Yb:YAG planar waveguide lasers grown by pulsed laser deposition: 70% slope efficiencies at 16 W of output power

Stephen J. Beecher*, James A. Grant-Jacob, Tina L. Parsonage, Ping Hua, Jacob I. Mackenzie,
David P. Shepherd, Robert W. Eason
Optoelectronics Research Centre, University of Southampton, SO17 1BJ, UK

ABSTRACT

We present our recent advances in the use of pulsed laser deposition (PLD) to fabricate active gain elements for use as amplifiers and laser oscillators. Record output powers exceeding 16 W and slope efficiencies of 70% are reported for optimized epitaxial growth of Yb(7.5%):YAG on to YAG substrates. We show for the first time that the performance of PLD material can meet or even exceed that of materials grown by more established methods such as the Czochralski technique. Details of fabrication, characterization and laser performance are presented in addition to outlining expected future improvements.

Keywords: Planar waveguides, pulsed laser deposition, rare-earth doped lasers, diode pumped lasers, crystalline thin films

1. INTRODUCTION

Pulsed laser deposition is a physical vapor deposition process involving the ablation of material from a target, the propagation of the material plasma and subsequent deposition of this material onto a substrate. This thin film growth technique was formerly most heavily exploited for the growth of superconducting thin films[1], but has since also been used to grow a range of other materials for application as ferroelectrics[2], and materials for optical waveguides[3]. In 1996 laser oscillation was achieved in a PLD-grown film of crystalline gadolinium gallium garnet (GGG) doped with neodymium[4], and this became the material of choice for PLD grown waveguide lasers for the next decade. A brief history of laser oscillators and amplifiers grown by PLD is presented in Figure 1, where we have divided the research into categories based on material system. Of note is the fact that all the materials, with the exception of one report of Cr:ZnSe, are oxides. Also of note is that the lasant ions encompass both trivalent lanthanides (Nd^{3+}, Er^{3+}, Tm^{3+} and Yb^{3+}) and the transition metals (Ti^{3+} and Cr^{2+}). After the first report of laser action where a pair of high reflectors were required to reach threshold[4], an Nd:GGG PLD laser was reported using an output coupler of 2.2% transmission and achieving a significantly higher output power of 30 mW with a slope efficiency of 20%[5]. Shortly afterwards Anderson *et al.* reported a Ti:sapphire planar waveguide where pulsed pumping achieved a 26% slope efficiency using a 35% transmission output coupler[6]. In the next decade the output powers of Nd:GGG waveguides increased to the watt level at the expense of a slight decrease in optical-to-optical efficiency, culminating in the report of over 4 W of output power[7]. In 2008 the group of Prof. Huber started publishing on the growth of cubic sesquioxide crystals by pulsed laser deposition and reported amplification in $Er:(Gd,Lu)_2O_3$[8], followed by reports of 1.8 mW of laser output from $Nd:(Gd,Lu)_2O_3$[9], and reaching 12 mW output power from $Yb:(Gd,Lu)_2O_3$[10]. Shortly after this was the first report of laser action in a non-oxide crystal grown by pulsed laser deposition[11], but this Cr^{2+}:ZnSe laser unfortunately would not run CW and the authors were unable to quantify the output power from it. Inspired by the results from Prof. Hubers group we started investigating cubic sesquioxide crystal growth, initially reporting 35 mW from $Tm:Y_2O_3$[12], and 83 mW from $Yb:Y_2O_3$[13], before reaching watt level output from $Yb:Y_2O_3$[14]. Since this watt level $Yb:Y_2O_3$ result we have increased the output powers achievable from PLD waveguide lasers significantly, producing 7.4 W from a $Yb:Lu_2O_3$ waveguide laser[15], and more recently an 11.5 W Yb:YAG laser[16]. Here we present our recent improvements in Yb:YAG growth leading to a record breaking 16.5 W output with a record breaking slope efficiency of 70% with respect to absorbed power. This is to the best of our knowledge the first time that PLD-grown optical gain media have performed as well, if not better than, the same crystal grown via more established techniques such as Czochralski growth.

