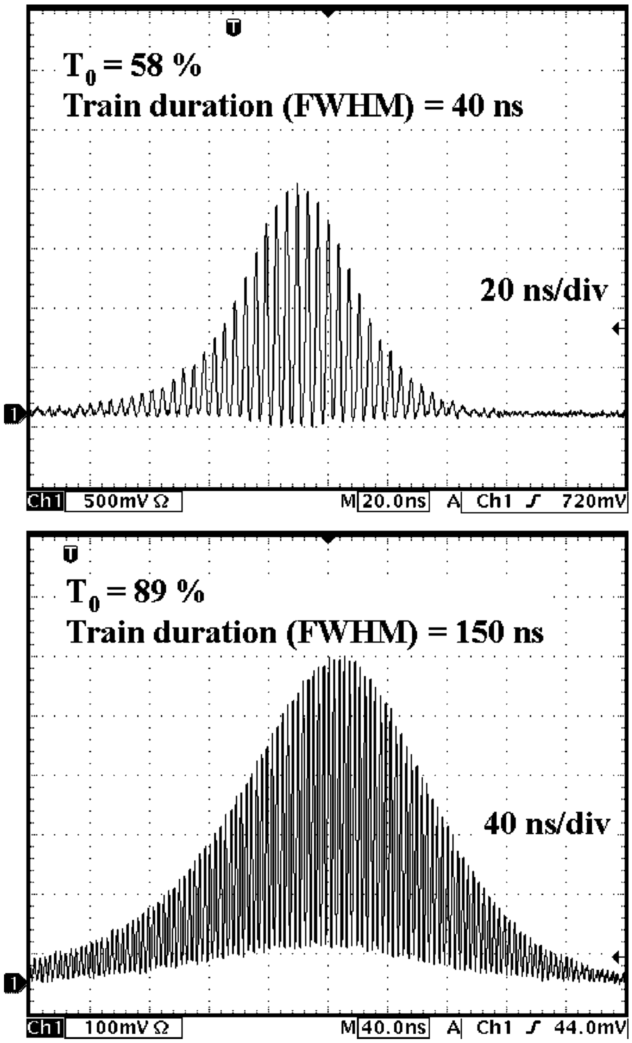

Fig. 5 Temporal development of pulse trains corresponding to V^{3+}:YAG transmissions T_0=58% and 89%.

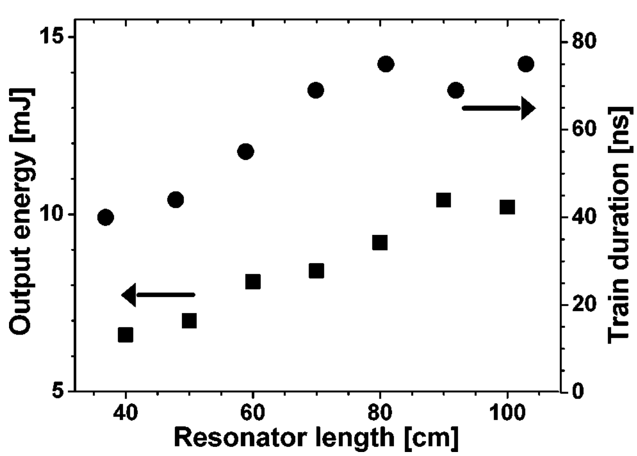

Fig. 6 Dependence of train energy (■) and train duration (●) on resonator length (1.8-mm diaphragm).

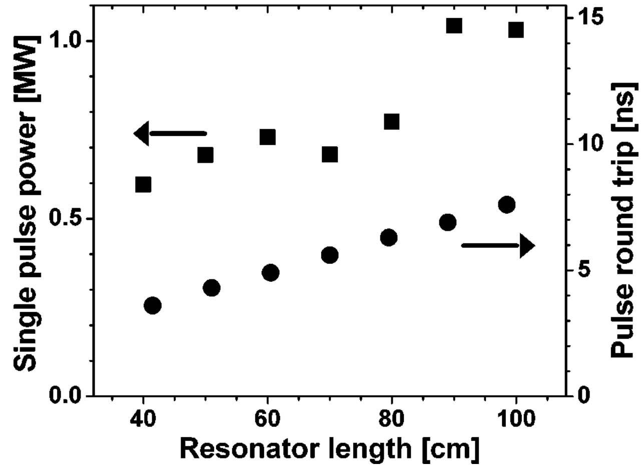

Fig. 7 Round-trip time (●) and power (■) of single mode-locked pulse as a function of the resonator length.

