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An Efficient, Diode-Pumped, 2μm Tm:YAG Waveguide Laser

A.Rameix, C.Borel, B.Chambaz, and B.Ferrand
LETI (CEA-Technologies Avancées) DOPT/SCMDO
CEA-Grenoble, 17 avenue des martyrs, 38054 Grenoble Cedex 9, France

D.P.Shepherd, T.J.Warburton, D.C.Hanna, and A.C.Tropper
Optoelectronics Research Centre
University of Southampton, Southampton, S017 1BJ, England

1. *Introduction*

Room temperature solid-state lasers emitting in the eye-safe two-micron spectral range are needed for medicine, optical communications and remote sensing (LIDAR). In the case of LIDAR the compactness of the system is a very important element, which has led us to investigate the performance of diode-pumped Tm:YAG epitaxial waveguides. Tm^{3+} doped host crystals, working on the $^3F_4 \rightarrow ^3H_6$ transition of the Tm^{3+} ions, have already operated as room temperature CW lasers[1-5]. However this transition acts as a quasi-three level laser leading to a relatively high threshold intensity requirement. The confinement of the pump and laser beams in optical waveguides leads to high intensities for relatively low powers. Thus higher gains per unit pump power and lower laser thresholds can be achieved if the extra propagation losses associated with the waveguide can be kept low. Liquid phase epitaxy (LPE) is now well known as an interesting technique for producing low-loss planar waveguides lasers: this method has already achieved good results in a multimode Nd:YAG waveguide where losses as low as 0,05 dB/cm were obtained and a submilliwatt threshold measured [6]. Moreover this technique allows the realisation of a wide variety of waveguides because the active dopant, the refractive index and the thickness of the epilayers are all readily controlled.

We report here the growth of Tm:YAG waveguides by liquid phase epitaxy on pure YAG substrates, the characterisation of these guides, and finally the 2,012μm room temperature laser operation by Ti:Sapphire pumping and by diode pumping.

2. *Liquid phase epitaxy growth*

Liquid phase epitaxy is a technology which is well suited to the realisation of crystalline thin film waveguide lasers. The Tm:YAG films were grown in the same way as has previously been described for Nd:YAG , Yb:YAG and Yb,Er:YAG **[7-9]**. The melt was composed of the solvent: a mixture of PbO and B_2O_3 in the molar ratio of 12 to 1, and the solute: an excess of Al_2O_3 with respect to Y_2O_3 . A gallium-lutetium codoping is necessary, to increase the refractive index and to decrease the lattice mismatch respectively [**10**]. The large size of the Ga^{3+} ion compared to the Al^{3+} ion means that compensatory doping by a small rare earth such as lutetium, is required to maintain the lattice match between the film and the substrate. The films were grown on one inch diameter pure YAG substrates with [111] orientation.

Good quality films were prepared at a growth rate of about 1μm/minute and at low supersaturation $\Delta T = T_s - T_{growth}$, where T_s is the saturation temperature and depends on the melt composition. The best range for ΔT is between 10 and 30°C. Film composition and thus lattice mismatch depends on the growth temperature, T_{growth}, and the melt composition. The film thickness depends both on the supersaturation and the growth duration. It was measured by weighing the substrate before and after the growth.

Table 1 presents the characteristics of the different compositions used. Initially films with varying concentrations of Tm, Lu and Ga were grown (melts A, B and C). In the following melts (D to H) no lutetium was added because of the low lattice mismatch noted in the first samples. In melts D and G we have also investigated the effect of not using gallium in order to see if laser action is still possible. From these different melts, films of 10 to 20 μm were grown at quite low supersaturation and hence at a small growth rate V_G. As for previous Nd:YAG and Yb:YAG epilayers, the waveguides are overlaid with an undoped YAG cladding epilayer of about 20μm thickness, in order to reduce scattering losses and protect the active layer during the end polishing process. The structure of the sample is shown schematically in Fig. 1. Each sample has two Ga,Lu,Tm:YAG waveguides due to the epitaxial growth taking place on both faces of the substrate.