* s.j.beecher@soton.ac.uk

2. PLD MATERIAL QUALITY

To place the current work in perspective it makes sense to look at historical reports of PLD waveguide lasers in comparison to the maximum theoretical performance possible from ideal material. Several methods exist for this but we will define a figure of merit (FOM) comparing the optical-to-optical efficiency from the laser with that achievable from the same material, using the same pump wavelength and extracting the same laser wavelength but in the absence of any losses and with the laser running sufficiently far above threshold to make the absorbed pump required to reach this level negligible. Explicitly the FOM for the laser is:

$$\text{FOM} = \frac{P_{out}}{P_{pumpabs}} \times \frac{\lambda_{laser}}{\lambda_{pump}} \tag{1}$$

Where P_{out} is the laser output power, $P_{pumpabs}$ is the absorbed pump power, λ_{laser} is the laser wavelength and λ_{pump} is the pump wavelength. For the non-trivial case of the $Tm:Y_2O_3$ waveguide laser reported in [12] we have neglected the contribution of cross relaxation which makes this FOM a slight over-estimate. Figure 1 presents the FOM for some of the work referenced in section 1.

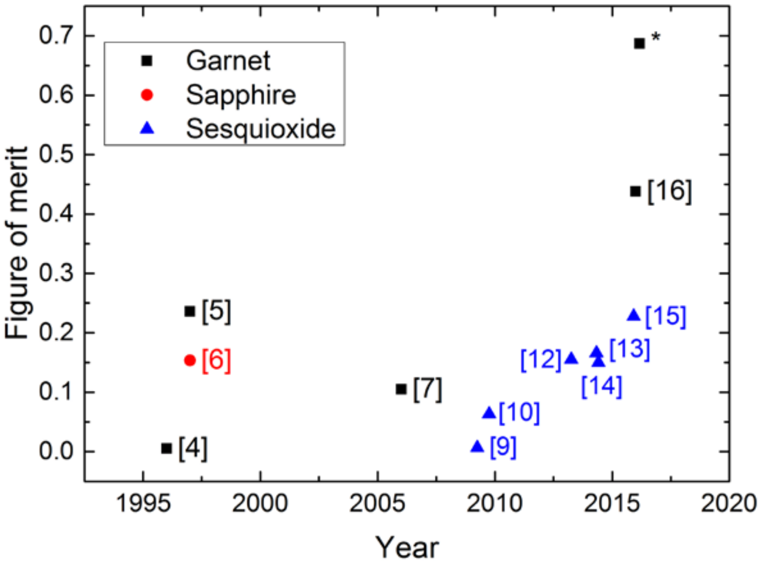

Figure 1. Figure of merit for some of the PLD waveguide lasers referenced in section 1. The current work is denoted by a *.

3. MATERIAL GROWTH

Growth parameters for the material reported in the work are identical to [16], except that the source material was prepared to be over-stoichiometric in Al_2O_3 and with a higher concentration of Yb_2O_3 in our target. This Al_2O_3 excess was designed to compensate for the preferential scattering of Al in comparison to Y from O_2 in the chamber during deposition, due to the significant atomic mass difference between the two elements. Previous studies from our group have shown that growth from stoichiometric targets result in an ~2.5% Al deficient film so our target was prepared with sufficient excess to allow for the growth of stoichiometric YAG. Due to our intention to grow stoichiometric material we rely on the Yb for Y substitution within the YAG crystal to provide the index increment required for index guiding. For this reason we have increased our dopant concentration significantly to 7.5%, around the maximum value achievable before detrimental processes appear to occur in Czochralski grown Yb:YAG crystals. The 12.0 µm layer of 7.5 at.% Yb:YAG was grown onto a <100>-YAG substrate of 10 mm x 10 mm x 1 mm. After growth two opposing facets were polished plane parallel. The modal properties of the structure were modelled, assuming an index increment between the core and cladding of 1.06 x 10^{-3}, and the two guided modes are shown in Figure 2.

