

Chapter

Advancements in Hollow-Core Fiber Lasers: Fundamentals and Applications

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Abstract

Hollow-core fiber lasers represent a transformative development in photonics, offering lower nonlinearities, higher damage thresholds, and broader spectral operation than conventional solid-core systems. The unique guiding mechanisms confine light within a hollow core, drastically reducing light-matter interaction. By minimizing overlap with the fiber walls, losses due to scattering and absorption are suppressed, enabling ultrashort pulse generation, mid-infrared operation, and improved power handling capabilities. Multiple fabrication approaches, including the stack-and-draw technique, facilitate precision control of fiber geometry at the sub-micron level. This structural complexity enables advanced designs such as Kagome-lattice and multilayer fibers, which expand operational bandwidth and reduce attenuation. Crucially, hollow-core fibers accommodate various gain media: from rare-earth-doped claddings to gas-filled cores supporting Raman or excimer transitions, empowering novel laser architectures. These systems benefit a wide array of applications, from ultrashort pulse compression and delivery to high-power industrial processing, where mitigating nonlinear effects is critical. Hollow-core fibers also show promise in telecommunications, reducing latency and nonlinearity, as well as in specialized sensing applications, leveraging the hollow region for extended interaction lengths. Despite ongoing challenges—such as reproducibility, mechanical stability, and loss minimization—emerging structural refinements hint at future breakthroughs, including ultra-low-loss mid-infrared guidance and quantum-level interactions. In medical instrumentation, these fibers enhance endoscopic imaging, multiphoton microscopy, and surgical procedures that demand precise beam delivery with minimized overall fiber damage. By uniting advanced fabrication with controllable gas-phase or doped gain, hollow-core fiber lasers are poised to redefine ultimate performance and reliability limits and open new frontiers in photonics innovation.

Keywords: hollow-core fiber lasers, photonic bandgap, anti-resonant structures, fiber fabrication, ultrafast pulses, mid-infrared operation, laser applications

1. Introduction

Optical fibers revolutionized photonics and telecommunications, providing a platform for rapid, efficient data transmission, as well as enabling significant developments in sensing, biomedical applications, and industrial processing. Traditionally, optical fibers have contained a solid-core—commonly made of silica—through which light is guided by total internal reflection. Over decades of intense research, this technology has matured, giving rise to a wide spectrum of fiber designs and fiber-based devices, including fiber lasers and amplifiers.

Despite their remarkable success, conventional solid-core fibers exhibit limitations, especially when dealing with high-power and short-pulse laser transmissions, nonlinear effects, or certain sensing applications that demand minimal light-matter interaction. These constraints provided the impetus to explore alternative fiber designs. The concept of a hollow-core fiber (HCF), one in which light propagates predominantly through a gaseous or vacuum region, was introduced as a promising route to mitigate some inherent limitations of solid-core fibers. Early prototypes demonstrated that guiding light in air or vacuum reduces nonlinearities and can enable higher damage thresholds. Over time, growing interest in hollow-core fibers led to significant breakthroughs in their structural engineering and fabrication methodologies. From this foundation, the idea of integrating hollow-core fibers directly into laser systems—hollow-core fiber lasers—gradually emerged. By leveraging unique optical properties, hollow-core fiber lasers aim to push the boundaries of what is achievable in terms of peak power, low nonlinearity, and spectral coverage. Their potential extends beyond traditional telecommunications; they hold promise in precision sensing, medical instrumentation, and industrial manufacturing.

Hollow-core fiber lasers take advantage of the reduced interaction between light and the fiber material, relying on elaborate photonic bandgap or anti-resonant structures to guide light through an empty (or gas-filled) core. Because of the lower overlap between the optical field and any solid medium, losses are suppressed, material-induced nonlinearities are minimized, and damage thresholds can be enhanced. These fibers also offer new degrees of freedom for doping, filling the hollow core with gases or liquids to achieve novel functionalities or tailored dispersion. The operational advantages, combined with ongoing improvements in manufacturing precision, pave the way for a broad application spectrum. Researchers have successfully demonstrated higher power delivery in hollow-core fibers, as well as the generation of ultrashort pulses with minimal distortion. Consequently, hollow-core fiber lasers are steadily transitioning from laboratory curiosities to commercially viable tools [1, 2].

This chapter begins by examining the fundamental principles of hollow-core fibers, focusing on their unique light-guiding mechanisms and how they differ from conventional solid-core fibers. We then explore the structural design and fabrication techniques that make these fibers possible, emphasizing the need for precision and reproducible optical performance. The chapter progresses by delving into the integration of hollow-core fibers into laser systems, shedding light on their operational dynamics and associated performance enhancements. In the next sections, we analyze the mechanisms that enable lasing in hollow-core fibers and discuss the impact of utilizing diverse gases within the hollow core for enhanced laser functionality. Finally, the chapter concludes with a detailed exploration of hollow-core fiber laser applications across various domains, including telecommunications, medical

instrumentation, industrial processing, and more, while considering the future outlook for these evolving technologies, including ongoing challenges and potential breakthroughs.

2. Guiding mechanisms of hollow-core fibers

2.1 Contrast with total internal reflection

Conventional solid-core fibers guide light via total internal reflection (TIR), which occurs when light travels through a medium of higher refractive index (the core) that is surrounded by a medium of lower refractive index (the cladding), as shown in **Figure 1**. This phenomenon is reliable but imposes certain constraints, such as material dispersion and nonlinear effects that are especially pronounced at higher light intensities.

Hollow-core fibers, however, rely on alternative guiding mechanisms because their core typically contains air (refractive index ≈ 1.0) or vacuum (refractive index = 1.0), which is lower than the refractive index of a silica cladding. Consequently, TIR cannot serve as the primary guiding mechanism in such a geometry. Instead, hollow-core fibers typically rely on photonic bandgap (PBG) guiding or anti-resonant guiding [3].

2.2 Photonic bandgap guiding

Photonic bandgap guiding is based on the notion that a periodic arrangement of dielectric materials can create a “bandgap” for certain wavelengths of light. The bandgap is analogous to how electron bandgaps exist in semiconductors. By engineering the microstructure of the fiber cladding—often in a hexagonal or other lattice pattern—light can be confined in the central hollow region for wavelengths falling within the photonic bandgap.

