

A subnanolitre tetherless optoelectronic microsystem for chronic neural recording in awake mice

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Supplementary Information

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Section 1. Theoretical Maximum Operational Depth of MOTE

For ballistic photons, up to 1 mm (wavelength-dependent) in depth, the attenuation over depth z can be approximated as¹:

$$P_z = P_{IN} \exp\left[-\frac{z}{l_e}\right] = P_{IN} \left[-\frac{z}{100 \mu m}\right] \text{ for } 623 \text{ nm excitation}$$

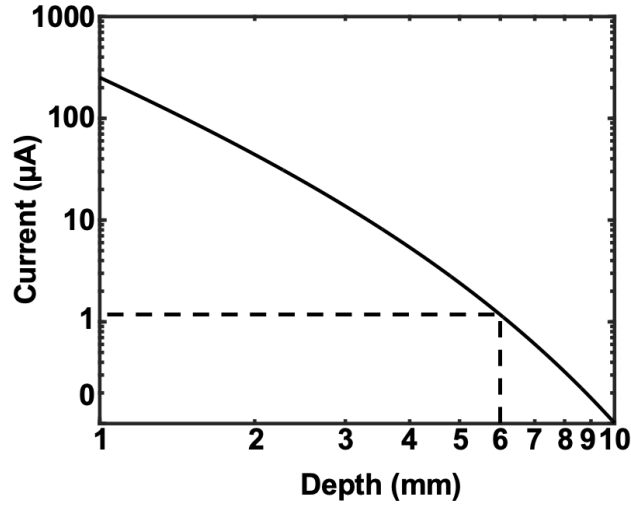
This covers the attenuation the MOTE's have faced in this work, of which maximal depth is $< 400 \mu m$; only 2 % of the incident optical power will reach $400 \mu m$. The tip of a MOTE touches deeper into the brain than the centre of its PVLED, the centre of which in Extended Data Figure 7c is likely $200 \mu m$ deep, where 13.5 % of the input optical power remains.

Beyond 1 mm, photons should be characterized as diffusive rather than ballistic, where scattered photons will also reach the PVLED – the MOTE's PVLED ($2400 \mu m^2$) is much larger than the photon wavelength (623 nm). In this diffusive regime, the attenuation can be described as following, if the initial beam size is much smaller than z :

$$P_z = P_{IN} \times \exp\left[-\frac{z}{\delta}\right] \times \frac{1}{z^2} \text{ where } z \text{ and } \delta \text{ are in mm}$$

The exponential term represents diffusive absorption and scattering (through δ) and the latter z^{-2} term describes the spherical spread of photons – while the attenuation length δ is wavelength dependent, $\delta = 2.8 \text{ mm}$ can be used for our work². It should be noted that if the initial beam size is larger than z on the surface, the initial size will dominate. The exact attenuation as well as the ballistic-diffusive changeover will require a Monte Carlo simulation^{3–6} using the scattering angular distribution, which will also consider the MOTE's orientation.

Staying below the heating limit⁵, and assuming PVLED dimensions of $50 \mu m \times 100 \mu m$ and the initial beam size $\ll 1 \text{ mm}$, one can make a rough estimate of how much optical power would become available as the powering light travels deeper into the brain. Supplementary Figure 1 shows how the optical power decreases over length; a MOTE should generate $1 \mu A$ of photocurrent (current with which its CMOS circuit was designed to operate) at 6 mm depth. Further simulation and experiments, which are beyond the scope of this manuscript, would be needed to confirm this projection.



Supplementary Figure 1 | An idealized approximation of the electrical power available of a MOTE at varying implantation depths. Based on the attenuation lengths reported by M. Wang, *et al.*^{1,2} and for the wavelengths a MOTE uses (since the attenuation lengths are wavelength-dependent), with a 60 μm × 250 μm PV area, $P_{IN} = 160 \text{ mW/mm}^2$, and PV efficiency of 15 %, it could be possible to use MOTEs up to 6 mm deep inside the brain.

For the emission pathway, a single photon at the emission wavelength (825 nm) has an energy of 2.4×10^{-19} joules where a MOTE emits 0.35 μW over 7 ns, corresponding to about 30,000 photons. While this too will be absorbed and scattered on their way to the detector by:

$$\exp\left[-\frac{6}{2.8}\right] \times \frac{1}{(6)^2} = 0.003255,$$

a photomultiplier tube, commonly used in optical imaging, instead of a “simpler” photodetector used in our manuscript, shall provide sufficient sensitivity required. However, this is merely a back-of-the-envelope projection, which we hope to demonstrate experimentally in future work.

