Performance Requirements for Countermeasures Lasers

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ABSTRACT

Performance requirements for laser sources, operating in the mid-IR, providing protection of airborne platforms from heat-seeking missiles are reviewed. The critical performance characteristic for a countermeasures laser is 'useful energy on target', which requires the laser to generate high brightness output in the appropriate spectral bands with rapid turn-on time. Integration with a compact beam director places an upper limit on the beam quality of the laser output. The key driver for the detailed laser design is to maximise the overall wallplug efficiency in order to minimise the complexity and volume, in turn maximising the reliability and reducing the cost. In particular routes to reduce the thermal management system for the laser produce the single largest improvement in overall wallplug efficiency, with the ultimate goal of realising a truly athermal laser. Candidate technologies for IR countermeasures lasers are briefly reviewed.

Keywords: IRCM laser, thulium fibre laser, Ho:YAG laser, OPO, ZGP, OPGaAs, OPSL, QCL

1. INTRODUCTION

Directed Infrared Countermeasure (DIRCM) systems are used to protect airborne platforms from IR-guided ('heat-seeking') missile threats, the primary threats in this class being Man Portable Air Defence Systems (MANPADs). They operate autonomously by detecting a missile launch, determining if it is a threat and activating one or more effectors which track its approach and direct a modulated beam of energy to defeat it. The modulated beam is directed at the missile seeker, jamming it and driving the missile away from the aircraft. This all occurs within a matter of seconds.

The use of lasers as the source of energy for the jamming has been deployed in the Northrop Grumman AAQ-24(V) NEMESIS system for military aircraft and is currently being promoted for Northrop Grumman Guardian system for civilian aircraft. The laser used in this Northrop Grumman DIRCM system, Viper^{TM}, sets the current benchmark for IRCM lasers, and future laser development. According to their publicity material, all the components, including all wavelength conversion and beam-forming optics, controller and power supply fit in a 13-inch diameter by 2-inch high chassis, weighing less than 10 pounds[1].

Mid-IR lasers have been, and continue to be, an active area of academic, industrial and military research interest and there have been a number of significant and relevant technology developments over the last decade, particularly in the area of fibre and semiconductor lasers.

This paper reviews the key performance requirements for a laser to be used in the mission-critical DIRCM application. Please note that this review is restricted to in-band lasers operating in the mid-IR wavelength band 2-5 μm. For a more general review of countermeasures lasers, encompassing out-of-band (damage) as well as in-band techniques the reader is referred to the comprehensive 2007 review paper (plus references therein) of Titterton[2].

Candidate technologies for next generation IRCM lasers include fibre-pumped solid-state lasers, optically pumped semiconductor lasers and quantum cascade semiconductor lasers. A brief review of the latest developments in these technologies is made. For a more comprehensive review the reader is referred to the 2009 review paper (plus references therein) of Sijan[3].

This paper also reviews the key drivers in the detailed laser design in order to realise more compact implementations and simpler architectures for potential future generation IRCM laser sources. As an example a generic Selex Galileo production targeting laser design is used to illustrate the key design drivers and constraints.

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2. DIRCM LASER REQUIREMENTS

The laser provides a number of properties (spatial and temporal coherence, monochromacity) useful in a range of military applications, principally based on being able to propagate a well-defined beam of light over long distances.

For the DIRCM application the critical performance characteristic is ‘useful energy on target’, in order for the countermeasure system to rapidly and reliably defeat the threat. This critical performance characteristic is impacted by a combination of the laser source and the beam director. It can be broken down into the following general requirements for the laser source:

- **Spectral coverage:** in general multi-wavelength output is required to match the atmospheric transmission windows in the mid-IR spectral region from 2-5 μm. Radiation generated outwith the low attenuation transmission windows is in effect wasted energy. A laser source that demonstrates wavelength diversity within the atmospheric transmission windows will be less susceptible to any counter-countermeasures employed by the threats. The ultimate in wavelength diversity is provided by a laser source generating broadband output simultaneously filling the bandwidth of the atmospheric transmission windows. Alternatively rapid wavelength tuning across the wavebands can provide diversity, as can device-to-device variation in the spectral characteristics of inherently fixed-line technologies.
- **Beam quality:** it is the far-field divergence of the of the laser output that sets the range-dependent beam size at the threat. In theory an arbitrarily small beam divergence would be optimum, as this maximises the radiant intensity for a given laser output power. However the beam divergence has to be married to the pointing accuracy of the beam director in order to keep the beam centroid jitter at the threat a fraction of the beam size, thus maintaining energy on target. Furthermore the requirement for a compact beam director limits the available optical apertures, hence the near-field beam diameter (otherwise an arbitrarily poor beam quality output can simply be expanded through a telescope to produce the desired far-field divergence). Diffraction dictates that this combination of near- and far-field beam requirements places the most stringent beam quality requirement on the longest wavelength output of the laser. In general this output should provide a beam as close to diffraction-limited as possible (beam quality factor M^2 as close to 1 as possible) in order to mimimise the aperture size of the laser output and beam director laser path. The corresponding M^2 factor for the shorter wavelength outputs can be relaxed appropriately. Laser output as close to diffraction-limited as possible has the additional benefit of reducing the laser beam contribution to any far-field centroid jitter at the target. A common boresight for the multiple output beams is essential.
- **Power:** the appropriate optical power must be directed at the threat in order to provide a robust defeat mechanism. This power level is clearly dependent on the beam divergence requirement in determining the radiant intensity incident at the target. Power levels of order a few watts are generally needed for in-band defeat by deception or ‘spoofing’ of the threat, as opposed to the many tens, if not hundreds, of kilowatts for an out-of-band damage countermeasures laser.
- **Turn-on time:** alternatively labeled time to full brightness (TTFB). The timelines involved in defeating a heat-seeking missile threat, from identification and tracking of the threat to deploying the countermeasure, are short, typically less than 10 s. The faster the laser can achieve full power in a stabilised beam with the correct far-field divergence the quicker an identified threat can be engaged and defeated. A TTFB figure of order tens of milliseconds will minimise the laser contribution to the overall timeline of the threat engagement. In general it is thermally-induced variations in laser performance that most severely impact TTFB e.g. in a solid-state laser if the thermal lens induced by absorption of pump light is sufficiently strong to dominate the laser output beam behaviour.
- **Modulation/duty cycle:** the laser source must generate the necessary temporal output for robust defeat of the threat. The ideal DIRCM laser provides continuous wave output which can then be readily modulated over a wide range of waveforms and duty cycles with minimal impact on the output beam characteristics. A high on/off contrast ratio is required. Duty cycle also refers to the operational duty factor i.e. the number of times the laser must fire in a given period of time. Sensitivity of the laser to the heat load in the active medium will impact the modulation flexibility, while the overall laser system heat load determines the thermal management requirements which in turn impacts the sustainable operational duty factor. Minimising both the sensitivity of the laser to heat load variations and the overall laser system heat load will optimise the modulation and operational duty cycle performance.
- **Efficiency:** There is a continued push from the military customer community to enhance the overall wallpug efficiency of laser sources, without impacting the key laser performance parameters. Maximising the overall

