

The Hollow Core Light cage: Trapping Light Behind Bars

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Abstract

Optical waveguides represent the key element of integrated planar photonic circuitry having revolutionized many fields of photonics ranging from telecommunications, medicine, environmental science and light generation. However, the use of solid cores imposes limitations on applications demanding strong light-matter interaction within low permittivity media such as gases or liquids, which has gas triggered substantial interest towards hollow core waveguides. Here, we introduce the concept of an on-chip hollow core light cage that consists of free standing arrays of cylindrical dielectric strands around a central hollow core implemented using 3D nanoprinting. The cage operates by an anti-resonant guidance effect and exhibits extraordinary properties such as (1) diffractionless propagation in “quasi-air” over more than one centimetre distance within the ultraviolet, visible and near-infrared spectral domains, (2) unique side-wise direct access to the hollow core via open spaces between the strands speeding up gas diffusion times by at least a factor of 10^4 , and (3) an extraordinary high fraction of modal fields in the hollow section ($> 99.9\%$). With these properties, the light cage can overcome the limitations of current planar hollow core waveguide technology, allowing unprecedented future on-chip applications within quantum technology, ultrafast spectroscopy, bioanalytics, acousto-optics, optofluidics and nonlinear optics.

Motivation

One of the key objectives in current photonics research is to reduce the geometric footprint of bulky optical components by replacing them with their compact on-chip integrated counterparts in a cost-efficient way. Remarkable progress has been made in the development of planar waveguides, which constitute the principle element of integrated photonic devices, with applications in quantum technology [1], nonlinear physics [2] [3] and biophotonics [4]. However, most waveguides rely on solid cores, limiting the design flexibility of photonic sensors that require intense light-analyte interaction in medium with a lower dielectric permittivity as gases and liquids. The sensitivity of waveguides to detect refractive index (RI) changes of analytes is correlated to the fraction of electromagnetic power in the sensing medium and thus efforts are concentrated on finding guidance schemes which allow an enhanced concentration of light in the low index medium.

One widely used sensing approach relies on evanescent waves. Integrated waveguides with exposed cores can provide access to the evanescent fields and found applications in areas such as spectroscopy and biosensing [5] [6] but can demand excessively long waveguide lengths to

compensate for weak light-matter interaction. Alternatively, single and multiple slot waveguides can concentrate evanescent fields in a low-index slot with sub-wavelength dimensions [7] [8] [9] [10] [11], whereas the fraction of electromagnetic power in one slot is typically low and the introduction of analytes into multiple narrow slots can be cumbersome.

A straightforward approach to reach intense interaction of waveguide modes and low index medium is to directly guide the light within the low index medium. Using anti-resonant reflecting optical waveguides (ARROWs), it is possible to confine light to hollow or low index cores by taking advantage of the reflection properties of a dielectric multilayer cladding. Though planar on-chip ARROWs have found application within biofluidics [12] [13] [14] and atomic spectroscopy [15] [16], they suffer from complex fabrication procedures, involving a large number of lithographic steps [17]. Moreover, they are not suitable for applications that require fast introduction or exchange of an analyte, as the core is accessible only via the waveguide end ports, leading to long analyte diffusion times. Drilling micrometer-size holes into the cladding to create sideways inlets partially solves that problem, which, however, impart additional losses and yields only a minor improvement due to the typically small number of holes that can practically be realized [16].

In parallel, significant advancements for guiding light in low index media has been achieved by the microstructured fiber optics community, opening new avenues in mid-IR gas lasers [18] [19], UV light sources [20] [21] photothermal gas trace analysis [22] and remote microparticle sensing [23]. Thanks to meticulous improvements in fiber drawing technology, sophisticated micro- and nanostructures surrounding a hollow fiber core have been realized with losses as low as a few dB/m. Besides effects such as photonic band gap guidance [24] or low-density of states [25] the anti-resonance effect [26] [27] has been identified as trendsetter for future high-performance fibers, particular since it demands cladding geometries with low complexity [28] [29] [30] [31] making fabrication straightforward. Even though hollow core fibers show lower losses than their planar counterparts and are simpler in design, they cannot be scaled down and integrated into planar waveguides architectures. Similar to planar ARROWs, they allow access to the central core section only via the end faces, which imposes restrictions on device performance, applicability and functionalization variability. Drilling holes through the microstructured cladding has been identified as one possible solution [32] but severely increases optical losses and substantially reduces mechanical stability.

Here, we introduce the concept of the on-chip hollow core light cage which allows guiding light in a hollow core up to centimeter distances on a monolithically integrated chip design. The cage consists of a discrete number of high-aspect ratio free-standing polymer strands spaced micrometers apart and arranged in a hexagonal lattice. By omitting some of the central strands, a hollow core is defined (Fig. 1a) that supports a mode that is anti-resonant with the cladding supermodes, facilitating guidance via the anti-resonance effect. The most striking features of the cage are (i) the direct access to the hollow core via the open sections between transversally separated strands, which can speed up gas diffusion times (e.g. acetylene) by at least a factor of 10^4 , (ii) the extraordinary high fractions of modal fields within its hollow section (>99.9%), and (iii) the diffractionless propagation in quasi-air over more than one centimeter within the ultraviolet, visible and near-infrared. The novel type of photonic element presented here allows the implementation of new classes of on-chip photonic devices with unprecedented functionalities and ease of fabrication.