Section 2. MOTE vs. Voltage Indicators

Among optical imaging techniques, voltage indicators, which link neural voltage to fluorescence, are closest to our MOTE. Supplementary Table 1 compares voltage indicators with a MOTE in key performance metrics.

	Voltage Indicator						MOTE
Name	ArcLight	ASAP Series			Quasar Series		
		ASAP2	ASAP3	ASAP5	Quasar2	Quasar3	
Bandwidth	<60 Hz ^{7–10}	<100 Hz ¹¹	<200 Hz ¹¹	<500 Hz ^{12–15}	1 kHz ¹⁶	1 kHz ¹⁷	>15 kHz
Sensitivity ($\Delta F/F_0$ per 100 mV unless noted otherwise)	40 % ⁷	36±2 % ^{11,18}	51±1% ¹¹	67 % ¹²	90±2 % ^{11,17}	40±2 % ^{11,17}	Input-referred noise = 14.8 μV_{RMS}
	*The minimum detectable subthreshold value is closely related to sensitivity, experiment conditions, and signal-to-noise ratio, with typical ranges for fluorescent voltage indicators being 1-2 mV.						
Common Introduction Methods	Viral vectors and transgenic ^{7–10,19}	Viral vectors and transgenic ^{11,18}	Viral vectors ¹¹	Viral vectors ^{12–15}	Viral vectors ^{11,16–18,20,21}	Viral vectors ^{11,17,18,22}	Direct stereotactic implantation
Response Time	Fluorescence-dynamic ^{16,23,24} : τ_{fast} = ~10 ms τ_{slow} = ~50 ms	Fluorescence-dynamic ^{11,18} : τ_{fast} = 1.5±0.13 ms τ_{slow} = 7.8±0.41 ms	Fluorescence-dynamic ¹¹ : τ_{fast} = 0.94±0.06 ms τ_{slow} = 7.24±0.38 ms	Fluorescence-dynamic ¹² : τ_{fast} = 0.8±0.1ms τ_{slow} = 44.2±13.0 ms	Fluorescence-dynamic ^{11,17,22} : τ_{fast} = 0.3±0.05 ms τ_{slow} = 3.2±0.4 ms	Fluorescence-dynamic ^{11,17,22} : τ_{fast} = 0.9±0.06 ms τ_{slow} = 11.7±0.41 ms	Electrode response time ^{25–27} : >10 μs .
	Measurement System & Operation Range	1) Single photon microscopy (wide field): superficial cortical layers (<300 μm) 2) Two-photon microscopy: cortical/olfactory bulb (<500-600 μm) ^{7–10,16,19,23,24}	1) Single photon microscopy: superficial cortical layers (<300 μm) 2) Two-photon microscopy: deep cortical layers/hippocampus (<500-600 μm) ^{11,18}	1) Single photon microscopy: superficial cortical layers (<300 μm) 2) Two-photon microscopy: deep cortical layers and hippocampus (<600 μm) ¹¹	Two-photon microscopy: deep cortical layers and cerebellum (<800 μm) ^{12–14}	1) Single photon microscopy: superficial cortical layers (<300-400 μm) 2) Near-infrared excitation: thin brain slices, in vitro (<400 μm) ^{11,17,22}	
Illumination	20~40 mW/mm ² ²⁰ .	Standard illumination required for cultured neurons is 46 mW/mm ² . For cultured rat cortical neurons, the required irradiance reaches 114 mW/mm ² ¹² .			Red = 10 W/mm ² ; Blue boost = 150 mW/mm ² for enhanced SNR & sensitivity) ^{16,17}		The incident LED irradiance for MOTE embedded in the cortex is limited to <70 mW/mm ² .

Lifetime	Viral vectors are well suited for fast and localized gene expression, typically lasting for several weeks to months. In contrast, transgenic approaches are better suited for long-term, systemic, or cell-type-specific stable expression, which can last for several months to years. Stronger illumination can enhance the signal-to-noise ratio (SNR) and the temporal resolution, but at the cost of accelerated photobleaching; typically, fluorescence signals remain stable for a few minutes to several hours under continuous illumination – blue light (e.g., 405 nm) can be used to partially restore the fluorescence signals ^{7–11,16–18,20,21,23,24,28} .	>1 year
Safety	The phototoxicity of genetically encoded voltage indicators (GEVIs) are yet to be fully characterized ²⁸ and strong light exposure (often needed to measure high-frequency action potentials) may exacerbate the phototoxicity.	Foreign body reaction (FBR) is observed, albeit minute. Further studies are needed.

Supplementary Table 1 | Detailed comparison between voltage indicators and MOTE.