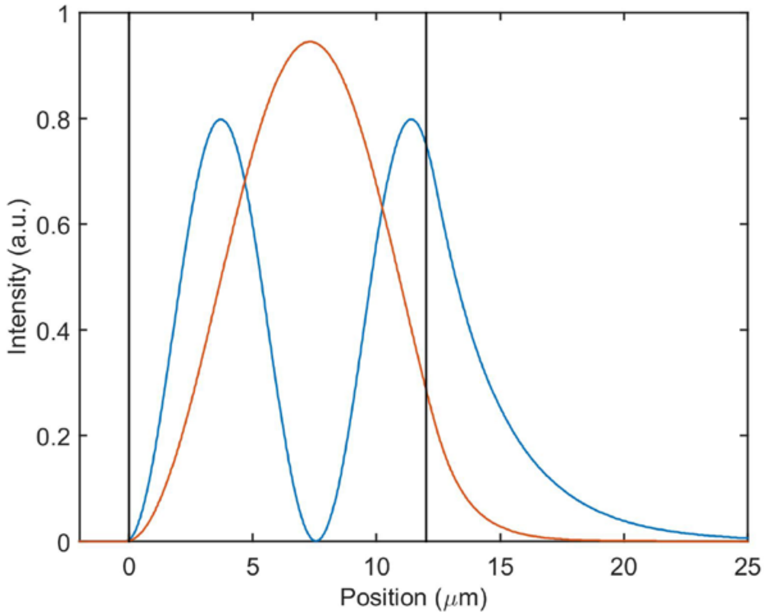

Figure 2. Guided modes of the waveguide. 0 μm represents the air to Yb:YAG interface and 12 μm is the Yb:YAG to YAG interface, both of which are marked with black vertical lines. The fundamental mode is in red while the only higher order mode is in blue.

4. MATERIAL SPECTROSCOPY

To compare our Al compensated film with our previously reported Yb:YAG [16], fluorescence lifetimes were taken using a conventional setup. We measure the same lifetime of 950 μs ± 10 μs for our new film, our previous uncompensated films and for bulk Czochralski grown Yb:YAG. A laser diode was then coupled into the waveguide and fluorescence exiting the film orthogonally to the guidance plane was captured using an optical fiber (62.5 μm core diameter 0.22 NA). This collection geometry minimizes the influence of spectrally dependent reabsorption on the shape of the collected fluorescence spectrum. From this fluorescence spectrum we then use the Früchtbauer-Landenburg equation to calculate the emission cross-section for the material. As previously reported for our growth from an un-compensated target we see a significant reduction of fluorescence at 1030 nm in comparison to Czochralski grown Yb:YAG,, while for our Al compensated film this has been almost completely rectified with the measured data very close to that reported for Czochralski grown Yb:YAG by Beil *et al.*[17].

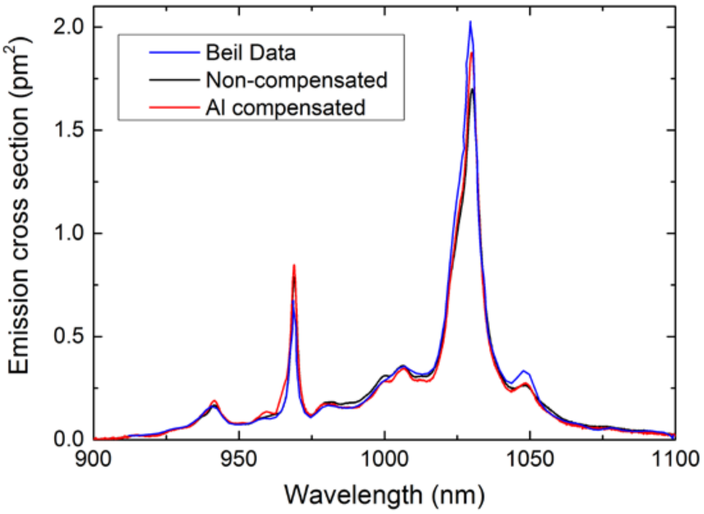

Figure 3. Spectroscopy of the guide reported in [16], the Al compensated guide reported here and the spectroscopy from a Czochralski grown sample reported in [17].

5. LASER PERFORMANCE

Two different setups were used for investigating the laser performance from the Yb:YAG planar waveguide laser. Initial low power measurements were taken using a home built 946 nm Nd:YAG laser as a pump source which produces 800 mW of output with a near diffraction limited beam quality ($M^2<1.1$). Higher power measurements were taken using a 940 nm diode bar producing 40 W of pump with an M^2 of ~1.6 for the fast axis and ~400 for the slow axis.