wallplug efficiency improves the installed system requirements such as the prime power from the platform. The volume and mass of the laser system will be minimised, reducing the footprint of the countermeasures system. An enhancement in overall wallplug efficiency indicates a reduction in the thermal management requirement, which in turn is a result of reducing the heat load. This has the additional benefit of reducing thermally-induced stresses in key components, increasing the laser system reliability. Enhancing the overall wallplug efficiency will reduce the complexity and parts count leading to an overall reduction in cost for the laser system.

It is the combination of far-field beam divergence and in-band power that determines 'useful energy on target', with the overall wallplug efficiency determining the mass/volume, reliability, and ultimately the cost, of the laser system. The laser system has to provide the performance as listed here over the full environment experienced by the airborne platform. This places severe requirements on the laser design in terms of ruggedness. Laser design considerations are dealt with in more detail in section 4.

3. CANDIDATE TECHNOLOGIES

The laser emission wavelengths of interest for defeating missiles in a DIRCM system are in the mid-IR waveband in the range 2-5 µm. Traditional solid-state laser designs have been restricted by the suitability of dopant and host materials capable of use as an optical gain medium. There is a dearth of efficient solid-state sources offering direct emission in the waveband of interest. The most efficient optical pump sources are near-IR laser diodes emitting at either 8xx nm or 9xx nm. These pump sources are generally edge-emitting multimode devices, in either broad area single emitter format, or multi-emitter bar format. Laser diode maturisation has taken place over a 10-20 year timescale as a result of several commercial drivers, most notably telecomms and industrial lasers. The solid-state laser acts as a brightness converter, absorbing the laser diode pump light and generating output at the red-shifted laser transition wavelength, using an optical resonator to produce an (ideally) near-diffraction-limited output beam. The conversion efficiency and output wavelength of a laser diode are both temperature-dependent, therefore active temperature control of the laser diode pump source is typically the major component of a solid-state laser thermal management system.

A laser transition in the mid-IR using these pump sources will naturally suffer an increasingly severe quantum defect with increasing laser wavelength. This manifests itself as an increasing heat load in the laser host material resulting in a stronger focal power thermal lens, plus increased thermally induced aberrations, which act to degrade laser performance. The conversion efficiency of the laser transition, hence the overall wallplug efficiency, is inversely proportional to the magnitude of the quantum defect. Use of a nonlinear wavelength conversion stage or stages to generate the mid-IR radiation from an out-of-band pump laser removes this quantum defect problem. Moreover, the requirement for several emission lines across a relatively broad spectrum resulted in first-generation DIRCM sources using an of out-of-band pump laser with nonlinear wavelength conversion to generate the in-band radiation.

The natural choice for an out-of-band pump laser is the ubiquitous neodymium-doped yttrium aluminium garnet (Nd:YAG), which has been extensively used in both military and commercial applications, and is probably the most robust fielded laser to date. YAG is a mechanically strong host material which allows lasing at high pulse energies, and also at high average powers. Higher efficiencies in high repetition rate or continuous wave operation is achievable using neodymium-doped yttrium vanadate (Nd:YVO_4), taking advantage of its superior absorption and emission cross-sections compared to Nd:YAG. The neodymium ion primary laser transition is at 1.064 µm, which requires cascaded nonlinear wavelength conversion stages using optical parametric oscillators (OPOs) in order to generate several emission lines in the range 2-5 µm. Typically Q-switched pump lasers are used; this is the simplest method for generation of high peak power pulses in order to achieve efficient conversion in the OPO stages. A simpler approach is to use one conversion stage and trade-off between wavelength coverage, power, complexity and cost.

In recent years there have been a number of developments in the field of fibre lasers. These are high efficiency, high brightness sources of radiation. The fibre geometry alleviates many of the thermal issues suffered by solid-state lasers; the large surface area to volume ratio is very efficient at dissipating heat, while diffraction-limited beam quality is guaranteed from a single-mode fibre source independent of the thermal loading. The fibre laser geometry naturally favours continuous wave or low-pulse energy operation due to the small core size (of order 10 µm for a single-mode step-index fibre). Optical fibre delivery offers significant flexibility in the configuration of the laser system. The majority of fibre lasers are based on doped silica fibre, which is an inherently robust material with a pedigree of large scale manufacturing in support of the telecomms industry. These advantages offer great potential for robust military operation. A number of commercial suppliers now offer either doped silica fibre or complete fibre laser systems. Therefore the fibre laser is now an attractive option as the pump source in an IRCM laser.

Similarly there have been rapid advances in semiconductor laser sources offering direct generation of mid-IR output. Optical and electrically pumped variants are under development, the latter in principle offering the ultimate long-term solution in terms of device efficiency (direct conversion of electrical input power to the wavelengths of interest). Given that the mid-IR semiconductor laser is directly generating the output beam, its brightness is the key optical parameter (unlike near-IR pump diodes where raw power at the desired wavelength suffices). By their very nature semiconductor lasers are low-peak power cw or quasi-cw devices. Efficient devices with low thermal loading are capable of modulation over a wide range of duty cycles and waveforms. The low-peak power nature of semiconductor laser technology significantly eases the damage threshold requirements of optical coatings.