In photonic crystal fibers (PCFs) designed for hollow-core guidance, the cladding can be viewed as a 2D photonic crystal that reflects electromagnetic waves of certain frequencies, preventing their radial escape from the core. This reflection keeps the light confined within the hollow center, thereby achieving low-loss propagation. By manipulating the geometry of the air holes and the arrangement of the cladding material, the photonic bandgap can be shifted to specific wavelength ranges. This design flexibility allows

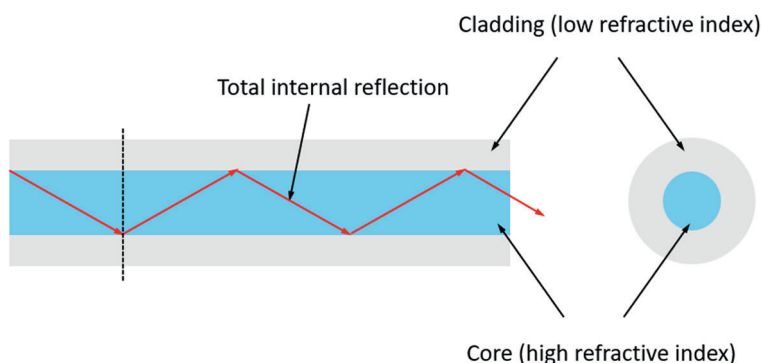


Figure 1.
Total internal reflection in solid-core fibers.

engineers to target operational windows anywhere from the visible to the mid-infrared, depending on application requirements, in order to realize bandgap tuning. While photonic bandgap fibers significantly reduce attenuation compared to older hollow-core prototypes, they still exhibit scattering and absorption losses stemming from imperfections in the microstructured cladding or residual overlap with the fiber material. Precise fabrication is thus crucial to minimize these losses.

Figure 2 shows two different structural implementations of photonic bandgap hollow-core fibers [4]. In **Figure 2(a)**, a photonic crystal fiber with a small hollow core is encircled by a periodic arrangement of large air holes within the cladding. This configuration creates a strong photonic bandgap effect, ensuring that light remains confined in the hollow region by preventing leakage into the surrounding medium. **Figure 2(b)** presents a microstructured fiber design with a larger hollow core enclosed by multiple concentric rings of small air holes separated by nano-bridges. This alternative design can offer enhanced transmission properties by further optimizing confinement loss and broadening the operational bandwidth. The selection between these two architectures depends on specific application requirements. While PCFs with large air-hole lattices in **Figure 2(a)** can provide highly selective guidance for specific wavelengths, they may suffer from higher losses due to scattering at the interfaces. In contrast, the multi-ring structure in **Figure 2(b)** can reduce confinement loss, enabling more stable propagation over longer distances, but may require greater fabrication precision to maintain uniformity in the nano-bridges. These designs exemplify the versatility of photonic bandgap hollow-core fibers in controlling light propagation. The ability to fine-tune structural parameters, such as air-hole size, periodicity, and core diameter, allows engineers to tailor the fiber's optical properties for applications ranging from low-loss optical transmission to high-power laser delivery and precision spectroscopy.

2.3 Anti-resonant guiding

An alternative, and often complementary, mechanism is anti-resonant guiding, also termed “inhibited coupling.” Anti-resonant hollow-core fibers can be engineered with thin-walled cladding tubes or “capillary” cladding structures, where the guiding principle is based on the reflection of light at specific angles that avoid resonance in the cladding walls [4].

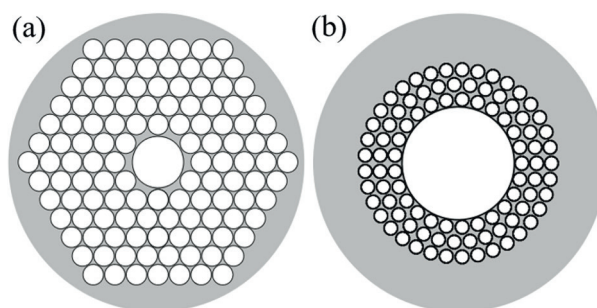


Figure 2. Various types of hollow-core photonic bandgap fibers. (a) Photonic crystal fiber featuring a small hollow core surrounded by a periodic array of large air holes. (b) Microstructured fiber featuring a medium-sized hollow core surrounded by several rings of small air holes separated by nano-size bridges [4].

One key design principle in anti-resonant hollow-core fibers involves carefully selecting the thickness of the cladding tubes so that the wavelengths of interest do not resonate within the glass, thereby minimizing light leakage. In this configuration, the glass tubes act as a reflective boundary at specific frequencies. Anti-resonant fibers can also provide significantly broader transmission bandwidths than photonic bandgap fibers. Typically, these fibers feature a single-ring arrangement of large glass capillary elements, which confine light in the hollow core while limiting its overlap with the glass walls. Because most of the light propagates through air, losses due to absorption and scattering in the cladding remain extremely low when the fiber geometry is precisely optimized. As a result, these fibers can handle higher average powers and deliver pulses with reduced distortion.

Figure 3 shows the fundamental principle of anti-resonant guidance in hollow-core fibers. In **Figure 3(a)**, the light is in an anti-resonance state, meaning that it primarily remains confined within the hollow core. This occurs because the thin-walled cladding tubes act as reflective barriers, preventing significant energy leakage into the surrounding structure. **Figure 3(b)** shows the on-resonance state, where the wavelength of light matches a resonant condition of the cladding structure. In this case, light couples into the high-index regions of the capillary walls, leading to energy leakage and creating a dip in the transmission spectrum. It has been demonstrated that the locations of these loss windows align with the resonant frequencies of the thin glass struts in the cladding and can be determined using the following equation:

$$\lambda_r = \frac{2t}{m} \sqrt{n^2 - 1} \quad (1)$$

where n is the refractive index of the glass cladding, t indicates the thickness of the surrounding struts, and m is an integer corresponding to the resonance order [3].

The effectiveness of anti-resonant guidance depends on precise control of the wall thickness (t) and the index contrast between the hollow core and the surrounding medium. If the structural parameters are not carefully optimized, unintended resonances may occur, leading to increased propagation losses. Additionally, compared to photonic bandgap hollow-core fibers, anti-resonant fibers often exhibit broader transmission bands and lower attenuation over specific wavelength ranges, making them advantageous for high-power laser delivery, mid-infrared transmission, and ultrafast pulse applications. The anti-resonant fiber design represents a versatile and tunable platform for optical waveguiding. The ability to manipulate capillary geometry, wall thickness, and material composition allows for enhanced light confinement and reduced transmission losses.

