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High-power laser subsystem for a 6U CubeSat mission

Gabriel Jantsch[a], Gabriela C.L. Lopes[a], Paola N. Pienta[a], and Gary B. Hughes[b]

gabriel.jantsch@grad.ufsc.br
gabriela.caroline@grad.ufsc.br
paola.nichele.pienta@grad.ufsc.br
gbhughes@calpoly.edu

[a]Joinville Technological Center, Federal University of Santa Catarina, Joinville, SC 89219-600 Brazil
[b]Statistics Department, California Polytechnic State University, San Luis Obispo, CA 93407-0405

ABSTRACT

A NASA Innovative Advanced Concepts (NIAC) study aims to develop a technique for interrogating the molecular composition of asteroids from an orbiting spacecraft. The measurement concept relies on a high-power laser aboard the spacecraft whose objective is to melt and evaporate a spot on the surface of the target; the heated spot is then viewed by a spectrometer through the plume of ejected material. A CubeSat mission is envisioned as a test of the concept in the space environment, with a laser and spectrometer aboard a main craft, and a target craft flying in formation. A systems analysis is presented to define operational and mechanical characteristics of a laser and optical subsystem for the envisioned CubeSat experiment. Target materials drive the target flux requirement; common compounds found in celestial bodies were evaluated for spectral absorption and thermal properties. Suitable lasers are identified to provide the required flux, taking into account their technical specifications of size, power, intensity, wavelength, laser aperture angle, and analysis of Gaussian beam propagation. Respecting the technical specifications that should be taken into consideration in order to obtain the desired outcome (from the action of the laser), optical components suitable for use in a CubeSat were considered. An optical analysis is presented, based on models of the energy dissipation of the laser beam through optical components and along its path and through the space environment. Results of simulations are presented, including selected scenarios for distance between the laser source and the target.

Keywords: Asteroid Composition, Laser, Wavelength, Gauss Beam, optical lenses

1. INTRODUCTION

Asteroids and meteoroids existing in space represent a great scientific opportunity for humanity. The study of these rocky bodies allows us to seek knowledge of their composition, the dynamics of the solar system and its history. From these points, it is possible to go further and allow a more in-depth study of these bodies with the purpose of research for exploration, where the knowledge of the elements that compose asteroids and meteoroids, actions can be applied in the development of research and technology in the space exploration and mining area. This paper presents the study of a high power laser subsystem applied to a CubeSat 6U mission that seeks to validate a sensor capable of determining the molecular composition of solar system targets from a distance. The proposed high-power laser subsystem will act to heat, melt and evaporate molecules present in asteroids and other cold solar system targets. Light emitted by the heated spot is analyzed through a spectrometer, which provides a means for determining the target's molecular composition and data sufficient to the further study of these bodies.

The measurement of the molecular composition of asteroids is performed by spectrometry. The laser used in the CubeSat must deliver sufficient flux to the target to cause melting and evaporation of materials present in the specimen, on the order of 10 MW/m^2 to the target surface from the operating distance. So, it is first necessary to acknowledge the elements usually present in this type of rocky bodies and the absorption wavelength of these elements, which is one of the main features in order to decide the proper laser model to be used in the study, comparing the information to the wavelength of the laser beam.

The main focus of the research are asteroids, rocky or metallic bodies and meteoroids (fragments of solid bodies that travel through space). Asteroids and meteoroids can be classified into subtypes, which can be seen in Fig. 1 and Fig.

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2. The study of asteroids and meteoroids allows us to know better its composition, the dynamics of space and its history. So, with the knowledge of the elements that compose them, actions can be applied to enable the extraction of resources. Getting to know these rocky bodies is of utmost importance to science and even planetary defense against potential asteroid impacts. And from the study applied there, the most varied actions can be developed contributing mainly in the development of research and technology in the space exploration and mining area.

