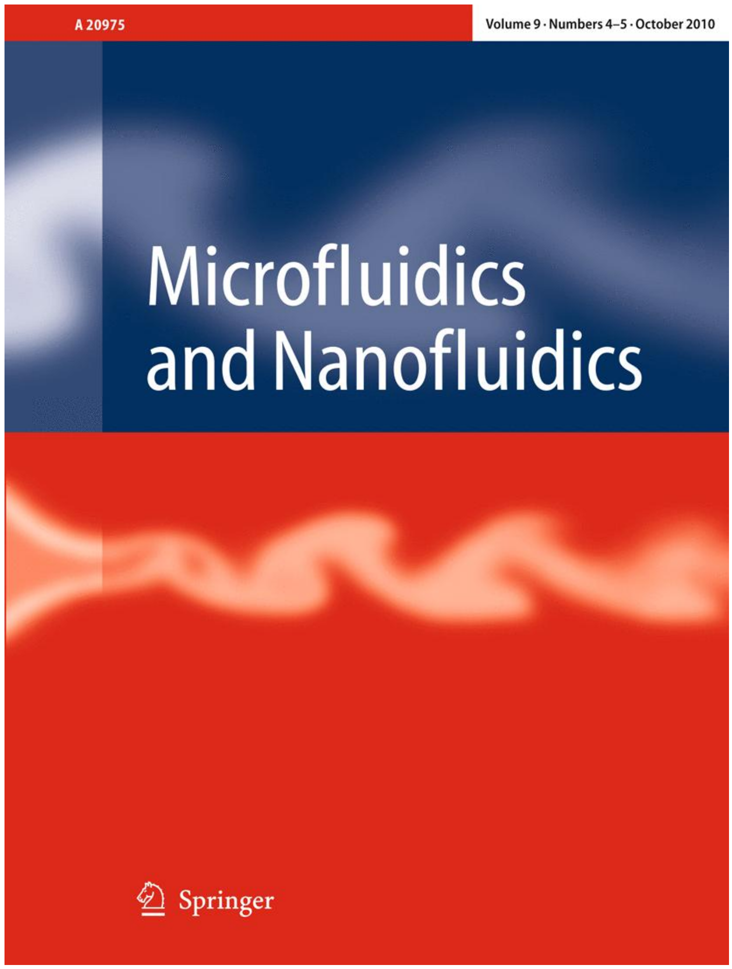
ISSN 1613-4982, Volume 9, Combined 4-5



Microfluid Nanofluid (2010) 9:989–994
DOI 10.1007/s10404-010-0610-7

SHORT COMMUNICATION

Submicro- and micro-diameter liquid core optical fiber

Kun Liu · Yonghao Xu · Fenfen Dai · Xianfeng Chen

Received: 6 February 2010 / Accepted: 22 March 2010 / Published online: 3 April 2010

Abstract We reported the first fabrication of submicro-/micro-diameter liquid core optical fiber. The diameter of the liquid core ranges from 360 nm to 2 μm with the outer silica diameter remaining as large as ten or hundred micrometer. These fibers with advantages of high strength, excellent uniformity and low optical loss about 1 dB/cm can be manipulated and assembled with high accuracy and used as micro- or submicro-scale devices. Besides, those potential in large nonlinear parameter may help to explore low-intensity nonlinear effects in future.

Keywords Submicro-wires · Fibers · Liquid crystals

1 Introduction

Nano-science and sub-wavelength-technology have attracted much interest in recent years because materials exhibit novel properties when structured at nanometer or sub-wavelength dimensions. In the past two decades, nanowires and sub-wavelength wires have been fabricated from a variety of materials using a wide range of techniques (Thurn-Albrecht et al. 2000; Sun and Xia 2002; Scheibel et al. 2003; Liu et al. 2005; Li et al. 2006; Oulton et al. 2008; Yan et al. 2009). Recently, sub-wavelength wires have been drawn from optical silica fibers, which open the way to a host of new optical devices for communications, sensing, biology, and chemistry. Likewise, the large nonlinear parameter will greatly reduce the required power for yielding nonlinear effects (Tong et al. 2003). The effective manipulation of nonlinearities at low power is an attractive research area for scientists and engineers due to the huge potential for all-optical communications. So far, to realize the authentic low-power nonlinear effects at mW level remains to be a challenging issue (Brambilla et al. 2005a; Mägi et al. 2007). Here, we reported the first fabrication of submicro-/micro-diameter liquid core optical fibers, signifying that liquid core fiber has gone to sub-wavelength dimensions. The high strength and excellent uniformity enable these fibers to be manipulated and assembled with high accuracy and used as micro- or sub-micro-scale devices in physical, chemical, biological, medical research, or all-optical communication. Besides, those potential in large nonlinear parameter may help to explore low-intensity nonlinear effects in future.

