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OSCILLATION AND DOUBLING OF THE 0.946-μ LINE IN Nd^{3+}:YAG*

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The paper reports oscillation and doubling of the 0.946-μ line in Nd^{3+}:YAG. Peak, Q-switched output powers of approximately 2 kW at 0.473 μ were obtained. The results of a calculation for optimum nonlinear coupling to an internal Q-switched laser are given.

The 1.06-μ line of Nd^{3+}:YAG has been shown to be a highly efficient source of both cw and Q-switched infrared radiation.[1,2] By frequency doubling in nonlinear crystals such as LiNbO$_3$ and Ba$_2$NaNb$_5$O$_{15}$, it has also been shown to be a potentially useful source of green (0.53 μ) radiation.[3] In this letter we report oscillation on the 0.946-μ line of the $^4F_{3/2} - {}^4I_{9/2}$ transition in Nd^{3+}:YAG, and also the doubling of this line to produce a Q-switched blue light source at 0.473 μ. Since the cross section of the 0.946-μ line is only about 1/14th as large as the 1.06-μ line, internal optimumly coupled second-harmonic generation is possible using KDP (KH$_2$PO$_4$). The lower cross section, and thus the lower gain at a given inversion, leads to longer pulse lengths than may be obtained with the 1.06-μ line at comparable peak power.

In Nd^{3+}:YAG the terminal state of the 0.946-μ line is 848 cm^{-1} above ground as compared to 380 cm^{-1} [4] for Nd^{3+} in glass or 471 cm^{-1} [5] for Nd^{3+} in CaWO$_3$. By measuring the relative spontaneous emission of the 0.946-μ line and the 1.06-μ line, its cross section was found to be $\sigma_{0.946} \approx 5.8 \times 10^{-20}$ cm^2.[6] To achieve a gain per unit length g requires an inversion $\Delta n = g/\sigma$. Assuming a ground-state dopant density of 6.0×10^{19} atoms/cm^3 (1.0% Nd), the lower level (848 cm^{-1}) has a room-temperature Boltzman population of about 1.0×10^{18} atoms/cm^3. The population inversion required for a gain of 6%/cm is therefore equal to the lower-state population at room temperature. At -40°C the lower-level population is reduced by $\frac{1}{3}$ and is of little consequence.

Figure 1 shows a schematic of the experimental arrangement. A 3-mm-diam by 75-mm-long Nd^{3+}:YAG rod is supported in a quartz cooling jacket which is mounted at the joint focus of a double elliptical cylinder pump cavity. The laser is pumped by two 3-in. xenon flash lamps placed at the other foci. Cooling is provided by a continuous stream of nitrogen gas which is bubbled through a Dewar of liquid nitrogen. The optical cavity employs a dispersive quartz Littrow prism at one end.

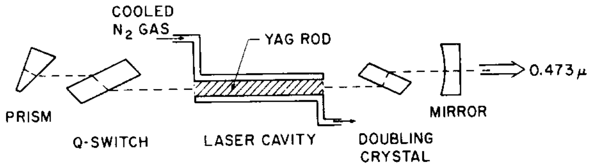

Fig. 1. Experimental arrangement for internal Q-switched second-harmonic generation of 0.946 μ. The Littrow prism and mirror are highly transmitting at 1.06 and 0.473 μ and highly reflecting at 0.946 μ. The laser is cooled by nitrogen gas bubbled through liquid nitrogen.

The dielectric coatings on the Littrow and the 3-m output mirror are very highly transmitting at 1.06 and 0.473 μ (89 and 70%, respectively) and very highly reflecting at 0.946 μ.[7]

Figure 2 shows measured threshold as a function of rod temperature for both the 0.946- and the 1.06-μ lines. The measured threshold is the elec-

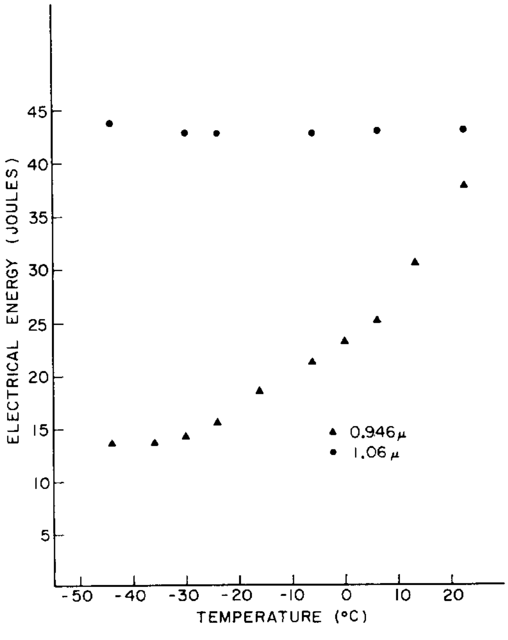

Fig. 2. Electrical threshold energy versus temperature for the 0.946- and the 1.06-μ lines.

