High-efficiency Pulsed Laser Transmitters For Deep-space Communication

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Abstract

Highly efficient laser sources are required for deep space optical telecommunication. This paper investigates the efficiency components for pulsed diode pumped solid state laser transmitters and determines the overall wall-plug efficiency applicable to a space-borne system. Thermal control of the pump diodes is critical to achieving optimum photon efficiency. Hence, a thermal model involving either a thermo-electric cooler or loop heat pipes is applied to the efficiency calculations. The electro-optical conversion efficiency for an optimized bulk design is expected to be up to 28 % with the overall wall-plug efficiency being in the 12-16 % range depending on the radiator temperature. A fiber based master-oscillator power-amplifier design is also investigated with passively cooled pumped diodes and promises high efficiency operation. Preliminary results from an evaluation model are also discussed.

Keywords: Optical communications, laser, high efficiency

Introduction

Deep space optical communication requires compact, efficient lasers that are capable of high peak powers with good beam quality. Diode-pumped-solid-state (DPSS) lasers using a pulse position modulation (PPM) format are well suited to such applications and have been extensively developed [1]. However, commercial laser development has focussed on increasing the peak power predominately, while not addressing high photon efficiency. This paper examines different schemes for maximizing the overall wall-plug efficiency of DPSS lasers with a detailed theoretical analysis of all the efficiency components. Particular attention is paid to optimizing the thermal design with the use of active loop heat pipes (ALHP) as an alternative to thermo-electrical cooling (TEC) of the pump diodes. A fiber based master-oscillator power-amplifier (MOPA) geometry with passively cooled pump diodes was also investigated. Finally, some preliminary experimental results from a laboratory prototype are presented with the aim of realizing these optimized high efficiency designs.

The first section details each component of the overall efficiency of the laser and tabulates the current efficiencies already documented in the literature. A comparison is then made to that which is theoretically achievable. Determining factors and estimates of the wall-plug efficiency of a flight laser transmitter are also given for three different architectures. A bulk diode pumped Nd:YAG is studied with TEC of the pump diodes as well as ALHP temperature control of the pump diodes and a Yb doped fiber amplifier with passively cooled pump diodes. The latter is possible due to the Yb doped fiber absorption being less sensitive to temperature induced wavelength variations of the pump source [2]. In the second section, the power requirements from thermal modeling of the pump diodes are derived based on the previous efficiency analysis. Finally, some preliminary results from an evaluation model of a bulk solid state diode pumped solid state and the specifications of a commercial fiber based MOPA pulsed laser are presented.

The transmit laser power requirements for a typical deep space mission are derived from the data rate or volume which is driven by the science requirements. Due to strict electrical power and mass budgets on deep space missions, it is extremely important that the laser transmitter efficiency be maximized. This translates directly into reduced launch costs and extended mission opportunities. An example of the laser requirements for a hypothetical deep space mission is as follows. Taking a downlink from a Mars orbiter at a distance of 1 – 2 AU and a daytime data rate of 160 kbps requires a laser with 1

W of average output power and 6 kW of peak power. The data is encoded and modulated in 256-ary or 8 bit PPM format to give bit error rates less than 10^{-6}. This implies a pulse repetition rate of 20 kHz. The link budget assumes an emitting aperture of 30 cm and receive aperture of 10 m and a high quantum efficiency avalanche photodiode detector with 3 dB of margin. The wavelength is assumed to be approximately 1 µm. Longer wavelength lasers are possible but the required output power is increased due to the decreased receive sensitivity of non Si detectors. Trade-offs in power, data rate and aperture size are then possible depending on the exact mission constraints.

