Continuous-Wave Upconverting Nanoparticle Microlasers

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Reducing the size of lasers to microscale dimensions enables new technologies[1] that are specifically tailored for operation in confined spaces ranging from ultrahigh-speed microprocessors[2] to live brain tissue[3]. However, reduced cavity size increases optical losses and requires greater input powers to reach lasing thresholds. Multiphoton-pumped lasers[4–7] that have been miniaturized using nanomaterials such as lanthanide-doped upconverting nanoparticles (UCNPs)[8] as lasing media require high pump intensities to achieve UV and visible emission and operate under pulsed excitation schemes. Here, we leverage the recently described energy looping excitation mechanism in Tm^{3+}-doped UCNPs[9] to achieve continuous-wave (CW) upconverted lasing action in stand-alone microcavities at excitation fluences as low as 14 kW cm^{-2}. CW lasing is uninterrupted, maximizing signal and enabling modulation of optical interactions[10]. By coupling energy-looping nanoparticles (ELNPs) to whispering gallery modes of polystyrene microspheres, we induce stable lasing for > 5 hours at blue and near-infrared (NIR) wavelengths simultaneously. These microcavities are excited in the biologically transmissive second near infrared widow (NIR-II), and are sufficiently small to be embedded in organisms, tissues or devices. The ability to produce CW lasing in microcavities immersed in blood serum highlights practical applications of these microscale lasers for sensing and illumination in complex biological environments.

Upconversion occurs in lanthanide-doped materials[11–13] through the step-wise absorption of multiple photons. Since upconversion is orders of magnitude more efficient than standard non-linear optical processes such as two-photon absorption[14], lanthanide-doped systems emerged as promising gain media for the production of visible-wavelength coherent radiation from NIR excitation[15]. To achieve the population inversion required for lasing, upconverting lasers still require high pump intensities ($\sim 10^7$-10^{10} W cm^{-2}; Fig. 1a) that constrain the gain media and the operating conditions used for such systems. Commonly, upconverting lasers are assembled from meter-long doped glass fibres to distribute and dissipate heat generated by high pump intensities. To maintain the high excited state populations required for upconversion, these delicate fibres are drawn from low-phonon energy metal fluoride glasses (e.g., ZBLAN) that have size and geometric limitations as well as strict processing requirements[16,17].

The use of UCNPs for upconverting lasers offers an avenue for fully solution-processed, bottom-up microlaser production, which in turn enables simple fabrication and assembly into a wide variety of photonic structures and device platforms[10]. These solution-processed upconverting lasers can be produced from biologically compatible materials by control of UCNP surface properties[8,18]. However, a major obstacle preventing the adoption of UCNP-based lasers has been the requirement of pulsed excitation[7] to avoid optical and thermal damage associated with intense CW excitation, a problem compounded by heat-induced increases in lasing thresholds. UCNPs exploiting an avalanche-like energy looping mechanism[9] can bypass these issues, resulting in solution-processed, bio-integrable CW upconverting microlasers.

We have designed laser microcavities to incorporate 3 technical innovations intended to lower upconverting lasing thresholds. First, the cavities are fabricated on polystyrene microspheres (diameter = 5 μm) that are known to host whispering gallery modes[19] (WGMs), closed-loop light paths that are guided by total internal reflection within a microsphere surface (Fig. 1b). Previously, the use of WGMs in large microspheres of bulk upconverting material has led to low-power lasing[20]. The smaller polystyrene cavities used in this work support both transverse electric and transverse magnetic propagating modes with high quality factors (Q), and the number and wavelength of the amplified modes can be selected by modulating the diameter of the microspheres. Additionally, polymers are attractive cavity materials for biological lasing applications because monodisperse libraries can readily be fabricated from biocompatible or biodegradable materials. One major limitation is that some organic polymers have been shown to degrade at the temperatures reached under sustained CW excitation[21].

