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Recent Progress in Hollow-Core Fibers

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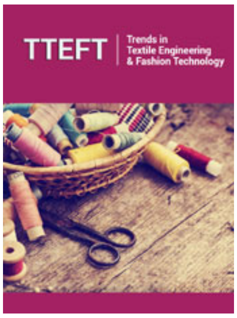

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Introduction

Since the theory of optical waveguide was proposed in 1966 [1], optical fibers have rapidly become the major role of global communication networks, and multiple fields such as fiber sensing and fiber lasers have been developed [2-3]. Reducing loss has been a primary goal in the development of fibers. However, despite significant efforts, the loss of traditional solid-core fiber has only been decreased by 0.0087dB/km in the last 22 years (from 0.1484 in 2002 [4] to 0.1397dB/km in 2024 [5]). Furthermore, the performance of conventional solid-core fibers in terms of damage threshold, delay, and radiation resistance is also insufficient to meet the requirements of new application scenarios such as high-power laser delivery and high-precision fiber optic gyroscopes.

Hollow-core fiber (HCF) seems to be an ideal optical waveguide [6], the greatest contribution of which is to confine light transmission within the air core, thereby overcoming the ultimate limitation of conventional solid-core fiber-the intrinsic constraints of silica materials. Based on the light-guiding mechanism, HCF are divided into hollow-core photonic bandgap fiber (HC-PBGF [7]) and hollow-core anti-resonant fiber (HC-ARF [8]). From the current development perspective, HC-ARF appear to have the upper hand when the goal is to achieve ultra-low loss. The latest result, reported by Microsoft and University of Southampton to show that HC-ARF have achieved an ultra-low loss of 0.05dB/km at 1550nm, which is nearly three times lower than that of conventional solid-core fiber.

This paper reviews the development of HCF and summarizes recent advancements in their applications, including high-power laser delivery and fiber-optic gyroscopes. Finally, we provide an outlook on future directions for the HCF.

The development of HCF

The development of HCFs is shown in Figure 1. The concept of photonic crystal fiber was first proposed by Philip Russell at the University of Bath in 1991. The first photonic crystal fiber was successfully fabricated in 1997 [9]; however, this initial demonstration was still based on an index-guiding mechanism, meaning it retained a solid-core structure. Two years later, Russell's team fabricated the world's first hollow-core photonic crystal fiber (also known as HC-PBGF), which experimentally demonstrated for the first time that light could be guided within an air core [10]. Subsequently, efforts to advance HC-PBGFs focused on strategies such as increasing the cladding air-filling ratio and improving the purity of the fiber preform materials [11]. However, as research progressed, a fundamental limitation emerged: a unique mode inherent to HC-PBGFs, known as the surface mode [12], proved exceptionally difficult to eliminate. This issue confined the transmission loss of HC-PBGFs to the range of 3-5dB/km [13] (with a record low of 1.2dB/km reported by the University of Bath in 2005 [14]). Ultimately, due to the persistent challenge of further loss reduction, HC-PBGFs were gradually abandoned.

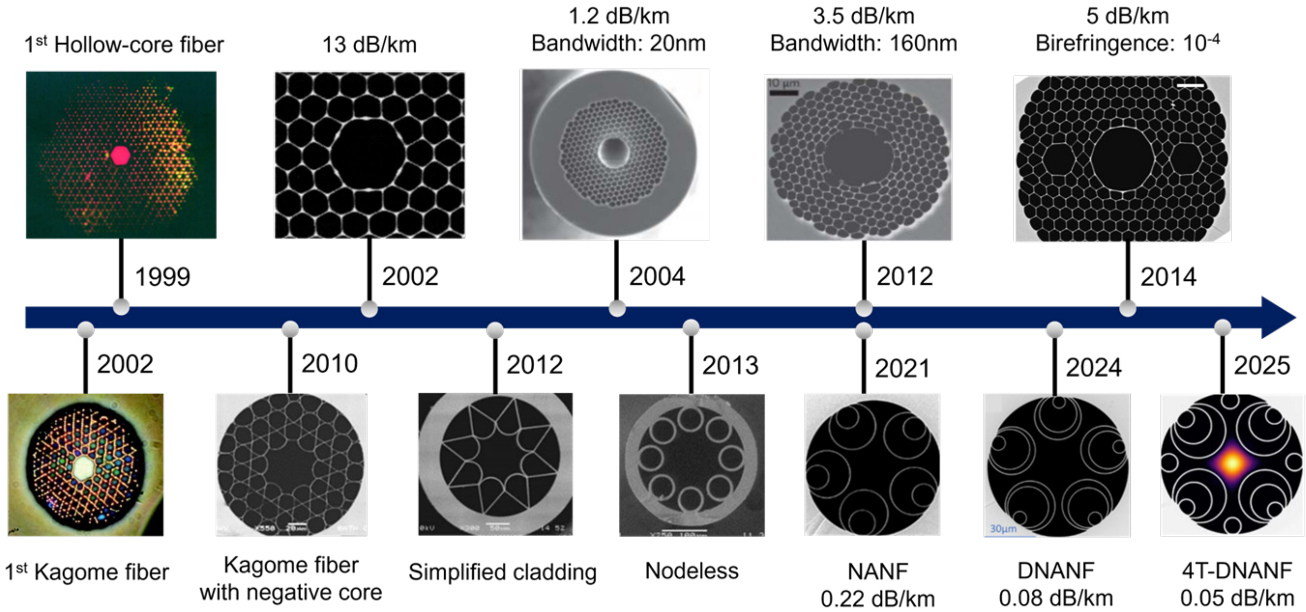

Figure 1: The development of hollow-core fibers.

