Crystal Growth, Spectroscopy, and Laser Characteristics of Ti:Al2O3

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Abstract—The vertical-gradient-freeze technique has been used to grow laser-quality Ti:Al2O3 single crystals. Ti3+-Ti4+ pairs have been shown to be responsible for the residual infrared absorption. Room-temperature oscillator and amplifier experiments are reviewed.

I. INTRODUCTION

SINCE its first demonstration by Moulton in 1982 [1], the Ti:Al2O3 laser has been the subject of extensive investigation. Both pulsed and CW lasers have been operated at high efficiency over a tuning range in excess of 200 nm centered at 800 nm. Laser performance has been improved thanks to advances in crystal growth and post-growth annealing. This paper reviews recent work at Lincoln Laboratory on the crystal growth, spectroscopy, and laser characteristics of Ti:Al2O3.

Section II describes the vertical-gradient-freeze growth of single crystals up to 5 cm in diameter with low residual infrared absorption. Crystals have been grown with doping levels up to 0.15 wt. percent Ti2O3, corresponding to the Ti concentration [Ti] = 5 × 10^19 cm^-3, and values in excess of 100 have been obtained for the ratio of the peak Ti3+ absorption at 490 nm to the residual infrared absorption at 850 nm.

Spectroscopic results are presented in Section III. The absorption cross section for Ti3+ has been determined by correlating absorption and magnetization measurements. The dependence of residual infrared absorption on Ti3+ absorption has been determined for both as-grown and annealed samples. The results show that the residual infrared absorption in vertical-gradient-freeze crystals is due primarily to Ti3+-Ti4+ pairs.

II. CRYSTAL GROWTH

A variety of techniques, all employing growth from the melt, have been used to grow Ti:Al2O3 single crystals. Crystals grown by the Czochralski [2], [3] and heat-exchanger [4], [5] methods are available commercially, and growth by the thermal-imaging float-zone method has recently been reported [6]. A seeded vertical-gradient-freeze (VGF) method that yields laser-quality crystals with relatively low residual infrared absorption has been developed at Lincoln Laboratory.

The VGF procedure has been described in some detail previously [7], [8]. In brief, a capped but unsealed tungsten crucible containing the seed and growth charge is placed inside a furnace that has a water-cooled stainless-steel jacket, as shown schematically in Fig. 1. The furnace is resistance heated by means of a cylindrical tungsten-mesh element that is thermally insulated on the top and sides by multilayer molybdenum heat shields. By decreasing the number of side shields from top to bottom and cooling the crucible from the bottom by contact with the water-cooled base of the furnace, a vertical temperature gradient is imposed on the crucible. The furnace is heated under vacuum until the charge is melted, then backfilled with He, and gradually cooled to room temperature so that the charge solidifies from the bottom up.

Since laser action in Ti:Al2O3 is due to Ti3+ ions, Ti2O3 rather than the more readily available TiO2 has been utilized as the source of Ti in growth by the VGF method. In initial experiments, a mixture of sapphire crackle and single-crystal Ti2O3 pieces was used as the charge. When such a mixture is employed in later runs requiring larger amounts of Ti2O3, which melts about 200°C lower than Al2O3, the seed was attacked by molten Ti2O3 that formed during initial heating and ran down between the unmelted sapphire pieces. This problem has been solved by using charges prepared by placing the desired Ti2O3-Al2O3 mixture in a flat-bottomed molybdenum crucible, melting under vacuum in the growth furnace, and furnace cooling. The amount of the black multiphase coating that is formed on the Ti:Al2O3 crystals following solidification [8] is greatly reduced by employing the prereacted charges. Initially, VGF growth of Ti:Al2O3 was carried out in an Ar atmosphere, but the crystals generally contained numerous bubbles and other imperfections. The concen-
stration of such defects is drastically reduced by using a He atmosphere, both because the trapping of bubbles is decreased by the lower density of He and because constitutional supercooling is decreased by the higher thermal conductivity of He, which increases the vertical temperature gradient at the growth interface and reduces the linear rate of solidification at a given cooling rate. With a He atmosphere, the temperature gradient is about 15°C/cm and the growth rate is about 2 mm/h. Since the use of He increases the heat loss to the furnace walls by conduction, additional heat shielding has been incorporated to reduce the radiative losses and minimize power consumption.

