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THE THERMAL MANAGEMENT SYSTEM OF LASER DIODE: A REVIEW

Rasheed Nema Abed
Department of Engineering Affair, Presidency of Al-Nahrain University, Department of Mechanical Engineering, Engineering College, Al-Nahrain University, Baghdad, Iraq
E-Mail: rasheednema@yahoo.com

ABSTRACT

This study is focused to review the recent advancements of laser diode and its temperature control mechanisms that include thermoelectric cooler, spray cooling methods, micro-channels and micro heat-pipes. These cooling methods are significant to make laser diode in compact size, light weight with more reliability. Moreover, these cooling systems can eliminate moving parts in laser diodes which can be powered by direct current and easy in switching. Furthermore, this study is focused to describe the challenges involved in the studied cooling methods of the laser diode and also illustrates the heat transfer coefficients and temperature control variables in different studied cooling methods of the laser diodes from literature. The proposed review illustrates the recent developments, advantages and limitations of different cooling methods of the laser diodes found in literature, and the provided review can be significant for future development of the cooling methods in future.

Keywords: laser diode, thermal management, thermoelectric cooler, spray cooling, micro-channel cooling, micro heat-pipe.

1. INTRODUCTION

Laser diodes have broad area of application for example; they are widely used in medical applications such as in surgical instruments, military applications such as in air craft controls, satellites controls, and have wide use in the industrial applications such as they are used to precisely cut the material in the production of sophisticated designed products. In most of the applications of these diodes, they are desired be of small size, light weight and highly efficient with higher reliability. Moreover one of the main concerned problems of the research community is to reduce the temperature of these diodes. The temperature of these diodes can effectively influence the performance of these diodes. For example increase in the temperature of the semiconductor i.e., active parts, of laser can cause optical damage in the laser diodes. Thermal management and thermal stress minimization are critical issues in the compact sized lasers. Therefore, tremendous breakthrough has been realized in the main optical electronic performances of high power semiconductor laser diodes in literature. For example, improvements have been proposed by different researchers in these diodes to reduce the temperature of diodes to produce ultra-high peak power, super-high electro-optical conversion efficiency, low beam divergence, high brightness, narrow spectrum line width, high operation temperature, high reliability, wavelength stabilization and fundamental transverse mode operation etc. Most of the literature described the improvements in the performance of diodes by improving the cooling methods of the diodes which includes thermoelectric coolers, macro-channel heat sinks, liquid-impingement jet or spray cooling, micro channel and micro heat pipe to control temperature of diodes [1]. Many researchers introduced different methods to control the temperature of laser diode when it is working on different ambient temperature for example, some researchers introduced methods to cool the diode when it is required to cool and some researchers developed other methods to maintain the temperature of the diodes when they are desired some times to increase the diode temperature to maintain its temperature to its stabilizing temperature (i.e., in the case of thermoelectric coolers).

