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**Microfluidic directional emission control of an azimuthally polarized
radial fibre laser**

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Lasers with cylindrically symmetric polarization states are predominantly based on whispering-gallery modes¹⁻⁷, characterized by high angular momentum and dominated by azimuthal emission. Here a zero angular momentum laser with purely radial emission is demonstrated. An axially invariant, cylindrical photonic bandgap fibre cavity⁸ filled with a microfluidic gain medium plug is axially pumped, resulting in a unique radiating field pattern characterized by cylindrical symmetry and a fixed polarization pointed in the azimuthal direction. Encircling the fibre core is an array of electrically contacted and independently addressable liquid crystal microchannels embedded in the fibre cladding. These channels modulate the polarized wavefront emanating from the fibre core leading to a laser with a dynamically controlled intensity distribution spanning the full azimuthal angular range. This new capability, implemented monolithically within a single fibre, presents opportunities ranging from flexible multidirectional displays to minimally invasive directed light delivery systems for medical applications.

Rotationally symmetric resonators capable of omnidirectional emission in the direction perpendicular to the axis of symmetry have been the subject of recent studies¹⁻⁷. These cylindrically symmetric sources rely on the excitation of whispering-gallery modes (Fig. 1, bottom), confined near the cavity boundary by total internal reflection. Light escapes these resonators only through diffraction losses or scattering from surface roughness, thus limiting control over the output coupling. Here we report on a cylindrical photonic bandgap (PBG) fibre cavity which supports purely radial modes (Fig. 1, top). In principle, this structure allows full control over output coupling and the potential for reduction in volume without compromising the quality factor. Additionally, the shorter

cavity length of these radial modes could allow for a larger free spectral range and consequently higher finesse as compared to whispering-gallery modes. Importantly, the radially directed emission from the extended cylindrical surface of this fibre laser is in contrast to the axial emission characteristic of conventional Bragg fibre lasers^{9,10} and planar annular Bragg resonators¹¹⁻¹⁴.

The fibre fabrication method is based on the thermal drawing of a macroscopic preform (Fig. 2a) assembled with all the solid materials and geometry of the resulting fibre (see Methods section for details).¹⁵ The preform consists of a hollow annular multilayered cavity comprised of a 35-layer structure of chalcogenide glass ($As_{25}S_{75}$) and polycarbonate (PC).¹⁶ Further out in the PC cladding are several pairs of conductive carbon-loaded polyethylene (CPE) electrodes which flank hollow channels. The composite structure is drawn under a high stress regime ($\sim 400 \text{ g/mm}^2$) yielding an axially invariant, rotationally symmetric, photonic bandgap fibre cavity with a transmission bandgap centered near 550 nm and a bilayer periodicity of 160 nm (Fig. 2b, top-right). The fibre core is surrounded by four electrically addressable microfluidic channels embedded in the fibre cladding (Fig. 2b, bottom). The challenge in drawing such a structure which is reduced in size by a factor of 100 lies in maintaining the integrity and symmetry of the multilayers down to the final scale while preventing the deformation of the hollow channels and electrodes.

Recent studies have demonstrated optofluidic fibre devices with dynamically tunable properties^{17,18}. In this work, a microfluidic pump (shown in Fig. 3a and described in Methods section) is utilized to transport organic dye-doped water plugs inside the fibre core. The internal surface of the fibre core is hydrophobic and not wet by the

aqueous plug, which remains intact during rapid movement at velocities of 35 mm/s (Fig. 3b). The pressure field is mediated through a transparent and immiscible fluid (e.g., silicone oil), allowing reversible transport of the lasing plug to any position within the fibre (Fig. 3b,c).

The laser wavefront emitted from the fibre core appears as an axially collimated ring-like beam in the far-field (Fig. 4a). The axial collimation results from the low diffraction facilitated by the smooth interfaces of the water plug, and the continuous translational symmetry of the laser cavity along the fibre axis. The penetration depth of the pump beam, combined with the circular cross section of the core, defines a cylinder from which laser light is emitted. (Note that the actual plug length, which is on the order of a cm, does not influence the laser emission). For the 1 mM R590 water plug used in our experiments, the penetration depth is $\sim 100 \mu\text{m}$. Therefore, the axial divergence angle, which is proportional to the ratio between the wavelength and the penetration depth, is expected to be $\sim 10 \text{ mrad}$.

