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Preface

A decade ago a book on optical microfibers and nanofibers could be hardly foreseen. In 2003, one of the authors (L.T.), in collaboration with scientists from Harvard and Zhejiang University, published an intriguing paper in *Nature* on the low-loss waveguiding of silica nanofibers. This paper introduced a new vision of micro/nanofibers as basic elements for miniature photonic devices and initiated numerous scientific publications on the topic of this book.

At first glance, microfiber-based photonic technology seems to be a reverse step from the lithographic photonic technology, just like wired circuits in relation to printed-in circuits in electronics. However, there are at least two important advantages of microfibers over lithographically fabricated waveguides: significantly smaller losses for a given index contrast and the potential ability for micro-assembly in three dimensions. These advantages could make possible the creation of micro/nanofiber devices that are considerably more compact and less lossy than devices fabricated lithographically. Furthermore, some microfiber-based devices possess unique functionalities, which are not possible or much harder to achieve by other means.

Nowadays research on optical micro/nanofibers is growing rapidly. The authors attempted to write a fairly comprehensive introduction to micro/nanofiber optical properties, fabrication methods and applications. The book will be useful for scientists and engineers who want to learn more about very thin – subwavelength diameter – optical microfibers and, eventually, to be engaged in microfiber photonics research. In particular, the authors hope that the contents of the book will attract students and stimulate their innovative ideas in this fascinating field of optics.

L.T. would like to acknowledge a number of his colleagues and students at both Zhejiang University in Hangzhou and Harvard University in Cambridge, MA, USA, for their direct or indirect help in micro/nanofiber research and the writing of this book. Special thanks to Professor Eric Mazur of Harvard University for his indispensable support and advice. Special thanks are also extended to Jingyi Lou, Rafael R. Gattass, Qing Yang, Guillaume Vienne, Jian Fu, Yuhang Li, Xiaoshun Jiang, Zhe Ma, Xin Guo, Shanshan Wang, Fuxing Gu, Zhifang Hu, and Keji Huang for their great help and contribution to the work.

M.S. would like to acknowledge the creative "Bell Labs" atmosphere at the OFS Laboratories (formerly the Optical Fiber Research Department of Bell Laboratories), which stimulated his research in micro/nanofibers and the work on this book. Special thanks are extended to his present and former Bell Labs/OFS Labs colleagues David DiGiovanni, Ben Eggleton, Yuri Dulashko, John Fini, Michael Fishteyn, Samir Ghalmi, Siddharth Ramachandran, Paul Westbrook and Andrew Yablon for the fruitful discussions and consultations.

The authors
April 2009

Contents

1 Introduction

In the past 30 years, optical fibers with diameters larger than the wavelength of guided light have found wide applications including optical communication, sensing, power delivery and nonlinear optics[1–6]. For example, by transmission of light through total internal reflection in optical fibers, the power of light has been sent to travel across the sea for telecommunications[1,2], to creep into buildings for safety monitoring[3,4], to puncture tissues for laser surgery[5], as well as many other applications ranging from illumination and imaging to astronomical research[7,8]. Recent advances in nanotechnology and the increasing demand for faster response, smaller footprint, higher sensitivity and lower power consumption have, however, spurred efforts for the miniaturization of optical fibers and fiber-optic devices[8–10]. Therefore, an important motivation for fabricating subwavelength-diameter optical fibers is their potential usefulness as building blocks in future micro- or nanometer-scale photonic components or devices and as tools for mesoscopic optics research. Also, it is always interesting to guide light and watch how it works on those scales that have not been tried yet.

1.1 A Brief History of Micro- and Nanofibers

The history of the guided transmission of light can be traced back to the 19^{th} century, when Daniel Colladon and John Tyndall directed beams of light at the path of water[7], in which light was confined by the internal reflection due to the refractive index change at the water-air interface. In 1880, William Wheeling patented an invention for piping light through pipes relying on mirror reflection[11]. In this idea, light was redirected, branched and delivered using a pipe in the same way that water is poured into and carried along a pipe. On the other hand, shortly after Wheeling's light pipe, Charles Vernon Boys, a British physicist, reported drawing very thin glass fibers from molten minerals using flying arrows in 1887[12], which might represent the first written record of taper drawing glass fibers with micro- or nanoscale diameters.