From these results it follows that on elongating the resonator from 40 cm to 1 m, the output energy increases from 6.6 to 10.1 mJ. At the same time, the pulse-train duration and the pulse round-trip time also increase while the number of pulses inside the train remains approximately constant (10 to 12). As a result, with the longer cavity, the power concentrated in a single pulse increased from 0.6 to 1.05 MW (see Fig. 7) and remained at this value for resonator lengths of 90 to 100 cm. For efficiency, the 100-cm resonator was found optimal; due to space limitations, any further increase of the resonator length was considered impractical.

4.3 *Single-Pulse Duration*

To measure the duration of individual pulses in a train, a vacuum photodiode (CTU) and 7-GHz oscilloscope (S7-19) with a CCD readout were used. The individual pulses recorded can be seen in Fig. 8. The pulse duration for the 40-cm resonator length [Fig. 8(a)] has been found to be the same as for the 100-cm resonator [Fig. 8(b)], and the values measured were around 1 ns.

5 Laser Performance at 1.08 μm

Alternatively, this laser can work at 1.08-μm wavelength with a rear mirror M_3 and a common output coupler M_1 (see Fig. 1). Due to the larger cross section of the 1.08-μm line in the Nd:YAP crystal, after opening the mechanical shutter[12] the population inversion stored at the $^4F_{3/2}$ energy level is used up by the 1.08-μm ($^4F_{3/2}\rightarrow{}^4I_{11/2}$) lasing channel, and thus the laser operation wavelength is switched from 1.34 to 1.08 μm. The initial transmission of the used V^{3+}:YAG sample at 1.08 μm at the used level of pumping was too high, and therefore *Q*-switching performance was not obtained with only the V^{3+}:YAG sample in the resonator; rather, free-running laser operation was observed. Thus, as an additional saturable *Q* switch at this wavelength, BDN II dye in a thin polymer film was used. This passive *Q* switch has shown several advantages.

For optimized giant-pulse generation, a specific *Q*-switch initial transmission was needed. This was achieved by simply placing several thin-film BDN II

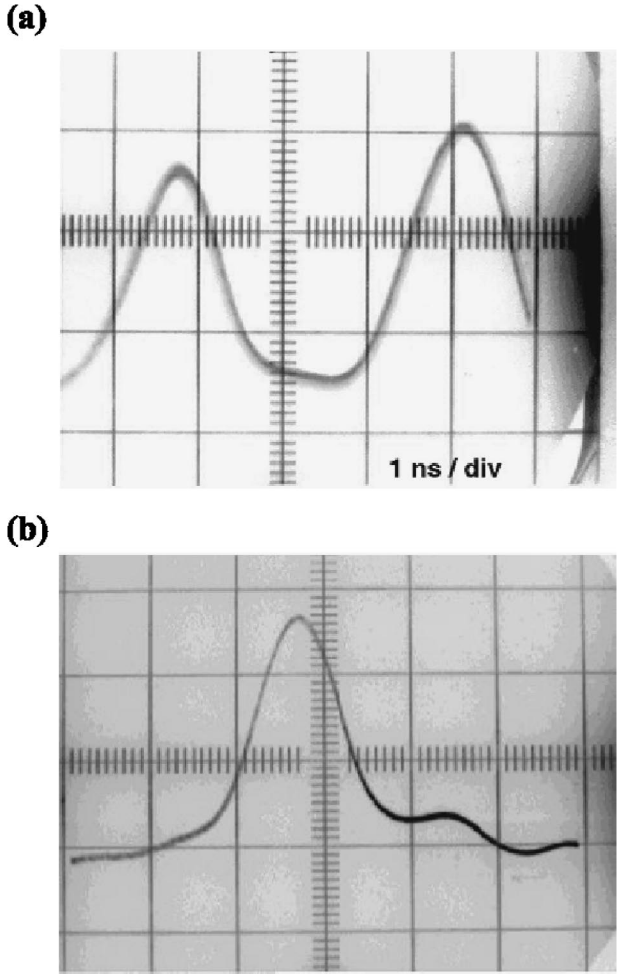

Fig. 8 Single-pulse temporal development for (a) 40-cm and (b) 100-cm resonator length. The pulse duration is 1 ns (FWHM) in both configurations.

samples in the resonator. The initial transmission of the optimized thin-film array was 8%. Due to the thinness of the films, almost no extra resonator alignment was found necessary after placing the Q switches inside the resonator. The performance of the BDN II thin-film Q switcher was very reliable, with no sign of degradation or laser-induced damage. Using an aperture D_2 with a diameter of 1 mm, approximately the same output energy was obtained. The output pulse duration was 20 ns, and the energy was 22 mJ. A sample temporal profile of Q-switched 1.08-μm pulses is shown in Fig. 9.

