Optofluidic Device for Sorting Microparticles using Optical Whispering Gallery Mode Resonances

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ABSTRACT

We describe the use of resonant amplification of light propelling forces for selective separation of fluid-suspended dielectric microparticles. The force amplification and the selectivity of the method is achieved using the whispering gallery mode resonances of the microparticles. The selectivity is determined by the inverse of the quality factor (Q) of the resonances in liquid (with $Q \sim 10^4 10^6$). We demonstrate that the evanescent field around a tapered optical fiber fed with ~ 20 mW power from a 1064 nm laser can selectively move polystyrene microspheres of up to 20 μm in diameter through distances of more than 50 μm, thereby establishing that the technique is sufficient for efficient separation.

Keywords: particle separation, whispering gallery, resonance, motion control

1. INTRODUCTION

A broad range of tasks require selection and separation of microparticles with specific properties from a large stock of similar objects. For example, this kind of sorting is necessary for building optical filters, photonic crystals, and other photonic devices, for separating certain types of microorganisms from biological mixtures, for controlling the size of droplets for industrial and medical applications, or for cleaning pathogenic cells from the blood of living organisms. Existing methods for separation have a variety of limitations. For instance, they may only be applicable to a limited type of particle, may have low-throughput, or may be insufficiently selective. Moreover, not all demonstrated methods are suitable for practical devices. Among existing techniques, optical methods of sorting occupy a special place due to their versatility and applicability to particles with a wide variety of physical properties. Brief reviews of various optical sorting techniques can be found in Refs. 1,2. These methods rely either on optical tweezing[3–8] or on light pressure created by the laser beam.[9–13] Optical methods can be combined with methods that sort by other physical properties, like photophoresis[10] or dielectrophoresis,[13] or with computerized image analysis.[14,15] However, all of these optical schemes are limited by their poor size selectivity with none of them able to separate particles with a precision better than 10% of the target size. Moreover, none of the methods can select particles by perfectness of their geometric shapes. Methods involving image processing are often not suitable for real-time sorting and their precision is diffraction limited. Finally, practical technological applications require on-chip integrated microfluidic devices,[16] however such integration is typically difficult for many of these techniques, especially for those based on optical tweezing and free-space optics.

In this work, we describe a new optical-based method for sorting microparticles that overcomes the limitations described above. The concept is applicable to a large class of microparticles that are made of dielectric materials

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and possess spherical, cylindrical, or elliptical symmetry. Such objects are characterized by Whispering Gallery Mode (WGM) resonances. WGMs appear as solutions of the Helmholtz equation with external driving force:[17]

$$\nabla^2 \psi_i + \frac{\omega_i^2}{c^2(\vec{r})} \psi_i = F(\vec{r}) e^{-i\omega t}. \tag{1}$$

Here $\vec{r}$ is the radius-vector, $F(\vec{r})e^{-i\omega t}$ is the external driving force with frequency ω that is distributed as $F(\vec{r})$, $c(\vec{r})$ is speed of light in the particle, and ω_i is the resonant frequency. The general solution for (1) can be written as:

$$u(\vec{r}, t) = e^{-i\omega t} \sum \frac{B_i}{\omega^2 - \omega_i^2} \psi_i(\vec{r}), \tag{2}$$

where the constants B_i are determined by boundary conditions, and the summation runs over all possible resonances ω_i. In the simplest case of the spherically-symmetric particle with dielectric constant ϵ, ψ_i is the function determined by radial, angular, and azimuthal eigennumbers N, l, and m:

$$\psi_{N,l,m}(r, \theta, \phi) = P_l^m(cos\theta) e^{im\phi} J_l(k_i r). \tag{3}$$

Here ϕ and θ are polar and azimuthal angles, P_l^m are associated Legendre polynomials, J_l are spherical Bessel functions, and $k_i = \omega_i \sqrt{\epsilon\mu}/c_0$, where c_0 is the speed of light in vacuum.

The WGM resonances possess very high quality factors (Q factors) with typical values in the range $Q \sim 10^4 - 10^6$; the positions, intensities and shapes of these resonances are strictly determined by the geometry and refractive indices of the particles as well as the refractive index of the neighboring environment.[18,19] Moreover, the parameters of WGM resonances are very sensitive to the smallest variations in any of these physical properties. Therefore, the WGM resonances can be used as a unique marker for a given type of resonator.

