Dual-beam interference from a lensed multicore fiber and its application to optical trapping

Barron, Ashleigh L.; Kar, Ajoy Kumar; Bookey, Henry T.

Published in:
Optics Express

DOI:
10.1364/OE.20.023156

Publication date:
2012

Dual-beam interference from a lensed multicore fiber and its application to optical trapping

Ashleigh L. Barron,* Ajoy K. Kar, and Henry T. Bookey

Institute of Photonics and Quantum Sciences, School of Engineering and Physical Sciences, Heriot Watt University, Edinburgh, EH14 4AS, UK

ab461@hw.ac.uk

Abstract: A multicore all-fiber probe is demonstrated that has been fabricated using an electric arc fusion splicer. Interference of the fiber output when coherent light is coupled into two cores is investigated. The properties of the fringes created when the fiber is probing different media were found to be in general agreement with a beam propagation method simulation. Optical manipulation of microspheres near to the end of the probe is examined and the potential for controlled trapping explored. Polymer microspheres with diameters of 2 microns were formed into regular patterns due to the presence of the interference fringes.

OCIS codes: (060.2310) Fiber optics; (230.1150) All-optical devices; (350.4855) Optical tweezers or optical manipulation.

References and links

1. B. Zhu, T. F. Taunay, M. Fishteyn, X. Liu, S. Chandrasekhar, M. F. Yan, J. M. Fini, E. M. Monberg, and F. V. Dimarcello, "112-Tb/s Space-division multiplexed DWDM transmission with 14-b/s/Hz aggregate spectral efficiency over a 76.8-km seven-core fiber," Opt. Express **19**(17), 16665–16671 (2011).
2. G. Zhang, Q. Zhang, Y. L. Shen, Q. L. Zhou, L. L. Hu, J. R. Qiu, and D. P. Chen, "Phase Locking of a Compact Nd_doped Phosphate Multicore Fiber Laser," Laser Phys. **21**(2), 410–413 (2011).
3. G. M. H. Flockhart, W. N. MacPherson, J. S. Barton, J. D. C. Jones, L. Zhang, and I. Bennion, "Two-axis bend measurement with Bragg gratings in multicore optical fiber," Opt. Lett. **28**(6), 387–389 (2003).
4. R. R. Thomson, H. T. Bookey, N. D. Psaila, A. Fender, S. Campbell, W. N. Macpherson, J. S. Barton, D. T. Reid, and A. K. Kar, "Ultrafast-laser inscription of a three dimensional fan-out device for multicore fiber coupling applications," Opt. Express **15**(18), 11691–11697 (2007).
5. N. J. Scott, C. M. Cilip, and N. M. Fried, "Thulium fiber laser ablation of urinary stones through small-core optical fibers," IEEE J. Sel. Top. Quantum Electron. **15**(2), 435–440 (2009).
6. A. G. Podoleanu, "Fiber optics, from sensing to non-invasive high resolution medical imaging," J. Lightwave Technol. **28**(4), 624–640 (2010).
7. H. Bao, S. Y. Ryu, B. H. Lee, W. Tao, and M. Gu, "Nonlinear endomicroscopy using a double-clad fiber coupler," Opt. Lett. **35**(7), 995–997 (2010).
8. S. Moon, S.-W. Lee, M. Rubinstein, B. J. F. Wong, and Z. Chen, "Semi-resonant operation of a fiber-cantilever piezotube scanner for stable optical coherence tomography endoscope imaging," Opt. Express **18**(20), 21183–21197 (2010).
9. L. Fu, A. Jain, H. Xie, C. Cranfield, and M. Gu, "Nonlinear optical endoscopy based on a double-clad photonic crystal fiber and a MEMS mirror," Opt. Express **14**(3), 1027–1032 (2006).
10. C. Liberale, P. Minzioni, F. Brugheri, F. De Angelis, E. Di Fabrizio, and I. Crisitiani, "Miniature all-fibre probe for three dimensional optical trapping and manipulation," Nat. Photonics **1**(12), 723–727 (2007).
11. N. Ma, F. Gunn-Moore, and K. Dholakia, "Optical transfection using an endoscope-like system," J. Biomed. Opt. **16**(2), 028002 (2011).
12. S. Y. Ryu, H. Y. Choi, J. Na, W. J. Choi, and B. H. Lee, "Lensed fiber probes designed as an alternative to bulk probes in optical coherence tomography," Appl. Opt. **47**(10), 1510–1516 (2008).
13. H. Y. Choi, S. Y. Ryms, J. Y. Kim, G. H. Kim, S. J. Park, B. H. Lee, and K. S. Cheng, "Microstructured dual-fiber probe for depth-resolved fluorescence measurements," Opt. Express **19**(15), 14172–14181 (2011).
14. A. N. Rubinov, V. M. Katarkevich, A. A. Afanas'ev, and T. S. Efendiev, "Interaction of interference laser field with an ensemble of particles in liquid," Opt. Commun. **224**(1-3), 97–106 (2003).
15. A. E. Chiou, W. Wang, G. J. Sonek, J. Hong, and M. W. Berns, "Interferometric optical tweezers," Opt. Commun. **133**(1-6), 7–10 (1997).
16. A. Casaburi, G. Pesce, P. Zemanek, and A. Sasso, "Two and three beam interferometric optical tweezers," Opt. Commun. **251**(4-6), 393–404 (2005).

