DESIGN AND REALIZATION OF A MULTI-WAVELENGTH DIODE LASER DEVICE FOR WOUND HEALING TREATMENT

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ABSTRACT

In recent years, the application of multi-wavelength low-level laser therapy for some acute and chronic diseases and improving the quality of treatment has brought a lot of positive achievements in medicine. It is increasingly popular in both experimental and clinical trials. It is highly demanded to design and develop phototherapy laser devices for specific applications. In this study, a multi-wavelength phototherapeutic device that emits in the red to near-infrared region, the phototherapeutic window region, is developed. The device uses laser modules, allowing easily focus laser beams on the targeted therapy zone. For the convenience of the user, the device integrates a digital control system, a touch screen that easily selects optimal parameters such as power, wavelength, and operating mode for specific therapeutic purposes. This paper presents the design and complete implementation of the device and the laser module fabrication technique as well. The main parameters of the laser therapy device are given, which meet the specifications of a phototherapeutic device and suit open and chronic wound healing based on the photobiomodulation effect.

THIẾT KẾ VÀ CHẾ TẠO THIẾT BỊ LASER DIODE ĐA BƯỚC SÓNG CHO TRỊ LIỆU VẾT THƯƠNG

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TỪ KHÓA

Trị liệu laser công suất thấp

Đa bước sóng

Điều biến quang sinh

Laser diode

Sợi quang đa mode

TÓM TẮT

Trong những năm gần đây, việc ứng dụng phương pháp điều trị Laser công suất thấp đa bước sóng đối với một số bệnh cấp tính, mãn tính và nâng cao chất lượng điều trị đã mang lại nhiều thành tựu tích cực trong y học. Nó ngày càng phổ biến trong cả thử nghiệm thực nghiệm và thử nghiệm lâm sàng. Các thiết bị laser quang trị liệu cho các ứng dụng cụ thể đang có nhu cầu rất lớn. Trong nghiên cứu này, một thiết bị quang trị liệu đa bước sóng phát ở vùng đỏ đến vùng hồng ngoại gần, vùng cửa sổ quang trị liệu, được phát triển. Thiết bị sử dụng các mô-đun laser, cho phép dễ dàng dẫn chùm tia laser vào vùng cần được trị liệu. Để thuận tiện cho người sử dụng, thiết bị tích hợp hệ thống điều khiển kỹ thuật số (Digital control), màn hình cảm ứng dễ dàng lựa chọn các thông số như công suất, bước sóng, chế độ hoạt tối ưu với mục đích điều trị cụ thể. Bài báo này trình bày thiết kế và chế tạo hoàn chỉnh thiết bị cũng như kỹ thuật chế tạo mô-đun laser. Các thông số chính của thiết bị trị liệu laser được đưa ra, đáp ứng các thông số kỹ thuật của thiết bị quang trị liệu, phù hợp cho điều trị các vết thương hở và mãn tính dựa trên cơ chế điều biến quang sinh.

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1. Introduction

Low-Level Laser Therapy (LLLT) is also known as cold laser therapy or photo biomodulation therapy [1], [2]. It uses a single wavelength or monochromatic light emitting from a low-intensity laser diode (10 mW ÷ 500 mW). The wavelengths are from approximately 600 nm (visible light) to 1000 nm (invisible infrared) as the “biological window” allowing the light to penetrate and thereby spread into the tissue and affect the cells. The depth of laser penetration varies, it is approximately 1 cm ÷2 cm, in the range from 600 nm to 700 nm, which is mostly used for skin and wound treatment. While at 800 nm - 900 nm a depth effect of approximately 3 cm ÷ 4 cm is obtained, which is primarily used for pain and tissue treatment. The laser works in pulse range from 0 Hz (continuous) to 5000 Hz, the duration of the pulse can range from 1 ms to 500 ms with a total irradiation time of 10 s to 3000 s and with intensity (power x irradiation time/ irradiated area) ranging from 10^{-2} J/cm^2 to 10^2 J/cm^2, for example, 50 mW/ cm^2 x 40 seconds =2000 mJ/cm^2 or 2 J/cm^2 [3].