Laser Efficiency Analysis

The efficiency of a solid state laser is determined by three key parameters: the pump semiconductor laser diode electrical – optical conversion efficiency, η_D, the coupling or transfer efficiency of the pump light into the active medium, η_T, and the optical – optical conversion efficiency of the active gain media, $\eta_{opt\text{-}opt}$. These parameters can be further broken down to give the overall efficiency as [3]:

$$\eta = \eta_D \, \eta_T \, \eta_{opt\text{-}opt} = \eta_D \, \eta_{T'} \, \eta_{abs} \, \eta_S \, \eta_Q \, \eta_B \, \eta_{ST} \, \eta_{ASE} \, \eta_E \, \eta_R$$

where $\eta_{T'}$ is the optical efficiency of coupling the pump light, η_{abs} is the absorption efficiency of the gain media, η_S is the stokes efficiency or ratio of the input pump photon energy to output photon energy, η_Q is the quantum efficiency or fraction of pump photons reaching the upper laser level, η_B is the spatial beam overlap of the resonator modes with the upper state inversion, η_{ST} is the storage or depletion efficiency, η_{ASE} represents the loss due to amplified spontaneous emission which is the reciprocal of the depopulation rate of the upper laser level, η_E is the fraction of absorbed energy extracted and η_R is the resonator loss including reflective and scattering losses. Sometimes the efficiencies are grouped as the transfer efficiency, η_T, upper-state lifetime efficiency $\eta_U = \eta_S\eta_Q$ and extraction efficiency under Q-switched operation, $\eta_{eq} = \eta_{ST} \, \eta_{ASE} \, \eta_E$.

Table 1and 2 lists the electrical-optical efficiency components for a bulk solid state laser and a fiber based geometry, respectively. Typically demonstrated values are shown first for cw and pulsed operation. The select column lists the optimum demonstrated values for each component or group of components but these have not necessarily been demonstrated in a single Nd:YAG device. However, in reference [4] greater than 15 % efficiency has been shown for a cw Nd:YVO_4 device. The second column lists the optimized value for each component based on current estimates as referenced in the table. Finally, the theoretical limit of each value is listed. These efficiency components may not be achievable simultaneously but serve as an ideal limit. The goal of this research is to explore the experimental realization of the optimized design and determine its impact on the wall-plug efficiency of a flight laser transmitter.

Case (1): 1064 nm Nd: YAG Laser Pumped at 810 nm			**Demonstrated**			**Optimized Design**	**Ideal (theoretical)**
			Cw	Pulsed	Select		
Diode Laser Efficiency		ηD	0.35[4]	0.19[1]	0.35[4]	0.5[8]	0.75[14]
Transfer Efficiency		ηT	0.63[5]	0.78[1]	0.78[1]	0.9[5,3]	0.95[3]
Stokes Efficiency		ηS	0.76			0.76	0.76
Quantum Efficiency		ηQ	0.8			0.95[3]	0.995[3]
Beam Fill Factor		ηB	0.9			1[9]	1[9]
		ηopt-opt	0.37[5,6]	0.55[1]	0.55[1]		
Depletion/Storage Efficiency		ηST				0.95[10]	1[15]
Extraction Efficiency		ηE	0.95			0.95[11]	0.99[15]
ASE Losses		ηA	1			1[12]	1[12]
Resonator Losses		ηR	0.71			0.95[13]	0.97[15]
E-O Efficiency		η	8%[3]	8%[1]	15%[7]	28%	51%

Table 1. Laser efficiency for a 1064 nm Nd:YAG laser pumped at 810 nm

Case (2): 1064 nm Yb: Glass Fiber Amplifier Pumped at 974 nm			**Typical Demonstrated**			**Optimized Design**	**Ideal (theoretical)**
			Cw - amp.	Pulsed	select		
Diode Laser Efficiency		ηD	0.2[16]	0.35[4]	0.35[4]	0.66[21]	0.75[24]
Transfer Efficiency		ηT	0.9[17]	0.7[18,19]	0.9[17]	0.96[16]	0.98[22]
Stokes Efficiency		ηS	0.91			0.91	0.91
Quantum Efficiency		ηQ	0.9			0.95[18]	0.98[25]
Beam (mode) Fill Factor		ηB	0.95			0.98[22]	1[26]
Optical – optical		ηopt-opt	0.775[16]	0.75[16]	0.775[16]	0.83[18]	0.89[25]
ASE Losses		ηA		0.9[18]	0.9[18]	0.98[22]	1[26]
Resonator w/ Q-switch		ηW		0.6[20]	0.6[20]	0.8[23]	0.9[22]
E-O Efficiency		η	14%	10%	15%	42%	59%