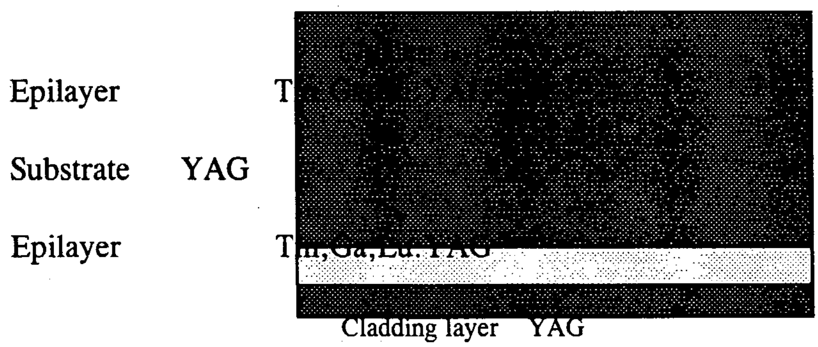

Fig. 1: Schematic structure of the sample.

3 Layer characterisation

3.1 Lattice mismatch, refractive index

Table 1: Composition and properties of several Tm:YAG epilayers

Melt	Growth conditions			Composition			Layer characteristics		
	T_s	T_G	V_G	X_{Tm}	X_{Lu}	X_{Ga}	Δa_{meas}	Δa_{calc}	Δn
	(°C)	(°C)	(μm)	(at.%)	(at.%)	(at.%)	(10^{-3} Å)	(10^{-3} Å)	(10^{-2})
A	1021	1004	0,93	4,8	15,2	7,2	-2,10	-2,4	1,6
B	1020	1010	0,70	6,6	20,9	8,4	-1,12	-1,1	1,2
C	1020	995	0,26	10,5	22,2	9,6	-	-1,6	1,0
D	1034	1026	0,60	8,1	0	0	4,23	4,5	-
E	1026	1019	0,47	8,2	0	4,1	-3,24	-3,7	1,2
F	1016	1005	0,33	14,1	0	3,6	-	-9,2	1,0
G	1044	1033	0,59	4	0	0	3,22	3,2	-
H	1033	1023	0,45	4	0	2	-0,76	-0,76	-

The doping level was measured by X-ray analysis, and the lattice mismatch by X-ray diffraction. We assume that the lattice mismatch can be expressed as: $\Delta a = 2.10^{-3} + \alpha_{Tm} X_{Tm} + \alpha_{Lu} X_{Lu} + \alpha_{Ga} X_{Ga}$ where the α_i coefficients represent the change of lattice parameter induced by the introduction of Tm, Lu, or Ga. The different concentrations, and the corresponding values of Δa permit the calculation of these coefficients. Using these coefficients a lattice mismatch can be calculated for each melt and is shown in Table 1 next to the measured values. There is a good agreement throughout the range of melt compositions used, suggesting that our fitted coefficients can be reliably used in this way. The substitution of yttrium by thulium and lutetium changes the lattice parameter by -0,0004Å and -0,0006Å per at.% respectively; the substitution of aluminium by gallium increases the lattice parameter by +0,002Å per at.%. The refractive index, was measured by the classical prism-film coupling technique (dark m-lines) and again is shown in Table 1. The missing values are either due to the fact that they have simply not been measured or they have been found to be difficult to measure.

3.2 Fluorescence spectra, fluorescence lifetime

Fluorescence spectra of Tm:YAG waveguides have been measured in order to compare them with bulk crystal fluorescence, and also to compare the guides with or without gallium (Fig. 2). The three spectra are quite similar. In contrast to previously reported work on Nd:YAG waveguides [7] we do not observe any significant broadening or shift of the peaks due to the introduction of gallium. This may be due to the relatively low Ga doping level and the relatively broad Tm spectrum. We have also measured the absorption spectra of the epilayers and we have observed that their shapes are identical to the spectrum of bulk crystal.