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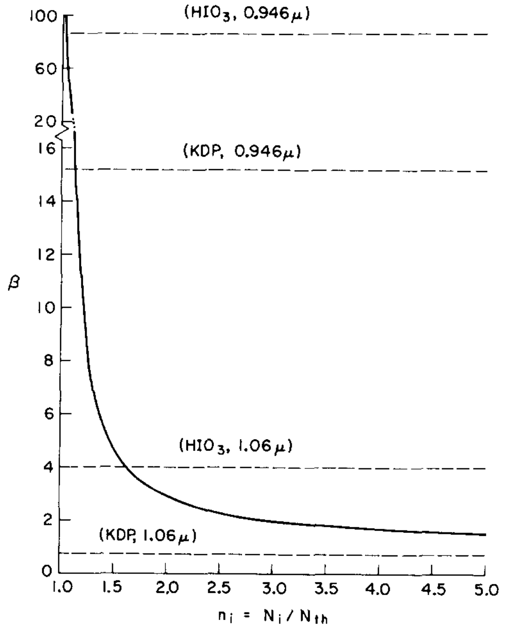

Fig. 3. Optimum second-harmonic coupling ratio β versus initial inversion for an internal Q-switched laser. $\beta = 1/t_1$ (SHG conversion efficiency/watt)/(gain/stored energy).

trical energy stored in the capacitor bank prior to firing. Rod temperature was measured by placing a thermocouple in contact with the laser rod at the cooling gas exhaust end. The threshold of the 1.06-μ line is a measure of the success of the Littrow prism and coatings. At any temperature, the maximum number of times above threshold which the 0.946-μ line may be operated is limited by the exponential gain occuring at the 1.06-μ line.

Light at 0.473 μ was generated in a 17-mm-long KDP crystal placed inside the laser optical cavity. The laser was Q-switched with a quartz acousto-optic switch, having a maximum 60% single-pass hold-off loss, measured at 6328 Å, and an opening time of about 1 μsec. Peak blue output powers of about 2 kW with a pulse length of about 0.18 μsec were obtained.

The results of a calculation of the internal second-harmonic conversion required to maximize the peak-generated second-harmonic power of a Q-switched laser is shown in Fig. 3. The coupling parameter β is plotted as a function of the initial inversion (the inversion at the moment the cavity is switched). This initial inversion is normalized to the threshold inversion of the cavity with the Q-switch open. It may be shown that

$$\beta = \frac{\xi}{\Gamma}\,\frac{1}{t_1},$$

where ξ is the single-pass second-harmonic conversion efficiency per incident fundamental power ($\xi = P_{sh}/P_F^2$), Γ is the laser gain per stored energy in the rod, and t_1 is the one-way cavity transit time. For example, in the case of small second-harmonic conversions, the absence of walk-off, and parallel Gaussian beams of area πW_0^2, $\xi = 2\eta^3\omega_1^2 d^2 l^2/\pi W_0^2$, where η is the wave impedance (η = 377/refractive index), d is the effective crystal nonlinearity, ω_1 is the fundamental frequency, and l is the crystal length. Also for a laser line of cross section σ with a uniform mode area A in the rod, then $\Gamma = \sigma/\hbar\omega_1 A$, where $\hbar$ is Plank's constant. With the above normalization the curve is valid for any combination of nonlinear material and laser line. It is seen that for lower cross-section lines, less crystal nonlinearity is required for optimum coupling.

The conversion efficiency obtainable with a nonlinear crystal is determined by its nonlinearity, and also by the walk-off angle ρ.[8] If the laser is focused to a beam radius of $w_0 = \sqrt{2}\,\rho l$, then walk-off will be of negligible consequence, and the conversion efficiency obtainable for a given nonlinear crystal becomes independent of crystal length. Based on this choice of spot size and a cavity length of 50 cm, the dotted lines of Fig. 3 show β for the four possible combinations of KDP and HIO_3 with the 0.946- and 1.06-μ lines. To the extent that β is greater than optimum it may be reduced by enlarging the spot size in the nonlinear crystal. β's greater than optimum lead to pulse-length expansion which will be reported on subsequently.

The 0.946-μ line is of interest as a result of good photodetectors available at this wavelength; and also when doubled as the first high-power (Q-switchable) line in the blue region of the spectrum. As a pump for $LiNbO_3$ optical parametric oscillators it allows tuning over the region 0.54–0.61 μ.

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