Appl. Phys. B 53, 6–10 (1991)

Applied Physics B Photo-physics and Laser Chemistry

A Flashlamp-Pumped 946 nm Nd:YAG Laser

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Received 15 April 1991/Accepted 15 May 1991

Abstract. Generation of 946 nm radiation from a commercially available, flashlamp-pumped Nd:YAG laser was investigated. By suppression of the high-gain 1.064 μm transition and with a specially designed cooling system, a stable emission at 946 nm was achieved in the temperature range 300–240 K. At a repetition rate of 10 Hz laser output powers of 100 mW and 500 mW were obtained at room temperature and 240 K respectively. The temperature dependence of unsaturated gain, slope efficiency and pumping threshold were determined.

PACS: 42.55.N, 42.60.By

There has been a constant interest in solid-state lasers, especially Nd:YAG lasers, with emission in a spectral region of 0.9–1.83 μm. To achieve lasing in this region, besides at 1.064 μm, is interesting for many applications but necessitates high-quality Nd:YAG crystals as well as efficient pump sources. Nowadays a lot of effort is being directed into the development of highly efficient diode-pumped Nd:YAG lasers and into the improvement of the output spectral characteristics such as linewidth and frequency stability [1]. Most work, however, deals with the generation of the high-gain 1.064 μm line. In recent years there has been an increasing amount of interest in the generation of radiation at 946 nm belonging to the $4F_{3/2} \rightarrow 4I_{9/2}$ transition [2–5]. Owing to the difficulties related to the smaller probability of that transition and the thermal population of the lower laser level, it is hard to compete with lasing at 1.064 μm. However, the generation of 946 nm radiation is very attractive because of the possibility to create a solid-state coherent light source for the blue region, reached by frequency doubling of the fundamental wave. The new nonlinear crystal $KNbO_3$ makes this goal realizable. There has already been successful work in developing diode-pumped cw 946 nm lasers at room temperature and efficient second harmonic generation [6, 7]. In these experiments a laser power of the order of 10 mW was obtained. A theoretical model of a longitudinally end-pumped 946 nm Nd:YAG laser accounting for the influence of the population of the lower laser level and the effect of the overlap of pump and laser field has been developed [3, 4]. There are also a few reports relating to pulsed 946 nm Nd:YAG lasers, but without a detailed study of their features [8–10].

In this paper we describe a 946 nm flashlamp-pumped Nd:YAG laser and provide a theoretical model of the main laser parameters for the flashlamp-pumping condition. By cooling the laser head and using selective optical resonators, a stable 946 nm generation in the temperature range 300–240 K is obtained. The simultaneous generation of laser radiation for both wavelengths 946 nm and 1.064 μm has also been observed. The temperature behaviour of different laser parameters has been evaluated.

1. Theory

In order to model the flashlamp-pumped 946 nm Nd:YAG laser we apply the approach used by Koechner [11] and Svelto [12] for 3- and 4-level laser systems and use rate equations (see [3]). In these equations the population of the lower laser level at thermal equilibrium is accounted for by introducing fractional population coefficients $f_{a,b}$ for the two laser levels ($N_2 = f_b N_u$ and $N_1 = f_a N_0$, where N_u and N_0 are the populations of the upper and lower manifolds, and N_2 and N_1 the populations of the upper and lower laser levels) (Fig. 1). Although Fan and Byer [3] called the model describing the laser with reabsorption losses a quasi-three level laser model it is

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** S. Dimov is supported by a fellowship from the Alexander von Humboldt Foundation

closer to a four-level laser system. This is also connected to the next assumption that there is no depletion of the ground state population, i.e. $N_u \ll N_0$ and $N_0 \approx N_g$ (N_g is the total dopant concentration of Nd^+-ions), which is valid for the condition $f_a \ll f_b$ [3]. With these assumptions the rate equation describing the population inversion $N = N_2 - N_1$ is:

$$\frac{dN}{dt} = (f_a + f_b) W_p N_g - (f_a + f_b) N c \sigma \phi - \frac{N - N^0}{\tau}, \quad (1)$$

where σ is the transition cross-section for $\lambda = 0.946\,\mu m$, $c = \frac{c_0}{n}$ is the speed of light in the medium, ϕ is the photon density in the resonator, $N^0 = N_2^0 - N_1^0$ is the equilibrium population difference between the two laser levels, τ is the overall lifetime of the upper laser level and W_p is the pump rate.