In literature several review articles have been presented by researchers in the field of thermoelectric coolers, For example, Muhammad hamid. Presented a review article to describe the literature work that is focused on the material with superior coefficient of performance and described them with their thermoelectric physical parameters such as, electrical conductivities, seebeck coefficient and thermal conductivity for a crystalline system. They also presented some basic knowledge of the thermoelectric material, their application and illustrated an overview of the parameters that affect their performance [2]. Dongliang Zhao presented a review on thermoelectric coolers and described literature studies which presented the development of thermoelectric coolers with advances in material, modelling and optimization approaches and application. Furthermore, their review also classified the literature studies of thermoelectric cooler on the basis of the mathematical models that have been developed in literature for different kind of thermoelectric coolers and they also illustrated several applications of the thermoelectric coolers studied in literature [3]. Hilaal Alam described a review with thermoelectric concepts and explained briefly the challenges involved in the enhancement of the figure of merits. They also reported various approaches adopted in bulk materials, complex structure and the recent nanostructures to circumvent the interdependency of parameter in achieving higher figure of merit i.e., higher ZT [4]. Riffat and Ma. presented a review on the improvement of coefficient of performance (COP) for the thermoelectric cooling system. They described the recent developments in the material for thermoelectric modules, optimization of module designs and applications [5]. Riffat and Ma., presented a review on the basic knowledge of the thermoelectric cooler and its application [6]. Bruno and Matteo, explained the literature studies on the single and two phase flow in micro-channel, single and two phase flow in porous media and jet impingement cooling [7]. Leonard L. vasiliev presented a review article to present the research that have been done in past for cooling using different cooling heat pipe methods [8]. Most of the review articles described mostly the thermoelectric cooler structure, designs, modelling techniques and their applications. These review articles are mainly focused on the improvement the thermoelectric coolers by modifying the structure of material, improving the COP and the modules of the thermoelectric coolers. However, there are several other methods which are used for the cooling applications. For example, spray cooling, micro channels, micro heat pipes and thermoelectric coolers. One of the major application areas of these cooling methods is in the cooling of laser diodes. These laser diodes have wide range of applications in the medical use, aerospace applications, military applications and several other areas of the recent developments. Due to wide application area of the laser diodes, the thermal management is a critical issue in this field of research. However, the cooling methods for laser diodes explained in several articles have not been collected in a review form and most of the review articles found in literature only focused on one type of the cooling method, i.e., using thermoelectric coolers. This motivates us to present a review on the area of the thermal management techniques that have been developed for the cooling of laser diodes. The collected information can be helpful for further development on the cooling techniques for the laser diodes and can benefit the wade range of its application area. Rest of the paper is organized as follows; Section 2 indicates a brief introduction about the laser diodes and describes its basic principle of working. Section 3 illustrates the literature work on the different cooling techniques used for cooling the laser diodes, i.e., spray cooling method, micro channel method, micro heat pipes and thermoelectric coolers. Section 4 indicates the advantages and disadvantages of the cooling methods for laser diodes and compared these cooling methods with discussion to highlight the shortcomings of the existing methods which can be fruitful for the further improvement of the cooling methods of the laser diodes in future. Section 5 describes the conclusion of the research and indicates some of the future research directions.

2. LASER DIODE

Laser diodes are a kind of semiconductor which is used to produce and amplifies high power electromagnetic radiation of specific frequency through process of stimulated emission. In laser diodes the light rays have same wavelength and they are coherent and travel long distances without diffusing. High power laser diode converts electric energy into light energy and the rest of energy is generated as waste heat.

In most of the applications, the packaging of laser diodes consists of sub-mount (base plate). The sub-mount is placed on TEC for rapid heat dissipation from it. The entire assembly of the laser diode, sub-mount and TEC is then mounted on a pure copper or copper-tungsten heat sink (package base) for further heat dissipation and cooling, as shown in Figure-1 [9, 28]. In efficient packaging design can cause poor product quality as temperature of the device core has a direct influence on output wavelength.

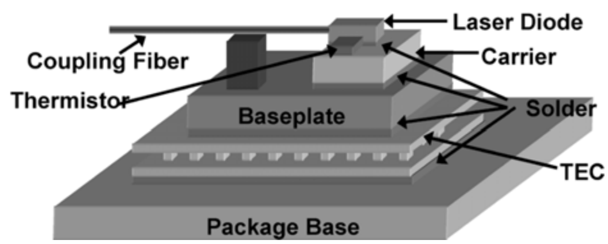

Figure-1. Schematic structure of a typical pump laser package [28].

Laser diodes are used in wide range of applications that includes metrology and medicine, defence applications e.g., laser speed guns are a typical application for pulsed laser diodes. Laser diodes are also used as navigational aids for ships, particularly in ports and harbor's, weather forecast at airports and in recent applications they are used in cars and automobiles to predict the distance between the moving automobiles on the road which can protect the possible accidents or hazards.

