

Review on developments of novel specialty fibers: performance, application and process

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Abstract This paper reviews the development progress of optical fiber, the producing and application of the specialty optical fiber in the world. Finally it states the leading technology of optical fiber of the world. Specialty optical fibers are series of optical fiber which could satisfy special requirements. Recently, the rapidly growing need from fiber to the home (FTTH), sensors, active optical link, energy conversion and delivery and fiber laser attracts researchers and optical companies to explore more possibilities of optical fiber and some novel specialty optical fibers were invented for the efforts. Bending insensitive optical fiber with the ability of extreme 3 mm bending diameter makes it possible to use the optical fiber as the electric wire in some extremely compact devices. Higher power was achieved in the fiber laser field with the development of rare earth doped fiber. Nanomaterials such as Au particles and ZnO nanostructures were utilized to extend the application in sensors and energy conversion. Pure silica design was commercialized to improve the radiation resistance of sensors based on fiber optics.

Keywords single mode optical fiber, bending-insensitive, rare earth doped fiber, nano technology

1 Introduction

Since the born of optical fiber in 1966, optical fiber technology has developed rapidly. Kinds of fiber were invented to improve the quality of human life, such as single mode telecommunication fiber, multi mode optical fiber, dispersion compensation fiber, and so on. Recent years, some novel designs have been used to demonstrate some potential possibilities in optical fiber's applications. More and more technologies have been used in design,

process and interdisciplinary research of optical fiber in the field of nano technology, laser manufacture and next generation optical telecommunication. This paper reviews some representative research works about optical fiber technology to illustrate the development trend.

2 Bending insensitive single mode optical fiber

As we known, the optical fiber is a kind of dedicated optical device in sense which is sensitive to environment such as bending, temperature, radiation, even the light wave itself. In the typical communication application, the optical fiber should be always protected well from bending and stress to avoid additional loss. However, customers are usually inclined to use electric wire or cable rather than optical fiber cable as the bending issues. Unfortunately, the optical fiber is indeed sensitive to bending.

Equations (1) and (2) [1] are the refractive index distribution associated with the bending radius. Here, $n(x,y)$ is the refractive index of the straight fiber, ν is Poisson's ratio, and P_{11} and P_{12} are components of the photoelastic (or elasto-optical) tensor. Again, the refractive index tilts with bending, but in this case it typically decreases toward the outside of the bend.

$$n' = n \left(1 + \frac{x}{R_{\text{eff}}} \right), \quad (1)$$

$$R_{\text{eff}} \equiv \frac{R}{1 - \frac{n^2}{2} [P_{12} - \nu(P_{11} + P_{12})]}. \quad (2)$$

Figure 1 shows the effective index distribution of bending optical fiber. From the graph, it is clear that the confinement and the mode field distribution will change enormously and this will cause the bending loss and polarization dependent loss both [1].