The rate of change of the photon density ϕ within the laser resonator is given by

$$\frac{d\phi}{dt} = c\phi\sigma N - \frac{\phi}{\tau_c}, \quad (2)$$

where $\tau_c = \frac{L'}{\gamma c_0}$ is the decay time of the photons in the resonator, L' being the effective resonator length and $\gamma = \frac{\delta + \gamma_1 + \gamma_2}{2}$ the total losses per pass in the resonator, c_0 the speed of light in vacuum, δ internal cavity losses and $\gamma_{1,2} = -\ln R_{1,2}$ where R_1 and R_2 are the reflectivities of the mirrors of the laser cavity.

The critical pump rate to reach the generation threshold under steady-state conditions $\frac{dN}{dt} = 0$, $\phi = 0$ is:

$$W_{cp} = \frac{N - N^0}{N_g \tau} \frac{1}{f_a + f_b}.$$

Our aim has been to obtain simple formulas describing the laser threshold, gain in the crystal and other laser parameters under flashlamp-pumping conditions allowing us to estimate these parameters also for other temperatures. Above threshold ($\phi > 0$) under steady-state conditions $\left(\frac{dN}{dt} = 0\right)$ the population inversion is given by:

$$N = \frac{(f_a + f_b) W_p N_g \tau + N^0}{1 + (f_a + f_b) c \sigma \phi \tau}.$$

By setting $\phi = 0$ we obtain a formula analogous to that derived in [3] for the unsaturated gain g_0 in the active medium:

$$g_0 = \sigma N_c = (f_a + f_b) W_p \tau N_g \sigma - \sigma f_a N_g.$$

In this case the unsaturated gain in the crystal depends strongly on the reabsorption losses due to the lower laser level population. Assuming the pump rate W_p to be proportional to the lamp input power P_{in} and substituting g_0 in the equation for the threshold condition:

$$2 g_0 l = (2\gamma_i + 2l\sigma f_a N_g) - \ln R_1 \quad (3)$$

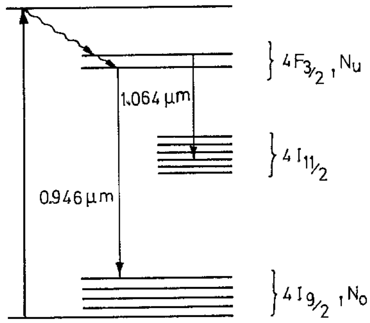

Fig. 1. Energy level diagram of the Nd:YAG laser

[12], we obtain at $P_{in} = P_{th}$:

$$-\ln R_1 = 2\theta P_{th} - (2\gamma_i + 2l\sigma f_a N_g)$$

$$P_{th} = \frac{\delta - \ln R_1}{2\theta}, \quad (4)$$

where $\delta = 2\gamma_i + 2l\sigma f_a N_g$ are the internal round-trip cavity losses, composed of losses due to reabsorption from the lower laser level and other contributions denoted as γ_i. The quantity $\theta = \frac{k}{I_s A (f_a + f_b)}$ is the effective pumping coefficient, $I_s = \frac{h\nu}{\sigma\tau} \frac{1}{(f_a + f_b)}$ the saturation intensity for the laser transition and k a pumping coefficient depending on system and materials parameters, l and A are the length and the cross-section of the active crystal. The threshold formula has the same form as for the four-level system but the material parameters enter differently. Measuring the pump threshold with different output mirrors the parameters θ, δ and correspondingly the unsaturated gain and losses at different temperatures can be estimated.

The slope efficiency is another important parameter describing laser output versus input above laser threshold. In [4] it was shown that the slope efficiency σ_s, which is proportional to the ratio $\frac{1 - R_1}{\delta}$ depends on the photon density in the cavity. The total internal round trip cavity losses $\delta = 2\gamma_i + 2\delta_s$ are composed of fixed cavity losses γ_i and saturable reabsorption losses δ_s. At intensities in the resonator far above saturation intensity I_s the population of the lower laser level does not influence the slope efficiency [4].

