

Solid-state diode pumped eye-safe lasers in remote sensing and ecological monitoring systems

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ABSTRACT

The perspective of using diode pumped solid-state 1.5 – 2 μm lasers for synthesis of laser measurement systems is discussed. Comparative estimations of atmospheric transmission in spectral windows of 1.0 – 1.1 μm, 1.5 – 1.7 μm and 2.0-2.3 μm are made, and characteristics of solid-state lasers and low-threshold receivers are considered. It is shown that lasers based on Yb-Er glass and crystals doped with erbium and holmium ions are preferable to lasers based on non-linear optical converters of neodymium-lasers radiation to the 1.5 – 2 μm spectral region by their "efficiency/cost" ratio.

Keywords: solid-state lasers, eye-safe lasers, near IR lasers, laser rangefinders

1. INTRODUCTION

Application of solid-state lasers of 1.5 – 2 μm spectral range in systems of laser sensing and monitoring is considered to be well-founded from the point of view of operators and accidental observers eye safety. While forming a technical image of laser measurement systems one must have a system efficiency basis as well as estimation of "efficiency/cost" index.

It is necessary to carry out a comparative analysis of currently available lasers of the mentioned spectral range as well as an analysis of propagation medium and photodetectors characteristics for the 1.5 – 2 μm spectral range.

In the present work we compare atmospheric transmission in spectral windows of 1.0 – 1.1 μm, 1.5 – 1.7 μm and 2.0 – 2.3 μm and consider solid-state lasers and low-threshold photodetectors characteristics. The main accent is made on the diode-pumped lasers, since owing to diode-pump application it is possible to increase the efficiency, reliability, lifetime, and to decrease the mass and size, of a system.

2. ATMOSPHERIC TRANSMISSION

For the most part 1 – 2 μm spectral range radiation extinction of atmosphere is associated with water vapor absorption and light aerosol scattering. Water vapor absorption coefficient depends on the temperature and relative humidity of the air and can be borrowed, for example, from Tables¹.

The radiation losses in the atmosphere are mostly caused by the light aerosol scattering. These aerosol losses can be related with meteorological optical range (MOR). The loss coefficient α and MOR relation is not simple and depends on the aerosol type and size. Nevertheless, the following empirical formula¹ is used for practical estimations:

$$\alpha = \frac{3.91}{L_M} \cdot \left(\frac{0.55}{\lambda} \right)^q \quad (1)$$

where $q = 0.585 (L_M)^{1/3}$.

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Table 1 shows several wavelengths radiation transmission coefficients for the sea level horizontal distance equal to doubled MOR at 23°C temperature and 80% humidity. Calculation takes into account the water vapor absorption and light aerosol scattering.

Table 1. Atmospheric transmission for the sea level horizontal route with a length equal to doubled MOR at 23°C and 80% humidity.

Wavelength λ , μm	Atmospheric transmission for MOR:		
	5 km	10 km	20 km
1.06	0.010	0.014	0.017
1.54	0.050	0.088	0.142
2.10	0.106	0.177	0.256

3. PHOTODETECTORS FOR MEASUREMENT SYSTEMS

In recent years new photodiodes based on InGaAs structure having high sensitivity low noise and bandwidth more than 200 MHz have been developed. Sensitivity spectral range of InGaAs photodiodes lies within 0.7 – 1.7 μm with the maximum near 1.6 μm . Sensitivity spectral region widening to 2.1 μm leads to increase of the photodiode dark current. In that case it is reasonable to use TE-cooled receivers to reach a high threshold sensitivity.

It is also silicon avalanche photodiodes that are used in neodymium laser based systems. The spectral sensitivity of the Si photodiodes at the wavelength of 1.06 μm is about 0.25 – 0.3 A/W, however the high avalanche multiplication coefficient (up to 10^2) simplifies the amplifier problem and decreases the influence of amplifier noise on the receivers threshold characteristics.

Table 2 contains parameters of some types of photodetectors based on InGaAs and Si avalanche photodiodes.

Table 2. Parameters of photodetectors.

Manufacturer	Type	Spectral response range, μm	Active area	Photo sensitivity S_λ A/W	NEP, $\text{W/Hz}^{1/2}$	Threshold sensitivity nW	Bandwidth MHz
Hamamatsu Photonics K.K.	InGaAs PIN Photodiode	0.9-1.7	\varnothing 0.5 mm	0.75 (1 mkcm) 0.95 (1.5 mkcm)	$8 \cdot 10^{-15}$	-	200
	InGaAs PIN Potodoide	0.9-2.1	\varnothing 1.0 mm	1.2 (2.1 mkcm)	$4 \cdot 10^{-13}$	-	40
	InGaAs PIN Potodoide (TE-cooled)	0.9-2.1	\varnothing 1.0 mm	1.2 (2.1 mkcm)	$1 \cdot 10^{-13}$	-	40
Analog Modules, Inc.	Si APD with preamp.	0.4-1.1	\varnothing 0.8 mm	-	-	3	40
	InGaAs PIN with preamp.	1.07-1.7	\varnothing 0.3 mm	-	-	50	40
	InGaAs APD with preamp.	1.06-1.7	\varnothing 0.2 mm	-	-	8	40

