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Research on the Advantages and Challenges of Replacing LEDs with Lasers in Functional Near-Infrared Spectroscopy Systems Based on Advanced Signal Processing Algorithms

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Abstract: Functional near infrared spectroscopy (fNIRS) has received increasing attention as a non-invasive, portable brain hemodynamic monitoring tool due to its potential for use in natural Settings. Traditional fNIRS systems commonly use light-emitting diodes (LEDs) as light sources, which have become the mainstream choice because of their low cost, easy integration, low heat output, and availability of a variety of near-infrared wavelengths. However, LEDs are limited by their low optical output power and broad wavelength range, which restrict their effectiveness in deep tissue penetration and signal quality. In contrast, Laser Diodes (LD) have the advantages of good monochromaticity and high optical output power, which can provide deeper tissue penetration and higher signal stability. Therefore, this study explores the feasibility of using lasers instead of leds in fNIRS systems and their impact on signal quality and imaging depth. By comparing the performance of LED and laser-based fNIRS systems, it is evident that lasers provide significant improvements in signal quality and imaging depth, although they face challenges in terms of cost, thermal management, and safety. The research in this paper provides an important reference for the future design of fNIRS system, especially in the application scenarios requiring high precision imaging.

Keywords: Functional Near-Infrared Spectroscopy (fNIRS), Neuroimaging, Brain Imaging, Light Emitting Diode (LED), Laser Diode (LD).

1. Introduction

Functional near-infrared spectroscopy (fNIRS) is a non-invasive optical technique used to measure brain activity by monitoring changes in blood oxygen levels. Due to its portability, cost-effectiveness, and ability to be used in natural environments, fNIRS has gained increasing popularity in fields such as psychology, neuroscience, and cognitive science [1]. Traditional fNIRS systems typically use light-emitting diodes (LEDs) as the primary light source because they are low-cost, energy-efficient, and easy to integrate into wearable devices. Additionally, fNIRS systems benefit from their compact design and robustness against motion artifacts, which allow brain studies during daily working, exercise, and rehabilitation[2].

However, LED-based fNIRS systems have inherent limitations. The penetration depth of LED light into tissues is limited, which restricts the depth of brain regions that can be monitored. Additionally, variations in LED light intensity can affect the consistency and accuracy of

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measurements. To address these limitations, there is growing interest in using lasers as an alternative light source in fNIRS systems.

Lasers can emit high-intensity, coherent light at precise wavelengths, offering several potential advantages. They can penetrate biological tissues more deeply, providing more detailed information about deeper brain structures. Furthermore, the stability and precision of laser light sources can improve the reliability and accuracy of fNIRS measurements, making them promising for advanced neuroimaging applications.

This study aims to explore the practical application of replacing LEDs with lasers in fNIRS systems. It will evaluate the performance differences between LED-based and laser-based fNIRS devices, focusing on signal quality, penetration depth, and overall system efficiency. By investigating these factors, the study seeks to demonstrate the potential advantages of integrating lasers into fNIRS technology and provide insights for advancing future neuroimaging capabilities.

2. fNIRS Technology Overview

2.1. The main content of fNIRS technology

The fNIRS is a non-invasive optical technology that utilizes near-infrared (NIR) light to measure brain activity by detecting oxygen-dependent metabolic changes in the brain. This technique involves the introduction of NIR light into the scalp, where the primary interaction mechanisms include scattering and absorption. Scattering, which predominates in superficial tissues such as the scalp and skull, causes the light to diffuse, limiting its penetration depth. Absorption, which is wavelength-dependent and occurs mainly in chromophores like hemoglobin, affects deeper tissues such as the brain cortex. Since the concentration of oxygenated (HbO2) and deoxygenated hemoglobin (Hb) varies with neural activity, these changes affect the detected light intensity, which forms the basis of the fNIRS signal. A sentence explaining that superficial tissues scatter more light, while deeper tissues absorb more, thus influencing signal depth and quality, would provide clarity. The light that is eventually detected by photodetectors placed on the scalp provides information about local changes in blood oxygen levels, which can be used to infer neural activity[3].