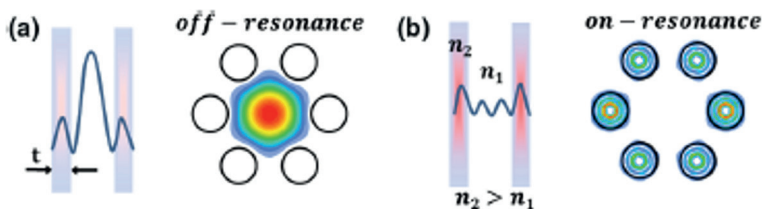


Figure 3. Principle of anti-resonant guidance when light is (a) in anti-resonance and (b) in an off-resonance state, light remains confined in the core [3].

2.4 Hybrid mechanisms

Some hollow-core fiber designs incorporate features of both photonic bandgap and anti-resonant guidance or alternate novel concepts such as nested capillary structures and Kagome-lattice cladding. Each approach seeks to broaden the operating bandwidth, minimize propagation losses, or enhance fiber robustness.

2.4.1 Kagome-lattice fibers

Named for its characteristic cladding pattern reminiscent of a traditional Japanese basket-weaving style, Kagome-lattice fiber typically has large air holes arranged in a hierarchical lattice. This geometry enables a form of inhibited coupling akin to anti-resonant fibers but can offer unique dispersion properties and broad bandwidths.

Figure 4 provides a detailed visualization of a Kagome-style hollow-core photonic crystal fiber (HC-PCF) [5]. In **Figure 4(a)**, a scanning electron micrograph (SEM) reveals the intricate Kagome-lattice structure, characterized by thin-walled capillary elements forming a distinctive hexagonal cladding. **Figure 4(b)** highlights the Star-of-David pattern, representing the unit cell that governs the fiber's photonic properties. This unique geometric arrangement enhances the fiber's ability to guide light through inhibited coupling, similar to anti-resonant hollow-core fibers but with additional dispersion control benefits. **Figure 4(c)** presents a calculated plot of effective refractive

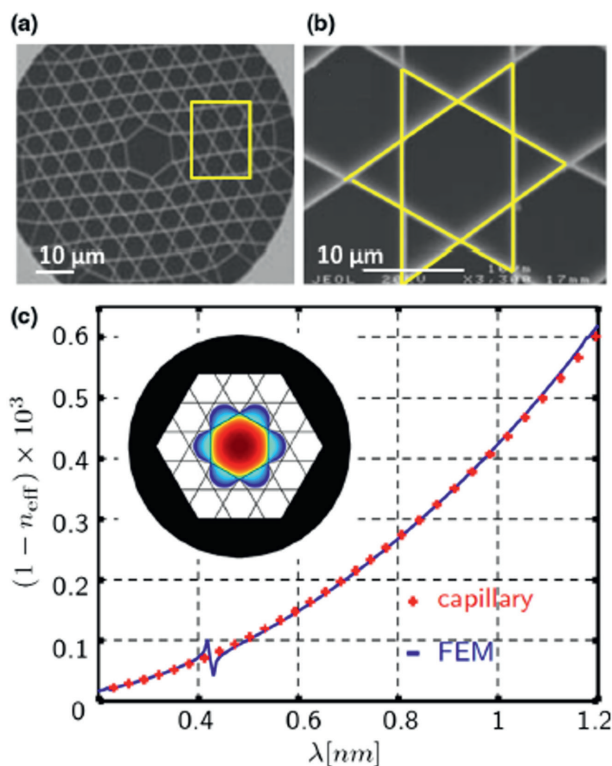


Figure 4.

(a) Scanning electron micrograph of a kagome-style HC-PCF. (b) Star-of-David pattern (light gray). The highlighted region represents the unit cell. (c) Calculated effective indices for a one-ring kagome structure in comparison with a capillary model. The inset shows the HE_{11} mode at 800 nm with the structure superimposed [5].

indices for a one-ring Kagome structure, comparing capillary-based modeling (red curve) with finite element method (FEM) simulations (blue curve). The inset shows the HE_{11} mode at 800 nm, illustrating how the Kagome-lattice supports guided modes by minimizing coupling to the cladding. Unlike conventional anti-resonant fibers, Kagome fibers exhibit low confinement loss over a wide spectral range, making them advantageous for ultrafast laser delivery, mid-IR applications, and nonlinear optics. The primary advantage of Kagome-lattice fibers is their exceptionally broad transmission window and low-loss guidance at shorter wavelengths, compared to other hollow-core structures. However, challenges remain in precise fabrication—ensuring uniformity in air-hole size, wall thickness, and symmetry is crucial to achieving optimal performance. Additionally, compared to photonic bandgap fibers, Kagome fibers typically exhibit higher losses at longer wavelengths, which may limit their applicability for certain long-distance optical transmission applications.

2.4.2 Multilayer fibers

Designs leveraging multiple concentric layers of thin glass tubes can refine the anti-resonant effect, creating multiple “rings” of reflection that further reduce leakage.

Figure 5 presents cross-sectional SEM micrographs of a hollow cylindrical multilayer fiber, demonstrating the structural complexity involved in multilayered anti-resonant fiber designs [6]. **Figure 5(a)** provides a broad view of the fiber, where the hollow core appears black, surrounded by polyether sulphone (PES) layers and cladding (gray). **Figure 5(b)** offers a magnified view of the multiple concentric thin layers, highlighting the As_2Se_3 layers (bright white) that contribute to the fiber’s photonic bandgap properties. The fundamental photonic bandgap is located at a wavelength of 3.55 μm , indicating its suitability for applications in the mid-infrared range. These multilayer structures play a crucial role in enhancing optical confinement by providing multiple anti-resonant reflections, thereby minimizing leakage losses. The incorporation of chalcogenide-based As_2Se_3 layers further optimizes the fiber’s ability to guide light at longer wavelengths, extending its applicability to infrared spectroscopy, environmental sensing, and free-space optical communication. While multilayered anti-resonant fibers offer low-loss guidance and broad operational bandwidths, their fabrication poses significant challenges. Ensuring precise