Comparison of the data given in Tables 1 and 2 shows that the output energy of 1.5 μm laser necessary for solving laser sensing tasks is several times less than in micron spectral region. In Table 3 estimations of laser rangefinder energy necessary for measuring range equal to MOR are given as an example. The estimations are made for the target reflection index 0.3, laser transmitter and receiver optics transmission 0.8, receiving optical objective diameter 5 cm. Silicon avalanche photodiode-preamplifier module was taken for the 1.06 μm radiation sensing, for 1.54 μm so was InGaAs avalanche photodiode-preamplifier module and for 2.1 μm – InGaAs PIN photodiode. Input current noise density of 2.1 μm photodetector amplifier was taken 1 pA/Hz^{1/2}. Signal excess over noise for all photodetectors – 7. Atmosphere background noise and laser radiation back scattering were not taken into account.

Table 3. Laser rangefinder energy necessary for measuring of the range equal to the MOR.

Wavelength λ , μm	Pulse duration τ , ns	Laser energy (mJ) for MOR:		
		5 km	10 km	20 km
1.06	15	12.2	33.5	112.5
1.54	30	5.2	11.8	29.7
2.10*	30	3.5	8.4	23.3

4. SOLID-STATE LASERS OF 1.5 – 2 μm SPECTRAL RANGE

To demonstrate the efficiency of lasers of 1.5 – 2 μm spectral range in laser sensing systems it is necessary to carry out a comparative analysis of currently available lasers of the mentioned spectral range and of neodymium-lasers of micron spectral region.

The most widespread solid-state laser of 1.5 μm spectral region is Yb-Er glass laser generating at the $^4I_{13/2} \rightarrow ^4I_{15/2}$ transition of Er^{3+} ion¹⁻³. Intensive absorption band of Yb ions near 0.95 μm , high quantum yield of sensitization and long lifetime of upper laser level (7 ms) allow to use as a pump source laser diodes with a not high total power (up to 100 – 200 W) operating in quasi-continuous mode with a pulse duration of up to 10 ms. For example the Yb-Er glass diode pumped laser with energy 10 mJ in pulse in a multimode run and 7 mJ in close to onemode conditions is reported⁴. One laser diode bar (by Dilas) with 100 W power, 5 ms pulse duration (the pump energy – 0.5 J) was used as a pump source. Commercial value of such pump sources is about 20\$ per Watt.

Low thermal conductivity of glass limits the pulse repetition rate of Yb-Er glass lasers at several Hz. Thermo-optical aberrations and induced birefringence in the active area lead to a lasing efficiency decrease and laser beam quality deterioration⁴.

Sensitization of 1.5 μm transition $^4I_{13/2} \rightarrow ^4I_{15/2}$ of Er ion by Yb ions in crystals is ineffective⁵⁻⁷ due to the short lifetime of $^4I_{11/2}$ state of Er (about 100 μs in YAG:Er and more then 1ms in fluorides), that is intermediate stage in the transfer of energy from the Yb ions to the laser level. At low Er ions concentration caused by the three-level type of laser transition and high concentration of Yb ions necessary for the pump radiation absorption, the most part of the energy absorbed by the medium is collected and decays on the Yb ions.

Among the different ways of pumping the 1.5 μm transition $^4I_{13/2} \rightarrow ^4I_{15/2}$ of Er ion in crystals⁸⁻¹² the most effective is a direct selective pump of the upper laser level $^4I_{13/2}$ of Er ion. The pump source may be laser diodes operating near the 1.48 μm as well as the Yb-Er glass laser in free running mode. Quasi-two-level lasing model is characterized by a low Stokes shift and minimizes heat generation in the active medium, which, in combination with high thermal conductivity of the crystal materials, promotes the increase of the average power and laser beam quality.

The YAG:Er(1%) laser operating at the wavelength 1.64 μm with a longitudinal pump by Yb-Er glass laser (1.53 μm) is reported in paper¹². At 55 mJ pump energy laser energy 15 mJ is obtained in free run mode and 5 mJ in Q-switched mode.

Diode pumped Yb-Er glass lasers efficiency in a free run mode reaches 20 % [4], high pump beam quality is not required. Thus the two-step laser model provides for the diffractive beam quality at the pulse repetition rate of tens Hz, while total efficiency is retained.

Among the nonlinear-optical lasing methods of 1.5 μm spectral region radiation it is necessary to mark parametric transformation of neodymium-lasers radiation (1.06 μm) in KTP crystals and SRS transformation of neodymium-lasers radiation (1.32 μm) in barium nitrate crystals¹³⁻¹⁵.

The parametric conversion efficiency of neodymium-lasers single-mode and single-frequency radiation in KTP crystals reaches 50 %. In a multi-mode case the efficiency is 30 – 40 %. So the neodymium-laser pulse energy of 30 mJ is needed to obtain 7 – 10 mJ in the 1.5 μm wavelength region. The total diode pump source pulse power of such a laser must be 1 kW with a pulse duration of 200 – 300 μs . Single laser diode bars as well as laser diodes stacked arrays can be used as a pump source. The value of such pump sources now is 8 – 10 \$ per Watt.