Under the conditions used in growing Ti:Al2O3 crystals suitable for laser applications, most of the Ti is incorporated as Ti^{3+} ions, but a fraction may be present as Ti^{4+} ions. This fraction increases with increasing ambient O2 partial pressure. During VGF growth, the O2 partial pressure is extremely low because hot tungsten is a highly effective oxygen getter. Therefore, the fraction of Ti^{4+} ions in as-grown crystals is only a few percent. For this reason, as discussed below, values as high as 100 have been obtained for the ratio of the peak Ti^{3+} absorption coefficient αm to the peak residual infrared absorption coefficient αr. It is anticipated that even higher values of αm/αr could be obtained in as-grown crystals by using a mixture of H2 and He to reduce the O2 partial pressure and therefore the fraction of Ti^{4+} ions.

Single crystals of Ti:Al2O3 up to 5 cm in diameter with excellent optical quality have been grown by the VGF method. During several runs, a single temperature excursion produced a temporary increase in solidification rate that caused the formation of bubbles and inclusions as well as a transient increase in the incorporation of Ti^{3+}. The resulting decoration of the solid–liquid interface, as shown previously for a 2.5 cm diameter crystal [8], reveals that the interface is flat over most of the crystal diameter and curves downward close to the periphery. This shape is very advantageous for single-crystal growth since it prevents the propagation of crystallites that may be nucleated at the walls of the crucible. The flat portion of the interface extends even closer to the periphery for 5 cm diameter crystals than for 2.5 cm diameter crystals.

The concentration of Ti^{3+} ions in Al2O3 crystals grown by the VGF method increases with distance from the seed because the distribution coefficient k, the ratio at the solid–liquid interface of the concentration in the solid to the concentration in the liquid, is less than one for Ti^{3+}. Since αm is proportional to the Ti^{3+} concentration [9], k has been evaluated by determining the dependence of αm on the fraction of the charge frozen [8]. The value of k obtained from this dependence is 0.21, while values of 0.079 and 0.087 have been found by taking the ratio of the first-to-freeze concentration to the concentration determined from the weights of Ti2O3 and Al2O3 in the charge. It seems likely that the lower values more closely approximate the equilibrium distribution coefficient, while the higher value is an effective coefficient obtained because growth at a finite rate results in the formation of a liquid boundary layer with higher Ti^{3+} concentration than the bulk of the melt.

Since the Ti^{3+} concentration in Ti:Al2O3 crystals grown by the VGF method varies with distance from the seed, laser rods should be cut perpendicular to the growth axis in order to minimize the variation in concentration along their lengths. As discussed below, optimum performance of Ti:Al2O3 lasers is obtained for light propagation perpendicular to the c axis. Therefore, the VGF crystals have been grown with their growth axis parallel to the c axis. Because of the flatness of the growth interface, the maximum length of laser rods with uniform Ti^{3+} concentration is almost equal to the crystal diameter.

The highest value of αm that has been measured for samples with good optical quality from VGF Ti:Al2O3 crystals is 5 cm⁻¹. From the relationship between αm and Ti^{3+} concentration that has been determined by magnetization measurements [9], this value corresponds to a Ti2O3 concentration of 0.15 wt. percent. In principle, much higher concentrations are possible since the maximum solubility of Ti2O3 in Al2O3 is 4.1 wt. percent [8]. The upper limit on the Ti^{3+} concentration that is compatible with good optical quality is probably set by the onset of constitutional supercooling during solidification. Therefore, there is a good possibility of increasing this upper limit by increasing the temperature gradient at the solid–liquid interface and reducing the rate of solidification since these changes increase the dopant concentration that can be present in the liquid without producing constitutional supercooling.

III. SPECTROSCOPY

Triply charged titanium Ti^{3+} ions substitute for octahedrally coordinated Al^{3+} ions in Al2O3 at sites with trigonal symmetry. The spectroscopic characteristics of Ti:Al2O3 are largely determined by the single 3d electron outside the closed argon core of the Ti^{3+} ions.

