PI-PPG: Motion-Robust and Bias-Reduced Wearable PPG via Light Polarization

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***Abstract*: Photoplethysmography (PPG) is widely used in wearable health monitoring, but conventional PPG sensors remain vulnerable to motion artifacts, ambient light interference, and skin-tone–related signal degradation. We present PI-PPG, a polarization-integrated PPG sensor system that improves signal fidelity and fairness in wearable cardiovascular monitoring. By combining high-efficiency polarized illumination with reflection-enhanced, cross-polarized detection, PI-PPG significantly reduces superficial scattering and motion-induced noise. Experimental validation across a range of Fitzpatrick skin types under both resting and active conditions demonstrates substantial gains, including >200% reduction in ambient light interference, >100% improvements in perfusion index and AC SNR, and >20% enhancement in cardiovascular feature detection. Notably, the system improves Heart Rate (HR) and Heart Rate Variability (HRV) accuracy by 28% for darker skin tones and reduces motion artifacts by 22% compared to conventional PPG. These advancements underscore the potential of PI-PPG to enhance detection efficiency, reliability, and fairness in wearable health sensing, thereby promoting equitable digital health solutions.**

Keywords—photoplethysmography (PPG), polarization, skin-tone, motion, bias, HR, HRV, wearable sensors, digital health

I. INTRODUCTION

Digital health monitoring through wearable devices increasingly utilizes photoplethysmography (PPG) due to its simplicity, low cost, and continuous, non-invasive monitoring capabilities [1]. Despite widespread adoption, commonly-used PPG technologies exhibit inherent limitations, notably diminished accuracy in individuals with darker skin tones and significant vulnerability to motion artifacts [2-3]. Increased melanin concentration in darker skin leads to higher light absorption and scattering, reducing reflected signal quality [4]. Motion artifacts further degrade signal integrity, especially during physical activities, critically limiting the practical effectiveness of these devices [5]. Additionally, traditional PPG sensors struggle to capture subtle pulse wave features due to poor SNR, constraining their use for advanced physiological assessment [6].

Addressing these challenges is essential not only for technical advancement but also to ensure equitable healthcare delivery. Wearable systems exhibiting biased or unreliable measurements perpetuate healthcare disparities, particularly affecting underserved communities [7]. Due to these biases, effective wearable monitoring is affected during daily activities and physical exertion, precisely when continuous physiological tracking is most beneficial.

While some efforts have previously explored polarization techniques primarily in remote PPG imaging or for reducing motion artifacts [8-9], these efforts focused on limited movements of the body parts such as wrist rotation [9], while missing out on more challenging and relevant intense periodic activities such as jogging, running, or climbing stairs. Moreover, many existing solutions have not demonstrated improved HR or HRV measurement accuracy specifically in darker skin tones using polarization-based approaches [8-9]. Recent reviews in wearable optical sensors have identified consistent overestimation of error rates (up to 15%) in darker tones, yet none have tested polarized filtering to mitigate this disparity [3]. Similarly, remote sensing studies also struggle with persistent bias against dark skin even when employing advanced optical techniques, underscoring the need for sensor-level interventions [2-3].

We present a polarization-integrated photoplethysmography (PI-PPG) sensor embedded on a wearable platform to mitigate these challenges. Our sensor uses polarized illumination, and an improved reflection-enhanced cross-polarized light sensor to overcome these limitations, in contrast to conventional approaches that rely on absorptive polarization filters [9]. Our reflective polarizer redirects unaligned polarized light back toward the skin, allowing depolarization through interaction with skin layers and partial recovery for subsequent detection, significantly enhancing photon capture efficiency compared to absorptive filters (Fig. 1). This approach emphasizes deeper tissue signals less affected by skin pigmentation and motion interference, thus significantly improving pulse wave feature resolution. Here, we detail the design, implementation, and systematic evaluation of our PI-PPG sensor compared to conventional systems, highlighting enhancements in signal robustness, skin-tone fairness, and pulse feature detection. Our findings validate PI-PPG to significantly advance wearable sensor technology toward more equitable digital health solutions.

II. METHODS

A Maxim 86146EVSYS evaluation system (Analog Devices) was utilized for wearable sensor testing due to direct access to optical sensor channels, raw PPG signals, and algorithm-generated outputs. High-performance metallic wire-grid polarizers were sourced from Mecan USA and incorporated into the polarized PPG (PI-PPG) system. The system was constructed using reflective polarizing elements laminated onto polymer substrates and strategically oriented along both the illumination and detection pathways (Fig. 1). Linear polarizers aligned with the LED sources were placed orthogonally to the detection-side polarizer to enable cross-polarized light capture. A custom finger-based setup was also developed to evaluate the impact of PI-PPG on ambient light interference and spectral performance across multiple wavelengths.