In most of applications of laser diodes are required to be placed in small equipments and sensors and due to which they are packaged into small size. Due to small packaging of these diodes, they heat up while working and therefore in most of its applications laser diodes are needed to be cooled for their efficient working. Furthermore, in most of its application area it is required to dissipate the generated heat in a short time because in-efficient heat dissipation can cause thermal stresses in the laser diode, and eventually cause irreversible damage to the laser.

The performance of laser diode is highly dependent on operating conditions. Without damage, the laser diodes can be used for more than their life period if

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the pulse generation time for the diode is for short duration in its application area.

Laser diode works on the principle of spontaneous emission of the pulse of light. In this principle, when a photon of energy is introduced into an atom of the medium, the electrons of the atom are excited to move into a higher energy level and the atom can reach to an excited state. However, the excited atom is unstable and its electrons always tries to get back to the ground state and release the excess energy that it originally gained from a photon of light radiation. Laser diodes contain a chamber in which atoms of a medium are excited, bringing their electrons into higher orbits with higher energy states. When the laser diode is subjected a small power (i.e., called as power of action) then these electrons jumped down to a lower energy state and can give off its extra energy as a photon with a specific frequency. By introducing more photons into the system, the photons can eventually encounter another atom with an excited electron. This can stimulate the electron to jump back to its original state, emitting two or more photons with the same frequency as the first one and their frequency is in phase with it [9]. In this way, a continuous emission of light is generated with the continuous jumping back of the exited electrons and this phenomenon can generate a coherent light.

High power laser diode or laser devices convert electric energy into light energy at about 10% - 50% efficiency. The rest amount of energy is emitted as waste heat and must be dissipated within a short amount of time. If the generated heat is not dissipated in short time, it can cause thermal stresses in the laser diode bar, and eventually cause irreversible damage to the laser. Inefficient cooling packaging design can results in poor product quality because temperature of the device core has a direct influence on output wavelength and band gap of laser light. It is proven in practical situations that for every 3^{o}C of change of temperature in the laser diode core, the wavelength of the laser light can change nearly 1 nm. Furthermore, the output power of the laser light decreases as temperature in the laser diode core increases. [9].

The performance and long life of the laser diode depends on its thermal management to achieve high efficiency of laser diode. Therefore, several cooling methods are used to dissipate the heat from the core of laser diode and different cooling methods are adopted in the laser diode packaging. In these methods heat sinks are mostly used for cooling and cooling can produce laser light with less distractions. Moreover, efficient cooling methods can try to dissipate the heat generated to maintain the laser action and its temperature. Laser diode cooling is a crucial concern for designing high power laser diode and also to dissipate the high heat flux generated from it. The recent developments of thermal management system of laser diode including literature including spray cooling method, micro channel method, micro heat pipes and thermoelectric coolers with their existing problems and some of the possible research directions for their improvement based on the literature work to date are explained in detail in the next section.

Due to recent developments of the electronic sensors in different application area several kinds of improvements has been suggested by researchers to improve the thermal management of the laser diodes. In last few years, lot of research has been done and is ongoing to improve the heat dissipation problem of the laser diodes. In literature four different kinds of the laser diode cooling techniques has been suggested by the researchers that are thoroughly explained in this section one by one.

3. THERMAL MANAGEMENT OF THE LASER DIODE

3.1. TEC cooling

Many researchers are produced about the physical properties of the thermoelectric material and the manufacturing technique of thermoelectric modules. The emphasis of recent research has therefore been the improvement of the COP of thermoelectric cooling systems by means of developing new materials for thermoelectric modules, optimization of module system design and fabrication and improvement of the heat exchange (heat sink and heat rejecter) efficiency.

Thermoelectric cooling is also used to produce -80^{o}C temperature to operate the sensors in infrared imaging systems for heat-seeking missiles and night-vision systems [13].