The proposed high-power laser subsystem will compose along with other subsystems a CubeSat, acting on the function of reaching and dissociating molecules of the elements present in asteroids and meteoroids, which are analyzed through a spectrometer, which provides its chemical composition and data sufficient to further study of these bodies. Firstly, it is necessary, during the development of the research, a base study to get previous knowledge about the elements usually present in this type of rocky bodies, and in this case, mainly the wavelength of absorption of these elements, which is one of the main features to decide the laser model that will be used in the study, considering the wavelength of the laser beam. The measurement of the molecular composition of asteroids is performed by spectrometry, so the laser used in the CubeSat must provide a wavelength range and intensity adequate to cause the emission of light from all types of atoms present in the specimen. The main bodies that are the focus of the research are asteroids, rocky or metallic bodies and meteoroids (fragments of solid bodies that travel through space). Asteroids and meteoroids can be classified into subtypes, and in Fig. 1 and Fig. 2 can be observed general classification of composition.

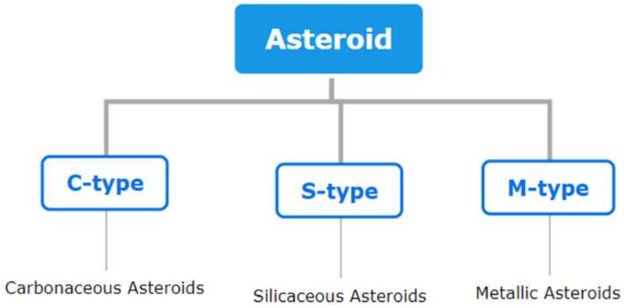


Figure 1. Major asteroid compositions and classifications.[9]

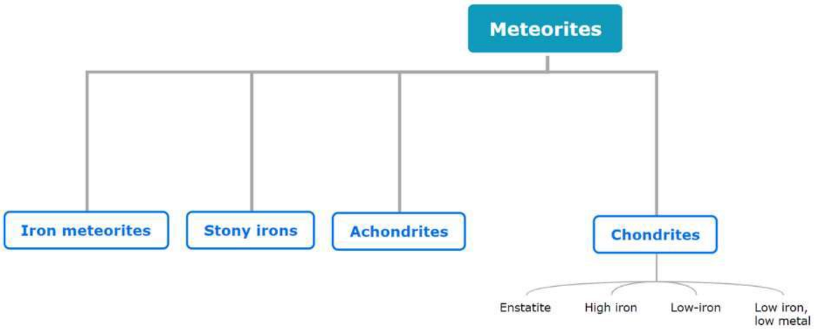


Figure 2. Main classifications of Meteorites.[10]

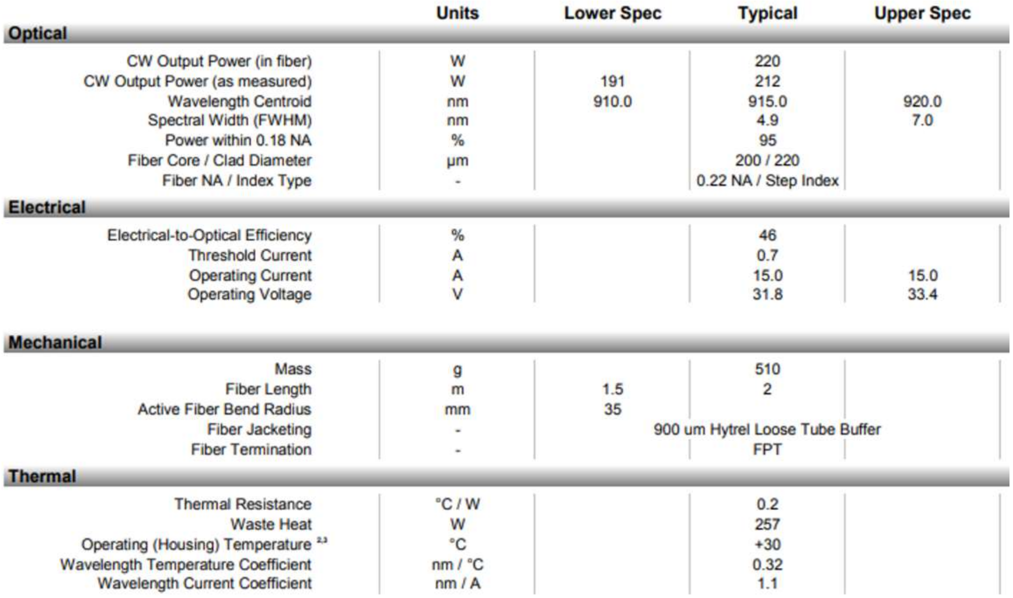
One of the main objectives of the high power laser subsystem is to study the composition of asteroids and meteoroids, but in order to have a better application and guarantee of subsystem functioning, it is necessary to study existing literature on the subject, where it's analyzed the composition of the already known bodies and their element's absorption waves. Then a laser model that acts in the appropriate wavelength is selected. Asteroids and meteoroids have a similar composition where it's possible to find elements such as iron, nickel, chromium, hydrogen, silicon, magnesium, oxygen, calcium, aluminum, nitrogen, sodium, titanium, cobalt, manganese, helium, tin, carbon, iridium, olivines in general, etc.[2] These elements dissociate in a very wide range of wavelength of absorption, allowing us to choose a laser model with a variant wavelength between 800 nm and 1050 nm.[3]

