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PbS Quantum Dots Filled Photonic Crystal Fiber for All-fiber Amplifier

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Abstract. In this paper, we have proposed a novel type of fiber amplifier by filling the PbS semiconductor quantum dots into the holes of photonic crystal fibers (PCFs) for the first time. Based on simulation results, we have found that the loss of PCF filled with PbS is slightly increased compared with the one without PbS at wavelength of 1310 nm. Furthermore, we have successfully fabricated the PbS-filled PCF with selective air-hole cladding by a new perfusion technique that can optimize the overall loss.

1. Introduction

In recent years, semiconducting quantum dots (QDs) based optical fibers for optical amplifier are As an important support platform for information technology, optical fiber communication plays an important role in the future information society. In optical communication, it is vital to enhance the utilization of optical band. With the development of low loss of anhydrous fiber, people reconsidered using 1310 nm wavelength to communicate[1], currently, mainly propose three types of fiber amplifiers, doped rare earth fiber[2], raman fiber [3]and quantum dot fiber[4,5] ,but an important problem is the development of optical amplifier used in 1310nm is not mature so that a stable and high gain optical amplifier supporting optical communication in 1310nm is needed.

On the other hand, quantum dots(QDs) show great potential in the application of optical amplifier[6-9]. Due to the size effect as well as quantum confinement effect, the semiconductor quantum dots based optical amplifier possesses the advantages of wide spectrum of amplification, low pumping conditions and high gain[10]. In particular, the Lead sulfide(PbS) QDs are attractive because the emission spectrum covers the telecommunication band ranging from 1200 nm to 1600 nm [11,12].In addition, PbS quantum dots have high quantum yield (QYs) and good photo thermal stability in practical applications [13,14]. At present, the processing technique of quantum dots becomes mature, but the research of quantum dots as the gain medium to compose quantum dot device for quantum dot fiber, especially for , still needs to go deeper.

In this work, we have proposed and demonstrated a novel method to fabricate optical amplifier with high gain by combining semiconductor quantum dot. Based on the capillary pressure, PbS quantum dots are filled into the air hole of photonic crystal fiber (PCF). Such PbS filled PCF enables to build optical amplifier system that isolates quantum dot from oxygen. We have established the model of the end face of the optical fiber in COMSOL and the mode field distribution of photonic crystal fiber and quantum dot photonic crystal fiber. We improved the filling method by dropping the overall loss of 3.5 dB.

2. Simulation of PbS Quantum Photonic Crystal Fiber

Through the model analysis, we can obtain the mode field distribution of the quantum dot photonic crystal fiber (QDPCF) model, according to the mode field distribution of the fundamental mode of PCF which is evenly distributed in the fiber core. Considering the weak fundamental mode penetrating in the cladding, the energy is mainly concentrated in the core in optical transmission with a low transmission loss. The quantum dots poured into the holes of cladding, and then dried into quantum dot films, which is equivalent to plate with a layer of PbS quantum dot films in the air holes. We build a QDPCF face model with Comsol, and simulated the mode field with adding 5 layers of air holes. The mode field distribution is as shown in Fig.1.

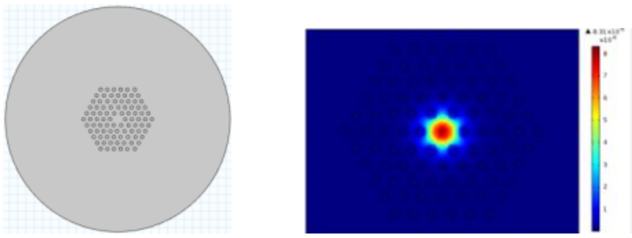
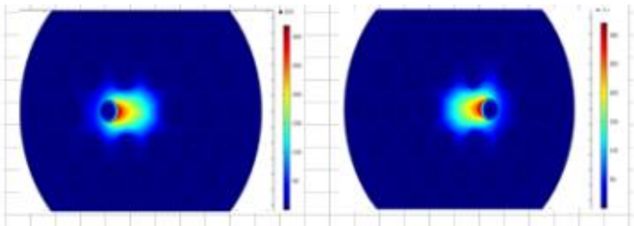


Fig. 1. (a) The schematic diagram of solid-core photonic crystal fiber (PCF); (b)The mode field distribution of the quantum dot filled in PCF.

