Multi-pulse operation of three-wavelength pulsed Q-switched $Nd:Y_3Al_5O_{12}$ laser

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By using a spatially dispersive resonator, three wavelength operation of $Nd:Y_3Al_5O_{12}$ laser in pulsed Q-switched regime at 1064, 1061, and 1052 nm was achieved. The laser output consisted of three pulses corresponding to the three generated wavelengths. The number of simultaneously emitted lines was increased by frequency doubling the laser output pulses in a potassium dihydrogen phosphate crystal.

The development of new solid-state active media for lasers has recently attracted much attention. A great number of new lasing wavelengths have been achieved this way.[1-3] However, some of the capabilities of the conventional solid-state active media have not been fully explored. With suitable dispersive elements in the resonator, most of the active media can be tuned to emit at different wavelengths, but in nonselective resonators only one wavelength is emitted due to the competition among the transitions. Recently,[4] we reported multiwavelength operation of a Nd-doped yttrium aluminum garnet (Nd:YAG) laser in free-running regime. The key element in the laser is the spatially dispersive resonator[5,6] which decreases the competition among the laser transitions. Here we report the further development of our previous work,[4] investigating the operation of a Q-switched Nd:YAG laser with a spatially dispersive resonator.

The experimental setup is shown in Fig. 1. The Pockels cell (PC) (Electro Optic Developments, model PC-18) used a potassium dideuterium phosphate (KD_2PO_4) crystal and was without antireflective coatings on the windows. An antireflection coated calcite Glan Prism (GP) was used. In our experiments we used four Brewster-angled prisms P1-P4, made of heavy glass TF-12 with $dn/d\lambda=0.03\ \mu m^{-1}$.[4] The reflection of the output mirror $M2$ in the spectral range 1040–1070 nm was 83%. The second harmonic generator (SHG) was a 20-mm-long potassium dihydrogen phosphate (KDP) crystal. The registration system included a scanning 0.6 m focal length monochromator MDR-23, a computer-controlled intensified charge-coupled-device array (CCD-A) and two p-i-n photodiodes, (PD1) and (PD2), connected to an oscilloscope (Tektronix model 466).

The losses introduced by the Pockels cell and the dispersive prisms were very high so that the threshold energy at 1064 nm was about 30 J. With prisms $P2$ and $P3$ separated by 60 cm and with a diaphragm diameter of 1.8 mm, the spectrum of the laser output consisted of three peaks corresponding to three of the known Nd-ion transitions: 1064, 1061, and 1052 nm. The typical temporal behavior of the lasing is shown in Fig. 2. The buildup time and the pulse width of the first Q pulse are ≈80 and ≈40 ns, respectively. The identification of the oscillograms showed that the first pulse always corresponds to the 1064 nm transition. The second pulse is the 1061 nm radiation. Its position always followed the 1064 nm pulse with a delay from 0 to 200 ns. In

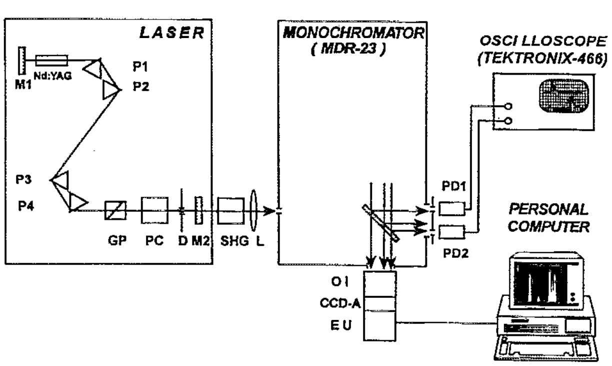

FIG. 1. Experimental setup for multiwavelength generation in pulsed Q-switched Nd:YAG laser. The components, not mentioned in the text, are: $M1$—100% mirror, OI—optical intensifier, EU—electronic unit.