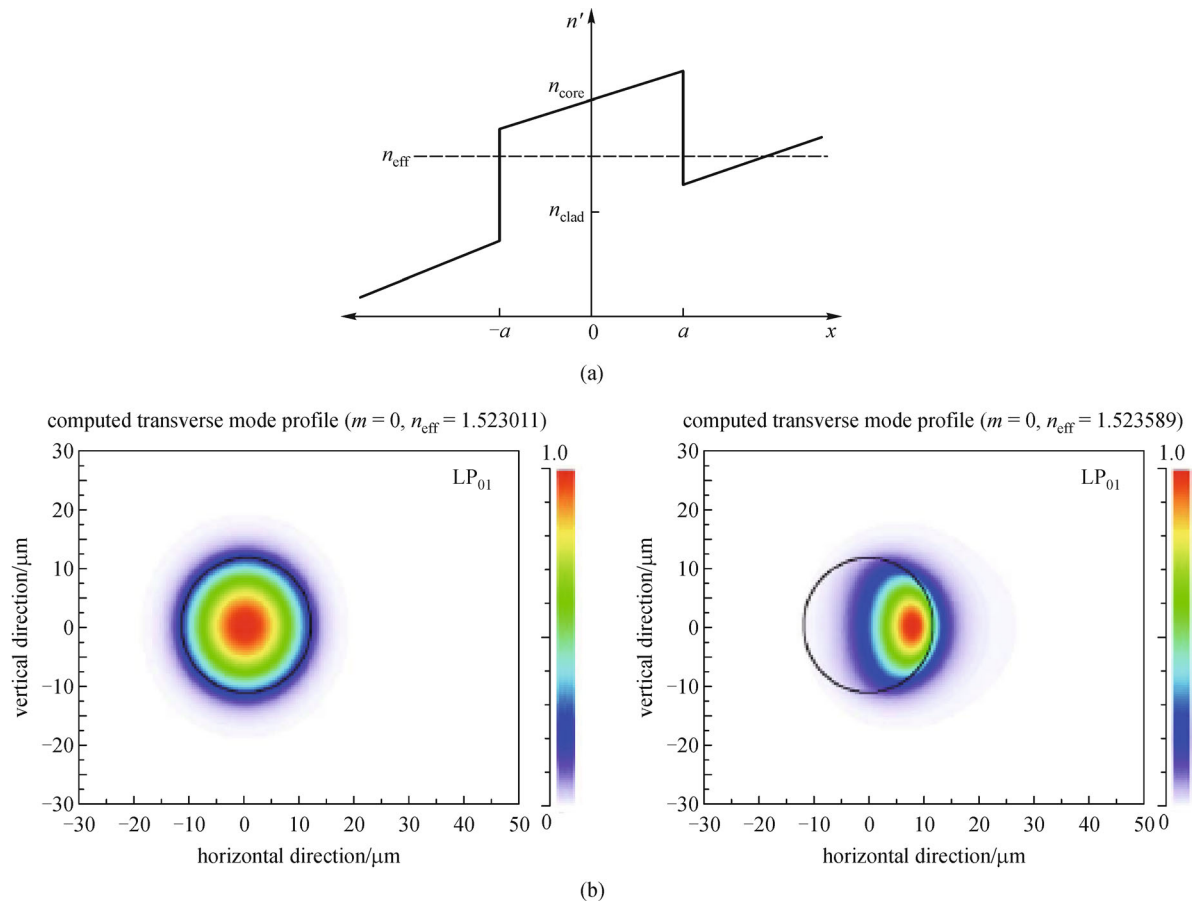


Fig. 1 (a) Refractive index distribution of bending fiber; (b) intensity distribution of bending fiber [1]. n_{eff} is effective refractive index, n_{core} is refractive index of core, n_{clad} is refractive index of cladding, LP₀₁ is the linear polarization mode-01

To minimize the side effect of bending, some technologies were introduced to the design. The most effective design is the microstructure design, which introduces periodical air hole around the core area to reduce the effective index of cladding. Nakajima et al. reported a novel hole assisted single mode fiber with ultra low bending loss [2], and a novel patchcord which could be bended to any radius. Figure 2 is the cross-section image of this fiber.

However, this kind of design is not appropriate for industrial production and the end should be prepared especially in the patchcord process. Fiberhome Telecommunication developed a novel designed single mode fiber based on the trench assisted solid optical fiber. This fiber could also be bended to the radius as small as 1.5 mm, and the bending loss of φ 5 mm \times 10 turns is below 0.1 dB which means the user could also use this kind of specially designed fiber like electric wire or cable, and for the patchcord manufactures, they could manufacture the free bending patchcord without optimizing any process.

Besides the bending insensitive ability, more and more researchers start to focus on the multi-path interference

(MPI) effect in the short length bending insensitive fiber (BIF). Because of the BIF index profiles, coherent MPI may arise from improper bends, staples and connections. This MPI can be found in a few mode BIFs, in which a higher order mode propagates as a weak replica of the signal and interferes with the fundamental mode at the output of the fiber [3]. Aida et al. reported an effective method to estimate the MPI in BIF statistically. Figure 3 shows the spectral loss variation and histogram of BIF, and they use the equations as below to calculate the MPI value.

$$MPI = (\text{Average of max. loss variation})^2 / [4Crest(N)^2], \quad (3)$$

$$Crest(N) = (4 \sum_{k=1}^N \sqrt{P_{\text{multi},k}}) / (\pi \sqrt{\sum_{k=1}^N P_{\text{multi},k}}). \quad (4)$$

Travagnin posted a more detailed work on the MPI measurement and stated that the MPI noise increases as the splice loss rises, and as the fiber cutoff wavelength increases for all kinds of BIF [4].

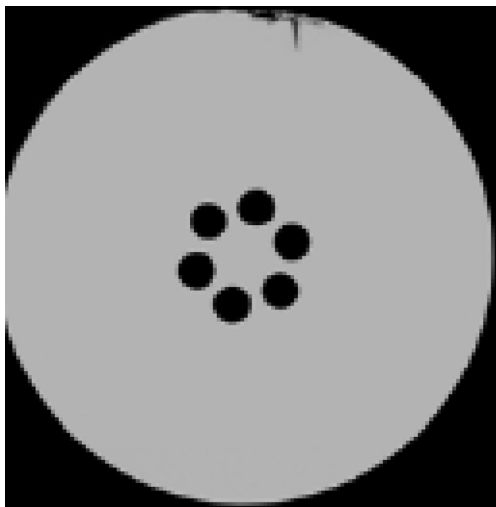


Fig. 2 Cross section image of hole assisted single mode optical fiber

3 Nanostructure modified optical fiber

As optical fiber has intrinsic dimensional advantage in length direction, it is more and more important in fiber sensor and overlapping with other technologies such as