If the resonance conditions are satisfied, the WGM resonator in an evanescent light field experiences a strong optical force.[20] In preliminary experiments,[21] such an evanescent field was created using an optical fiber tapered to a diameter of $\sim 1 - 2$ μm. The resulting force was able to move spherical polystyrene microparticles with diameters of approximately $5 - 20$ μm. The particles were suspended in water and the fiber was fed with coherent light from a laser with wavelength tunable in the range of 1240-1260 nm. The power of the laser was ~ 50 mW. Under the resonant condition, the force created by the evanescent optical field was sufficient to move spheres for a distance of up to 0.3 mm. We are poised to to use this phenomenon under hydrodynamic flow in order to decompose a mixture of micrometer-scale particles by selective redirection of particles in a desired size range, and to create controllers that will use the resonance condition to further separate particles within this range.

In our concept, the evanescent light field interacts strongly with a microparticle only if the light frequency matches closely with the WGM resonance frequency. Assuming the precision of the method is inversely proportional to Q,[22] the precision of sorting identical microspheres by variation in diameter $\Delta D/D$ can reach as high as $1/Q \sim 10^{-4} - 10^{-6}$ μm; that is, we can selectively separate the microspheres with diameters that differ by as little as $\sim 10^{-5}$ μm. Thus, the major advantage of our concept is that it allows sorting particles with extremely high size selectivity. Furthermore, the selected particles have nearly perfect spherical, elliptical, circular, or cylindrical shapes. The proposed selection process is tunable and controllable. For instance, the sorting precision can be externally controlled by the rapid tuning of the propelling laser's wavelength. It is important to note that this high performance can be achieved with moderate values of laser power $\lesssim 50$ mW. The proposed device can serve as a prototype for an integrated microfluidic chip for particle selection and sorting.

2. EXPERIMENT

A conceptual drawing of a simple sorting device is shown in Figure 1. In the center of the device is a microfluidic cell with two channels associated with two loops of microfluidic flow, labeled A and B, and a tapered optical fiber (red) that runs across both channels. Loop A carries a suspension of assorted particles, while loop B acquires and stores the selected particles. The fiber is fed with the appropriate wavelength of laser light to select a desired size and shape. Whenever a particle from loop A approaches the taper, it interacts with the evanescent field of the taper. If the particle's WGM resonance frequency matches the frequency of the laser, the light propelling

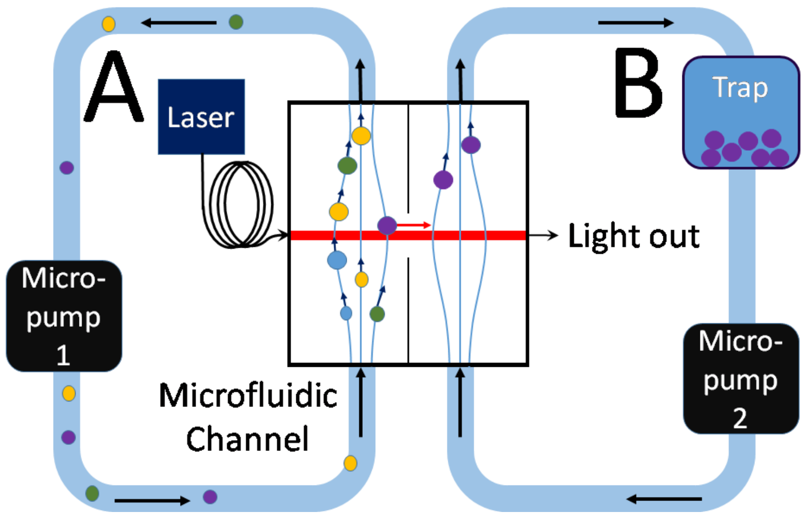

Figure 1: Block diagram of the conceptual sorting device. At the center is the opto-fluidic chip, with hydrodynamic streamlines going around a tapered optical fiber (red). Loop A circulates a suspension with particles of different diameters (shown with different colors). Evanescent field of the laser in the fiber (red) selectively displaces the particles, the resonant frequencies of which match the laser, to the right (purple particles). The flow circulating in loop B directs them to the storage trap.

force shifts it towards loop B, which carries it to the storage trap. If the resonant frequency of the particle is far from the laser frequency, the light force on such a particle is negligible, and the particle continues its trip through the loop A. Having circulated for several times, all the particles from loop A with resonance frequencies matching the laser, will end up in the trap in loop B, thereby achieving particle selection.