![Schematic diagram of apparatus for vertical-gradient-freeze-growth of Ti:Al2O3 crystals.](image-url)
Crystals of undoped Al₂O₃ are very transparent in the near infrared (IR) and visible regions from approximately 2000 nm in the IR to 400 nm on the short-wavelength side of the visible. In the ultraviolet (UV) region between 400 and 200 nm, absorption increases towards shorter wavelengths, arising from the long-wavelength tail of the band edge occurring below 200 nm.

Crystals of Al₂O₃ doped with Ti³⁺ are pink. The pink color is caused by a broad double-humped absorption band extending from approximately 400 to 600 nm in the blue-green region of the visible spectrum. This band, which peaks at approximately 490 nm, is due to phonon-assisted excitation of the 3d electron of the Ti³⁺ ions [10]. Absorption bands with peaks at 266, 216, and 185 nm are observed in the UV region [11]. The origin of these bands is not as well established.

Optical pumping in the blue-green absorption band produces a broad fluorescence band that extends from approximately 600 to 1050 nm and peaks at approximately 750 nm in the IR. Moulton [11] achieved laser action in this fluorescence band and demonstrated tuning of the laser emission from 660 to 990 nm.

A relatively weak absorption band is observed in the IR region from approximately 650 to 1600 nm. This absorption, which we refer to as the residual IR absorption, has been shown to be due to Ti³⁺–Ti⁴⁺ pairs [12].

A. Blue-Green Absorption Band

Fig. 2 shows the blue-green absorption spectra for a typical as-grown VGF sample of Ti:Al₂O₃ observed with light polarized either parallel to the c axis (π polarization) or perpendicular to the c axis (σ polarization). The double-humped absorption for either polarization is due to phonon-assisted transitions from the 7²T₂ ground state to the Jahn–Teller split 3²E₉(E₉/2) and 3²E₅(E₅/2) excited states of Ti³⁺ ions. In the region between 400 and 630 nm, the absorption is stronger for the π polarization than for the σ polarization. At the peak of the blue-green band, the ratio of the absorption coefficients for the π and σ polarizations is 2.3. Since this absorption band is used for optical pumping into the upper lasing levels, optimum performance for Ti:Al₂O₃ lasers is obtained in the π polarization, requiring light propagation perpendicular to the c axis in the laser rods.

The absorption cross section at the peak of the blue-green absorption band for the π polarization has been determined [9] by combining the measurements of optical absorption and the concentration [Ti³⁺] of Ti³⁺ ions for the same specimen. The concentration was obtained by measuring the magnetization arising from the magnetic moment of the 3d electron of the Ti³⁺ ion. Fig. 3 shows a plot of the absorption coefficient αₚ at 490 nm in the π polarization as a function of [Ti³⁺] for a number of as-grown VGF samples. Fit of the data to a straight line through the origin yields a value for the absorption cross section αₚ = (9.5 ± 1.0) x 10⁻²⁰ cm².

B. Residual IR Absorption

Fig. 4 shows the residual IR absorption spectra for the π and σ polarizations for the as-grown VGF sample of Fig. 2. The absorption is stronger for the π polarization than for the σ polarization. Thus, the polarization anisotropy for the residual IR absorption is opposite to that for the blue-green absorption. We ascribe this residual IR absorption to the Ti³⁺–Ti⁴⁺ pairs. Consequently, the residual absorption coefficient αᵣ is proportional to the concentration of these pairs, and therefore to the product [Ti³⁺][Ti⁴⁺]. Assuming that Ti is present only as Ti³⁺ or Ti⁴⁺, [Ti³⁺] = [Ti¹⁻]–[Ti³⁺]. Since αᵣ is proportional to [Ti³⁺],

\[ αᵣ = C(α₀ - αₚ) \]

where C is a constant and α₀ is the value of αₚ when all the Ti ions are in the Ti³⁺ state. Equation (2) may be written in the form

\[ αᵣ = C \frac{1 - β}{β} αₚ \]

where

\[ β = \frac{αₚ}{α₀} = \frac{[Ti³⁺]}{[Ti]} \]
Measurements of the blue-green absorption and the residual IR absorption for a number of as-grown VGF samples show that \( \alpha_r \) is proportional to \( \alpha_m \). This dependence is illustrated in Fig. 5, which is a plot of \( \alpha_r \) at 850 nm versus \( \alpha_m \) at 490 nm, both for the \( \pi \) polarization. The observed variation of \( \alpha_r \) with \( \alpha_m \) is then consistent with the predictions of the Ti\(^{3+}\)-Ti\(^{4+}\) pair model, provided \( \beta \) is the same for all the as-grown samples.