Table 2. Laser efficiency for a 1064 nm Yb:glass fiber amplifier pumped at 974 nm

Parameter	**Value (W)**	**Notes**
Average Optical Output Power	1	Assumption from link budget
Power to diode: 35% efficiency 50% efficiency 75% efficiency	6.67 3.57 1.96	Depends on overall efficiency and pump diode efficiency from Table 1,2
Power for thermal control of laser comp: TEC Loop Heat Pipe Passive	 0-25 0-1 0	Calculated from thermal model, varies with radiator temperature and pump diode efficiency – see below
Auxiliary heaters, control electronics of laser dedicated thermal subsystem down to radiator	0.5	Estimated. Could be reduced to 0.1 W.
Thermal control to compensate for diode aging effects	0.2	Estimated. Could be reduced to 0 W.
Auxiliary electronics, e.g. monitor photodiode, thermisters etc	0.3	Estimated.
Power consumption for Q-switch or pulsing mechanism	1	Optimum for E-O Q-switch
DC-DC power conversion inefficiency (90% for most V & I, 50 % for E-O Q-switch)		Calculated from above
Total Input Power	P	Sum of above
Total Wall-plug Efficiency	1/P %	

Table 3. Wall-plug laser efficiency parameters.

The wall-plug efficiency of a flight laser transmitter, in addition, takes into account all the possible power requirements. These include the thermal control of the laser components and electronics, auxiliary control electronics for monitor photodiodes, thermisters etc, power consumption for the Q-switch and the DC-DC power conversion efficiency of all the drive electronics. Once these are known or at least estimated the true wall-plug efficiency can be quoted. Table 3 lists the efficiency component values.

Thermal Modeling of Semiconductor Pump Laser Diodes

Table 3 shows that besides the pump diode electrical-optical efficiency, the main variable that impacts the wall-plug efficiency is the thermal control of the pump diode. In order to minimize the thermal power requirements, three different pump diode cooling architectures were investigated. Traditionally TEC is the most common approach so a detailed thermal model for such a device was used to predict the power requirements. A standard BiTe structure, as used in space-borne applications, was employed. A new technology that is being explored is the use of active loop heat pipes. These involve a saturated ammonia solution which is able to transport the heat to a remote heat sink on the spacecraft with minimal power requirements and temperature stability of less than 0.5 ^{o} C. Data for the power requirements of the LHP were taken from calculations based on the specifications of a commercially available device [26]. As mentioned earlier fiber based amplifier geometries have broad absorption features and do not require stringent temperature controlled wavelength stability. This allows the use of passively cooled pump diodes with the more efficient InGaAs material systems [21]. These can be designed to operate at the correct wavelength for a given temperature a priori.