K. Liu · Y. Xu · F. Dai · X. Chen (✉)
Department of Physics, The State Key Laboratory on Fiber Optic Local Area Communication Networks and Advanced Optical Communication Systems, Shanghai Jiao Tong University, 800 Dongchuan Rd., Shanghai 200240, China
e-mail: xfchen@sjtu.edu.cn

2 Experimental

The fabrication of the SLCOF is divided into two steps. First, a heater was employed to draw a hollow fiber to a sub-wavelength diameter hollow fiber. Second, a pair of T-branches was used to fill the liquid. The fabrication of submicron-diameter silica wires has been reported by Tong et al. (2003), which demonstrated a two-step drawing process to fabricate samples with diameters down to 50 nm. Samples drawn in this way are, however, very short (only tens of millimeters) and have no untapered fiber connection, which makes it difficult to launch light into them. Likewise, the optical coupling makes some loss of the power. Here, a different drawing method was introduced by use of a specially designed electric stripe heater shown in Fig. 1a (Brambilla et al. 2005b; Mägi et al. 2007).

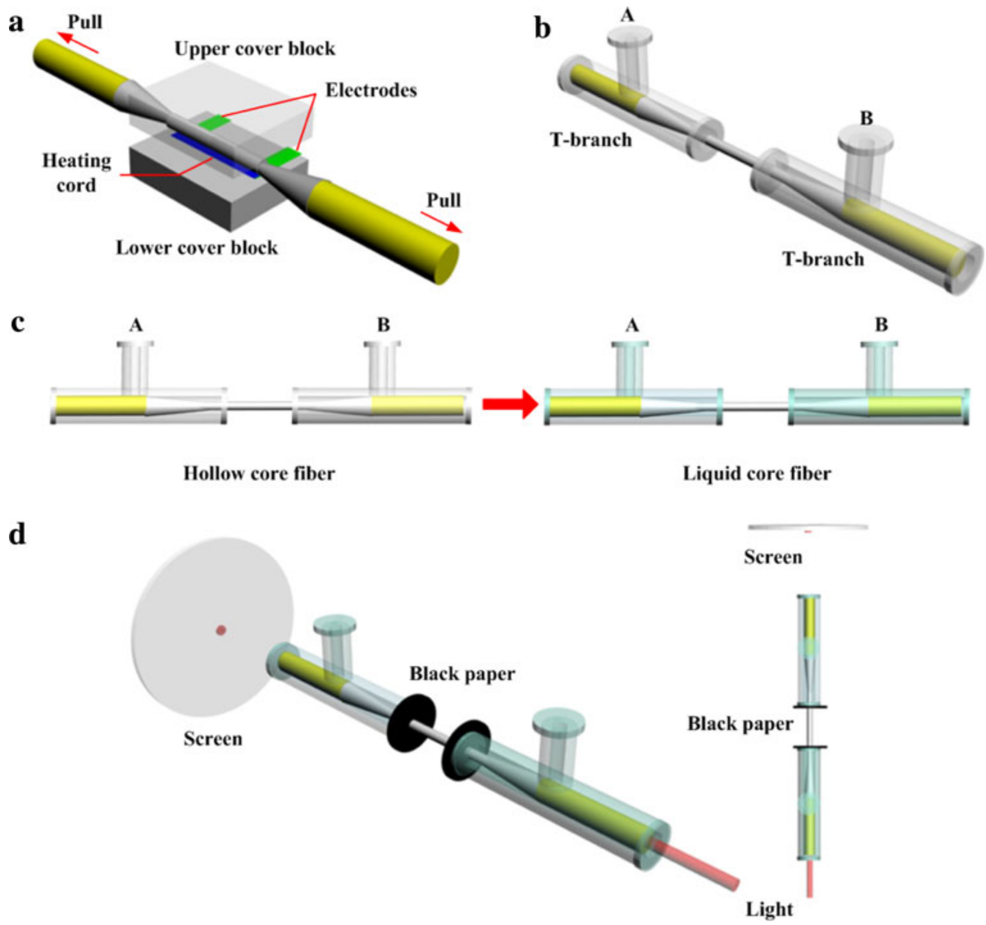


Fig. 1 The fabrication process of SLCOF. **a** Presents the fabrication process of a sub-wavelength diameter hollow fiber using heating method; the pulled fiber passes above the heating cord with length of 15 cm, and the distance between them is about 0.5 cm. By properly altering the supplied voltage, the temperature of the electric furnace can be carefully controlled to achieve more stable taper diameter. **b** Presents a sub-wavelength diameter encapsulated by a pair of T-branches. **c** Presents the process of filling liquid through tube *A*, *B*. **d** Presents the test of guiding light using the fabricated SLCOF

The pulled fiber is placed in an electric strip heater which is 10 cm long with two sides fixed at the edge of the revolving table driven by a stepper motor, which could offer elaborate control in the fiber pulling process. Long heating region with relatively small volume in the furnace exhibits excellent heat preservation and steady temperature distribution during the drawing. The cross-sections of the tapered hollow fibers have been shown in