Solar Lasers: Another Dimension in Renewable Energy Applications

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1. Introduction

Increasing demand of energy resources by the human society, and the depletion of conventional energy sources have made researchers to think for various possible energy sources. As fossil fuels pollute environment and going to be exhausted soon, it has become a need of hour to go for renewable, green energy alternatives. Sun is naturally available vast source of energy in the form of sunlight. In last few decades, solar cells have been promising source to encourage green energy and to reduce dependence on fossil fuels. There are some limits in converting light into electrical domain which confine the efficiency of photovoltaics. Several attempts have been made to improve silicon solar cell efficiency such as texturing, polishing, doping with different materials, introducing surface defects and introducing nanostructures, thin film technology, multiple reflection mechanism and quantum confinements have been taken into account and increase in the efficiency has been reported, upto a certain limit. Many scientists and researchers are involved in solar cell research, in order to find new ways to improve the efficiency of the photovoltaics. Hope one day they will come up with great results. Meanwhile several scientists are looking for direct solar energy applications like lightning, reduction of MgO to Mg in sea water, solar laser systems, solar heaters, solar cookers and many other possibilities. Since solar cells convert solar energy into electricity which is then used for various applications including lightning, heating etc. Some of these works can be carried out directly by sunlight rather converting first it into electricity and then convert it back to light and/or heat.

On other hand Laser is a device which generate light with some specific properties which is then used for many applications such as optical communication, material processing, medical/bio-medical surgeries, metrology, meteorology, reprography, military defence/security equipments, spectroscopic application, heating, sensing, optical data writing and processing,imaging and holography, linear and nonlinear optics, entertainment and many other fields of science and technology [2]. The word Laser stands for acronym of Light Amplification by Stimulated Emission of Radiation. The Laser was invented by Theodore H. Maiman at Hughes Laboratories, in 1960 [1]. When a radiation interacts with matter, there are several phenomenon taking place. Max Planck published a paper in 1900, introducing relationship between energy and the frequency of radiation, saying that energy could be emitted or absorbed only in discrete manner-which he called quanta of the energy. Max Planck received the Nobel Prize in physics his discovery of elementary energy quanta in 1918. Planck also explained “blackbody” radiation, mentioning that when a material is heated with some radiation of some wavelengths of light, it doesn’t radiate all frequencies of light equally when heated. In 1917, Einstein proposed the most important phenomenon which made lasers possible, called stimulated emission. He stated that, electrons could be stimulated to emit light of a particular frequencies other than that of absorbed and emitted spontaneously [1,2]. On April 26, 1951, Charles Hard Townes of Columbia University in New York conceives his maser (microwave amplification by stimulated emission of radiation) idea, and in 1954 he demonstrated first MASER at Columbia University. 1955, Nikolai G. Basov and Alexander M. Prokhorov attempt to design an oscillators and proposed a method for the negative absorption which is now known as the pumping. Nicolaas Bloembergen developed the microwave solid-state maser in 1956 [1]. Nov. 13, Gordon Gould (Columbia University graduate student) jots his ideas for building a laser. In 1959 Gould and TRG applied for the laser-related patents stemming from Gould's ideas, and they were granted US Patent on March 22, 1960. On May 16, 1960, Theodore H. Maiman, constructs the first laser [1]. In 1963, Herbert Kroemer and his team at University of California, and Zhores Alferov (A.F. Ioffe Physico-Technical Institute in St. Petersburg, Russia), independently proposed ideas to build semiconductor lasers from heterostructure devices. For the work they were awarded Nobel Prize in 2000 [1]. For construction of amplifiers and oscillators based on the maser-laser-principle Townes, Prokhorov and Basov were awarded the Nobel Prize in physics in 1964. Kao proposed his work on fiber laser in 1966 for which he was awarded 2009 Nobel Prize in physics. In 1966, French physicist Alfred Kastler won the Nobel Prize in physics for his method (developed between 1949 and 1951) of stimulating atoms to higher energy states [1, 2]. Later on some other physicists got Nobel Prize in laser spectroscopy and laser cooling. So Laser systems were evolved gradually. In last few decades Laser technology attracted scientists, physicists and technologists because of its uniqueness in coherence, high power, better control, both continuous and pulsed mode operation, and reliability. Laser has revolutionised the modern technology.