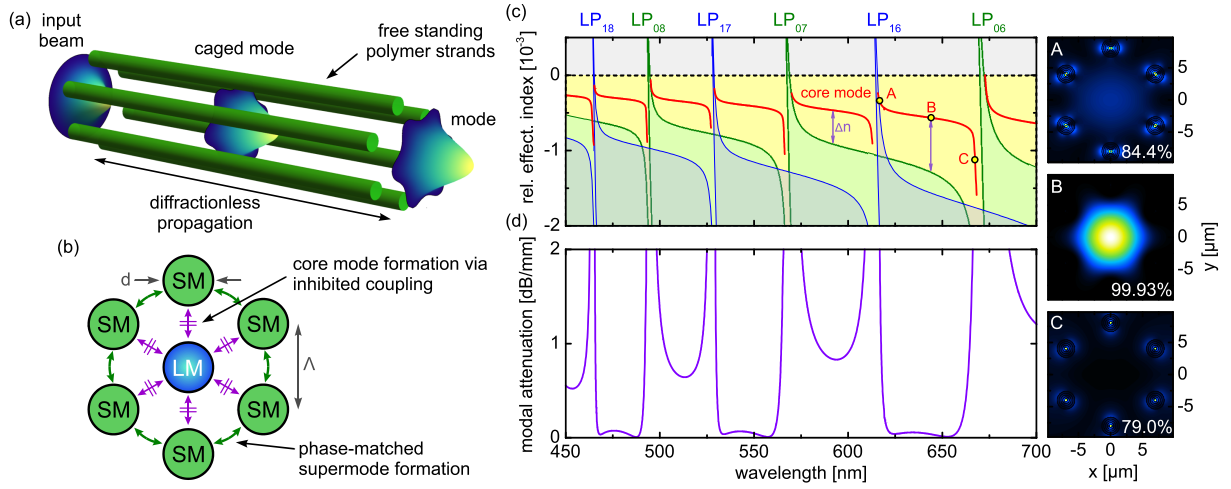


Fig. 1: The light cage. (a) Schematic of the light cage consisting of a free-standing array of suspended dielectric strands. The three colored contours represent the propagating mode at difference locations (left: Gaussian input beam, middle: mode caged between the strands, right: output mode). (b) Scheme illustrating the formation of leaky modes inside the cage. (c) Dispersion map (spectral distribution of the relative real part of the effective mode index ($\text{Re}(n_{\text{eff}})-1$)) of the various modes involved (yellow (gray): region of leaky (guided) modes). The filled green and blue areas refer to regions of non-zero cladding density of states and are associated with the lowest-order strand modes (green: LP_{0x} , blue LP_{1x} (x : mode order)). The labels on the top of the plot name the different isolated strand modes. The red curves represent the dispersion of the fundamental mode of the air core. The three images on the right show spatial Poynting vector distributions at the wavelengths indicated by the yellow dots (A: LP_{16} -supermode (615 nm), B: supported leaky defect mode (640 nm), C: LP_{06} -supermode (670 nm), the linear color scale range from 0 (dark) to 1 (white)). The numbers in each distribution correspond to the fraction of power guided inside the core section f_p (for details see Supplementary Information). (d) Modal attenuation of the fundamental core mode as a function of wavelength.

Theoretical background

The formation of core modes in the light cage is caused by the anti-resonance or the inhibited coupling effect, which results from the sophisticated reflection properties of the microstructured cladding. Modes in the cage continuously dissipate energy along the transverse direction and are thus referred as leaky modes [33]. Unlike waveguides relying on total internal reflection, leaky modes have complex propagation constants and radially growing field amplitudes beyond a finite radial distance which is called the radiation caustic [31].

The leaky modes supported by the light cage emerge for two reasons, (i) the formation of cladding supermodes (SMs) – a consequence of coupling between the modes of isolated strands – and (ii) an inhibited coupling of the central core mode to these SMs (Fig 1b). The behavior can be understood on the basis of the dispersion of the different possible modes supported by the light cage (Fig. 1c). Above the RI of the core, i.e., for effective indices $\text{Re}(n_{\text{eff}}) > 1$ (grey region in Fig. 1c) each linearly polarized strand mode (named LP_{nx} where n & x represent radial and azimuthal index, respectively) remains well confined to the strand and can be considered as its isolated guided mode. The situation changes drastically for $\text{Re}(n_{\text{eff}}) < 1$ (regions below the horizontal black dashed line in Fig. 1c): Here the individual strand modes extend largely into the cladding, inducing a strong coupling of adjacent

strand modes and leading to the formation of ring-type SMs. Since all strands are identical, phase-matching is achieved at all wavelengths and SMs with dispersions very different from those above $n_{eff} = 1$ are obtained. The propagation of a low loss mode in the central hollow section, i.e. the reduction of transverse energy dissipation requires the core mode to be in anti-resonance (not phase-matched) with any other cladding mode, demanding the identification of the regions of zero density of cladding states (zDOS).

Besides methods such as Floquet-Bloch analysis [34] or plane wave expansion [35], one straightforward approach to find the zDOS regions was introduced by Birks *et. al.* [36] within the context of fiber optics. It analyzes the dispersions of the two cladding SMs, limiting the effective index regions of cladding states (referred in the following as edge cladding modes) in a nearest-neighbor-coupling approximation [37] [38]. Conceptually, this approach is analogous to the formation of bonding and anti-bonding states of diatomic molecules and is directly applicable to two identical parallel running cylindrical waveguides with the assumption that only modes of identical LP-mode order interact. The “bonding state” (SM with the lowest possible value of n_{eff}) is characterized by a maximum field amplitude at exactly half the inter-strand distance (referred as pitch Λ in the following (Fig. 1b)), whereas the “anti-bonding state” (SM with the highest possible value of n_{eff}) has zero field amplitude at this symmetry point. All other SM states lie within these two extremal cases and the effective index domains outside these regions refer to zDOS. Albeit the approach is based on a scalar wave approximation, it successfully identifies states with high accuracy even for large RI contrast structures (e.g., chalcogenide filled silica PGB fibers (index contrast ~ 0.44) [39]).