The rapid development of HC-ARF has rekindled researchers' interest in HCF. The earliest HC-ARF was a Kagome-cladding fiber reported in 2002 by Fetah Benabid at the University of Bath [15]. This fiber attracted significant attention because its cladding holes lacked a strictly periodic arrangement, yet it could still guide light through an air core. This led to the understanding that a different light-guiding mechanism-anti-resonant guidance [16]-was at work, distinct from the photonic bandgap effect. Over the past decade, researchers have proposed various theoretical models to explain this guiding mechanism, which has greatly accelerated the advancement of HC-ARF. Key breakthroughs contributing to the reduction in transmission loss include the introduction of a negative-curvature core [17], nodeless design [18], and multi-reflection layers [18]. As a result, the attenuation of HC-ARFs has decreased by four orders of magnitude over two decades, achieving a record low loss of 0.05dB/km and a single-draw length of up to 83km. Notably, beyond ultra-low loss, HC-ARF also exhibits excellent performance in terms of delay, bandwidth, radiation resistance, and damage threshold. These superior properties have greatly facilitated their application in ultra-broadband communication networks, high-power laser delivery, and high-precision fiber optic gyroscopes.

The application of HCF

The applications of HC-ARFs are determined by their advantages as shown in Figure 2. Considering the ultra-low loss, ultra-low delay and ultra-low dispersion, they can be applied in fiber communication networks and delay-sensitive systems [19]; considering their ultra-high damage threshold and ultra-low nonlinearity, they are suitable for high-power laser delivery, including KW-level continuous-wave lasers [20-21] and GW-level pulsed lasers [22]; and due to their radiation resistance, they can be used in high-precision fiber optic gyroscope systems [23]. Additionally, when HC-ARFs are extended to wavelength bands such as the ultraviolet [24], visible [25] and mid-infrared [26], they exhibit better performance than existing solid-core optical fibers. Except HC-ARF, HC-PBGF is mostly used in sensing field, such as irradiation environment [27].

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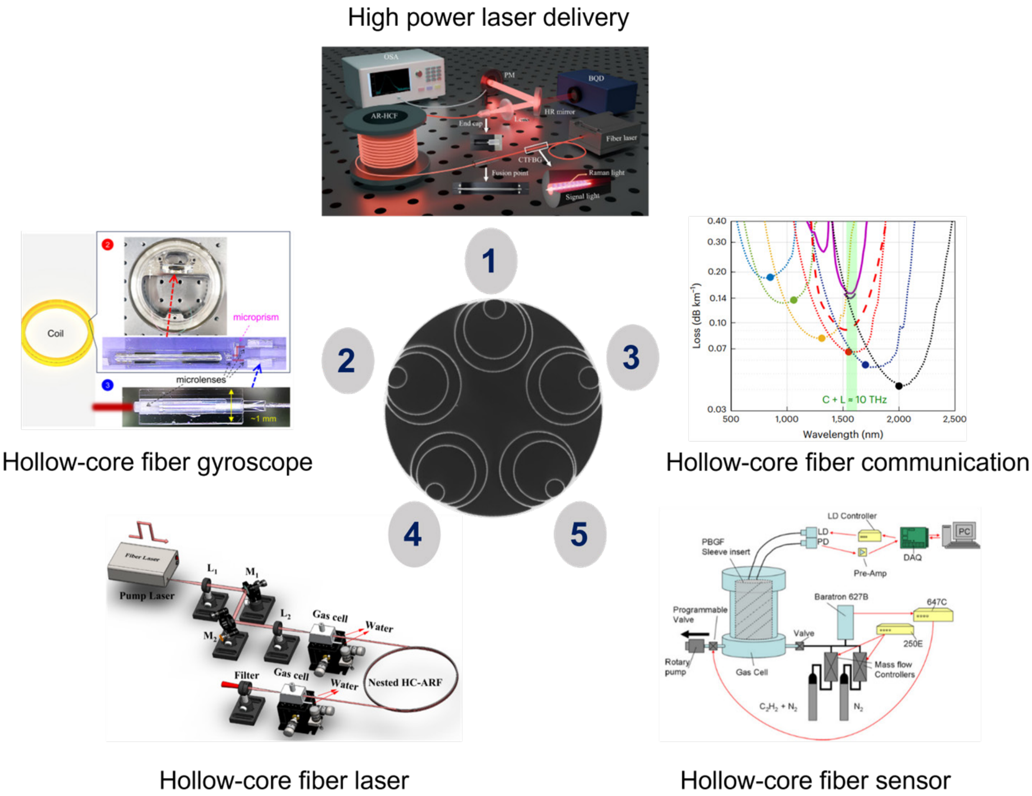

Figure 2: The application of hollow-core fibers.

Summary

As an emerging technology, HCFs have transitioned from theory to reality, and advanced from laboratory research to mass production after more than two decades of development. While HC-PBGFs have not demonstrated significant advantages in ultra-low loss, they can achieve a high birefringence on the order of 10^{-4} and a millimeter-scale bending radius [28]-performance metrics that remain challenging for HC-ARFs to match. In contrast, the absolute advantages of HC-ARFs have facilitated their demonstration applications in multiple fields and attracted attention from researchers worldwide such as ultra-low loss, ultra-low delay and other aspects. Looking ahead, further increasing the single drawing length, optimizing the uniformity of fiber structure, and promoting their widespread application in more fields will be the development trends of HC-ARFs.

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