The treatment mechanisms of the LLLT are explained when the light source is placed in contact with the skin, allowing the photon energy to penetrate tissue, where it interacts with various intracellular biomolecules to restore normal cell function and enhance the body’s healing processes. The cell absorbs photons of light, becomes activated, changes the cell’s membrane permeability and increases the speed of cellular metabolism as well as promotes the release of nitrogen oxide (NO), which is the result of cytochrome c oxidase (Cco/NO) activity, then promote the production of adenosine triphosphate (ATP) and promote vasodilation [4] – [7]. It releases NO and increases the redox chemistry which leads to the production of reactive oxygen species and synthesis of collagen, blood vessel formation, and less infection. All that effects promote the pain relief and healing of wounds [8].

LLLT is a safe, non-invasive technology approved by both the US Food and Drug Administration and Health Canada for several chronic and degenerative conditions, temporary pain relief, cellulite treatment, body contouring, lymphedema reduction, hair growth, and chronic musculoskeletal injuries. It increases microcirculation, lymphatic drainage, and cellular metabolism, thereby relieving many acute and chronic conditions and healing wounds. Numerous articles are using the LLLT for anti-inflammatory [9] and analgesic effects [10], tissue healing [11], bone reconstruction [12] treating tendinopathy, and improving lymphedema [13]. LLLT is ready for clinical trials over myocardial infarction [9]. Recently, it is recommended to use as a modality to attenuate cytokine storm at multiple levels, enhance recovery, and reduce the use of ventilators in COVID-19 [1], [14] – [16].

Semiconductor lasers with many advantages such as compact size, a wide range of output power, wavelength versatility, low cost per watt, etc. [17], [18]. However, for direct application, high brightness and good beam quality are required. All of these have to do with packaging sometimes even largely rely on packaging technologies. These techniques and technologies require sophisticated optical systems and increased precision of the semiconductor laser packaging in terms of positioning tolerances relative to the mounting substrate and smile of the semiconductor laser. Packaging technology has become an important part of high-power semiconductor laser development. With the vast advances in semiconductor laser chip and bar technology in recent years, packaging has become one of the bottlenecks of the advancement of high-power semiconductor lasers [19], [20].

Recently, Jafarpour et al. [12] developed a design of a multi-wavelength low-level laser therapy device for assisting bone reconstruction applications. Where three wavelengths at 635 nm, 520 nm, and 480 nm with an output power of 300 mW were used. In this device, a complicated system for alignment was used. A three-step alignment was designed to generate single or multi-wavelength laser beams. Two mini right-angle half-silvered mirrors were used to align the three laser beams. To focus the laser beam onto the targeted point, a focus lens was connected to a linear system, to move the lens on a linear axis. The intensity of the laser beam was adjusted and focused onto the targeted zone by using a precise control system. A multi-mode optical fiber was used to guide the laser beam onto the healing zone.

In Vietnam, there are some kinds of multi-wavelength phototherapeutic semiconductor laser devices on the market. Most of them are imported at a very expensive, and some of them are simply manufactured in Vietnam. They normally have two wavelengths. For example, in [21] phototherapy equipment using light-emitting diode (LED) at 650 nm and 940 nm were reported. The output power from 10 mW and 100 mW was obtained. The device is capable of operating in pulse mode with a frequency range from 5 Hz to 128 Hz.

In this work, we present a multi-wavelength diode laser device like the device reported in [12]. However, in this device, to avoid all misalignment optics, diode laser modules are fabricated and packaged which are compact, stable, and very easy to use. The device has different treatment programs which can be easy-adjust (digital control) by the control screen on the device. The output power of each wavelength at the end of optical fiber reaches about 300 mW. The device can work from continuously (0 Hz) to 10000 Hz. In what follows, the design and realization of the diode laser are introduced. Five main parts of the device are shortly described. The packaging process of module lasers is given in detail. Then, the optical characteristics of the output of optical fibers and the beam quality of each wavelength are discussed. Finally, the conclusion is carried out.

2. Design and realization of the diode laser device

As mentioned before, low-level laser therapy needs maximum output power from 10 mW to 500 mW for the treatment, we need the maximum output power per channel to be 300 mW. Thus, the equipment is designed so that the laser beam works stably on time without being overheated. Figure 1a shown the block diagram of the multiple wavelength equipment. The inside and completion of the device are shown in Figure 1b and Figure 1c. One complete multiple wavelength device includes five main parts: Programmable Logic Controller (PLC) (1), Human-Machine Interface (HMI) (2), TEC Controllers and Driver (3), Laser modules (4) corresponding to 670 nm, 780 nm, 805 nm, and 980 nm, and Optical fibers (5).

