Compact, diode-pumped, solid-state lasers for next generation defence and security sensors

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Abstract. Low-cost semiconductor laser diode pump sources have made a dramatic impact in sectors such as advanced manufacturing. They are now disrupting other sectors, such as defence and security (D&S), where Thales UK is a manufacturer of sensor systems for application on land, sea, air and man portable. In this talk, we will first give an overview of the market trends and challenges in the D&S sector. Then we will illustrate how low cost pump diodes are enabling new directions in D&S sensors, by describing two diode pumped, solid-state laser products currently under development at Thales UK. The first is a new generation of Laser Target Designators (LTD) that are used to identify targets for the secure guiding of munitions. Current systems are bulky, expensive and require large battery packs to operate. The advent of low cost diode technology, merged with our novel solid-state laser design, has created a designator that will be the smallest, lowest cost, STANAG compatible laser designator on the market. The LTD delivers greater that 50mJ per pulse up to 20Hz, and has compact dimensions of 125x70x55mm. Secondly, we describe an ultra-compact, eye-safe, solid-state laser rangefinder (LRF) with reduced size, weight and power consumption compared to existing products. The LRF measures 100x55x34mm, weighs 200g, and can range to greater than 10km with a single laser shot and at a rep rate of 1Hz. This also leverages off advances in laser pump diodes, but also utilises low cost, high reliability, packaging technology commonly found in the telecoms sector. As is common in the D&S sector, the products are designed to work in extreme environments, such as wide temperature range (-40 to +71°C) and high levels of shock and vibration. These disruptive products enable next-generation laser sensors such as rangefinders, target designators and active illuminated imagers.

1. Introduction
Solid-state lasers are well suited for long range sensor applications in the defence and securities (D&S) sector. Q-switched sources can generate very high peak power (100's MW), short duration (typically ns) pulses with good beam quality. This allows the signals to propagate and be detected over large distances. In this paper, we will describe developments in solid-state lasers used in two key sensor functions, namely, laser target designation (LTD) and laser range finding (LRF). LTDs are used for laser guiding of munitions. According to a recent report [1], by 2020, 90% of all munitions will be laser guided. The shift to laser guided munitions will lead to unprecedented target accuracy and hence decrease in collateral damage, with the majority of munitions landing within 2m of their intended target. LRFs are used in sensors heads and target locators and use compact eye-safe laser transmitters to measure distances of 10's of km to an accuracy of better than 1m [2].
Next generation systems will require a step-reduction in size, weight and power (SWaP) for application in un-manned autonomous vehicles (UAVs) and ultra-light, compact, man-portable systems, examples of which are shown in Figure 1. In addition to low SWaP, sensor products in the D&S sector are required to work in the harshest environments in the world. Typically, products need to operate over a very wide temperature range and withstand high levels of shock and vibration. Furthermore, the unit production volumes for the next generation sensors are likely to be much higher than traditionally encountered in the sector due to a big increase in the number of sensor platforms. As a result, cost is becoming a strong driver in these markets.

![Figure 1: Reductions in Size, Weight and Power (SWaP) are key drivers for the next generation of sensors, such as hand-held target locators (left) or gimbals for UAVs (right).](image)

We describe the development of new LTDs and LRFs with improved SWaP and lower cost. The key enabler for the new designs is the recent availability of low cost, high performance, high reliability, semiconductor laser diodes, driven by demand in market sectors such as advanced manufacturing and communications [3]. The new pump sources give solid-state lasers, typically, a 10-fold improvement in efficiency compared to flash-lamp systems, allowing big gains in compactness and reliability. In addition, we have produced designs that are compatible with low cost, high reliability, high volume, package technologies, that are commonly found in the telecoms sector. Technologies such as hermetically sealing, low out-gassing materials, and high precision component alignment, along with the possibility of automation, will bring huge benefits.

In the next two sections, we describe the design of the products and present experimental results.

