Microfluid Nanofluid (2011) 10:447–451
DOI 10.1007/s10404-010-0665-5

SHORT COMMUNICATION

Magnetic-fluid core optical fiber

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Received: 8 May 2010 / Accepted: 21 June 2010 / Published online: 8 July 2010

Abstract We report the first fabrication of magnetic-fluid core optical fiber (MFCOF). Paraffin-based magnetic fluid is selected as the liquid and filled in a hollow core fiber with the core-diameter of 5 μm and the length of 20 cm. The optical properties of MFCOF were investigated by sending light into them. The wires allow multi-mode operation, and have an optical loss less than 0.6 dB/cm. In contradiction to the traditional liquid core optical fiber, the optical properties of MFCOF can be tunable under the external magnetic field, which may find applications in device physics on combined fields of magnetic fluid and nonlinear fiber optics.

Keywords Liquid core fibers · Magnetic fluids

1 Introduction

Optofluidics fundamentally aims at manipulating fluids and light at the microscale and exploiting their interaction to create highly versatile systems. A wide variety of optofluidic devices have recently been demonstrated (Cheng et al. 2004; Sun et al. 2007; Psaltis et al. 2006). Combining fluids and light have produced all sorts of creative devices, such as adaptive optical lenses (Kuiper and Hendriks 2004; Dong et al. 2006) or optofluidic microscopes (Heng et al. 2006). Further opportunities were made available with the recent attempts to synergetically combine both integrated devices and microfluidic systems. In the context of biochemical sensing, fluids can be used to carry substances to be analyzed through highly sensitive microphotonic circuits. Conversely, microfluids can be exploited to control microphotonic devices, making them tunable, reconfigurable, and adaptive. The growing interest in optofluidics has led to a series of recent achievement in liquid-core waveguides (Liu et al. 2010; Schmidt and Hawkins 2008; Hawkins and Schmidt 2008). Various kinds of fluids have been attempted as a liquid core (Payne and Gambling 1973; Hartog 1983), including water (Martelli et al. 2005) and nonlinear liquids, such as carbon disulfide, Toluene and chloroform (Xu et al. 2008; Dai et al. 2009).

Here, we demonstrated a new kind of liquid core optical fiber based on magnetic fluid. Although a variety of remarkable effects, such as Hall effect (Ren et al. 2005), shear-excited sound (Muller and Liu 2002), one-dimensional patterns (Wirtz and Fermigier 1994), solitons (Richter and Barashenkov 2005) convective instabilities (Luo et al. 1999) and thermal lens effect (Pu et al. 2005) have been observed in magnetic fluid, and fibers with "magnetic" cores have been theoretically investigated (Reyes and Rodriguez 1997), there are also some reports about magnetic fluids have been used as cladding (Chieh et al. 2007; Horng et al. 2005; Pu et al. 2007), but no attempts were made to explore novel effects in magnetic fluid core fiber. More surprising results may be anticipated when such distinctive fluid is combined with optical fibers, as light can be strongly confined in the waveguide here. Potentially, those notable effects associated with magnetic liquid can be extended to integrated optofluidics thanks to the combination with fibers.

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2 Experimental

In the fabrication of MFCOF, a Silica T-branch with diameter of 10 mm is selected to encapsulate the hollow fiber with a core-diameter of 5 μm. The magnetic liquid chosen here is paraffin-based Fe_3O_4 magnetic particles. The magnetic particle size was 10 nm. During the fabrication process, a hollow fiber was fixed by integrated with a capillary and then encapsulated into the T-branch with glue at front; the end of the tube was sealed by a silica plate with a thickness of 1 mm (see Fig. 1a). Then magnetic fluid was injected into the tube from the upside, which was also sealed by a cap later. After packing, the magnetic fluid was forced into the hollow fiber using a vacuum (see Fig. 1b, c). In contradiction to our previous study on the fabrication of sub-wavelength liquid core fibers (Liu et al. 2010), where the mixture of Toluene and carbon disulfide were filled into the hollow hole due to capillary action (5 or 6 h needed), here the magnetic fluid was pumped into the fiber by means of a driving force, which only costs about several minutes or less. The negative pressure of the vacuum is 5 Pa. Moreover, the magnetic field can generate chain formation which gives rise to the birefringence effect inside the core (Di et al. 2006).