2. DETERMINATION OF LASER SUBSYSTEM REQUIREMENTS

In order to ensure that the laser reaches the target with the optimum power density, power and wavelength suitable for light emission, it is necessary to consider the absorption wavelengths of the materials. Another point that must be considered is the lasers dimensions. Since the subsystem should integrate a 6U CubeSat, it should fit the CubeSat technical specifications to be allocated within the space.

It is important for the project that the wavelength of the beam is in the absorption range of the elements, because if the parameters of the wavelength are smaller than the absorption wavelength of the material, it will not have its molecules dissociated to be captured by the spectrometer, and if it is larger, it will burn the material rather than dissociate its molecules. In order to guarantee the maximum efficiency of the laser subsystem applied for the dissociation of molecules at a certain distance from the rocky body, it was defined that the laser must have an output power of approximate to 200 W, able to operate continuously for a few seconds, respecting the wavelength surveyed within the elements' range and also smaller dimensions than the 6U CubeSat. Studying these basic technical requirements that the laser must meet, a NLight supplier coupled fiber diode laser was selected with the following technical specifications shown in Fig. 3 and Fig. 4.

Based on the technical specifications and the requirements discussed above, the laser shown on Fig. 4 was considered the most adequate option for use in the experiment, provided that its laser beam has the capacity of arriving with the power density appropriate to the target. In order to verify this possibility, a mathematical model has been made.



	Units	Lower Spec	Typical	Upper Spec
Optical				
CW Output Power (in fiber)	W		220	
CW Output Power (as measured)	W	191	212	
Wavelength Centroid	nm	910.0	915.0	920.0
Spectral Width (FWHM)	nm		4.9	7.0
Power within 0.18 NA	%		95	
Fiber Core / Clad Diameter	μm		200 / 220	
Fiber NA / Index Type	-		0.22 NA / Step Index	
Electrical				
Electrical-to-Optical Efficiency	%		46	
Threshold Current	A		0.7	
Operating Current	A		15.0	15.0
Operating Voltage	V		31.8	33.4
Mechanical				
Mass	g		510	
Fiber Length	m	1.5	2	
Active Fiber Bend Radius	mm	35		
Fiber Jacketing	-		900 um Hytrel Loose Tube Buffer	
Fiber Termination	-		FPT	
Thermal				
Thermal Resistance	°C / W		0.2	
Waste Heat	W		257	
Operating (Housing) Temperature [2,3]	°C		+30	
Wavelength Temperature Coefficient	nm / °C		0.32	
Wavelength Current Coefficient	nm / A		1.1	

Figure 3. Laser subsystem specifications.[4]