Fig. 2a–d, observed by a scanning electron microscope (SEM). The minimum core diameter of the samples is about 370 nm with the outer silica diameter as large as tens micrometers. Unlike the fragile sub-wavelength-diameter fiber, the large outer diameter of SLCOF can protect the fiber from breaking off. Many samples were fabricated using this method, and the maximum length of the fiber can be tens of millimeters. The excellent uniformity of diameters and surface smooth can be seen in Fig. 2e–h. Fig. 4a shows the inner diameter and the outer diameter has a perfect linear relation in the taping process, which provides a simpler method for measuring the core diameter. By use of this linear relation, the core diameter can be determined according to the outer diameter which is easier to be measured due to the large scale.

In the second step of filling the liquid, two rubs concerning encapsulation and coupling should be well solved. Silica T-branches with diameter of 10 mm are selected to encapsulate the sub-wavelength-diameter hollow fiber fabricated in the first step. The liquids chosen here are a mixture of toluene and carbon disulfide with a ratio of 50%. The nonlinear refractive index of toluene and carbon disulfide are, respectively, 1.3e−19 and 1.2e−18. To fill the liquid, a sub-wavelength-diameter hollow fiber was first put into a capillary. Then we use glue to encapsulate the capillary into two T-branches. The tube ends with a silica plate with a thickness of 1 mm, serving as an optical window (see Fig. 1b). After packaging, liquid was filled into one T-branch, and placed a period of time (about 6 h). The liquid automatically enters the core of the hollow fiber and arrives at another tube owing to the capillary action. Then, the liquid was filled into the other T-branch to prevent the air bubbles caused by evaporation of liquid. So far, the fabrication of a SLCOF was finished (see Fig. 1c).

The optical properties of SLCOF were investigated by sending light into them (see Figs. 1d; 3). If the core were not filled with liquid, light could not propagate in the SLCOF. The 632.8 nm wavelength was employed to test whether light can propagate in the SLCOF. While using a