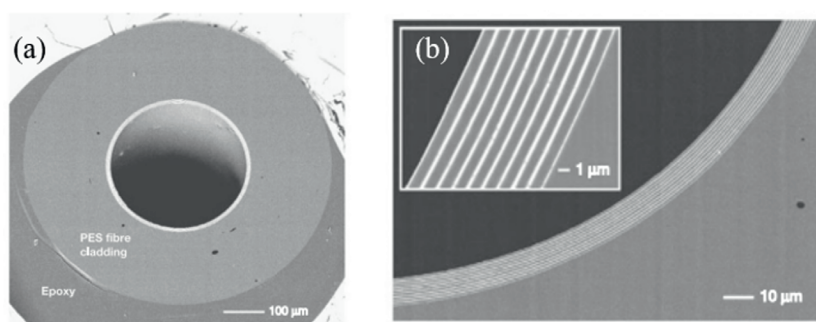


Figure 5. Cross-sectional SEM micrographs at various magnifications of hollow cylindrical multilayer fiber mounted in epoxy. The hollow core appears black, the poly ether sulphone (PES) layers and cladding gray, and the As_2Se_3 layers bright white [6].

layer thickness is essential, as small variations can shift the anti-resonance conditions, leading to undesired transmission losses. Additionally, the mechanical stability of the structure must be carefully considered, as multiple thin layers can introduce fragility, impacting long-term performance and reliability.

By virtue of these designs and their underlying physical principles, hollow-core fibers achieve a fundamentally different optical behavior compared to their solid-core counterparts, leading to unique capabilities in transmitting and shaping high-intensity laser light.

3. Hollow-core fiber material and fabrication

3.1 HCF material considerations

Hollow-core fibers are typically fabricated using high-purity silica glass because of their low absorption in the near-infrared range, robust mechanical properties, and well-established manufacturing techniques. However, the thickness and geometry of the silica elements in the cladding are carefully controlled, often at the sub-micron level, to realize specific bandgap or anti-resonant structures.

Fused silica is the most common choice for structural elements in hollow-core fibers due to its transparency and thermal stability. Minimal contamination during the fabrication process is critical to maintain desired transmission characteristics.

For certain specialized applications (e.g., mid-infrared transmission), other glass materials such as chalcogenides or fluorides may be employed. These materials can open bandgaps in longer-wavelength regions but may come with trade-offs in mechanical robustness or fabrication difficulty.

3.2 HCF fabrication

3.2.1 Preform fabrication

As with standard optical fibers, hollow-core fiber production starts with the creation of a preform—a larger-scale version of the fiber geometry, which is then drawn down to final fiber dimensions.

The stack-and-draw method is one commonly used technique for microstructured fibers, which involves stacking capillary tubes and rods in a deliberate arrangement that mimics the final cross-sectional pattern. The stack is consolidated and drawn at high temperatures to collapse and fuse the silica elements in the desired geometry. Alternatively, for some complex hollow-core structures, the preform can be formed by drilling arrays of holes into a solid silica rod, followed by acid etching to smooth the hole surfaces. This approach, while simpler in concept, can be limited by the drilling accuracy and the ability to produce intricate designs. Achieving the correct microstructure often requires multiple draws, each with precise control of temperature and draw tension. This incremental approach allows repeated adjustments to the geometry, ensuring that the final microstructure is accurately scaled down.

3.2.2 Drawing process

Once the preform is assembled, it is placed in a fiber-drawing tower that applies heat to soften the glass, while a controlled tension is used to pull and reduce it to the

desired diameter. Maintaining stable draw tension and temperature profiles is critical in controlling the internal microstructure's dimensions.

High tension or speed can distort microchannels or produce uneven wall thickness. Conversely, insufficient tension can cause the collapse of air holes. The furnace temperature, usually in the range of 1800–2000°C for silica, must be precisely managed. A slightly higher or lower temperature can drastically affect the uniformity of the final structure. Real-time monitoring of the outer diameter of the fiber ensures consistency and is often coupled with feedback mechanisms that adjust the draw speed on the fly.

3.2.3 Post-processing and coating

Hollow-core fibers sometimes require protective polymer coatings or additional layers that safeguard against mechanical abrasion or moisture ingress. For certain high-power laser applications, specialized coatings (e.g., polyimide, high-temperature resins) may be used to withstand elevated thermal loads.

Standard acrylate or polyimide coatings used as protective coatings are commonly applied to the outer surface. These coatings, however, must be chosen to avoid outgassing or degradation under high optical intensities. To integrate hollow-core fibers into laser systems, precise cleaving is needed to create a clean, perpendicular end face. Connectorization methods range from standard ferrule-based connectors to custom end caps that minimize reflection or facilitate coupling to free-space beams.

Figure 6 provides a detailed visualization of the fabrication process for photonic crystal fibers (PCFs) using the stack-and-draw method [7]. Figure 6(a) outlines the sequential steps involved, beginning with the fabrication of capillaries (~1 mm thick) that are then stacked into a preform with a carefully arranged geometry. This

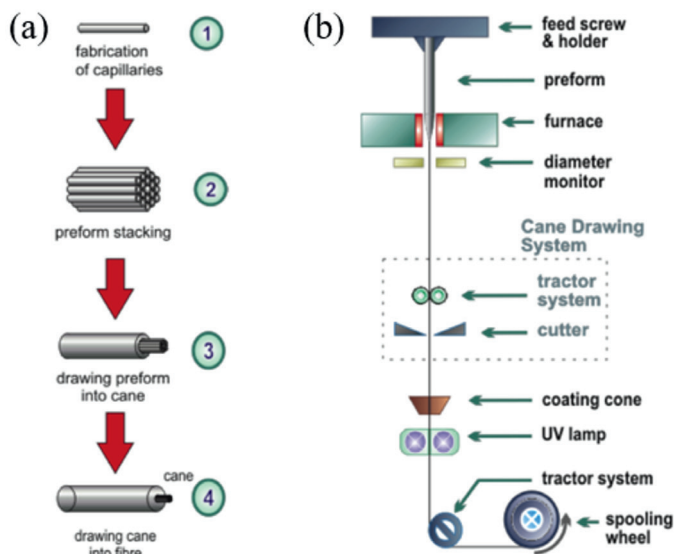


Figure 6. (a) Steps in the fabrication of photonic crystal fibers. (1) ~1 mm thick capillaries are drawn to precise dimensions and then (2) stacked to form the desired “preform.” (3) The preform is fused together and drawn down in size to a “cane” (~1 mm in diameter). (4) In the final drawing step, the cane is drawn down to fiber and encased in a glass tube, forming the outer cladding. (b) Fiber fabrication system [7].

preform is fused and drawn into a cane (~1 mm diameter) before undergoing a final drawing process to form the fiber, ensuring that the hollow core and microstructured features are accurately preserved at the nanoscale. **Figure 6(b)** presents an overview of the fiber-drawing system, illustrating key components such as the furnace, diameter monitor, coating system, and spooling mechanism. The preform is heated and stretched, reducing its dimensions while maintaining its structural integrity. The inclusion of a UV lamp and coating system is crucial, as it applies protective layers to the fiber, enhancing mechanical durability and long-term stability.

