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Circuit-free Cardiovascular Monitoring via Electrically Passive Nanophotonic Patch for Sub-beat Hemodynamics

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Summary:
We report on a monolithic nanophotonic patch (OptoPatch) that converts arterial pulsation into camera-readable colour shifts via mechanochromic diffraction, removing the need for on-body electronics, batteries, or external optics. A single-material PDMS film carries a strain-sensitive metasurface on one face and a suction-cup adhesive on the other. In 13 volunteers recorded under hand-held smartphone imaging, OptoPatch recovers high-fidelity pulse waves, essential for highly deployable cardiovascular monitoring, and accesses inter-beat hemodynamics. Signal extraction is improved by gridded ROI tracking combined with harmonic SNR estimation.

Keywords: photonic, metasurfaces, mechanochromic sensing, wearable-sensor, smartphone, cardiovascular-monitoring, diffraction-based strain

Background

Continuous cardiovascular monitoring supports an expanding range of clinical and home-based care, but wearable sensors still rely on electrical transduction (electrocardiography (ECG), photoplethysmography (PPG)) with its associated circuitry, power and packaging overhead. Remote camera-based approaches such as remote PPG eliminate the on-body burden but access low-bandwidth features of the pulse wave through diffuse tissue transmission and remain sensitive to light-melanin interactions. Photonic-crystal and metasurface-based strain sensors have shown that mechanical-to-optical transduction can in principle be fully passive [1], yet published implementations typically require spectrometric readout, offsetting the practical advantage of a "wireless" front-end [2]. Truly circuit-free wearables recovering clinically meaningful pulse-wave morphology with commodity imaging hardware remain less explored.

We address this gap with OptoPatch, a single-material elastomeric patch whose surface diffracts ambient light into visible-spectrum colours that shift with the strain imposed by the underlying arterial pulse. The device avoids on-body electronics or complex optical interrogators; readout is by commodity RGB camera.

Sensor and Transduction Principle

OptoPatch is a monolithic poly(dimethylsiloxane) (PDMS) film carrying a surface-relief diffractive nano-patterned surface and a microscale structured adhesive surface on the opposite face. Both structures are replicated in a single casting step, using wafer-scale maskless photolithography and two-photon polymerization.The adhesive micro-suction-cup array provides residue-free, reusable adhesion to skin, allowing single-material pattern-transfer type fabrication.

Adhered over the radial artery, pulsatile arterial expansion elongates the diffractive structure along its periodic axis and locally tilts the film about the artery's curvature (Fig. 1) [3]. Both effects modulate the diffraction condition: periodicity elongation redshifts each order, and angular tilting changes which order reaches a fixed observation angle. Under broadband ambient illumination, the net result is a shift in observed colour. A camera recording the film surface produces an RGB time series that tracks diffraction-encoded deformation of the film induced by arterial diameter expansion. Because transduction occurs via surface diffraction at the film–air interface rather than through tissue-transmitted light, the mechanism is, by design, independent of dermal melanin absorption. As the active diffraction area spans several cm², and individual subregions experience non-uniform ambient illumination, local tissue curvature, and flexion.

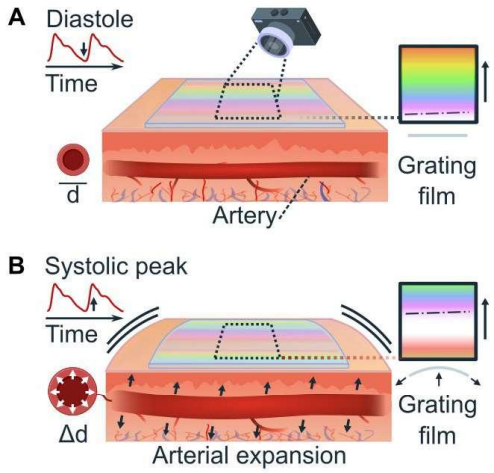

Figure 1: (A) OptoPatch above an artery. (B) The artery expands, shifting an observed diffraction pattern.

Single ROI-mean colour time series then dilutes the cleanest pulsatile regions with less informative ones. We divide the tracked ROI into an N × M patch grid and compute, for each patch and RGB channel, a harmonic signal-to-noise ratio (SNR) against a globally estimated fundamental frequency per sliding window. The output waveform is then the harmonic-SNR-weighted, polarity-aligned sum across patches and channels.

Results

In strain-mapped goniometry under uniaxial tension (0, 5, 10%) over observation angles 0–70° we observed RGB sequences matching Fresnel–CIE 1931 simulations. Alongside the broad angular window, in uniaxial tensiometer testing at P = 2100 nm, strains of order 0.2 - 2% produced colour shifts well above the camera noise floor, making hand-held imaging viable. No appreciable drift in amplitude was observed over 1000 strain cycles.

In 13 healthy, consenting volunteers, a 2100 nm period (3 × 3 cm² active area) OptoPatch was placed over the radial artery of the non-dominant hand and smartphone video recorded at 60 FPS under ceiling-panel illumination. Continuous non-invasive blood-pressure (cNIBP) reference (Finapres) was recorded simultaneously on the same limb. Fig. 2A compares patch fusion (“Composite”) and conventional ROI-mean tracking (“Intensity). Fusion preserves harmonic structure across the full ∼130 s recording; the ROI-mean trace degrades after ∼40 s as the user shifts and the cleanest pulsatile pixels are averaged out. Fig. 2C shows beat-resolved correspondence. Ensemble-averaged OptoPatch and c-NIBP waveforms align, with reflected-wave onset resolvable in both channels. Median inter-channel magnitude-squared coherence from 0.5–8 Hz exceeded 0.7 across the cohort,

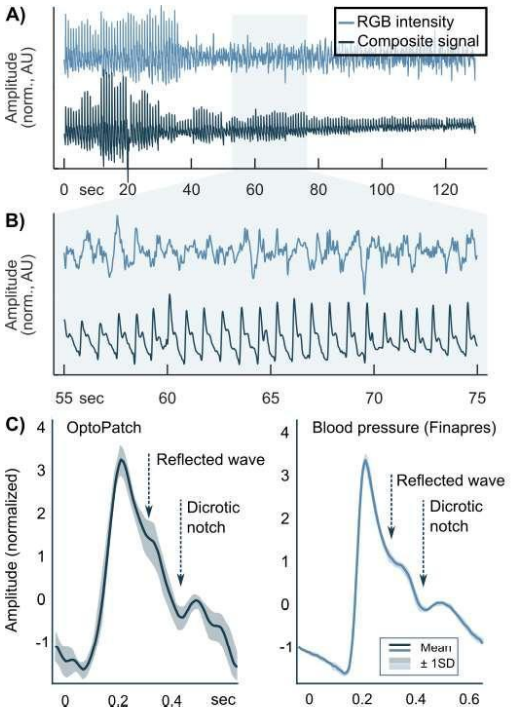

Figure 2: A: Recording from OptoPatch over 2 minutes. B: excerpt from A, indicating stability issues in simple ROI intensity tracking. C: Ensemble waveforms from OptoPatch (left) and cNIBP (right), indicating capture of sub-beat hemodynamic phenomena such as distal wave reflections.

demonstrating that the colorimetric signal preserves dynamic wave content beyond fundamental heart-rate tracking. Per-beat ensemble Pearson correlations had mean of 0.94, SD 0.034. These results indicate mechanochromic sensors as a potential avenue towards wireless, electrically passive cardiovascular sensors.

This work extends methods presented in [3].

References

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