6 Amplification

The 1.34- and 1.08-μm oscillator output pulses were amplified in a Nd:YAP amplifier (crystal dimensions 7 $\times$120 mm), and mean energies of 27 and 94 mJ were obtained, respectively. The corresponding power in a single mode-locked pulse at 1.34 μm reached 2.7 MW, and the power in a Q-switched 1.08-μm pulse was equal to 4.7 MW. The energy histograms of the recorded pulses are shown in Fig. 10.

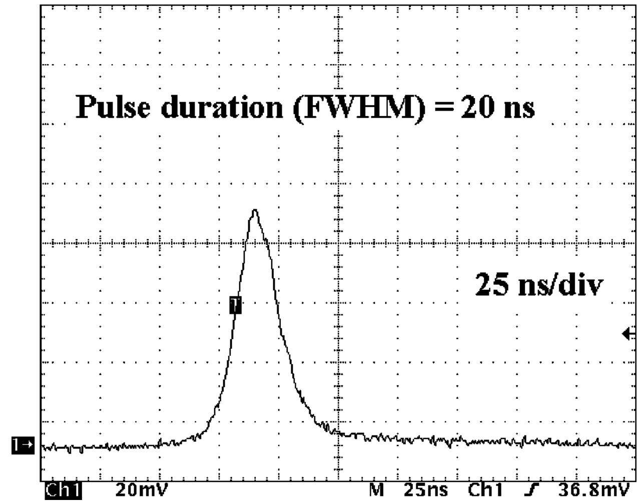

Fig. 9 Sample 1.08-μm pulse temporal profile.

7 Radiation Delivery by Means of Hollow Glass Waveguides Coated with COP and Ag

To deliver radiation to a potential place of interaction, COP- and Ag-coated hollow glass waveguides with an inner diameter of 1 mm and a length of 1 m were used. The waveguide consists of a hollow glass tube with a silver

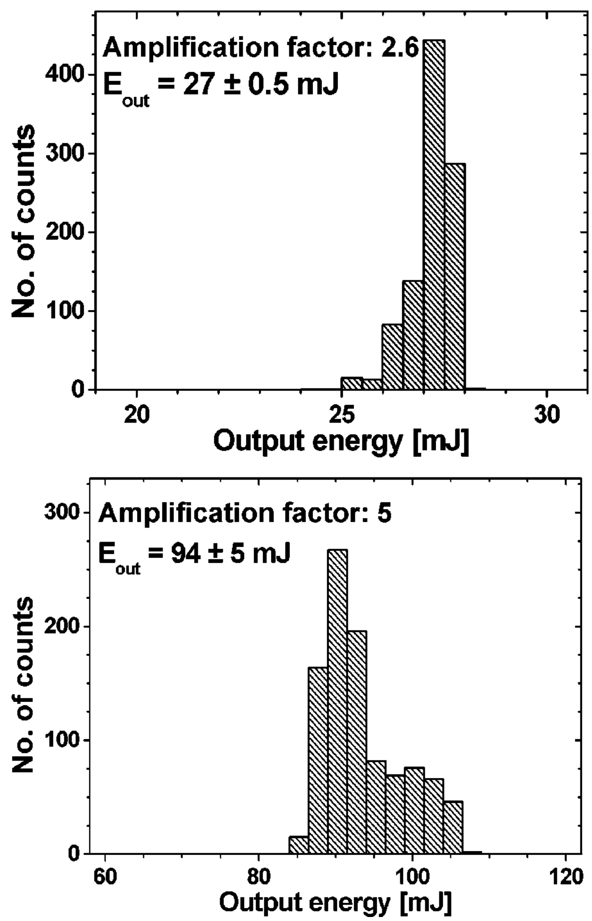

Fig. 10 Histograms of amplifier output energy at both operation wavelengths (1.34 and 1.08 μm).