The tapered optical fiber, shown in red in Fig. 1, is one of the most critical elements of the design. We have developed two techniques to fabricate tapered fibers. Each of these techniques demonstrates good coupling to the WGM resonances but come with their own pros and cons.

In the first technique, the tapered fibers are fabricated by chemical etching of a standard single-mode fiber in the meniscus of a vessel overfilled with hydrofluoric acid (HF).[23] As shown in Figure 2(a), the fiber for etching is fixed in a Plexiglas frame that later may serve as a basis for the microfluidic device. During etching, the diameter of the taper is periodically monitored with an optical microscope. Chemical etching results in smooth 3-5 mm-long tapers with diameters $\lesssim 1$ μm in the thinnest region.[24] While many aspects of such a tapered fiber are ideal for use in a concept device, HF is a highly dangerous chemical that requires special care, a prepared environment, and hours of focus to create a single tapered fiber. Also, in the etched region a small sag develops that is difficult to fix without breaking the taper. These factors make it difficult to combine the chemically etched fiber with any microfluidic device that is more complicated than a simple bath.

The second tapering technique relies on pulling a heated fiber. For this technique, we built a low-cost, simple, yet functional instrument, inspired by a similar device from the Optomechanics Lab of the Worcester Polytechnic Institute.[25] The device consists of a heater, two motorized stages, and transmission monitoring equipment. The heater is made of a $\sim$2-cm-long piece of ceramic tube with kanthal wire coiled in it. The inner diameter of the coil is $\sim$3 mm; the coil is 6-7 turns of Kanthal wire. The wire diameter is 0.5-0.7 mm. The fiber is fed through the heater and each side is clamped to a separate motorized stage. When the heater temperature reaches $\sim 1100^{\circ}$C, the stages are activated and begin pulling at 0.12 mm/s. For a uniform taper, it is important

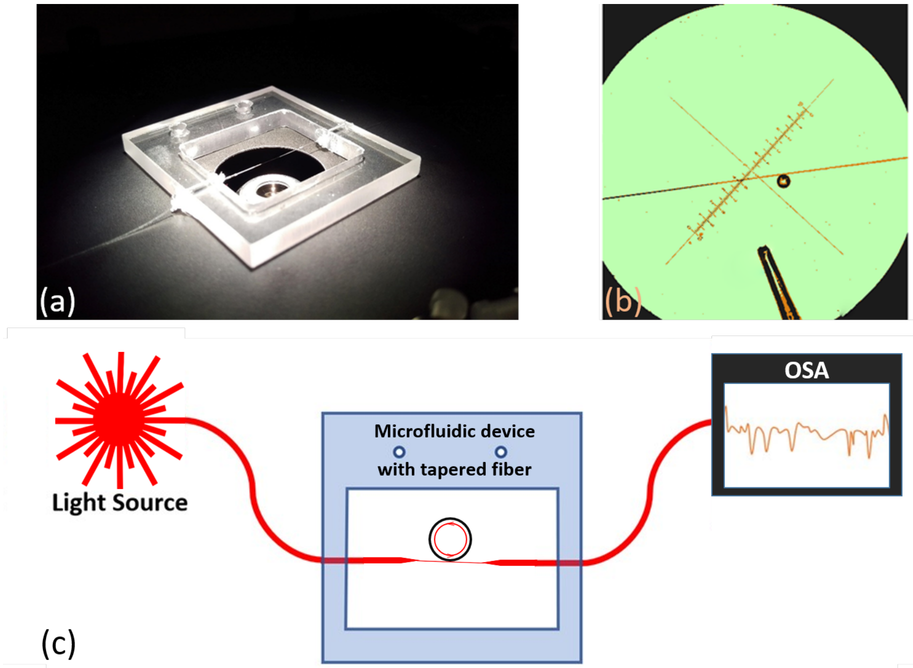

Figure 2: The testbench. (a) Snapshot of the tapered fiber holder. (b) Microscopic view of tapered fiber in contact with $\sim 10\ \mu$m sphere. (c) Setup for exploring coupling of microparticles to evanescent light of tapered fibers, and measuring WGM resonance spectra using an Optical Spectrum Analyzer (OSA).