Figure 1d and Figure 1e are the control screams of the device. The HMI is the TFT touchscreen with the microprocessor ARM9 400 MHz, a resolution of 1024 x 600 pixels, and the operating system Wince 5.0. Which is to easily adjust (digital control) the main parameters of the laser beam from each laser module separately, such as power density, mode of operation, and duration. An adapter with an input of 100 VAC÷240 VAC, 50/60 Hz is used that allows the device directly plug into the 220 V power source. For example, after switching on the device, touch the "start" (Figure 1d), and the screen display as in Figure 1e. Then, enter the parameters such as frequency (0 Hz ÷ 50000 Hz) for selecting mode operation, voltage (1 V ÷10 V) for putting output power, and duration (6500 seconds to 18 hours) for setting treatment time. The EX3G PLC will execute the commands from the HMI and communicate with the power supply in the equipment. Microcontroller MTD 415T of Thorlabs maintains the temperature of the system at $25^{o}C$ with an error of $0.001^{o}C$ to keep the Peltier thermoelectric element working with maximum thermal radiation of 3 W for each laser module. The power supply for four laser modules works at 12 V with up to 1.5 A maximum current for each module. The envelopes of the laser modules are made of high-quality heatsink aluminum with a mechanically solid construction, highly avoiding the penetration of steam (< 40%). The fibers which guide the light to the wounded areas are the Multimode Fiber Optic. Patch Cables with a diameter of 400 μm, Numerical Apertures (NA) = 0.50, and two SMA connectors on both ends.