2. Experimental

The theoretical model describes the laser system under steady-state conditions, but it can also be applied to pulsed operation for sufficient long pump pulses [12]. The investigation was carried out with a system, based on the commercial pulsed DCR-1 Quanta Ray laser. Two linear Xe flashlamps are used to pump the Nd:YAG crystal with a diameter of 6.3 mm and length of 60 mm. The end faces are antireflection coated for 1.064 µm. The lamps and the active crystal are installed in a double elliptical gold plated pump cavity. The power supply allows pump energies up to 100 J at 25 Hz repetition rate and a 250 µs duration of the pump pulses.

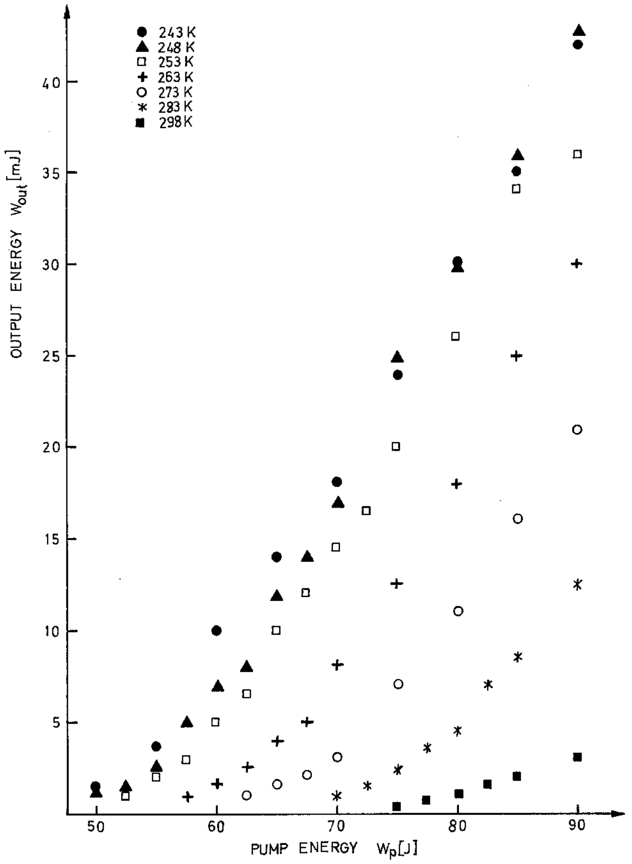

Fig. 2. Laser output energy from the 946 nm laser with a 96% output coupler versus electrical pump energy for different temperatures.