The SRS transformation efficiency of neodymium-lasers multi-mode radiation ($1.32\text{ }\mu\text{m}$) in barium nitrate crystals reaches 50 %. But the efficiency of $1.32\text{ }\mu\text{m}$ laser is smaller owing to the 3 – 5 times smaller value of induced transition $^4F_{3/2}$ - $^4I_{13/2}$ cross section of Nd ions.

The most widespread active medium of diode pumped two micron lasers is $\text{YLiF}_4\text{:Tm-Ho}$ crystals with 5I_7 - 5I_8 Ho ion laser transition. The lucky coincidence of Tm ions absorption band (785 nm) and radiation spectrum of AlGaAs laser diodes, cross-relaxation exchange of absorbed energy quantum for two laser level excitations makes $\text{YLiF}_4\text{:Tm-Ho}$ crystals fit for diode pumped two micron lasers¹⁶.

The $\text{YLiF}_4\text{:Tm-Ho}$ laser with a pulse energy of 30 mJ has been reported.¹⁷ The pump is laser diode stacked arrays (360 W each) with a pulse duration of 1 ms. Pump pulse energy reaches 3 J. With a high power laser diode stacked arrays as a pump source the two micron laser with the pulse energy of 20 J and repetition rate of 10 Hz is developed for the space based lidar^{18, 19} in the system of global wind measurements.

However the low absorption cross section of the 3H_6 - 3H_4 pump transition of Tm ions and spectroscopic scheme features that don't allow to change dopant concentrations arbitrarily, embarrasses the creation of low-threshold $\text{YLiF}_4\text{:Tm-Ho}$ lasers with transverse diode pump. The YAG:Yb-Ho crystals are more perspective for the two micron lasers with the energy of 10 – 20 mJ²⁰. The YAG:Yb-Ho crystals spectroscopic scheme is an analogue of that of the Yb-Er glass. Yb ions are characterized by an intensive and wide absorption band near $0.95\text{ }\mu\text{m}$. High Yb ions concentration provides for pump absorption even in thin (about 1mm) active medium layers and an effective sensitization of Ho ions. The long lifetime of the upper laser level (10 ms) and the low activator concentration allow using low power diode sources as a pump.

In paper²¹, creation of YAG:Yb-Ho crystal diode pumped laser is reported. With a total pump power of 30 W and pulse duration of 10 ms the obtained output energy was 17.5 mJ in a free run mode and 3.5 mJ in Q-switched mode. For creation of two micron YAG:Yb-Ho laser with 8 – 10 mJ energy per pulse, 100 W power and 5 ms pulse diode bar is needed.

One of the ways to increase the pulse repetition rate of two micron laser is a direct pump of the upper laser level of Ho ion. Such pump technique minimizes heat generation in the active medium that removes thermo-optical problems and makes possible the active medium cooling in order to increase the energy extraction efficiency. With a continuous $1.9\text{ }\mu\text{m}$ wavelength diode pump of $\text{Y}_3\text{Al}_5\text{O}_{12}\text{:Ho}$ crystal, a 38 % efficiency of the optical pump to laser radiation transformation has been obtained²². With a $\text{MgF}_2\text{:Co}$ ($1.88\text{ }\mu\text{m}$) tunable laser pump of $\text{Lu}_3\text{Al}_5\text{O}_{12}\text{:Ho}$ crystal an 80 % lasing efficiency for the absorbed pump power has been obtained²³. The two micron Ho:YLF active mirror configuration laser is reported in.²⁴ A 50% slope efficiency is obtained with a Tm:YAG ($2.01\text{ }\mu\text{m}$) laser pump of a 0.4 mm thickness Ho:YLF plate.

The direct pumping of the upper laser levels of Er and Ho ions is a promising direction of development of $1.5 - 2\text{ }\mu\text{m}$ lasers. The search for optimal active medium and development of $1.5 - 1.9\text{ }\mu\text{m}$ range laser diodes can lead to a substantial progress and a rise of new application fields of $1.5 - 2\text{ }\mu\text{m}$ lasers.

CONCLUSION

The wide class of solid-state lasers that proves itself in electronics and engineering technique, in optical location and communications in a micron wavelength region for the last years have been enriched with a new $1.5 - 2\text{ }\mu\text{m}$ spectral range lasers providing energy, spectral and time performance satisfying the optical monitoring objectives.

The eye-safe spectral range allows choosing freely the operating modes and laser energy and power levels for atmospheric and object sensing systems. Low absorption and scattering of $1.5 - 2\text{ }\mu\text{m}$ wavelength radiation greatly reduce energy requirements of lasers. New laser media coupled with diode pump sources and low- threshold photodetectors of $1.5 - 2\text{ }\mu\text{m}$ spectral range create conditions for building information laser systems with technically based efficiency.

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