Supplementary Table 2 summarizes the key differences between genetically encoded voltage indicators (GEVIs) and a MOTE. GEVIs and MOTEs have varying strengths and weaknesses, and their preference will depend on the application. Still, a MOTE stands out in its temporal resolution, making it well suited for fast neurons not only in mouse models but also in other popular animal models such as songbirds. Furthermore, a MOTE is much less limited by scattering (as its PVLED size is many multiples of the wavelength and the neural recording is encoded through PPM), compared to GEVIs which depend on conventional imaging setups; for this reason, even with a three-photon microscopy, the functional depth of GEVIs will be limited to 1 mm where it is likely that a MOTE will be able to function at a much deeper depth. Lastly, because a MOTE does not depend on fluorescence dynamics, its neural recording is illumination-insensitive, and the signal degradation is gradual over many months (likely due to FBR).

	GEVIs	MOTE
Temporal Resolution	500 Hz ~ 2 kHz	>15 kHz
Spatial Resolution	Multi-cell, population-level	Single channel but can be expanded
Sensitivity	While a MOTE has a higher sensitivity (input referred noise of 14.8 μV_{RMS}) compared to GEVIs (V_{min} 1–2 mV), a MOTE is unlikely to be placed right next to the strongest “signal point” such as an axon hillock, and hence a direct comparison of these sensitivity numbers would not be fair nor practical.	
Invasiveness	Genetically and/or virally invasive	Physically invasive
Operational Depth	<800 μm even with two-photon and scattering limited	Theoretically up to 6 mm and not scattering limited
Lifetime	Limited by photobleaching; effects of gene-editing and viral injection to be further characterized	One year, but graduation electrodes degradation is observed; effects of the foreign body reaction to be further characterized
Signal Stability	Reduces under strong illumination	Illumination-insensitive
Flexibility	Gene & viral specific (<i>i.e.</i> , limited to specific neurons/animal models)	Direct electrical recording allows any animal models to be targeted

Supplementary Table 2 | Key differences between genetically encoded voltage indicator (GEVIs) and MOTE

Section 3. MOTE Power Consumption Breakdown

Our MOTE is designed to operate with 1 μW (1 μA at 1 V) yet a MOTE does not shut off abruptly even below the design bias point – even when less power is available, a MOTE will be able to still function, though with degraded performance (*i.e.*, noise performance), down to 0.5 μA and 0.6 V. Of the 1 μW , a MOTE spends most of its power on low-noise amplification and filtering, so to best record local field potentials (LFPs) and action potentials (APs). The light emitting diode (LED) driver then consumes the second most to generate a sufficiently strong bright pulse position modulation (PPM) pulse for data uplink – it should also be noted that the LED efficiency is a function of current density.

The total surface area of a MOTE is 24,675 μm^2 (and 20 μm thick), and while the amplifier and filter block does occupy a significant portion of the area for filter capacitance as well as reduced flicker noise, the frame block which outlines all the other CMOS blocks to provide light shielding and shunting of unwanted Si-photocarrier^{29,30} takes the most area, highlighting a special challenge in developing a heterogeneously integrated CMOS-based system like a MOTE for optoelectronic applications. Fig. 3c illustrates the power and area distributions, whereas Extended Data Table 2 details the numeric breakdown.

Section 4. Angle-Dependent Link Efficiency

To evaluate how the angular position of the MOTE relative to the microscope objective affects the optical link efficiency, we have conducted Monte Carlo simulations as well as an *in vitro* experiment based on a brain phantom consisting of 1.1- μm diameter non-fluorescent polystyrene beads (Merck LB11 Latex Beads, polystyrene) in agarose gel (Biowest Agarose G-10); the bead concentration was set to $5.4 \times 10^9 / \text{mL}$ to emulate the scattering properties of the mouse cortex (grey matter)³¹. The agarose-beads mixing was done as follows:

1. Weigh 127 mg of agarose powder.
2. Add 24.5 mL of DI water to the agarose powder and boil to dissolve the agarose powder.
3. Wait for the temperature to drop to 40 °C and add 1 mL of latex microspheres (Merck LB11 Latex Beads, polystyrene) to the agarose solution.
4. Use low-speed (200 RPM) magnetic stirring (Magnetic Stirrer 0003671000, IKA Works (Asia) Sdn Bhd) for >10 seconds to mix.
5. Dispense the mixed solution into a Petri dish using a pipette to achieve the desired thickness.
6. Let the Petri dish sit at room temperature for 10 minutes until the gel-beads mix is fully solidified.