While the stack-and-draw method provides high precision in fiber fabrication, several challenges arise. Ensuring consistent hole size and uniformity during the drawing process is essential to maintain low-loss optical guidance, particularly in anti-resonant and photonic bandgap hollow-core fibers. Additionally, maintaining tight control over the drawing tension, temperature gradients, and glass viscosity is necessary to prevent structural deformations that could compromise fiber performance. Overall, the stack-and-draw technique remains one of the most effective methods for fabricating microstructured hollow-core fibers, allowing for tailored optical properties, low attenuation, and precise mode control.

3.3 Practical constraints and ongoing research

Despite significant advances, the reproducible mass production of hollow-core fibers with extremely low loss and broad bandwidth remains challenging. Any slight variation in wall thickness or hole geometry can increase scattering and degrade performance. Current research efforts focus on

1. Loss reduction: Pushing the attenuation of hollow-core fibers down to single-digit dB/km or even below 1 dB/km for specific wavelength ranges.
2. Larger core diameters: Scaling the diameter of the hollow core to accommodate higher laser powers or to reduce modal overlap with the cladding.
3. Reliability and robustness: Enhancing mechanical stability and bend tolerance, as many hollow-core designs are more fragile or have higher bend losses than conventional fibers.
4. Exotic materials and hybrid designs: Combining specialized glasses or doping the cladding to achieve novel dispersion or gain properties.

When executed effectively, the design and fabrication strategies for hollow-core fibers enable potent advantages in laser performance, outlined next in the context of emerging hollow-core fiber laser systems.

4. Hollow-core fiber lasing mechanisms

4.1 Transition from passive waveguides to active lasers

In many early demonstrations, HCFs were regarded primarily as passive waveguides—excellent for transmitting high-power or ultrafast pulses. However, as fabrication techniques improved and interest in advanced photonic systems grew,

researchers began to incorporate active gain mechanisms directly into or around the hollow core. Achieving lasing action in a hollow-core fiber can be conceptually likened to conventional fiber lasers, yet there are key differences dictated by the guiding physics and the minimal overlap between the optical mode and any solid material. Solid-core fiber lasers rely on doping the silica core with rare-earth ions (e.g., ytterbium, erbium) and using total internal reflection for confinement. Hollow-core fiber lasers can achieve gain either by embedding dopants in the cladding walls or, more intriguingly, by filling the hollow core with active media (gases or other materials) to induce lasing. Because the light mainly propagates in air or a vacuum, the laser mode experiences reduced losses and can exhibit lower nonlinear distortions once the correct resonance conditions for amplification are satisfied.

4.2 Gain mechanisms in hollow-core fibers

4.2.1 Rare-earth doped cladding

A straightforward path to realizing lasing in hollow-core fibers involves doping the microstructured cladding with rare-earth ions (such as erbium or ytterbium). Although this approach may seem similar to conventional solid-core fiber lasers, the geometry is unique.

In hollow-core fibers, the fundamental mode has a relatively small overlap with the fiber walls, where the dopant resides. Achieving efficient amplification thus requires careful engineering of the fiber structure to increase the fraction of the mode that interacts with the doped regions without incurring excessive loss.

Pump light can be launched into the cladding or directly into the hollow core. If the pump is delivered through the core, its evanescent field can excite dopants in the cladding. Alternatively, if the cladding is designed with additional waveguiding features, the pump might be confined separately from the signal beam, allowing for cladding pumping schemes analogous to double-clad solid-core fibers.

Despite promising early results, balancing low propagation loss with sufficient mode-dopant interaction remains an engineering challenge. This is one reason why many researchers have pivoted toward direct use of gas-phase or other exotic gain media in the hollow region.

4.2.2 Gas or vapor gain media

One of the most distinctive features of hollow-core fibers is the ability to fill the central void with various substances that can act as the laser gain medium. The hollow geometry provides a long interaction length for absorption and stimulated emission, analogous to traditional gas lasers like CO₂ or He-Ne, but now in a flexible, fiber-like format.

First, gases such as CO₂, He-Ne, or excimer mixtures can provide strong laser lines. For instance, CO₂ offers well-known vibrational transitions in the mid-infrared, while rare-gas mixtures (e.g., He-Xe) may support deeper UV or VUV lasing. Second, the gas pressure, composition, and temperature within the hollow core can be finely tuned to optimize gain and manage the linewidth of the lasing transition. This level of control is more challenging in typical solid-core lasers. Third, optical pump requirements: Gas-phase gain media often demand specific pump wavelengths or discharge conditions. Some configurations employ electrical discharges or radio frequency (RF) excitations in tandem with optical pumping.

4.2.3 Hybrid approaches and in-cavity nonlinearities

Another route to achieving lasing in hollow-core fibers involves exploiting nonlinear processes:

Gas-filled hollow-core fibers can be used to generate Raman gain based on stimulated Raman scattering (SRS). By carefully choosing the gas (e.g., hydrogen, deuterium), the Raman shift can be harnessed to produce coherent laser output at new wavelengths.

With appropriate phase-matching conditions inside the hollow core, it is possible to achieve coherent frequency generation or even parametric oscillation such as four-wave mixing (FWM) [8]. This approach might require an external cavity that includes the hollow-core segment as the primary nonlinear element.

These hybrid or nonlinear processes can be particularly attractive for achieving tunable laser operation, as the resonant frequencies of the gas-phase transitions can often be shifted or broadened by adjusting the gas pressure or composition.