These fibers could be thinner than one micrometer, and were mentioned as "the finest threads" of glasses. Several years later, the approach for drawing these kinds of thin fibers was developed into one of the "laboratory arts", as documented in the book *On Laboratory Arts* by Richard Threlfall[13]. However, at that time these "finest threads", here we call them micro- or nanofibers (MNFs), were not prepared for light transmission, but for mechanical applications such as springs for galvanometers due to their high uniformity and excellent elasticity[12]. Also, due to their small dimensions, it was difficult to precisely determine the thickness of the fiber when its value went below the wavelength of visible light. To the best of the authors' knowledge, one of the earliest examples of optical guiding in MNFs was reported in 1959 by Narinder S. Kapany, in which a fiber bundle consisting of numerous micro- and submicrometer-diameter fibers was used for transmission of images[14]. In 1960 Theodore Maiman invented the first laser[15], and shortly afterwards Charles Kao and George Hockham proposed the possibility of achieving low optical loss in high-purity glasses in 1966[16], which greatly advanced the establishment of fiber optics for the optical communications industry.

From the 1970's, along with a thriving fiber optics research industry, microfibers tapered from standard glass fibers (usually mentioned as fiber tapers or tapered fibers with waist diameters of several to tens of micrometers) started to play their role as optical waveguides[17–22]. Based on these microfibers, a number of possible applications including optical couplers[23–25], filters[26,27], sensors[28,29], evanescent field amplification[30] and supercontinuum generation[31] were demonstrated. In 1999, a theoretical work on microfibers with subwavelength diameters was reported by J. Bures and R. Ghosh[32], based on theoretical calculation. They predicted the enhanced power density of the evanescent field in the vicinity of the fiber, which might be used in atomic mirrors.

In 2003, L. Tong and co-authors experimentally demonstrated low-loss optical waveguiding in MNFs with diameters far below the wavelength of the guided light[33], which renewed research interests in optical MNFs as potential building blocks for miniaturized optical components and devices. A few years later, a number of works on the fabrication and/or properties of subwavelength-diameter MNFs were reported[34–62], and a variety of MNF-based components or devices, ranging from resonators[63–73], interferometers[36,74], filters[75–77] and lasers[78–81] to sensors[82–95], were demonstrated or proposed, together with many other MNF-based applications in nonlinear optics[96–106] and atom optics[107–115].

Besides the above-mentioned glass MNFs, there are a number of other free-standing one-dimensional fiber or wire-like micro- or nanostructures, ranging from crystalline whiskers to semiconductor nanowires and polymer MNFs[116–125] that have been extensively investigated and show potential for optical wave guiding. Among these structures, physically drawn polymer MNFs, although they were not initially targeted for light guidance, exhibit similar properties as glass MNFs regarding extraordinary uniformity and long length for low-loss optical waveguiding[126–131], and are thus within the scope of this book.

1.2 Concepts of MNFs and the Scope of this Book

To introduce the concept of an MNF, it is helpful to compare it with the principles of a standard glass fiber. Shown in Fig. 1.1 is a cross-section view of a typical step-index-profile optical fiber, which consists of two parts (the protective buffer layer is not shown here): a solid cylindrical core, surrounded by a cladding with relatively low refractive index. Depending on various applications, the diameter of the fiber ranges from tens of micrometer (e.g., for fiber-optic sensing) to larger than one millimeters (e.g., for laser power delivery), and correspondingly the core diameter ranges from several micrometers to hundreds of micrometers. In a standard single-mode fiber for optical communications, e.g., Corning SMF28, the fiber and core diameters are 9 and 125 μm, respectively. As illustrated in Fig. 1.2(a), in the view of ray optics, the light conducted along the fiber is confined and guided inside the fiber by means of total internal reflection, as has been well depicted in many textbooks when introducing fiber optics.

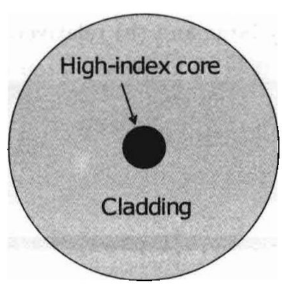

Fig. 1.1. Cross-section view of a standard optical fiber.