To minimize the thermal degradation of the cavity materials, the second innovation we incorporate is the use of Tm^{3+}-doped energy-looping

nanoparticles (ELNPs)[9] as gain media in these WGM microresonators. When excited non-resonantly at 1064 nm, ELNPs exhibit upconverted luminescence with characteristic blue and NIR Tm^{3+} emission peaks (Supplementary Fig. 1). The 1064-nm light used to excite ELNPs reduces the thermal load of the gain medium, since the ELNP host matrix, $NaYF_4$, and the polystyrene cavity both absorb less at 1064 nm than at 980 nm, which is used to excite nearly all other UCNP lasers. Additionally, 1064 nm falls within the NIR-II window of photon energies that transmit efficiently through tissue. Most significantly, the ELNPs upconvert the 1064 nm light to visible and NIR light using an avalanche-like energy looping mechanism[9] that, compared to other UCNPs, more-efficiently achieves the population inversion required for lasing. These cavities are robust, exhibiting no signs of damage or degradation under normal operating conditions (Supplementary Fig. 2).

The third essential feature of our upconverting microcavities is the controlled deposition of hydrophobic ELNPs on the outer surface of the polystyrene microspheres (Fig. 2 and Supplementary Fig. 3). As illustrated by a finite element method (FEM) simulation of the electric field intensity $|E|^2$ of an equatorial transverse magnetic WGM at 807 nm (Fig. 2d, Supplementary Fig. 4), this design maximizes the overlap of the ELNP gain medium with the cavity optical whispering gallery modes. ELNPs were deposited on the surface of the 5-μm polystyrene microspheres by partial swelling of microspheres in a polar solvent mixture to drive van der Waals interactions between hydrophobic surfaces on the ELNP and the outer region of the microsphere, followed by deswelling. Using this solution-phase process, the thickness of the ELNP coating is tuned by adjusting ELNP and microsphere concentrations (Fig. 2a and b, Supplementary Fig. 5). TEM cross sections demonstrate that most of the nanoparticles form a halo on or near the outer surface of the microsphere, with few particles embedded deeper within the polystyrene matrix (Fig. 2b).

Optical images of emission from the microspheres under 1064 nm illumination (Fig. 2c, left) match the simulated WGM spatial distribution (Fig. 2c, right, and Fig. 2d). Spectrally, the observed NIR emission modes match simulated optical mode positions for a 5-μm-diameter polystyrene bead (Fig. 2e), confirming both the size of the cavity and its effective coupling to the ELNP emission near 800 nm. Experimental *Q*-factors for these ELNP-coated microspheres range between 10^3 and 10^4 (Supplementary Fig. 6). Both transverse electric and transverse magnetic modes are present, and their relative intensities can be controlled by adjusting the input coupling position of the pumping laser (Supplementary Fig. 7).

Lasing is observed from these ELNP microcavities when the CW 1064 nm pump laser intensity is raised above a threshold value. This value is determined by plotting both microcavity output power and spectral linewidth narrowing as a function of pump power and noting where the simultaneous

change in slope occurs for both quantities (Supplementary Fig. 8). For the representative device highlighted in Fig. 3a, b, we determined that the 807 nm laser mode dominates the spectrum when the pump laser is focused at the edge of the microsphere (Supplementary Fig. 9 and 10). The exact input coupling efficiency of the pump laser is difficult to determine in this configuration, so to provide the most conservative estimate of the lasing threshold, we assume 100% of the excitation (in a diffraction-limited spot) couples to the WGM for all thresholds listed, thus providing upper bounds for the lasing thresholds. Emission spectra from the ca. 800 nm luminescence band for pump powers below, near, and above threshold (Fig. 3a) show that cavity modes from the microsphere modify the ELNP spontaneous emission even at low pump powers. Above the threshold, a primary lasing mode at around 807 nm emerges, narrowing and increasing in relative intensity (Supplementary Fig. 8). The full emission intensity versus pump intensity curve for this mode (Fig. 3b), overlaid on its intensity-dependent linewidth plot shows a lasing threshold of 17 kW cm^{-2}. Beyond the lasing threshold, the mode linewidth narrows to < 1 nm (see Methods). Also present in Fig. 3b are slope-change features corresponding to the onset of multimode lasing and the onset of the blue lasing (Fig. 3c, d). Demonstrating the robustness of this microcavity design and its fabrication, lasing was achieved in each of the 114 microresonators tested. A distribution of lasing thresholds –observed for the 22 measured devices that were produced with optimal ELNP and coating specifications (Fig. 3e and Supplemental Fig. 10) – shows thresholds as low as 14 kW cm^{-2} and a mean value of 44 kW cm^{-2} with a standard deviation of 23 kW cm^{-2}. Previous UCNP lasing systems excited at 980 nm exhibited peak-intensity pumping thresholds of ~10^{10} W cm^{-2} using Yb^{3+},Er^{3+}-codoped UCNPs[5], and ~10^{7} W cm^{-2} with Yb^{3+},Tm^{3+}-codoped UCNPs[6]. Unlike the complex pulse sequences required to avoid thermal damage with these high power densities[5,6], the low lasing thresholds in our upconverting microcavities enable excitation with modest CW lasers.