The dispersion map of our light cage shows that large regions of zDOS are obtained (yellow regions in Fig. 1c), which allow formation of leaky core modes (Poynting vector distribution shown on the right side of Fig. 1). Considering a six strand structure (Fig. 1a) the simulated leakage losses of the fundamental core mode are remarkably low ($< 1\text{dB/mm}$) despite the fact that the six strands occupy only 15% of the entire cage cross-section (Fig. 1d, for simulation details see Methods). Here, we introduce the term structural openness factor, which is defined as the fraction of open space between strands relative to inter-strand distance (details in supplementary section). Large gaps between the rods lead to a large structural openness factor of $f_0=0.625$, whereas conventional hollow waveguides including ARROWs and hollow core fibers have openness factors of 0. Interestingly, despite the light cage providing such a large structural openness factor, the fraction of electromagnetic power carried by the fundamental mode in the core section f_p (defined in Supplementary Information) reaches values $> 99.9\%$ in the center of the transmission bands (e.g., 640nm, image B in Fig. 1c) and values around 80% in close proximity to the edges of the transmission bands (images A and C in Fig. 1c).

The modal attenuation is dominated by the coupling of the core mode to LP_{0x} and LP_{1x} SMs, leading to an attenuation distribution that is characteristic for anti-resonant waveguides (Fig. 1d). It is interesting to note that at a fixed wavelength, a larger difference between the effective indices of core mode and most upper edge modes causes losses to reduce [40], being the reason for the alternating loss minima and maximum present in every second transmission band (purple vertical arrows in Fig. 1c).

The physics of the modes in the vicinity of high loss regions (i.e., resonances) can be qualitatively understood on the basis of coupled-mode-theory in the limit of vanishing coupling constants and nearest neighbor coupling (see Supplementary Information for details). For the six strand structure

only two out of the seven Eigenvectors have significant fractions of amplitude in the core, corresponding to the lower and upper dispersion branches of the core mode anti-crossing in the vicinity of one fixed LP-resonance. Both Eigenmodes reveal constant amplitude distributions across all strands (i.e., the strand modes are in-phase), and are distinguishable by a zero or π -phase difference between core mode and strand SM.

Design, structure and setup

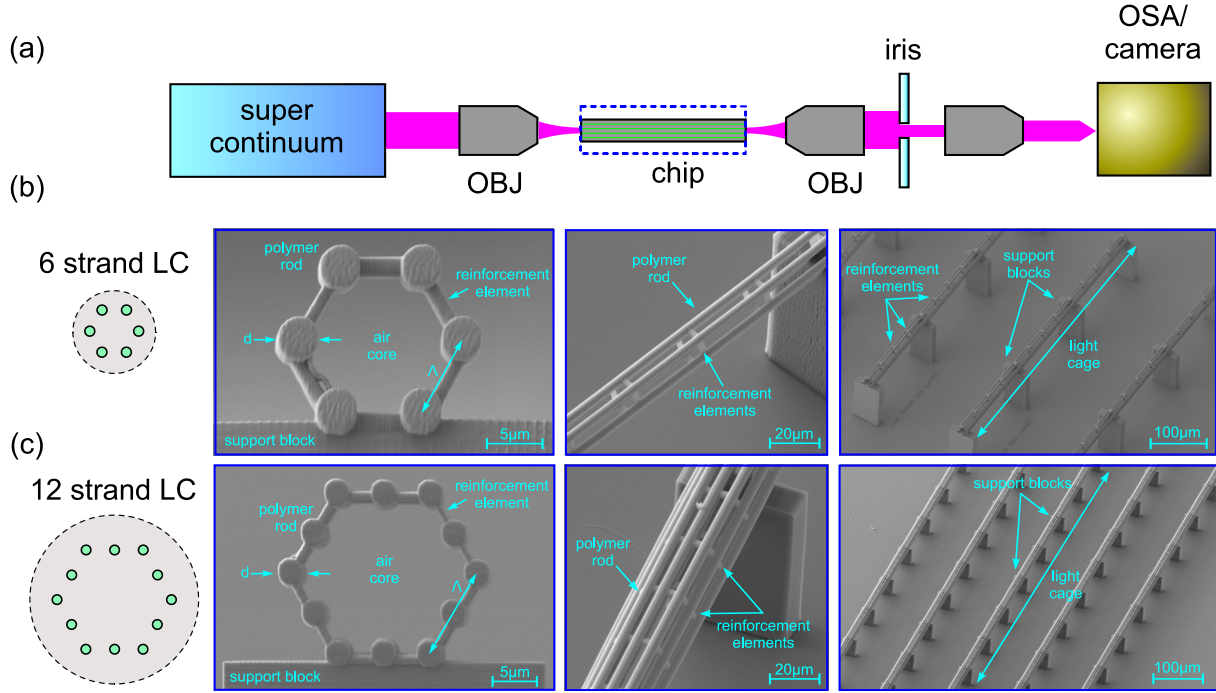


Fig. 2: (a) Setup used for the optical characterization of the light cages (OBJ: objective, OSA: optical spectrum analyzer). The magenta parts refer to the probe beam. The lower images show the two light cage geometries that have been investigated (left column: schematics of the two geometries; middle and right columns: Scanning electron micrographs (SEMs) of cross sections and top views of selected samples). (b) Six strand light cage. (c) Twelve strand light cage.