The Ti\(^{3+}\)-Ti\(^{4+}\) pair model has been confirmed by measuring the variation of \( \alpha_r \) with \( \alpha_m \) in a partially oxidized sample, which provides a spatial gradient in \( \beta \) but a constant value of the [Ti]. Values of \( \alpha_r \) and \( \alpha_m \) were measured at a number of locations lying along the direction exhibiting the gradient in \( \beta \). The observed dependence of \( \alpha_r \) on \( \alpha_m \) is shown in Fig. 6. The data points fit the parabolic curve given by (1), with \( C = 0.284 \) and \( \alpha_0 \) = 3.14. Using this value of \( C \) along with the measured values of \( \alpha_r \) and \( \alpha_m \) in Fig. 5, we obtain \( \beta = 0.97 \) for the as-grown VGF samples. This value implies that 97 percent of the Ti ions are in the Ti\(^{3+}\) state and the remaining 3 percent are in the Ti\(^{4+}\) charge state.

Measurements of \( \alpha_r \) and \( \alpha_m \) have also been made for a number of as-grown samples from a lightly doped Ti:Al\(_2\)O\(_3\) crystal grown by the heat-exchanger method (HEM). The values of \( \alpha_m \) at 490 nm for these samples range from \( -0.4 \) to 1.0 cm\(^{-1}\), and \( \alpha_r \) increases linearly with \( \alpha_m \) from \( -0.0025 \) to 0.0065 cm\(^{-1}\). These results imply that the residual IR absorption due to the Ti\(^{3+}\)-Ti\(^{4+}\) pairs is negligible in the HEM samples, indicating that 1) \( \beta \approx 1 \), and 2) a different mechanism, as yet not understood, is responsible for the relatively small residual absorption in these samples.

Annealing of the as-grown VGF samples in a reducing atmosphere results in the conversion of Ti\(^{4+}\) ions into Ti\(^{3+}\) ions. Consequently, the residual IR absorption decreases appreciably. After annealing, the ratio \( \xi = \alpha_r / \alpha_m \) (850 nm)/\( \alpha_m \) (490 nm) is typically about \( 1 \times 10^{-2} \).

IV. OSCILLATOR AND AMPLIFIER STUDIES

Laser rods cut from Ti:Al\(_2\)O\(_3\) crystals grown by the VGF method were used in oscillator and amplifier experiments. Both CW and pulsed oscillators have demonstrated high efficiency and wide tuning range at room temperature. Stable single-frequency operation and fast electrooptic tuning have been demonstrated in the CW case. In the amplifier experiments, double-pass gain as high as \( 10^4 \) has been measured.

A. CW OSCILLATORS

1) Efficiency: The pump source for the CW oscillator experiments was an Ar-ion laser operating in all the blue-green lines. The Ti:Al\(_2\)O\(_3\) laser rod, supported by a water-cooled heat sink, was placed at the waist of an astigmatically compensated three-mirror cavity. For a Brewster-cut rod with a length of 1.8 cm and a doping level of 0.024 wt. percent Ti\(_2\)O\(_3\), corresponding to [Ti] = \( 8 \times 10^{18} \) cm\(^{-3}\), the maximum laser output power was 1.6 W for an incident power of 12 W [13]. Two other Brewster rods and three normally cut rods with antireflection coat-
ings, all with different Ti$^{3+}$ concentrations, were investigated in detail [14]. For each rod, the output was measured as a function of incident pump power. The measured slope power efficiency $\eta_s$ is related to the transmittance $T$ of the coupling mirror by

$$\eta_s = \eta_iX A \left[ \frac{T}{T+L} \right]$$

where $\eta_i$ is the internal quantum efficiency, the pump to laser wavelength ratio $\chi \equiv \lambda_p / \lambda$, $A$ is the fraction of the incident pump power absorbed, and $(T + L)$ is the total cavity loss. From the slope efficiencies measured for different couplers, $\eta_i$ and $L$ were determined for each rod.