2. The Laser Operation

The concept of emission is borrowed from black body emission. Whenever a material is exposed to an electromagnetic radiation and it absorbs the radiation, it re-emits the absorbed energy in the form of another electromagnetic radiation. There are discrete energy levels in the atoms, molecules and hence in the material. So the energy is absorbed in the form of quanta. Quantization of energy is well established concept governed by Max Planck. Absorption of energy can be correlated as excitation of an electron from a lower energy level to a higher energy state. The emission of the radiation can be mediated by multiple energy levels. Sending of electrons to the upper energy states by electromagnetic perturbation or by some other means, is called pumping. If material has some intermediate states which have longer life times (known as metastable states), electrons first come to that state, from the higher energy levels. Due to this difference in life times of highest energy state and the metastable state, accumulation of electrons takes place in the metastable state which causes population inversion (number of electrons becomes more than that of the ground level). From the metastable state the electrons come to the ground level by single or multiple transitions by releasing energy in. The released energy as mentioned earlier can be any form of the electromagnetic radiation depending the energy gap of the levels participating in the transition and the life times of the participating energy levels. When the emission takes place in the form of light, it is known as radiative emission otherwise it is known as non-radiative emission. If the emission takes place and the photons and added randomly and there is no correlation in emitted photons, this is known as spontaneous emission.

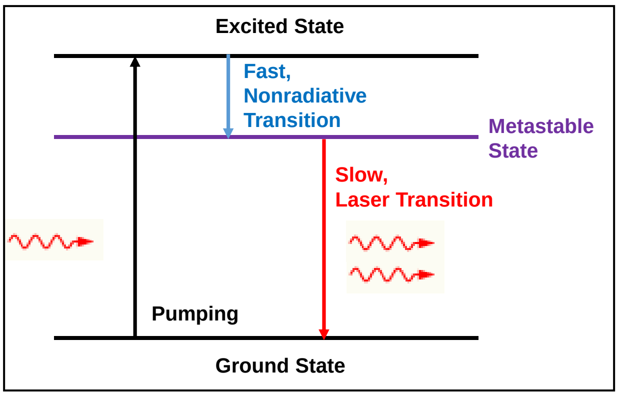

Figure 1. Representation of Lasing mechanism in a three level laser system

If one photons stimulates the transition process and adds coherently to the emitted photon, this process is known as stimulated emission. LEDs are one of the exemplar device based on spontaneous emission, and Lasers are best exemplar devices based on stimulated emission. To get stimulation amplification, all the emitted photons should be coherently added to the stimulated emitted photons, for that purpose optical cavity is formed which provides the feedback mechanism. The laser cavity comprises of one highly reflecting mirror and other slightly less reflecting mirror to pass the radiation partly. So overall the main steps in the laser operation are absorption, relaxation to metastable state, population inversion, spontaneous emission, feedback, stimulated emission, amplification and then the output coherent radiation. The basic laser operation is represented in the figure 1.

3. Types of Lasers

The first demonstrated laser was a solid state laser which was developed using Ruby crystals. Later on various solid, liquid and gas, material were invented and used for laser as active media. Based on the active media laser can be classified mainly in to three categories Solid state, Liquid and Gas Laser. Apart from those three types there are Plasma lasers and liquid crystal lasers, Metal vapour laser, dye lasers are other especial class of lasers. Based on the pumping mechanism laser can be classified into two categories optically pumped and electrical pumped. Apart from those two categories free electron lasers and nuclear pumped lasers are also there. Most of the gas lasers are electrical (electrical gas discharge) pumped, Semiconductor lasers are mainly electrically pumped (pn diode: direct electrical pumping) and Solid state lasers other than semiconductors, are mainly optically pumped lasers. Some of the examples of solid state lasers are Ruby, Nd:YAG, Nd:Glass, Nd:Cr:YAG, Er:YAG, Nd:YAF, Nd:YVO_4, Nd:$YCa_4O(BO_3)_3$ or (Nd:YCOB), Ti:Sapphire, Tm:YAG, $Ytterbium_2O_3$, Ho:YAG, Ce:LiSAF, Ce:LiCAF, Sm:CaF2, Fiber Lasers (Raman, EDFA, Nd/ Yb:Glass). Some of the semiconductor lasers active media are GaN, InGaN, AlGaInP,AlGaAs InGaAsP, lead salt, VCSEL, Quantum cascade laser and Hybrid silicon laser [2]. Some gas lasers are Helium–neon laser, Argon laser, Krypton laser, Xenon ion laser, Nitrogen laser, Carbon dioxide laser, Carbon monoxide laser, Some chemical lasers like all gas phase iodine laser, Excimer laser, Free electron laser, Gas dynamic laser Nuclear pumped laser (special class of laser). Chemical lasers are mainly liquid state or gas lasers like Hydrogen fluoride laser, and Deuterium fluoride (DF), Chemical oxygen–iodine laser [2]. Dye lasers mainly use organic dye as lasing medium. Mostly those are found in liquid state but there are some examples of solid state dye also [2].

