CHIN. PHYS. LETT. Vol. 26, No. 5 (2009) 054216

Nonlinearity of InP-Doped Fibers *

ZHANG Ru(张茹)**, CHEN Xi(陈曦), WANG Jin(王瑾), DUAN Yu-Wen(段予文)

Key Laboratory of Optical Communication and Light-wave Technologies (Ministry of Education), School of Sciences, Beijing University of Posts and Telecommunications, Beijing 100876

(Received 30 December 2008)

By combining nano-technology with fiber technology, an optical fiber doped with semiconductor nano-particles as InP is fabricated by using the modified chemical vapor deposition (MCVD) method. Proved by experiment, the fiber has excellent waveguide characteristics, and the concentration of InP is approximately 0.1%. By using a scanning electron microscope, a stereo-scan photograph of the fiber is obtained, and based on the graph, presentations of the fiber under both magnetic and electronic fields are simulated, the effective core area $A_{\rm eff} \approx 10\,\mu m^2$ is calculated, and so is the nonlinear index $\gamma = 10.53\,W^{-1}/Km$ of the fiber. This research leads a new method of high nonlinearity fiber fabrication.

PACS: 42.81.Bm, 42.50.Gy

Nowadays, research on functional optical fibers has become a hotspot in the optic communications field. In 1966, Kao and Hockham[1] predicted that low-loss optical fibers would be applied in communications, which explored a virgin field called optic communications and focused almost all the sights of researchers on this planet. In 1970, the Corning Glass Works fabricated a single-mode fiber by pure silicon, and breakthrough of 20 dB/km attenuation of the fiber is a marker of the optic communications age. With the development of optic communications, new optical devices are widely used in communication systems. As the core of these optical devices, optical fiber with a high nonlinear coefficient plays an important role for future agile optic communications.[2]

The idea that doping a normal optical fiber with some special kind of materials in order to change the characteristic of the fiber and obtain a high nonlinearity fiber is derived from the Er doped fiber and the Nd doped polarization-maintaining fiber, which uses a common method of element doping.[3] It is based on this theory that high nonlinearity optical fibers doped with lanthanon as Er, and semiconductor elements as Ge, S, and P are fabricated.

The photonic crystal fiber (PCF) has an extraordinary core structure, such as adjustable-diameter of the core, the air hole, and the distance of two holes; and this makes it become a path in obtaining the high nonlinearity fiber. The nonlinear parameter γ is defined as[4]

$$\gamma = \frac{n_2 \omega_0}{c A_{\rm eff}}, \tag{1}$$

where n_2 is the nonlinear refractive index of the fiber, and ω_0 is the working frequency, c is the velocity of light in vacuum, $A_{\rm eff}$ is known as the effective core area. It can be easily seen from Eq. (1) that the nonlinear parameter is in proportion to the nonlinear refractive index, and in inverse proportion to the effective core area. In order to increase the nonlinear coefficient, two ways are viable based on the PCF: the first one is to reduce the effective core area by a special design of the core. In 2003, researcher Petropoulos *et al.*[5] presented a small-core lead-silicate holey fiber with a nonlinear coefficient as high as $640\,W^{-1}km^{-1}$ at about 1550 nm; the other way is to increase the nonlinear refractive index of the fiber material. Ebendorff *et al.*[6] reported a bismuth oxide glass holey fiber with a nonlinear refractive index as high as $2.02 \times 10^{-19}\,m^2/W$, and the nonlinear coefficient is $1100\,W^{-1}km^{-1}$ at about 1550 nm, which is thousands of times the nonlinearity of conventional fibers. However, PCF suffers from its costly production, complex procedure, inflexibility in connecting with conventional optical fiber, and inconvenience to produce in batches. These limit applications of high nonlinearity PFCs.

At the same time, nano-technology has been developing. Hopefully a novel optical fiber will be obtained by combining optical fiber with nano-technology. There have already been no-cladding nano-scale fibers with a 50 nm diameter core, and taper nano-scale fibers. Although these are only fibers whose geometry size attains a nano-scale, and do not use nano-material in their fabrication, their success paves the way for the application of nano-material in fiber fabrication. Meanwhile, we fabricated an InP material doped inner cladding fiber, which has a gain characteristic.[7–9]

Generally, nano-particles are in the nano-scale, i.e. about 1–100 nm, which is larger than an atom but smaller than common particles. They have many characteristics of heat, magnetism, optics, and sensitivity, different from the common particles. That is an advantage of using nano-material in fiber fabrication.[10]

Considering that the transmission of the wave is in the core of a fiber, some kind of nano-material is doped in the core to change the structure of the core,

*Supported by the National Natural Science Foundation of China under Grant Nos 60544002 and 60871082.