A brief review of the latest developments in these fields is given in the following sections.

3.1 Fibre-pumped mid-IR lasers

The highest efficiency, longest wavelength laser source is the thulium fibre laser. The emission wavelength is typically in the range 1.9-2.0 μm which is just out-of-band. Optical-to-optical conversion efficiencies of 50% are routinely reported[4,5], with output powers approaching 1 kW in a MOPA architecture[6]. Pump diodes at a wavelength of approximately 790 nm are used, with the reported high efficiencies achieved by taking advantage of the '2-for-1' cross-relaxation process in thulium[7], itself due to the serendipitous near-equal spacing of the low-lying energy levels of the thulium ion. High efficiency on the laser transition acts to alleviate the deleterious effects of photodarkening[8].

The thulium fibre laser is used to pump a holmium-doped YAG (Ho:YAG) solid-state laser stage with an output wavelength at 2.1 μm. This resonant pumping scheme has a low quantum defect, hence the thermal loading in the host material is low and high optical-to-optical conversion efficiencies in excess of 60% are routinely achieved[9,10]. This laser can be Q-switched, with no loss in conversion efficiency, in order to generate high peak power pulses to drive efficient nonlinear conversion in an OPO stage. The unconverted Ho:YAG laser output after the OPO stage provides in-band output at the short wavelength end of the 2-5 μm waveband.

Recently 10 W of output from a holmium fibre laser has been reported[11]. In this instance a relatively short pump wavelength was used, but in principle a thulium fibre laser pumped holmium fibre laser is feasible, replicating the high efficiencies of the bulk Ho:YAG laser but with the added flexibility offered by an all-fibre geometry.

The nonlinear material of primary interest for the OPO stage is zinc germanium phosphide (ZGP). It has the most favourable properties of commercially available materials, combining a large nonlinear coefficient of 70 pm/V with wide transparency across the mid-IR. Birefringent phasematching is used, with angle or temperature tuning in order to generate the required output wavelengths. The principal issue concerning ZGP is the defect-related absorption at the pump wavelength (typically in the range 5-10%/cm for good quality material), resulting in a thermally-induced lens which has to be taken into account in the OPO resonator design. A secondary issue is the low level of absorption (worst case value 3%/cm typically quoted) at the OPO wavelengths, which limits the utility of ZGP in low-peak power regimes of operation, as does the presence of walk-off in this birefringently phasematched material. ZGP OPOs have been shown to work well in the Q-switched pumping regime, with 50% optical-to-optical conversion efficiency routinely reported[9,10]. Note that periodically poled lithium niobate (PPLN), a more mature and more widely available commercial material, can readily be pumped in the 1-2 μm waveband, but is limited to a maximum wavelength of approximately 4 μm at reasonable output powers by the onset of lattice absorption. Therefore complete wavelength coverage is not possible with this material system.

In the thulium fibre pumped mid-IR laser design the majority of the heat load is generated in the pump diodes of the thulium fibre laser. Advantage can be taken of the flexibility of the fibre geometry to separate the fibre laser source from the wavelength conversion stages via a length of standard silica glass delivery fibre. In this way the laser can be separated into a pump source (power supply, thermal management, pump diodes plus fibre laser) plus a near-passive, very compact optical head containing the Ho:YAG laser , ZGP OPO and associated optics. Power scaling to 12.5 W in a single ZGP OPO has been demonstrated[10], with the compact footprint of the Ho:YAG laser and OPO stages unchanged from a lower power version (and also maintaining the high conversion efficiencies recorded at lower powers). The cascaded nature of the optical chain results in the multiple wavelengths producing collinear output beams.

A top-level estimate of the electrical-to-optical conversion efficiency from electrical drive power for the pump diodes to useful optical output is 15%, based on figures of 50% electrical-to-optical diode efficiency, 50% optical-to-optical fibre laser efficiency, 60% optical-to-optical Ho:YAG laser efficiency and 50% optical-to-optical ZGP OPO efficiency. A factor of 2 is added to the overall efficiency figure because the unconverted Ho:YAG laser output after the OPO stage also forms a useful output. These figures serve to highlight that the cascaded nature of the design, with multiple optical stages, impacts the overall electrical-to-optical efficiency even if each individual stage demonstrates high conversion efficiency. Note that the figure of 15% is not the overall wallplug efficiency; the thermal management system and power supply efficiencies, amongst many other factors, have also to be taken into consideration.

A key emerging nonlinear material is quasi-phasematched (QPM) gallium arsenide (GaAs), which is the long wavelength analogue of the ubiquitous PPLN. Effective nonlinear coefficient values are in the range 60-122 pm/V for the QPM structure (based on published data), along with a wide transparency window stretching into the far-IR. Unlike ZGP there is no defect-related absorption at the pump wavelength; good quality material should also be free of absorption at the OPO wavelengths. There is no walk-off to consider in the QPM structure, therefore tight focusing geometries can be employed. QPM GaAs offers the intriguing possibility of a quasi-cw or true cw mid-IR OPO for the DIRCM application. The major hurdle to overcome, paralleling the development of high quality PPLN, is to minimise the scattering losses at the interfaces of the domain-reversed material. One of the most promising methods for fabricating a QPM structure in GaAs is to grow the optical structure on an orientation-patterned (OP) template of domain-reversed material. Standard semiconductor growth techniques for both steps can be used (MBE and HVPE/LPE respectively), using photolithography and etching to complete the template. An optical-to-optical conversion efficiency of 46.5% in an OPGaAs OPO, generating 2.85 W of average output power when pumped by a Q-switched Ho:YAG laser, has recently been reported[12]. The combination of symmetric crystalline structure and refractive index isotropy allows for a range of pump polarisation states to be supported in QPM GaAs, including random polarisation (unlike birefringent ZGP where a linearly polarised pump beam is essential)[13,14]. Waveguide geometries can also be employed in order to confine the pump light and increase the interaction length[15].