A TEC is composed of a number of semiconductor element pairs which are connected electrically in series and thermally in parallel, and each pair includes a p-type semiconductor column and an n-type semiconductor column. Thermoelectric modules are solid state heat pumps that utilize the Peltier effect, During operation, DC current flows through the thermoelectric module, causing heat to be transferred from one side of the thermoelectric device to other, creating a cold and hot side. Strongly depends on thermoelectric materials. The most important performance index of thermoelectric materials is the figure of merit (ZT) which is defined by $ZT= \alpha^2 T\sigma/k$, where α is the Seebeck coefficient, T is the absolute temperature, σ is the electrical conductivity, and k is the thermal conductivity of the material. A higher ZT value will lead to a better TEC performance, thus, high α and σ, as well as low k are desired for thermoelectric materials, thermoelectric cooler can explain in Figure-2 [14, 15].

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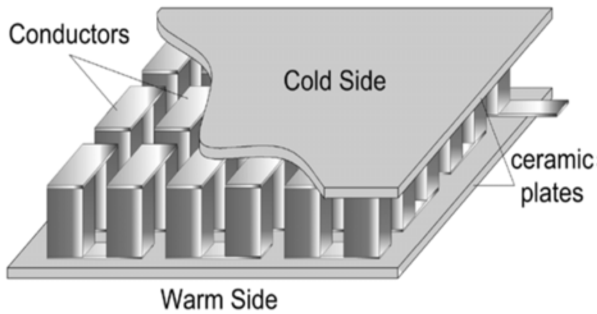

Figure-2. Thermoelectric cooler [15].

The thermoelectric is a promising technique for cooling as well as to cool ambience without using harmful chemicals like CFC and moving parts. Thermoelectric cooler has been widely used in military, aerospace, instrument, and industrial or commercial products, as a cooling device for specific purposes. This technology has existed for about 40 years [5].It is, however, already in use to cool diode lasers [10], critical electronics [11], and portable refrigeration [12].

Now, thermal management system of the thermoelectric cooler (TEC) is an essential component of the advanced new generation of the laser-based manufacturing systems that should offer a broad range of machining parameter modes. TEC modules are the preferred choice to be used as the actuator of such a thermal management system due to their application (cooling/heating) operation, solid-state nature, fast response, small form factor, reduced maintenance requirements, absence of noise and vibrations, and the capability to provide a precise control of the temperature [17]. Many researchers have been used a TEC to maintain the temperature of the submount of the laser diode at 25ºC because the TEC is used as a heat sink to maintain the heat sink at constant temperature [20, 22, 25, 28-29, 32-34].

In 1992 H. Van Tongeren firstly proposed to use the TEC to cool the laser diode, and reported the thermal modelling and experimental investigations on Butterfly packages for pump lasers. The aim of this experiment is to improve the thermal package resistance and performance of the TEC when operate at ambient temperature 65ºC and the thermal dissipation in the laser crystal of 1W power by TEC. It also can keep the temperature of base plate at 25ºC when operating at a current of 1A [35]. And then, many researchers did a lot of work to investigate the feasibility and cooling performance of this thermal management by using finite element method analysis of the semiconductor disk laser. The theoretical researches show that [19, 26-27, 32]. Afterwards the experimental method of the D.Y. qiu. In his experiment he found out that the thermal management methods can reduce the waste heat generation the diode pump alkali vapour lasers (DPALs) method can be alternative to the most develop and successful of high power laser system [21].

Then the researcher did a lot of work to improve the cooling performance of the TEC. Such as M. Gasik designed functionally gradated material (FGM) based TEC system for laser-based solar space power system (SSPS) analyses to optimize the design of the TEC system [16].