5.1 Diffraction limited pumping

The 946 nm Nd:YAG laser was focused using a pair of cylindrical lenses so as to predominantly couple into the fundamental mode of the waveguide for one axis (a $1/e^2$ diameter of 11 μm) and to be quasi-collimated over the length of the waveguide at a diameter of 100 μm for the other. Fluorinated fluid was used to attached a dichroic mirror (HT 910-990 nm, HR 1020-1100 nm) to the pump input facet of the waveguide and the other waveguide facet was left open relying on the ~8% reflection from the YAG – air interface to provide the feedback required for oscillation. Laser threshold occurred at ~150 mW of absorbed power and the slope efficiency with respect to absorbed power was 69%. The beam quality from this planar waveguide laser was close to diffraction limited with $M^2 = 1.15$ measured for the unguided plane and $M^2 = 1.25$ measured for the guided axis at maximum output power. Imaging of the waveguide facet at maximum pump power shows a laser mode of ~210 μm diameter in the unguided axis, confirming that our pump spot size is significant smaller than the laser mode size and hence promoted near-diffraction-limited performance.

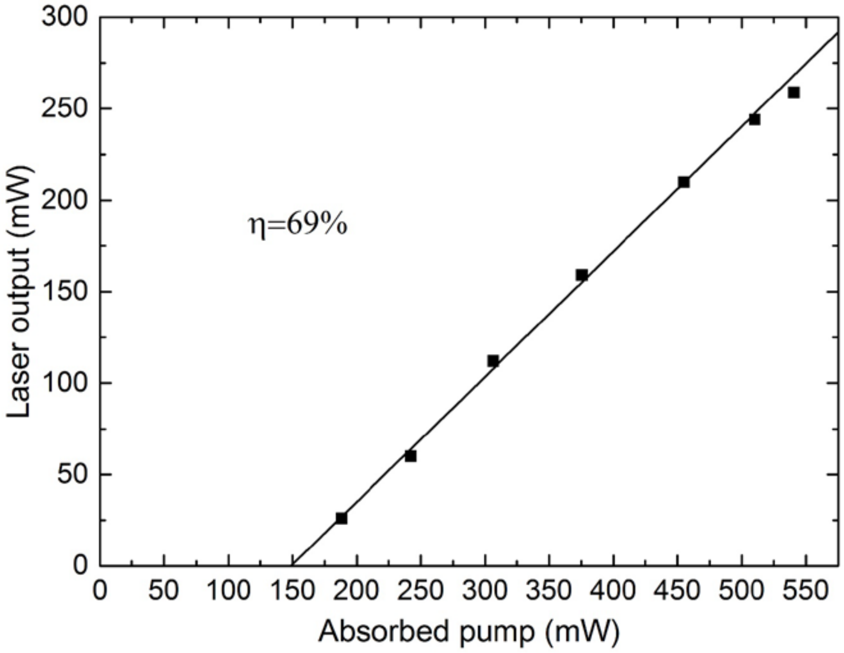

Figure 4. Laser performance of the Al compensated guide when pumped by a diffraction-limited 946 nm Nd:YAG laser.

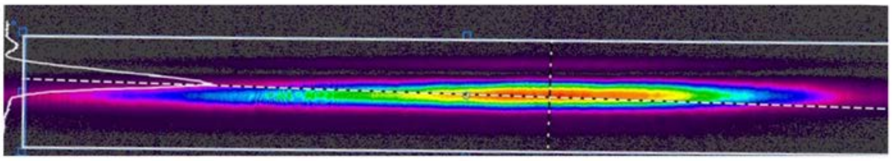

Figure 5. Output laser mode from the 946 nm pumped waveguide laser. The M^2 was measured as 1.15 in the unguided axis and 1.25 in the guided axis.

5.2 Diode bar pumping

The fast axis of the 940 nm diode bar was expanded using a 2.5 X magnification telescope, while the slow axis was focused to a diameter of 1.5 mm using a cylindrical lens and an acylindrical lens (Asphericon model number CHL12-10) to focus the expanded fast axis to a diameter of 10.6 µm. The slow axis focus was positioned 2.2 mm in air after the fast axis focus, corresponding to the longitudinal center of the guide taking into account the refractive index of YAG. The same dichroic mirror used in section 5.1 was attached to a kinematic mirror mount and brought into close proximity to the pump input facet of the waveguide. As in section 5.1 the other facet was left open relying on the ~8% Fresnel reflection to provide feedback. Threshold occurred at 2.6 W of absorbed power and the slope efficiency with respect to absorbed power was 70% up to the pump power limit with no signs of roll-over being observed. Emission occurred at a central wavelength of 1030 nm with a 3 dB width of ~0.4 nm.