that the fiber is pulled from both ends; this creates a necked portion where the heater has softened the core. To control the diameter of the taper, the transmission of the fiber is constantly monitored. Transmission tends to decrease smoothly over the course of the pull. When transmission approaches a previously-determined cutoff level, pulling is stopped. The pulling technique results in a $\sim$ 3-cm-long tapered region that is ideally straight and smooth. In the thinnest part, the diameter of the fiber can be $\lesssim 1\ \mu$m. The pulled fiber can be mounted in a microfluidic chip of almost any degree of complexity. Currently, the pulling process cannot make tapers any smaller than a few millimeters, thereby limiting the minimum size of the chip in which it would be installed. Also, to minimize loss of evanescent light, the channel for the fiber should have sufficient clearance for the whole length of the tapered region.

The quality of the coupling between optical microparticles and the tapered fiber (Fig. 2(b)) is evaluated by measuring light absorption spectra in the fiber when a microsphere is attached to it. Fig. 2(c) shows a diagram of a simple instrument for these measurements. The instrument consists of either a white light source or a tracking laser generator, a frame holding the tapered fiber with a microsphere attached, and a high-resolution Optical Spectrum Analyzer (OSA). Whenever the wavelength of light is in resonance with the resonator, the transmission of the fiber decreases dramatically and forms an inverse Lorentzian curve.

Figure 3 presents examples of the light absorption spectra of two different microspheres coupled to an etched fiber (diameter of the taper $\sim 2\ \mu$m). The first microsphere had a diameter of 45 μm and was made of soda-lime glass (panels a and b) while the second had a dimeter of 17 μm and was made of barium titanate glass (panels c and d). Our spectrum analyzer was the AP2060A from Apex Technologies; the light source was a built-in tracking laser generator. Deep and sharp WGM resonances are revealed through the periodic minima in the transmission spectrum.[26] The Q-factors of the resonances were $\sim 52,000$ and 8000 for the 45 μm and 17 μm microspheres, respectively. These spectra confirm the good quality of the coupling of the evanescent light from the tapered fiber to the microsphere resonators.

As was mentioned, previously we were able to successfully move large (up to 20 μm) polystyrene microspheres suspended in water in the evanescent field along the tapered fiber using laser light of wavelength $\sim$ 1250 nm.[21]