The cylindrical symmetry of the emission stems from the isotropic fluorescence of the dye and its coupling to the fibre cavity modes. Below threshold, the measured isotropic and unpolarized spontaneous emission populates all the available fibre modes. However, above threshold, a purely azimuthally polarized beam emerges from the PBG fibre cavity (Fig. 4b) which indicates coupling to specific low-threshold fibre modes. These modes are the high-Q TE_{0n} modes with an electric field polarization identical to what we measure in the radial laser emission. This isotropic emission is in contrast to the anisotropic emission observed from dye-doped solid plugs.²⁰ In a low viscosity solvent such as water, fluorescence randomization occurs due to the fast molecular reorientation of

the dye, which happens on a picosecond scale²¹, much faster than the nanosecond scale of the fluorescence lifetime²². Thus fluorescence anisotropy is not expected, which is consistent with our experimental observations.

A 1mM Rhodamine 590 (R590)-doped water plug is introduced into the fibre core and pumped by a linearly polarized Nd:YAG laser at 532 nm (see Methods section for details). A typical measurement depicting the dependence of output energy on input energy shows a clear threshold at 165 nJ (Fig. 4c). The spacing between individual lasing peaks reveals an average separation of 1.78 nm for a fibre with an 80 μm core (Fig. 4d). Considering the free spectral range of the longitudinal modes in a Fabry-Perot resonator, $\Delta\lambda \approx \lambda_0^2/2nd$, where λ_0 is the central lasing wavelength, and n is the refractive index of the dye solution ($n = 1.33$), a cavity length $d = 78 \mu\text{m}$ is calculated, which agrees well with the fibre core diameter and further confirms the radial nature of the emission.

So how can we use the intrinsic radial emission and azimuthal polarization state to achieve a useful effect? The problem of directing coherent light is recognized as an important one for a variety of applications. Current solutions could be classified into ones that utilize moving mechanical parts and ones that rely on non-mechanical mechanisms²³⁻²⁸. While having advantages such as high angular precision, the non-mechanical solutions are nevertheless constrained to a narrow angular range. Here we demonstrate an approach that facilitates directional intensity control within a full 2π radians.

Thus far the hollow microchannels (Fig. 2b) have been empty. But now, we exploit them by infiltrating them with liquid crystals (LCs) in order to create a novel hybrid fibre device capable of modulating the coherent laser emission as a function of angle. The linearly polarized annular wavefront escaping the PBG cavity simultaneously

interacts with the multiple LC microchannels surrounding it, each of which can be independently controlled. In the absence of an applied electric field, the LC director points along the microchannel axis. Applying a potential difference across an electrode pair flanking an LC-infiltrated microchannel generates an electric field perpendicular to the LC director. Above a threshold voltage, the applied field produces a torque on the LC molecules which leads to their rotation²⁹. The optical anisotropy of LC molecules together with the control on their spatial orientation provides a mechanism to continuously modify the linearly polarized state of the laser light passing through each microchannel. Fixing a thin external linear polarizer around the fibre, this mechanism is used to modulate the azimuthal laser intensity distribution. We note that although a whispering-gallery-like emission with a precise polarization state could also in principle be modulated by an annular array of LC channels, the non-radial nature of this emission in the vicinity of the cavity would pose significant practical challenges to enable this oblique transmission to be efficiently modulated.

We demonstrate the principle of directional emission control by contacting two oppositely facing LC microchannels to allow for simultaneous and independent tuning of the light intensity emitted from opposite sides of the same fibre (shown in Fig. 5a and described in Methods section). A R590-doped water plug is positioned in the core of the fibre and axially pumped as described previously. A thin polarizer sheet is wrapped around the fibre with its transmission axis aligned along the fibre axis such that the emitted light is blocked in the absence of an applied electric field or below the threshold voltage. Above the threshold voltage, independent intensity modulation of laser light passing through each LC-filled microchannel is clearly visible in the images (left and right

sides of Fig. 5a) and is further substantiated by measuring the laser spectra as a function of driving voltage (Fig. 5b). The measurements reveal a maximum extinction ratio of ~9 dB.