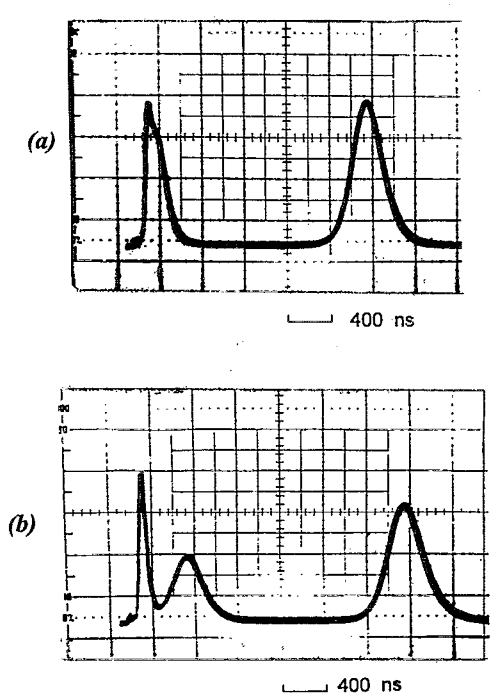

FIG. 2. Typical oscillogram of the Q pulses (200 ns/small div.). (a) Overlapping "1064 nm" and "1061 nm" pulses; (b) separated "1064 nm" and "1061 nm" pulses.

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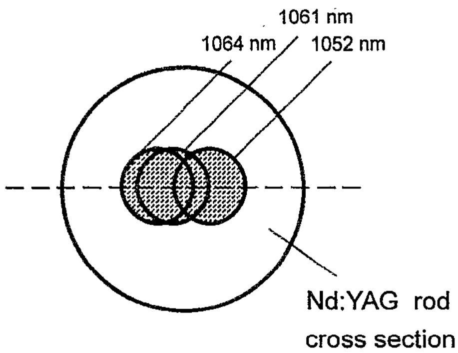

FIG. 3. Cross section of the beam waists in the active medium.

more than 90% of the shots, the 1064 nm pulse and the 1061 nm pulse were overlapped—Fig. 2(a). Another case, not so frequently observed, is when the second 1061 nm pulse is separated from the 1064 nm pulse [Fig. 2(b)]. The third pulse, delayed about 2000 nm after the 1064 nm pulse, was identified to be radiation with wavelength 1052 nm. We explain the fluctuation in the pulse positions with the sensitivity of the pulse delay to the ratio $n_i \sim n_{\rm th}$, especially when $n \approx n_{\rm th}$ (n_i—initial inversion before Q switching, $n_{\rm th}$—threshold inversion). Similarly, the different buildup times T_b are due to the different threshold inversions $n_{\rm th}$ and different cross sections of these transitions:[7,8]

$$T_b = \frac{(25+5)}{(n_i/n_{\rm th})-1} \frac{T_{\rm res}}{L-\ln(R)}, \qquad (1)$$

where L is the total round-trip loss, R is the reflection of the output mirror, and $T_{\rm res}$ is the round-trip time.

If we determine the ratio $n_i/n_{\rm th}$ from the pulse durations for the three lines and substitute in Eq. (1), we obtain qualitative agreement with the experimentally measured times:

$$T_{b,1064} < T_{b,1061} \ll T_{b,1052}. \qquad (2)$$

The observed difference from the exact values is an indication that the dynamics of this multiwavelength laser is more complicated than in the case of purely independent generation at these transitions. In fact, due to the low dispersion in our cavity, there is a significant overlapping of the active regions for all of the generated wavelengths (see Fig. 3). An exact solution for the laser dynamics should account for the fact that n_i for the second and third lines is not constant and depends on the instantaneous intensity of the first line. The transversal inhomogeneities of the population inversion due to the partial overlapping of the active regions for the different lines should also be taken into consideration. The last reason was expected to produce variations in the temporal characteristics for different regions of the output beam cross section. Using a slit 0.4 mm wide we scanned the laser output beam cross section in order to study the temporal pulse shapes. No detectable difference in the pulse width was observed.