**To whom correspondence should be addressed. Email: rruzhang@yahoo.com

© 2009 Chinese Physical Society and IOP Publishing Ltd

to focus the wave, and to reduce the effective core area on the one hand, on the other hand, to heighten the nonlinear refractive index, so as to obtain a novel optical fiber which has a high nonlinearity.

InP is an important compound semiconductor of the Ⅲ-Ⅴ cluster, a new material used in electronics after Si and GaAs. Its crystalloid appears dark gray, and has a structure of sphalerite. The crystal lattice constant is 5.869A. The forbidden bandwidth is 1.35 eV under normal temperature. It has a direct transition of band structure, and the sending wavelength is 0.92 μm. In addition, InP has characteristics such as high chance of electron transfer and wide forbidden bandwidth, but Si and Ge do not have these.

After our comprehensive consideration in relative factors such as the working-wave of the optical fiber, the energy bandwidth of the semiconductor, the effective refractive index, the melting point, and the viscosity, InP is chosen as the doped nano-material so that the optical fiber doped with nano-material would be widely and conveniently connected with other optical devices. It is anticipated to have a high nonlinear index.

The manufacture of optical fiber involves two stages. In the first stage, a vapor-deposition method is used to make a cylindrical preform with the desired refractive-index profile and the relative core-cladding dimensions. A typical preform is in length 1 m and diameter 2 cm. In the second stage, the preform is drawn into a fiber using a precision-feed mechanism that feeds it into a furnace at a proper speed. During this process, the relative core-cladding dimensions are preserved. In both the stages, preform fabrication and fiber drawing involve sophisticated technology to ensure the uniformity of the core size and the index profile.

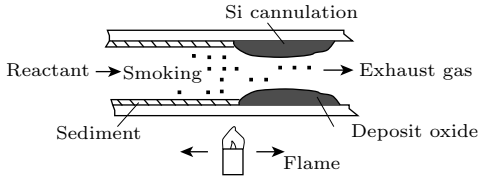


Fig. 1. Schematic diagram of the MCVD process.

Several methods can be used for making a preform. The three commonly used methods are modified chemical vapor deposition (MCVD), outside vapor deposition (OVD), and vapor-phase axial deposition (VAD). The MCVD method is chosen here in consideration of the special characteristic of the nano-material InP. In order to prevent the reaction of oxygen and InP, improvement is made to the MCVD.

Figure 1 shows a schematic diagram of the MCVD process. In this process, materials of $SiCl_4$ etc. are mixed with oxygen, react with each other under a high temperature of 1800°C, and produce smoke in the glass tube. The smoke is hydrolyzed to some powder of oxide such as SiO_2, and slowly the powder is deposited on the inner of the glass tube. To ensure uniformity, the flame is moved back and forth across the tube length. The refractive index of the cladding is controlled by C_2F_2; when a sufficient cladding thickness has been deposited with multiple passes of the torch, we ventilate the inert gas N_2 to the glass tube for a while to avoid the reaction of InP nano-material and oxygen under high temperature. Then the grains of InP, which are at the nano-scale of 15–20 nm, are taken into the region of sediment with N_2 and other gases to form the core. When all the layers have been deposited, we heat the loose preform to a temperature of about 2000°C, then it is collapsed to the solid preform. In the process, we control the pressure, temperature, and velocity of the gas in the glass tube at a proper level so that the grains of InP are hopefully equally doped in the Si core.[11,12]

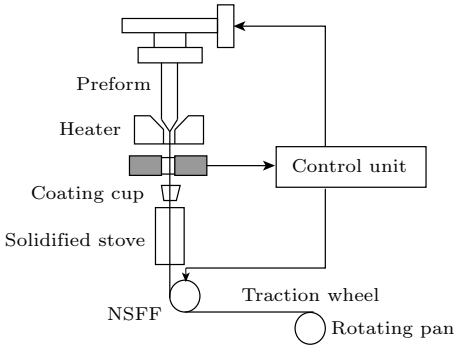


Fig. 2. Drawbench device.

The solid preform is put on the drawbench machine to be heated for the preparation of the drawbench. In order to produce an optical fiber doped with nano-material InP with high quality and to avoid the part and volatilization of InP in the Si core, the technology of stably low temperature and evenly slow rate of drawbench is chosen. The temperature will be controlled between 1600 and 1700 degrees centigrade, the rate must be slower than 5 m/min, and the structure of the device of the drawbench is shown in Fig. 2.[13]

After the fabrication of the fiber, some tests and experiments are given on this fiber to obtain its concentration of doped material, appearance of the core, and the waveguide characteristic.