The precise control over the omnidirectional intensity distribution from the surface of a thin and flexible fibre presents a wide range of intriguing opportunities. The ability to introduce a directionally emitting laser catheter into a blood vessel could enable spatial and angularly selective irradiation of diseased sections while sparing healthy tissue (see Supplementary Fig. S1) in conjunction with treatments such as photodynamic therapy³⁰. A lab-in-a-fibre application would involve utilizing the fibre laser to interrogate fluids in the adjacent microchannels. Finally, the integration of a modulator and light source in a single fibre represents an important step towards the realization of flexible and directional fabric displays (see Supplementary Fig. S2).

Methods:

Fibre fabrication. The multilayer film is fabricated by thermal evaporation of a 4 μm thick $\text{As}_{25}\text{S}_{75}$ layer onto each side of a 10 μm thick PC (Lexan) film. This film is subsequently rolled onto a Teflon lined mandrel and additional thicker PC films are added to increase the outer diameter to 30 mm, after which this preform is consolidated under vacuum at ~190 °C until the individual layers fuse together into one solid part. After consolidation, groups of three pockets with prescribed dimensions are machined along the length of the preform. The two outer pockets are filled with CPE strips while the center pocket is left empty. Additional PC films are rolled around the preform to a 40 mm diameter and a second consolidation step ensues. During the subsequent thermal

drawing process, the preform is scaled down by a factor of ~ 100 , resulting in the vacant pockets being pulled into hollow microchannels, the CPE strips drawn into continuous electrodes which are contacted post draw, and the multilayer glass / polymer microstructure drawn into a nanostructured optical cavity lining the inner core of the fibre.

Microfluidic controls. Bidirectional pumping of fluid into and out of the fibre is achieved by alternating the electrical actuation of microdispensing valves (Lee Company VHS M/2) connected to pressurized and depressurized silicone oil reservoirs. Depressurization is achieved using a standard Venturi-based vacuum generator.

Laser characterization. The organic laser dye Rhodamine 590 (Exciton) dissolved in DI water at 1 mM concentration is infiltrated into the fibre core with a syringe. The pump beam from the second harmonic (532 nm) of a linearly polarized Nd:YAG laser (Continuum Minilite II) with a nominal pulse duration of 9 ns and 10 Hz repetition rate is coupled into the fibre core through a 10 cm focal length lens. A small fraction of the pump beam is diverted with a beam splitter to monitor the input pump energy using a laser energy meter (Molelectron EPM 1000 with the J4-09 probe). A 10x objective lens is used to collect a fraction of the light emitted radially from the fibre and focused directly onto the entrance slit of a spectrometer (Ocean Optics USB4000-UV-VIS). The polarization of the emitted light is measured by rotating a linear polarizer positioned between the fibre and the spectrometer.

Intensity modulation using LCs.LCs (Merck MLC-2058) are introduced into the microchannels by capillary action, resulting in the LC director aligning parallel to the fibre axis. A function generator (Stanford Research Systems DS345) operated at a sinusoidal 100 Hz is used to drive a high voltage amplifier (A. A. Lab Systems A-301) which is connected to the electrodes. A 10x objective lens is used to image each LC-filled microchannel to a CCD camera (Motic Moticam 1000) and a series of images are recorded as the voltage is changed. The CCD camera is replaced with a spectrometer to measure the laser spectra.

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Figure 1 | Comparison between radial and whispering-gallery modes. (top) Schematic drawing of the radially emitting fibre laser structure and energy density plot for a high-Q TE_{0n} fibre cavity laser mode. The outgoing, radially-directed red arrows denote the direction of laser emission. The white arrows overlaid on the energy density plot denote the polarization of the mode, which is also indicated in black arrows outside the cavity on the schematic. The periodic PBG structure surrounding the fibre core corresponds to layers of $As_{25}S_{75}$ (purple) and polycarbonate (yellow). (bottom) Schematic drawing of a cylindrical structure which supports high-Q whispering-gallery modes. The primarily azimuthally-directed red arrows denote the tangential laser emission of the high angular momentum modes. The energy density plot corresponds to a high order whispering-gallery mode supported by the cylindrical structure shown in blue. The polarization of this mode is indicated by the white dots overlaid on the energy density plot and the black dots on the schematic. Note: the color scheme indicated in the figure applies to both top and bottom energy density plots.