Electrocardiogram (ECG) signals were recorded using a Polar H10 chest strap, which served as the ground truth for cardiac activity. The Polar Sensor Logger app was employed to log ECG data and compute heart rate (HR) and heart rate variability (HRV) metrics.

The study included 100 datasets (30 participants) spanning Fitzpatrick skin types II–V. A skin tone sensor was used to measure each subject's skin tone at the wrist site. Each subject followed a controlled activity protocol consisting of: 2.5 minutes rest, 2.5 minutes walking (2 mph), 1 minute rest, 2.5 minutes jogging (4 mph), 1 minute rest, 4 minutes running (5.5–6 mph), 1 minute rest, and 2.5 minutes stair climbing or exercises. PPG signals were recorded in parallel using both traditional (without polarization integration) and PI-PPG systems, with ECG data providing a synchronized reference.

Signal processing involved spectral filtering techniques to isolate physiological signal components (AC, DC, Noise). The AC signal which contains information about the pulsatile blood flow, and therefore features like HR and HRV were extracted from raw ppg using bandpass filter (0.75-4 Hz), DC using low pass filter (cutoff - 0.1 Hz), and noise using high pass filter (cutoff - 10 Hz). Signal quality metrics such as perfusion index (PI) and AC signal-to-noise ratio (SNR) were calculated where,

$$\mathrm{PI} = \mathrm{AC}/\mathrm{DC} * 100 \qquad (1)$$

$$\mathrm{AC\ SNR} = 20\times\log_{10}(\mathrm{AC}/\mathrm{Noise})\ [\mathrm{dB}] \qquad (2)$$

These metrics are critical indicators of PPG signal reliability, where perfusion index reflects the amplitude of the pulsatile signal relative to the non-pulsatile baseline, and is often used as a proxy for peripheral perfusion. Meanwhile, AC SNR quantifies the clarity of the pulsatile waveform against background noise, directly impacting the accuracy of downstream physiological measurements such as HR and HRV.

Cardiovascular features such as HR and HRV were derived using both external [10] and internally-developed algorithms incorporating spectral and waveform morphology analysis. These features were then compared with ECG-derived ground truth to evaluate accuracy, motion robustness, and error distribution across different skin tones and motion conditions.

III. RESULTS

Our reflective polarization sensor design demonstrates notable performance as a wearable PI-PPG solution, significantly improving light capture efficiency compared to conventional absorptive polarization filters. Biological tissue layers inherently depolarize reflected light, generating partially cross-polarized components effectively utilized by our sensor.

When tested in configurations designed for finger-based PPG recording at rest, this innovative reflective polarizer design achieves an impressive 200% reduction in ambient light interference (Fig. 2a). Ambient light rejection is critical in PPG sensors because external light can interfere with the weak optical signals used to detect blood volume changes, leading to baseline drift, signal distortion, and reduced measurement accuracy. Thus, this design significantly improves baseline stability, AC SNR, accuracy under bright ambient conditions, and power efficiency - particularly in scenarios involving loose contact, motion artifacts, or low signal levels. These improvements were validated across three wavelengths typically employed in wearable PPG systems namely green (532 nm), red (660 nm), and infrared (940 nm) (Table 1). In this configuration, the system also showed >100% improved perfusion index (PI) and >39% improved AC SNR with polarization across all three wavelengths. The improvements were recorded to be significantly higher for red led compared to green in this case, which could be due to different tissue penetration profiles of these wavelengths.

TABLE I.

	Signal Metric	**Green**	**RED**	**IR**
Regular PPG (no polarization)	PI	0.8%	0.3%	0.4%
	AC SNR	12.9dB	7.4dB	9.5dB
PI-PPG	PI	2.3%	1.0%	0.9%
	AC SNR	17.9dB	17.0dB	17.9dB
% improvement	PI	187.5%	233.3%	125%
	AC SNR	39.3%	128.7%	88.0%

Table 1. Improvements in PPG signal quality with polarization-integration in terms of perfusion index (PI) and AC SNR for three led wavelengths typically used in wearable systems at rest using finger-based PPG.

We calculated the impact of PI-PPG setup on motion-based noise in PPG signals acquired from the wrist, where motion artifacts are typically more pronounced compared to finger measurements (Fig. 2b, Fig. 3). While the general trend of the signal remains the same, we calculate that the DC noise in signals can be reduced by more than 10-fold employing the reflective-polarizer setup. Since a large fraction of the motion-noise on a wrist-wearable can originate from leaking ambient light during displacement of the wearable during activities, and specular reflection of light from the skin, it is evident that the polarized filter setup can reduce the impact of both of these noise sources. The impact is particularly noticeable during intense activities such as jogging or running, which employ relatively high amplitude, high frequency arm movements. To the best of our knowledge, this is the first report that studies the impact of polarization for motion artifact-suppression during such high-intensity but commonly practiced wellness activities.