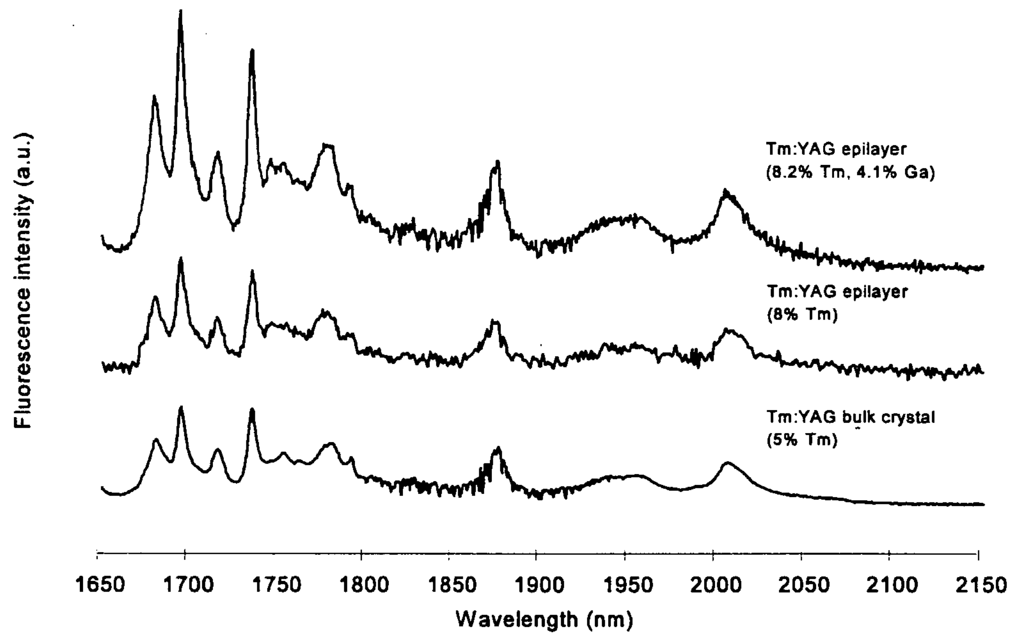

Fig. 2: Fluorescence spectra of Tm:YAG

The fluorescence lifetime has also been measured for different epilayers and the results are given in Table 2. In spite of the lack of data it is possible to deduce a trend. An increase of the Tm concentration decreases the fluorescence lifetime, while an increase of the Ga concentration seems to increase it. The effect of the Tm doping level on the lifetime is due to cross relaxation.

Table 2: Fluorescence lifetime of the $^3F_4$ level in Tm:YAG

X_{Tm} (at.%)	X_{Ga} (at.%)	Fluorescence lifetime (ms)
4		2.4
8		1.3
8	4	2.1
13	4	1.3

4 *Laser results:*

4.1 *Experimental set-up*

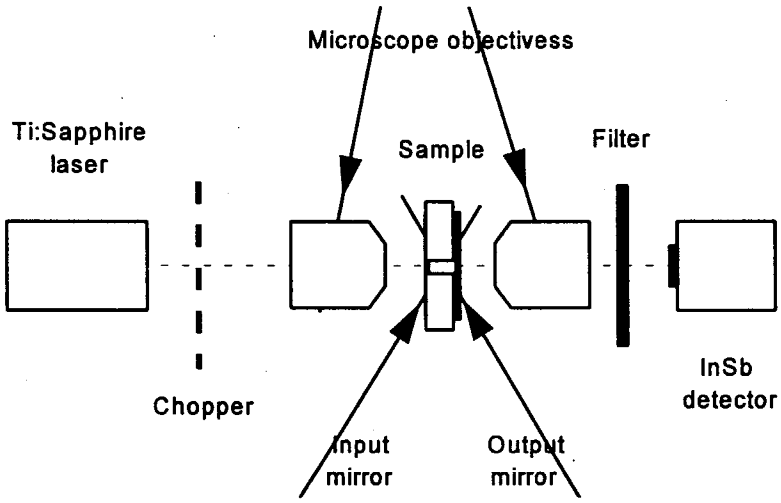

Fig. 3: Experimental set-up for laser tests.

In order to assess the laser performance in a planar waveguide configuration, the samples were prepared by cutting and end polishing. As has already been mentioned, the Tm doped layers are overlaid with an undoped YAG cladding layer, which helps to protect the doped layer during the polishing . To test the guides we used two planar mirrors coupled to the end faces of the crystals to form the resonator cavity. These thin, light-weight mirrors are held in place by a thin film of fluorinated liquid between the crystal and the mirror. Various doping levels and waveguide dimensions have been used for these experiments. Both a diode and a Ti:Sapphire laser have been used as the pumping source. Most of the guides have lased easily and so only the best results will be presented in this article.