The waveguide characteristic is the most basic characteristic of a fiber. For the sake of proving this speciality of the fiber, one end of the fiber is exposed under a light source, and an electron microscope is used to observe if there is any light wave in the other end of the fiber. Figure 3 reveals that a light wave can be detected in the other end of the fiber, and this experiment shows that this novel optical fiber has an excellent waveguide characteristic.

In the experiment of ICP, a sample weighing 0.1181 g reaches a concentration of 1018 μg/g. In order to erase the error in experiment, an empty bottle sam-

ple is used in the contrast, and its result is 4.62 μg/g, which is far lower than the result we obtained before, and higher than the detection limit of the system. The percentage concentration of P in the fiber is 0.1%.



Fig. 3. Waveguide characteristic of the fiber.

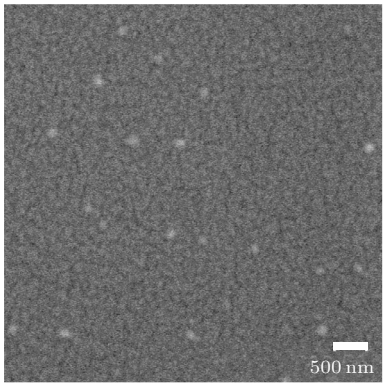


Fig. 4. Stereo-scan photograph of the fiber.

A scanning electron microscope (HITACHI S-4800 FE-SEM) is used to observe the appearance of the core section of the fiber. Figure 4 shows an image of part of the Si core doped with InP nano-material, and the magnification times is 100 K. In the photograph, 10 grids stand for 500 nm, meaning that the width of each grid is 50 nm. The diameter of the white dot in the photograph is about one third of a grid, which is approximately 20 nm. It is close to the bulk of the InP nano-material doped in the Si core in our study. The InP particles in the Si core present some regular structure and form a new micro-structure.

Like all electromagnetic phenomena, the propagation of optical fields in fibers is governed by Maxwell's equations. In the international system of units, these equations are

$$\nabla \times E = -\frac{\partial B}{\partial t}, \tag{2}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t}, \tag{3}$$

$$\nabla \cdot D = \rho_f, \tag{4}$$

$$\nabla \cdot B = 0, \tag{5}$$

where E and H are the electric and magnetic field vectors, respectively, and D and B are the corresponding electric and magnetic flux densities. The current density vector J and the charge density ρ_f represent the sources for the electromagnetic field. In the absence of free charges in a medium such as optical fibers, $J = 0$ and $\rho_f = 0$.

According to Maxwell's equations, we should calculate the energy distribution of the core under both the electronic field and magnetic field condition, by using the finite element method (FEM). In order to simplify the problem, we consider $\hat{\boldsymbol{n}} \times \boldsymbol{H} = 0$ of the boundary condition of the fiber, which is an idealization condition, and the nature condition $\hat{\boldsymbol{n}} \times \boldsymbol{E} = 0$.

Furthermore, to set up a reasonable model of the core is important to the simulation. Based on the graph of SEM, we have considered the size of the particles, and the distribution and distance of particles. A regular distributing particle model is formed, as shown in Fig. 5. In order to embody the influence of InP particles in the fiber, we set the refractive index of the particles to 2.8 while the other part is 1.4, the refractive index of silicon. Using this model, in combination with the FEM, we simulate the energy distribution under both electronic and magnetic field conditions, and obtain propagation constants of $\beta = 5.67898 \times 10^6$ and $\beta = 5.6693 \times 10^6$, respectively.

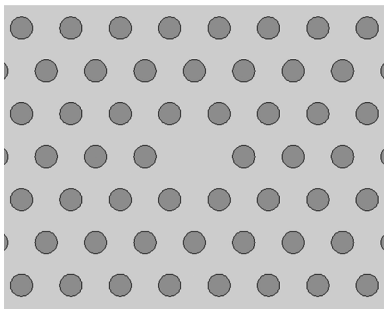


Fig. 5. Model of the optical fiber.

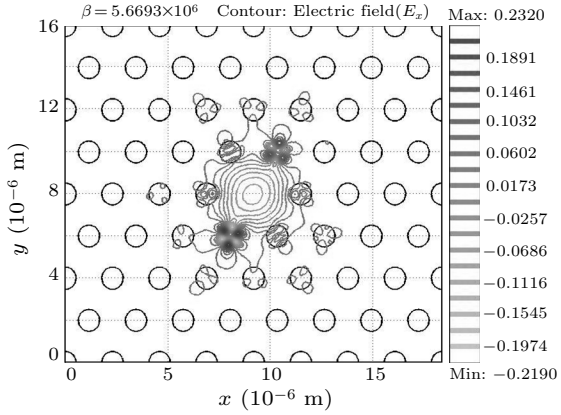


Fig. 6. Presentation of electronic field and propagation constant.