#170438 - $15.00 USD Received 13 Jun 2012; revised 19 Sep 2012; accepted 20 Sep 2012; published 24 Sep 2012

17. M. P. MacDonald, L. Paterson, W. Sibbett, K. Dholakia, and P. E. Bryant, "Trapping and manipulation of low-index particles in a two-dimensional interferometric optical trap," Opt. Lett. **26**(12), 863–865 (2001).
18. M. P. MacDonald, G. C. Spalding, and K. Dholakia, "Microfluidic sorting in an optical lattice," Nature **426**(6965), 421–424 (2003).
19. E. I. Altinoğlu and J. H. Adair, "Near infrared imaging with nanoparticles," Wiley Interdiscip Rev Nanomed Nanobiotechnol **2**(5), 461–477 (2010).

1. Introduction

Multicore optical fiber (MCF) is attracting much interest due to its potential use in a variety of fields for data and telecoms applications [1], fiber lasers [2] and sensors [3]. The recent development of three dimensional optical interconnects created using ultrafast laser inscription has eased problems of integration [4] allowing arbitrary core arrangements to be connectorized to commercial v-groove fiber array components. This maturation of MCF technology has led to the exploration of different devices that these new fiber geometries have enabled. In certain areas it is the compact nature of MCF that is of interest. In endoscopy, fiber bundles are generally used to deliver and collect light for surgical applications such as urinary stone removal [5] or in diagnostic applications such as OCT [6] and confocal microscopy [7]. The optics on the distal end of these fiber probes have seen a large number of advances [8, 9]. However, if added functionality can be achieved without external components, savings in costs and improvements in lifetime and reliability can be made. Previous work in this area has used focused ion beam milling [10] or chemical etching [11] to shape the end of fiber bundles or MCF whilst other groups have exploited the fiber end shaping capability of fiber fusion splicers to fabricate probes from multiple fibers [12, 13]. Optical trapping using fibers increases the flexibility and integration over bulk optic systems [10]. Interferometric optical trapping allows the manipulation of multiple particles [14–18]. In this work, we demonstrate how simple shaping of the end of a single MCF can enable a single fiber probe, with no external components, which can then be used to demonstrate single fiber interferometric optical trapping and, with additional cores, multifunctional miniature fiber probes that can be configured for specific clinical applications. We believe this is the first demonstration of the shaping of multicore fiber using a standard electric arc fusion splicer and the first demonstration of interferometric optical trapping using an MCF.

2. Lensed fiber fabrication

The four-core MCF used can be seen in Fig. 1(a). The fiber known as a Gemini Fiber G4 is a commercial fiber supplied by Fibertronix AB. This fiber was fabricated by drawing down four standard telecommunications fiber preforms together to create a single four-core fiber. The four 7μm diameter cores were in a square array with inter-core spacing of 80 μm and a diagonal core spacing of 113 μm. The fiber was cleaved and placed in a Sumitomo T-36 fusion splicer. The fiber was aligned to the splice point and a 14 second arc was performed. This method shapes the end of the fiber as shown in Fig. 1(b). The shape and behavior of the lensed fiber was shown to vary with both the material and the diameter of the fiber. Lensing the fiber in such a way was found to be an efficient and repeatable technique using this conventional equipment. This method has many advantages over methods such as focused ion beam milling and chemical etching including a reduction in time, fabrication costs, safety and commercial viability. When a white light source was coupled into the fiber, no scattering was visible at the output indicating that the surface quality of the lens is relatively smooth and clean.