Figure 7 shows the generation of deep-ultraviolet (DUV) light using rare gases in a kagome PCF [9]. The figure shows how the ultraviolet emission spectrum can be tuned between 176 and 550 nm by varying the gas type and pressure. The color-coded spectra correspond to different gases—Xe (red), Kr (green), and Ar (blue)—demonstrating their distinct atomic transition lines in the UV range. The rightmost section of the graph also highlights an experiment using Ne gas, with a larger-core kagome fiber (37 μm) compared to the 27 μm core used for Xe, Kr, and Ar. This experimental setup leverages SRS and FWM processes within the hollow-core fiber to efficiently generate narrowband ultraviolet pulses with pulse energies exceeding 75 μJ . Such gas-filled hollow-core fibers allow for precise spectral tunability, making them valuable for ultraviolet spectroscopy, high-resolution lithography, and plasma diagnostics. While rare-gas-filled hollow-core fibers offer flexible wavelength generation in the ultraviolet (UV) range, several challenges must be considered. Gas pressure, fiber geometry, and pump pulse characteristics must be carefully optimized to maximize conversion efficiency while minimizing spectral broadening and losses. Additionally, guiding light in the deep-UV regime poses material constraints, as fiber transmission losses tend to increase at shorter wavelengths, necessitating the use of optimized hollow-core structures with low-loss designs.

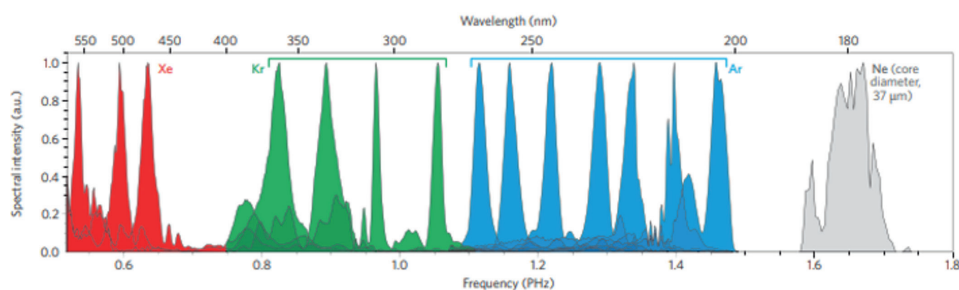


Figure 7.

Generation of deep-ultraviolet light: The ultraviolet signal, optimized to be a narrow band, can be tuned from 176 to 550 nm by varying the pressure and the gas. Pulse energies of more than 75 nJ in the deep ultraviolet, with relative bandwidths of ~3%, are generated from pump pulses of a few microjoules. The kagome PCF had a core diameter of 27 μm for the Xe, Kr, and Ar experiments and 37 μm for the Ne experiment [9].

4.3 Resonator designs and cavity integration

To form a complete laser, one requires a resonator that provides feedback at the lasing wavelength. Several cavity configurations are possible for hollow-core fiber lasers.

4.3.1 Fabry–Pérot cavities

Mirrors can be attached or fusion-spliced to the fiber ends, although precise alignment and reflection control can be challenging due to the microstructured cladding and the potential for high coupling losses.

Figure 8 shows the Fabry–Pérot cavity, a fundamental resonator configuration used in hollow-core fiber lasers and other optical systems [10]. The structure consists of two partially reflective mirrors (R_1 , R_2) positioned at opposite ends of an optical medium with refractive index n and length L . Light undergoes multiple reflections between these mirrors, leading to constructive or destructive interference depending on the wavelength and cavity length. The arrows inside the cavity indicate the round-trip propagation of the optical field, which undergoes reinforcement or attenuation based on resonance conditions. In hollow-core fiber lasers, this cavity design can be implemented by attaching mirrors to the fiber ends as reflectors. The challenge lies in achieving precise alignment to minimize coupling losses and ensure efficient feedback for lasing action. Unlike solid-core fiber cavities, where strong confinement is provided by total internal reflection, hollow-core fibers rely on photonic bandgap or anti-resonant guidance, making mirror alignment and loss control even more critical. While Fabry–Pérot cavities offer simplicity and strong mode selectivity, they are also highly sensitive to environmental perturbations, such as temperature fluctuations and mechanical vibrations, which can alter the cavity length and shift resonance conditions. Additionally, achieving low-loss coupling between free-space optics and hollow-core fiber cavities remains an engineering challenge, often requiring specialized splicing techniques or adaptive optics for precision alignment.

4.3.2 Ring cavities

In some systems, light is coupled out of the hollow-core fiber and back into it via free-space optics, enabling more flexible access to the intracavity beam (e.g., for tuning or introducing additional elements).

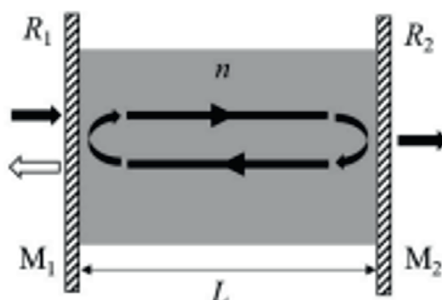


Figure 8.
Fabry–Pérot cavities [10].

Figure 9 shows a ring cavity, a resonator configuration where light circulates in a closed-loop path rather than undergoing back-and-forth reflections as in a Fabry–Pérot cavity [11]. The figure shows a triangular ring resonator, with gain media positioned along the optical path to provide amplification. Mirrors at the vertices control the direction of light propagation, ensuring that the circulating beam undergoes repeated amplification. Unlike linear resonators, ring cavities inherently support unidirectional lasing, minimizing spatial hole burning and improving mode stability. In hollow-core fiber laser systems, ring cavities can be implemented by coupling light out of the fiber and back into it using free-space optics. This approach allows greater flexibility for inserting intracavity elements, such as spectral filters, modulators, or nonlinear materials, to tailor laser performance. Additionally, ring cavities are advantageous in applications requiring narrow linewidth, stable frequency operation, or reduced feedback-induced instabilities. While ring cavities offer superior mode discrimination and unidirectional lasing, they also introduce challenges in alignment and loss management. Any misalignment between optical elements can lead to higher insertion losses, reducing overall efficiency. Moreover, maintaining phase coherence in the circulating beam is crucial for achieving stable lasing conditions, requiring precise control over cavity length and optical feedback.

4.3.3 Fiber Bragg gratings

While designing or inscribing Bragg gratings in the thin walls of hollow-core fibers is complex, there has been ongoing research into specialized microstructured gratings or external Bragg reflectors that are closely integrated with the fiber ends.