2. Laser Target Designator

2.1. Laser Design

Q-switched, Nd:YAG lasers were adopted near the beginning of target designation in the 1960’s due to their ability to deliver high output energies with high efficiency. This led to the seekers on the laser-guided munitions being tuned to 1064nm, which remains the chosen wavelength in the Standardised Agreement for designators (STANAG 3733).

Developing diode pumped Nd:YAG solid state lasers for application as target designators poses several design challenges. Firstly, operating a Nd:YAG laser over a broad ambient temperature range raises the issue of non-uniform pump absorption. Around the ideal pump wavelength of 808nm, the laser diodes tune at approximately 0.3nm/°C. Thus, a system specified to operate over an ambient temperature range of –46°C to +71°C can result in the pump wavelength drifting by 32.8nm. Unfortunately, the optical absorption of Nd:YAG varies dramatically over this wavelength range [4]. Despite the absorption profile being smoothed out somewhat by the 4nm laser pump line-width, the resulting absorption length required to achieve 90% absorption of the pump ranges from 6 to 50mm over temperature, as shown in Figure 2. Stabilising the pump absorption by reducing the pump
wavelength shift using either temperature or wavelength control [5] are not practical due to system electrical power consumption requirements and their higher cost.

![Figure 2: 90% absorption length of 1 atomic % Nd\textsuperscript{3+}:YAG.](image)

A solution is to adopt an end-pumped geometry to allow for the large differences in absorption length over the temperature range [4]. We end-pump a 50mm laser rod with a diode pump source consisting of a 10- bar, 808nm, QCW stack, with each bar fitted with a cylindrical fast axis collimation lens. The output of the entire array is focused and collimated into the end of the rod and results in constant laser gain over temperature. Crucially, we have also eliminated the parasitic lasing effects that can limit the output energy in end-pump designs.

The second key system challenge is the need for a relatively long laser pulse width. Although not specifically stated in the STANAG requirement, a pulse width of between 10-20ns is favoured by the target seekers, but is also required to avoid issues such as laser induced coating damage due to the greater than 50mJ required for designation. To achieve a pulse width in this range, the cavity length has to be of the order of 20cm long. Hence, in order to benefit from the compact diode pumps, the laser cavity needs to be folded several times to reduce size.

The straight resonator is first folded into a U-shaped geometry, made up of a corner cube at one end and a plane mirror substrate at the other. The plane mirror substrate is coated in two regions to act as both the high-reflector mirror and the output coupler. The action of the corner cube, coupled with this configuration of end mirrors, results in a resonator that is significantly less sensitive to misalignment. The U-shaped resonator is further reduced in size with a second fold using two extra mirrors. Each of these fold mirrors reflects both arms of the laser resonator and hence does not adversely affect misalignment insensitivity. This was confirmed by modeling the resonator misalignments in Zemax via a Monte-Carlo analysis, as shown in Figure 3. The double folded cavity, coupled with the compact end-pumped geometry, allows the designator to be fitted into dimensions of (LxWxH) 125x70x55mm.

![Figure 3: Folded laser resonator model used for misalignment sensitivity calculations.](image)
Q-switching is achieved using a \( \text{LiNbO}_3 \) Pockels cell, in conjunction with a polariser and waveplate. The waveplate has the dual function of zeroing the retardation due to the corner cube and setting the remaining retardation to a quarter wave. In a double pass, the combination of corner cube and waveplate act as a half wave plate and, in conjunction with the polariser, this creates the low-Q state of the resonator. The Pockels cell is used at its quarter-wave voltage to switch to the high-Q state.

2.2. Experimental Results
The laser has been tested over a range of temperatures with no active cooling. The output pulse energy with time at 20Hz is shown in Figure 4 for −35°C, room temperature and +55°C operation. The output pulse energy of the laser is selectable by changing the pump pulse duration. This allows for the capability of using the laser in a low-energy mode for short-range operation.