The signals obtained from fNIRS primarily reflect several physiological changes in the brain, including cerebral metabolic rate of oxygen (CMRO2), regional cerebral blood flow (rCBF), and cerebral blood volume (CBV) [4]. When neurons in the brain become active, they require more energy, which is supplied in the form of oxygen. This increased demand for oxygen triggers a physiological response in the brain, leading to the dilation of local blood vessels, a process known as neurovascular coupling. This dilation increases regional cerebral blood flow (rCBF), which delivers more oxygenated blood to the active regions of the brain, thus increasing the cerebral metabolic rate of oxygen (CMRO2). The resulting increase in CBV further supports oxygen delivery to activated neurons. These changes in rCBF, CMRO2, and CBV alter the concentrations of oxygenated hemoglobin (HbO2) and deoxygenated hemoglobin (Hb) in the blood. The fNIRS detects these shifts by measuring the intensity of near-infrared (NIR) light reflected from the brain tissue. Since HbO2 and Hb absorb NIR light differently, changes in their concentrations during brain activity cause corresponding variations in the detected NIR signal. These hemodynamic changes form the basis of fNIRS measurements, as they provide indirect but reliable information about neural activity through blood oxygenation levels.

However, these signals are often contaminated by noise from sources such as heartbeat, respiration, and other physiological activities. These noise sources interfere with the signal by introducing artifacts at specific frequencies that overlap with the hemodynamic response of the brain. For example, cardiac pulsation generates periodic fluctuations in the signal at around 1-1.5 Hz, while respiration introduces slower oscillations typically within the 0.2-0.4 Hz range. Additionally, movement artifacts

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or muscle activity can produce low-frequency noise, further complicating the signal interpretation. These different noise sources affect the overall quality of the signal and may obscure the true neural activity being measured. To mitigate these effects, sophisticated signal processing techniques, such as band-pass filtering, independent component analysis (ICA), or motion correction algorithms, are employed to isolate and remove these artifacts, allowing for more accurate measurement of the hemodynamic response.

To further illustrate the noise sources and their frequency characteristics, here is a table 1:

Table 1: The noise sources and their frequency characteristics

Noise Source	Frequency Range	Effect on Signal	Mitigation Strategy
Heartbeat (Cardiac)	~1-1.5 Hz	Periodic fluctuations in intensity	Band-pass filtering, ICA
Respiration	~0.2-0.4 Hz	Slow oscillations affecting baseline	Low-pass filtering, ICA
Motion Artifacts	Low-frequency	Irregular, large signal deviations	Motion correction algorithms
Muscle Activity	~10-100 Hz	High-frequency noise, spiking signal	High-pass filtering

One of the key advantages of fNIRS is its high temporal resolution compared to other imaging modalities like fMRI and PET [2]. Additionally, fNIRS systems are generally portable and low-cost, making them suitable for bedside monitoring and other point-of-care applications. Another significant advantage is the ease with which fNIRS can be combined with other technologies, such as EEG. While fNIRS measures the vascular response to neural activity by detecting changes in oxygenated and deoxygenated hemoglobin, which are slower but more sustained over time (temporal resolution in seconds), EEG provides millisecond temporal resolution by measuring the brain's electrical activity. Together, they provide a fuller picture: fNIRS captures the slower hemodynamic response, while EEG tracks rapid electrical signals. This combination allows researchers to connect changes in brain oxygenation with specific neural events, offering a more comprehensive understanding of brain function.

Despite these advantages, fNIRS has certain limitations. The most notable is its limited penetration depth, which restricts its ability to monitor deep brain structures. Furthermore, the stability of the light source and the consistency of the signal can be affected by different environmental conditions. For instance, temperature fluctuations may affect the LED or laser sources in fNIRS systems, causing drifts in intensity. Humidity could alter the optical properties of the skin and hair, affecting light scattering. Additionally, ambient light (especially in wearable or outdoor fNIRS setups) can introduce noise, which requires shielding or filtering to maintain signal integrity.

The fNIRS has been widely applied in fields such as psychology, neuroscience, cognitive science, and clinical practice. Its non-invasive nature and portability make it particularly well-suited for studies involving populations that cannot easily undergo traditional brain imaging.