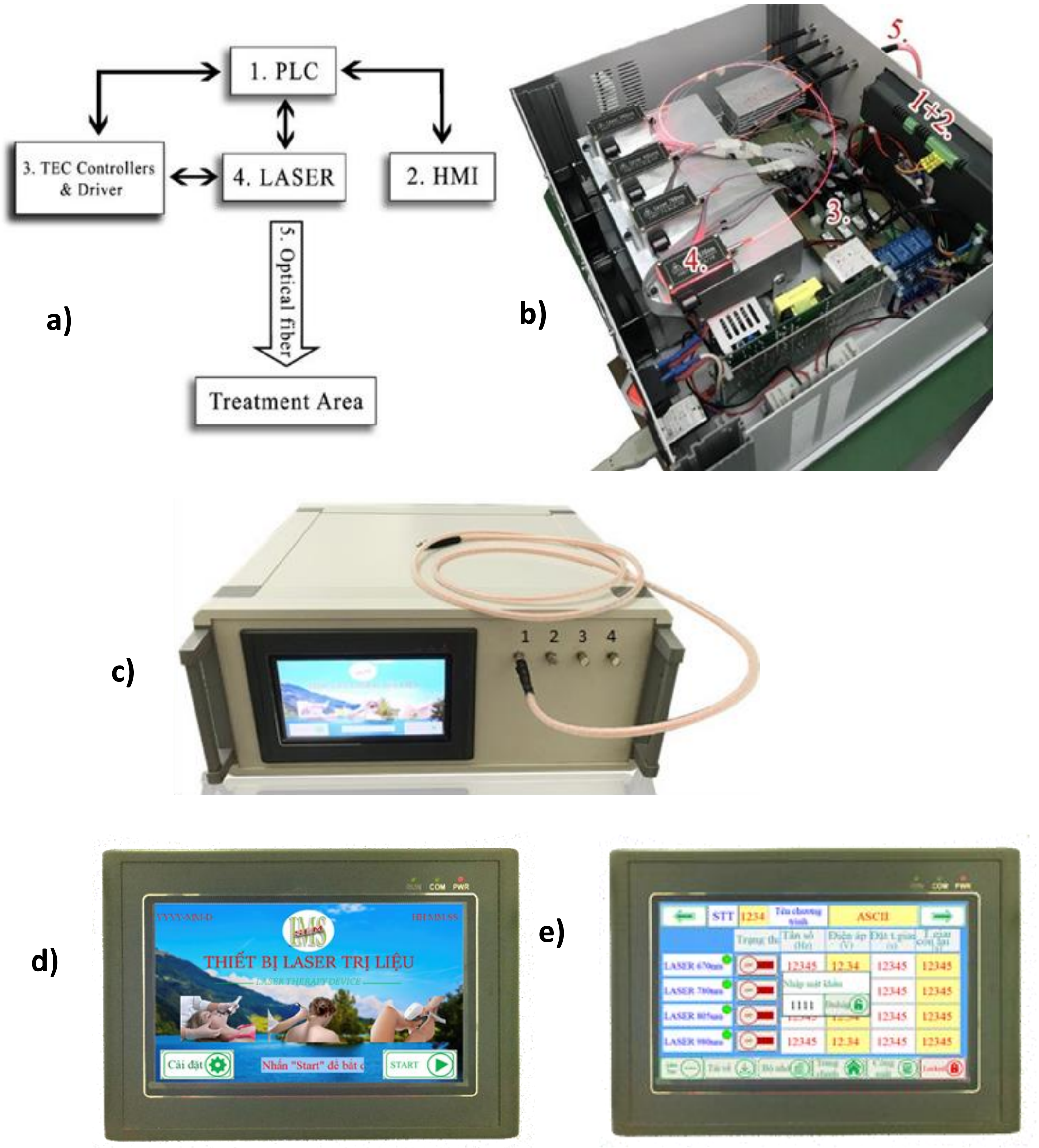


Figure 1. *(a) The block diagram of the multiple wavelength device, (b) The inside (c) Completed equipment, and (d-e) the control screens of the device.*

The fabrication of a laser module is presented in Figure 2. Figure 2a describes the mounting process of the laser chip (6) on the C-mount heatsink base (7) to couple the optical fiber. The fiber is multimode and silica core with a diameter of 400 µm and NA = 0.5 and SMA connectors. The position adjustment and alignment for coupling are done by using Melles Griot's 6-Axis Nanomax-HS High Precision Flexure Stage (9) with the precision in sub-micrometer scale and is observed by Carl Zeiss 2000C stereomicroscope with the maximum magnification up to 230 times. After precise adjustment so that the coupling efficiency is up to 90%, the optical fibers will be fixed by Toresal TS10 epoxy. This epoxy has a low thermal expansion coefficient and good coupling between glass and metal, and it is heated up to 50^{o}C in 60 minutes for solidification. Then, we put the laser into the module envelope and obtain the result in Figure 2b. The module envelope and its mechanical details are made of proper heatsink aluminum and designed appropriately for the coupling process as well as increase the heat sink for the laser. Finally, the laser module is packed like in Figure 2c in a clean low-humidity environment.

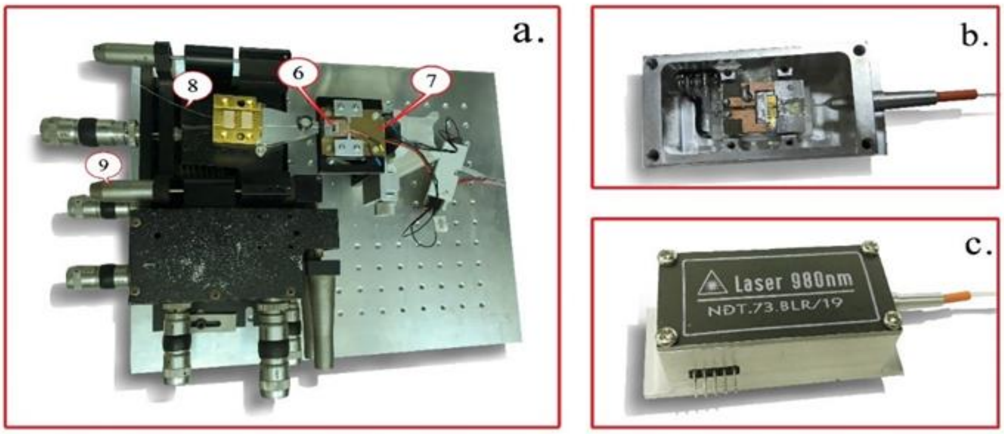


Figure 2. *(a) The setup for coupling of the laser chip to the optical fibre, (b) The laser chip is fixed on the module envelope after coupling, and (c) The complete packed laser module*