The experimental results show that $L$ is equal to the residual IR absorption of the laser rods, as measured with a spectrophotometer. The internal quantum efficiency was generally between 55 and 75 percent, compared to 85 percent measured for Ti:Al$_2$O$_3$ pulsed oscillators [11]. The difference between the two cases is that the degree of overlap between the pump and laser beams is smaller in the CW oscillators, which have a filament-like active region, than in pulsed oscillators, which have a larger beam cross section. This explanation is supported by the following experimental results. With the experimental setup of Fig. 7, the fluorescence from the laser active region is observed by a detector in the direction perpendicular to the laser rod. In Fig. 8, the measured fluorescence, which is proportional to the population inversion in the laser rod, is plotted versus the incident pump power for three different situations. When lasing is prevented by using an absorber to spoil the cavity, the fluorescence is proportional to the pump power. The fluorescence at maximum pump power is given by point $A$. When the absorber is removed, lasing occurs and the fluorescence at the maximum pump power is reduced to the value given by point $B$; however, this value is still higher than the fluorescence at threshold (point $C$), showing that the population inversion is not entirely clamped at the threshold value. Fig. 9 shows the fluorescence profile across the waist of the pump beam for the same three situations; the population inversion is, in fact, clamped at the threshold value at the center of the laser beam, but not in the wings. Geometrical considerations may account for the inversion "not used" by the laser.

We note that the nonradiative component of the recombination process [11], [15] does not cause a reduction in $\eta_i$, although this component is responsible for the increase of the laser threshold with temperature [14]; once threshold is reached, the population inversion and nonradiative recombination are clamped in such a way that the absorption of each additional photon results in the emission of a stimulated photon.

2) Tuning Characteristics: Tuning studies were made using a Brewster-cut laser rod located at the waist of a standing-wave three-mirror cavity. Tuning was accomplished with a three-plate intracavity Lyot filter. No attempt was made to optimize the laser output power; less than 1 percent of the power circulating in the cavity was sampled by a near-Brewster intracavity plate. When an intracavity prism was added to prevent branch jumping of the Lyot filter, laser emission was obtained from 693 to 948 nm [13], a range limited by the bandwidth of the cavity mirrors. The threshold at the limits of the tuning range (9.5 W) was five times larger than the value at the center (1.9 W). For the reported dependence of emission cross section on wavelength [11], [16], spectrally flat mirrors should have yielded a tuning range from 670 to 1020 nm in this case. An attempt to extend the tuning range to longer wavelengths by using a set of cavity mirrors centered at 850 nm was unsuccessful. At the higher pumping levels, it appears that thermally induced wavefront distortions [17] increase the cavity internal losses and raise the laser threshold.
In another series of experiments [18], single-frequency operation of a Ti:Al₂O₃ laser was achieved by using a ring cavity configuration that included the Lyot filter and a 0.5 mm thick etalon. Tuning between 750 and 850 nm with a maximum output power of 500 mW was demonstrated [17] with 9 W of Ar-ion pump laser power incident on the laser rod. The additional loss introduced by the intracavity dispersive elements causes an increase in the threshold, a decrease in the efficiency, and a reduction in the tuning range. These effects are not as important for pulsed oscillators. For the latter, because the average thermal load is relatively low, high gain may be achieved in the wings of the emission spectral profile [19] with negligible thermal effects.

Fast electrooptic tuning of the CW Ti:Al₂O₃ laser has been accomplished by using intracavity LiNbO₃ birefringent filters with an applied transverse electric field [20]. In order to preserve a wide tuning range, it is necessary to minimize the insertion loss introduced by the intracavity filters.

3) Design Considerations: High efficiency and low threshold are obvious goals in designing a Ti:Al₂O₃ laser. In addition, in order to tune over the wings of the gain profile, it must be possible to operate at pumping levels several times the gain-center threshold without thermal distortion.