The optical properties of MFCOF were investigated by sending light into them. If the core were not filled with liquid, light could not propagate in MFCOF. A laser beam with the wavelength of 632.8 nm and the output power of 8 MW was launched into the fiber to test whether the light can propagate in MFLCOF. In order to obtain a higher coupling efficiency, a five-dimensional adjustment of racks and lifts was adopted here. The scheme of the test of guiding light is shown in Fig. 1d.

Figure 2 shows the experimental test of guiding light with (a), (b) at the volume fraction of 0.03%, and (c), (d) at the volume fraction of 0.15%. Lengths of both optical fibers are the same, about 20 cm long. From the pictures, we can learn that the intensity of the output light is higher at a lower volume fraction. This is because Fe_3O_4 magnetic particles are naturally non-transparent. The higher the volume fraction of Fe_3O_4 magnetic particles is, the lower the transmitted power. Figure 2b and d presents an interesting light spot with petal-shaped structures around the beam center. More accurate detect of the output light profile with a laser beam analyzer (LS-2000) were carried out and the results are shown in Fig. 3.

When using a laser beam analyzer to detect the output beam after the MFCOF, light spot lattice was observed which reflects the fine structures of the petal-shaped light spot. Figure 3a–c present the spot lattices corresponding to applied magnetic field of 0Oe, 309Oe and 810Oe, respectively, with a magnetic fluid volume fraction of 0.03%. Figure 3d–f shows the similar results while the magnetic fluid volume fraction is increased to 0.15%. Comparison among Fig. 3a–c or Fig. 3d–f indicates that the increase of the external magnetic field simultaneously reduce the transmitted power as well as the number of the spot lattices. The detailed variation of the transmitted power with the magnetic field is shown in Fig. 3g.

The mode of the MFCOFs observed by the laser beam analyzer (LS-2000) is shown in Fig. 4, where (a) and (b) show the intensity along X,Y distribution of the mode of the MFCOFS with a magnetic fluid volume fraction of 0.03% and (b) and (d) with the volume fraction of 0.15%, respectively. We determined the optical loss of the MFCOFs by measuring their transmission as a function of the length (see Fig. 5) captured by a CCD. The inset image

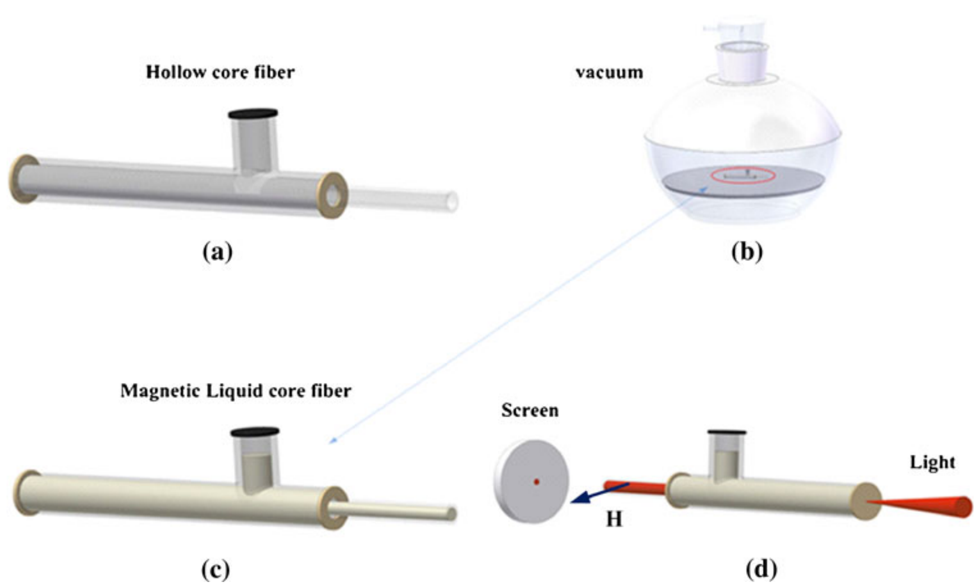

Fig. 1 Schematic representation. **a** A hollow fiber with 5 μm encapsulated by a T branch, **b** a vacuum equipment to pump the magnetic fluid into the hollow fiber, **c** a hollow fiber filled with paraffin based magnetic fluid, and **d** the test of guiding light using the fabricated MFCOF