The current trends in technology development suggest that the long-term solution for the fibre-based mid-IR laser could take the form shown schematically in figure 1.

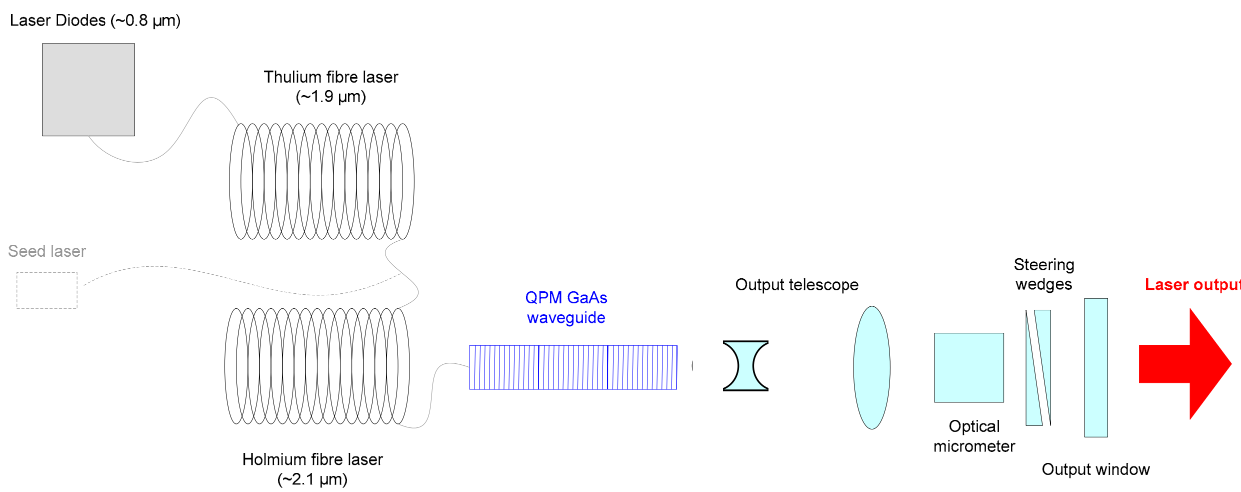

Figure 1: Schematic of potential long-term solution for a fibre-based mid-IR laser

An all-fibre solution is in principle possible, using a thulium fibre to pump a section of holmium fibre, which is in turn spliced onto a section of QPM GaAs waveguide (or alternative material should a superior candidate be identified). This arrangement also allows for a seed laser to be incorporated for the holmium stage, if it is advantageous to generate higher peak power pulsed output, rather than true cw, to enhance the nonlinear conversion efficiency. The overall parts count is significantly reduced as compared to the standard bulk solid-state laser and OPO combination. Bulk optics are only required at the output end, with a telescope to expand the collinear beams in order to generate the required far-field beam divergence. Beam steering to align the output for integration with a beam pointer is performed using the known robust combination of an optical micrometer for linear displacement, in tandem with a pair of steering edges for angular adjustment. Common boresight of the output beams is maintained over the full environment.

Considerable development, both in the holmium fibre laser technology, and in the fabrication of low-loss QPM nonlinear materials, is still required. The fibre laser stage could be further simplified if the thulium fibre laser itself could be forced to operate efficiently at a wavelength close to 2.1 µm. An attractive hybrid solution would involve a sufficiently high brightness laser diode source emitting close to 2.1 µm pumping the QPM waveguide structure directly.

3.2 Optically pumped semiconductor lasers (OPSLs)

OPSLs are potentially attractive laser source for the DIRCM application. Instead of electrically pumping the semiconductor laser, as with conventional laser diodes, a laser source is used to optically pump the semiconductor gain medium. In this respect OPSLs more closely resemble bulk solid-state lasers. Greater flexibility in optimising the optical properties of the semiconductor gain medium is possible because its electrical properties do not simultaneously need optimisation, as with a conventional laser diode.

Two distinct geometries exist for OPSLs operating in the mid-IR, namely edge-emitting, where the optical pump beam forms a gain stripe between the facets of the chip, and surface emitting, where the chip is pumped and emits through its top face. With the surface emitting geometry a distributed Bragg reflector (DBR) mirror on the chip, plus a separate output mirror, form the resonator. The surface-emitting geometry is referred to as VECSEL (vertical external cavity surface emitting laser) or SDL (semiconductor disc laser), given its similarity to the bulk solid-state laser thin disc geometry. This surface-emitting geometry lends itself to power scaling while maintaining good beam quality, hence it acts as an efficient brightness converter for low beam quality high power laser diode pump sources. Absorption of the pump light occurs within the thickness of the OPSL structure i.e. a few microns, in both edge and surface emitting geometries. Therefore the beam quality of the pump light is not critical, as long as it can be focussed to the required size in the plane of the semiconductor chip. Efficient heat removal through the back surface of the SDL chip occurs when it is bonded to a heatsink, and also via the top surface if a transparent heatspreader is used.

To date most of the work with SDLs has taken place in the near-IR, using frequency doubling for efficient generation of visible wavelengths. Laser products based on this technology are now commercially available at power levels up to 8 W[16]. A comprehensive review article detailing developments in SDLs spanning the near-IR and mid-IR is available[17].

Generation of 5 W cw from an type II quantum well SDL emitting at 2 µm has been reported[18]. A simple and compact external cavity is used to ensure good beam quality. Heatsinking of the semiconductor chip is key to produce an efficient laser source. In this case a diamond heatspreader plate is used. With the heatsink cooled to below room temperature using a thermoelectric cooler (TEC), an optical to optical conversion efficiency of 20% is achieved. The corresponding M^2 value for the output beam is less than 1.5.