It is noticeable that in the reflection region where light hits the interface, a certain fraction of light penetrates the boundary of the high-index core, propagates as an evanescent field in the cladding, and finally comes back into the fiber core, forming the reflected ray with a slight shift in the axial direction known as the Goos-Hanchen shift[132,133]. When the diameter of the core decreases, the light penetrates the boundary more frequently, and the probability of propagation outside the core (as evanescent waves) increases, as shown in Fig. 1.2(b).

When the core diameter goes below the wavelength of the light, a considerable fraction of the power of the light propagates outside the core, as illustrated in Fig. 1.3. In such a case, the diameter of the fiber core is not thick enough for generating a steady-state electromagnetic field through the interference of reflected light rays, which means that ray optics (as depicted

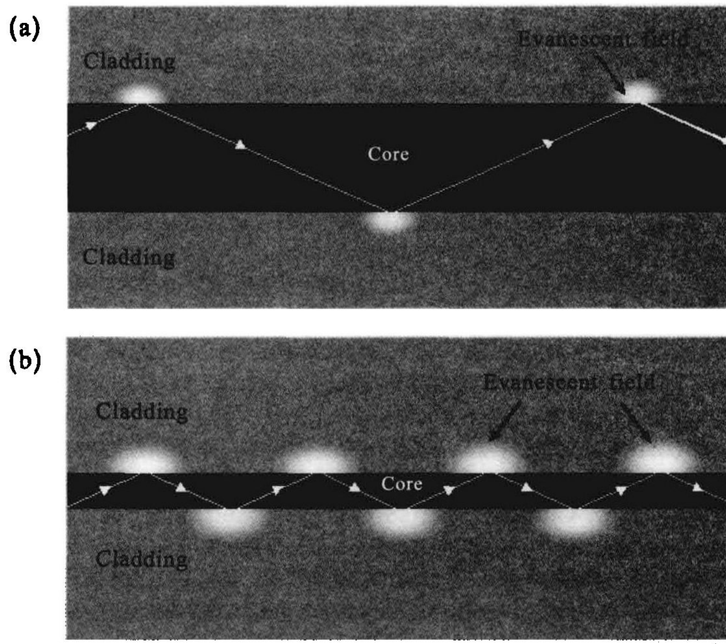

Fig. 1.2. Optical waveguiding in a standard optical fiber relying on internal total reflection with (a) relatively large and (b) relatively small core diameters.

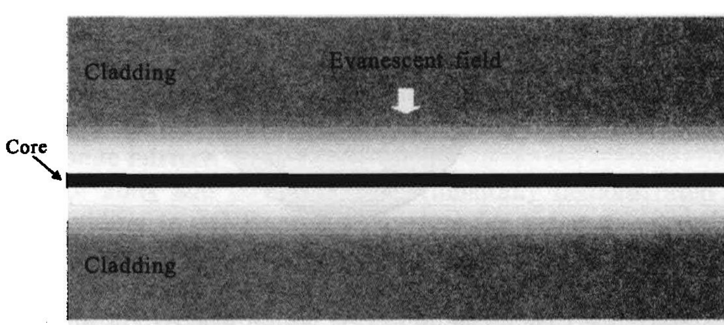

Fig. 1.3. Optical waveguiding in a micro- or nanofiber with core diameter below the wavelength of the propagating light.

in Fig. 1.2) is no longer applied, and the light ray should be treated as an electromagnetic field. For a fiber with a core diameter below the wavelength of the light, a high index-contrast between the core and the cladding is desired for obtaining a certain degree of optical confinement[34,134], which is required for light waveguiding in practical applications of these sub-wavelength-diameter optical fibers. Since the refractive index of an optical fiber (mostly made of silica) is not high, low-index media (or environment) such as a vacuum, air, water and polymers are usually used as claddings.