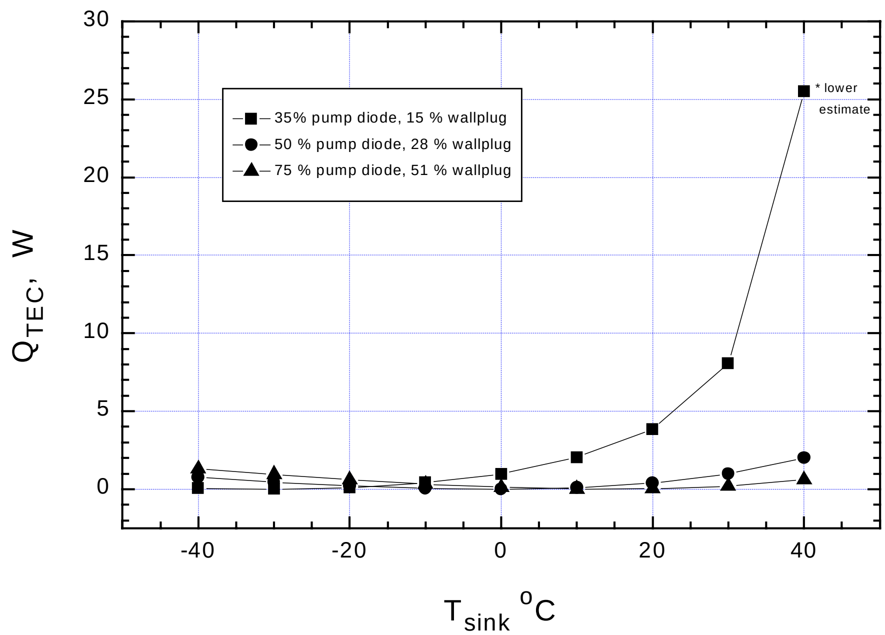

Figure 1. TEC power required for 1 W output power laser transmitter as a function of radiator heat sink temperature. Inset give efficiency values used in calculations.

The results from the thermal modeling of the TEC are shown in Fig. 1 for the three pump laser diode efficiencies derived earlier. The thermal resistance of the diode was taken as 5 K/W and the heat sink ranged from –40 to +40 ^{o} C as typical for spacecraft. Q_{TEC} represents the power required to drive the TEC in order to maintain a device temperature of 20 ^{o} C for varying heat sink temperatures. When the more efficient pump diodes are used, the power requirements are below 2 W comparable to LHP. However, using current diodes with efficiency around 35 % causes a dramatic increase in the power requirements at the higher heat sink temperatures.

Figure 2 compares the overall wall-plug efficiency using the three different cooling architectures, each involving the range of pump diode efficiency, over the varying heat sink temperature range. As expected, the passively cooled pump diodes in the fiber based geometry is the most efficient architecture. However, there is a peak power limitation of fibers due to the optical damage threshold so they may not be suitable for a particular mission where extremely high peak powers, on the order of MW/pulse, would be required. ALHPs provide a more efficient design over a wider temperature range.

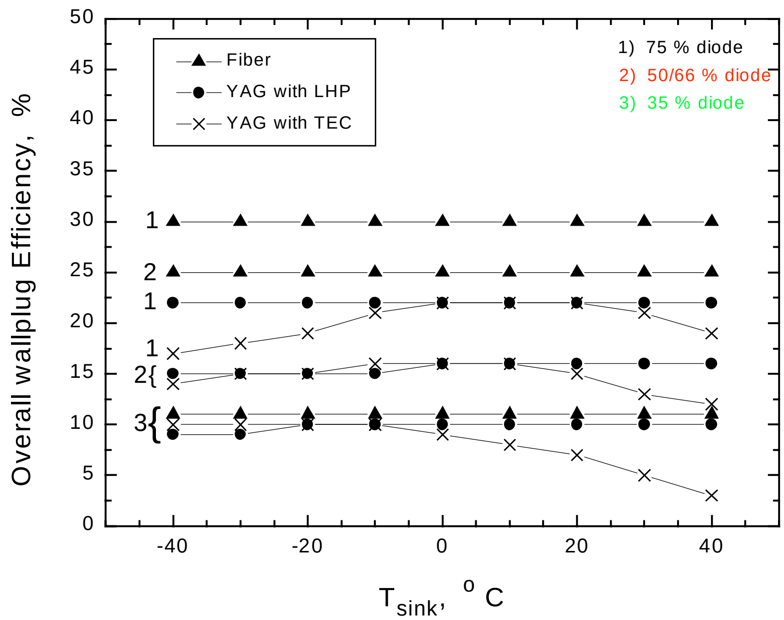

Figure 2. Overall wall-plug efficiency for pulsed laser transmitter as a function of radiator heat sink temperature. Insets give efficiency values.