The only reports in the open literature on optically pumped semiconductor lasers emitting at wavelengths around 4 µm are those published by the Air Force Research Labs[19,20]. A monolithic unstable resonator edge emitter design is used with a concave rear mirror machined on the semiconductor chip. With the unstable resonator design the beam quality was improved by an order of magnitude to an M^2 of 3, with a 15% reduction in output power compared to the standard broad stripe multimode emitter. Using a fibre-coupled 1.9 µm diode bar pump source, optical-to-optical conversion efficiencies of ~25% have been achieved at cryogenic temperatures (80-100K), with output powers at the watt level. These devices do not lase at room temperature. Cryogenic cooling in field-deployable lasers requires a closed cycle Stirling cooler, which are inherently inefficient devices (5% efficiency typically quoted[21]). The cooling capacity required scales with the average power. A top-level estimate of the electrical-to-optical conversion efficiency from electrical drive power for the pump diodes to useful optical output is 4%, based on figures of 15% electrical-to-optical diode efficiency[22] and 25% optical-to-optical OPSL efficiency. Currently there are no known sources of room temperature long wavelength output using the SDL geometry.

Using optical pumping the semiconductor composition and structure can be readily designed to give output across the waveband of interest. Simultaneous dual-wavelength operation from a single edge-emitter OPSL has recently been reported[23].

In the longer term it is desirable to seek room temperature solutions for long wavelength generation in order to optimise the overall wallplug efficiency, ideally using the SDL geometry to provide a power scalable geometry with good beam quality. Overcoming the non-radiative Auger recombination losses at these longer wavelengths is a significant challenge for non-cryogenic operation.

3.3 Electrically pumped semiconductor lasers

At the short wavelength end of the 2-5 μm waveband bipolar laser diodes in the GaSb materials system are available commercially from two sources in Germany[24,25]. Single emitter and bar formats are available, with a maximum power of 0.5 W from a broad area single emitter, with an electrical-to-optical efficiency in the range 15-20%. The output beam is highly multimode in the slow-axis direction, therefore a prohibitively large near-field aperture is needed in order to produce the desired far-field divergence, even if a beam circularisation technique is used. A tapered emitter geometry for the laser diode allows the generation of high powers from a single emitter in a near diffraction-limited beam. Tapered devices are commercially available in the near-IR at the 2 W power level (electrical-to-optical conversion efficiency approximately 45%) with an M^2 of approximately 1.5, but not at the longer wavelengths of interest here[24].

Emission from a conventional semiconductor laser is based upon the band-gap transition of that particular material, with highest powers achieved in the near-IR. Tuning of the output wavelength can be achieved by altering the particular structure grown, and by variation of the doping of the semiconductor. However for longer wavelength emission based upon band-gap transitions lower band-gap materials are required, which are inherently more temperature sensitive and hence less efficient (non-radiative Auger recombination losses start to dominate these low band-gap transitions).

The quantum cascade laser (QCL) can provide direct generation of the longer wavelengths of interest. The key to QCL versatility is the fact that it is not based upon a band-gap transition, rather an intersubband transition between two conduction band energy levels within the quantum well structure. Therefore reliable and well-understood semiconductor materials (most notably indium phosphide and gallium arsenide) can be selected to generate laser output at room temperature in a wavelength range unrelated to the material band-gap. Multiple gain regions are used, with electrons cascading from one gain region to the next. Hence the growth structure is complicated with respect to other semiconductor lasers, with 30-50 gain regions per single emitter, and multiple layers per gain region (plus associated electron injection regions). High quality growth is key to the rapid advance in QCL performance in the last decade, supported by continuing improvements in contact metallurgy, waveguide geometry, bonding methods, submount material, heatspreaders and device orientation (e.g. epi-side up/down and buried structures), improvements primarily associated with improving the thermal management at the chip level[26].

A room temperature cw output power of 3 W from a single emitter chip at a wavelength of 4.6 μm[27], at an electrical-to-optical conversion efficiency of 13%, has recently been reported by Pranalytica. The beam quality of the output at this power level is not detailed; however the stripe width of 11.6 μm suggests that the output should be near diffraction-limited. This device was fabricated in GaInAs/AlInAs on an InP substrate. Simply scaling the emitter width to scale the output power comes at the price of reduced beam quality, as with conventional edge-emitting laser diodes.

The combination of highest room temperature cw power and shortest wavelength reported in the open literature for this material system is 100 mW at at wavelength of 3.8 μm[28]. Antimonide-based QCLs producing emission in the range 3-3.5 μm are a topic of research for a number of groups. It is unclear which materials system will best fill the gap in wavelength coverage for QCLs in the mid-IR.

The current trends in technology development suggest that the long-term solution for the semiconductor laser could take the form shown schematically in figure 2. It assumes sufficiently high brightness single emitters are available at the short and long wavelength extremes in order to simply need two laser chips. The electrically-driven semiconductor laser will ultimately offer superior electrical-to-optical conversion efficiency to its optically pumped equivalent. It is also assumed that multiple wavelengths around 4 μm can efficiently be generated from a single chip. The separate sources require beam combining to generate collinear output beams, with one source having to be steered onto the axis defined by the second source. If sufficient brightness or wavelength coverage cannot be generated by this minimum number of sources, additional sources are needed, which adds an additional layer of beam combining, implying an increase in parts count and complexity, with a consequent reduction in overall efficiency.

As shown in figure 2 the complexity is terms of parts count for the semiconductor laser based IRCM source is comparable to the fibre laser based solution in figure 1. The principle unanswered question is whether the electrical-to-optical efficiency of the semiconductor lasers (diodes, OPSLs and QCLs) will improve sufficiently to offer a marked enhancement in overall wallplug efficiency over the fibre-laser based solution.

A robust beam combining method for the separate semiconductor laser sources is essential in order to guarantee that a common boresight will be maintained over the full environment.