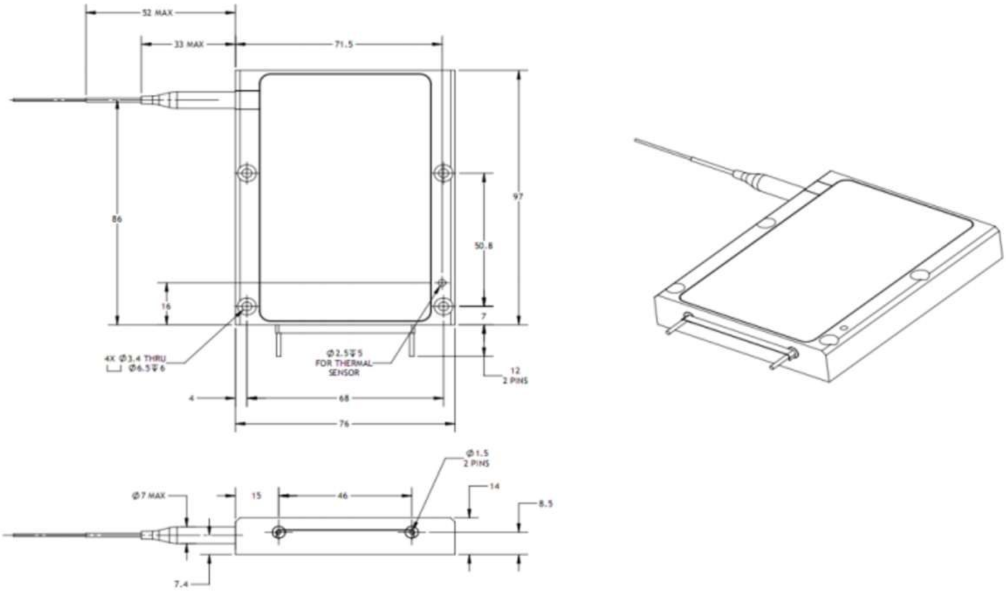


Figure 4. Subsystem technical drawing. Package dimension: 97 x 76 x 14 mm.[4]

3. OPERATION SYSTEM MODEL

Based on parameters set at the beginning of the project, the beam is projected to reach the target with an approximate power of 220 W, considering no loss of energy, and mainly with a power density of 10 MW/m². Therefore, to prove, the following calculations and symbologies explained in the Table 1 and Table 2.

Table1. Definition of Symbols

Symbol	Meaning	Symbol	Meaning
I	Power Density	A	Area
P	Power	$\frac{f}{D}$	*f* number
D	Beam Diameter	θ	Beam Divergence
ω	Beam Radius	Δ	Focus depth
M^2	M Squared	λ	Wave-length
NA	Numerical Aperture	k	Wave number

Table 2. Design Parameter Values

Symbol	Value
P	$220\ W$
λ	$9.15 \cdot 10^{-7}\ m$
NA	0.22
$Dcore$	$2 \cdot 10^{-4}\ m$
$Dbeam$	$2.1 \cdot 10^{-4}\ m$
$Wbeam$	$1.05 \cdot 10^{-4}\ m$

For the value $Wbeam$ will be used a number a little larger than the radius of the fiber core, because the beam propagates in the exit, by the edges of the nucleus. Angle at which the beam diverges along the path is given by the Eq. (1a):[5]

$$2\theta = \frac{4}{\pi} \cdot \frac{\lambda}{2\omega} \tag{1a}$$

$$\theta = 2.774 \cdot 10^{-3} \tag{1b}$$

Eq. (2a) give us incidence of laser power in a given area:[5]

$$I = \frac{P}{A} \tag{2a}$$

$$A = 2.2 \cdot 10^{5} cm^{2} \tag{2b}$$

As discussed earlier, power density is one of the initial prerequisites. Eq. (2a) was used to find out the area required for the beam to focus on the body.

Focus depth: the beam's diameter increases as the distance from the focal spot increases. The focus depth is the point where the beam's diameter is approximately 5% of its original value, as shown in Eq. (3) and Fig. 5:[8]

$$\Delta = \left(8 \cdot \frac{\lambda}{\pi}\right) \cdot \left(\frac{f}{c}\right) = 0.12273 \text{ m} \tag{3}$$

f/#: as shown in Eq. (4a), is the relation between the focal length of the system and the diameter of the entrance pupil. It is a dimensionless number that is a quantitative measure of lens speed.[5]

$$\frac{f}{D} = \frac{f}{c} \tag{4a}$$

$$2 \cdot \omega = \left(\frac{4}{\pi}\right) \cdot \left(\lambda \cdot \frac{f}{D}\right) = \lambda \cdot \left(\frac{f}{c}\right) \tag{4b}$$

$$\frac{f}{c} = 2 \cdot \frac{\omega}{\lambda} = 229.51 \tag{4c}$$

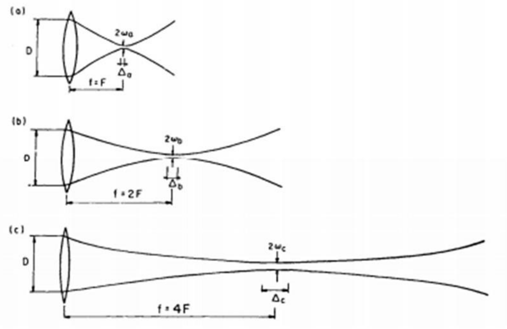


Figure 5. Focus depth of the laser beam as a function of distance and *f*/#.