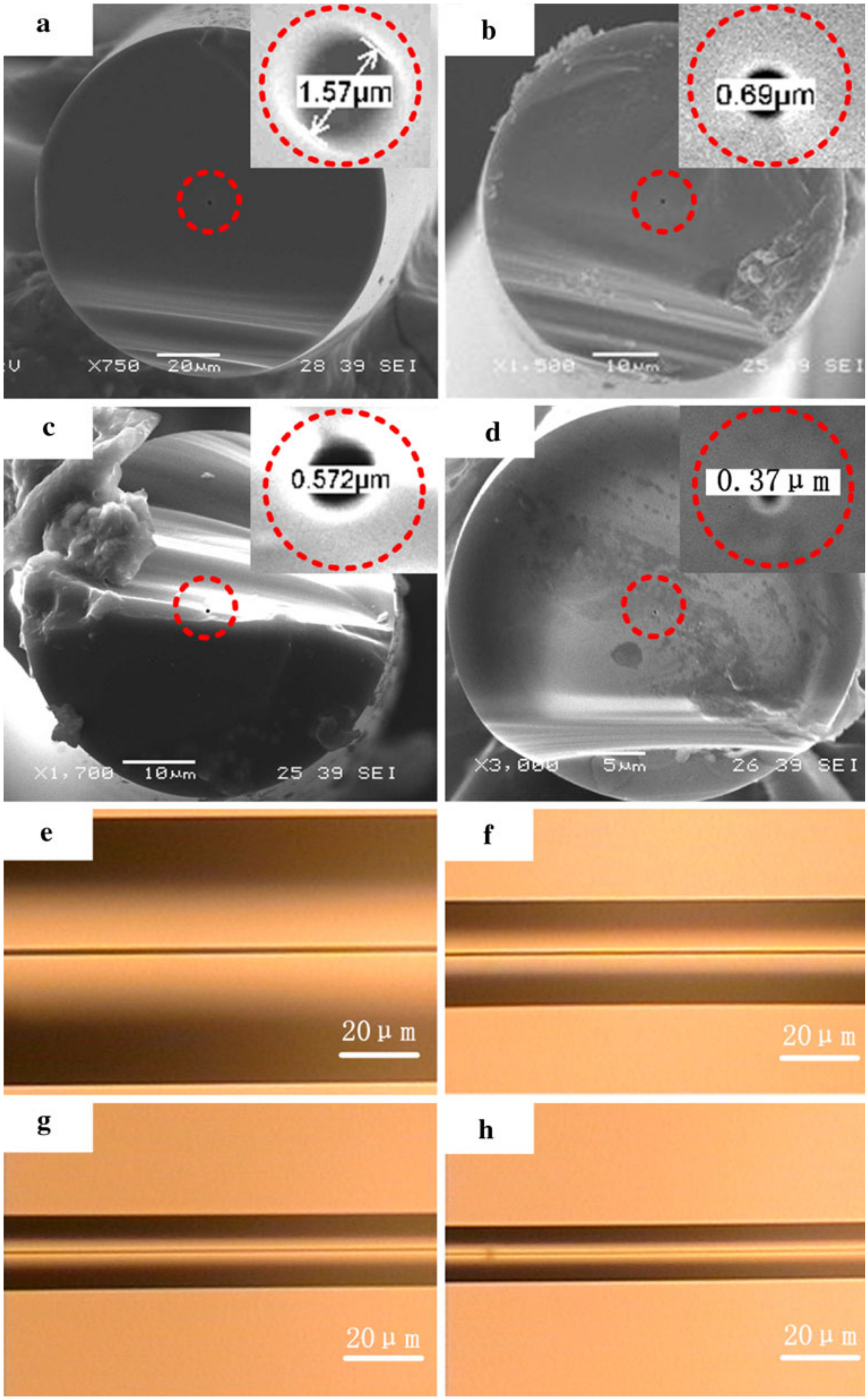


Fig. 2 SEM of cut-off layer and overall picture of hollow fiber. **a–d** Present the SEM of cut-off layer with hollow radius of 1.57, 0.69, 0.572, and 0.37 μm, respectively, while, **e–h** presents the overall picture of those hollow fibers, correspondingly