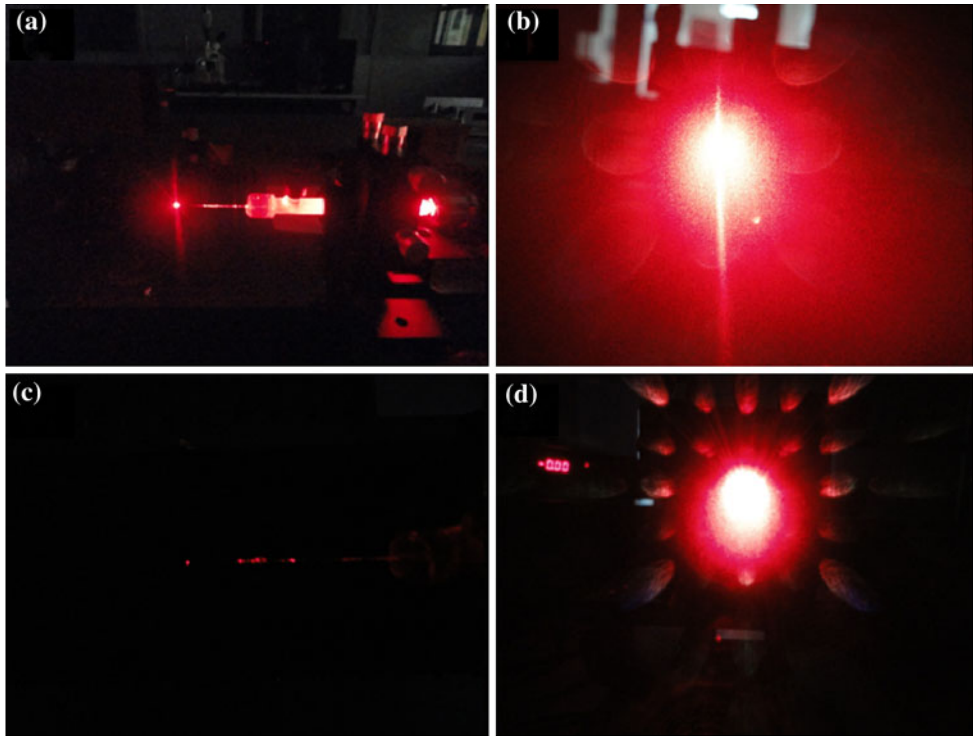

Fig. 2 The experimental setup for the test of guiding light with **a**, **b** at the volume fraction of 0.03%, **c**, **d** at the volume fraction of 0.15%