3. Optical characteristics at the output

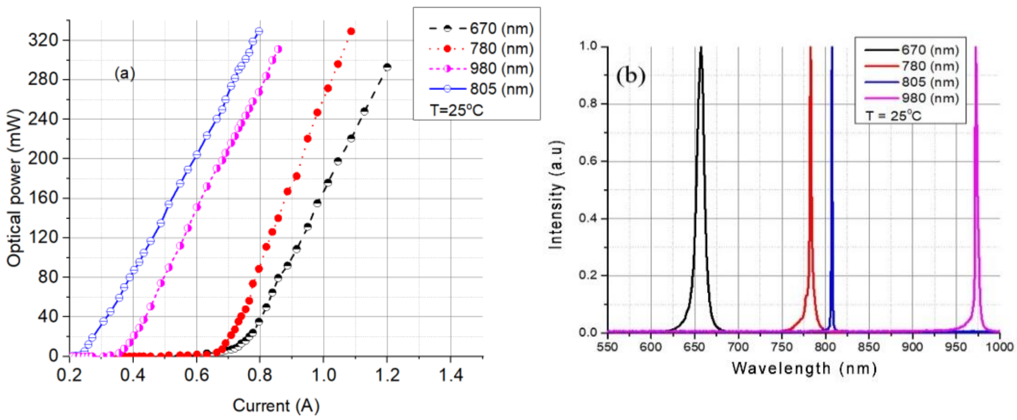


Figure 3. *(a) Characteristic curves of light power versus driving current of the laser modules 670 nm, 780 nm, 805 nm, and 980 nm, respectively (b) Spectrum characteristics of the laser modules 670 nm, 780 nm, 805 nm, and 980 nm, respectively*

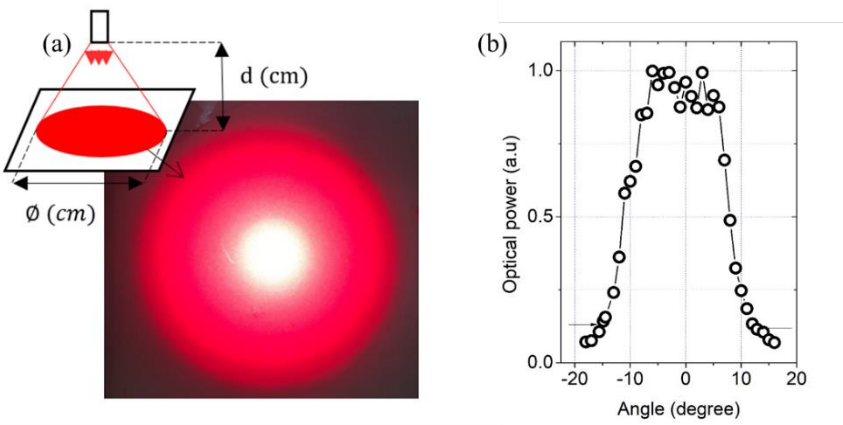
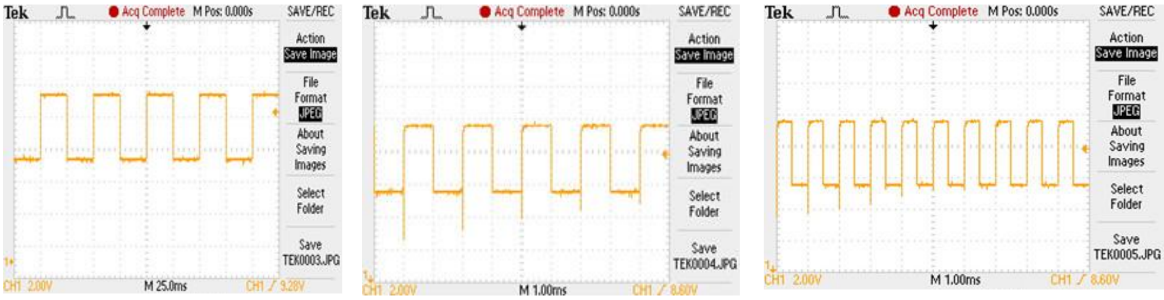


Figure 4. *(a) The radiation distribution of 670 nm laser on the screen, d = 50 cm and Ø=20 cm, (b) Intensity distribution at the output of the optical fibres of the laser module 670 nm at 25°C.*