nanotechnology. Ju's group reported a novel design which utilized fiber technology and nanotechnology. A novel optical fiber having its cladding doped with Au nanoparticles was developed by modified chemical vapor deposition process. Absorption peaks of the optical fiber preform and the fiber appearing at 585 and 428 nm respectively, were due to surface plasmon resonance (SPR) of the incorporated Au nano-particles (NPs) in the cladding [5]. Figure 4 shows the refractive index and the propagation of light through the cladding of the fiber doped with Au NPs. The refractive index difference between the core and cladding was about 0.00125, enabling light signal to propagate into the cladding region not into the core. The cladding width and total diameter of the optical fiber were 2.6 and 124.3 μm , respectively. To confirm formation of Au NPs in the cladding, the optical fiber preforms were examined by transmission electron microscope (TEM) and UV-VIS spectrophotometer. Optical absorption of the optical fibers was also measured to confirm the propagation of light and the existence of Au NPs by the cut-back method using the Optical Spectrum Analyzer. Then, to characterize SPR sensing property, optical absorption of the fiber was measured by putting small drops of the refractive index matching oil with various refractive indices ($n = 1.406\text{--}1.436$) on the surface

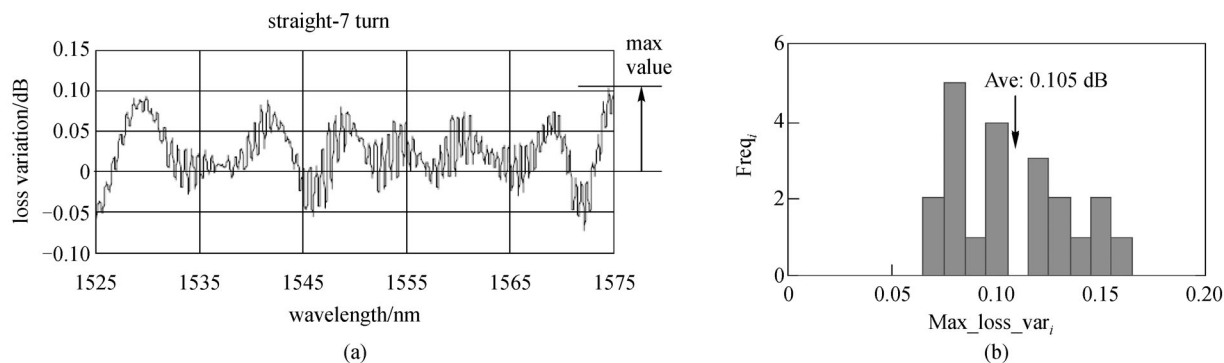


Fig. 3 (a) Example of spectral loss variation; (b) histogram of maximum spectral loss variation [4]

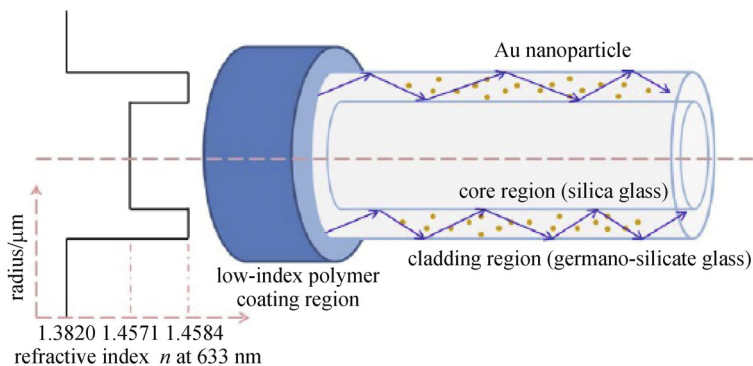


Fig. 4 Refractive index and propagation of light through the cladding of the fiber doped with Au NPs [5]

of the fiber. The total and detector lengths of the fiber used for the SPR measurement are 50 and 5 cm, respectively, as shown in Fig. 5.

In 2012, Wang’s group reported a novel structure which combines optical fiber and nano materials for the solar cell application. In this work, the researcher deposited a compound structure with ZnO nanowires, indium-tin oxide (ITO) film and electrode on the surface of optical fiber as shown in Fig. 6. A novel device with 3.3 V voltage and 7.65 μ A was fabricated successfully, which could be a candidate for the power source for nanosystems in biologic sciences, environmental monitoring, defense technology and even consumer electronics [6].

4 Rare earth doped fiber

Because of huge advantages in the electric power consumption, size, response speed, and conversion efficiency, fiber laser is more widely applied in industrial fields of shipbuilding, automobile manufacturing, aerospace, military equipment, etc., compared to traditional

carbon dioxide lasers. Moreover, fiber lasers can also be used in communication systems to support higher transmission speeds, which are the future of high-bit-rate dense wavelength-division multiplexing (DWDM) system and the foundation for future coherent optical communications.

Rare earth doped fiber’s application has become even more widespread as fiber lasers, amplifiers core components, including rare earth doped fiber ytterbium-doped fiber, erbium-doped fiber, thulium-doped fiber, erbium and ytterbium co-doped fiber.