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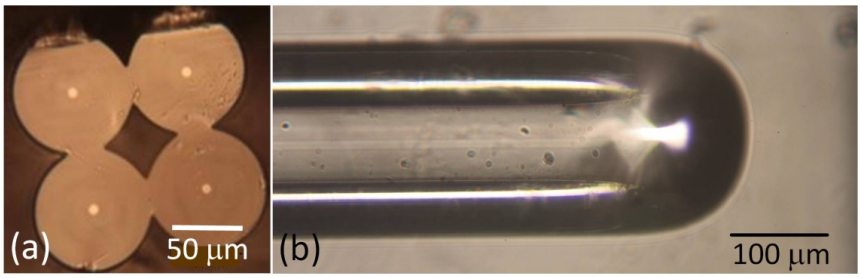

Fig. 1. (a) End face image of the Gemini 4-core fiber, (b). Shaped end of the fiber after lensing.

3. Simulation

The modified end of the MCF was modeled using a beam propagation method (BeamPROP, RSoft Design Group Inc.) the geometry of which is shown in Fig. 2(a) and 2(b). A simple curved section is used to represent the lensed fiber end and its radius of curvature is estimated from Fig. 1(b). For this model the structure was approximated by using a spherical section of radius of curvature 82.5 µm following a straight section of 5.6 µm and diameter 165 µm. This matched the curvature at the core areas.

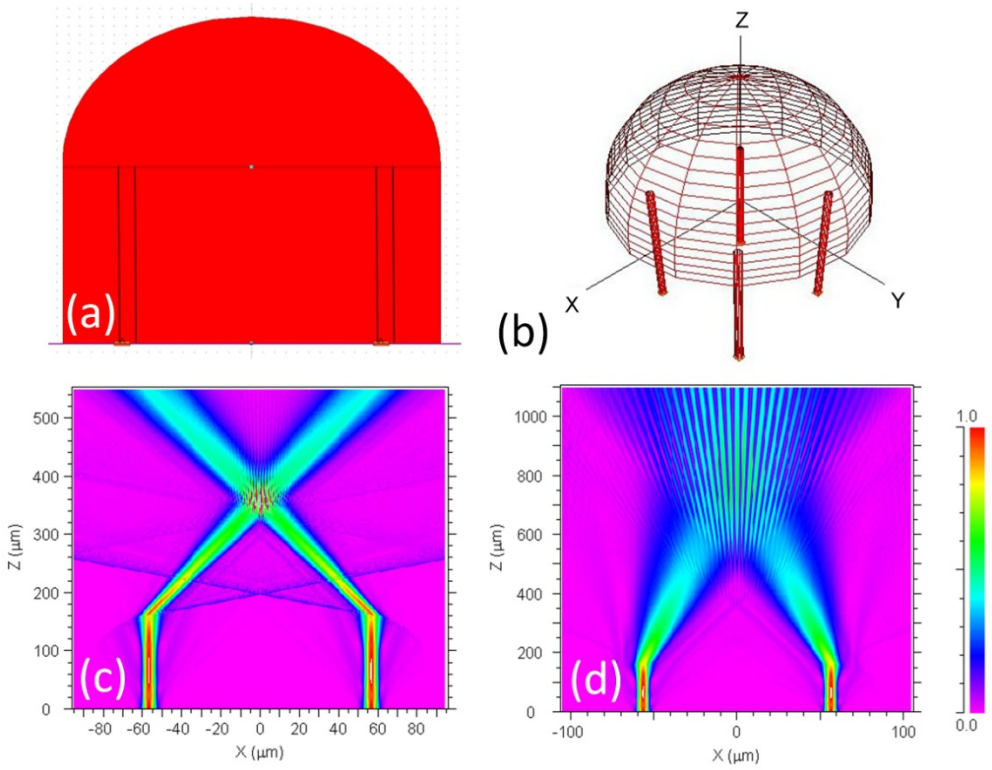

Fig. 2. (a) Beam Prop model layout of modified Gemini fiber end, (b) Three dimensional model layout of modified Gemini fiber end, (c) Beam propagation model output of the diagonal cores of the modified Gemini fiber in air, (d) Beam propagation model output of the diagonal cores of the modified Gemini fiber in water.

As can be seen in Fig. 1(b), the actual structure of the shaped fiber end is complex with apparent tapering of the cores distorted due to the curvature of the fibre, making it difficult to ascertain the exact internal structure of the lensed region. The output when light is coupled

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into two of the diagonal cores was modeled for when the fiber is in a medium of both air and water (Fig. 2(c) and 2(d)) respectively. The medium into which the fiber is inserted is shown to vary the output of the fiber as expected via the changes in refractive index contrast. In water the distance from the end of the fiber to the point where the beams cross, the area of the crossing point and the fringe spacing increased compared to when the fiber is in air. The model shows the distance from the output of the fiber to the crossing point increasing from 195 µm in air to 535 µm in water whilst the fringe spacing increased from 1.22 µm in air to 3.35 µm in water.