The light cages presented here were fabricated using 3D nanoprinting (Figs. 2b and c, for fabrication details see Methods) of photoresist on polished silicon wafer substrates. They are built by repeating a unit segment composed of three types of elements. The first is the actual cage and consists of a hexagonal array of six or twelve free standing cylindrical polymer strands (strand diameter $d = 3 \mu\text{m}$) with lengths of $180 \mu\text{m}$ and various inter-strand distances Λ (itches, from 6 to $9 \mu\text{m}$). The second element is a reinforcement ring, which transversely connects adjacent strands, included every $45 \mu\text{m}$ along the cage with a length and thickness of $2 \mu\text{m}$ and $1 \mu\text{m}$, respectively. These reinforcement elements increase the mechanical stability of the structure, preventing the collapse of the cage during development of the photoresist. Finally, two solid polymer blocks (cross-section: $50 \mu\text{m} \times 20 \mu\text{m}$) at the edges of the segment lift the cage to a height of $80 \mu\text{m}$. Light cages consisting of six (Fig. 2b) and twelve (Fig. 2c) strands of various total lengths have been fabricated. The investigated six strand cages contain 1 to 4 unit segments, corresponding to total lengths of 180 , 360 , 540 and $720 \mu\text{m}$ with maximal aspect ratios (length-to-diameter) of the polymer strands up to 250. Substantially longer cage lengths have been realized for the twelve strand geometry: Here light cages with a maximum unit segment number of 60 have been implemented, giving rise to sample lengths that exceed 1cm (10.5mm) and to strand aspect ratios >3500 . All fabricated light cages show a clear

optical mode transmitted through the structure as outlined in the characterization section. A large number of different light cages have been fabricated on a single Si wafer with a lateral separation distance between the cages of 200 μm , whereas in recent experiment even higher device densities have been achieved. The input sections of the cages start at the same distance relative to the edge of the wafer, making in-coupling of light straightforward.

Optical characterization relies on a transmission setup (Fig. 2a) that consists of a broadband light source, objectives for exciting and collecting the supported mode, a visible-infrared spectrometer and a camera with narrow band-pass filters to record the output mode at different wavelengths (see Methods for further details).

Results

To confirm light guidance inside the light we start our investigation by experimentally analyzing the optical properties of the six strand cage geometry (Fig. 3). As indicated by the output mode profiles measured at different wavelengths (upper row in Fig. 3), a fundamental core mode with a six-fold symmetry resembling the geometry of the cage is supported at ultraviolet, visible and near infrared wavelengths. The spectral distribution of the transmission for various cage lengths (Fig. 3a) reveals a series of pronounced dips with maximal extinctions of up to 10 dB, which roughly overlap with the cut-off positions of the various LP_{0x} and LP_{1x} - modes of the strands (indicated by the colored bars on top of each diagram of Figs. 3a and b). The dips are therefore associated with a coupling of the central core mode to SMs formed by low-order strand modes. The difference between the spectral positions of calculated cut-offs and measured dips can be explained by slight deviation of the fabricated rods from the perfect cylindrical shape assumed in simulations and by uncertainties in the RI of the polymer, which may vary with laser exposure conditions (see Methods). It is important to note that all fabricated cages show their transmission dips at identical wavelengths – a result which is associated with similar modal dispersions, i.e., identical strand cross sections, revealing the high quality and reproducibility of the fabricated cages. The overall transmission drop towards longer wavelengths we attribute to a higher susceptibility of the propagating mode on fabrication inaccuracies (e.g., surface roughness). Particularly interesting is the double-dip feature at around 1.06 μm (grey dashed circle in Fig. 3a), resulting from polarization mode splitting of the LP_{13} mode into TE_{03} - and TM_{03} -polarized modes.

Both mode profiles and transmission measurements clearly confirm leaky mode formation inside the light cage via the anti-resonance effect, in particular since a defined output mode image can only be recorded when the light is coupled into the cores of the cages. Light launched in empty sections between two consecutive cages diffracts, reaching beam diameters that are order of magnitude larger compared to the lateral cage dimension (Fig. 3c).