![Figure 4: Output pulse energy at 20Hz](image)

3. Eye-safe, Diode pumped, Solid-state, Laser Range Finder
The second laser system that benefits from low cost, compact, laser diode arrays is for application in laser range finders (LRFs). LRFs need to be eye-safe for most applications, and hence the 1500-1600nm emission wavelength range is most attractive. Furthermore, diode pump solid-state sources are ideal for long-range, high accuracy time-of-flight LRFs. They have very high peak powers to allow propagation over 10’s of km, and narrow pulse widths (nanoseconds) to allow accurate time-stamping of the returned signal.

3.1. Laser Design
Our laser is based on a diode-pumped, Erbium:Ytterbium (Er:Yb) Glass (1535nm), passively Q-switch solid-state laser. Figure 5 shows a schematic of the resonator design. The laser gain block is formed from an Er:Yb glass laser rod pumped by 2x1cm, 940nm pump diodes. In order to maximize efficiency, the components size should be matched closely to the optical mode. The laser rod is less than 1.5mm in cross-section in order to maximize the gain efficiency from the 1mm diameter laser spot.

![Figure 5: Exploded view of laser resonator configuration](image)
Positioning and handling of such small components lends itself to utilising many of the technologies already developed for low cost, compact, high reliability telecoms style packaging. As a result, our laser has an efficient pump arrangement that need only be passively aligned (to within +/- 50um) to ensure efficient pumping of the gain region. Furthermore, the laser rod is mounted to produce good thermal contact to the transmitter package. The laser cavity is formed by a highly reflecting (HR) back reflector deposited on the laser rod, and a separate, partially reflecting output coupler (OC) at the front. Q-switching is achieved with a Cobalt (Co\(^{2+}\)) doped Spinel (MgAl\(_2\)O\(_4\)). The output coupler is actively aligned to achieve the required energy and beam profile. Finally, there is an integrated photodetector to allow the laser driver to shut-down the pump current when a Q-switch pulse is emitted. The whole resonator is hermetically sealed within a package that measures (LxWxH) 40x14x10mm, as shown in Figure 6.

The design and assembly technique ensures a compact, low cost, high reliability product, which can be easily integrated into a host system. We have developed a LRF with the transmitter, which measures 100x55x34mm and weighs less than 200g. Furthermore, the small size of the components means that the design is suitable for assembly automation to significantly reduce cost.

3.2. Experimental Results

Devices have been tested over a range of temperatures (-38 to +71\(^\circ\)C) and at repetition rates up to of 1Hz. The device was mounted onto an aluminium base to act as a heat sink and passively cooled. The laser fired from the first shot at all temperatures. Figure 7(a) shows that the pulse energy over temperature was around 1mJ, and shows good uniformity. There was no evidence of thermal runaway as illustrated by a 500 shot run (8.2mins) shown in Figure 7(b). The pump time varied from 1.7ms at low temperature, up to 2.1ms at high temperature, as shown in Figure 8(a). The laser output is a typical Q-switch pulse, as shown in Figure 8(b) and varies between 6 and 8ns over temperature. The beam profile is a single TEM\(_{00}\) gaussian, as shown in Figure 8(c) with a temperature variation of the beam divergence shown in Figure 8(d). The electrical power drawn at 1Hz is around 0.8W. As is typical for Q-switch solid-state lasers, the electrical to optical efficiency is quite low (<1%).

![Figure 6: Image of transmitter package](image)

![Figure 7](image)
Figure 8: Performance over temperature (a) pump time, (b) typical Q-switch pulse shape, (c) laser beam far-field at 25°C, (d) beam divergence ($1/e^2$) over temperature.

4. Conclusion
The two applications described above demonstrate the potential of compact diode pumps and telecoms-style manufacturing techniques applied to defence and security applications. We would expect further improvements in SWaP over the next few years, driven by the demand for higher performance pump heads for the advanced manufacturing sector. Furthermore, costs will decrease, leading to the sensors becoming more commoditised than is typical in the D&S sector. Under these conditions, we would expect to see, for example, high performance rangefinders and active imagers appearing in the low cost civilian UAVs that look set to emerge over in the coming years.

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