For demands of high-power, high stability and good environmental adaptability, researchers focused their work on rare earth-doped optical fiber doped with rare earth ion concentration upgrade technology, photonic darkening effect of inhibiting, anti-damage threshold technology, nonlinear effects control technologies, efficient coupling technology, thermal management and control techniques to optimize the beam quality and other properties, and achieved a series of progress in rare earth-doped fiber doping process, preform preparation process, the drawing process, etc.

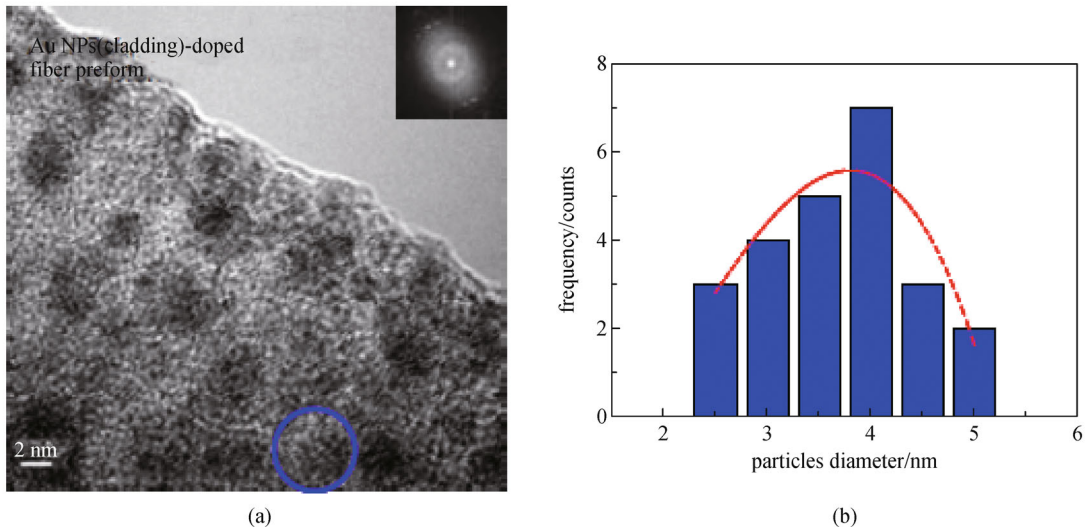


Fig. 5 TEM image (a) and size distribution (b) of Au NPs incorporated in the cladding of optical fiber preform [5]

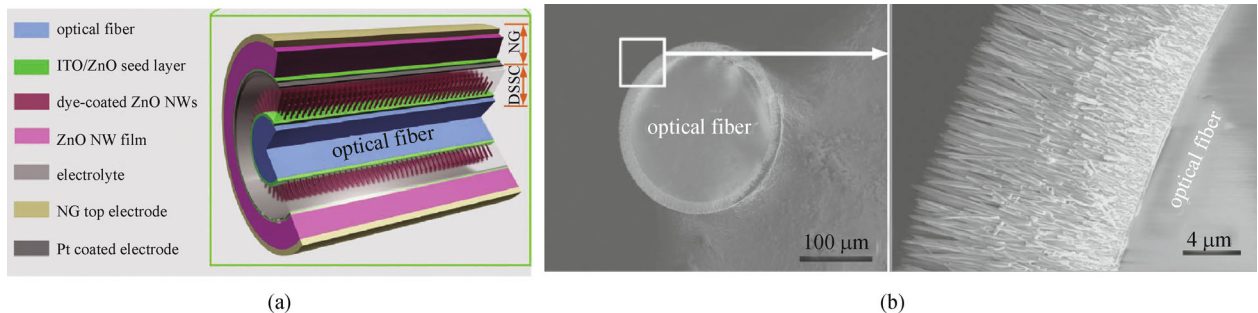


Fig. 6 (a) Optical fiber based solar cell structure; (b) ZnO nanowire on the surface of optical fiber [6]

4.1 Photo-darkening effect suppression technology

Photo-darkening affects the power stability of Yb-doped silica fiber lasers and amplifiers. There are final output power degradation and time depend on the operating conditions of the given laser system [7] as well as on the chemical composition and fabrication process of the fiber. Photo-darkening could be tested by the system shown in Fig. 7 [8].

Microstructure of rare earth doped fiber which is based on conventional doping system will be changed because of the high power pump light effects. Table 1 shows the increase of Al-Oxygen Hole Center (Al-OHC) in fiber microstructure of Yb-doped silica fiber, which has been affected by high power pump.

Figure 8 shows that by doping a new different charged ion, the photo-darkening effects in rare-earth doped fiber will be minimized effectively.

4.2 Efficient coupling technology

GTWave Southampton Optoelectronics Research Centre (ORC) technology has been proposed recently. This method consists of a doped fiber and a signal fiber which is surrounded by at least one multimode optical fiber contacting with each other, the entire GTWave is coated with low refractive index of the polymer cladding layer, as shown in Fig. 9.