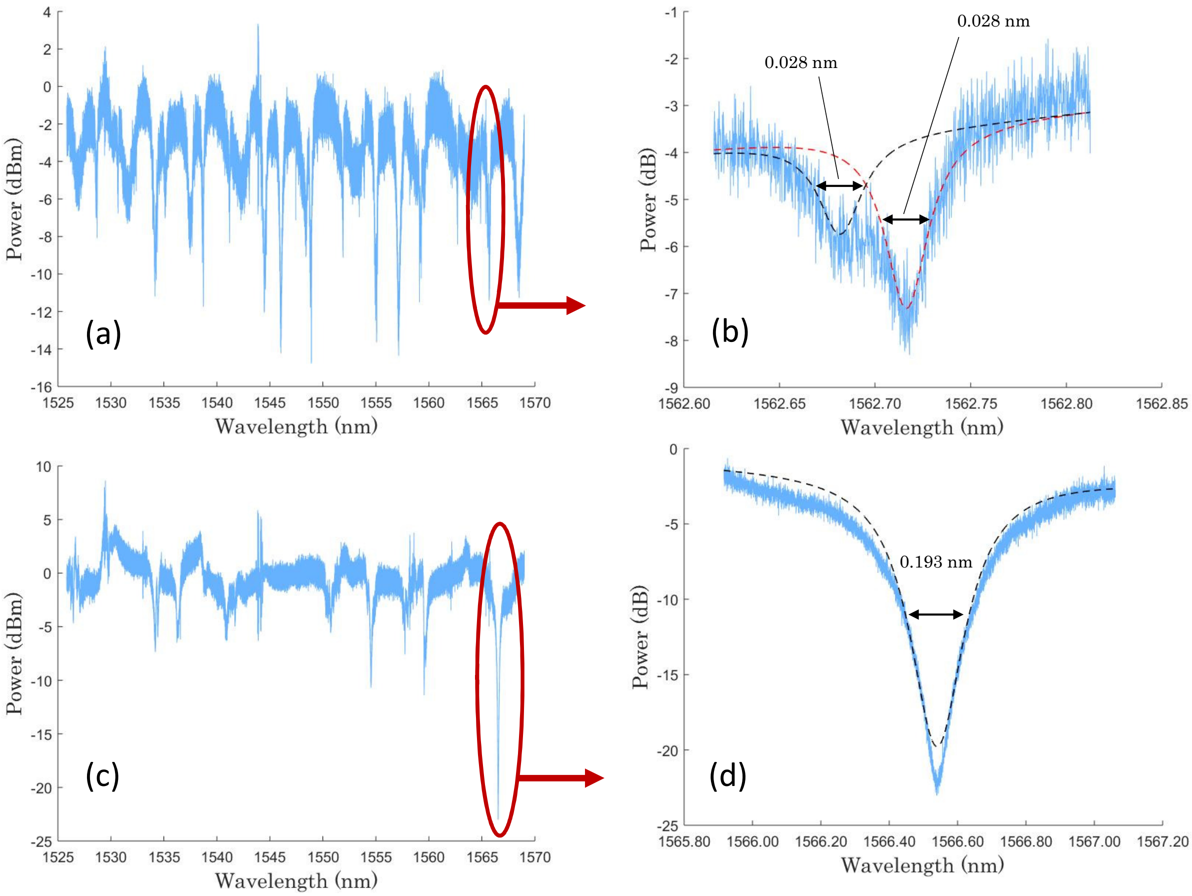

Figure 3: Examples of high-resolution WGM resonant spectra of microspheres, coupled to the tapered SMF28 fiber with taper diameter ~ 2 μm in air. Sphere diameter and material: (a) and (b) 45 μm, soda-lime glass, refractive index 1.52; (c) and (d) 17 μm, barium titanate glass, refractive index 1.9. Panels (a) and (c) show panoramic view of the spectra, (b) and (d) are focused on the encircled regions. Dashed lines show Lorentzian fits to the observed peaks.

In order to interact with the evanescent field, a particle should come sufficiently close to the taper. The effective reach of the evanescent field depends on the wavelength of light. Light absorption in water also depends on the wavelength of light: increasing the wavelength dramatically increases absorption.[27] Therefore, the efficacy of this method of moving particles strongly depends on the wavelength of light. In order to explore the boundaries and limitations of the method, we immersed the tapered fiber in a suspension of microspheres in deionized water and, and repeated the experiment using wavelengths of 1064 nm, 808 nm and 1550 nm. Figure 4 shows examples of successful propulsion of polystyrene microspheres (refractive index of 1.59) with diameter of (a) 5 μm and of (b) 10 μm using the evanescent light from a fiber fed with the 20 mW of 1064 nm laser light. These experiments demonstrate that this wavelength is reasonably efficient for transporting the particles with diameters up to ~ 20 μm over distances of $\sim 50 - 100$ μm.

Much smaller efficiencies were observed using 808-nm light. Although light at this wavelength was able to capture the microspheres, it could not hold them for sufficiently long times to transport them over distances