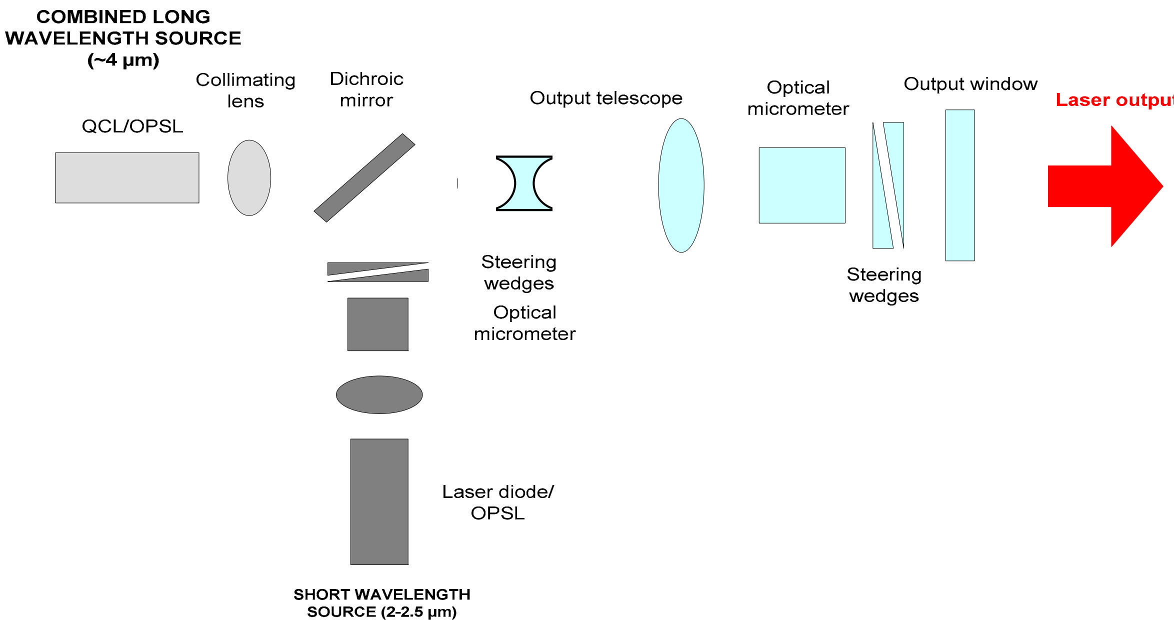

Figure 2: Schematic of potential long-term solution for a semiconductor-based mid-IR laser

Considerable development, both in the shorter wavelength laser diodes and longer wavelength QCLS, plus their OPSL counterparts, is needed to achieve this long-term solution.

4. LASER DESIGN CONSIDERATIONS

As mentioned previously in section 2 there is a general trend towards enhancing the overall wallplug efficiency of military laser systems, without compromising the optical performance required. The main benefits to be had include:

- Reduced prime power requirement from the platform
- Reduced mass/volume
- Reduced complexity and cost
- Increased reliability
- Improved performance over the full environment

Airborne platforms are typically limited in space and power available to support additional functionality. Reducing the power and footprint of a DIRCM laser source eases installation issues; combined with reduced cost smaller, lower value platforms can also then be considered for protection.

Whilst the core laser technology is often the most interesting subject in most of the open literature by virtue of novelty, many more mundane elements are overlooked when reporting emerging, low TRL approaches. Addressing interface control requirements for the electrical, mechanical and optical interfaces constitute a major proportion of the overall laser, and these packaging and system integration issues are left to manufacturers such as SELEX Galileo to address.

The supporting infrastructure for the laser system incorporating any core laser technology will have broadly similar elements: power supply, thermal management (temperature control and heat exchanger), control cards etc. For example, a control card is essential in a system for both interfacing with rest of the DIRCM system, and for internal monitoring/housekeeping of the laser. A large proportion, typically around 50%, of the parts count or bill of materials (BoM) is associated with the supporting infrastructure elements. Generally the parts count is related to cost and reliability, and it is a major consideration for laser manufacturers.

The overall laser system outcome can be surprisingly agnostic to core laser technology as many of perceived benefits of a new technology route do not necessarily translate to a compact, low-cost, manufacturable laser system.

It is instructive to consider the case of a Selex Galileo production-standard target designation laser as a general example to highlight these issues. This organisation has a long history of manufacturing target designation lasers, and currently has several fully qualified designs in production. Product details are available from the Selex Galileo website[29]. The target designation laser design is based on diode-pumped Q-switched Nd:YAG slab laser technology. An OPO stage is used to convert the output to the eyesafe region in the range 1.5-1.6 µm for use in training mode. Typically 300 mJ is produced at 1 µm, and up to 100 mJ in the eyesafe region, at a PRF of 20 Hz, based on the performance over the product range (not on a specific design). Power consumption is approximately 300 W, resulting in an overall laser wallplug efficiency of approximately 2% (Nd:YAG laser only). Representative conversion efficiencies for the optical modules are 50% electrical-to-optical efficiency for the pump diodes (quasi-cw array stacks), 25% optical-to-optical efficiency for the Nd:YAG slab laser, and 30% optical-to-optical efficiency for the OPO.

The architecture of this class of laser is shown in figure 3.