GTWave pumping is a unique coupling structure,

different from conventional transport mode pumping, tapered fused bundle (TFB) pumps light along the fiber axis gradually coupled to the signal fiber [9]. This requires a certain length to achieve coupling of the pumping light without larger outer diameter and higher numerical aperture. The pump light in this structure is coupled along the side of the fiber length by the coupling rather than a single point, which minimizes fiber damage or deformation to improve the pumping efficiency to achieve high power.

4.3 Large mode area fiber mode control technology

Large-mode technology can effectively enhance the stability of high-power fiber. However, the increasing of mode field diameter will lead to multi-mode oscillation. So it is necessary to find ways to control mode diameter.

Many inherent troubles of Holey fiber technology may be avoided according to leakage losses essence of endlessly single-mode (ESM) property. Target-oriented design method (TODM) brings potentialities of triple clad fibers (TCF) with arbitrarily available structure and performance into full play in transmission performance based on the scalar wave equation combined with infinitesimal calculus of fiber performance.

The TCF consists of a core, a depressed cladding, a raised cladding and an outer cladding with the uniform refractive index n_{cl} . The outer radius, the refractive index, and the relative refractive index difference of the core are

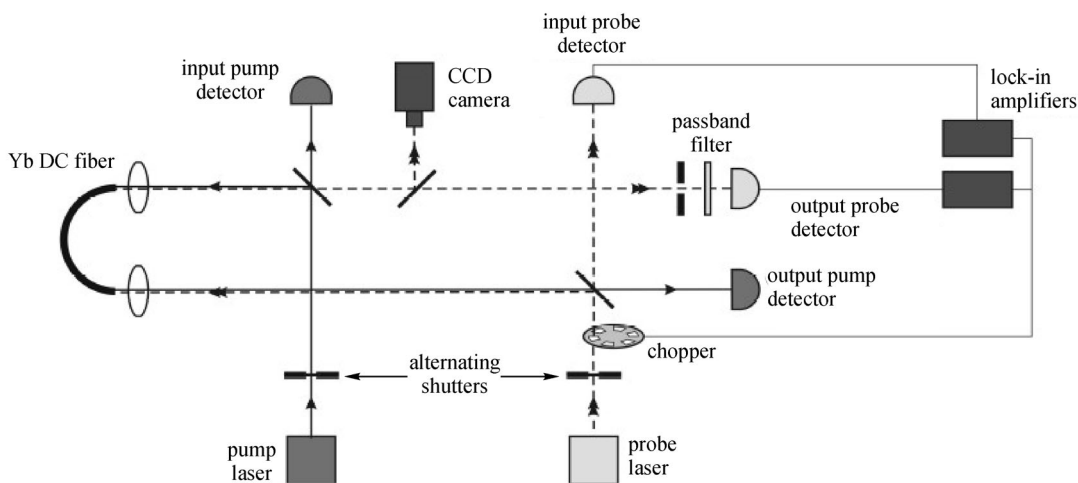


Fig. 7 Schematic illustration of the photodarkening characterization setup [8]

Table 1 Quantitative analysis of color centers in Al-Yb co-doped silica glasses by ESR measurements [8]

sample	spin density/(spins · g ⁻¹)			
	Si-E'	Si(H)-E'	Al-E'	Al-OHC
original fiber	2.0×10^{14}	2.9×10^{13}	–	–
photodarkened fiber	1.9×10^{14}	2.8×10^{13}	–	1.4×10^{14}

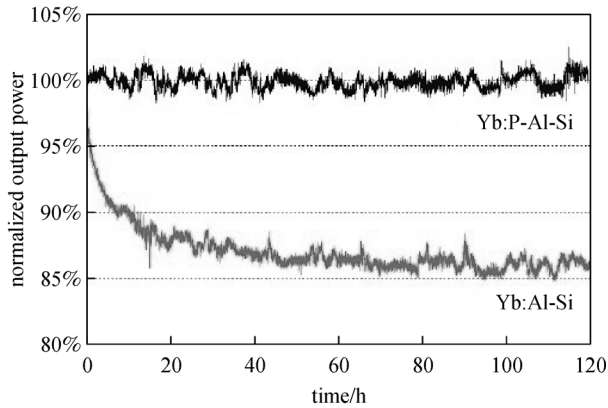


Fig. 8 Output power loss over time for 1064-nm fiber amplifiers built with 2 m of fiber [8]

a , n_{co} and Δ_{co} ; and the depressed cladding and the raised cladding are n_1 and Δ_1 ; respectively. The index profile of the TCF is shown in Fig. 10. Equation (2) shows that the cutoff wavelength λ_{c11} is influenced by the TCF structure.

$$\lambda_{c11} = \frac{2\pi a \sqrt{n_{co}^2 - n_{cl}^2}}{V_c}, \quad (5)$$

where $V_c = 2.4048$ for the step profile fiber.