The results can be summarized in the following table where the range is determined by the heat sink temperature:

Laser Architecture	Optimized Design	Theoretical Limit
Nd:YAG with TEC	12 –16 %	17 –22 %
Nd:YAG with ALHP	15 - 16%	22 %
Yb:Glass fiber	25 %	30 %

Table 4. Summary of wall-plug laser efficiency for a 1 W average output power laser transmitter. The optimized design involves a 50% (66% for fiber based) and the theoretical involves a 75 % pump laser diode efficiency.

Experimental Development

In order to experimentally realize energy efficient lasers for future NASA deep space optical communications, a multi-pronged approach of assembly, test and characterization of evaluation models has been initiated. We have assembled a Nd:YAG laser breadboard with an emphasis on demonstrating the high wall-plug efficiency. We have also recently procured a pulsed fiber laser from IPG Photonics with a reported wall plug efficiency of 10% for comparison [27].

The Nd:YAG laser breadboard functional specifications and requirements are listed below:

Pump mechanism: End - pumped using diode lasers

Output Peak Power:	> 4 kW peak power @ 10 KHz (1 W average power)
Pulse width:	≤ 30 ns at pulse repetition rate of 2 - 15 kHz
Input Pump Power:	4 W CW
Expected Efficiency:	≥ 10% wall plug

