Self-alignment of glass fiber nanospike by opto-mechanical back-action in hollow-core photonic crystal fiber: supplementary material

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S1. SIMULATION OF OPTICAL SPRING EFFECT

Three-dimensional FEM simulations, based on precise optical measurements of the shapes of the pre-taper and nanospike, were used to calculate the resonant frequency shift induced by F_{opt} , the optical spring stiffness being represented by k_{opt} (see Fig. S1a, where the double-headed arrow denotes the insertion length). The values of k_{opt} (proportional to input power) at different nanospike-offset values were calculated using the response curve for F_{opt} in Fig. 3a. In this way the resonant frequency shift for each offset and input power could be calculated. The resulting values of $f_{\text{R}}^2 - f_{\text{m}}^2$ are plotted as a function of input power in Fig. 3b. Fig. S1b&c shows the displacement profile for the fundamental flexural mode of a free nanospike and an optically trapped nanospike using 450 mW input power. The existence of a strong optical spring appreciably distorts the shape of the flexural mode.

Fig. S1 **a**, Configuration for simulation of the optical spring. **b**, Simulated fundamental flexural mode for a free nanospike and **c**, mode shape at 450 mW input power.

S2. GRADIENT FORCE WITH GAUSSIAN BEAM

In conventional optical tweezers trapping is achieved by focusing a Gaussian beam on to a particle in free space. To compare with HC-PCF, we set the Gaussian beam waist radius equal to the MFD of the fundamental mode in the HC-PCF, which is 8.4 μm . The configuration is sketched in Fig. S2. Because the nanospike diameter is much less than the wavelength it will only slightly distort the Gaussian beam, making it reasonable to consider the nanospike as a row of cylindrical nano-objects of length dz and local radius $R(z)$ [1]. In the Rayleigh regime, each object can be considered to experience a uniform electric field over its surface, so that the gradient force can be expressed as:

$$F_{\text{grad}}(\mathbf{r}) = (\mathbf{p}(\mathbf{r}) \cdot \nabla) E(\mathbf{r}) \quad (\text{S1})$$

where $\mathbf{p}$ is polarization of the induced dipole moment on the particle, E is the applied electric field and $\mathbf{r}$ is the coordinate. Supposing that the electric field is aligned in the x direction, by substituting into Eq. S1 the expression for the induced dipole moment of a cylindrical dielectric particle with infinitesimal length dz , the overall gradient force acting on the nanospike within the insertion length L can be written as:

$$\begin{aligned} F_{\text{grad},x} &= \int_0^L F_{\text{grad},x}(z) dz \\ &= \int_0^L \frac{R^2(z)}{4cn_m(n_p^2/n_m^2 + 1)} [\nabla I(\mathbf{r})]_x dz \end{aligned} \quad (\text{S2})$$

where n_p and n_m are the refractive indices of the materials forming the nanospike and the surrounding environment, c is speed of light in vacuum and $I(\mathbf{r})$ represents the Gaussian beam intensity distribution.

Fig. S2 Configuration for simulating the optical gradient force on the nanospike when it is placed in a focused Gaussian beam.

S3. SIMULATION OF HYSTERESIS

As stated in the main text, the observed hysteresis can be understood through the interplay between the mechanical and optical forces acting on the nanospike. The mechanical stiffness can be numerically explored by applying a force to the final 50 μm section of the nanospike and monitoring the displacement. This yields a mechanical stiffness k_m of 0.36 pN/ μm . The mechanical restoring force can then be written as

$$F_m = -k_m (\delta - \Delta) \quad (\text{S3})$$

where δ and Δ represents respectively the offsets of the nanospike and the base.