Many researcher presented to optimize the active region of the laser diode, from them M.N. Sysak, V. Spagnolo, and J. Fu for optimization the active region design to reduce the thermal resistance of laser diode mounting to improve heat removal from the active region of the laser diode [18, 23-24]. Furthermore, A. Rantamaki improved the mode-locked laser performance for the semiconductor saturable absorber mirror (SESAM) for the thermal management of the laser diode, equipped with intracavity heat spreader of semiconductor laser diode for achieving high power short pulse operation [30],

Now researcher try to improve the thermal management system of pulse laser to control on pulse width, like V. Novak was compared a standard pulse-width modulation controller and a variable-voltage controller based on TEMs for a thermal management system of pulse laser. They showed that the design of the thermal management system based on the variable-voltage controller offers a significant performance advantage over the pulse-width modulation design [17]. After him the investigation of miniature thermoelectric module (MTEM) was showed by Shen limei for pulse laser cooling. She analysed the effect of the pulse-width of laser. The efficient utilization of step-change voltage for pulse cooling load may be produces a stable temperature for pulse laser. the MTEM can deal with not only the low cooling load of continuous laser, but also high cooling load of pulse laser with discuss the influence of thermal resistance between the MTEM and the ambient to maintain the temperature of laser under higher ambient temperature, The fitting equation can also be applicable for the design and optimization of a temperature controller as well as proper thermal management for a laser module cooled by TEC [63].

3.2. Spray cooling

Spray cooling as the high heat flux removal technique has potentials for high power systems. The spray cooling with phase change takes advantage of relatively large amounts of latent heat and is capable of removing high heat fluxes from surfaces with low superheat. Recent applications of spray cooling involved the cooling of different kinds of electronics. In the application, a major portion of heat transfer results from nucleate boiling heat transfer. [37]

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In the spray cooling process, liquid coolant is sprayed onto a heating surface to form a cohesive or ruptured thin liquid film and then is evaporated with heat removal. Obviously, the spray cooling process covers an extremely complicated heat and mass transfer process, which is dependent of the coolant, the velocity and diameter of sprayed droplets, the pressure in spray chamber, the spray angle and the surface characteristics [42].

Spray cooling can be used to transfer large amounts of energy from the laser diode at low temperatures by utilizing the latent heat of evaporation of the working fluid, because of its efficiency and ability to isothermally remove heat, spray cooling is a leading candidate to cool high-power diode laser arrays in terrestrial environments and consider direct cooling of the components eliminating the thermal contact resistance between the heat sink and the chip that exists with conventional methods, such as finned heat sinks, we can explain the method of spray cooling as shown in Figure-3 [53].

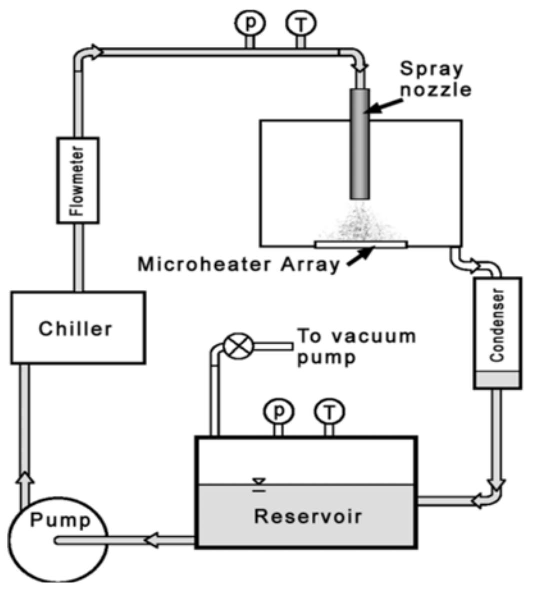

Figure-3. Diagram explain spray cooling device [53].