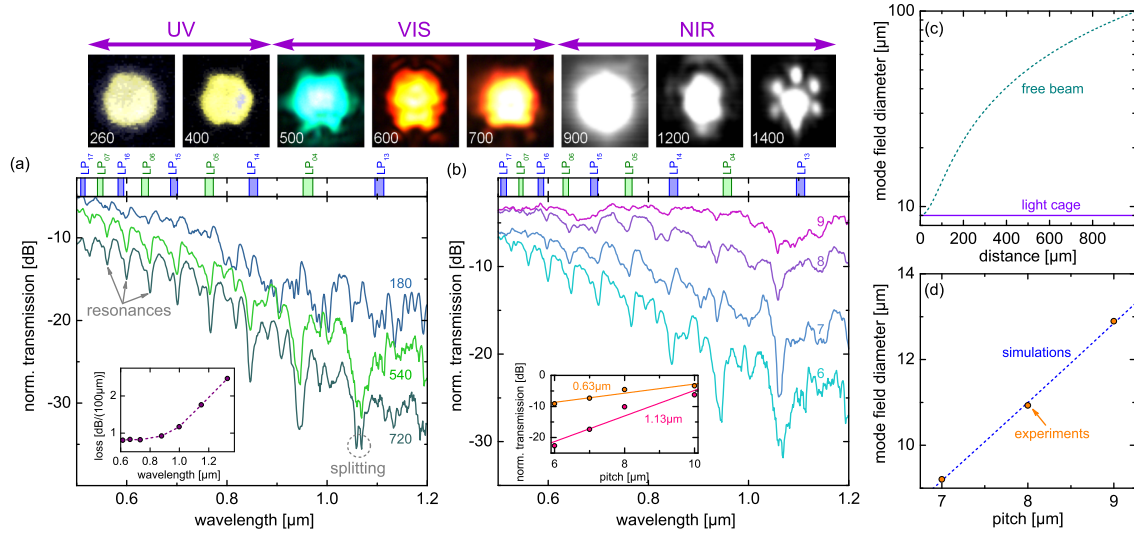


Fig. 3: Measured spectral characteristics of the six strand light cage geometry (strand diameter $\approx 3 \mu\text{m}$; examples of structures shown in Fig. 2b)). (a) Normalized transmission of three light cages with different lengths and identical pitch (blue: $180 \mu\text{m}$, green: $520 \mu\text{m}$, dark green: $720 \mu\text{m}$; pitch: $6 \mu\text{m}$). Lower left inset: Spectral distribution of the off-resonance modal attenuation of a cage $\Lambda = 6 \mu\text{m}$ (the dashed purple line is a guide-to-the-eye). Upper right inset: sketch of the six strand geometry. (b) Normalized transmission of four light cages of different pitches and identical length (pink: $9 \mu\text{m}$, purple: $8 \mu\text{m}$, blue: $7 \mu\text{m}$, light blue: $6 \mu\text{m}$; length: $540 \mu\text{m}$). Inset: Normalized transmission as function of pitch at two selected wavelengths (orange: $0.63 \mu\text{m}$, pink: $1.13 \mu\text{m}$; dots: measured data, solid lines: fit). The colored bars on top of (a) and (b) refer to the cut-off positions of the isolated strand modes ($d = 3.1 \mu\text{m}$, green: LP_{0x} , blue: LP_{1x} (x : mode order)). The width of each bar results from considering strand thickness variation of $\pm 15 \text{nm}$ around the average diameter. The upper row of images show measured output mode profiles at selected wavelengths (wavelengths (in nm) are indicated in the respective image). (c) Comparison (simulations) of the spatial evolution of the diameter of a Gaussian beam (initial beam waist diameter $9 \mu\text{m}$) diffracting in free space (dark cyan) to the simulated mode field diameter of the mode of the light cage (pitch $7 \mu\text{m}$) at 700nm . (d) Mode field diameter of the output mode for three six strand light cages with different pitch (orange points: measurements, blue dashed line: simulations, wavelength: 700nm).

Analyzing the transmission of identical cages with different lengths at those wavelengths no transmission dips are present allows determining the off-resonance modal attenuation. Between 600 nm and $1.2 \mu\text{m}$ the six strand geometry reveals off-resonance losses of about $1 \text{dB}/(100 \mu\text{m})$, indicating that this cage geometry allows reasonable sample lengths of the order of a few the millimeters using the current fabrication method (inset of Fig. 3a). The measured loss is about 10 times higher compared to simulations, which we attribute to fabrication-induced surface roughness and the impact of the reinforcement elements on optical transmission. The impact of the pitch has been also studied by measuring the transmission of cages of identical length but with different inter-strand distances (Fig. 3b). More pronounced dips and an overall lower transmission are observed for smaller pitches, revealing a stronger mode-strand interaction and an increasing influence of fabrication inaccuracies towards smaller values of Λ . To quantify this, we exponentially fitted the transmission at two selected wavelengths (inset of Fig. 3b) showing that increasing Λ by one micrometer leads to an increase in transmission by a few dB (at $\lambda = 0.63 \mu\text{m}$: $1.47 \text{dB}/\mu\text{m}$; at $\lambda = 1.31 \mu\text{m}$: $4.12 \text{dB}/\mu\text{m}$). From the spectroscopic perspective, the cage with $\Lambda = 9 \mu\text{m}$ is of particular interest, since it yields a relatively flat transmission over large ranges of the visible and near infrared

(transmissions variation $<3\text{dB}$ between 500nm and $1\mu\text{m}$). We have also measured the output mode field diameter ($\lambda = 700\text{ nm}$) for three light cages of identical length ($720\mu\text{m}$) but with different pitches superimposed onto the modal diameter predicted by the simulations (Fig. 3d). The linear increase of the output diameter with increasing pitch is well described.

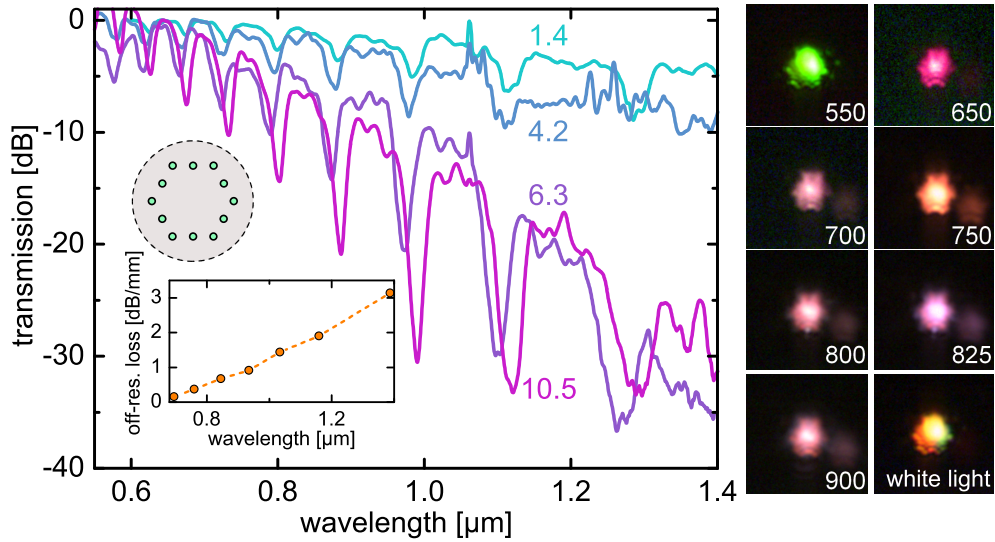


Fig. 4: Measured spectral distribution of the transmission through various twelve strand light cages (examples of structures shown in Fig. 2c). The different colored curves refer to different light cage lengths (black: 1.4mm, dark red: 4.2m, red: 6.3m, light red: 10.5mm). The inset shows the spectral distribution of the off-resonance losses (the dashed purple line is a guide-to-the-eye). The images on the right refer to output mode profiles at selected wavelength (wavelengths (in nm) are defined the numbers of the respective image). The profile on the bottom right shows the transmission of white light through the twelve strand structure.