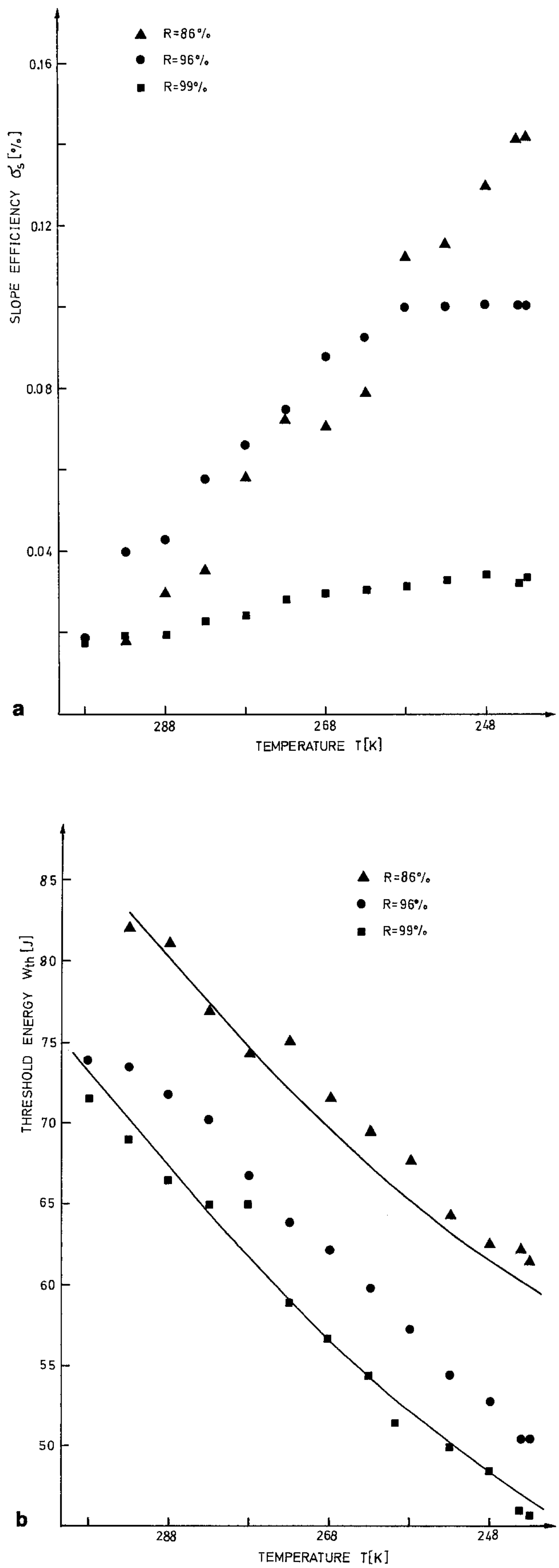

Fig. 3a, b. Temperature dependence of **a** slope efficiency and **b** generation threshold for different output mirrors. Solid line in **b** represents the calculated generation threshold

In order to achieve laser operation at 0.946 µm the following modification of the commercial laser system had to be made:

- A new optical resonator design. Two different types of resonators have been examined: A resonator with dichroic mirrors, ensuring high reflection for $\lambda = 0.946$ µm (spherical mirror with a radius of curvature 5 m and $R_2 = 99.9\%$, plane output mirror) and high transmission for $\lambda = 1.064$ µm ($R_{1,2} < 5\%$ for each mirror). The second one is a dispersive resonator with a Littrow prism as a back mirror, high-reflection coated for both wavelengths. The resonator length is 70 cm.
- The cooling system of the laser rod also had to be changed so that laser operation at temperatures down to 240 K was possible. A 50% ethylene glycol and water mixture is used as the coolant and is cooled down in an external heat exchanger operated with liquid nitrogen. Dry nitrogen gas is blown over the crystal faces to prevent icing.

A stable long-time 946 nm generation at room temperature was obtained with both optical resonators. An average output power of 100 mW at 10 Hz repetition rate was measured with the dichroic resonator. The less than 5% reflectivity of the mirrors for 1.064 µm is crucial to prevent oscillation at that wavelength when the high pumping powers required to reach threshold for 0.946 µm are used. A well-defined and stable TEM_{00} operation was achieved near the generation threshold. Laser emission could be tuned to either one of the two wavelengths at