When the quantum dot coated film leaning to the left cladding, the mode field distribution is as in Fig. 2(a). Oppositely, when the quantum dot coated film leaning to the right cladding, the mode field distribution is as in Fig. 2(b).



(a) (b)

Fig.2. The mode field distribution (a).The left side of the refractive index is high; (b).The right side of the refractive index is high

It is can be found that the fundamental mode meets the condition of total reflection in the transmission. Because the refractive index of cladding is increased after adding quantum dot films into cladding, which results in weakened bound of fundamental mode. So the energy leakage ratio of fundamental mode will be increased, and the energy fundamental mode is leaning to the quantum dot coated film. We calculate the limiting loss of the optical fiber by the imaginary part of the effective refractive index of the fundamental mode based on method reported by previous report . We find that the confinement loss of the PbS-filled PCF is slightly increased by 1.3 dB/km compared with the PCF without PbS at operation wavelength of 1310 nm.

3. Preparation of PbS Quantum Photonic Crystal Fiber

The PbS QDs were synthesized according to the Cademartiri method[8]. They were then modified by In the experiment, we have fabricated two kinds of PbS-filled PCF: one is PCF with all of air-hole cladding filled with PbS; the other is PCF with selective air-hole cladding filled with PbS. Both PCF devices are made by capillary action. The quantum dots are prepared by ultrasonic vibration at first, and then poured into air hole of photonic crystal fiber. The PCF should be put into a vacuum oven at once and dried vacuum for 12 hours at 25 ℃.

The fabricated PCF with all the air-hole cladding filled by PbS is measured by Scanning Electron Microscope (SEM) and the results are shown in Fig. 3. silicon (Si) and Oxygen (O) refer to photonic

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crystal fiber itself. and S (shown in Fig. 3(c))and Pb (shown in Fig. 3(d)) appear on end face of the fiber. This indicates that PbS quantum dots have been filled into air holes of photonic crystal fiber.

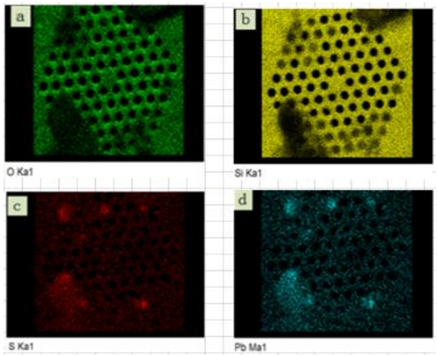

Fig.3. The elemental analysis by scanning the end face: (a)O of elements (b) Si of element (c) S of element(d) Pb of element

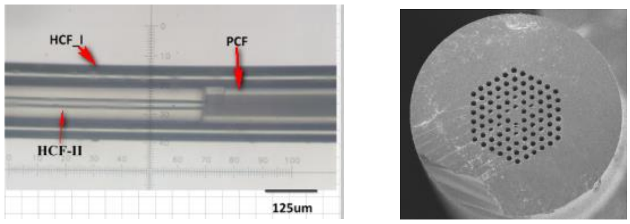

Fig. 4. (a) Microscopic image of PCF for filling PbS in selective air hole cladding: the hollow core fiber (HCF-I) is used to fix the fibers; the HCF-II is used to deliver the PbS to the targeted air-hole cladding. (b) Scanning Electron Microscope image of end-facet of the fabricated PCF with selective air-hole cladding filled with PbS.

Moreover, we can selectively fill the PbS into air holes of PCF. The microscopic image is shown in Fig. 4(a): the hollow core fiber (HCF-I) is used to fix the fibers; the HCF-II is used to deliver the PbS to the targeted air-hole cladding. The end-facet of fabricated PbS-filled PCF is shown in Fig. 4(b). In this way, we can complete the selective filling of three layer of air holes. Then we take out the fiber and fuse the ends with single-mode fiber pigtail to measure the overall loss.

In the absence of pumping light injection, optic transmission spectrum of 1310 nm in two cases as shown in Fig.5(Without filling shown in Solid line,Selectively filling shown in second line,Ordinary filling shown in lower line) , the overall loss is approximately dropped 3.5dB in same of fiber length.