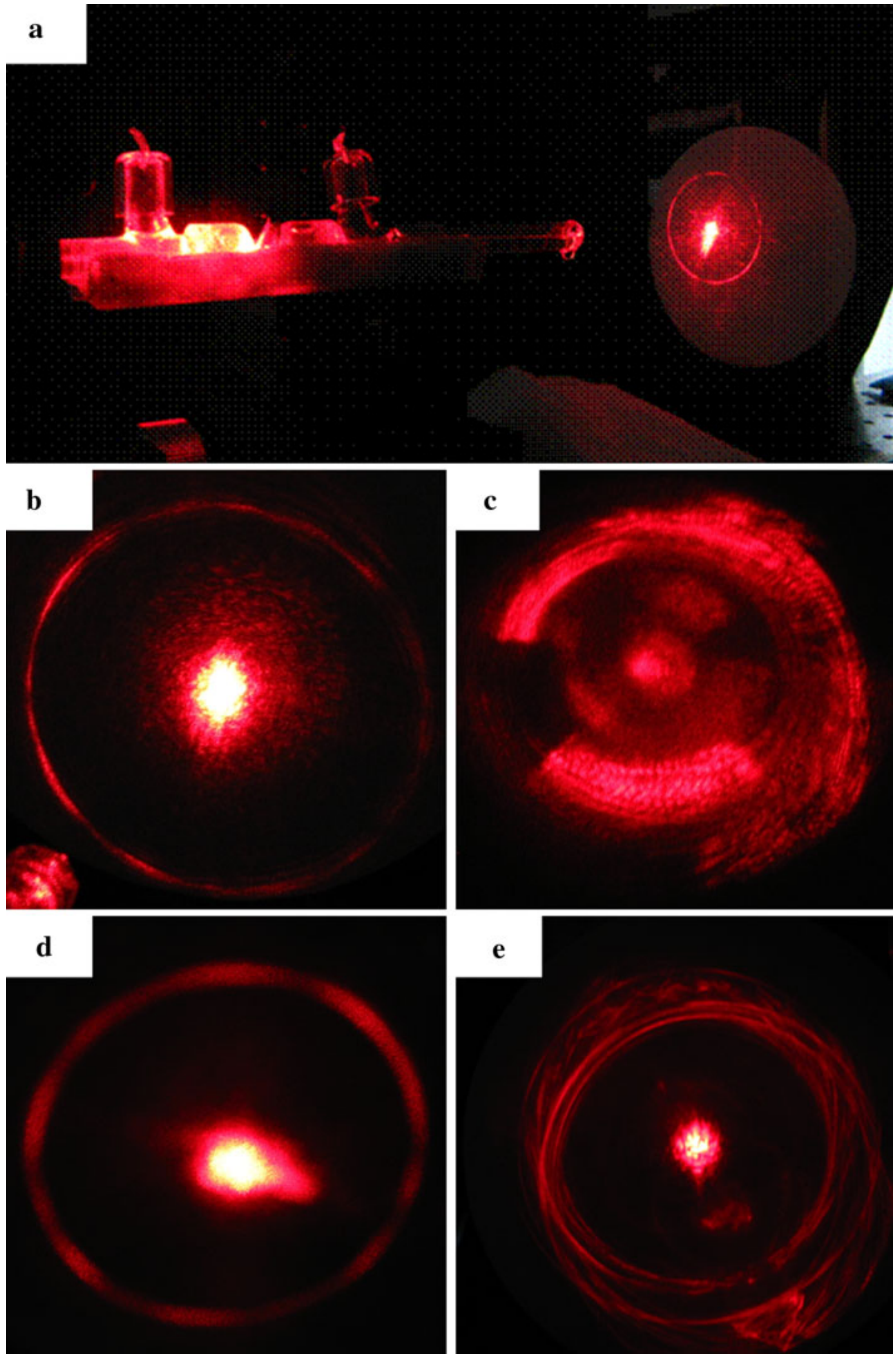


Fig. 3 The experimental test of guiding light. **a** Presents the experiment setup for test of guiding light. **b–e** Presents the beam spot coming from the SLCOF with radius of 1.57, 0.69, 0.572, and 0.37 μm, respectively

five-dimensional adjustment of racks and lifts as a coupling device, a power meter was employed to detect transmission at the output port. To reduce the contribution from scattered light, the SLCOF was surrounded by two pieces of three-layer black paper, so that we can guarantee the measured power come from the optical fiber. Fig. 3 demonstrates that such SLCOF is capable of guiding light into it. Fig. 4b shows the optical transmission at different core scales. The loss was separated into the coupling loss and the propagation loss. The increasing loss with decreasing wire diameter can be attributed to the coupling loss. The propagation loss was determined by measuring the transmission energy at each point on the transmission path captured by a CCD. The result show SLCOF has a relatively low optical loss of 1.312 dB/cm for sample with 370 nm core diameter, which has better performance than results achieved by Tong et al. (2003) which reported a loss of about 0.2 dB/mm. The loss of SLCOF is, however, much larger than that of photonic bandgap fibers (Peucheret et al. 2005). Besides of the coupling loss, some

