Focusing Microprobes Based on Integrated Chains of Microspheres

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Abstract—The concept of nanoscale photonic jets has emerged as a novel way of focusing light with subwavelength spatial resolution. Practical focusing systems are, however, limited in their resolution by the multimodal structure of beams delivered by flexible waveguides or fibers. In this work, by using numerical modeling, we show that the chains of microspheres assembled inside the bores of the hollow waveguides or microcapillaries provide significant advantages over single lenses in such applications. It is also shown that the chains of microspheres are capable of focusing light in contact with tissue. Experimental studies are performed for spheres with sizes from 10 to 300 µm with different indices of refraction ranging from 1.47 to 1.9. The focusing and transport properties of such chains are found to be in good agreement with numerical modeling results.

1. INTRODUCTION
Recently it has been demonstrated that a small wavelength-scale microsphere with a refractive index of about 1.6 produces a narrow focused beam, termed a ‘nanoscale photonic jet’ [1–7]. The photonic nanojet propagates with little divergence for several wavelengths into the surrounding medium, while maintaining a sub-wavelength transverse beam width. A fundamental principle in diffraction-limited optics [8] requires that the spatial resolution of focusing devices be limited by the wavelength of the incident light (λ) and by the numerical aperture of the objective lens systems. Microspheres allow obtaining focused beams with effective volumes of the order of (λ/n)³, where n is the sphere’s refractive index [7]. The concept of nanojets is attractive for designing focusing microprobes that can be used for detecting nanoparticles [1], dry laser cleaning [9], multiplexed imaging [10], nanopatterning [11], Raman spectroscopy [12], and optical data storage [13]. It should be noted, however, that photonic nanojets from single spheres require strictly plane-wave or conical illumination which is not readily available in devices using flexible optical delivery systems.

More recently, periodic focusing of light has been observed in chains of polystyrene microspheres assembled on substrates [14–17]. In these chains, the photonic nanojets were quasi-periodically reproduced along the chain giving rise to “nanojet-induced modes” (NIMs). The coupled nanojets decreased in size along the chain, reaching wavelength-scale dimensions, even for non-collimated input beams. The periodicity, spectral transmission properties, and losses of NIMs were studied [14, 15] for such chains.

In this work, we study focusing properties of chains of microspheres assembled inside the cores of hollow waveguides or microcapillary tubing. Using ray tracing ZEMAX-EE software [18] we show that chains of microspheres have significant advantages over single lenses in such systems. They filter the nanojet-induced modes with the best focusing properties in such structures. This allows reduction in the sizes of the focused beams to wavelength-scale dimensions while maintaining high optical transmission. Using high index spheres, we demonstrate that these structures are capable of focusing light into tissue or a sample in close proximity to the end sphere. Light propagation effects observed in such chains are found to be in a good agreement with numerical modeling results.

2. NUMERICAL MODELING
An example of a delivery system based on a hollow waveguide is illustrated in Fig. 1(a). Multiple reflections by the sidewalls of the waveguide lead to formation of a number of modes incident on a focusing element at different angles. A single sphere with size matching the diameter of the bore can be integrated with the hollow waveguide. Each waveguide mode is focused at the focal plane of a spherical lens, as illustrated in Fig. 1 by numerical ray tracing performed using ZEMAX-EE software [18]. In our modeling we used spheres with radius a = 150 µm and λ = 2.96 µm. It
is well known that in the limit $a \gg \lambda$ the index of refraction of the sphere must be close to 2 to provide maximum intensity of focused light at the "shadow" surface of the sphere [1–3], as illustrated in Fig. 1(b). In the limit of geometrical optics, each spot size is determined by the spherical aberrations. According to a more rigorous physical optics approach, each focused spot in Fig. 1(b) should have at least diffraction-limited dimensions [8]. If the incident beams have a continuous angular distribution, all the focused spots originating from the individual modes are overlapped near the back surface of the sphere forming a broad intensity distribution with characteristic sizes well in excess of the diffraction limit. Thus, the spatial resolution of optical microprobes based on single spheres is expected to be significantly below the diffraction limit due to multimode illumination.

Focusing effects in a chain of microspheres are illustrated by numerical ray tracing in Fig. 2 for high (1.97) index spheres. Only illumination along the axis leads to efficient coupling of light to optical modes propagating in such chains. Axial beams (red) are periodically focused inside the structure with the periodicity depending on the index of refraction. The meridional beams, however, are scattered away from such chains due to reflections of light beams provided at the spherical interfaces. Propagation effects inside the chain are modeled by taking into account multiple refractions and reflections at the spherical interfaces. Only refracted beams are shown in Fig. 2 to simplify the images.