The dependence of the optical power versus the injected current of laser modules is shown in Figure 3a for T = 25°C. The threshold currents of 670 nm, 780 nm, 805 nm, and 980 nm laser modules respectively are 0.24 A, 0.38 A, 0.7 A, and 0.75 A. The coupling efficiency of each module is 90%. The output laser powers are 329 mW at 0.8 A of 670 nm module, 311 mW at 0.85 A of 780 nm module, 329 mW at 1.09 A of 805 nm module, and 293 mW at 1.2 A of 980 nm module. The output power of each channel is almost over 300 mW to meet the requirement of the therapy needs. Optical spectra were measured with a spectrometer OCEAN OPTICS USB2000 having an optical resolution of 2 nm (FWHM) and a responsive from 200 nm to 1100 nm. At the operating temperature of 25^{o}C and the laser power of 50 mW, the spectra of the laser modules 670 nm, 780 nm, 805 nm, and 980 nm respectively are shown in Figure 3b. The spectrum of the laser module has narrow width around the peak of the corresponding spectrum, which ensures the efficiency of the lighting of each wavelength module on the wound. Besides the power–current characteristics and the spectrum of each laser, the far-field radiation distribution is also very important in the realization of the light intensity distribution of the laser on the wound. According to this demand, we also carried out measuring the laser intensity distribution of one laser module and obtained the results in Figure 4.



20 Hz *500 Hz* *1000 Hz*

Figure 5. *Pulse patterns at different frequencies when the laser module operating in the pulse modes*

Figure 4a represents the circularly equal distribution of the 670 nm laser beam, obtained on a screen that is 50 cm far from the head of the optical fibers (d = 50 cm) and the diameter of the circle is Ø=30 cm. We can notice that the intensity of the beam is highest at the center of the circle and gradually decrease to the edges. Figure 4b is the characteristic curve that represents the light intensity distribution at the output of the optical fiber of the 670 nm laser module at the temperature of 25^{o}C. The curve is measured using the slit-scanning method [22] showing a view angle of approximately 30^{o} at $1/e^2$ of maximum intensity.

Pulse patterns at different frequencies when the laser module is in the pulsation mode are illustrated in Figure 5.

4. Conclusion

In this paper, we have successfully developed a multiple wavelength laser device. The device has a TFT touchscreen with a resolution of 1024 x 600 pixels. Along with EX3G PLC, it allows adjusting the main parameters of the laser beam for each laser module separately, such as power density, mode of operation, and duration. Each laser module uses a Microcontroller MTD 415T and a Peltier thermoelectric element controlling with maximum thermal radiation of 3 W having an error of 0.001^{o}C. The electrical circuit supplying four laser modules can supply up to 1.5 A maximum current for each module. The module laser is fabricated with a coupling efficiency of up to 90%, and the output power of each output channel reaches 300 mW. The spectra of laser modules show the clear peak wavelengths in the therapeutic window. The light beam at the outside of the optical fiber of 30 cm is obtained. These parameters are well-suited for healing open and chronic wounds based on the photobiomodulation effect. In the future, experimental testing for open and chronic wound treatment will be performed to assess the therapy abilities of the device.

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REFERENCES

[1] S. Soheilifar, H. Fathi, and N. Naghdi, "Photobiomodulation therapy as a high potential treatment modality for COVID-19," *Lasers Med. Sci*., vol. 36, no. 5, pp. 935–938, 2021.

[2] E. Colombo, A. Signore, S. Aicardi, A. Zekiy, A. Utyuzh, S. Benedicenti, and A. Amaroli, "Experimental and Clinical Applications of Red and Near-Infrared Photobiomodulation on Endothelial Dysfunction: A Review," *Biomedicines*, vol. 9, no. 3, 2021, doi: 10.3390/biomedicines9030274.

[3] G. Sun and J.Tunér, "Low-level laser therapy in dentistry," *Dental Clinics*, vol. 48, no. 4, pp. 1061-1076, 2004.

[4] M. E. D. A. Chaves, A. R. D. Araújo, A. C. C. Piancastelli, and M. Pinotti, "Effects of low-power light therapy on wound healing: LASER x LED," *Anais brasileiros de dermatologia*, vol. 89, pp. 616-623, 2014.

[5] R. O. Poyton and K. A. Ball, "Therapeutic Photobiomodulation: Nitric Oxide and a Novel Function of Mitochondrial Cytochrome C Oxidase," *Discov. Med*., vol. 11, no. 57, pp. 154–159, 2011.

[6] L. F. de Freitas and M. R. Hamblin, "Proposed Mechanisms of Photobiomodulation or Low-Level Light Therapy," *IEEE J. Sel. Top. Quantum Electron*., vol. 22, no. 3, pp. 348–364, 2016.