Another way to control the mode diameter is the chiral coupled core (3C) fiber technology. This 3C fiber core diameter is much larger than conventional double-clad large mode area fiber, and the ability to achieve single-mode output. Chiral coupling fiber consists of a core center and at least one spiral surrounding the central core around the core satellite (see Fig. 11). This structure is designed to force high order optical modes in the central core to be coupled to the satellite core while only LP_{01} mode transmission in the central core.

5 Orbital angular momentum transmission fiber

Optical fiber communication, as the backbone of today's

telecommunications, supports voice, video, and data transmission through global networks. A critical issue in optical communications research is the challenge of meeting the needs of the inevitable growth in data transmission capacity. DWDM has been proven to be an efficient solution that provides a multiplicative-factor (on the order of 100) increment. Fueled by emerging bandwidth-hungry applications, much work has been focused on increasing the data spectral efficiency by utilizing polarization, amplitude, and phase manipulations of the optical field.

It is known that photons can carry orbital angular momentum (OAM), which is associated with azimuthal phase dependence of the complex electric field. Light beams carrying OAM can be described in the spatial phase form of $\exp(i\ell\phi)$ ($\ell = 0, \pm 1, \pm 2, \dots$). As OAM has an infinite number of orthogonal eigenstates, it provides another degree of freedom to manipulate the optical field.

OAM based free-space and fiber optical communication systems have been proposed for spectral and energy efficient communication links, which can meet the latest trend in the field of optical communications. In free-space optical communication links, multiplexing Laguerre–Gaussian (LG) modes carrying OAM has been demonstrated to be an efficient way to increase the spectral efficiency and data capacity. Moreover, the OAM modes based optical communication system can potentially provide improved security. There are many other applications of optical OAM modes beyond data communications, including microscopy, laser cutting of metals, and optical tweezers. Consequently, efficiently maintaining the OAM modes in an optical fiber, which can potentially facilitate many applications, is of great importance. Some recent research has shown the capability of OAM excitation and transmission (1 km) in fiber. Though the reach and stability of OAM mode propagation in the ring fiber needs further investigation, it can potentially open the door to a host of different applications.

In multimode step-index fiber, unwanted radially higher order modes can easily be excited. Thus a strict restriction to the mode coupling is posed. A small change in the launching condition, such as variation of angle, mode spot

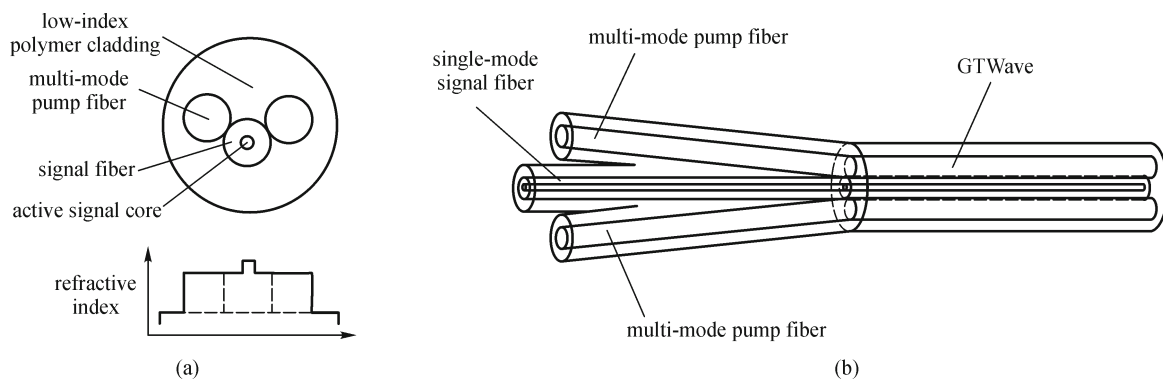


Fig. 9 (a) Cross-section and refractive index profile of GTWave; (b) side view of GTWave [9]

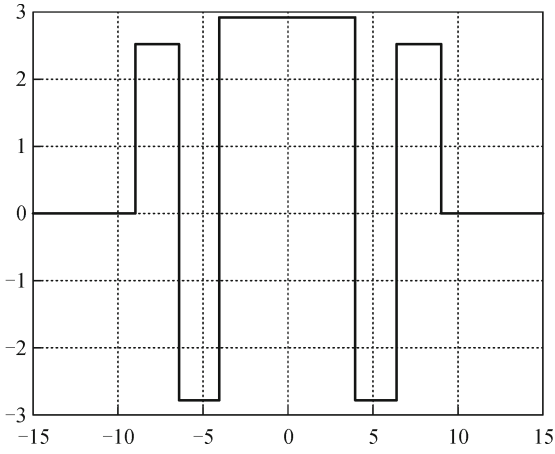


Fig. 10 Index profile of TCF [9]