4. Experimental results

An Nd:YLF laser source (Elforlight: model L 500-1047) was used to assess the lensing properties of the modified MCF. This provided up to 800 mW at 1047 nm, which is close to the specified fiber cut off wavelength of 1 µm. The water absorption is also less here than at 1550nm [19]. The experimental set up used for coupling light into the two cores is shown in Fig. 3.

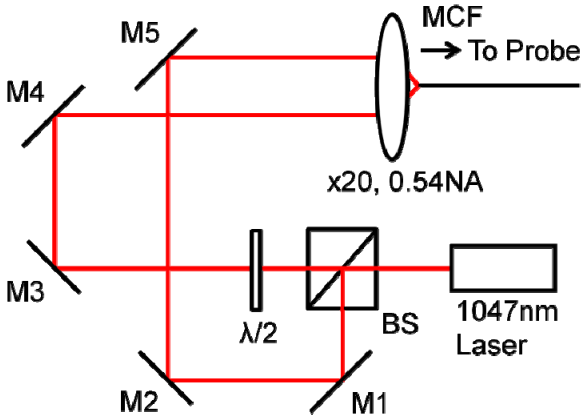

Fig. 3. Experimental set up of dual core coupling. MCF – multicore fiber, M1-M5 – metal coated mirrors. BS – 50:50 beam splitter.

After propagation through a 50:50 beam-splitter, light was coupled into two diagonal cores. This was achieved by propagating the two beams through a x20, 0.54NA microscope objective with an offset to allow both cores to be illuminated evenly. A half wave plate was used to adjust the polarization of one of the input beams so as to improve fringe visibility. Mirrors, M1-M3 and M4-M5 were used to ensure the two beams entered the coupling objective at the angle and offset for optimum coupling into the two diagonal cores.

The shaping of the end of the fiber refracts the core output to produce a crossing point in the far field. In air this is approximately 250 µm from the end of the fiber which increases to approximately 500 µm when the fiber is in water. At the crossing point high contrast interference fringes are produced. In air these were measured to have a fringe spacing of 1.83 µm which increases to 4.29 µm in water as shown in Fig. 4(a) and 4(b). When the fiber is in water the intensity across each fringe is also less than in air, this is due to water absorption and the beam diverging more as shown in the simulations. In general the observed fringe properties for immersion in air and in water are in agreement with our simulation of an equivalent although simplified structure. To test the uniformity in the lensing of the MCF we measured the fringe spacing in air for 10 different lensed fibers, the fringe spacing was shown to vary by 0.3 µm from the average value of 2µm.

The interference fringes produce intensity gradients across the crossing point that can be used for aligning particles along the fringes. Similar fringe patterns, produced using free space optics, have previously been shown to allow micro-particle manipulation at low powers

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[14]. A solution of microspheres was held between two cover slips and kept in place using a vinyl spacer between them. The fiber was positioned in air outside the cover slips and an imaging system was positioned at the other side as depicted in Fig. 4(c). With light coupled into two of the diagonal cores the microspheres were moved to the crossing point of the beams. Having the fiber in air increases the intensity and the crossing point as the beams diverge less than when in water, the fringe spacing is also shorter than in water therefore small microspheres with diameters close to the fringe spacing were used. Using this set up, the microspheres are observed to align along the fringes as shown in Fig. 5(a-d). The combined power from two cores at the end of the fiber was found to be 30 mW in air when a combined power in the two input beams incident onto the fiber is 250 mW. The intensity gradients created across each fringe produce a well in which the microspheres are trapped. The movement of the microspheres is restricted to along the fringes. These results show this probe can be used for interferometric optical tweezing in one dimension, aligning microspheres along the fringes.

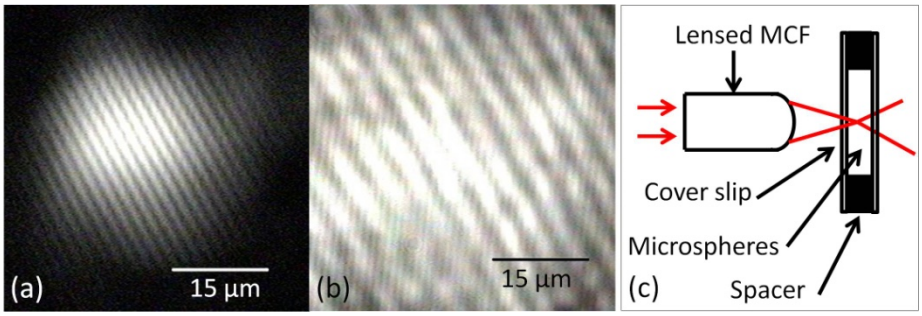

Fig. 4. (a) Interference fringes produced at the crossing point of the diagonal cores in air, (b) Interference fringes produced at the crossing point of the diagonal cores in water, (c) Schematic of the trapping experimental set up.