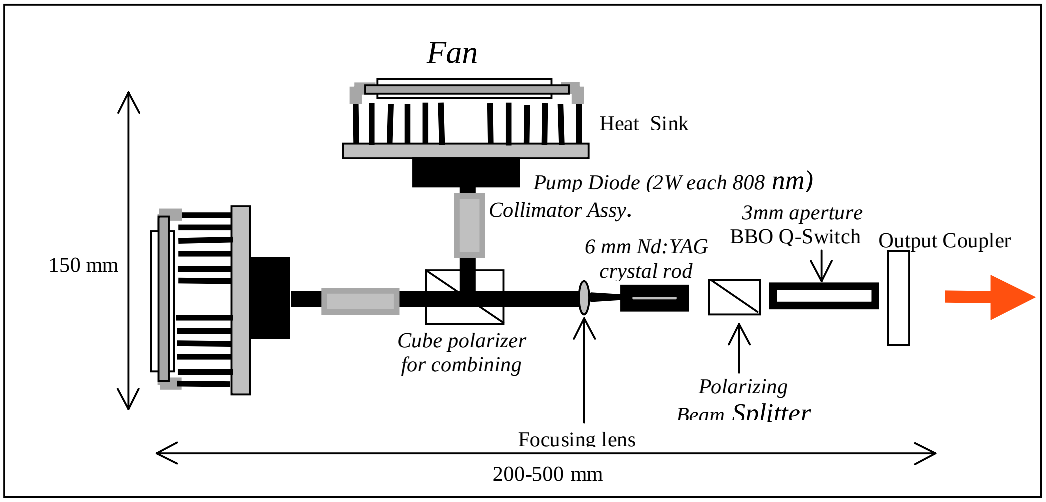

Figure 3 A Schematic view of the Nd:YAG laser breadboard

Figure 3 shows a schematic layout of the Nd:YAG laser breadboard assembled at JPL. The pump power is provided by a pair of 2 W output power diodes. These diodes were hand selected for high electrical-to-optical conversion efficiency, 52% and 48% respectively, with an emitting area of 150 µm. The alternative of using a single 4 W diode was rejected because the efficiency suffered as well as the diode emitting area would increase to 500 µm thus limiting the power density achievable in the crystal. In the current version of the breadboard laser we are relying on polarization combination following collimation. This is currently yielding a transfer efficiency of 83%. We are working on improving the transfer efficiency to 97% with better optical coatings and a mirror combination scheme. A BBO electro-optic Q-switch is used since the low capacitance of BBO provides for <1.5 W of power consumption compared to 6-7 W required for acousto-optic crystals. The optical-to-optical conversion for Q-switched output at a repetition rate of 10 kHz was ~23%. We assume that the electrical-electrical conversion for the diode and Q-switch power supply are 90% and 75% respectively based on analysis. This produces a wall plug efficiency of 7%, and with the improvements in transfer efficiency alone can be increased to 8%. We are striving to achieve >15% wall plug efficiency and expect to achieve this by improving the optical-optical conversion efficiency and the use of a more efficient Q-switch. Figure 4 shows a photograph of the breadboard laser.

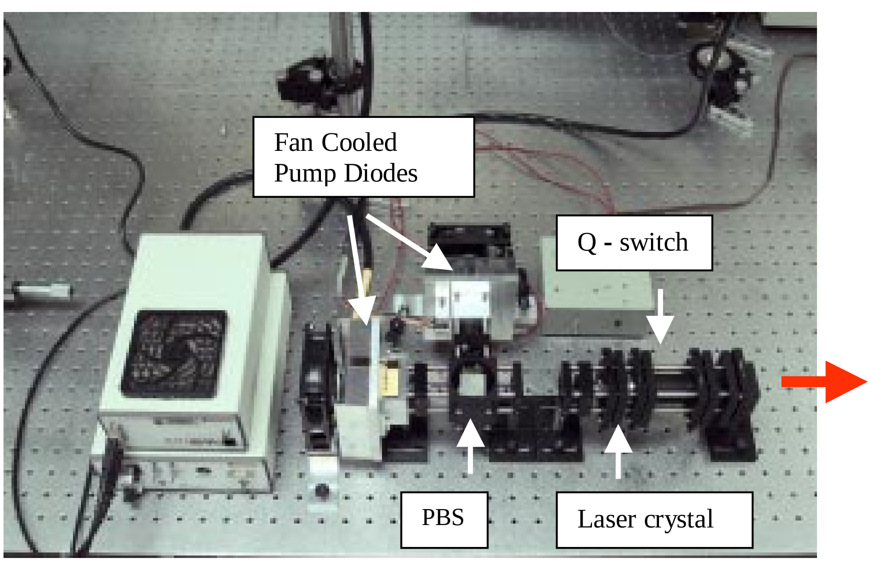

Figure 4

Nd:YAG pulsed laser evaluation model.

The fiber based pulsed laser transmitter is currently being tested and the results will be reported at a later date. The specifications for the MOPA design are as follows:

Wall-plug efficiency	8 – 10 %
Wavelength	1060 +/- 5 nm
Spectral Width	< 0.3 nm
Output power	1W avg., 8 kW peak
Beam quality	$M^2 < 2$
Pulse repetition rate	3 – 20 kHz
Pulse duration	< 30 ns at 3 kHz
Cooling method	Conductive
Volume	< 2 lit.

Summary

Developing a high efficiency laser transmitter is critical to deep space mission acceptability of optical telecommunications. The current work addresses optimizing the overall wall-plug efficiency of diode pumped solid state lasers and determining the thermal power requirements for a variety of architectures. With an optimized design, it is proposed that the electrical – optical efficiency can be extended to 28 % and the overall wall-plug efficiency can reach 16% for a bulk device or 25 % for a fiber based device. Active loop heat pipes for temperature controlling pump diodes are a new technology that provide improved efficiency compared to TEC pump diodes and over a wider radiator temperature range. Fiber based amplifiers or lasers are expected to yield the highest overall efficiency but may have limited mission applicability due to peak power limitations. Preliminary experimental results have achieved wall-plug efficiencies of approximately 8 % and further work is ongoing to realize the higher efficiencies.

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