When the nanospike is strongly offset from the center ($\delta > 3 \mu\text{m}$), a proportion of the input power excites higher order modes (HOMs) in the HC-PCF core; evidence of this can be seen, for example, in the measured near-field mode profile in the inset of Fig. 5c. It turns out that consideration of the first HOM (the LP_{11}) is essential for explaining the observed hysteresis. This mode overlaps strongly with the nanospike mode at larger values of nanospike offset δ and so is most likely to be excited. The dashed orange curve in Fig. S3a plots the change in the LP_{11} mode index versus δ for a tip diameter of 150 nm. The corresponding optical force (normalized to 1 W launched power) is shown as the orange solid curve. The inset shows the calculated (by FEM) intensity profile for the LP_{11} mode when the 150 nm diameter glass strand is offset 3 μm from core center. The results for the LP_{01} mode (blue dashed and solid curves, the same as Fig. 3a) are also shown for comparison. It is clear that if all the power is in the LP_{11} mode, the optical force distribution is completely different: the equilibrium position sits at $\sim 3.5 \mu\text{m}$ offset (rather than at the center). Furthermore, for the same power, the optical spring force for the LP_{11} mode is stronger than that for the LP_{01} mode due to the smaller size of the modal lobes, which yield higher intensity gradients.

By calculating the overlap integral between the LP_{01} and LP_{11} core modes and the nanospike mode at different offsets, the relative power in LP_{01} and LP_{11} modes could be estimated and the total optical force calculated (solid green curve in Fig. S3). It can be seen that there is negligible power in LP_{11} mode when the offset is less than 2 μm . This is also consistent with the agreement between simulation and measurement in Fig. 3b when the input power is less than 20 mW. For larger values of offset, however, the LP_{11} mode starts to be excited and the optical force (F_{opt}) is strongly affected.

Fig. S3 Simulation of bistability and hysteresis behavior. **Top**, simulated effective mode indices and optical forces for LP_{01} (blue dashed and solid lines) and LP_{11} modes (orange dashed and solid lines) versus the nanospike offset δ . The optical forces were calculated by launching 1 W power into each mode. The green solid line represents the total optical force by considering the coupling efficiency into the two modes (see text). Inset: intensity mode profile for the LP_{11} mode when the nanospike is offset by 3 μm from the core center. **Bottom**, numerical solving of force balance equation at a input power of 98.2 mW. Blue solid curve: $-F_{\text{opt}}$; dashed curves: F_m at different base offset values (indicated by the number beside the curve). The intersection points correspond to the equilibrium positions of the nanospike. The nanospike follows the path from A to E during the forward and backward scanning process.

The equilibrium positions of the nanospike are found by balancing F_{opt} and F_m . Fig. S3b plots $-F_{\text{opt}}$ (solid blue curve) and F_m (dashed curves) at different values of base offsets Δ for 98.2 mW launched power. The intersection points indicate equilibrium positions. For outward scanning of Δ , the nanospike moves successively from A to B. When further increase in Δ , the nanospike jumps from B to C (not to C', which is unstable). The switching point of the nanospike is therefore given by the Δ value corresponding to B ($\Delta = 8.3 \mu\text{m}$). Similarly, for inward scanning, the switching happens from D to E when only one stable equilibrium point is possible ($\Delta = 6.8 \mu\text{m}$). In this way the switching point of the nanospike can be approximately predicted (dashed arrows in Figs. 5b and 5c).

This pronounced bistability and hysteresis is a consequence of the strong interaction between the optical force and the mechanical motion of the nanopike. The excitation of the LP_{11} mode actually has the advantage that it allows trapping of the nanopike at large base offset values, thus preventing it from attaching to the core wall.

S4. FABRICATION OF THE NANOSPIKE

The nanopike was fabricated in two stages. In the first stage a SMF (125 μm cladding, 5.8 μm core diameter) was adiabatically pre-tapered to a tip diameter of 400 nm by scanning an oxybutane flame along the fiber while stretching it. The total length of the pre-taper was ~ 20 mm. In the second stage the last ~ 1 mm of the pre-taper was chemically etched by dipping it into a 20% solution of

HF in water. Surface tension creates a meniscus, with the result that HF etching gradually reshapes the spike to a nanoscale tip. The final diameter could be controlled by varying the duration of the etch. After rinsing for 10 minutes in deionized water the nanopike was ready for use. Note that although it is possible to directly taper a SMF down to a tip diameter of 150 nm, this results in much longer and difficult-to-handle nanopikes whose much lower resonant frequencies are easily disturbed by laboratory noise.

REFERENCES

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