In 1988 C.H. Lee and I. Mudawer firstly proposed to use spray cooling to cool laser diode then developed a new mechanistic critical heat flux (CHF) model for vertical sub-cooled flow at high pressure and high mass velocity [64]. Then the other researcher did experimental work as J.J. Huddle focused on the thermal analysis of using spray-cooled diode laser arrays to precise and uniform temperature control of the diode lasers at a constant boiling point over the entire cooling surface [36]. Many researchers did a lot of work on experimental method to investigate of confined and closed loop spray cooling with multiple nozzle spry cooling in the spray chamber at constant pressure was exposed to a heated surface [37-38, 40-42]. Some researcher used spray cooling in medical application such as H. Strempel used laser effect on epidermal and explained time delay between the application of cooling spray and the emission of the laser pulse to explain the cooling time as short as necessary in order to avoid undesired side effects [39].

3.3 Micro-channel

Micro-channel is one of the most active fields of heat transfer research today in electronics and microelectronics device, the use of micro-channel heat sinks in the thermal management of electronic and optical devices has been studied for about three decades. Micro-channel heat sinks are strong candidates for the effective removal of heat dissipation from devices, such as, integrated circuits and semiconductor lasers. Micro-channel heat sinks are utilized generally with liquid coolants which provide higher heat transfer coefficients compared to gaseous coolants. The heat is removed from the surface either by single-phase liquid flow or phase changes of the coolant with flow boiling (two-phase flow) [51].

Micro-channel heat sink with a high local heat transfer efficiency, which comprises parallel longitudinal micro-channels etched in a silicon substrate and transverse micro-channels electroplated on a copper heat spreader and this Micro-channel heat sinks bonded directly onto the high power density electronic components, this will be Improve thermal management systems of the laser diode.

High power laser diode and laser bars is required very efficient thermal systems that enable to remove the heat fluxes resulting from the high power operation, The Micro-channel package with laser diode allows stacking of several high power laser diodes in an array and the sub-assembly is then cooled using water cooling channels, Micro-channel flows are driven by pumps with mean flow velocities in the range of few millimeters per second to many centimeters per second, and the Flow in micro-channels will be mainly laminar Higher Surface Density, Higher Heat Transfer Coefficients, Low Thermal Resistance and Volumetric heat transfer rate depends inversely on square of the channel diameter, Figure-4 explain the shape of the micro-channel [44-45].

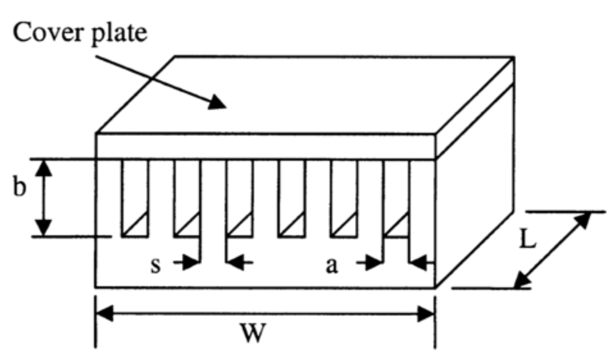

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Figure-4. Schematic of micro-channel geometry [45].

In 1981 D.B. Tuckerman and R.F.W. Pease firstly proposed to use micro-channel to cool laser diode. The thermal resistance about 0.1°C/W for 1cm^2 area and this device was tested up to 790W/cm^2 and measure maximum substrate temperature rise to 71°C above the input water temperature [65]. Some researcher as S. A. Payne used helium gas pumped in micro-channel as a working fluid flowing with speed 0.1 Mach to cool high power laser diode [47]. Many researchers used micro-channel and developed micro-channel heat exchanging system for the thermal management for the best performance coefficient for high-density laser diode by using a closed-loop system cooling to achieve very low thermal impedance required for the laser diode cooling application [43, 46, 48, 52].

Furthermore, another research used double-side cooling technology as J. Wang presented of the packaging of high power density double quantum well (DQW) semiconductor laser array, and improved the heat dissipation by bonded the DQW laser bar to the "sandwiched" between two micro-channel cooler based water-cooled-packaged [50].