2.2. Led-based fNIRS system

The fNIRS system measures changes in oxygen levels through a series of optical and electronic processes. The system uses LEDs to emit NIR light, typically within the 650 to 950 nm range. These wavelengths are specifically chosen to optimize the contrast between the absorption peaks of HbO2 and HbR. HbO2 primarily absorbs light near 850 nm, while HbR absorbs more strongly around 760 nm [5]. By selecting wavelengths that correspond to these absorption peaks, the fNIRS system

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enhances the sensitivity and accuracy of distinguishing between the two forms of hemoglobin, thereby improving the signal contrast and penetration depth through the scalp and skull tissues.

As the emitted light enters the scalp, it undergoes multiple scattering and absorption events, penetrating the outer layers of the head before reaching the brain tissue. During this process, photons interact with hemoglobin molecules, where different amounts of light are absorbed depending on the concentrations of HbO2 and HbR. The remaining photons that are not absorbed are scattered back and detected by photodetectors placed on the scalp.

In an fNIRS system, LEDs are used as the light source because they can generate NIR light within specific wavelength ranges that effectively penetrate the scalp and skull tissues and are absorbed by hemoglobin. A typical LED light source is chosen to operate at two or more wavelengths, with one corresponding to the absorption peak of HbO2 and the other to the absorption peak of HbR. By selecting these specific wavelengths, the fNIRS system can distinguish and measure the concentrations of these two types of hemoglobin [6].

Once the scattered light is detected, the system applies the Beer-Lambert Law to quantify the changes in light intensity [7]. The Beer-Lambert Law describes the relationship between the absorption of light and the concentration of the absorbing substance—in this case, hemoglobin. The law is mathematically expressed as:

$$A = \varepsilon \cdot c \cdot l$$

where A is the absorbance, ε is the molar absorptivity, c is the concentration of the absorbing species, and l is the path length the light travels. In fNIRS, this equation allows the system to convert the changes in light intensity into concentration changes of HbO2 and HbR, providing quantitative data about cerebral oxygenation.

To ensure the accuracy of these measurements, sophisticated signal processing techniques are employed to reduce noise and artifacts. Common methods include filtering (such as low-pass, band-pass, and high-pass filters), baseline correction, and independent component analysis (ICA). Filtering helps remove physiological noise, such as those caused by heartbeat and respiration, which can interfere with the true hemodynamic response. Baseline correction normalizes the signal to account for slow drifts in the data, ensuring that the concentration changes reflect real neural activity rather than external interference. These preprocessing steps significantly enhance the signal's accuracy, allowing the system to reliably estimate oxygenation levels in real time.

2.3. Application scenarios

Once the fNIRS data is processed, it is often transmitted to external devices for further analysis or display via wireless communication modules. Bluetooth Low Energy (BLE) is commonly used in wearable fNIRS systems due to its low power consumption and ability to support real-time data transfer over short distances. Some systems may also incorporate Wi-Fi to extend the range and bandwidth of data transmission, allowing for real-time monitoring and analysis in more complex setups. These wireless communication technologies enable continuous monitoring without tethering the user to a stationary system, supporting applications in dynamic environments.

By using these techniques, wearable fNIRS devices can continuously monitor brain activity over extended periods without interfering with the user's normal activities. For instance, fNIRS can be applied to monitor fatigue levels during exercise, where changes in brain oxygenation can indicate cognitive fatigue or physical exhaustion. Similarly, during cognitive tasks, fNIRS can assess the brain’s oxygenation response to different stimuli, providing insights into task performance and mental workload. These applications illustrate the flexibility and utility of fNIRS in both clinical and everyday settings.

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3. Comparative study of LED and Laser in fNIRS

3.1. Advantages of Laser over LED

In fNIRS systems, lasers exhibit significant advantages over LEDs in several key areas. These advantages permeate the entire system workflow and are particularly evident in interactions with the human body. Firstly, lasers possess extremely high monochromaticity and coherence, enabling them to emit nearly pure single-wavelength light with consistent phase alignment [8]. Monochromaticity means that the light emitted by the laser has an extremely narrow wavelength range, which reduces the scattering of light in biological tissues due to different wavelengths, thus significantly reducing signal loss. According to the scattering coefficient formula

$$\mu_s' \propto \lambda^{-b}$$

The scattering coefficient A describes the degree to which light is scattered in biological tissue, and b is a parameter related to tissue properties, generally between 0.5 and 2. It can be seen that a longer wavelength will result in a lower scattering coefficient, while a shorter wavelength will result in a stronger scattering.