The beam quality for both the guided and unguided axis was measured for a range of pump powers to ascertain the effect of the thermal load on the laser mode. For the guided axis the beam quality starts at M^2 =1.3 for low pump powers, close to the value of 1.25 seen when the waveguide was pumped by a diffraction-limited source. As the pump power is increased the beam quality degrades slightly reaching a value close to 1.5 for the highest output power. For the unguided axis the large pump mode size allows multiple resonator modes to oscillate leading to an M^2 of 8 at low pump powers. As the absorbed pump power and thermal lens strength in the unguided plane increases, the fundamental mode size will decrease. As expected we see an increase in the unguided M^2 with increasing absorbed pump power up to an M^2 = 16 for maximum output power. It should be noted that no attempt has been made at this point to control the modality in either the guided or unguided axis and techniques exist to allow preferential oscillation on the fundamental mode in principal allowing M^2 <1.5 for both axes [18].

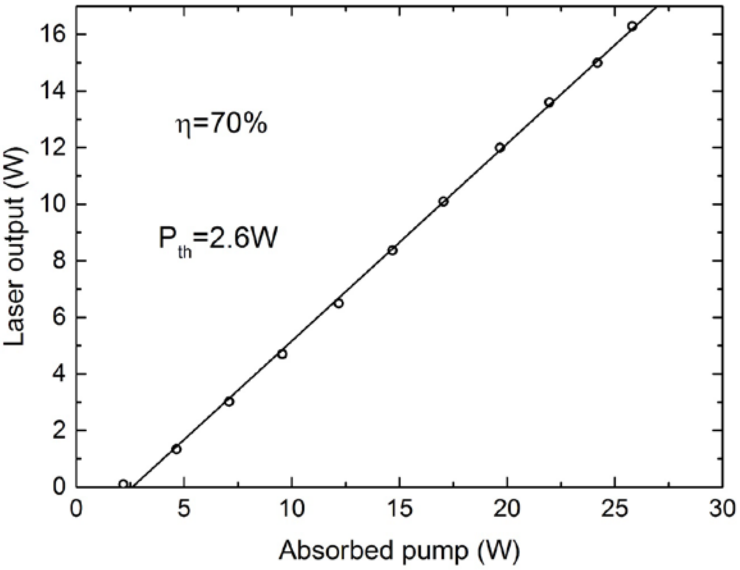

Figure 6. Laser performance of the 7.5% Yb:YAG PLD-grown waveguide laser when pumped by a 940 nm diode bar.

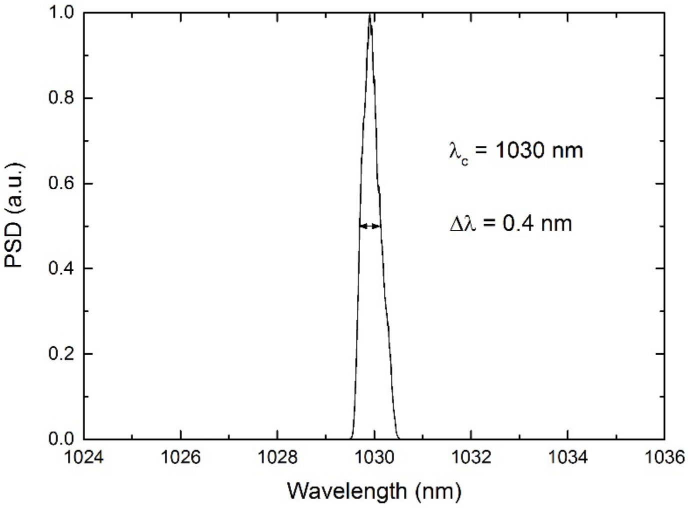

Figure 7. Laser spectrum when running at full power.

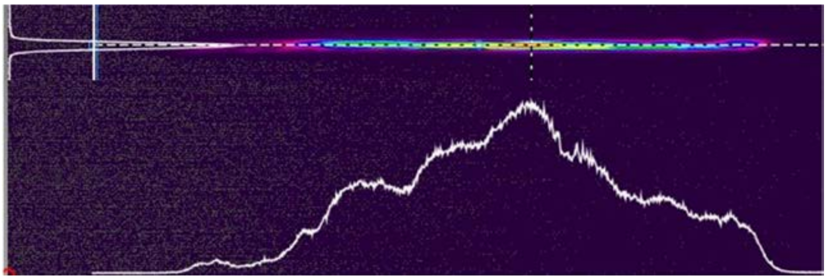

Figure 8. Output laser mode from the 940 nm diode bar pumped planar waveguide laser.