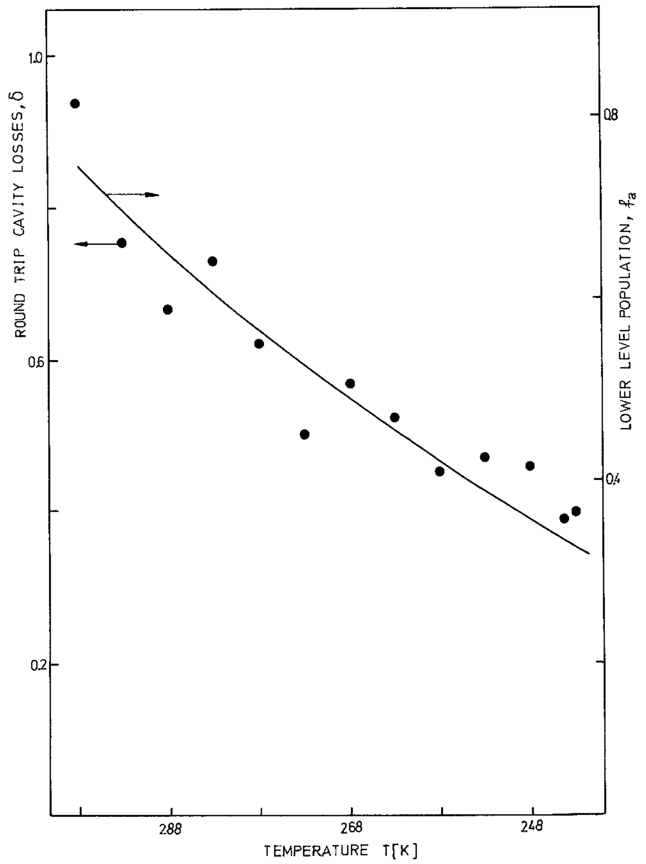

Fig. 4. Round-trip cavity losses as a function of the temperature of the active medium. The points show the experimental data. The solid line gives the lower laser level population f_a versus temperature

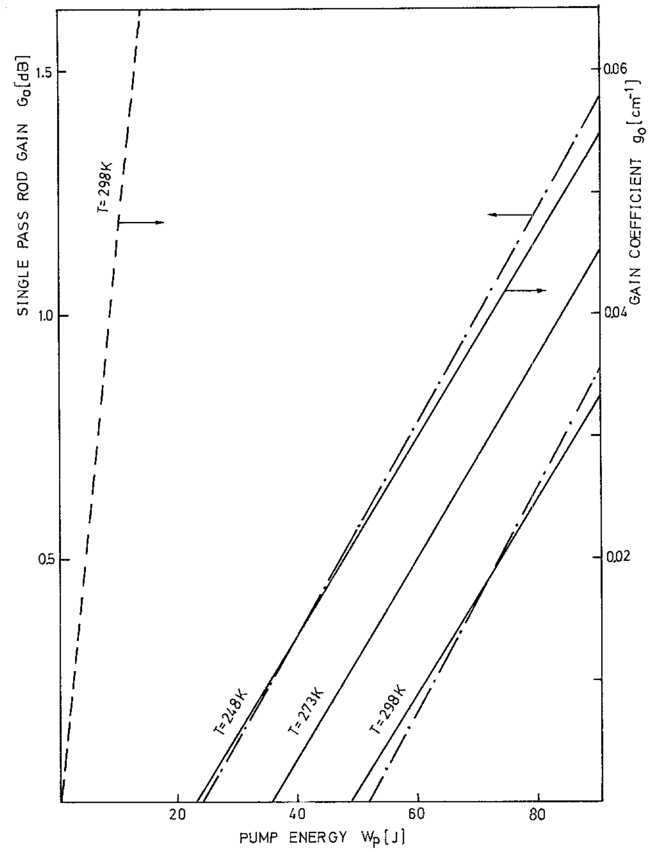

Fig. 5. Unsaturated gain coefficient g_0 in the Nd:YAG crystal for both the 1.064 μm and the 0.946 μm transitions as a function of the pump energy at different temperatures. The dashed and solid lines represent the unsaturated gain coefficient g_0 for 1.064 μm and 0.946 μm respectively. The dotted lines represent the calculated small signal, single pass gain G_0 for the 0.946 μm line for two temperatures

room temperature when the dispersive resonator was used.

The temperature dependence of the 946 nm laser output versus pump energy for different output couplers with reflectivities in the range 86%–99% was measured. A typical output power of 500 mW at 10 Hz repetition rate with an 86% output mirror at 240 K was obtained. An example of the experimental results is shown in Fig. 2. It can be seen that decreasing the crystal temperature leads to a strong increase of the output power.

The slope efficiency σ_s and the generation threshold W_{th} at different temperatures have been calculated by least square fits to the output-input characteristics. These values are shown in Fig. 3a, b respectively. Cooling of the active medium from room temperature to 240 K leads to an eightfold increase in slope efficiency.