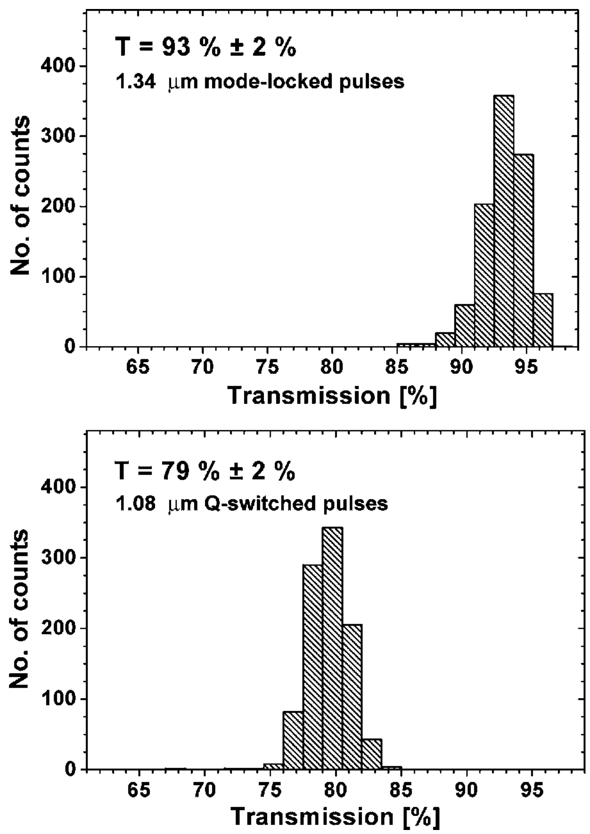

Fig. 11 Histograms of measured transmission of a COP- and Ag-coated hollow glass waveguide for 1.34- and 1.08-μm operation wavelengths. The maximal available energy was used for this measurement (27 mJ at 1.34 μm, and 94 mJ at 1.08 μm).

layer deposited on the inner wall, which had been coated with a thin film of COP. The output beam from the laser system was focused by a BK7 glass lens ($f = 50$ cm) to the input waveguide protector, to which a waveguide was attached. To prevent spark generation, a strong air stream was directed to the focal region of the input waveguide lens, and the waveguide front face was placed 1 cm behind the focal point. To investigate the transmission, a computer-operated two-channel Molectron JD 2000 joulemeter-ratiometer with two fast-response thermal detectors (Gen-Tec model ED-100A and ER200) was used. The input waveguide energy was monitored with a beamsplitter placed in front of the waveguide input and the first joulemeter head. At the same time, the output energy was monitored with the second energy detector. In each measurement set, about 1000 input-output energy values were recorded and processed. The obtained transmission histograms for both operation wavelengths are shown in Fig. 11.

The waveguide used was originally manufactured for optimal performance at 1.5-μm wavelength. However, it was found that it gives satisfactory performance also at 1.34 μm, where the throughput was as high as 93%, and even at 1.08 μm, where the 80% transmission is still satisfactory for application purposes. A single hollow waveguide is thus used for radiation delivery at both operation wavelengths. The transmission characteristics of the bent waveguide (at 90 and 180 deg, with bending radius equal to 20 cm) were measured for the same waveguide type in Ref. 4. In that work the waveguide was found to be sufficiently rugged. It can be concluded that this hollow waveguide is suitable for high-power double-wavelength laser radiation delivery.

8 Conclusion

A passively Q-switched and mode-locked Nd:YAP oscillator-amplifier laser system with the possibility of switching between 1.34- and 1.08-μm lasing wavelength has been developed. The V^{3+}:YAG saturable absorber used for Q switching and mode locking of the 1.34-μm transition was characterized by measurements of the saturation intensity $I_S = 10$ MW/cm^2. The optimal performance of the laser oscillator was obtained by varying the initial saturable-absorber transmission and the resonator length. A COP- and Ag-coated hollow glass waveguide was used for efficient high-power radiation delivery. The laser system can be considered as a candidate for medical or industrial applications.

Acknowledgments

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Jan K. Jabczyński: Biography and photograph not available.

Krzysztof Kopczyński: Biography and photograph not available.

Zygmunt Mierczyk: Biography and photograph not available.

Mitsunobu Miyagi graduated from Tohoku University, Sendai, Japan, in 1965, and received his ME and PhD degrees from the same university in 1967 and 1970, respectively. He was appointed research associate at the Research Institute of Electrical Communication, Tohoku University, in 1970. From 1975 to 1977, on leave of absence from Tohoku University, he joined McGill University, Montreal, PQ, Canada, where he was engaged in research on optical communication. In 1978, he became an associate professor at the Research Institute of Electrical Communication. He spent a month at Tianjian University, China, as a consultant to the International Advisory Panel of the Chinese University Development Project and the Chinese Review Commission of the Chinese Ministry of Education in 1985. Since 1987, he has been a professor in the Department of Electrical Communications, Graduate School of Engineering, Tohoku University. From April 1999 to March 2001, he was a Councilor of Tohoku University. His research activities cover fiber optics, integrated optics, and guided-wave technology and its application in the mid-infrared, especially the design and fabrication of IR hollow fibers for high-powered lasers in industry and medicine. Dr. Miyagi is a member of the Institute of Electronics and Communication Engineers of Japan, the Laser Society of Japan, IEEE, and the Optical Society of America. In 1989, he was awarded the Ichimura Prize for his contribution to IR hollow fibers and their application. He was also appointed an SPIE Fellow in 2001.

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