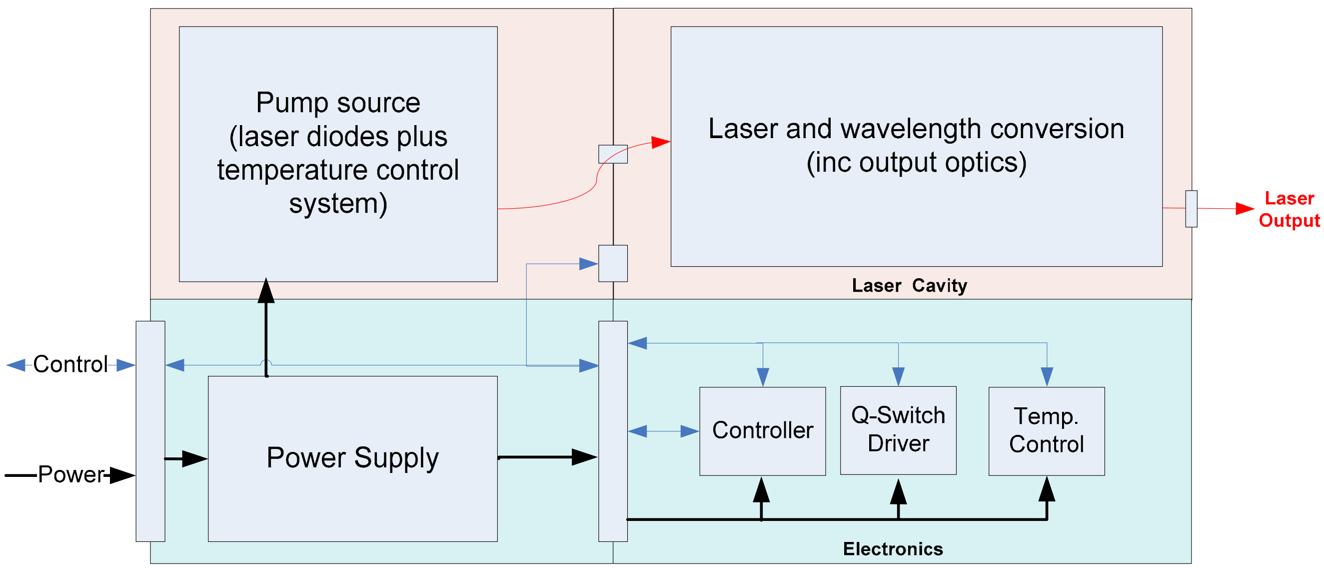

Figure 3: Generic architecture of target designation laser

The footprint is split approximately equally between the optical modules and the ancillary support modules. Figures that highlight this further include:

- Thermal management accounts for approximately 40% of the total power budget (primarily associated with the laser diode pump source, where a conduction-cooled TEC arrangement is typically used)
- Power supply/filter efficiency accounts for approximately 25% of total power budget
- Photon generation accounts for approximately 20% of the total power budget
- Control accounts for approximately 15% of total power budget
- Chassis accounts for approximately 30% of the volume

Filtering of the platform input power with its associated efficiency, the efficiency of the power supply module, and the volume of chassis required to provide a stiff structure (plus hermetic sealing of the pockets within the chassis), are all present independent of the core laser technology. A change in core laser technology that reduces the parts count and complexity of the optical module, but does not significantly improve the electrical-to-optical efficiency of the photon generation, will not significantly reduce the overall laser wallplug efficiency; hence the mass/volume, overall complexity, and cost will not be significantly reduced, nor will the reliability be enhanced. The generic target designation laser example considered here highlights that the most significant improvement to be had in overall wallplug efficiency for the baseline laser design is based on reducing the thermal management power budget.

Furthermore, the baseline (ambient) performance must be inset by the following factors in order to meet the specified performance in a production-standard design.

- **Design:** An inset from lab-based 'hero' results is required in order to provide a repeatable baseline performance.
- **Manufacture:** This inset is required to take account of moving from the one-off prototype build type scenario, where the laser is typically hand-crafted by highly qualified design engineers using the best components procured in low volume, to the full production scenario where components are ordered in large volumes for rapid assembly on a production line. The natural variation in quality of sub-components when used in volume must be taken into account.
- **Environment:** The laser system design constraints are also extenuated by the need to operate over the military airborne operational environment. The principal contributions are:

  Temperature – the typical range is -40°C to +60°C. Temperature impacts the key laser parameters (power, beam quality and boresight), and can significantly complicate the thermal management.

  Vibration – the laser must be capable of operating in the harsh vibration environment typical of airborne platforms. Vibration impacts the key laser parameters (in particular boresight, but also power and beam quality).

  Altitude – the primary impact here is the reduction in air pressure with altitude on laser systems using forced air cooling as part of the thermal management system. A secondary impact is on any distortions to the chassis, hence the optical beam path, produced by altitude-induced pressure differences.
- **End of life:** In a typical solid-state laser the critical component is the laser diode pump source. An excess of pump power is provided at the start of life i.e. when first built, in order to take account of the drop in laser diode optical output with time, in order to still meet the specified performance at the end of life. Alternatively an extra level of control is required in order to increase the laser diode drive current over time to maintain constant optical output.

To accommodate these extremes, it is common for manufactures to model in detail laser characteristics over the whole environmental envelope and introduce sufficient design margin to ensure minimum performance in operation and through life. Using such a worst-case design philosophy in excess of 50% can readily be added to the start-of-life output power requirement. This generally results in manufacturable systems being conservative in performance in comparison with reported performances in the open literature of similar core laser technology. Perturbation-stable resonator designs are critical in order to minimise the effects of any misalignments induced by movements of optical components over the temperature and vibration range. Careful design of the overall optical layout, combined with a suitably robust chassis design, is required in order to minimise any boresight shifts over the temperature and vibration range.

In terms of reliability a mean time before failure (MTBF) figure of several thousand hours, combined with a storage lifetime of order 10 years, is typical for military airborne laser systems. Minimising the thermal loading, hence stressing, of key components is a major step towards maximising the MTBF figure. Similarly reducing the overall parts count acts to enhance the overall MTBF figure of the laser system.

A lengthy and expensive qualification programme is required, prior to production commencing, in order to verify that the design of a prototype laser system will operate to specification over the full environment. Therefore in order to displace an incumbent technology, which is by definition already a fully-qualified product, any new technology has to offer a significant enhancement in performance, combined with a reduction in cost, in order to justify the investment.

The power budget allocation, plus the insets to performance required, discussed previously indicate that the single largest contributor to the laser system power budget is the thermal management system. Although the numbers listed are associated with a generic target designation laser, the same holds true for an IRCM laser. Therefore a design change that significantly reduces the thermal management requirements will have a significant knock-on effect in improving the overall wallplug efficiency. The ultimate solution would be a truly athermal laser, where no active temperature control is needed at all, and where the laser performance is completely independent of the ambient temperature. Clearly this is not the case based on current candidate technology performance, both for the solid-state and semiconductor laser options; equally clearly a truly athermal laser design is an extremely challenging goal. Chassis material choice and design, plus the detailed optical layout design, can be used to minimise the effect of temperature-induced distortions on the laser performance. However this itself does not eliminate the need for a thermal management system. Reducing the heat load generated by maximising the conversion efficiency of the optical stages in the laser will directly reduce the power requirements of the thermal management system. However if the key output parameters of the optical stages are temperature-dependent there is still a need for active temperature control. Alternatively the performance at ambient has to be scaled in order that the specified output is still achieved at the temperature extremes.

