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LASER OPERATION OF A Nd:LaF_3 THIN FILM GROWN BY MOLECULAR-BEAM EPITAXY

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Abstract

We present the first laser operation of a dielectric waveguide fabricated by molecular-beam epitaxy. Details of the growth process, the Nd:LaF_3 spectroscopic properties, and the laser performance at 1.06µm are given.

Introduction : Rare-earth (RE) doped waveguide lasers have attracted considerable attention due to the confinement provided by the waveguide configuration leading to a reduced pump power threshold and a high gain per unit pump power compared to bulk laser media. Waveguides fabricated on planar substrates offer an alternative method of realizing this kind of laser with potential advantages over glass fibres, such as access to the high gain and absorption cross-sections of crystal hosts and the possibility of integrating different devices on a single substrate. In this way, highly-compact, diode-pumped, solid-state laser systems can be envisaged.

Molecular-beam epitaxy (MBE) has demonstrated a high suitability for the growth of thin films of RE-doped insulating materials on different types of substrates. In our previous work on RE-doped CaF_2, we have shown that the thermodynamical conditions imposed during MBE growth (low temperature and growth rate) favourably modify the incorporation of RE ions compared to other high-temperature growth techniques used for bulk materials. We have also observed a high degree of uniformity in thickness and composition of the layers [1].

This letter reports the first (to the best of our knowledge) demonstration of laser operation in a dielectric waveguide fabricated by MBE, using a Nd^{3+}-doped-LaF_3 thin film grown on a CaF_2 substrate. Nd^{3+} has been used for the first demonstration of such a device because of the high efficiency of the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition, and its absorption bands around 800nm and 860nm for which commercially available laser diodes exist. Fluoride crystals are interesting as laser hosts due to their low phonon energy which leads to a wide transparency band (LaF_3 is transparent from 0.2μm to 11μm) and efficient upconversion mechanisms. Moreover, LaF_3 has a refractive index close to that of silica, allowing low-loss fibre coupling, and has been reported to be a very good host for RE incorporation. Good laser properties have been obtained for the bulk material, and in particular Nd:LaF_3 has been shown to be a promising candidate for diode-pumped lasers [2].

Growth conditions : It is well known that rare-earth trifluorides (LaF_3, CeF_3 and NdF_3) with a hexagonal tysonite structure can be grown epitaxially on Si(111) and GaAs(111) substrates [3,4]. In this work Nd-doped-LaF_3 thin films were grown on (111) oriented CaF_2 substrates under ultra-high vacuum conditions using two separate cells filled with LaF_3 and NdF_3. Due to the refractive index difference between CaF_2 and LaF_3, the growth of doped-LaF_3 layers on CaF_2 substrates produces an optically active waveguide without post-treatment requirements. The layers were found to be free of cracks and exhibited a featureless surface under optical microscopy. The monocrystallinity of the layers was confirmed by in-situ high-energy electron diffraction (RHEED) observation. The growth rate was 0.7 µm/hr and the substrate temperature was 520 °C. For the laser sample the thickness of the doped layer was 3.6 µm. A cladding layer, 0.5 µm thick, of pure CaF_2 was grown on top of the Nd:LaF_3 film giving a guide with a symmetric, step-index profile.

Spectroscopic properties : The fluorescence properties were studied in different wavelength ranges corresponding to the infrared down-conversion transitions $^4F_{3/2} \rightarrow {}^4I_{11/2}$ (1.06µm) and $^4F_{3/2} \rightarrow {}^4I_{13/2}$ (1.3µm), and the visible upconversion transitions from the $^4D_{3/2}$, $^4G_{7/2}$ and $^4G_{5/2}$ levels. These transitions were excited using the 800nm or 860nm absorption bands of Nd^{3+} with a tunable Ti:Sapphire laser. Samples with calculated Nd^{3+} content between 0.5 and 5 at.% were investigated and the maximum fluorescence intensity was observed for 1 at.% doped layers. Further details of these spectroscopic studies will be published elsewhere. Figure 1 shows the polarized fluorescence spectra in the 1 μm region of nominally 1at.% Nd:LaF_3 at room temperature. The spectra show that the main peaks are centred at 1.041μm for the TE polarization and at 1.063μm for the TM polarization, and are in good agreement with those found for Nd:LaF_3 bulk material [2]. The fluorescence decay of the $^4F_{3/2}$ level of the Nd:LaF_3 was observed to be a non-exponential function, with the intensity dropping to 1/e of its initial value in 470μs, a value which suggests that the doping level maybe somewhat higher than the calculated value [2].

Laser performance : For the results described here, we used a waveguide doped with nominally 1at.% Nd. The crystal was 7.5 mm long with parallel-polished end faces. A tunable Ti:Sapphire laser was used as the pump source tuned to the Nd^{3+} absorption near 790nm. The TE polarized pump light was coupled into the guide with a X20 microscope objective proceeded by two cylindrical lenses shaping the beam in the non-guided plane of the thin film. This set up produced measured spot sizes ($1/e^2$ radius of intensity) at the front face of the waveguide of 1.8 μm and 14 μm in the guided and non-guided directions respectively. The laser cavity was formed by butting two plane dielectric mirrors M1 (HR at 1.06 μm) and M2 (77 % R at 1.06 μm) directly onto the polished end faces. TM polarised laser oscillation at 1.063 μm was observed at thresholds as low as ~140 mW of pump incident on the X20 objective, corresponding to an absorbed power of approximately 103 mW. Using this 77% reflectivity output coupler, we observed the laser output results shown in figure 2 (on this occasion the threshold was a little higher at ~140mW absorbed). An output slope efficiency of 11% with respect to absorbed power was obtained, with an output power of 28mW for the maximum available 440mW of absorbed power. The threshold decreased to 85mW of absorbed power when using an HR output coupler.

This performance compares favourably to recent reports of laser oscillation in Nd:YLF waveguides grown by liquid-phase epitaxy [5], where a threshold of 115mW was achieved and the maximum power output was 100 μW (input power of 240mW) for a planar waveguide.

The waveguide propagation losses were calculated to be 1.2±0.4dB/cm by measuring the laser threshold for various values of output coupling [6]. The high threshold and losses for this initial demonstration could be due to many factors including imperfect parallelism of the end faces, a moderate quality of the substrate surface which increases the roughness of the grown layers, strain-induced scattering within the waveguide, and a negative thermal lensing. The threshold could be lowered by the formation of channel waveguides, as demonstrated by Rogin et al for Nd:YLF waveguides [5], and the losses could be reduced by an optimization of the growth parameters, by the use of a shorter waveguide, and by a better polishing of the substrate surface. All these possible improvements are currently under investigation and channels waveguides have been already fabricated and are currently being assessed.

Summary : We have demonstrated the first laser action in a dielectric waveguide fabricated by MBE. The Nd:LaF_3/CaF_2 waveguide has propagation losses around the 1dB/cm level and gives a TM polarised laser output at 1.063μm at pump power thresholds as low as 85mW. CW output powers of up to 28mW have been observed with a slope efficiency of 11%. Future work will concentrate on lowering the propagation losses and fabricating channel waveguides by ion-milling. This should lead to compact and efficient waveguide lasers which could exploit the wide transparency range of fluoride crystals.

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Figure captions

Figure 1. Polarised waveguide fluorescence and lasing spectra. The relative heights are not significant.

Figure 2. Output power against absorbed pump power.