Extended Data Figure 3 shows the simulation results (Extended Data Figure 3a), experimental setup (Extended Data Figure 3b and 3c), and the experimental results (Extended Data Figure 3d). The collection efficiency denotes how much light emitted by the MOTE is collected by the photodetector through the objective, the PV cell flux denotes how much optical power (from a light source outside the brain) can reach the MOTE, and the link efficiency is the product of the collection efficiency and the PV cell flux. In the experiment, this link efficiency is captured by measuring the average pulse heights (measured by the photodetector) of the MOTE's PPM optical output. Relative plots normalize the simulation and experimental results per given depth by its maximum, to better portray the angular dependence.

In both simulation and experiment, the absolute link efficiency drops with the implantation depth, yet the angular dependency decreases with the implantation depth as scattering becomes more dominant. At shallow depths, the MOTE is heavily impacted by the tilt angle as the photons remain ballistic with weak tissue scattering. However, there are often sufficient link margins at such depths because the tissue attenuation is also weak. At deeper depths, where the link margin becomes scarce and link efficiency becomes critical, the tilt angle has less impact because of scattering. At such depths, such chiplets may be operable even for angles larger than 90° (*i.e.*, upside down), where the shadowing by the chiplet itself can be mitigated through scattering (LED light originally emitted downwards can be reflected upwards through tissue backscattering).

Interestingly, when we examine the absolute magnitude of the collection efficiency at large angles ($>90^\circ$), backscattering (photons that initially travel deeper into the tissue then scatter back to the surface) starts to dominate photon collection efficiency, and the absolute efficiency at shallow implantation depths starts to outperform deeper implantation depths again near 120° .

We also noted that since the LED size is much smaller than the scattering length, the emitter's behaviour is very similar to that of a point source, but with a directional emission. In addition, the flux of PV cells tends to increase slightly with angle at deeper depth (Extended Data Figure 3a). This is because the depth is defined as the midpoint of the MOTE – when we tilt the MOTE, since light intensity decays exponentially with tissue depth, the 'upper' half of the MOTE receives much more light to compensate for the less light received by the 'lower' part of the MOTE, and therefore the total light received by the entire device increases.

Section 5. MOTES in vivo Measurement on Day 365

Mouse 1 was euthanized on the 369th day after surgery, and the last measurement was taken on the 365th day. At the time of euthanasia, the mouse was just shy of 1 year and 8 months old (592 days old). The last measurement on the 365th day showed a significantly weaker local field potential (LFP) response to the mechanical stimulus. Interestingly, we also observed that the MOTE movements between day 296 and day 365 were noticeably larger than the movements between day 7 and day 296, where Extended Data Figure 8 summarizes these findings. We speculate that the weakened LFP response is in large part due to the foreign body response (FBR), particularly on the electrode surface, and partially due to the unexpected MOTE movements between day 296 and day 365 (the mouse's head could have collided on the cage wall, and/or the head-bar cement started to degrade, creating a minute gap between the cover glass and the brain). It should be noted that we have not observed any noticeable changes in the output pulse position modulate (PPM) pulses, in terms of their timing and strength, indicating that the CMOS circuit consisting of 307 transistors (Extended Data Table 2 and ***Section 3. MOTE Power Consumption Breakdown*** of this Supplementary Information) and the encapsulation of the MOTE are well intact over these 365 days.

Section 6. MOTE's AlGaAs Photovoltaic Light Emitting Diode (PVLED)

Characterization in the PV and LED modes

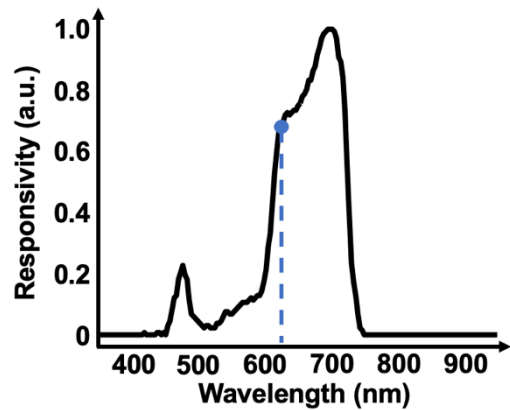
AlGaAs microscale photovoltaic light emitting diode (PVLED) provides the means to transduce optical power into electrical power (PVLED in its PV mode) to power up the underlying complementary metal-oxide-semiconductor (CMOS) circuit, and to transduce the output voltage pulses (in which measured neural signals are encoded) into optical pulses (PVLED in its LED mode). This optoelectrical interplay requires detailed characterization of the AlGaAs PVLED to allow facile co-design with the CMOS circuitry and integration microfabrication, and this section illustrates such characterization results.