In some applications (e.g., ultra-precise laser surgery) a short focusing depth is required in a fluid or tissue. It is well known, however, that the focusing properties of microprobes based on single lenses are limited in a fluid due to its high index of refraction [19]. In contrast, the chains of microprobes can be enclosed in a tube, so that all the beads except the last sphere are completely isolated from the fluid. Only the last sphere is exposed to fluid (or tissue) with index 1.33, as illustrated in Fig. 2. The focusing effects are observed to be preserved in a fluid despite its index of refraction. This opens up the possibility of using similar focusing structures in a liquid or in direct contact with tissue. Detailed study of the focused beams' sizes involves taking into account the diffraction effects. This task requires a rigorous solution of Maxwell's equations without assumptions used in geometrical optics, which goes beyond the scope of the present work. It should be noted, however, that spot sizes comparable to the wavelength of light were observed [14] in chains of 3 $\mu$m polystyrene microspheres coupled to multimodal light sources (dye-doped spheres).

3. EXPERIMENTAL RESULTS

Chains of microspheres made from borosilicate glass ($n = 1.47$), soda-lime glass ($n = 1.50$), polystyrene ($n = 1.59$), and barium titanate glass ($n = 1.9$) were assembled inside plastic and glass microcapillaries as well as inside hollow waveguides. Infiltration was performed using micromanipulation and micro-pneumatic propelling of spheres with diameters from 10 to 300 $\mu$m. In order to provide tight packing of microspheres, while keeping the chains straight and symmetric.
along the long central axis of the cylindrical structure, the size of microspheres should match the hole size in the microcapillary tube, as shown in Figs. 3(a) and 4(a).

The light attenuation properties of chains of microspheres inside capillary tubing were investigated by imaging through the sidewall using scattered light, as illustrated for 50 µm polystyrene beads in Fig. 3(b). The studies were performed using dye-doped fluorescent (FL) polystyrene spheres with the same 50 µm size as local light sources. The FL excitation was provided at 460–500 nm by a mercury lamp. The FL emission was provided in a 500–570 nm spectral range. A fraction of this power was coupled to modes propagating in the chain formed by undoped spheres away from the source. These propagation effects were visualized with an inverted IX-71 Olympus microscope due to scattered light, as shown in Fig. 3(b).

The positions of bright spots observed in Fig. 3(b) correspond to areas at the spherical surfaces near the touching points of the neighboring spheres. Since the conditions of collection of scattered light were fixed along the chain, one can assume that the power contained in the bright spots should be proportional to the power of modes propagating inside the chain. In order to estimate the total power contained in the bright spots, the intensity distribution was integrated within each spot and represented by red dots in Fig. 3(c). This experimental power distribution along the chain was observed to be in reasonable agreement with the results obtained by numerical ray tracing using ZEMAX-EE software [18], also shown in Fig. 3(c). It should be noted that smaller losses ∼ 0.1 dB/sphere were reported [15] for very long chains (up to 100 beads) formed by much smaller (5 µm) polystyrene spheres. Similar results were obtained for chains formed by the borosilicate (n = 1.47) and soda-lime glasses (n = 1.50). For chains formed by high index (n = 1.9) barium titanate glass spheres the experimentally measured transmission was less than the theoretical values due to absorption of light by the microsphere material at 510–570 nm.

In order to test the focusing properties of the microprobe in the presence of a tissue-like medium, the structure formed by barium titanate glass microspheres with a = 125 µm was completely embedded in a gel, so that the surface of the end sphere was in contact with the medium with index around 1.4, similar to the case considered earlier by theoretical modeling in Fig. 2. Illumination was provided at λ = 630 nm by the single mode fiber inserted in a capillary tube holding the chain of microspheres. The gel makes visible the beam inside such a “tissue”, due to light scattering properties, as shown in Fig. 4(b). The beam is focused in the vicinity of the surface of the end sphere with the beam waist measuring about 5 µm. Due to significant beam divergence the intensity distribution has a small depth of ∼ 10–20 µm. Thus, such structures are capable of focusing light into tissue in contact mode and may provide laser interaction with the tissue in close proximity to the end sphere.
4. CONCLUSIONS

Conventional single lens-based microprobes based on multimodal delivery systems can focus light to spot sizes which are a priori significantly larger than the diffraction limited dimensions. In this study we demonstrate that a trade-off between focused spot sizes and transmitted power can be conveniently controlled in microprobes by using chains of microspheres. Increasing the number of spheres in such chains generally provides smaller focused spot sizes at the expense of transmitted power. Simple integration of microsphere arrays with flexible fibers and hollow waveguides permit sharp focusing of a light beam and operation in contact mode with tissue. Thus, microsphere arrays can be used in a variety of biomedical and photonics applications as a compact focusing tool. We show that such structures allow one to obtain focused beams with spot sizes of several wavelengths and with a treatment depth of approximately 10–20 µm in tissue. Potential applications include ultra-precise laser procedures on the eye and brain or piercing a cell, and the coupling of light into photonic nanostructures.

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