With the calculations made, the minimum distance between laser source and target is verified in order to ensure that the beam will arrive on the target with the proper specifications. For this, we also define the base lens as a parameter. The chosen lenses, a collimator and a convex flat focal lens, are of Zinc Selenide, selected for their low absorption in infrared wavelengths and their visible transmission as well as are ideal for high power applications.[6] For calculation purposes, the Zinc Selenide lenses we have chosen have a refractive index of 2.3278. The wave number we find to is given by Eq. (5a):

$$k = \frac{2\pi}{\lambda} \tag{5a}$$

$$k = 6866869.188 \tag{5b}$$

We also need to find the M², as we can see from Eq. (6,) that determines how intensely a collimated beam of a given diameter can be focused.

$$M^{2} = \left(\frac{\pi * \theta}{\lambda}\right) \cdot NA = 2095.3565 \tag{6}$$

So we can calculate the EFL of our subsystem, which is the focal distance between lens and object as can be seen in Fig. 6 related to Eq. (7):

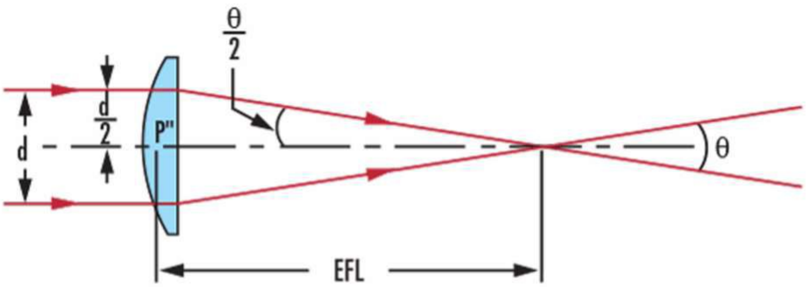


Figure 6. Focal distance between lens and object

$$EFL = f = \sqrt[3]{\frac{(\pi * k * D^4)}{(2 * \pi * M^2)}} = 0.0222 \text{ m} \tag{7}$$

So it's possible to conclude that the minimum distance between the converging lens and the target is 0.0222 m. It's also possible to calculate the EFL for the beam diameter considering the ideal power intensity (10 MW/m²). The calculations are presented by Eq. (8), Eq. (9a,b) and Eq. (10).

$$I = \frac{P}{A} \tag{8}$$

$$r = \sqrt{\frac{P}{\pi I}} \tag{9a}$$

$$r = 0{,}0026463 \text{ m} \tag{9b}$$

Then,

$$D = 0.0052926 \text{ m} \tag{10}$$

Considering this beam diameter, from the ideal power density, it is substituted in the same EFL Eq. (7) and reach a focal distance of 1.64 m.

4. EXPERIMENT

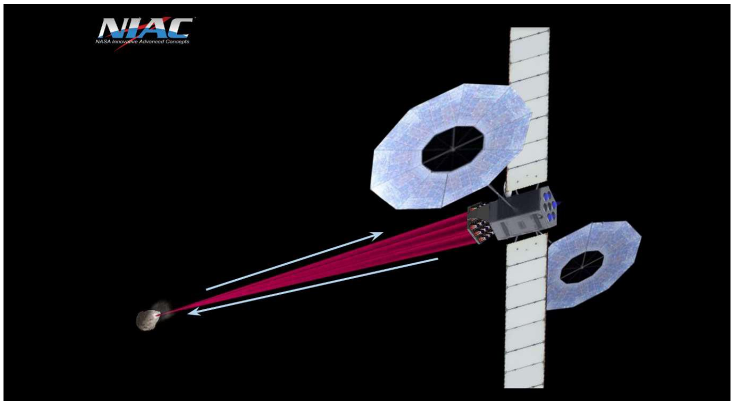


Figure 7. The CubeSat experiment is intended to provide a space environment validation of the spectroscopy sensor system.