We further examine the impact of our polarization setup on PPG signal features including pulse wave fiducial points, and cardiovascular health markers. Pulse wave features appeared notably sharper with the polarization filter, clearly identifying secondary waveform peaks and notches previously undetectable (Fig. 3a,b). Reliable detection of these features can enable advanced physiological analyses and assessments including but not limited to vascular ageing, respiration rates, and blood pressure [11].

Evaluations also included critical cardiovascular parameters, specifically heart rate (HR) and heart rate variability (HRV), which are crucial indicators of cardiovascular health and correlate closely with wellness metrics such as stress, recovery, and autonomic nervous system balance [12]. We observe that the tested wearable systems routinely had poorer outcomes for feature determination for darker skin tones. Detection accuracy for HR reported as mean absolute error (MAE) improved by up to 28% in darker skin tones using the PI-PPG system compared to non-polarized setups (Fig. 3c). We also observed a notable 22% reduction in motion artifact-induced errors in HR MAE compared to non-polarized, traditional PPG sensors (Fig. 3c). This improvement was translatable to a range of motions from relatively lower intensity to higher intensities (Fig. 3d). Finally, our PI-PPG system yielded at least 20% improvement in HRV root mean square of the successive differences (RMSSD) accuracy when sampled at 25 Hz (Fig. 3e). RMSSD is a key HRV metric indicative of autonomic nervous system activity [13]. This improvement was even higher (as high as 6-fold) when PPG signal was up-sampled at higher frequencies (100 Hz) (Fig. 3e). HRV is more accurate at higher frequencies as it is a measure of the microsecond differences between ppg peaks, and higher sampling rate enables more precise identification of ppg peak location. We observe that while HRV errors are reduced at higher sampling rates, performance for darker skin tones was still considerably worse. PI-PPG shows considerable promise by more than 2-fold reduction in this error.

IV. CONCLUSION

This work presents a novel reflective polarization-integrated PPG (PI-PPG) system that addresses persistent challenges in wearable optical sensing namely, motion artifacts, ambient light interference, and skin-tone bias. Our results demonstrate that integrating polarization-based optics with reflective light recapture significantly improves signal quality across multiple metrics, including perfusion index and AC SNR. The system achieves more than 200% ambient light rejection and delivers sharper, higher-fidelity pulse waveforms across green, red, and IR wavelengths. These improvements are particularly impactful in challenging real-world conditions, such as high-intensity motion, where traditional PPG systems often fail to maintain signal integrity. Improving the detection of features such as fiducial points in PPG systems can be critical towards enabling the detection of health metrics such as cuff-less blood pressure monitoring on wearable devices.

Importantly, PI-PPG also advances health equity in digital monitoring. By reducing error in cardiovascular feature estimation including HR and HRV, across diverse Fitzpatrick skin tones, the technology demonstrates a tangible step toward mitigating bias in wearable health systems. Our data show up to 28% improvement in HR accuracy and over 2-fold reduction in HRV error for darker skin tones, metrics that directly affect the quality and fairness of health insights delivered by consumer and clinical wearables. With promising implications for next-generation optical biosensing, future work will focus on miniaturizing the PI-PPG architecture, improving efficiency for wrist-based form factors, further mitigating power-losses in polarization-based optical systems, and conducting large-scale real-world validation across broader demographics and use cases.

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V. FIGURES

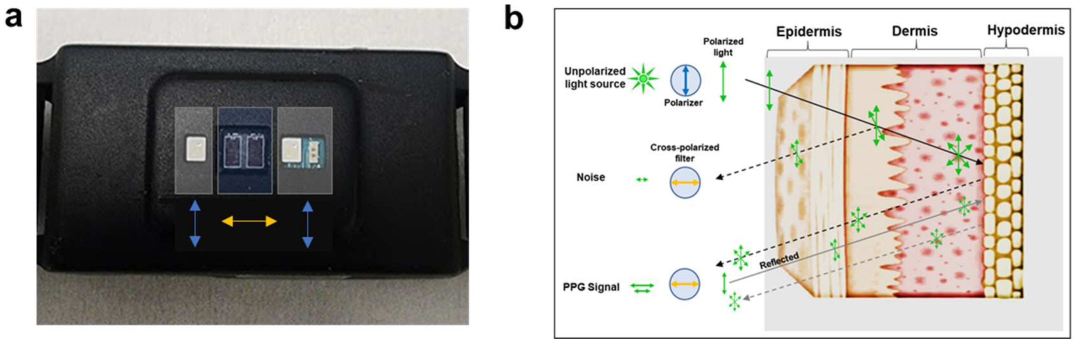

Fig. 1. PI-PPG working principle: a) A watch prototype showing the PI-PPG setup where LEDs (left and right) and PDs (center) are arranged in orthogonal polarization orientation. b) schematic showing PI-PPG working model with reflective sensor-enhanced light capture, and cross-polarization detection for noise removal.