6-1) Characterization of the AlGaAs PVLED in the PV mode

A 700 nm source would have been ideal to power up a MOTE, yet in practice, we found it hard to obtain a 700 nm light source that can provide as much irradiance as the 623 nm light source used in this work. Supplementary Figure 2 shows the PV responsivity of the AlGaAs PVLED used in this work, which is integrated on top of a CMOS chip, and we plan to utilize a near-700 nm source in future work to increase the optoelectrical conversion efficiency.

A MOTE is designed to operate with the electrical power of 1 μ W (1 μ A at 1 V), though it can operate at below and above that level – at a lower power level, the performance (such as input referred noise and sampling frequency)

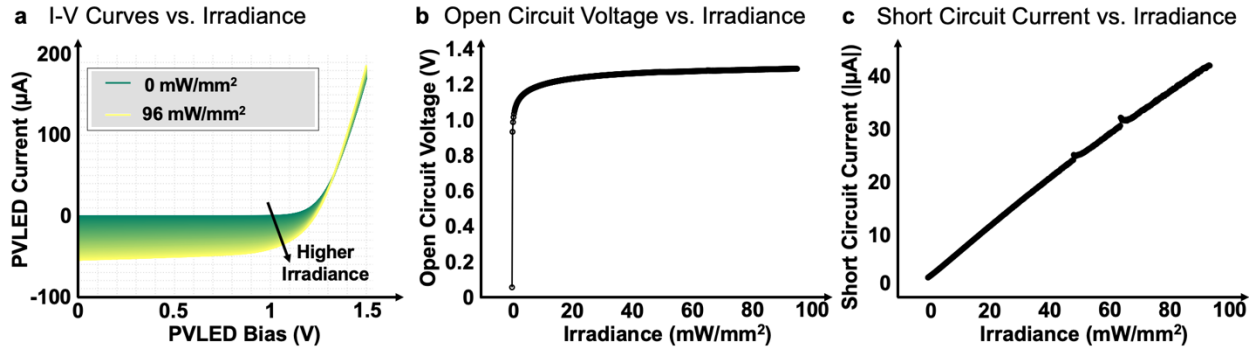
would degrade, and as the CMOS biasing is largely governed by the proportional to absolute temperature (PTAT) circuit, a higher available power does not linearly improve the performance. Electrical characterization (measured in air and therefore not accounting for tissue absorption/tissue losses – see **Section 1. Theoretical Maximum Operational Depth of MOTE** of this Supplementary Information for an in-depth analysis) of the AlGaAs PVLED over varying irradiance shows that the PVLED can indeed provide



Supplementary Figure 2 | MOTE's AlGaAs PVLED responsivity in its

PV mode. Although the 623 nm source used in this work does not provide the maximum responsivity, it still provides 70 % of the maximum conversion efficiency.

sufficient electrical power well below the safety heating limit of the brain⁵; a MOTE will start to function when as low as 4 mW/mm² (623 nm) is delivered to its PVLED surface. Supplementary Figure 3 illustrates the I-V characterization across varying irradiance and summarizes the resulting open circuit voltage (V_{OC}) and short circuit current (I_{SC}).

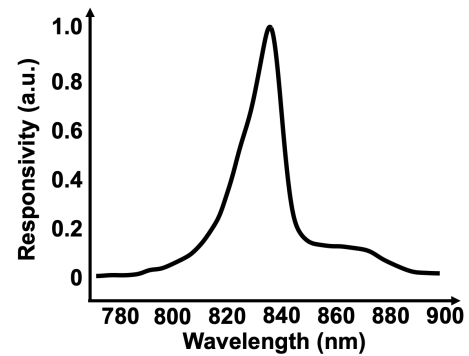


Supplementary Figure 3 | Electrical characterization of MOTE's AlGaAs PVLED across 0~96 mW/mm² irradiance. a, I-V measurements against an irradiance sweep (0 to 96 mW/mm²). **b**, Open circuit voltage (V_{OC}) vs. irradiance. **c**, Short circuit current (I_{SC}) vs. irradiance.