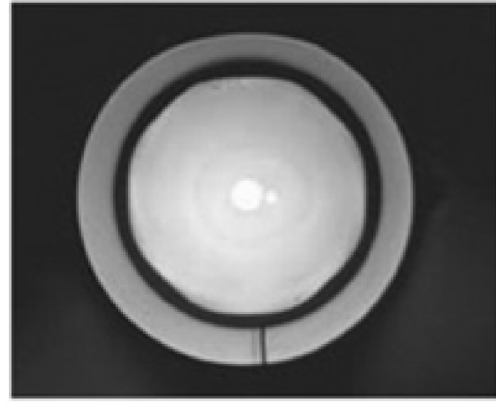


Fig. 11 Fiber end of 3C fiber [9]

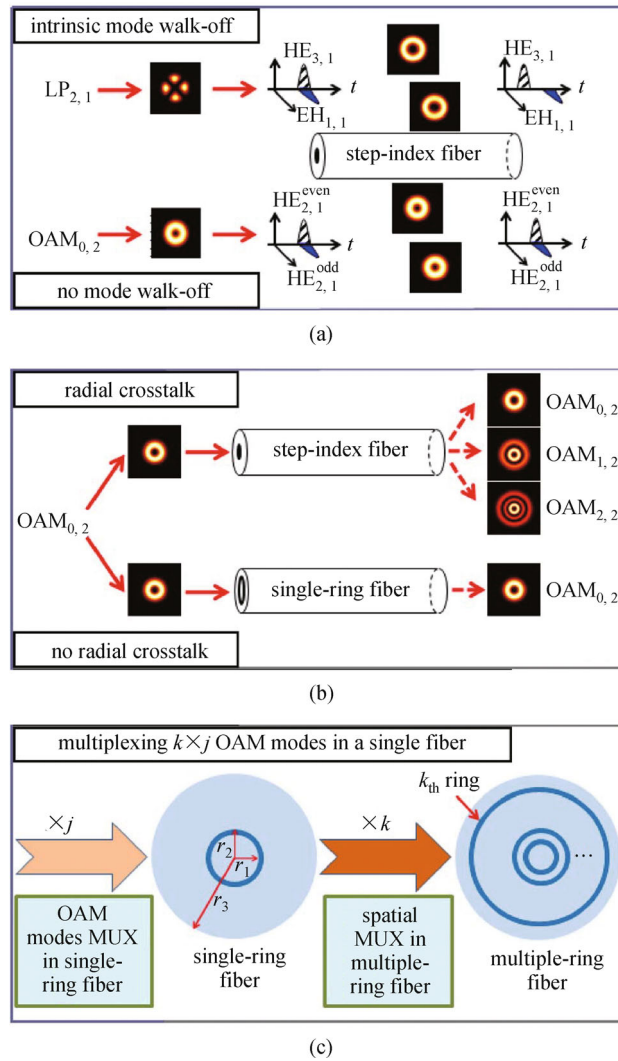


Fig. 12 Comparison of different schemes for multiplexing multiple optical spatial modes for fiber transmission. (a) Higher order LP modes are composed of two fiber eigenmodes ($LP_{2,1} = HE_{3,1} + EH_{1,1}$) having different propagation constants. The two fiber eigenmodes walk off as they propagate along the fiber. OAM modes are composed of two fiber eigenmodes with same propagation constant ($OAM_{0,2} = HE_{2,1}^{even} + i \times HE_{2,1}^{odd}$), and thus, there is no walk-off after propagation; (b) to multiplex multiple OAM modes into multimode step-index fiber, a small change of launching condition can excite radially higher order modes and results in the crosstalk. With proper design, single-ring fiber can support only radially fundamental modes with reduced crosstalk; (c) j OAM modes with different azimuthal phase order can be multiplexed into the single ring fiber. Using a multiple-ring fiber with k rings can increase the multiplexed mode number with another factor of k . This can potentially transmit $k \times j$ OAM modes in a single fiber [10]

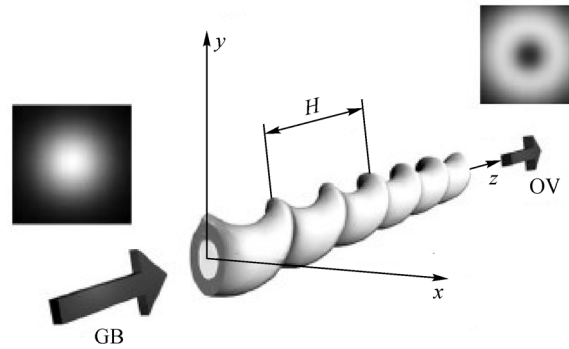


Fig. 13 Geometry of the problem: schematically shown generation of the optical vortex (OV) from the incident Gaussian beam (GB). Insets show intensity distribution of the corresponding fields [11]