The experimental set-up used to test the laser waveguides is shown in Fig. 3. Either a Spectra-Physics Ti:Sapphire laser pumped by a 5W Coherent Argon laser or a 1W GaAlAs SDL multimode diode array emitting at 785 nm was used as a pumping source. The diode was collimated with a 8 mm focal length, 0,5 numerical aperture lens, and an anamorphic prism pair. The feedback effect on the pumping diode was monitoring using a partially reflecting plate and a silicon detector. No feedback effect was observed during Ti:Sapphire pumping. The pump beam was end-coupled using a microscope objective appropriate to the particular guide being investigated.

The input mirror had 90% transmission at the pump wavelength (785nm), and 0,2% transmission at the expected laser wavelength (2 μm). Two output mirrors were used, one with 94,8% transmission at the pump wavelength, and 15% transmission at the laser wavelength; the other mirror did not transmit anything at 785nm, and had about 3% transmission at 2μm. All these values were measured with mirrors butted to a YAG substrate. The detectors used were a cooled InGaAs detector in the case of Ti:Sapphire pumping and a PbS detector for the diode pumping.

4.2 Results

Direct measurements can be used to find the pump power incident on the launch objective P_i, but it is also interesting to know the corresponding absorbed pumped power P_a. If we assume that we only have a single pass of the pump light due to the high single pass absorption and low reflectivity of the mirrors at this wavelength these two terms are related by,

$$P_a = P_i T_O T_{Mi} LA$$

where T_O and T_{Mi} are the known transmissions of the launch microscope objective and input mirrors. L and A are the launch efficiency and the absorption respectively and it can be seen that these do not have to be known independently in order to calculate the absorbed power. The LA product can be found by measuring all the pump power transmitted (both launched and not launched) when light is optimally launched into the guide (P_{og}) and when it is simply incident on the substrate (P_{os}) as in [8]. Thus,

$LA = 1\text{-}P_{og} / P_{os}$

When the output mirrors have a significant reflectivity a slightly more complicated expression needs to be used to relate incident to absorbed pump power that accounts for as many passes of the pump as is required before the additional absorbed pump power become negligible. In this case L and A need to be found separately which can be done by finding A from the absorption spectrum of the waveguide measured through a relatively thick film of whichever doping level is being studied. In this way we are able to express all the thresholds and slope efficiencies given in this paper in terms of absorbed power.

Using the experimental set-up shown in Fig. 3 laser emission was observed at 2,012μm using a 500 SPEX monochromator. According to the Tm:YAG waveguide room temperature fluorescence and absorption spectra, this wavelength does not fit to the highest emission cross-section, but to a maximum in the region where Tm:YAG shows significantly smaller absorption.

4.3 Ti:Sapphire pumping

We obtained CW laser action with most of the tested guides. It is difficult to see a significant trend over the range of thickness and doping levels (Table 3). This may be due to the fact that using the butted mirrors to form the cavity can lead to some variations in the results found from one occasion to another.

Table 3: Laser results of Tm:YAG guides pumped by a Ti:Sapphire laser.

				mirror T=3%		mirror T=15%	
Melt	thickness (μm)	X_{Tm} (at.%)	X_{Ga} (at.%)	threshold (mW)	slope efficiency (%)	threshold (mW)	slope efficiency (%)
D	17,2	8	0	-	-	191	17
E	14,1	8	4	-	-	72	45
E	23,3	8	4	26	40	45	68
F	16,8	13	4	-	-	96	39
G	14,9	4	0	-	-	164	-
H	13,6	4	2	-	-	41	45
H	23,8	4	2	23	35	74	48