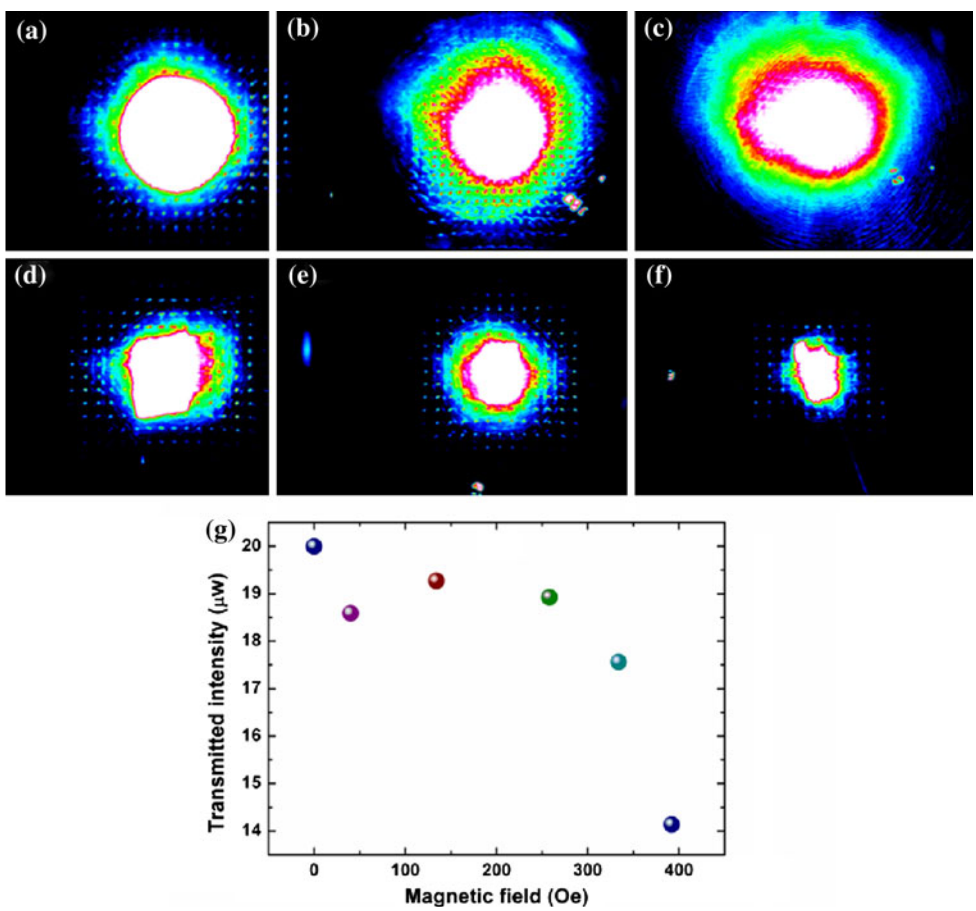

Fig. 3 Magnetic tunable properties of the MFCOF. **a**–**c** The beam images corresponding to applied magnetic field of 0Oe, 309Oe and 810Oe, respectively, with a magnetic fluid volume fraction of 0.03%. **d**–**f** The similar results while the magnetic fluid volume fraction is increased to 0.15%. All these images were observed by a laser beam analyzer. **g** The transmitted intensity of MFLCOF as a function of magnetic field, the direction of which is parallel to polarization of incident light and the magnetic fluid volume fraction is 0.15%

provides the details of the method employed to determine the optical loss of a specific MFCOF. The optical loss was calculated by means of a Loss-Measurement software.

3 Results and discussion

In this paper, we fabricated the first magnetic fluid core optical fiber (MFCOF). The diameter of the hollow hole is 5 μm and the length is 20 cm. Light can be launched into the MFCOF by optical coupling. During the detective process of guiding light, the images of petal-shaped structures scattered around the beam center appeared in our experiment (see Fig. 2b, c). A series of spot lattices were later discovered in further experiment. The small spot lattices (see Fig. 3a–f) and the petal-shaped spots show similar characteristic, with the former reflecting the fine structures of the latter. The origin of scattered spots was due to Fourier transform of complex amplitude of the input laser spot, which has nothing to do with the nanoparticles. Several control samples were performed. The scattered dots can be obtained by use of water fluid with no magnetic particles and even when directly observing the laser beam with the CCD. It is impossible for the nanoparticles to self-arrange in a lattice. Figure 3a–f tells us that the pattern of these spot lattices can be manipulated by the external magnetic field. With the increase of the field intensity, spot lattices are decreasing or even vanish, because the magnetic particles formed chains and the number of the particles were reduced due to the applied magnetic field (Di et al. 2008). Figure 3g shows the transmitted intensity of MFLCOF as a function of the magnetic field. It is very

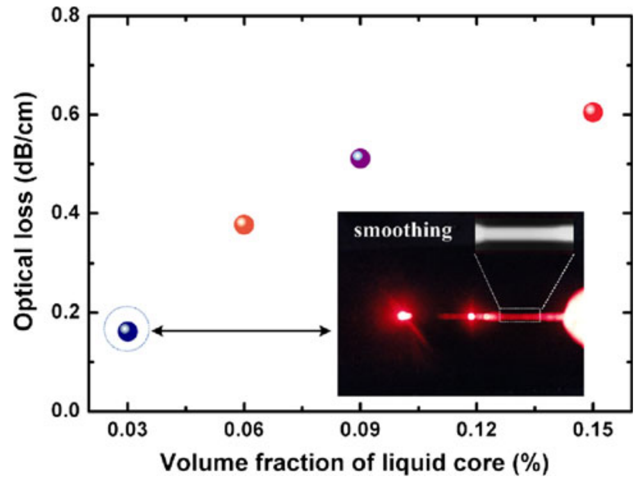

Fig. 5 Optical loss of the MFCOF at different magnetic fluid volume fraction. The inset image presents the details of the method to determine the optical loss of a MFCOF with a volume fraction of 0.03%. The light used to calculate the optical loss needs smoothing before it was sent to the Loss-Measurement software