An interim step to reducing the thermal management requirements is to operate at elevated temperature, based on the premise that heating has a lower power requirement than cooling. This is a standard technique used with the laser diode pump source in military solid-state lasers. Here there is a trade-off between the electrical-to-optical conversion efficiency of the laser diodes against the peak power requirement for the overall laser system. A second interim step is to operate in heat capacity mode, using the self-heating of the laser diode pump source (or the semiconductor laser direct generation source) to maintain the temperature during firing. Active temperature control is still required for both solutions; therefore there is not a significant impact on the overall parts count and complexity. The peak power requirement is reduced, but the overall wallplug efficiency is not significantly improved.

For the candidate technologies considered in section 3 there are a number of issues to address in order for maximum wallplug efficiency solutions to be achieved. The proposed all-fibre route shown in figure 2 minimises the parts count and complexity of the traditional solid-state laser route. The electrical-to-optical efficiency, from laser diode electrical input power to useful mid-IR optical output power, will be enhanced from the current bulk optic version because of the removal of the optics trains between each of the optical modules, and by continued improvements in laser diode efficiency. The conversion efficiency of the optical stages (fibre laser and OPO) is unlikely to increase significantly, given the high conversion efficiencies of the optical stages of the current bulk optic solution. Therefore the upgrade path is principally associated with reducing the parts count, with a reduction in mass/volume, and a reduction in cost. Opportunities to reduce the thermal management system involve reducing the temperature sensitivity of the fibre laser stage, primarily considering the laser diodes, but also the gain fibre itself. An enhancement in electrical-to-optical efficiency to 20% is predicted, equating to an overall wallplug efficiency not exceeding 5% (any further increase would necessitate a significant reduction in the thermal management system power requirement). A key issue is the development of the QPM GaAs nonlinear wavelength conversion element.

For the direct generation semiconductor laser solutions an electrical-to-optical conversion efficiency in excess of 25% is required in order to demonstrate a clear advantage over the fibre-based route. As small a number of emitters as possible to meet the output power/brightness requirement is important, in order to minimise the beam combining requirements (as shown in figure 3). The electrical-to-optical conversion efficiency target is most likely to be met by the electrically-pumped semiconductor laser solutions. However, power scaling and high brightness output favour the OPSL solution, in particular the SDL geometry. Opportunities to reduce the thermal management system involve reducing the temperature sensitivity of the conversion efficiency of the semiconductor laser stages. This is particularly challenging for the long wavelength OPSL solution, given the difficulty in overcoming Auger recombination losses at non-cryogenic temperatures. A key issue is development of the semiconductor materials systems, both for the electrically-pumped and optically-pumped variants.

Materials growth is a major development issue for both the fibre and semiconductor laser based options. The key materials are QPM GaAs and QCL chips respectively. For QPM GaAs the challenge is to be able to fabricate low loss material in production volumes; for QCLs the challenge is efficiency improvements in production volumes. Both are semiconductor-based, with comparable volumes of material required, hence to first approximation costs are comparable. At this time it is unclear if there are any major commercial applications, with comparable specifications to the DIRCM application, to support development of these materials. If development occurs solely to support the DIRCM application the full cost benefit usually associated with semiconductor fabrication in volume will not be realised.

5. CONCLUSIONS

The DIRCM application sets a demanding specification on the laser source. In order to maximise ‘useful energy on target’ the laser has to demonstrate the following general properties:

- Simultaneous multi-wavelength output in the mid-IR 2-5 μm waveband, with wavelength diversity
- High brightness output
- Low beam jitter
- Fast turn-on time
- Modulation flexibility
- High operational duty cycle

Integration with a compact beam director places an upper limit on the beam quality of the laser output. The laser system has to provide the performance as listed here over the full environment experienced by the airborne platform.

Furthermore there is a push towards maximising the overall wallplug efficiency of the laser, without compromising any of the key optical functions. There are many benefits to be had:

- Reduced prime power requirement from the platform
- Reduced mass/volume
- Reduced complexity and cost
- Increased reliability
- Improved performance over the full environment

Cost reduction is the principal driver for both the laser manufacturer and the end user.

Historically the solid-state laser, using an out-of-band pump laser with cascaded wavelength conversion stages to generate multi-wavelength in-band output, has been the favoured route for the IRCM laser. The continuing maturation of fibre laser technology, particularly the thulium fibre laser, has improved the efficiency of the pump laser stage. Continuing developments in nonlinear materials, in particular ZGP and QPM GaAs, has enhanced the performance of the long wavelength generation stage. The main advantages offered by this route are technology maturity, power scalability, high brightness output, wavelength diversity and collinear output beams.

Recent developments in semiconductor laser solutions for direct generation in the mid-IR waveband have significantly closed the performance gap with the solid-state laser route. In particular there have been rapid improvements in the performance of QCLs operating at the long wavelength end of the mid-IR waveband in the last 5 years. An electrically pumped semiconductor laser such as the QCL is in principle the most efficient route to mid-IR laser output. However further development of this technology, in order to enhance the device efficiency, is required, combined with the development of high brightness laser diodes at the short wavelength end of the mid-IR waveband. If a robust beam combining method is used this solution promises a low complexity optical module. Optically pumped semiconductor lasers are offered as a power scalable high brightness alternative, but at the price of reduced maximum efficiency as compared with fully optimised electrically pumped semiconductor lasers.

The single largest contributor to the overall power requirement of a typical laser system is the thermal management system. Therefore a laser technology which makes a significant step closer to truly athermal performance offers the best route forward to maximising the overall laser wallplug efficiency. Such a performance enhancement is needed in order to displace the incumbent technology.

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