Now the researchers try to improve the thermal management system in regard to the laser diode. They designed micro-channel heat sink with special geometrical configuration and analysed Micro-channel heat sink with the effects of channel width, channel depth, fin width for high power laser diode with water cooling to enhance the performance of micro-channel [49, 51].

3.4 Micro heat-pipe

A micro heat-pipe is a simple device that can quickly transfer heat from one point to another, often referred to as the superconductors of heat as they possess an extraordinary heat transfer capacity. Through the phase change of its working fluid micro heat pipes are very effective heat transfer device relative to conventional heat spreaders. Micro heat pipes can also be used to raise the thermal conductivity to spread a concentrated heat source over a much larger surface area [54, 60].

Micro heat pipe consist of hallow tubes that have been evacuated and then filled a coolant liquid, it has high value of surface tension is desirable in order to enable the heat pipe to operate against gravity and to generate a high capillary driving force.

A heat pipe is a device that can quickly transfer heat from one end to the other. It utilizes the latent heat as well as the sensible heat of the vaporized working fluid; the effective thermal conductivity may be several orders of magnitudes higher than that of the good solid conductors. A heat pipe consists of a sealed container, a wick structure, a small amount of working fluid that is just sufficient to saturate the wick and it is in equilibrium with its own vapour, the main purpose of wick are to generate the capillary pressure, the length of the heat pipe can be divided into three parts, evaporator section, adiabatic section and condenser section, the working principle of a heat pipe. High heat flux from the laser diode input at the evaporator region vaporizes the working fluid and this vapour travels to the condenser section through the inner core of heat pipe at the condenser region, the vapour of the working fluid condenses and the latent heat is rejected via condensation. The condensate returns to the evaporator by means of capillary action in the wick, when thermal energy is supplied to the evaporator, this equilibrium breaks down as the working fluid evaporates, Figure-5 explain the shape of the heat-pipe [54].

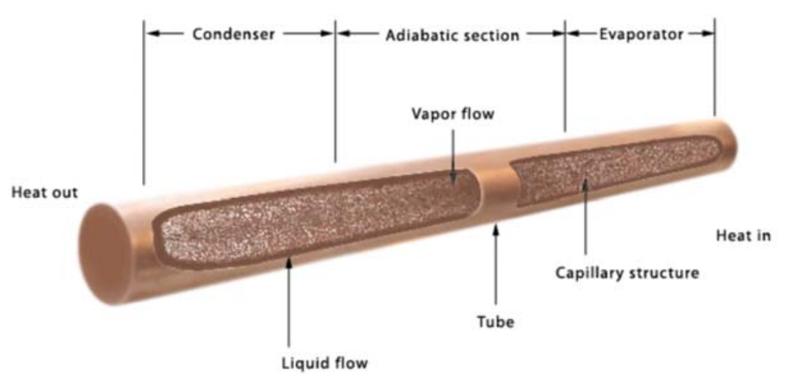

Figure-5. Heat pipe [54].

In 1995 A. K. Mallik, firstly proposed a simulation and experimental work to design micro heat-pipe to cool laser diode, then has been fabricated Vapour-deposited micro heat pipe arrays (VDMHP) as an integral part of semiconductor devices to act as efficient heat spreaders by reducing the thermal path between the heat sources and heat sink [55]. some researcher used numerical simulation such as M. J. Marongiu by

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Investigated micro heat-pipes have been incorporated in different configurations into micro-channel heat sink designs, The addition of micro heat-pipes into a micro-channel heat sink system to allow the increase of heat dissipation capabilities without increasing the flow through (pumping power) [56].

The other such as W. Chao focused on numerical simulation of a silicon micro flat heat pipe with axially micromachining triangle grooves by increase the performance of micro flat heat pipe [60].

Many researchers explained the new design considered thermal management system of a variety electronic device to improve the temperature precision, this designed for suitable implementation of micro heat-pipe in an experimental method for low temperature InP/lnGaAs based processes to improve the performance of the heat sink for this device [57-58].