We have also studied the temporal behavior of the laser pulses when the intracavity diaphragm D was translated in the plane of dispersion, changing in this way the gain/loss conditions for each line. When the 1064 nm line approaches the Nd:YAG rod edge, the time sequence of the emitted pulses was the same as in Fig. 2. The buildup time of the 1052 nm pulse decreased and reached a value of 800 ns when the losses for the 1064 nm pulse were so high that this line was close to the threshold condition.

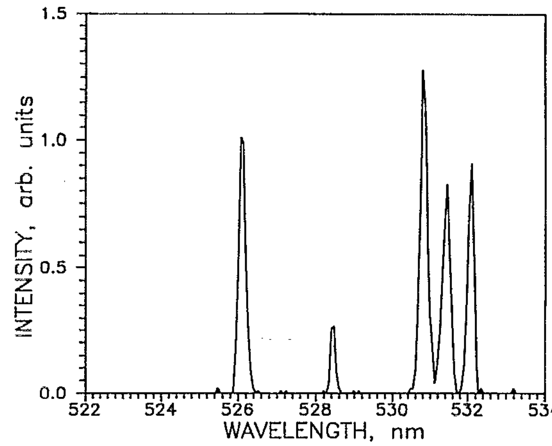

FIG. 4. The output spectrum of the second harmonic generation. The doubled and the sum frequencies are shown.

We found that the output beam shape is elliptical, but the distribution in both the horizontal and vertical planes is close to Gaussian, showing that the TEM_{00} mode gives the main contribution in the mode structure. The difference between horizontal and vertical divergence is explained by the astigmatism of the four prisms. The full-angle horizontal divergence (in the plane of the prism dispersion) is 2.4 mrad and the vertical divergence is 1.2 mrad.

The three closely situated spectral lines of this laser can be simultaneously doubled in a KDP crystal. The calculated doubling efficiency spectral curve of a 2-cm-long KDP crystal for an angle $\theta \approx 41° \, 12'$ between the wave vector and the crystal axis is wide enough so that all three lines can be doubled with the same orientation of the crystal. The spectrum of the second harmonics of the laser output is shown in Fig. 4. Besides the directly doubled frequencies 532 nm, 530.75 and 526 nm, the sum frequency of the 1064 nm and the 1061 nm pulses is also seen. The small peak at 528.4 nm corresponds to the sum frequency of the 1061 nm and the 1052 nm radiation. Additional more accurate investigation showed that this 528.4 nm signal appeared as two pulses coinciding in time with the position of the 1061 and 1052 nm. These experiments proved that besides the main pulses small amount of background radiation with wavelengths 1061 and 1052 nm contributed for the sum frequency generation at 528.4 nm. The sum frequency of the 1064 and 1052 nm pulses is also present but with a very low intensity.

It is clearly seen from Fig. 3 that only a small portion (about 15%) of the active medium volume was used for laser generation. The lasing at the five most efficient transitions, at 1052, 1061, 1064, 1074, and 1078 nm,[7] situated close to the 1064 nm line, can be simultaneously achieved with a significantly decreased threshold and with a higher efficiency if a laser rod with a proper cross section is used. It might be a double-side flashlamp- or diode-array pumped crystal with rectangular cross section. The resonator could be more compact if the prisms were made of an optical material with higher dispersion in this spectral region (e.g., KRS 5).[9]

In conclusion, we describe a Q-switched Nd:YAG laser that emits in a single flash at 1064, 1061, and 1052 nm. The output of the laser shows an interesting behavior. The output radiation consists of three Q-switched pulses in a time sequence corresponding to the three generated lines. The number of generated wavelengths can be higher if prisms with greater dispersion and a wider active medium (for example, slab form) are used. The KDP crystals with their wide spectral phase-matched curves in this spectral region are suitable for simultaneous doubling of the radiation of these multiwavelength lasers.

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