The results in Fig. 2 and Fig. 3a reflect two different dependences of the slope efficiency. The first is its dependence on the light intensity in the resonator due to saturation of the reabsorption losses at constant temperature:

$$\sigma_s \approx \frac{1}{\delta_s\left(\frac{I}{I_s}\right)_{T_{const}}},$$

and the second is its dependence on the temperature determined reabsorption losses:

$$\sigma_s \approx \frac{1}{\delta_s(T)}.$$

At lower temperatures the effect of saturation of the slope efficiency at higher pump levels is obvious (Fig. 2). It can be seen from Fig. 3a that with a decrease of the crystal temperature the slope efficiency grows due to the decrease of the thermal population of the lower laser level. Due to the decreased generation threshold (Fig. 3b) and increased light intensity in the cavity, the saturable part of σ_s starts to saturate when the temperature is decreased. With decreasing output coupling the saturation starts earlier. At the same time with decreasing temperature the generation threshold decreases continuously (Fig. 3b). Only with the 86% output mirror has no saturation of the slope efficiency been observed in the pumping range of the power supply, due to the high output losses.

According to (4) it is possible to derive the temperature dependence of the internal losses δ and the pumping coefficient θ from the measured threshold values versus output losses. The estimations have been obtained by least squares fits. Both the measured and the predicted temperature dependences of the internal cavity losses are shown in Fig. 4.

A comparison between the gain in the active medium for the 0.946 μm and the 1.064 μm laser transitions has also been made. The calculated small-signal, single pass gain G_0 and unsaturated gain g_0 at different temperatures are plotted in Fig. 5. Despite the rapid growth of the 946 nm gain at lower temperatures, it still remains rather small because of the smaller cross-section of the transition and the residual lower level population. In the calculation of the gain the small temperature changes of the pumping coefficient and the transition cross-section for the two wavelengths [13] have been ignored. The following values of the basic parameters have been assumed: total dopant concentration $N_g = 1.4 \times 10^{-20}\,\mathrm{cm}^{-3}$ [11], stimulated emission cross-section $4 \times 10^{-20}\,\mathrm{cm}^2$ and $3.5 \times 10^{-19}\,\mathrm{cm}^2$ [14] for 0.946 μm and 1.064 μm transitions respectively. The necessary data for the calculation of the $f_{a,b}$ coefficients have been taken from [14].

3. Conclusion

The temperature behavior of a 946 nm flashlamp-pumped Nd:YAG laser has been studied. An output power of 500 mW at 10 Hz repetition rate and 0.15% overall slope efficiency at 240 K were obtained.

From the theoretical analysis it can be seen that including the thermal population of the lower laser level (with the assumption of negligible depletion of the ground state manifold $N_u \ll N_0$) does not change dramatically the mathematical description of the flashlamp-pumped quasi three-level system in comparison to the four-level system. This population merely leads to additional reabsorption losses in the resonator and the necessity of increasing the pump power in order to reach the threshold. The system behaves more like a four-level than a three-level system, where a depletion of the ground state must be assumed.

In order to improve the output laser parameters, cooling to ≈255 K is advisable. Cooling to temperatures lower than 255 K is not necessary, because the population of the lower laser level will not change much more [9]. A pulsed mode of operation under these conditions ensures easier saturation of the slope efficiency.

We should mention that the values obtained for the laser output parameters can be considerably improved with a better optimised laser system. This improvement involves an optimisation of the pump cavity and the use of a laser crystal that is anti-reflection coated for 0.946 μm. In our case the standard 1.064 μm anti-reflection coated Nd:YAG crystal introduced 2% additional reflection losses for 946 nm. For example, the measured overall slope efficiency of the same laser system at 1.064 μm was only 0.86% for 22% output mirror transmission. Under similar conditions better optimised pulsed Nd:YAG laser systems have 2–3% slope efficiency for 1.064 μm [15].

Obviously the main problems with the pulsed, flash-pumped 946 nm Nd:YAG laser are the small pumping efficiency, resulting in heating of the laser crystal and problems concerning efficient cooling of the active medium. Pulsed mode, and especially Q-switched mode, leads to inversion population and gain in the active medium far above the threshold values. This ensures a bigger pulsed power and a better conversion efficiency for harmonic generation. On the other hand, due to the high gain, the suppression of the 1.064 μm is more difficult compared to cw lasers. Experimental work on a Q-modulation of the 946 nm Nd:YAG laser, amplification and frequency doubling of the fundamental wave is in progress.

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