Then the research used the disk-shaped miniature heat pipe (DMHP), as H.T. Chien which Presented a novel packaging base for the TO can package of laser diode to verify the thermal performance of DMHP as heat spreader of laser diodes [59].

4. ANALYSIS AND COMPARISON

The four main methods for laser cooling are discussed in the above part. In this part we want to talk about the cooling characteristic, the existing problems or shortcomings of each method.

TEC is easy to package with laser diode and maintain the temperature of laser at 25 ^{o}C by just adjusting the electric current. It also could be used to cool all kinds of laser diodes with the range of heat flux 0.1-10 W. The long-life of TEC is matched well with the requirement of laser. TEC small commercial packages to be developed that are capable of precise temperature control in a variety of applications.

And the existing problem or short coming of the TEC is high cost and poor power efficiency, low COP in larger temperature difference of the TEC this will causes a poor operational thermal economics. A high thermal conductivity causes too much heat leakage through heat conduction will be reduce the figure of merit (ZT) the deleterious effects of electrical and thermal contact resistances, which increase greatly with TEC leg shortening.

Spray cooling relatively dissipate large amount of latent heat and capable of removing high heat from surfaces with low superheat major portion of heat transfer results from nucleate boiling and low surface temperature give high uniformity. This technology is to ensure a minimum temperature gradient between emitters and along the cavity length of the emitter, the heat transfer coefficient increase with increasing heat flux, the applied pressure drops across the nozzle to maintain the optimum thermal performance of closed loop spray cooling system. The existing problem is lower performance of fluorocarbon to extract the heat flux, then the multiple nozzle spray cooling in the confined spray chamber and the flow circulated within and the pressure difference generated by the micro pump maintain the circulation flow, and the system evacuated before filling a proper amount of the working fluid, non uniform heat transfer coefficient (h) with one jet. Micro-channel cooled package with laser diode pumping to achieve high power output pumping, military or medical applications with typical wavelength (806-808) nm, 880nm, 980nm and output power 100-900 W, it offers lower thermal impedance, the flow flowing inside the channel must be laminar flow which leads to heat sink having very low thermal impedance required for the laser diode.

The existing problem such as electrochemical deposition of material in the cooling channels, erosion and/or corrosion of the cooling channel walls, or pitting of the material underneath defects in the Au typically used to coat the micro-coolers, higher heat flux, the pump needs more power to manage higher pressure drops of the system and the disadvantage that the width of the micro-channel increase cause decrease in channel number and this lead to decrease in heat exchanger, then this cause decrease in heat transfer coefficient and the thermal deformation can be further increased.

The heat pipe application range from 19 KW/cm^2 axially, 300W/cm^2 radially, and work at temperature from 1400 to 1500^{o}K and work specifically enclosure capillary structure, working fluid then typically designed to carry less than 25W of power low in cost and high in reliable and it used the advantages of high strength, anti-corrosion, stainless steel aluminium, copper and composite material. The heat-pipe can operate as a nearly isothermal device; it is that both the evaporator and condenser operate independently.

Existing problems of the heat pipe is the high porosity of the wick, and the use of low-thermal-conductivity working fluids all combine to impede the flow of heat from the heat pipe wall to the liquid–vapour interface.

5. CONCLUSIONS

This paper reviews the development of laser diode cooling in the recent decade from aspects of advances in cooling methods such as: thermoelectric cooling, spray cooling, micro-channel cooling, micro heat-pipe cooling.

We explain above that the TEC is easy to package with laser diode and maintain the temperature of submount of the laser at 25^{o}C. It also could be used to cool all kinds of laser diodes with the range of heat flux 0.1-10 W.

Spray cooling relatively dissipated large amount of latent heat and capable of removing high heat from surfaces with low superheat major portion of heat transfer results from nucleate boiling and low surface temperature give high uniformity.

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