Similar to the top-down drawing technique for conventional fiber fabrication, the MNFs are usually fabricated by physically drawing viscous melts or solutions, as illustrated in Fig. 1.4. Usually, materials used for drawing MNFs are glass fibers, bulk glasses or polymers[33,35–37,43–48,126–131]. When the starting material is partially melted by heating or dissolved by solvents, it is possible to obtain appropriate viscosity for MNF drawing at a certain area, and high-quality MNFs with diameters down to 30 nm can be obtained when a proper drawing speed is applied. Compared with many other techniques that have been used for MNF or other one-dimensional nanostructure fabrication[116–120], a physical drawing technique yields MNFs with unparalleled uniformities regarding sidewall smoothness and diameter uniformity. The excellent uniformity of the MNF does not only enable low optical waveguiding loss, but also bestows the MNF with high mechanical strength and flexibility. For example, Fig. 1.5(a) gives an SEM image of a 450-nm-diameter silica MNF (supported on a coated silicon wafer), clearly showing the extraordinary uniformity of the fiber. Fig. 1.5(b) gives an SEM image of a knotted 500-nm-diameter silica MNF. The fiber was first knotted to a size of about 50 μm under an optical microscope, and then transferred onto the sidewall of a human hair. No breakage was observed under these micromanipulations, indicating the high mechanical strength and flexibility of the taper-drawn glass MNF.

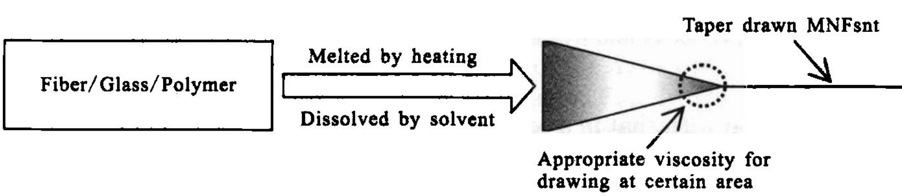

Fig. 1.4. Schematic illustration of physical drawing MNFs.

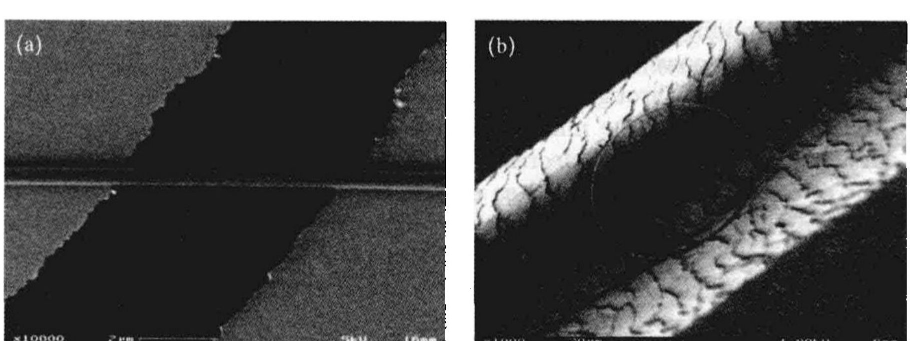

Fig. 1.5. SEM images of typical MNFs. (a) A 450-nm-diameter silica MNF placed on a coated silicon wafer. (b) A knotted 500-nm-diameter silica MNF placed on a human hair.

Due to its tiny endface, the lens-focus and butt-coupling methods for light launching in the conventional fiber are not applicable to the MNF. Instead, taper-squeeze or evanescent coupling is usually employed due to its high efficiency and convenience for managing light in subwavelength-diameter fibers. As shown in Fig. 1.6, for MNFs directly drawn from the starting fiber, taper squeeze is a simple approach for squeezing light from the thick fiber into the thin MNF; while for freestanding MNFs, evanescent coupling between two closely contacting MNFs has proved efficient and convenient for sending light from the launching fiber to the target MNF[33,41,46,56].