At the same time, the high coherence of lasers means that the emitted light maintains a uniform phase. This characteristic is particularly beneficial for optical measurements of biological tissues, as the coherent beam can effectively reduce random interference effects during tissue penetration, thereby enhancing the signal quality.

It is worth mentioning that when light passes through biological tissues, due to the influence of scattering and absorption, the light waves in different light paths may produce phase differences, which will lead to interference phenomena, thus affecting the accuracy of the signal. For coherent light sources, such as lasers, the interference of this random phase drift to the signal can be reduced due to the consistent phase of the light waves, thus improving the signal-to-noise ratio (SNR). This is crucial when light penetrates the scalp and skull to reach brain tissue, as lasers can more effectively interact with hemoglobin, ensuring the system can accurately measure cerebral oxygen levels, especially in imaging thick tissues or deep brain regions[9].

Secondly, the high optical output power of lasers allows for greater penetration depth compared to LEDs. The energy density ($E = \frac{P}{A}$) of laser beams, where P is power and A is the beam area, can achieve higher concentrations of light, thus penetrating more deeply through biological layers such as the scalp and skull. This is vital for functional imaging studies of deep brain structures, as lasers can provide clearer, higher-resolution signals, ensuring accurate data acquisition in complex neuroimaging applications. For instance, in advanced neuroimaging applications such as brain-computer interfaces (BCI) and cognitive load monitoring, the high penetration capability of lasers offers reliable technical support for fNIRS systems in exploring deep brain functions [10].

Another key advantage of lasers is their stability during long-term monitoring. In contrast to LEDs, which may experience fluctuations in output due to temperature changes or prolonged operation, lasers maintain stable light output even under varying environmental conditions. This stability is particularly important in clinical environments where consistent monitoring of brain activity is required, such as in surgical procedures or intensive care units. For instance, while LEDs tend to shift their output wavelength and intensity with temperature changes, lasers remain unaffected due to their higher thermal resistance and ability to maintain a stable output regardless of the surrounding conditions.

Lasers also demonstrate unique advantages in interactions with the human body. Due to the high directionality and collimation of laser beams, fNIRS systems can more accurately direct light to the target brain region, reducing unnecessary tissue light loss, enhancing signal acquisition efficiency, and minimizing environmental light interference. In addition, lasers' precise wavelength control

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reduces errors caused by wavelength drift. In fNIRS systems, this ability to finely tune and stabilize the emission wavelength is crucial for accurate measurements of hemoglobin absorption, which depends on specific wavelengths. High-precision wavelength tuning in lasers can be achieved through techniques like external cavity diode lasers (ECDLs) or by utilizing distributed feedback (DFB) mechanisms. These technologies ensure that the wavelength is consistently maintained, reducing measurement errors and improving the accuracy of cerebral oxygenation data. By selecting appropriate miniaturized lasers and optimizing system design, lasers in fNIRS systems can retain their optical performance advantages while effectively addressing challenges related to size and cost, especially in wearable devices. This provides robust technical support for efficient brain imaging systems.

3.2. Feasibility analysis of Laser instead of LED in most cases

In functional near-infrared spectroscopy (fNIRS) systems, the feasibility of replacing LEDs with lasers is particularly strong in terms of radiation standards, safety, and stability. First, due to their high energy density, lasers must comply with stringent international radiation safety standards, such as IEC 60825-1. This standard classifies lasers into categories based on their potential hazards, ranging from Class 1 (safe under all normal conditions of use) to Class 4 (potentially dangerous to eyes and skin) [12]. To meet these requirements, modern lasers are equipped with multiple safety mechanisms, such as automatic power limiters, beam expanders, and emergency shut-off switches, ensuring that radiation levels remain within safe limits during use. Additionally, by selecting appropriate wavelengths and using pulsed operation modes, lasers can minimize radiation exposure, making them suitable for medical device applications.