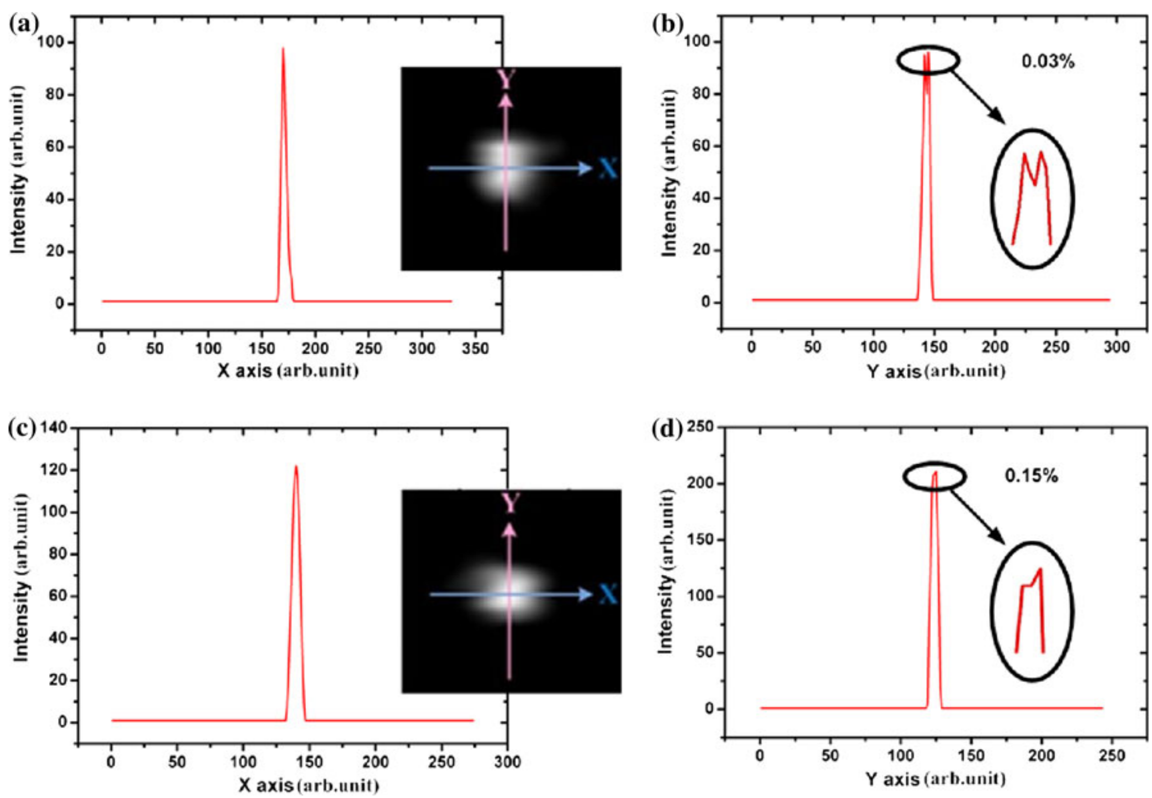

Fig. 4 Mode distribution of the MFCOF. **a**, **b** The intensity distribution of the mode along *X*, *Y* axis at a magnetic fluid volume fraction of 0.03%, and **c**, **d** are at 0.15%. The inset image was observed by the laser beam analyzer connected with an attenuator

clear that the transmitted power is decreasing with the magnetic field, which is consisted with the theory of transmittance (Susamu et al. 1987; Di et al.2007; Pu et al. 2006). In other words, along the direction of magnetic field, the absorption of light was enhanced with the magnitude of the field compare to other directions. The mode and the optical loss of MFCOFs are given in Figs. 4 and 5, respectively. The result shows that the MFCOF allows multi-mode operation, and has an optical loss of less than 0.6 dB/cm. The theoretical about mode calculation as follow: refractive index of the magnetic-fluid core and the cladding are 1.48 and 1.46, respectively. (Here, we use the refractive index of liquid paraffin as that of the liquid core, considering the volume fraction of the magnetic particles was very small and has little impact on the calculation of the mold operation.)

$$V = \pi\frac{D}{\lambda_0}(n_2^2 - n_1^2)^{\frac{1}{2}} = 3.14 \times \frac{5}{0.632} \times (1.48^2 - 1.46^2)^{1/2} = 6.023 > 2.405 \quad (1)$$

We found the peak intensity distribution is double peaks along Y axis, indicating the waveguide is multimode, which is in accordance with the theoretical result.

4 Conclusion

In summary, the first MFCLOF was fabricated and successfully launched the light into it. MFCOF exhibits tunable properties compared with traditional liquid core optical fiber. Our results bridge the gap between micro-liquid core fiber and magnetic fluid. Combined results may create a surprising field of opto-magnetic-fluidics in future.

Acknowledgments This research was supported by the National Natural Science Foundation of China (No. 60508015 and No. 10574092), the National Basic Research Program "973" of China (2006CB806000), and the Shanghai Leading Academic Discipline Project (B201).

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