As can be seen from Fig. 7, in practice, the performance of the laser subsystem is characterized when it is in space at a certain distance from the rock body. When properly positioned and its operational capacity is attested, the laser beam of the subsystem will be connected, continuously reaching the object in space for a few seconds and causing the dissociation of its molecules, which will have its spectrum analyzed for identification, thus discovering the composition of the rocky body.

5. CONCLUSIONS

Based on the research and calculations presented in this article, it's concluded that the data presented contribute to validating the experiment theoretically, as well as to verify the technical information regarding the operation of the laser beam. We can also observe that the necessary distance between the CubeSat and the rocky body for the experiment is relatively small, but it can be increased if the power density desired on the target is lower.

Also, the beam divergence angle is small and will affect the linearity of the laser along its path, allowing the positioning of the system at a greater distance from the target object. It is also possible to analyze the beam power applied in the rocky body, the deflection it will suffer is relatively small, allowing the application of this system in the use for space defense in the face of collision threats between the planet and asteroids and meteoroids. The subsystem presented is theoretically possible, aiming at the spatial exploration, with relatively low financial resources required in the research of different asteroids and meteoroids through space.

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REFERENCES

[1] Act for Libraries. "Type and Classification of Asteroids". Available at: http://www.actforlibraries.org/type-and-classification-of-asteroids/

[2] Borghi, R. and Santarsiero, M. "M^2 factor of Bessel–Gauss beams," *Optics letters*, 22(5), pp.262-264 (1997).

[3] Ockert-Bell, M.E., Clark, B.E., Shepard, M.K., Isaacs, R.A., Cloutis, E.A., Fornasier, S. and Bus, S.J. "The composition of M-type asteroids: Synthesis of spectroscopic and radar observations," *Icarus*, 210(2), pp.674-692 (2010).

[4] Edmund Optics Ltd. "What are Cylinder Lenses?". Available at: https://www.edmundoptics.fr/resources/application-notes/optics/what-are-cylinder-lenses/

[5] Goubau, G. and Schwering, F. "On the guided propagation of electromagnetic wave beams," *IRE Transactions on Antennas and Propagation*, 9(3), pp.248-256. (1961).

[6] Greivenkamp, J.E. *Field guide to geometrical optics* (Vol. 1). SPIE Press, Inc., Bellingham, WA (2004).

[7] II-VI Infrared. "Choosing the Right Focusing Lens". Available at: http://www.iiviinfrared.com/resources/choose_focus_lens.html

[8] II-VI Infrared. "Zinc Selenide". Available at: http://www.iiviinfrared.com/Optical-Materials/znse.html

[9] Mandel, L. and Wolf, E. *Optical coherence and quantum optics*. Cambridge University Press. Chap 5. p 267 (1995).

[10] Millman, P.M. "The Chemical Composition of Cometary Meteoroids," *International Astronomical Union Colloquium*, Vol. 39, pp. 127-132 (1977).

[11] Morgano, M.A., Queiroz, S.D.N. and Ferreira, M.M.C. "Determinação dos teores de minerais em sucos de frutas por espectrometria de emissão óptica em plasma indutivamente acoplado (ICP-OES)," *Ciênc Tecnol Aliment*, 19(344), p.e8 (1999).

[12] Nlight. "Fiber Coupled Diode Laser". Available at: http://www.nlight.net/products/diode-lasers/119-element-e18-Fiber-Coupled-Diode-Laser.

[13] Porto University. "Lasers" (2007). Available at: https://web.fe.up.pt/~mines/OpE/Acetatos/Lasers/lasers1.pdf

[14] Prado, M. "Meteorite classifications and compositions." Available at: http://www.permanent.com/meteorite-compositions.html.

[15] Siegman, A.E. "Defining, measuring, and optimizing laser beam quality," *Laser Resonators and Coherent Optics: Modeling, Technology, and Applications*, Proc. of SPIE, Vol. 1868, pp. 2-13 (1993).

[16] Siegman, A.E. "How to (maybe) measure laser beam quality," *Diode Pumped Solid State Lasers: Applications and Issues*, p. MQ1, Optical Society of America (1998).

[17] Smith, W. *Modern Lens Design*, McGraw-Hill (2005).

[18] Svelto, O. *Principles of lasers* (5th Ed). New York: Plenum press (2010).