Figure 10 shows the principle of wavelength-selective feedback in fiber laser cavities based on FBGs [12]. The figure shows two FBGs (FBG1 and FBG2) inscribed within the fiber core, separated by a distance d , effectively forming a distributed mirror that selectively reflects specific wavelengths while allowing others to transmit. The lower portion of the figure represents the equivalent cavity model, where the reflectors (R_1 and R_2) define the effective cavity length (d_{eff}) and determine the resonance conditions. In hollow-core fiber laser systems, incorporating Bragg gratings is particularly challenging due to the thin-walled microstructured geometry of the fibers. Unlike conventional solid-core fibers, where FBGs can be directly inscribed using UV laser writing or femtosecond pulses, hollow-core fibers require specialized

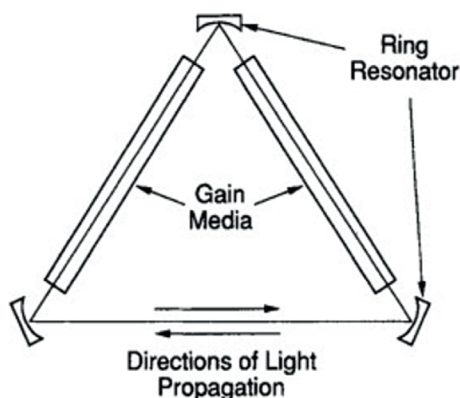


Figure 9.
Ring cavities [11].

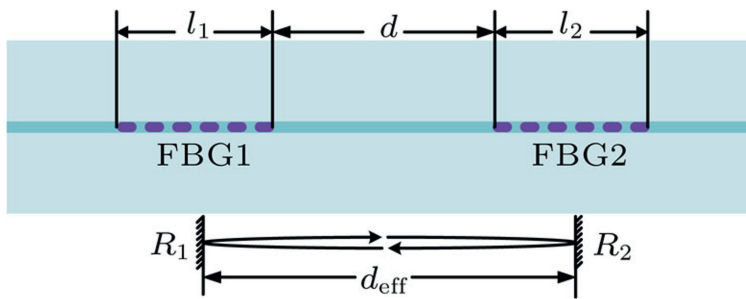


Figure 10.
Fabry-Pérot cavities based on fiber Bragg gratings [12].

fabrication techniques. This has led to the development of external Bragg reflectors, which can be integrated at the fiber ends to achieve the desired spectral filtering and feedback for lasing. While FBGs offer excellent wavelength selectivity, low-loss feedback, and high stability, their implementation in hollow-core fibers is limited by fabrication complexity and mechanical fragility. Additionally, achieving precise control over grating reflectivity and bandwidth is crucial to optimizing the laser's performance, particularly in high-power or ultrafast pulse applications. Another consideration is the thermal and environmental stability of the FBGs, as fluctuations in temperature or mechanical strain can shift the Bragg resonance wavelength, impacting laser stability.

Each approach aims to preserve the fiber's low-loss waveguiding characteristics while ensuring sufficient feedback and gain. Future research on advanced micro- and nanoscale structuring of the fiber ends may streamline the creation of integrated resonator architectures.

4.4 Lasers challenges and prospects

Key obstacles in realizing robust hollow-core fiber lasers include ensuring low propagation loss, high modal overlap with the gain region, and mechanical stability over the fiber's length. Nonetheless, the potential benefits—extremely high damage thresholds, minimal nonlinearities, and flexible gain tuning—continue to drive innovation. As micro- and nano-fabrication methods improve, we can anticipate hollow-core fiber lasers operating across broader wavelength ranges and delivering higher outputs than ever before, cementing their position as a unique tool in the photonics landscape.

5. Hollow-core fiber lasers with different gas types

5.1 Rationale for gas-filled hollow cores

One of the most compelling advantages of hollow-core fibers is the ability to introduce gases into the central region where the light propagates. This differs from solid-core fiber lasers that typically rely on glass-bound dopants. Gas-filled hollow cores offer opportunities to exploit a wide variety of atomic or molecular transitions, which can be tuned by pressure, temperature, or gas composition. This section surveys the major gas choices and their respective implications for hollow-core fiber lasers.

5.2 Common gas choices and their characteristics

Figure 11 provides a comparative overview of the laser wavelength ranges that can be supported by solid-core fibers (red bars) and hollow-core fibers (blue bars) [2]. Solid-core fiber lasers, which primarily rely on rare-earth-doped glass (e.g., Yb, Er, Tm, Ho, Dy), are typically confined to operational wavelengths within the near-infrared (NIR) region, spanning approximately 0.8–3 μm . In contrast, HCFs exhibit a significantly broader operational window, extending into the mid-infrared (mid-IR) and far-infrared (FIR) ranges, with key transitions associated with gas-phase species such as CO, CO₂, and HF.

A crucial advantage highlighted in this comparison is the ability of hollow-core fibers to operate at wavelengths that are challenging for conventional solid-core fibers, particularly in the mid-IR region (3–10 μm). This capability is especially beneficial for applications in molecular spectroscopy, environmental sensing, free-space optical communication, and industrial laser processing. Additionally, the figure underscores how chalcogenide glass-based hollow-core fibers can extend the usable wavelength range even further into the mid-IR, enhancing their potential for chemical and biomedical diagnostics. While gas-filled hollow-core fibers provide access to unique spectral regions, their performance depends on gas selection, pressure control, and the optimization of anti-resonant or photonic bandgap guidance mechanisms. Moreover, transmission losses at longer wavelengths remain a challenge, as material absorption and structural imperfections can limit efficiency. Compared to solid-core fiber lasers, which benefit from well-established fabrication techniques and high gain efficiencies, hollow-core fiber lasers require careful engineering to balance optical confinement, mode quality, and nonlinear interactions.

5.2.1 Carbon dioxide (CO₂)

CO₂ lasers are well known for their strong emission lines around 9–10 μm in the mid-infrared region, and bulk CO₂ systems have been mainstays in cutting, welding, and engraving for decades. By integrating CO₂ gas into hollow-core fibers, one can create more compact, flexible, high-power mid-IR laser sources while leveraging