As the pump fluence is increased beyond the NIR lasing threshold, we also observe simultaneous CW blue lasing action from these microcavities (Fig. 3c, d). This lasing originates from the $^1D_2 \rightarrow {}^3F_4$ and $^1G_4 \rightarrow {}^3H_6$ transitions in Tm^{3+}, which are populated by additional excited state absorption events (e.g., from the NIR-lasing $^3H_4$ state to the high-energy $^1G_4$ state; see Fig. 4). When the pump excitation power is increased near the blue lasing threshold, multiple cavity modes emerge from the spontaneous emission bands near 450 nm and 475 nm (Fig. 3c). The blue lasing thresholds are 2- to 10-fold greater than the NIR lasing thresholds in these systems, as can be seen in the output power versus pump intensity curve for a representative microsphere laser (Fig. 3d).

Notably, the use of optically inactive $NaGdF_4$ shells on our ELNPs is required for achieving the low threshold CW lasing observed here. These shells passivate energy loss to the ELNP surface[29], thereby reducing a major loss

channel within the microlasers and hence lowering the threshold (Supplementary Fig. 11). A single monolayer (0.4 ± 0.2 nm) shell on each ELNP only partially passivates ELNP surface losses, leading to NIR lasing thresholds ranging from 550 to 1500 kW cm^{-2} in measured devices (Fig. 3f). Slightly thicker shells (1.7 ± 0.2 nm) lower the observed thresholds to ca. 200 kW cm^{-2}, while even thicker (3.3 ± 0.2 nm) shells yield even lower thresholds of ca. 50 kW cm^{-2} (Fig. 3f and Fig. 3c).

Based on the above observations, we conclude that the low thresholds of these microlasers are a consequence of using Tm^{3+}-doped core-shell nanoparticles that exploit the avalanche-like energy looping mechanism[9] (Fig. 4), along with the spatial overlap of the ELNPs with microcavity WGMs. The looping mechanism amplifies the population of excited states such as $^3F_4$ through a positive feedback loop of excited state absorption (ESA) from an intermediate state followed by cross-relaxation (CR) back down to the same intermediate state (Steps 2 and 3 in Fig. 4, respectively). In this CR process, a highly-excited Tm^{3+} ion transfers a fraction of its energy to a neighboring Tm^{3+} ion in its ground state, resulting in *two* Tm^{3+} ions in the same intermediate excited state. This looping process effectively doubles the population of an excited state, and repeated looping therefore can amplify the population of excited states non-linearly. This process ultimately leads to population inversion in the $^3H_4$ state, which is responsible for the 800 nm band emission. Once the $^3H_4$ excited state is sufficiently populated, additional ESA events are possible, including a 1064 nm-resonant transition to the $^1G_4$ state (Step 5, Fig. 4) responsible for blue emission and, in these ELNP-coated microcavities, blue lasing. These ESA events may be coupled to numerous CR processes (Step 6 and 7, Fig 4), thereby producing additional loops that amplify the populations of higher excited states.