6-2) Characterization of the AlGaAs PVLED in the LED mode

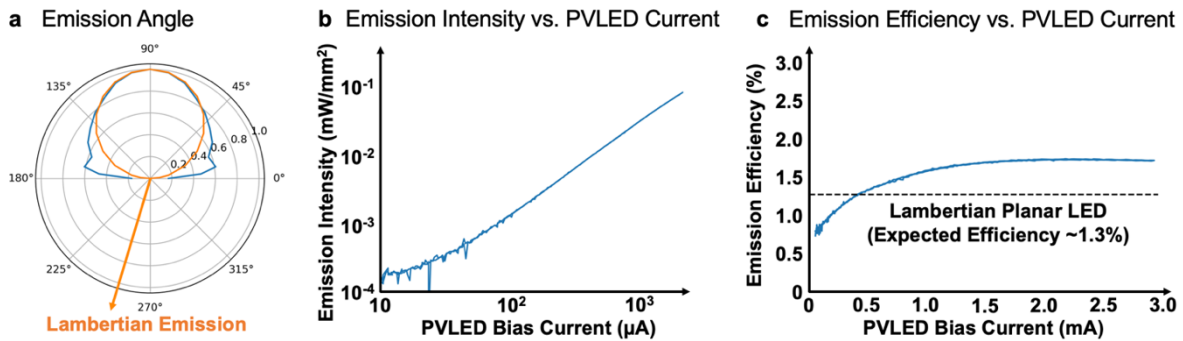
The PVLED emission is centred around 825 nm and peaks at 835.8 nm. Supplementary Figure 4 reports the emission spectrum. As our optical filter placed before the detector (not to be overwhelmed by the powering 623 nm source) is centred at 835 nm with a bandwidth of 70 nm (Semrock 835/70 nm BrightLine® single-band bandpass filter), most of the emission, although not all, is captured by the photodetector (THORLABS APD410A).

MOTE's AlGaAs PVLED is designed to emit vertically and horizontally through so-called window layers, in anticipation that directionality of the initial emission might matter less in a highly scattering environment. Supplementary

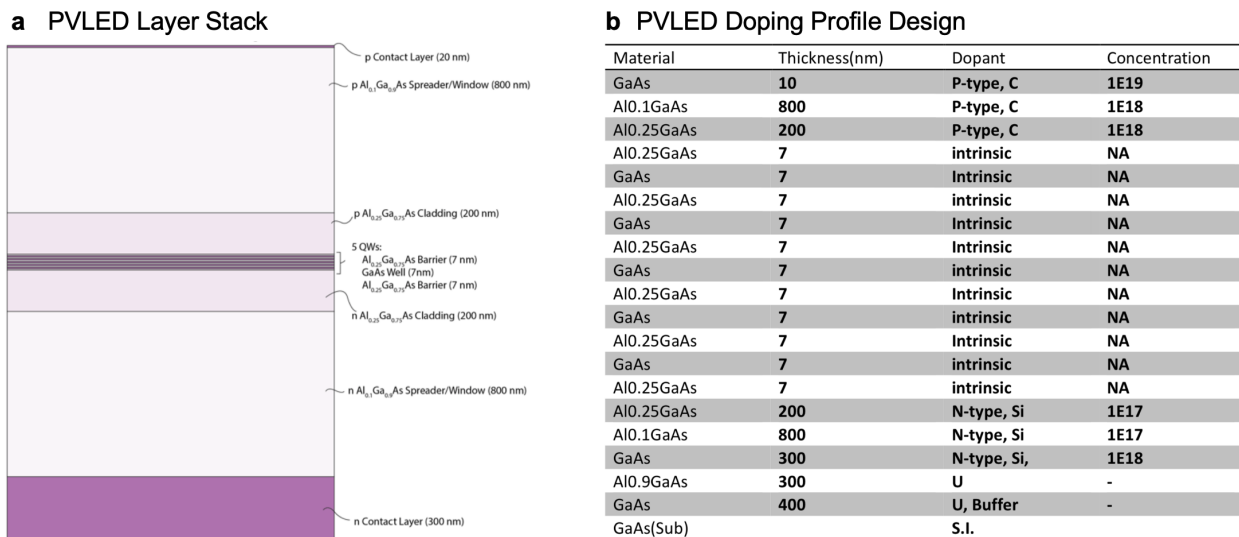


Supplementary Figure 4 | MOTE's AlGaAs PVLED emission spectrum in its LED mode. The peak is at 835 nm while the full width at half maximum (FWHM) centre is 825 nm.

Figure 5a shows such emission, whereas Supplementary Figures 5b and 5c illustrate the emission intensity and efficiency as a function of the AlGaAs PVLED bias current (**SUPPLEMENTARY VIDEO 8** also shows the emission vs. bias). Although the attainable emission efficiency of this PVLED is near 2 %, due to the limited power budget (the peak current injected into the PVLED in its LED mode is 70 μ A), the MOTE's emission efficiency hovers around 0.5 – 1 %, which we hope to improve in our future work. Supplementary Figure 6 details the design of the PVLED stack, including the doping concentration.