A theory developed for longitudinally pumped lasers in a standing-wave cavity [21], when modified for a ring cavity, predicts a threshold pump power

$$P_{th} = \frac{\pi}{2} \left(1 + a^2\right) w_o^2 \left(T + L_i + \xi x\right)\left(\frac{\Lambda_1}{\lambda}\right) f_a \left(\frac{1}{\alpha_m}\right)$$

(5)

where $a = w_o / w$, with $w_p$ and $w$ being the radii of the pump and laser beams, respectively; the saturation intensity $I_s = (hc)/(\lambda \sigma_{\text{eff}})$ = 2.6 $\times$ 10⁵ W/cm² for $\lambda$ = 780 nm, $\sigma_{\text{eff}} = 3.0 \times 10^{-17}$ cm²; and $\tau_l = 3.15$ μs; $L_i$ is the insertion loss of intracavity optics; the normalized rod length $x = \alpha_m d$, with $\alpha_m$ and $d$ being the absorption coefficient for pump radiation and the laser rod length, respectively; and $A = 1 - \exp(-\chi)$. The laser threshold is minimized by choosing a cavity mode with a small beam radius $w$ in the gain medium and pumping only within that mode. However, as $w$ is decreased to the point that the confocal parameter $b = 2\pi w_o^2 / \lambda$ where $\lambda$ is the refractive index and $w_o$ is the beam waist radius approaches the length $d$ of the laser rod, the value of $w$ changes along the length of the rod to $(2)^{1/2} w_0$ at either end of the rod. Further decrease of $w_0$ by tighter focusing of the pump and laser beams does not result in a significant decrease in the threshold, as predicted by (5), because the resulting high inversion and gain are no longer available over the entire crystal length. Assuming focusing of the pump and laser beams so that an effective beam cross-sectional area

$$\pi w^2 = \lambda d / n$$

(6)

can be entered in (5), the threshold pump power is given by

$$P_{th} = \frac{\pi}{2} \left(1 + a^2\right) w^2 \left(T + L_i + \xi x\right)\left(\frac{\Lambda_1}{\lambda}\right) f_a \left(\frac{1}{\alpha_m}\right)$$

(7)

where $f_o = (1 + a^2) / (2n)$ is a geometrical factor on the order of unity. The slope efficiency given by (4) is also a function of the normalized length and can be rewritten in the form

$$\eta_s = \chi A \left(\frac{T}{T + L_i + \xi x}\right) f_i$$

(8)

by setting $\eta_i = 1$ and introducing a geometrical coupling factor $f_i$, different from $f_o$, that approaches unity [21].

High efficiency requires: 1) a long rod ($x > 1$) to achieve high absorption of the pump power ($A \approx 1$), and 2) high output coupling ($T > L_i + \xi x$). Fig. 10 shows plots of $\eta_s$ versus $x$ for different values of $T$, assuming $L_i = 0$, $f_i = 1$, and $\xi = 0.01$ for annealed Ti:Al₂O₃ crystals regardless of doping level. For each value of $T$, there is an optimum value of $x$ that maximizes the slope efficiency, and the optimum value of $x$ is larger for larger $T$. For $T = 15$ percent, the maximum efficiency is 50 percent, which is close to the limiting value $\chi = 62$ percent. In contrast, for $T = 1$ percent, the maximum efficiency is only 20 percent due to the effect of residual absorption. Imposing the condition of maximum efficiency, the threshold given by (7) can only be reduced by increasing $\alpha_m$, i.e., increasing Ti concentration. Fig. 11 is a plot of $P_{th}(\alpha_m)$ versus $x$ for the same values of $T$ as in Fig. 10, assuming $f_o = 1$, $L_i = 0$, and $\xi = 0.01$. We note that $P_{th}(\alpha_m)$ at the optimum values of $x$, shown by arrows in Fig. 11, increases with $T$. A comparison of Figs. 10 and 11 illustrates the tradeoff between increased efficiency and higher threshold for values of $x$ less than the optimum value $x_0$. However, for $x > x_0$, the efficiency decreases while the threshold increases.