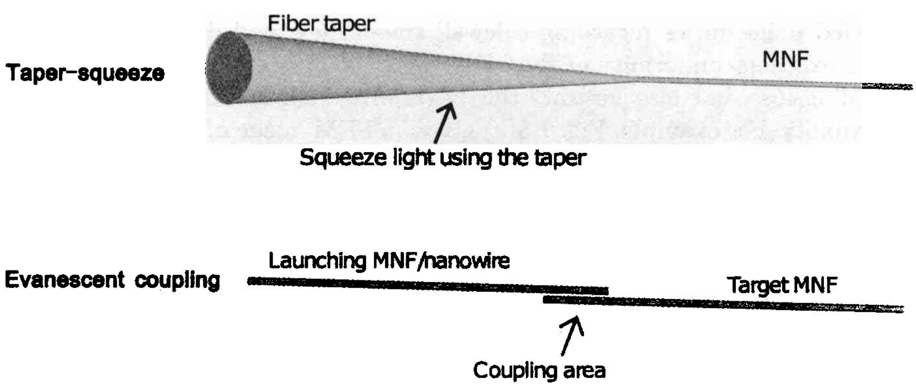

Fig. 1.6. Taper-focus and evanescent coupling approaches for optical launching of MNFs.

Compared with that in a conventional optical fiber, the high index contrast and subwavelength diameter of the MNF make it possible to guide light with a number of interesting properties, such as tight optical confinement[34], a high fraction of evanescent fields[34], manageable large waveguide dispersion[34,52], field enhancement[32] and low optical loss through sharp bends[41], making the MNF highly potential for a variety of photonics applications. For example, when guiding a 633-nm-wavelength light, a 450-nm-diameter silica MNF confining 80% power inside the fiber core (see Fig. 1.7(a)), makes it possible to guide the light through a 5-μm-radius bend with negligible bending loss[41], which is desired for the miniaturization of optical circuits and components. When the fiber diameter decreases to 200 nm, more than 90% power moves out of the fiber and is guided as evanescent waves (Fig. 1.7(b)), which may offer MNF-based optical sensing with high sensitivity. In addition, the low-dimension cross section, manageable dispersion and field enhancement have proved helpful in achieving nonlinear optical effects with low threshold on a miniaturized scale, and the abounding evanescent fields have been found useful for atom trapping and guidance with great versatility.

This book is intended to provide a general introduction to up-to-date research on subwavelength-diameter optical MNFs. Starting from a brief overview of optical MNFs in this chapter, Chapter 2 is devoted to theo-

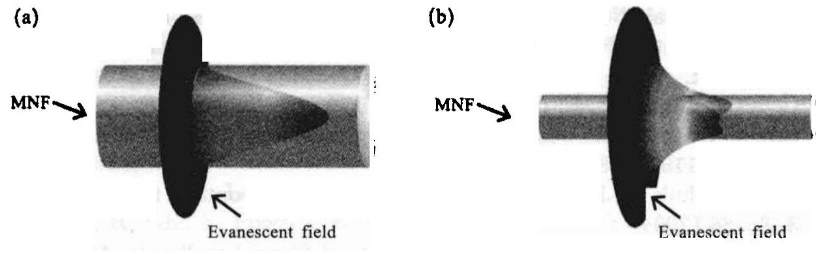

Fig. 1.7. Calculated Poynting vectors of silica MNFs guiding 633-nm-wavelength light with diameters of (a) 450 nm and (b) 200 nm.

retical waveguiding properties of MNFs that may provide a comprehensive understanding of light guiding in subwavelength-diameter MNFs, as well as evanescent coupling between two MNFs and the theory of MNF-based interferometers and resonators. Chapter 3 introduces typical techniques for physical drawing glass and polymer MNFs. Electron microscope investigations of as-fabricated MNFs are also presented. Chapter 4 is complementary to Chapter 2, offering experimental properties of MNFs including micromanipulation, mechanical strength, optical losses and effects of the substrate, which are critical to practical usage of MNFs. Chapter 5 introduces various MNF-based photonic components and devices including linear waveguides, waveguide bends, optical couplers, interferometers, resonators, filters and lasers, that have been reported so far. MNF optical sensors, as one of the most widely concerned applications of MNFs, are introduced in Chapter 6. Finally, Chapter 7 provides a brief summary of applications of MNFs in nonlinear optics, atom optics and other possibilities.

Although we are trying to provide a comprehensive account of this topic, we do not promise a complete coverage of MNF research. We apologize that we cannot cover all the work in this book. Finally, since optical MNFs or nanowires are frontiers of broad areas including photonics, nanotechnology and materials science, we hope that those who are working in these areas will benefit in some measure from this book, and find it interesting and stimulating.

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