As second geometry we investigate light cages consisting of twelve strands (Fig. 2c, pitch: $7\mu\text{m}$) using the transmission setup presented in Fig.2a. A clear core mode is observed at all wavelengths (selected examples of output mode images are shown on the right-handed side of Fig. 4), whereas the larger core diameter allows using more than ten times longer cage lengths compared to the six strand structure, reaching the centimeter domain (Fig. 4). The off-resonance losses are between 0.2dB/mm at visible wavelength and increase towards 3dB/mm for $\lambda > 1.3\mu\text{m}$, which is one order of magnitude smaller compared to the six strand geometry. These measured losses are of the same order as those of other types of planar ARROWS [41] [42] whereas the light cage concept additionally allows side-wise access through the strands which is impossible to achieve in ARROWS. Particular the longest sample (length 10.5mm , pink curve in Fig. 4) shows very clear and ripple free transmission dips (fringe contrast up to 20dB) which are comparable to those observed in fiber devices [38], clearly confirming that the anti-resonance effect is the origin of the light guidance. The overall transmission drop towards longer wavelength we again attribute to the increasing susceptibility of the core mode on fabrication inaccuracies.

An outstanding feature of the light cage is the accessibility to the core section through the side-wise open spaces between the strands. This presents an ideal opportunity for the fast introduction of gases in the core section for real-time spectroscopic applications. The speed-up of gas diffusion into the cage compared to a capillary is demonstrated in the following on the example of acetylene: Here

we consider the diffusion of acetylene into an initially air-filled capillary of length L_C through the open ends (Fig. 5b) and compare that to transverse diffusion into the cage along one traverse axis as a simplest case scenario (Fig. 5a). The key parameter describing the diffusion process is the fill-up time t_s after which a certain target concentration ratio of acetylene and air K_s inside the capillary is reached (inset of Fig. 5c). Since the dimensions of the openings considered here are of the orders of a few micrometers, the diffusion process is within the hydrodynamic flow (Poiseuille) regime (Knudsen number < 0.01). This means that the diffusion process only depends on the distance between the open ends and is independent of the radius of the openings (see Methods for details). Therefore, the diffusion into the cage can be approximated by the diffusion into a capillary of length equal to the lateral extension of the cage (Fig. 5a). Considering $K_s = 0.99$ and $L_C \leq 1\text{mm}$, an analytic expression for t_s can be derived (see Methods sections for details), allowing for the definition of a Figure-of-Merit parameter f_{FoM} which reflects the improvement in fill-up time, i.e., the diffusion speed-up, provided by the lateral open environment of the cage:

$$f_{FoM} = \left(\frac{L_C}{L_{PC}} \right)^2 \quad (1)$$

The parabolic dependence of f_{FoM} on capillary length reveals that the key benefit of the light cage comes from the large aspect ratio of the structure. As an example, given $L_{PC} = 10\text{ }\mu\text{m}$ (Fig. 5c), the diffusion of acetylene into the light cage is about 10^4 times faster compared to a capillary of length of 1mm. The derived FoM-parameter (blue dashed line in Fig. 5a) perfectly matches corresponding results obtained from full numerical analysis (red line in Fig. 5c, $D_{acetylene} = 0.17774\text{ cm}^2\text{s}^{-1}$), see Methods section). As a consequence, the FoM parameter is independent of the gases used (as gas-gas diffusion coefficients are all mostly of the order of $(0.1...0.5)\text{ cm}^2\text{s}^{-1}$), revealing that the light cage concept can be applied to any spectroscopic application that requires fast data acquisition.

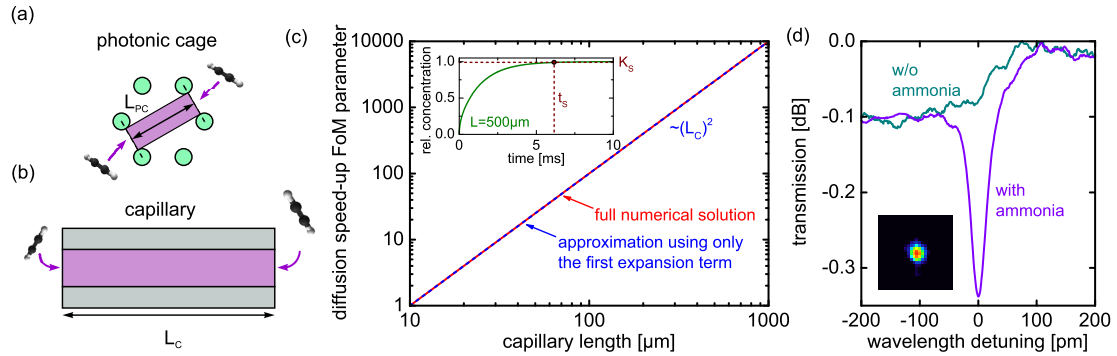


Fig. 5: Illustrations of the areas of gas diffusion (indicated by the purple areas) within (a) the light cage and (b) a capillary. (c) Dependence of the diffusion speed-up Figure-of-Merit parameter f_{FoM} on capillary length comparing the diffusion of acetylene into a capillary and a light cage (both initially filled with air, target concentration ratio $K_s = 99\%$). The red line corresponds to the full numerical solution (for details see Method section), the dashed blue line to the approximation given in Eq. 1. The inset shows the definition of the diffusion fill-up time t_s to reach the target concentration ratio K_s . (d) Laser scanning absorption spectroscopic detection of ammonia inside a twelve strand light cage (length 6.4mm). The measurements have been performed in the vicinity of a strong ammonia absorption line (wavelength: 1493.9465nm). The purple and dark cyan lines show the transmission in case light cage is filled with either ammonia or air, respectively. The inset shows a measured mode profile at the central absorption wavelength.