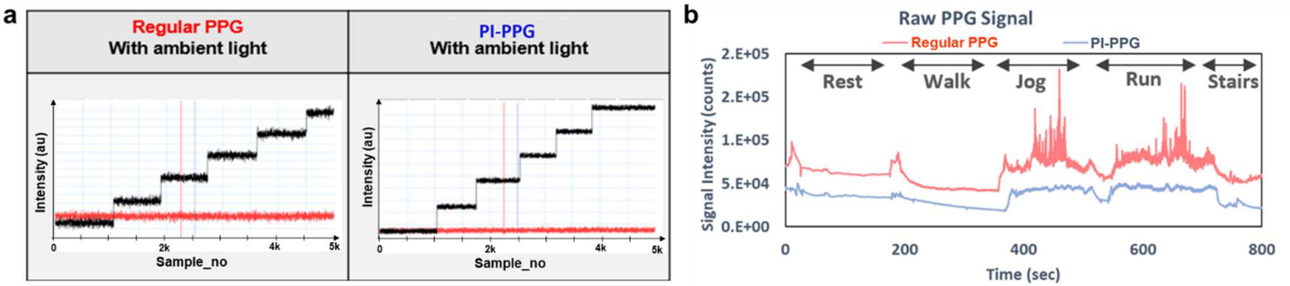

Fig. 2. Noise reduction: a) Ambient noise reduction on a finger-based PI-PPG setup b) Motion noise reduction during different activities on a wrist-based PI-PPG

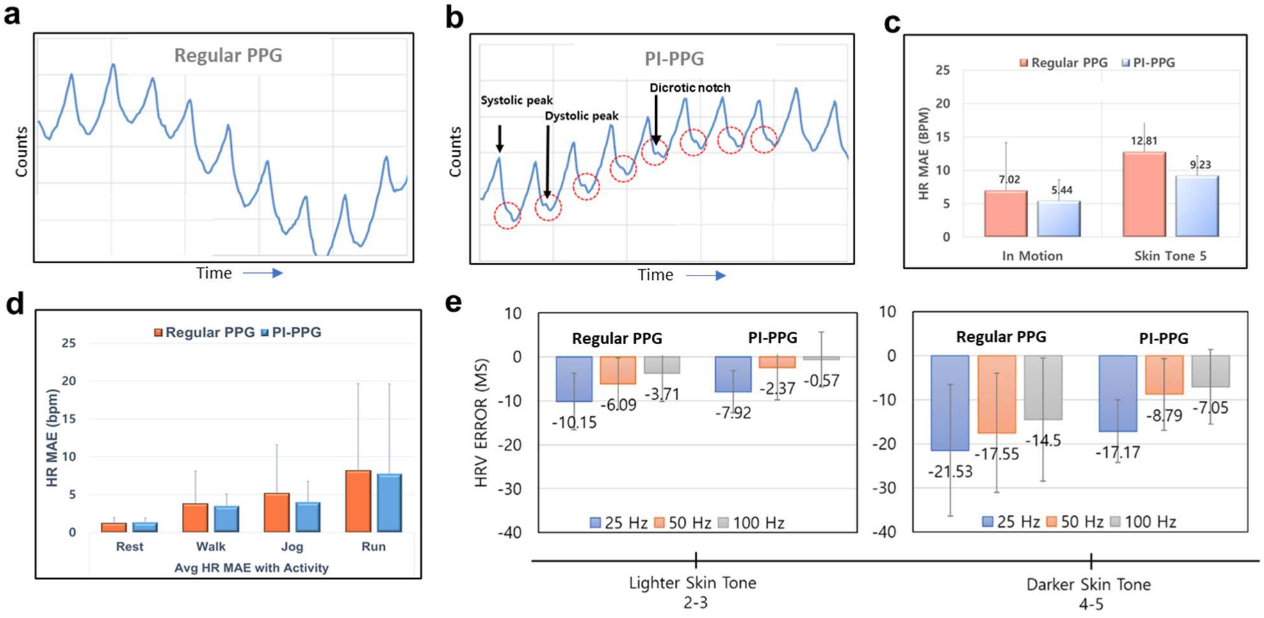

Fig. 3. Improved feature detection on wrist with PI-PPG: a,b) Improved pulse wave fiducial point detection c) Motion-error and skin tone-bias reduction for HR. d) Motion-error reduction for activities with varying intensities using PI-PPG e) Improved accuracy and reduced skin tone bias for HRV detection at varying PPG sampling frequencies.