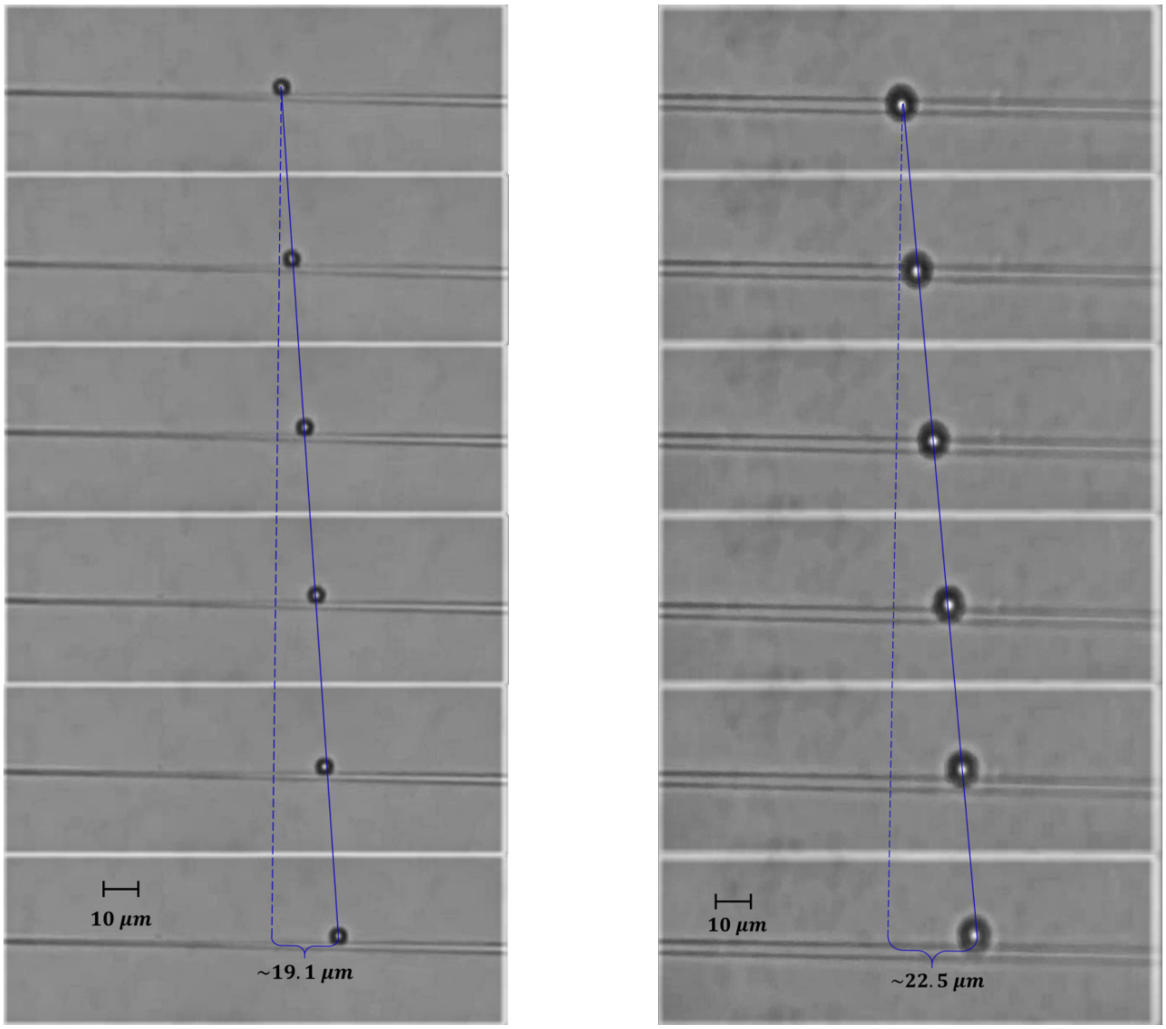

Figure 4: Motion of (a) 5 μm and (b) 10 μm microspheres along the tapered fiber (from left to right). In both cases, the taper diameters are $\sim 2\mu$m. The time interval between frames is 0.2 s. Laser power is 20 mW, and wavelength is 1064 nm.

needed for sorting. At 1550 nm, the light absorption in water increases.[27] As a result, the evanescent light causes local temperature increase that induces strong convective flows. These flows, in turn, suppress or even completely destroy selectivity of the device.

3. DISCUSSION

The above described experiments persuasively demonstrate that coherent light with wavelength in the range $1000 - 1300$ nm allows for selective control of microparticle motion due to WGM resonances. Using a light source within this range, one can build a microparticle sorting device similar to the sketch shown in Figure 1. This device can be further developed for simultaneous selection of several types of particles, directing them to different microfluidic channels. Longer wavelengths of light, which induce motion of water along the fiber, can be used to purge the device in case it becomes clogged with particles or dirt. Shorter wavelengths can be used to increase selectivity by matching multiple WGM resonances.

The proposed WGM resonant sorting chip can work in combination with other sorting methods. For example, those relying on properties, such as fluorescence or the presence of magnetic or electric dipole moments. Equipped with a feedback circuit that is capable of switching off and on the light sources and adjusting their wavelengths, the optical propulsion method would allow for the development of a smart sorting device that can find applications in a variety of fields from optics and photonics, to biotechnology, medicine, and the drug industry.

4. SUMMARY

We have described a new concept for a device to sort microparticles with spherical, cylindrical, elliptical and similar types of symmetries with an unprecedented level of selectivity, determined by the Q-factors of the WGM resonances of the particles. The working principle of the device is based on the giant amplification of the force of evanescent light acting on a particle when its frequency matches one of the particle's whispering gallery mode resonances. This sorting technique can work alone or in combination with other methods.

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