Among the diversity of Lasers, solid state lasers have their own importance because of very high power, stability in operation, portability, compact design, and operation in both continuous & pulse mode. Neodymium-doped yttrium aluminium garnet laser crystal (Nd:YAG) provides the laser system designer with the most versatile solid state laser source in use today [3]. Nd^{3+}:YAG is a four-level gain medium, offering substantial laser gain even for moderate excitation levels and pump intensities. The gain bandwidth is relatively small, but this allows for a high gain efficiency and thus low threshold pump power [4]. Other active materials are also used based on the requirement of emitted wavelength, compatibility of the system and other aspects.

4. Solar energy as Laser Pumping Source

With the invention of the laser, scientists started looking for various pumping sources for the lasers. First demonstrated Ruby laser was optically pumped solid state lasers. Those days mostly flash lamps were used for the purpose. Later on electrical pumping (Gas discharge) and then after invention of semiconductor lasers, direct electrical pumping and diode lasers pumping came into existence. In that series itself, sunlight attracted scientists as a source of laser pumping, due to abundance amount of energy (3.5 to 7.0 kWh/m^2 [5]) per day, Broad spectrum, No dependence on electricity, Not hazardous contents like mercury and available everywhere (but obviously in daytime only). Typical Solar Spectrum on earth in day time is shown in figure 2. Apart from the above mentioned benefits, there are several other merits of using solar energy like clean environment, no separate power supply required, no different pumping source for different types of laser (as sunlight has broad spectrum) etc.

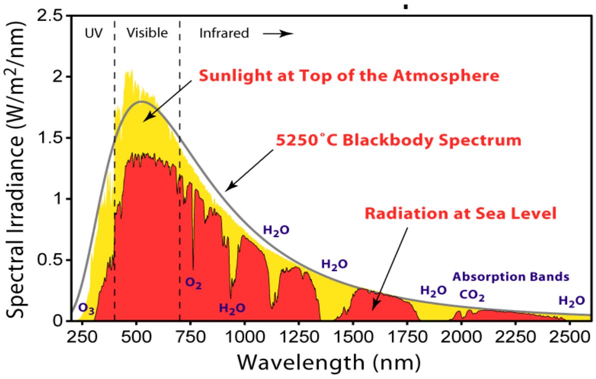

Figure 2. Typical Solar Spectrum (Based on American Society for Testing and Materials (ASTM) Terrestrial Reference Spectra) [5]

5. Conclusion

Solar energy is a potential pumping source for the lasers used for various applications. Many research groups around the globe, are looking for the possibility to increase the solar laser efficiency. The first solar-pumped solid-state laser was reported by Young in 1966 [6]. This work was almost forbidden for several decades. In last few years this work has again gain significant interest, and scientists and physicists have started working on solar energy as a laser pumping source. Several Researchers have approached up to 120 of watt power in continuous mode [7,8]. Now the main concern apart from the improvement in the efficiency is to achieve specific laser light properties from the solar laser so that their domain of application can further be broadened, in order to encourage green energy sources and to meet increasing demand of energy source. The only natural bottleneck there is, availability of the sunlight, as we know it's only available in the day time. Apart from that, sunlight monitoring is required as it varies with time (throughout the day), season and place to place. But the monitoring can be done upto a certain limit and this problem can be solved. So in near future we can expect compact, high power and field portable , useful solar laser systems (operating in the daytime only !!) .

6. References

[1] Mario Bertolotti, "The History of the Laser", trans. Bollati Boringhieri. Philadelphia: Institute Physics, **(2005)**.

[2] Weber, Marvin J. Handbook of laser wavelengths, CRC Press, (**1999**).

[3] http://www.roditi.com/Laser/Nd_Yag.html

[4] MC. Rao, "Applications of Nd: YAG Lasers in material processing: Fundamental approach" IJAPBC-2(3)**, (2013)**

[5] "Introduction to Solar Radiation", Newport Corporation, Oct 29, **(2013).** (http://www.newport.com/Introduction-to-Solar-Radiation/411919/1033/content.aspx)

[6] C. G. Young, "A sun pumped cw one-watt laser", Appl. Opt. 5(6), 993-997 **(1966)**.

[7] T. Yabe, et. al., "100 W class solar pumped laser for sustainable magnesium-hydrogen energy cycle," J. Appl. Phys. 104(8), 083104-1-8 **(2008)**.

[8] T. H. Dinh, et. al. "**120W** continuous wave solar-pumped laser with a liquid light-guide lens and an Nd:YAG rod", Opt. Lett. 37(13), 2670-2672 **(2012)**