In terms of safety, while the high intensity and focused nature of laser beams pose certain risks, these concerns have been effectively addressed through advanced technological measures. For instance, lasers often include automatic power adjustment systems and eye-safe filters to prevent accidental exposure that could harm the eyes or skin. Furthermore, the use of optical isolation and protective enclosures enhances the overall safety of the system, enabling lasers to safely replace LEDs in fNIRS applications.

Regarding stability, lasers demonstrate significant advantages over LEDs. Lasers can maintain highly stable light output over extended periods, making them less susceptible to external environmental changes. This stability is crucial for the precise monitoring required in fNIRS systems, particularly in long-term, continuous operation settings, whether in research or clinical environments. Additionally, lasers exhibit superior wavelength stability compared to LEDs, providing consistent measurements across varying conditions, reducing experimental errors, and ensuring data reliability [13].

In summary, lasers not only demonstrate technical feasibility as a replacement for LEDs in fNIRS systems but also provide enhanced performance through superior radiation control, safety, and stability. This makes lasers particularly well-suited for more complex and demanding neuroimaging applications, where they offer significant potential for broader use.

3.3. Challenges in Laser applications

However, despite their superior optical performance and stability, the larger size and higher heat dissipation requirements of lasers remain challenges in wearable device design. To address these challenges, the latest generation of miniaturized lasers, such as the Vertical-Cavity Surface-Emitting Laser (VCSEL) from Vertilas, can be utilized. VCSEL lasers feature small size, low power consumption, and high beam quality, making them ideal for integration into portable or wearable devices. Vertilas's VCSEL lasers not only excel in power and wavelength stability but also offer significant advantages in spectral monochromaticity and coherence, making them ideal for fNIRS applications. Additionally, the LP980-SF series laser diodes from Thorlabs are also worth considering. These lasers provide high optical output while maintaining a relatively small size and low thermal management requirements. Thorlabs' laser diodes can precisely control the output wavelength and maintain stable light output even in harsh environments, making them highly suitable for wearable fNIRS systems that require long-term stable operation. To address the high heat output of lasers, efficient thermal management solutions, such as using heat-conductive materials and optimizing heat dissipation structures, can be employed to keep the laser within a safe operating temperature range. Moreover, utilizing a pulsed operation mode (ns pulse width) to reduce average power consumption can effectively minimize heat accumulation [11].

4. Conclusion

This study explored the feasibility and advantages of replacing LEDs with lasers in fNIRS systems. The comparison between LED-based and laser-based fNIRS systems highlights several key advantages of using lasers.

Firstly, the integration of laser-based fNIRS systems with other neuroimaging techniques, such as functional magnetic resonance imaging (fMRI) and electroencephalography (EEG), shows great potential for multimodal imaging. This integration could enhance the comprehensiveness and depth of brain function research by leveraging the strengths of different imaging modalities, resulting in more detailed datasets crucial for complex brain studies and clinical applications.

Secondly, lasers provide higher light intensity and stability, significantly enhancing signal quality and measurement accuracy. The precise wavelength control and stable light output ensure that laser-based systems can maintain consistent data collection, which is essential for both research and clinical settings where long-term monitoring is required.

Additionally, the greater penetration depth of lasers allows for the detection of signals from deeper brain tissues, which is particularly beneficial for studies that require more in-depth brain data. While this improvement over LEDs is significant, it remains a notable advantage rather than the core innovation.

Despite these advantages, there are also challenges and limitations. Cost and power consumption are significant obstacles; lasers are more expensive than LEDs, which increases the overall cost of fNIRS systems and limits their widespread adoption, especially in large-scale applications. Additionally, lasers consume more power, necessitating complex power management systems to ensure battery life and system stability. Future research should focus on optimizing laser-based system designs to reduce both costs and power consumption, making these systems more accessible and practical for a wider range of applications.

In summary, this study demonstrates the significant potential of lasers in fNIRS systems, particularly in multimodal imaging applications. Lasers provide higher-quality brain imaging data and offer new directions for neuroscience research and clinical applications. However, to enable the widespread adoption of laser-based fNIRS systems, further efforts are needed to improve both their technical performance and economic feasibility.

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