[7] V. V. Boras, D. V. Juras, A. A.Rogulj, D. G.Pandurić, Ž.Verzak, and V. Brailo, "Applications of low-level laser therapy," *A Textbook of Advanced Oral and Maxillofacial Surgery.* IntechOpen, 2013.

[8] W. Posten, D. A. Wrone, J. S. Dover, K. A. Arndt, S. Silapunt, and M. Alam, "Low-level laser therapy for wound healing: mechanism and efficacy," *Dermatologic Surgery*, vol. 31, no. 3, pp. 334-340, 2005.

[9] J. M. Bjordal, R. A. B. Lopes-Martins, J. Joensen, and V. V. Iversen, "The anti-inflammatory mechanism of low-level laser therapy and its relevance for clinical use in physiotherapy," *Physical Therapy Reviews*, vol. 15, no. 4, pp. 286-293, 2010.

[10] H. J. Lee, "Meta-analysis of pain relief effects by laser irradiation on joint areas," *Photomed Laser Surg.*, vol. 30, no. 8, pp. 405–417, 2012.

[11] L. D. Woodruff, J. M. Bounkeo, W. M. Brannon, K. S. Dawes, C. D. Barham, D. L. Waddell, C. S. Enwemeka, "The efficacy of laser therapy in wound repair: a meta-analysis of the literature," *Photomed Laser Surg.*, vol. 22, no. 3, pp. 241-247, 2004.

[12] T. Jafarpour and F. Smith, "Design of multi-wavelength low-level laser therapy device for assisting bone reconstruction applications," *Majlesi Journal of Electrical Engineering*, vol. 14, no. 2, pp. 117-125, 2020.

[13] S. Tumilty, J. Munn, S. McDonough, D. A. Hurley, J. R. Basford, and G. D. Baxter, "Low-level laser treatment of tendinopathy: a systematic review with meta-analysis," *Photomedicine and laser surgery*, vol. 28, no. 1, pp. 3-16, 2010.

[14] S. Mokmeli and M. Vetrici, "Low-level laser therapy as a modality to attenuate cytokine storm at multiple levels, enhance recovery, and reduce the use of ventilators in COVID-19," *Canadian journal of respiratory therapy*, vol. 56, pp. 25-31, 2020.

[15] M. A. Vetrici, S. Mokmeli, A. R. Bohm, M. Monica, and S. A. Sigman, "Evaluation of adjunctive photobiomodulation (PBMT) for COVID-19 pneumonia via clinical status and pulmonary severity indices in a preliminary trial," *Journal of Inflammation Research*, vol. 14, pp. 965-979, 2021.

[16] M. Nejatifard, S. Asefi, R. Jamali, M. R. Hamblin, and R. Fekrazad, "Probable positive effects of the photobiomodulation as an adjunctive treatment in COVID-19: A systematic review," *Cytokine*, vol. 137, 2021, Art. no.155312.

[17] T. N. Vu, Q. T. Tran, B. Sumpf, A. Klehr, J. Fricke, H. Wenzel, and G. Tränkle, "16.3 W Peak-Power Pulsed All-Diode Laser-Based Multi-Wavelength Master-Oscillator Power-Amplifier System at 964 nm," *Applied Sciences*, vol. 11, 2021, Art. no. 8608.

[18] T. N. Vu, “Development and analysis of diode laser ns-MOPA systems for high peak power application,” *Cuvillier Verlag*, vol. 41, pp.25-36, 2017.
[19] Y. Yan, Y. Zheng, H. Sun, and J. A. Duan, “Review of Issues and Solutions in High-Power Semiconductor Laser Packaging Technology,” *Frontiers in Physics*, vol. 9, 2021, doi: 10.3389/fphy. 2021.669591.
[20] X. Liu, W. Zhao, L. Xiong, and H. Liu, *Packaging of high-power semiconductor lasers*. Springer, New York, 2015, p. 412.
[21] L. V. L. Le, “Research and manufacturing phototherapy equipment using light-emitting diode and applying in physiotherapy,” *Thu Dau Mot University Journal of Science*, vol. 30, no. 05, pp. 98-104, 2016.
[22] J. Zheng, S. Zhao, Q. Wang, X. Zhang, and L. Chen, “Measurement of beam quality factor (M2) by the slit-scanning method,” *Optics & Laser Technology*, vol. 33, no. 4, pp. 213-217, 2001.