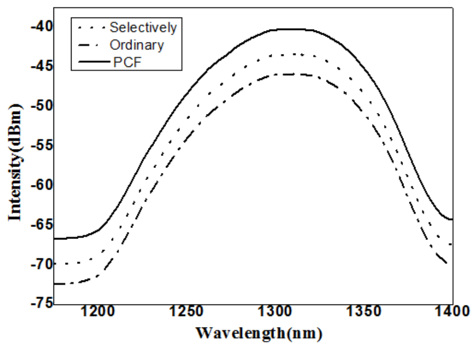

Fig. 5. The transmission spectrum at 1310nm(Without filling shown in Solid line,Selectively filling shown in second line, Ordinary filling shown in lower line)

4. Conclusion

In this work, the quantum dot is injected into the holes of the 10 cm photonic crystal fiber , and it is dried under the normal temperature vacuum condition, then the photonic crystal fiber is pigtailed by single-mode fiber, using 980nm laser whose power is 2mW as a sign light source. Moreover, this method is more simple and controllable compared with growth method where the quantum dot in solution is unstable so that it is worth studying to improve the growth method. We find that the confinement loss of the PbS-filled PCF is slightly increased by 1.3 dB/km compared with the PCF without PbS at operation wavelength of 1310 nm. Selectively filling compared with ordinary filling that the overall loss is approximately dropped 3.5dB in same of fiber length.

References

[1] Turkiewicz, Jarosław Piotr. "Cost-effective n × 25 Gbit/s DWDM transmission in the 1310 nm wavelength domain." Optical Fiber Technology 17.3(2011):179-184.\
[2] Seo Y S, Lim C H, Fujimoto Y, et al. 9.6 dB Gain at a 1310 nm Wavelength for a Bismuth-doped Fiber Amplifier[J]. Journal of the Optical Society of Korea, 2007, 11(2):63-66.
[3] Pang, F., Sun, X., Guo, H., Yan, J., Wang, J., & Zeng, X., et al. (2010). A pbs quantum dots fiber amplifier excited by evanescent wave. Optics Express, 18(13), 14024-14030.
[4] Cheng C, Hu N. Broadband Pb Se Quantum-Dot-Doped Fiber Amplifiers from 1250 nm to 1370 nm[J]. Acta Optica Sinica, 2016, 36(4):0406002.
[5] Cheng C, Hu N, Cheng X. Experimental realization of a PbSe quantum dot doped fiber amplifier with ultra-bandwidth characteristic[J]. Optics Communications, 2017, 382:470-476.
[6] Sapra, S, et al. "Unraveling internal structures of highly luminescent PbSe nanocrystallites using variable-energy synchrotron radiation photoelectron spectroscopy. " Journal of Physical Chemistry B 110.31(2006):15244-50.
[7] Lobo, A, et al. "Photoelectron spectroscopic investigations of chemical bonding in organically stabilized PbS nanocrystals. " Journal of Physical Chemistry B 109.37(2005):17422-8.
[8] Peng, Xiaogang, et al. "Epitaxial Growth of Highly Luminescent CdSe/CdS Core/Shell Nanocrystals with Photostability and Electronic Accessibility." Journal of the American Chemical Society 119.30(1997).
[9] Akiyama T, Kuwatsuka H, Simoyama T, et al. Nonlinear gain dynamics in quantum-dot optical amplifiers and its application to optical communication devices[J]. IEEE Journal of Quantum Electronics, 2001, 37(8):1059-1065.
[10] Cheng Cheng, Lin Yanguo, and Yan Jinhua. "Red Shift of Photoluminescence Spectrum of CdSe/ZnS-Quantum-Dot Doped Fiber." Acta Optica Sinica 31.4(2011):0406002.
[11] Bakueva L, Musikhin S, Hines M A, et al. Size-tunable infrared (1000–1600 nm) electroluminescence from PbS quantum-dot nanocrystals in a semiconducting polymer[J]. Applied Physics Letters, 2003, 82(17):2895-2897.
[12] Klem E J D, Levina L, Sargent E H. PbS quantum dot electroabsorption modulation across the extended communications band 1200-1700 nm[J]. Applied Physics Letters, 2005, 87(5):053101-053101-3.
[13] Hatami S, Würth C, Kaiser M, et al. Absolute photoluminescence quantum yields of IR26 and IR-emissive Cd(1-x)Hg(x)Te and PbS quantum dots--method- and material-inherent challenges.[J]. Nanoscale, 2015, 7(1):133-43.
[14] Lee K R, Homan S B, Kodaimati M S, et al. Near-Quantitative Yield for Transfer of Near-Infrared Excitons within Solution-Phase Assemblies of PbS Quantum Dots[J]. 2016, 120(39).