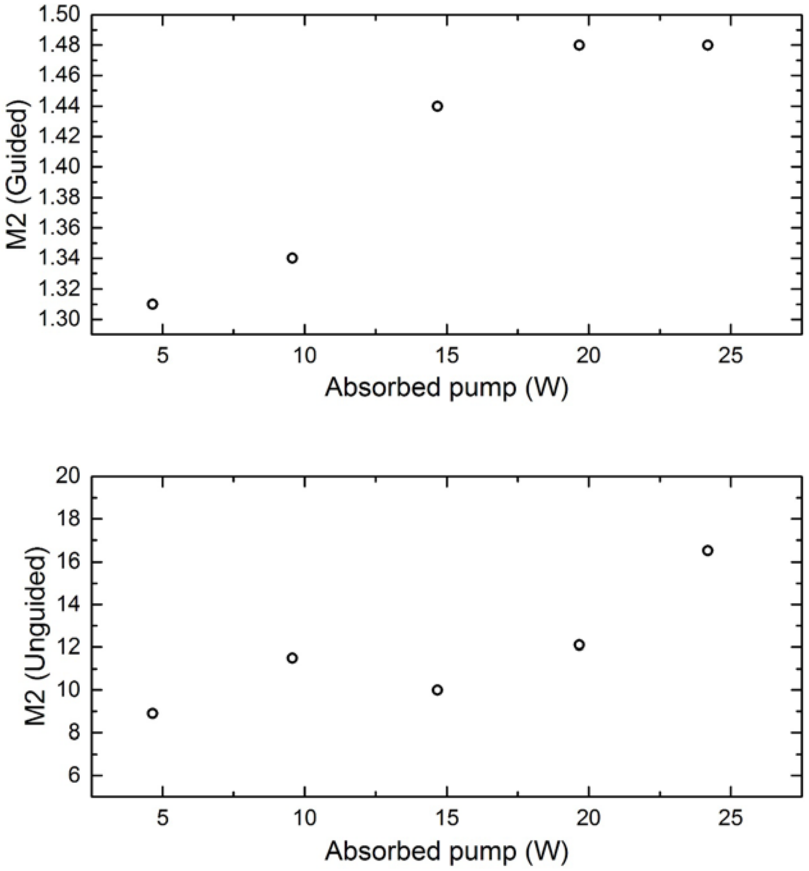

Figure 9. Beam quality of the diode pumped waveguide laser. Top, the beam quality in the guided axis. Bottom, the beam quality in the unguided axis.

6. CONCLUSIONS

We have for the first time demonstrated that laser quality crystal films can be grown by pulsed laser deposition with slope efficiencies of 70% for a planar waveguide laser obtained, strongly competing with what is achievable from bulk lasers at this power level. Reaching this material quality has involved careful consideration of several growth parameters including the lattice matching between the substrate and grown film and the stoichiometric transfer of material from target to substrate. From a spectroscopic point of view a very slight improvement can still be made in the films to reach fluorescence properties indistinguishable from Czochralski grown material. From a device point of view we are now in a position to implement these waveguides as gain modules for a variety of applications mainly in application areas requiring parameter combinations with which fiber and bulk systems struggle, e.g. high gains at high peak powers and moderate pulse energies. In the next 12 months we will be assembling a test system for amplifying 2 μJ femtosecond pulses up to the 200 μJ level in a single amplification stage.

ACKNOWLEDGEMENTS

The authors would like to acknowledge support from the Engineering and Physical Sciences Research Council (EPSRC) grant no. EP/L021390/1 and EP/J008052/1 (data for the work undertaken as part of this funding as per the EPSRC Research Data Management policy can be found at DOI:10.5258/SOTON/389330).

REFERENCES

[1] D. Dijkkamp, T. Venkatesan, X. D. Wu *et al.*, “Preparation of Y-Ba-Cu oxide superconductor thin films using pulsed laser evaporation from high Tc bulk material,” Appl. Phys. Lett., 51(8), 619-621 (1987).