Finally, a number of compelling and diverse applications for these stand-alone microlasers, including *in vivo* biosensing[30] and deep-tissue optogenetics[31], require operation in demanding aqueous environments. We are able to observe lasing action when the microcavities are immersed in fetal bovine serum (FBS; Fig. 5a-c), demonstrating the viability of our devices in biological media (Fig. 5b). NIR microcavity emission spectra of microspheres immersed in FBS when pumped below, near, and above threshold (Fig. 5c) exhibit *in situ* CW lasing thresholds ca. 250 kW cm^{-2} (Supplementary Fig. 8) – these increased thresholds are expected due to the smaller the refractive index (n) contrast between the cavity and the environment. The change in environment also produced observable spectral shifts of the lasing modes ($\Delta\lambda$ = 2.1 nm, Fig. 5b), indicating utility in sensing applications. More generally, the small footprint, low CW lasing thresholds, and solution-processability enable integrated photonics applications[32], such as self-assembly into phased arrays for increased optical directionality or active waveguiding (Fig. 5d and Supplementary Fig. 15).

Beyond reporting on local index or material changes in the environment, more sophisticated applications can be foreseen. For example, these microlasers can potentially respond to small changes in temperature[33] or pressure – critical information from the biological perspective – due to the sensitivity of the lasing modes to cavity shape and size. Temperature measurements can be easily calibrated using mode shifts ($\Delta\lambda$; Fig. 5e)[33]. The total increase in temperature due to lasing action in biological media has been measured to be 0.38 °C as pump laser intensity is increased from just above threshold to 1051 kW cm^{-2} (Fig. 5f), presenting a minimal impact for biological media and tissue. For devices in air, an increase of < 2 °C is observed when pumped at ~200 kW cm^{-2} (Supplementary Fig. 12). Notably, the intensity and wavelength of the CW lasing is stable over five hours of continuous excitation at 300 kW cm^{-2} (Fig. 5g and Supplementary Fig. 13). In contrast, CW lasers based on semiconductor nanoparticles destabilize in less than one hour under significantly lower fluences[10,34]. As bright, stable, and local light sources, energy-looping microlasers enable subcellular imaging, tracking, and probing (Supplementary Fig. 14 and Supplementary Movie 1). Manipulation and trapping (both optical and thermal)[35] of small particles and molecules such as proteins and DNA are also possible.

In conclusion, we demonstrate CW UCNP lasing in 5 μm microcavities at thresholds as low as 14 kW cm^{-2}. These upconverting microlasers, based on fully solution-processed colloidal assemblies of energy looping nanoparticles, present a viable solution for small, stand-alone coherent light sources. Their ease of fabrication, storage, and deposition combined with their ability to operate continuously for hours in liquids and biological media immediately allows the realization of novel *in vivo* imaging, sensing, and probing measurements at depths well below sample surfaces, as required for optogenetic and similar investigations. With these properties, we expect upconverting nanoparticle microlasers to enable novel photonic architectures, which until now were precluded by laser design and material constraints.

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Data Availability

The data that support the plots and other findings within this paper are available from the corresponding author upon reasonable request.

Additional Information

Supplementary information is available in the online version of the paper. Reprints and permission information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to E.M.C, B.E.C., or P.J.S.

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Author contributions
The scientific concepts, ideas and experimental designs were the result of interactions and discussions between A.F.B., N.J.B., E.S.L, L.M., F.S. B.E.C., P.J.S., and E.M.C. E.M.C., E.S.L, C.T., and B.T. synthesized the nanoparticles, and A.F.B., E.S.L., L.M., B.E.C., and E.M.C. fabricated the microlasers. A.F.B., K.Y., E.S.B, N.J.B., E.S.L., L.M. and F.S. conducted the spectroscopic measurements. K.Y., K.B., and E.M.C. performed the theoretical modeling. M.V.P. and S.A. conducted the electron microscopy. A.F.B., B.E.C., E.M.C. and P.J.S. wrote the paper, in coordination with all the authors.

Competing financial interests
The authors declare no competing financial interests.

Figure Captions

Figure 1 | Use of microsphere cavity modes and energy looping nanoparticles for achieving CW, upconverting lasing at low powers. **a,** Graphical comparison of lasing thresholds and cavity size between our microcavities and other upconverting (UC) systems[5,6,16,22–24] and multi-photon pumped (MPP) architectures[7,25–28]. Thresholds for pulsed experiments represent peak power densities. Thresholds extrapolated for future microsphere devices reflect likely improvements in input coupling (e.g., waveguide coupling) and UCNP composition (e.g., exploiting high lanthanide doping and heterostructuring)[14]. NPs, nanoparticles. **b,** Schematic of excitation and lasing in the ELNP-coated microbeads. WGM, whispering gallery mode; TIR, total internal reflection. **Inset:** 3D schematic depicting lasing WGMs in a microsphere.