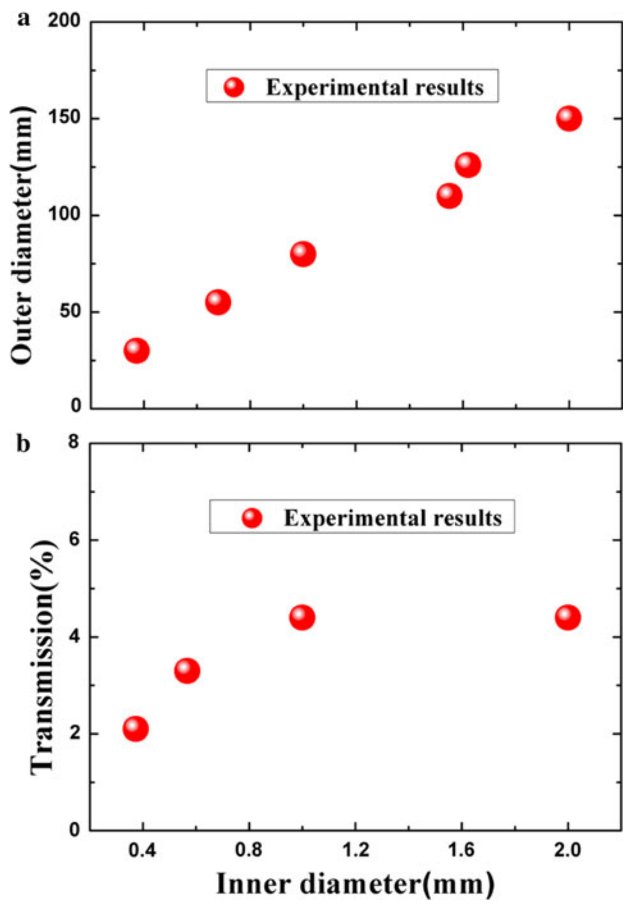


Fig. 4 Basic characteristics of the SLCOF. **a** Shows the inner diameter has a linear relation with the outer diameter. **b** Presents the optical transmission of SLCOF with different radius. The decline of the transmission for sample with radius less than 0.6 μm is attributed to coupling loss

air bubbles may severely influence the light propagation and cause large loss. An improved method for filling the liquid is, hence, necessary in future.

3 Results and discussion

The first low-loss submicro-/nano-diameter liquid core optical fibers (SLCOF) with toluene and carbon disulfide were successfully fabricated. The diameter of the hollow holes ranges from 2 μm down to 400 nm, while the outer silica diameter remains as large as ten or hundred micrometer. Light can be launched into these fibers by optical coupling, having an optical loss of about 1 dB/cm. The results bridge the gap between two important contemporary realms of research—liquid core fiber and submicro-science. This symbolizes a beginning that liquid core fibers are about to enter a submicro era. Likewise, our previous study has theoretically demonstrated that when the diameter is 0.5 μm with the wavelength satisfying 800 nm, the nonlinear parameter of the SLCOF filled with the carbon disulfide shows an enhanced value which is about 18 W^{-1} m^{-1} (Xu et al. 2008). This is 16,000 times larger than in standard silica single mode fibers (Mägi et al. 2007).

This enhanced nonlinearity has potential to exploit nonlinear effects such as “Polarization Instability” (PI) (Winful 1986), “Polarization Modulational Instability” (PMI) (Wabnitz 1988), “Self-phase modulation” (SPM) (Shimizu 1967), “Cross-phase modulation” (XPM) (Islam et al. 1987), “Stimulated Raman Scattering” (SRS) (Garmire et al. 1963), “Four Wave Mixing” (FWM) (Stolen et al. 1974), and “Supercontinuum” (Corkum et al. 1986). These nonlinear effects above as well as dispersion can be easily manipulated through liquid properties such as temperature, concentration, or mixing ratio.