As noted above, the operation of CW Ti:Al₂O₃ lasers at high power levels is influenced by thermal distortions due to the pump laser beam. Such distortions make the characteristics of the cavity modes dependent on pump power level. A simple argument, which is supported by the experimental results [17], shows that thermal focusing can compensate for the diffraction spreading of the beam with resulting beam trapping. Trapping develops when the average heat generated per unit length in the pumped filament is

$$H_T = X_T \left(\lambda / w^2\right)^2$$

(9)

where $X_T = 2K / \pi n (dn / dT)$, $K$ being the thermal conductivity. Taking $K = 0.35$ (W·cm⁻¹)°C⁻¹, $n = 1.76$, and $dn / dT = 1.4 \times 10^{-5}$ °C⁻¹, we obtain $X_T = 9.0 \times 10^4$ W·cm⁻¹ for Ti:Al₂O₃. Stable operation with power-independent cavity parameters is expected when the heat load is much lower than $H_T$. With the lasing threshold given by (5), the average heat generated per unit length for an incident pump power of $s$ times threshold is approximately given by

$$H = sP_{th} A [1 - \chi] / d.$$

(10)
The value of \( s \) at \( HT \) is given by the critical excitation level

\[
s_T = \left( \frac{1}{1 - \chi} \right) \frac{\pi n_X e}{x(T + L_i + \frac{1}{x})} \alpha_m
\]

which for Ti:Al\(_2\)O\(_3\) becomes

\[
s_T = 0.31 \frac{\alpha_m (\text{cm}^{-1})}{x(T + L_i + \frac{1}{x})}. \tag{11}\]

Fig. 12 shows \( s_T/\alpha_m \) versus \( x \) for the same values of \( T \) as in Figs. 10 and 11, assuming \( L_i = 0 \) and \( \chi = 0.01 \). Note that in order to achieve stable operation at pump power levels many times above threshold, it is necessary to use a high value of \( \alpha_m \), a low value of \( T \), and a normalized rod length \( x \) as small as possible, with a corresponding loss in efficiency.

B. Pulsed Oscillator

Pulsed operation of a Ti:Al\(_2\)O\(_3\) laser with quantum efficiency of 85 percent was demonstrated by Moulton [11]. Rapoport and Khattak [16] and DeShazer et al. [22] have also obtained high quantum efficiencies with pulse energies up to 80 mJ in oscillators pumped by electrooptically \( Q \)-switched frequency-doubled Nd:YAG lasers. In each case, the pulse repetition frequency was 10 Hz, the same as the repetition frequency of the pump laser.

In recent experiments at Lincoln Laboratory [23], the pulse repetition frequency has been increased to 5 kHz. The pump source was a CW-pumped, acoustooptically \( Q \)-switched, frequency-doubled Nd:YAG laser with an output of 80 ns pulses at a 5 kHz repetition rate. A Brewster-cut Ti:Al\(_2\)O\(_3\) laser rod was placed at the waist of a three-mirror, astigmatically compensated, folded cavity similar to the one used in the CW experiments except that the transmittance of the coupling mirror was 15 percent. The output of the Ti:Al\(_2\)O\(_3\) laser consisted of 100 ns single pulses with an energy of 0.075 mJ, not followed by afterpulses. The laser operated at about 20 times threshold, and the average output power of 350 mW corresponds to 35 percent of the absorbed pump power at 532 nm. The laser output was in turn frequency doubled into the blue by using a KNbO\(_3\) crystal cut for noncritical phase matching.

C. Pulsed Amplifier

Small-signal gain as high as 10\(^4\) has been measured in a double-pass Ti:Al\(_2\)O\(_3\) amplifier longitudinally pumped by an electrooptically \( Q \)-switched, frequency-doubled Nd:YAG laser [24]. By using a CW Ti:Al\(_2\)O\(_3\) oscillator at 790 nm to probe the gain at different excitation levels, the emission cross section was determined to be \( \sigma_e = 3.0 \times 10^{-19} \text{cm}^2 \), consistent with earlier measurements [11], [16], [22]. The single-pass gain was 180 at an incident pump energy of 7 J/cm\(^2\). The laser rod was damaged at approximately 12 J/cm\(^2\). Internal parasitic oscillations were avoided by tilting the laser rod and external parasitics by tilting all the other optical interfaces. Shortening of the decay lifetime was observed at the higher excitation levels. This effect, which has an impact on the amplifier design, is probably due to inversion depletion caused by amplified spontaneous emission.

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REFERENCES


Abstract:

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