Figures 6 and 7 show contour views of the energy distribution under both electronic and magnetic field conditions. The wave energy is focused in the center of the core because we doped the InP particles in the

core and a new structure is formed. The particles and the structure restrict the wave propagation in a specific area as small as they can. This area, where the wave is restricted, is thought to be effective in the core. Thus we obtain the effective core area $A_{\text{eff}} \approx 10\,\mu\text{m}^2$, which is less than an average level of a normal fiber (about $20\,\mu\text{m}^2$ to $100\,\mu\text{m}^2$). Considering the effect of the doped material InP, we use $n_2 \approx 2.6\times10^{-20}\,\text{m}^2/\text{W}$ as the nonlinear refractive index of the fiber, and obtain $\gamma = 10.53\,\text{W}^{-1}/\text{Km}$ of the fiber, implying that this new kind of optical fiber has a higher nonlinear index than a normal fiber.

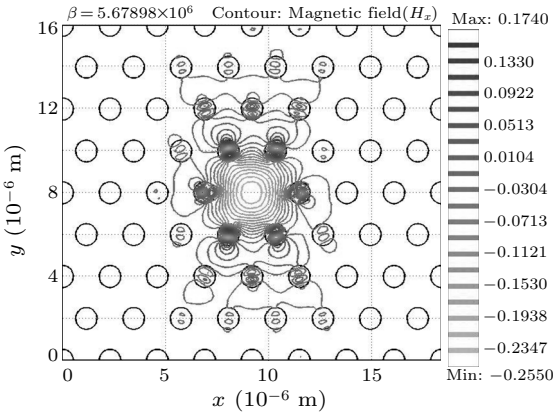


Fig. 7. Presentation of magnetic field and propagation constant.

By controlling the pressure, temperature, and velocity of gases in the glass tube, we manufacture an optical fiber doped with nano-material InP through MCVD technology. As proved by experiment, the novel optical fiber has an excellent wave-guide characteristic, its percentage concentration of P in the fiber is 0.1%, and a stereo-scan photograph of the core appearances is obtained with SEM. The nano-particles doped in the core restrict the wave propagation in the core and change the nonlinear refractive index of the fiber, and this fiber is expected to have a high nonlinear index. In order to prove this characteristic of the fiber, a reasonable model of the core is formed based on the characteristic of the core in experiment. By using this model, the energy distribution of the core and the propagation constant are simulated, and we obtain the effective core area $A_{\text{eff}} \approx 10\,\mu\text{m}^2$. Based on the result, the nonlinear index $\gamma = 10.53\,\text{W}^{-1}/\text{Km}$ of the fiber is obtained, implying that this kind of fiber has a high nonlinear index; a new way of high nonlinearity fiber fabrication is explored by combining nano-material with fiber fabrication.

References

[1] Kao K C and Hockham G A 1986 *International Conference on Advanced Infocomm Technology* (New Jersey 4–10 February 1986) p 493
[2] Diament P 1990 *Wave Transmission and Fiber Optics* (New York: Macmillan) chap 3 p 199
[3] Guang J R, Qiang Z and Peng W 2007 *Acta Phys. Sin.* **56** 994 (in Chinese)
[4] Agrawal G 1995 *Nonlinear Fiber Optics* (San Diego CA: Academic) chap 9 p 345
[5] Petropoulos P, Ebendorff H H and Finazzi V 2003 *Opt. Express* **11** 3568
[6] Ebendorff H H, Petropoulos P and Asimakis S 2004 *Opt. Express* **12** 5082
[7] Guan L M 2006 *Board of Optronics Lasers* **17** 137
[8] Zhang R and Zhang Q F 1997 *J. Atom. Mol. Phys.* **14** 577
[9] Zhang R, Guan L M and Lee G L 2007 *Chin. Phys. Lett.* **24** 998
[10] Zhu J et al 2003 *Nano-device and Materials* (Beijing: Tsinghua University) p 11 (in Chinese)
[11] Ainslie B 1991 *J. Lightwave Technol.* **9** 220
[12] Yong Q Y, Hai S T and Ding N 2007 *Opt. Commun. Technol.* **31** 60
[13] Dove J, Russell H and Kim J 2001 *Optical Devices for Fiber Communication* Ⅱ (New York: Macmillan) chap 35 p 62