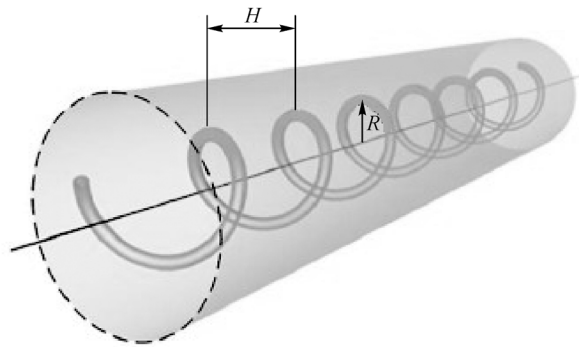


Fig. 14 Model of a helical core fiber manufactured by drawing from a preform with an off-centered core [12]

size, or deviation from the center, can excite higher order modes in radial direction, resulting in serious crosstalk, as shown in Fig. 12(b). On the other hand, a properly designed high-index single-ring fiber can support only the radially fundamental modes and, thus, potentially reduce the crosstalk induced during mode excitation. To multiplex multiple OAM modes simultaneously, the number of the eigenmodes supported by the fiber should be increased by increasing either the core radius or the refractive index difference between the core and cladding. In this scheme, a single-ring fiber can provide 1-D mode-division multiplexing of the optical OAM modes. Similar to the concept of multiple-core fiber, by using a multiple-ring fiber with small inter-ring crosstalk and launching OAM modes with different azimuthal phase into the high-index ring regions, one can potentially achieve multiplexing of the optical OAM modes in another spatial dimension [10].

Related researches report, analyze and demonstrate the OAM signals transmission characteristics with different forms of fiber media, such as long-period twisted elliptical fibers which is shown in Fig. 13 [11], long-period helical core optical fibers which is shown in Fig. 14 [12], etc.

6 Conclusions

There are critical developments in optical telecommunica-

tion which could completely change our methods of using optical fiber and the transmission signal type in optical fiber. Optical fiber could be more bending insensitive with solid structure which enable us to use optical fiber like electric wire for more convenient. The telecommunication capacity will increase explosively with the advent of orbital angular momentum transmission fiber. Optical fiber technology will be combined with nanotechnology and material science in the sensor and solar cell fields to solve the efficiency and size problems. The new design of 3C optical fiber will make it possible to achieve higher power output in rare-earth doped fiber without sacrificing the beam quality. The co-dopant technologies will also increase the laser power generated by fiber laser. More and more specialty fiber will improve the quality of optical device performance and also the quality of life.

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References

1. Schermer R T, Cole J H. Improved bend loss formula verified for optical fiber by simulation and experiment. *IEEE Journal of Quantum Electronics*, 2007, 43(10): 899–909
2. Nakajima K, Shimizu T, Fukai C. Single-mode hole-assisted fiber

with low bending loss characteristics. In: Proceedings of IWCS. 2009, 9: 9–3

3. Aida K, Zhu C, Sugie T. Statistical estimation of multi-path interference in short bend-insensitive fiber from spectral insertion loss measurement using ASE test signal. In: Proceedings of CLEO: Science and Innovations. Optical Society of America, 2012, CTh4G.6: 1–2
4. Travagnin M. BER penalty induced by coherent MPI noise in FTTH optical links. *Journal of Lightwave Technology*, 2013, 31(18): 3021–3031
5. Ju S, Watekar P R, Jeong S, Kim Y, Jeon P, Boo S, Han W T. Development of Au nano-particles cladding-doped optical fiber for surface plasmon resonance sensor applications. In: Proceedings of 3rd International Conference on Sensor Device Technologies and Applications. 2012: 89–94
6. Pan C, Guo W, Dong L, Zhu G, Wang Z L. Optical fiber-based core-shell coaxially structured hybrid cells for self-powered nanosystems. *Advanced Materials*, 2012, 24(25): 3356–3361
7. Koponen J, Laurila M, Hotoleanu M. Inversion behavior in core and cladding-pumped Yb-doped fiber photodarkening measurements. *Applied Optics*, 2008, 47(25): 4522–4528
8. Laperle P, Desbiens L, Zheng H, Drolet M, Proulx A, Taillon Y. Relations between phosphorus/aluminum concentration ratio and photodarkening rate and loss in Yb-doped silica fibers. *Proceedings of the Society for Photo-Instrumentation Engineers*, 2010, 7580: 75801Y-1–75801Y-8
9. Gapontsev V P, Fomin V, Platonov N. Powerful Fiber Laser System. US Patent 7593435B2, 2009
10. Yue Y, Yan Y, Ahmed N, Yang J Y, Zhang L, Ren Y X, Huang H, Birnbaum K M, Erkmen B I, Dolinar S, Tur M, Willner A E. Mode properties and propagation effects of optical orbital angular momentum (OAM) modes in a ring fiber. *Photonics Journal, IEEE*, 2012, 4(2): 535–543
11. Alexeyev C N, Fadeyeva T A, Lapin B P, Yavorsky M A. Generation and conversion of optical vortices in long-period twisted elliptical fibers. *Applied Optics*, 2012, 51(10): C193–C197
12. Alexeyev C N, Yavorsky M A. Generation and conversion of optical vortices in long-period helical core optical fibers. *Physical Review A*, 2008, 78(4): 043828



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