To test that the alignment was caused by the interference and not due to the intensity of the light, the intensity when both beams are present was reduced to the same intensity when one beam is present. Alignment was only seen when the both beams are present showing that the interference fringes are causing the alignment. This effect can also be seen when one beam is blocked to remove the fringes, the microspheres are shown to spread out in all directions as can be seen in Fig. 5(a), but when the fringes are reintroduced the microspheres become ordered and align along the fringes as can be seen in Fig. 5(b), 5(c) and 5(d).

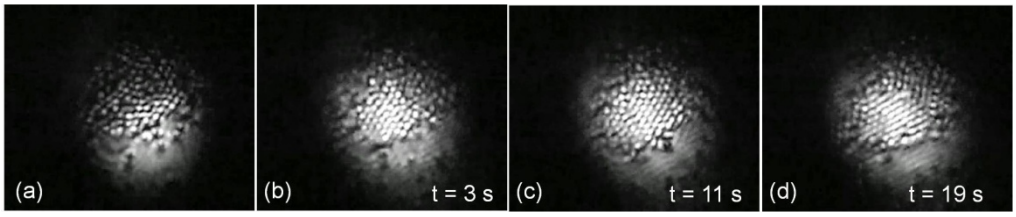

Fig. 5. Single-frame excerpts from video recording of the manipulation of 2µm microspheres (Media 1). (a) Disordered microspheres when interference fringes are not present, (b) Microspheres 3 seconds after fringes are reintroduced, (c) Microspheres 11 seconds after fringes are reintroduced, (d) Microspheres aligned along the fringes when the interference fringes are reintroduced.

5. Conclusions

We have demonstrated one dimensional interferometric optical trapping, using a single fiber, lensed using a conventional fusion splicer. The use of a standard fusion splicer is a robust and low cost way of functionalizing the end of a multicore optical fiber. It produces repeatable

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results with high quality, scatter free surfaces at the end of the fiber without the need for any further annealing step. The use of a splicer to functionalize the end of the fiber has many advantages over the current methods using focused ion beam milling or chemical etching including commercial viability and large reductions in fabrication time and costs. The use of equipment found in most optical fibers laboratories is also appealing.

The shaping of the end of the fiber produces an overlap in the far field of the output from the diagonal cores. The longitudinal position of this overlap point depends greatly on the surrounding material. In air this was found to be 250 μm from the fiber end, whereas when immersed in water this lengthens to over 500 μm, this was predicted by our simulations. This overlap leads to the generation of a high contrast fringe set that can be used for optical trapping. The fringes could be swept upon manipulation of the MCF. The exact internal structure of the shaped fiber would be very difficult to model as it would not be possible to know exactly how the cores are shaped during the arc, our approximation of the core structure may explain the slight discrepancy between our modeled and measured fringe spacing however even this simplified model shows good agreement with the observed behavior of the probe.

Aside from fiber manipulation, active phase control on different fiber channels will allow greater control of the fringes. Using directly written three dimensional interconnects will allow us to integrate the fiber probe with phase modulators. Such interconnects will enable us to investigate manipulation with three and four beam interference patterns which should allow us to hold particles in two dimensions. Optical tweezing using this type of lensed fiber could be achieved if we were to increase the curvature of the lens region. This can be achieved if we first taper the fiber before forming the lens section – it is the fiber diameter that is a critical parameter in determining the lens shape.

This work now allows us to explore the development of a single fiber optical trapping platform without using complicated and expensive etching or milling processes and without the use of external components. Potential applications involve transferring optical trapping techniques to the in vivo environment, reducing diagnosis time and making further clinical tools available at the point of care.

Acknowledgments

The four-core “Gemini” fiber was supplied by Fibertronix AB. H. Bookey acknowledges the support of a Royal Society of Edinburgh Scottish Government Research Fellowship. This work is funded by the UK Engineering and Physical Sciences Research Council (EPSRC) through grant EP/GO30227/1. A. Barron acknowledges the funding from EPSRC. The authors would like to thank Lynn Paterson for providing the microspheres.

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