4 Conclusion

Although silicon fibers have gone to submicro or nano scale for several years, liquid core fibers remain micro scale limited by techniques. The SLCOF reported here signifies that the liquid core fibers have gone to submicro. The high strength and excellent uniformity enable these fibers to be manipulated and assembled with high accuracy and used as micro- or submicro-scale devices. Owing to those potential in large nonlinear parameter, an intensive and systematic study on low-intensity nonlinear effects via SLCOF is necessary 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).

References

Brambilla G, Koizumi F, Finazzi V, Richardson DJ (2005a) Supercontinuum generation in tapered bismuth silicate fibres. Electron Lett 41:795–797

Brambilla G, Koizumi E, Feng X, Richardson DJ (2005b) Compound-glass optical nanowires. Electron Lett 41(7):400–402

Corkum PB, Rolland C, Srinivasan-Rao T (1986) Supercontinuum generation in gases. Phys Rev Lett 57:2268–2271

Garmire E, Pandarese F, Townes CH (1963) Coherently driven molecular vibrations and light modulation. Phys Rev Lett 11:160–163

Islam MN, Mollenauer LF, Stolen RH, Simpson JR, Shang HT (1987) Cross-phase modulation in optical fibers. Opt Lett 12:625–627

Li L, Yang YW, Li GH, Zhang LD (2006) Conversion of a Bi nanowire array to an array of Bi–Bi_2O_3 core–shell nanowires and Bi_2O_3 nanotubes. Small 2:548–553

Liu SH, Tok JBH, Bao ZN (2005) Nanowire lithography: fabricating controllable electrode gaps using Au–Ag–Au nanowires. Nano Lett 5:1071–1076

Mägi EC, Fu LB, Nguyen HC, Lamont MR, Yeom DI, Eggleton BJ (2007) Enhanced Kerr nonlinearity in sub-wavelength diameter As_2Se_3 chalcogenide fiber tapers. Opt Express 15:10324–10329

Oulton RF, Sorger VJ, Genov DA, Pile DFP, Zhang X (2008) A hybrid plasmonic waveguide for subwavelength confinement and long-range propagation. Nat Photonics 2:496–500

Peucheret C, Zsigri B, Hansen TP, Jeppesen P (2005) 10 Gbit/s transmission over air-guiding photonic bandgap fibre at 1550 nm. Electron Lett 41:27–29

Scheibel T, Parthasarathy R, Sawicki G, Lin XM, Jaeger H, Lindquist SL (2003) Conducting nanowires built by controlled self-assembly of amyloid fibers and selective metal deposition. PNAS 100:4527–4532

Shimizu F (1967) Frequency broadening in liquids by a short light pulse. Phys Rev Lett 19:1097–1100

Stolen RH, Bjorkholm JE, Ashkin A (1974) Phase-matched three-wave mixing in silica fiber optical waveguides. Appl Phys Lett 24:308–310

Sun YG, Xia YN (2002) Large-scale synthesis of uniform silver nanowires through a soft, self-seeding, polyol process. Adv Mater 14:833–836

Thurn-Albrecht T, Schotter J, Kästle GA, Emley N, Shibauchi T, Krusin-Elbaum L, Guarini K, Black CT, Tuominen MT, Russell TP (2000) Ultrahigh-density nanowire arrays grown in self-assembled diblock copolymer templates. Science 290:2126–2129

Tong LM, Gattass RR, Ashcom JB, He S, Lou JY, Shen MY, Maxwell I, Mazur E (2003) Subwavelength-diameter silica wires for low-loss optical wave guiding. Nature 426:816–819

Wabnitz S (1988) Modulational polarization instability of light in a nonlinear birefringent dispersive medium. Phys Rev A 38:2018–2021

Winful HG (1986) Polarization instabilities in birefringent nonlinear media: application to fiber-optic devices. Opt Lett 11:33–35

Xu YH, Chen XF, Zhu Y (2008) Modeling of micro-diameter-scale liquid core optical fiber filled with various liquids. Opt Express 16:9205–9212

Yan RX, Gargas D, Yang PD (2009) Nanowire photonics. Nat Photonics 3:569–576