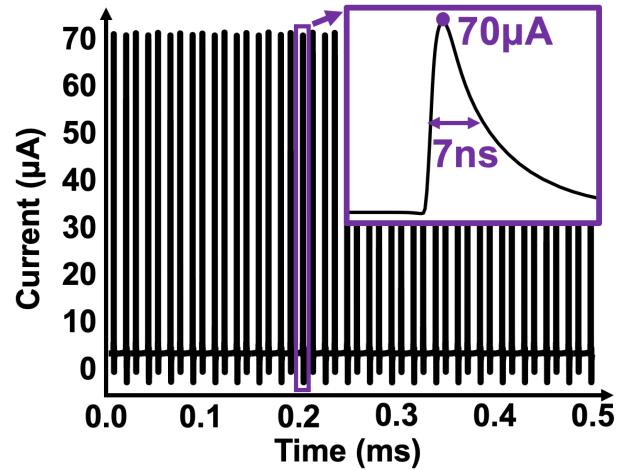
Supplementary Figure 5 | Characterization of MOTE's AlGaAs PVLED emission in the LED mode. **a**, Emission angle compared to the Lambertian emission. **b**, Emission intensity as a function of the PVLED bias current. **c**, Emission efficiency as a function of the PVLED bias current.



Supplementary Figure 6 | Design of MOTE's AlGaAs PVLED. **a**, PVLED layer stack including large window layers above and below the quantum wells (QWs). **b**, Detailed doping profile of the PVLED layer stack.

6-3) Current amplitude to drive the PVLED for data uplink

The LED driving current does not change drastically as a function of the incoming (powering) light intensity because the CMOS system is biased through the proportional to absolute temperature (PTAT) circuit. However, the current does increase, near logarithmically, with the increase in available power, somewhat tracking the change in open circuit voltage (V_{oc}). Supplementary Figure 7 shows the injection of simulated current into the MOTE PVLED in its LED mode, providing about 70 μA of peak current at 7 ns FWHM. Because the emission efficiency of PVLED LED mode is a function of current density (see Supplementary Figure 5c), less than 1 % of this electrical power is transduced to



Supplementary Figure 7 | Simulation of the current injected into AlGaAs PVLED in its LED mode when the available electrical power is 0.95 μW . The peak current amplitude is 70 μA , lasting several nanoseconds in simulation (our photodetector is band-limited at 10 MHz; hence the measured optical pulses are 100 ns wide).

PPM photons and collected by the objective, and therefore the optical power collected by the objective is less than $<350 \text{ nW}$ ($1 \text{ V} \times 70/2 \text{ } \mu\text{A} \times 0.01$).

*It should be noted that while the instantaneous power during pulsing (for several nanoseconds) can reach 70 μW as the MOTE's stacked capacitors (so-called charge pump – see Fig. 3b, right) instantaneously dump stored charges into the PVLED, the average nominal power consumption of a MOTE is 1 μW .

6-4) Minimum optical power required to power up the MOTE

When there is no tissue absorption/scattering, 4.4 mW/mm^2 is the light intensity required to power up the implant and for the implant emission to be detected and decoded by our detector system. At that intensity, in the PV area of $2400 \text{ } \mu\text{m}^2$, the available optical power is 10.6 μW and the available electrical power is 0.95 μW ; the power conversion efficiency

(PCE) is 9.0 % with a fill factor of 61 % and the corresponding I_{SC} and V_{OC} are 1.45 μA and 1.08 V respectively.

6-5) Minimum detectable optical power at the external receiver

The optical loss in the optical path of the receiver (RX), consisting of a beam splitter and a filter, is <10 % (Semrock 835/70 nm BrightLine® single-band bandpass filter; FF01-835/70-25 and 775 nm edge BrightLine® multiphoton single-edge dichroic mirror; FF775-Di01-25x36). The minimum detectable power, largely set by the photodetector (THORLABS APD410A, maximum gain = 26.5 MV/W & bandwidth = 10 MHz), is ~0.13 nW. Although the peak voltage from the detector should be a few volts (26.5 MV/W $\times$ ~100 nW), because of the band-limitation (hence low-pass filtering), the peak output voltage of the photodetector is on the order of a few hundred mV. Autofluorescence, which acts as background noise, is ~100 mV_{PP} – while the minimum detectable power of the external receiver itself is low (sub-nanowatt), this autofluorescence sets a practical noise floor and commands the minimum optical power required for reliable data transmission (~300 nW peak emission, which requires electrical power ~0.95 μW , which then requires optical power ~10.6 μW , for which we needed to provide optical intensity of ~4.4 mW/mm²).