Figure 2 | Preform and fibre structure.**a**, Photograph of the drawn preform. The black strips are the CPE electrodes. The orange reflection from $\text{As}_{25}\text{S}_{75}$ glass is seen in the center of the structure. (inset) Several meters of fibre is coiled around a US quarter. **b**, (bottom) Scanning electron microscope (SEM) micrograph of the multimaterial fibre device. The fibre core is surrounded by four light modulators. (top left) Zoom view of the CPE electrodes flanking a hollow microchannel, which is filled with LCs post draw. (top right) Zoom view of the multilayer structure forming the PBG cavity. The white and grey layers correspond to $\text{As}_{25}\text{S}_{75}$ and PC, respectively.

Figure 3 | Microfluidic laser system.**a**, Schematic of the microfluidic system used to transport the gain medium plug within the fibre core. The system is composed of an optical / fluidic coupler at the input facet of the fibre and a set of pressure driven, electrically actuated microdispensing valves at the distal end, allowing for bidirectional flow control. Silicone oil (refractive index, $n = 1.38$) is in light blue and the organic dye-doped water plug (refractive index, $n=1.33$) is the red cylinder. **b**, The dynamics of the system is recorded as the plug is optically pumped and simultaneously set into an oscillating motion by alternating the valve actuations. The blue circles correspond to the measured plug position. The black curve is a sinusoidal fit to the data. Plug velocities up to 35 mm/s are achieved before the drop disperses into two or more fragments. **c**, Photographs of the lasing plug at two different positions along the fibre. The radially emitted laser light is seen scattering from a screen with a “rle” logo positioned behind the

fibre. (The green pump light is also seen along the fibre axis. This is due to the transmission bandgap shift, which arises from filling the core with the silicone oil.¹⁹)

Figure 4 | Laser characterization.**a**, (top) Schematic of the fibre laser threaded through a funnel, the surface of which is used to register the radially emitted wavefront. The red cylinder in the fibre core is a Rhodmaine 590 (R590)-doped water plug. (bottom) Picture of the fibre threaded through the funnel. The radially emitted light emanating from the dye-doped plug is seen as a ring-like pattern scattered from the inner surface of the funnel. The green light at the center is from the pump beam.**b**, Polarization of the radial laser light emitted from the fibre, measured by rotating a linear polarizer in the plane shown by the vectors in the inset. **c**, (left) Output energy dependence on pump energy for a R590-doped water plug showing a threshold of 165 nJ. (right) Spectra measured from the fibre laser below threshold (A), near threshold (B), and above threshold (C). **d**, Resolved spectra from the emission of an 80 μm core fibre just above the laser threshold. The measured quality factor, given by $Q = \lambda_0 / \delta\lambda$ (where $\delta\lambda$ is the spectral width of a given mode) is ~ 615 ; this is lower than expected from theory, which is due to the limited resolution of the measurement setup and a non-ideal fibre structure.

Figure 5 | Azimuthally controlled laser emission.**a**, Schematic of the fibre device depicting the simultaneous control of two oppositely facing LC-filled microchannels, labeled as LC₁ and LC₂. The light blue strips correspond to the LC-filled microchannels and the black strips correspond to the in-fibre electrodes (see Fig. 2). V_1 and V_2 are the voltages applied to the electrode pairs which flank LC₁ and LC₂, respectively. The

transmission axis of the linear polarizer which surrounds the fibre points in the z-axis. The width of the LC-microchannels is 30 μm , and their distance from the fibre centre is 160 μm (see Fig. 2b), leading to an angular resolution of $\sim 11^\circ$ for this structure. (left and right side) In contrast to recording the far field laser intensity as in Fig. 4a, here we directly image the laser light at the plane of the LC-filled microchannels as the applied voltage V_1 and V_2 are varied. The light intensity passing through LC_1 (LC_2) does not change as a function of the voltage V_2 (V_1), which indicates the independent control available in each direction. (The randomly dispersed red dots seen in the microchannels with V_1 and V_2 at 0V arise due to scattering of the laser light from a non-ideal alignment of the LCs.) **b**, Laser spectra measured for laser light transmission through LC_2 as a function of V_2 .

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Author contributions: A.M.S., L.W., and O.S. planned the experiments. A.M.S. and L.W. performed the experiments. A.M.S., L.W., and F.S. designed the fibre structures. A.M.S. and L.W. fabricated the fibres. O.S. and S.L.C. carried out simulations. A.M.S., L.W., O.S., F.S., Y.F. and J.D.J. conceived the presented ideas. A.M.S., J.D.J. and Y.F. co-wrote the manuscript. J.D.J. and Y.F. supervised the research. All authors analyzed the data.

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