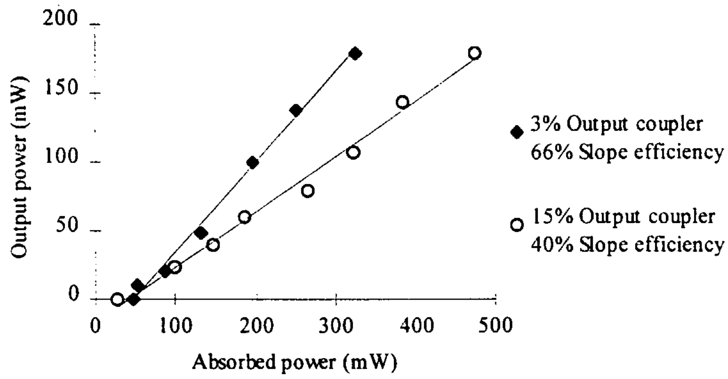

Fig. 4: Output power versus absorbed pump power for a Ti:Sapphire pumped 23μm Tm:YAG waveguide (melt E).

Yet it seems possible to affirm that, even if the Gallium is not necessary to obtain a lasing effect, it improves the performances in term of threshold and slope efficiency. Nevertheless the general result of low threshold and good slope efficiency is quite clear. Fig. 4 shows the output performances of the best performing waveguide studied here. These results appear to be comparable to the best reported results for bulk Tm:YAG lasers[11]. If we can use these low-loss thin films as a basis for fabricating channel guides, as has recently been achieved by ion-milling of epitaxial YAG thin films [12] then further significant reduction in the laser threshold could be obtained as long as the propagation losses can be kept low.

4.4 Diode pumping

For compact applications diode pumping schemes are preferred, therefore diode pumping experiments have been investigated at room temperature. Only a few guides amongst the ones previously investigated have been tested by diode pumping, and principally with the 3% transmission mirror. Laser performances are reported in the Table 4. The results obtained for diode pumping in the best performing guide are shown in Fig. 5. This is the same guide as was used in the results of Fig. 4 and the results are quite similar. This shows how well suited to diode-array pumping planar waveguides are, as the line focus produced by focusing down the diode output can be a good match to the laser mode of such guides. The highest output slope efficiencies measured (66% with Ti:Sapphire pumping and 64% with diode pumping) are amongst the highest reported figures for this system and are approaching the theoretical limit imposed by the difference in energy of the pump and laser photons combined with the well known cross-relaxation process that can give two laser photons for every pump photon (78%).

Table 4: Laser results of Tm:YAG guides pumped by a GaAlAs diode.

				mirror T=3%		mirror T=15%	
Melt	thickness (μm)	X_{Tm} (at.%)	X_{Ga} (at.%)	threshold (mW)	slope efficiency (%)	threshold (mW)	slope efficiency (%)
D	17,2	8	0	53	20	-	-
E	23,3	8	4	23	45	39	64

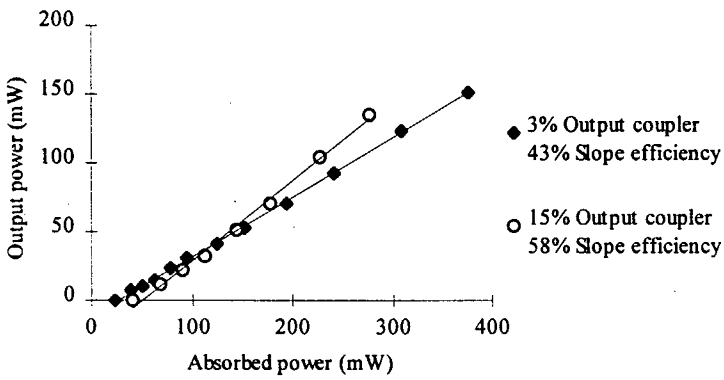

Fig. 5: Output power versus absorbed pump power for a diode pumped 23μm Tm:YAG waveguide (melt E).

5 *Conclusion*

We have shown excellent laser performance from a Tm doped epitaxially grown YAG planar waveguide. Both Ti:Sapphire pumping and diode-array pumping have been demonstrated with high output slope efficiencies of up to 68% at laser thresholds of a few tens of milliwatts. It is hoped that channel guides fabricated by ion-milling of these planar thin films will lead to lower thresholds than could be achieved in an equivalent bulk laser system, giving the possibility of highly compact diode-pumped systems. Alternatively for higher power operation the geometry of the planar thin film should be well suited to diode-bar pumping and also allow efficient heat removal.

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