Section 7. Pulse Position Modulation (PPM) vs. Amplitude Modulation (AM)

Although a MOTE's pulse position modulation (PPM) is not digital, PPM's efficacy over amplitude modulation (AM) can be seen from Shannon's channel theorem³²:

$$C = B \log_2 \left(1 + \frac{S}{N} \right) \quad | \quad \frac{S}{N} = 2^{\left(\frac{C}{B}\right)} - 1 \quad | \quad SNR = 10 \log_{10} \left(2^{\left(\frac{C}{B}\right)} - 1 \right)$$

- $\frac{S}{N}$ = signal-to-noise power ratio.
- B = bandwidth of the channel / transmitted signal in Hz.
- C = channel capacity, in bit per second (bps).

For a given channel capacity, the required S/N is determined by the difference in channel bandwidths (of PPM and of AM). For PPM, using the time-bandwidth product (TBP) for a Gaussian pulse ($\kappa = 0.44$) and noting that the FWHM of a PPM optical pulse is 64 ns, we obtain the following:

$$\Delta f = \frac{0.44}{64 \times 10^{-9}} \approx 6.875 \text{ MHz} = B$$

For amplitude modulation, the bandwidth is twice the carrier frequency (which would be 2×13 kHz in this case). This reduction in bandwidth leads to a much higher required SNR; 47 dB (in power) higher.

Section 8. Radio Frequency (RF) Near-Field vs Far-Field Coupling

The efficiency in using radio frequency (RF) for power and communication can be characterized for near-field or far-field regimes, similar to the ballistic and diffusive regimes for photons discussed in **Section 1. Theoretical Maximum Operational Depth of MOTE** of this Supplementary Information.

8-1) Near-Field

In the case of a single-turn loop antenna, calculating the transmission efficiency of the transmitting and receiving coils involves the coupling coefficient (k) and quality factors (Q):

$$\eta = \frac{k^2 Q_1 Q_2}{1 + k^2 Q_1 Q_2}$$

η : Efficiency, ranging from $0 \leq \eta \leq 1$

k : Coupling coefficient, a function of the coil distance and geometric alignments

Q_1, Q_2 : Quality factors of the transmitter and receiver coils, where $Q = \frac{\omega L}{R}$

$\omega = 2\pi f$: Angular frequency

L : Inductance of the coil

R : Equivalent resistance of the coil

The coupling coefficient (k) is calculated as follows^{33–36}:

$$k = \frac{M}{\sqrt{L_1 L_2}}, \quad M = \mu_0 \cdot N_1 \cdot N_2 \cdot \frac{\pi r_1^2 r_2^2}{(r_1^2 + r_2^2 + d^2)^{3/2}}$$

M is the mutual inductance between the two coils.

μ_0 : Permeability of free space ($4\pi \times 10^{-7}$ H/m)

N_1, N_2 : Number of turns in the transmitter and receiver coils

r_1, r_2 : Radii of the transmitter and receiver coils

d : Distance between the centres of the two coils

L_1, L_2 : Self-inductances of the transmitter and receiver coils

In conclusion, the near-field coupling has an inverse sixth-order dependency on the distance:

$$k \propto \frac{1}{d^3}, \eta \propto \frac{Q_1 Q_2}{d^6}$$

8-2) Far Field

The far-field region begins at a distance $R > \frac{2D^2}{\lambda}$, where D is the diameter of the larger coil and λ is the wavelength. The power received by the second coil from the first can be calculated using the Friis transmission formula as follows:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2$$

P_r : Power received by the second coil (receiver)

P_t : Power radiated by the first coil (transmitter)

G_t, G_r : Gains of the transmitter and receiver coils

λ : Wavelength of the signal

R : Distance between the two coils

The transmission efficiency η in the far-field is:

$$\eta = \frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2$$

In the far-field, a small circular coil behaves like a magnetic dipole antenna, and its radiation properties are governed by its size relative to the wavelength. The total radiated power of a single coil in the far-field is:

$$P_t = \frac{I_0^2 R_r}{2}$$

I_0 : Current through the coil and R_r : Radiation resistance of the coil

The effective aperture of the receiving coil is:

$$A_e = \frac{G_r \lambda^2}{4\pi}$$

G_r : Gain of the receiving coil and λ : Wavelength of the transmitted signal

Using the radiated power and effective aperture, the received power is^{37,38}:

$$P_r = P_t \cdot \frac{A_e}{4\pi R^2} = P_t G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2$$

In conclusion, the far-field coupling has an inverse second-order dependency on the distance:

$$\eta \propto \frac{1}{R^2}$$

Although the far-field coupling is more facile, microscale implants will fall under the near-field regime with the inverse sixth order dependency on the distance. Optical power transfer/communication, on the other hand, compares favourably in its diffusive regime (see **Section 1. Theoretical Maximum Operational Depth of MOTE** of this Supplementary Information).

A similar analysis can be performed on ultrasonic transduction, which has been well documented by D. Seo, et al³⁹.

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