To verify that the light cage concept can be applied to gas-related integrated spectroscopic applications we used a twelve strand light cage (Fig. 2c) to detect a strongly absorbing gas via laser scanning absorption spectroscopy. Here we choose ammonia as the gas of interest and selected a center laser wavelength in the near infrared to address one strong absorption lines (more than 10cm^{-1} [43]). The light cage (length 6mm) was placed into a home-made gas cell that was filled either by air or a desired gas and the frequency of a narrow bandwidth infrared laser coupled into and out of the light cage was scanned across one near infrared resonance of ammonia (for details see Method). A clear core mode was found at all wavelengths considered (inset of Fig. 5d). The resulting transmission spectrum (purple curve in Fig. 5d) shows a strong dip which solely arises because of the presence of ammonia in the light cage core and fully disappears in case the cage is filled with air (dark cyan curve in Fig. 5c).

Conclusion

Here, we have introduced the concept of the on-chip light cage which supports a mode that propagates without diffraction mostly in air over more than one centimeter distance in the hollow core of a planar integrated waveguide structure. The cage was implemented using 3D-nanoprinting and consists of a single ring of free-standing cylindrical polymer strands of $3\text{ }\mu\text{m}$ diameter arranged hexagonally around the hollow core with large open transverse strand separations up to $9\text{ }\mu\text{m}$. Two types of geometries have been implemented, showing distinct light transmission and clear core modes at all wavelength considered, confirming the anti-resonance effect being the origin of the observed light guidance. Particular the twelve strand geometry with a maximum sample length of 10.5mm (strand aspect ratios >3500) shows losses below 0.5dB/mm at visible wavelength, which is of the same order as other types of ARROWS. Simultaneously the light cage concept provides the unique feature of side-wise access through the spaces between the strands, making this device highly attractive for application demanding long range light-matter interaction on an on-chip platform that is straightforwardly accessible. The large open sections between the strands are a unique feature of the light cage concept which distinguishes it from all other types of hollow core waveguides because it allows time-efficient exchange of an analyte within the core section.

The optical measurements show fundamental mode propagation within the ultraviolet, visible and near-infrared spectral domains and pronounced transmission dips, confirming leaky mode formation via the anti-resonance effect and the high quality of the fabricated structure. Remarkably, more than 99.9% of the electromagnetic energy of the fundamental core mode is confined to the core section even though the strands occupy a fraction of the entire cross section of the cage (six strands: 15%, twelve strands: 4%). The advantage of the sidewise access to the core has been demonstrated theoretically by comparing the diffusion of acetylene into the cage and a capillary, showing that the diffusion into the cage is at least about 10^4 times faster compared to a capillary and experimentally by detecting ammonia using laser scanning absorption spectroscopy.

The presented light cage concept offers extraordinary capability for diffraction-less propagation of light across a wide spectral range over centimeter distances inside a hollow core on an integrated on-chip platform while simultaneously providing side-wide accessibility to the core section. Besides detecting low-molecular weight gases within environmental or life science, the concept is especially tempting for high-precision on-chip micron-scale atomic spectroscopy and metrology (e.g., measuring the Rydberg states or absorption of alkali vapors and gases) or for integrating sophisticated spectroscopic applications such as ultra-fast transient absorption or cavity ring down

spectroscopy into an on-chip environment. Moreover, when combining with optofluidics the light cage concept represents a new platform for integrated bioanalytics. The large aspect ratio structures implemented here by two photon absorption direct laser writing clearly allows for the implementation of new classes of sophisticated on-chip photonic devices with few process steps.

The idea of transferring concepts from fiber optics to planar waveguide technology via 3D nanoprinting represents a ground-breaking strategy, as the typical concept transfer direction is opposite. Moreover, this idea is not restricted to cage-type hollow core waveguides but can be extended to unlock physical effects such as endlessly single mode operation, guidance in core-less twisted structures, or low-density of state guidance for planar waveguide technology. With this motivation significant impact in areas such as nonlinear optics, biophotonics, quantum optics, bioanalytics or metrology can be envisioned.

Methods

Fabrication

The light cage structures were fabricated on silicon wafer substrates by two-photon-absorption direct-laser-writing in a UV sensitive photoresist (IP-Dip, Nanoscribe) in a dip-in configuration using a commercial femtosecond laser based lithography system (Photonic Professional GT, Nanoscribe). Writing in the lateral direction was achieved by moving the laser-beam by galvanometric-mirrors while piezo actuators moved the sample in the vertical axis. The fabrication was performed in a single step, starting with writing the supporting blocks, followed by the individual strands, (such that each individual strand was completed before moving to the next strand) and finally the supporting rings. The writing order was selected to minimize self-shading from previously written structures. The supporting blocks and rings were written layer-by-layer with a slicing distance (gap between adjacent layers) and hatching distance (gap between neighboring lines) of 250 nm. The strands were fabricated by the exposure of multiple writing lines aligned along the longitudinal axis of the strand, written with a finer slicing and hatching distances of 100 and 150 nm, respectively, to minimize surface roughness. For long range fabrication, a limitation is imposed by the limited (~200 μm) lateral movement of the Galvano-mirror scanner. For this reason, the entire writing is performed in sub-segments, each ~180 μm long and written consecutively by moving the system's mechanical stage. After the laser-writing step, the structures were immersed in a bath of photo-resist developer (PGMEA, Sigma-Aldrich) for 20 min, followed by 2 min rinsing in Isopropanol bath and subsequently dried under a gentle stream of nitrogen.

Transmission setup

The probe light emitted by a supercontinuum source (NKT SuperK COMPACT supercontinuum source; spectral range, 450-2400 nm) was coupled into the individual cage using a 20x objective. After passing through the cage the light was collected again by a 20x objective and guided to the diagnostic tools (optical spectrum analyzer (OSA) and cameras). Narrow band pass filters inserted into the output beam path allow for measurement of the output mode at selected wavelengths. This setup ensures exciting a fundamental mode in the core of each cage over a spectral range from 450 nm to 1.7 μm . The sample was mounted on a x-y-z translation stage to allow selective coupling of the input beam to any individual structure of a series of cages on the same substrate. Each measured transmission spectrum has been normalized to the transmission of the collimated laser beam through the setup without any sample. Measurements of the output mode profile at UV wavelengths

have been conducted by using a similar transmission setup, except with a Xenon light source (Mikropack HPX-2000, spectral range 200 – 2000 nm) and a UV sensitive camera (Coherent LaserCam HR). The spectral distribution of the modal attenuation is obtained by linearly fitting the experimental transmission data (given in dBm) of cages of identical pitch but different lengths at fixed wavelengths.