[2] R. Ramesh, K. Luther, B. Wilkens *et al.*, “Epitaxial growth of ferroelectric bismuth titanate thin films by pulsed laser deposition,” Appl. Phys. Lett., 57(15), 1505-1507 (1990).

[3] K. E. Youden, T. Grevatt, R. W. Eason *et al.*, “Pulsed laser deposition of Ga-La-S chalcogenide glass thin film optical waveguides,” Appl. Phys. Lett., 63(12), 1601-1603 (1993).

[4] D. S. Gill, A. A. Anderson, R. W. Eason *et al.*, “Laser operation of an Nd:Gd3Ga5O12 thin-film optical waveguide fabricated by pulsed laser deposition,” Appl. Phys. Lett., 69(1), 10-12 (1996).

[5] C. L. Bonner, A. A. Anderson, R. W. Eason *et al.*, “Performance of a low-loss pulsed-laser-deposited Nd:Gd3Ga5O12 waveguide laser at 1.06 and 0.94 µm,” Opt. Lett., 22(13), 988-990 (1997).

[6] A. A. Anderson, R. W. Eason, L. M. B. Hickey *et al.*, “Ti:sapphire planar waveguide laser grown by pulsed laser deposition,” Opt. Lett., 22(20), 1556-1558 (1997).

[7] T. C. May-Smith, J. Wang, J. I. Mackenzie *et al.*, "Diode-Pumped Garnet Crystal Waveguide Structures Fabricated by Pulsed Laser Deposition," Conference on Lasers and Electro-Optics 2006, OSA Technical Digest (CD). CMFF7.

[8] A. Kahn, H. Kühn, S. Heinrich *et al.*, “Amplification in epitaxially grown Er:(Gd,Lu)2O3 waveguides for active integrated optical devices,” J. Opt. Soc. Am. B, 25(11), 1850-1853 (2008).

[9] A. Kahn, S. Heinrich, H. Kühn *et al.*, “Low threshold monocrystalline Nd:(Gd, Lu)2O3 channel waveguide laser,” Opt. Express, 17(6), 4412-4418 (2009).

[10] H. Kühn, S. Heinrich, A. Kahn *et al.*, “Monocrystalline Yb3+:(Gd,Lu)2O3 channel waveguide laser at 976.8 nm,” Opt. Lett., 34(18), 2718-2720 (2009).

[11] J. E. Williams, V. V. Fedorov, D. V. Martyshkin *et al.*, “Mid-IR laser oscillation in Cr2+:ZnSe planar waveguide,” Opt. Express, 18(25), 25999-26006 (2010).

[12] J. W. Szela, K. A. Sloyan, T. L. Parsonage *et al.*, “Laser operation of a Tm:Y_2O_3 planar waveguide,” Opt. Express, 21(10), 12460-12468 (2013).

[13] A. Choudhary, S. Dhingra, B. D’Urso *et al.*, “Q-switched operation of a pulsed-laser-deposited Yb:Y2O3 waveguide using graphene as a saturable absorber,” Opt. Lett., 39(15), 4325-4328 (2014).

[14] S. J. Beecher, T. L. Parsonage, J. I. Mackenzie *et al.*, “Diode-end-pumped 1.2 W Yb:Y2O3 planar waveguide laser,” Opt. Express, 22(18), 22056-22061 (2014).

[15] T. L. Parsonage, S. J. Beecher, A. Choudhary *et al.*, “Pulsed laser deposited diode-pumped 7.4 W Yb:Lu2O3 planar waveguide laser,” Opt. Express, 23(25), 31691-31697 (2015).

[16] J. A. Grant-Jacob, S. J. Beecher, T. L. Parsonage *et al.*, “An 11.5 W Yb:YAG planar waveguide laser fabricated via pulsed laser deposition,” Opt. Mater. Express, 6(1), 91-96 (2016).

[17] K. Beil, S. T. Fredrich-Thornton, F. Tellkamp *et al.*, “Thermal and laser properties of Yb:LuAG for kW thin disk lasers,” Opt. Express, 18(20), 20712-20722 (2010).

[18] S. P. Ng, and J. I. Mackenzie, “Power and radiance scaling of a 946 nm Nd:YAG planar waveguide laser,” Laser Phys., 22(3), 494-498 (2012).