Figure 2 | **Upconverting microlaser structure and whispering gallery mode properties. a**, Scanning electron micrograph of a 5 μm diameter polystyrene bead coated with ELNPs. **b,** Transmission electron micrograph of a cross section of the microsphere cavity in the proximity of its equatorial plane showing that most of the nanoparticles lie on or near the outer surface of the microsphere. **c,** *Left*: Widefield image of a lasing microsphere displaying optical modes circulating around the cavity. Excitation occurs at a diffraction limited spot on the side of the bead, as marked. *Right*: Simulated field distributions in the x-y plane calculated for a 5 μm polystyrene microsphere, plotted in log colour scale. **d,** 3D representation of the numerical simulation of $|E|^2$ for the transverse magnetic whispering gallery mode at 807 nm circulating around a 5 μm dielectric sphere. **e,** Simulated NIR spectra of WGMs supported by a 5 μm polystyrene microsphere, overlaid on the experimental emission spectra of ELNPs and ELNP-coated beads

pumped near lasing. μcavity, microcavity. Scale bars: 1 μm unless otherwise indicated.

Figure 3 | **Upconverting microlaser characterization. a**, NIR spectra for pump laser intensities below, near, and above the lasing threshold. **b**, Microcavity emission intensity and spectral linewidth from the main NIR lasing mode at 807 nm as a function of pump intensity. FWHM, full width at half maximum. **c,** Blue emission spectra for pump laser intensities below, near, and above the blue lasing threshold. **d,** Emission and mode linewidth vs. pump intensity for the lasing mode at 450 nm. **e**, Lasing threshold distribution for 22 microspheres with near-optimal coatings, as determined by systematic EM and optical studies of ELNP compositions and coating thicknesses. **f**, Influence of epitaxial $NaGdF_4$ nanocrystal shells on laser thresholds. Shell thicknesses measured by TEM: 0.4, 1.7 and 3.3 nm (all values ± 0.2 nm).

Figure 4 | **Energy looping nanoparticle energy transfer and emission mechanisms:** Looping mechanism in Tm^{3+} doped NaYF4. Energy levels represent $4f^{12}$ manifolds of Tm^{3+}. Arrows are manifold-to-manifold transitions as described in the legend. The thickness of the arrows 1-5 varies logarithmically with the rate of the steady-state transitions at 1064 nm excitation (10^5 W cm^{-2}). The thickness of arrows 6-8 have been enhanced for clarity.

Figure 5 | **Lasing in aqueous environments, temperature sensing calibration, characterization of microlaser temperature versus pump power, and evaluation of laser stability. a**, Schematic showing microlaser excitation in blood serum. **b**, Spectral shifts recorded for the lasing beads in air and blood serum. **c**, NIR spectra for pump laser intensities below, near, and above the lasing threshold with the bead submerged in serum. **d,** Wide-field image of upconverting microlasers in a self-assembled 2-D array; scale bar is 5 μm. **e,** Mode spectral shifts as a function of temperature (for T = 20-30 °C); s = the slope of the linear fit, in units of nm/ degree C. Error bars were determined from measured room temperature variations and standard deviations of average spectra. **f**, Spectra of the main laser mode at two input powers for a microlaser in blood serum. $\Delta\lambda$ = 0.03 nm as pump intensity is increased from 353 kW cm^{-2} to 1051 kW cm^{-2}. Using the calibration curve in **e**, this translates to a ΔT in serum of 0.38 °C for this change in pump intensity. The blue dotted lines are peak fits. Vertical lines indicate the centre wavelength of the fitted mode. **g**, Intensity and wavelength of the laser mode over a period of 5 h under an excitation power of 300 kW cm^{-2}, displaying intensity variations below 15% and wavelength shifts less than 0.025 nm.