Laser absorption spectroscopic setup

An extra cavity tunable laser (Photonetics, TUNICS 1550) was used to scan the wavelength between 1493.5 nm and 1494.5 nm in 1pm step with power of 400μW. The collimated light was coupled into and out of the light cage using aspheric lenses (Thorlabs, C240TME-C, C280TME-C). The coupling was monitored by an infrared camera (ABS, IK1513). The output beam was directed to a photodetector (Thorlabs, S155C, PM100) which was connected to a computer for recording. The sample was exposed to ammonia gas in a custom-made gas cell. The cell consists of 3D-printed rectangular frame, enclosing a volume of 21 mm x 5 mm x 18 mm with two syringe needles glued into the top frame for injecting and replacing the gas. After placing the sample in the frame, two cover slips were glued on the frame perpendicular to the optical path. The ammonia gas was pumped into the gas cell from a 100ml syringe through one needle on top of the cell. A syringe pump (Landgraf Laborsysteme HLL, LA-30) was used to pump the gas at a constant speed of 0.5 ml/min. Since the density of ammonia is smaller than air, the end of the input needle was placed near the top of the cell and the output needle was placed near the bottom. In this configuration, the ammonia gas pushes the air out and leaves ammonia in the cell.

Simulations and design

Electromagnetic simulations: The simulations of the electromagnetic properties of the supported core modes have been performed by Finite Element modeling using a commercially available mode solver (Comsol Multiphysics) and by a freely available multipole code (Cudos MOF Utilities). The simulations assume all strands to have perfect cylindrical shapes made from a material with the RI given by the following Cauchy's equation ($n_{polymer} = A + B/\lambda^2 + C/\lambda^4$ ($A: 1.5273$, $B: 6.5456 \cdot 10^{-3} \mu m^2$, $C: 2.5345 \cdot 10^{-4} \mu m^4$)) [44]. It is important to note that the RI of the polymer depends on the actual exposure conditions, which are different here from those used in the cited publication, yielding an uncertainty inevitably considered in simulations. The mode field diameter is defined as twice the effective modal spot size which is the second moment of the optical intensity distribution. Here, the effective modal spot is calculated as a quadratic mean of the modal spot sizes w_x and w_y along the x and y directions (perpendicular to the longitudinal axis of the cage), respectively [45].

$$w_x^2 = 4 \frac{\iint |S_z(x,y)| \cdot x^2 dx dy}{\iint |S_z(x,y)| dx dy} \text{ and } w_y^2 = 4 \frac{\iint |S_z(x,y)| \cdot y^2 dx dy}{\iint |S_z(x,y)| dx dy}$$

The MFD is then defined as twice the effective modal size, $MFD = 2w_{eff} = 2\sqrt{\frac{w_x^2 + w_y^2}{2}}$

Knudsen number: The Knudsen number K_n describes the influence of capillary wall on gas diffusion inside a capillary and is defined by the ratio of the mean free path of the gas molecules m and the diameter of the capillary d [46]. Considering the diffusion of acetylene ($m = 0.334$ nm [47]) into a capillary with micrometer-size bore, K_n is significantly smaller than unity (for acetylene $K_n < 0.001$), so that the diffusion process is described by Poiseuille flow (i.e., hydrodynamic flow), which relates to

the fact that the probability of a molecule to interact with another molecule is much higher than its probability to interact with the wall.

Gas diffusion in the hydrodynamic flow regime: The relative spatial concentration distribution of a gas along the length of an initially air-filled capillary of length L_c is described by [48] :

$$\Delta C_z(z, t) = 1 - \frac{4}{\pi} \sum_{j=1,3,5,\dots}^{\infty} \frac{1}{j} \sin \frac{j\pi z}{L_c} \exp \left(- \left(\frac{j\pi}{L_c} \right)^2 Dt \right) \quad (2)$$

with the diffusion coefficient D , the time t , and longitudinal coordinate along the capillary z assuming a constant gas concentration outside the capillary at any time. The average relative concentration inside the capillary is obtained by integrating this equation along the capillary length, leading to

$$\Delta C(t) = 1 - \frac{8}{\pi^2} \sum_{j=1,3,5,\dots}^{\infty} \frac{1}{j^2} \exp \left(- \left(\frac{j\pi}{L_c} \right)^2 Dt \right) \approx 1 - \frac{8}{\pi^2} \exp \left(- \left(\frac{j\pi}{L_c} \right)^2 Dt \right) \quad (3)$$

Due to the infinite sum, calculating the diffusion speed-up figure-of-parameter $f_{FoM} = t_s^{cap} / t_s^{cage}$ requires numerical determination of the fill-up times. However, it is important to note that since for the situation of the light cage, $L_c \leq 1\text{mm}$ resulting in the first-order term ($j = 1$) to dominate the infinite sum of Eq. 4 for sufficiently long times and leading to an analytic expression for $\Delta C(t)$ (right-handed side of Eq. 4). By defining a relative target concentration K_s (visualized in the inset of Fig. 5) this expression can be solved for the fill-up time:

$$t_s = \frac{L_c^2}{\pi^2 D} \ln \left[\frac{8}{\pi^2 (1 - K_s)} \right] \quad (4)$$

which shows a parabolic dependence on capillary length and allows to straightforwardly derive the figure-of-merit parameter (Eq. 1).

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Author Contributions

Optical Simulations and optical characterization were performed by C.J., G.L., B.J., H.L. and M.S. S.M and M.S designed the research and interpreted the results. Fabrication of the light cage was done by A.B and J.G.