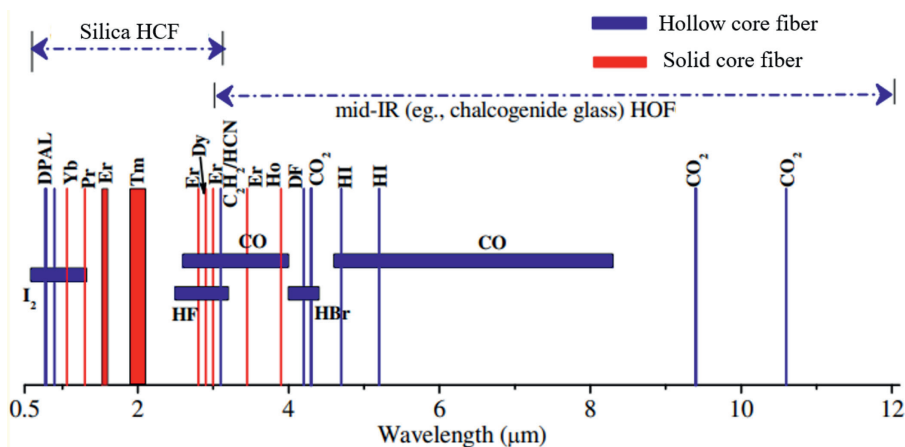


Figure 11. The comparison of laser wavelength range between solid-core and hollow-core fibers [2].

the reduced nonlinearity and enhanced damage threshold that hollow-core designs provide. Furthermore, the hollow geometry permits precise gas management, allowing adjustments in pressure and composition to fine-tune output characteristics or broaden specific transitions.

Nevertheless, maintaining low propagation losses at mid-IR wavelengths poses significant challenges, since material absorption in silica and scattering at microstructured interfaces can become more pronounced in this spectral range. Researchers are therefore investigating alternative fiber materials, such as chalcogenide glasses, and advanced anti-resonant cladding structures to minimize loss and further improve power handling. Additionally, excitation conditions (e.g., electrical discharge or optical pumping) must be carefully optimized to achieve consistent, high-efficiency lasing. By overcoming these technical hurdles, gas-filled hollow-core fiber CO₂ lasers could provide a new generation of mid-IR laser systems that combine the robustness and compactness of fiber-based architectures with the well-established capabilities of CO₂-based sources.

5.2.2 Rare-gas mixtures (He-Ne, Ar, Kr, Xe)

Rare gases and their ions, such as helium, neon, argon, krypton, and xenon, can generate discrete emission lines that span the ultraviolet, visible, and infrared regions. A well-known example is the He-Ne laser transition at 632.8 nm, though other rare-gas transitions at different wavelengths are also possible, offering a rich set of spectral lines. In a hollow-core fiber laser, the gain mechanism for these rare gases often relies on optical pumping or low-voltage electrical discharges, which populate the excited states necessary for stimulated emission. Although the cross-sections for these transitions tend to be relatively small, the extended interaction length afforded by the hollow core can help compensate for this limitation, boosting overall gain. By carefully adjusting the gas pressure, composition, and pumping conditions, it is possible to tune across multiple spectral lines, although each transition may demand specific resonator configurations or pumping schemes to achieve optimal performance. This inherent versatility makes rare-gas-filled hollow-core fibers an appealing platform for generating laser radiation at wavelengths that are not readily accessible using conventional solid-core fiber lasers.

5.2.3 Molecular hydrogen (H₂) and deuterium (D₂)

Hydrogen and deuterium both display substantial Raman shifts, making them especially well-suited for SRS processes and frequency conversion. By selecting an appropriate pump laser wavelength and intensity, the Raman gain in these gases can shift the output to spectral regions that would otherwise be unreachable by conventional solid-core lasers. Hollow-core fibers further enhance this approach because their tight mode confinement over extended interaction lengths enables more efficient gas-phase Raman lasing compared to bulk cells or externally pumped systems. This geometry mitigates issues such as splicing losses or alignment difficulties, helping to maintain high optical quality at elevated intensities. Additionally, tuning the gas pressure and composition within the hollow core offers a high degree of flexibility in controlling the Raman gain characteristics. These attributes position hydrogen- and deuterium-filled hollow-core fibers as robust, broadband sources for a variety of applications, from specialized spectroscopy and remote sensing to advanced research in nonlinear photonics and ultrafast science.

5.2.4 Excimer mixtures

Excimer lasers function by exploiting short-lived exciplex states, such as ArF, KrF, or XeCl, which emit in the UV or even vacuum ultraviolet (VUV) spectral ranges. This high-energy output has proven invaluable in fields like photolithography, materials processing, and cutting-edge scientific research requiring precise UV radiation. By adapting excimer processes to a hollow-core fiber format, one could create a more compact source with better beam quality and potentially a lower overall footprint. However, the inherent chemical reactivity and limited lifetime of excimer gases introduce engineering hurdles, particularly in maintaining gas purity and preventing contamination within the fiber. Careful management of gas pressure, composition, and flow is crucial to achieving stable lasing, while specialized coatings and robust sealing techniques may be required to mitigate plasma-induced damage and extend the operational lifetime of the laser.

5.3 Gas handling and pressure control

Managing gas pressure and composition within hollow-core fibers is essential for achieving reliable, high-performance lasing with gas gain media. Two common design approaches involve sealed versus flowing gas systems, as shown in **Figure 12**. In a sealed configuration, the fiber ends are closed off, trapping a fixed volume of gas that cannot be refreshed or altered. This arrangement simplifies mechanical handling and alignment, but it also restricts the possibility of fine-tuning pressure or composition over time. A flowing system, in contrast, circulates gas continuously through the hollow core, enabling real-time adjustments to parameters such as pressure, mixture ratio, and even temperature. Beyond these tunable parameters, the gas flow itself serves as an effective means of removing excess heat from the lasing region, thereby mitigating thermal distortions that can degrade performance. By actively transporting heat away from the fiber core, the flowing configuration supports higher operating powers and improved beam quality [13]. However, these benefits come at the cost of more complex coupling and sealing, as fiber termination points must incorporate gas feed-throughs that maintain both vacuum integrity and precise optical alignment.

Each gas exhibits an optimal pressure window in which lasing efficiency peaks, striking a balance between adequate population inversion and minimizing collisional quenching. Shifting the pressure within the hollow core can move spectral lines, alter gain bandwidth, and significantly affect beam quality. This tunability is especially valuable for experiments seeking to exploit transient or specialized molecular transitions. At the same time, it highlights how hollow-core fibers can function as tailored laser cells, where the internal environment is as crucial to design as the optical waveguide itself.

A related challenge involves mitigating contamination. Hollow-core fibers, especially those fabricated from silica, are sensitive to moisture, oxygen, and other impurities that may be introduced inadvertently if the system is not properly sealed. Even trace amounts of contaminants can degrade optical properties, alter gain processes, or lead to damage under high optical power. For these reasons, fiber handling must be carried out under carefully controlled conditions, often in a dry or inert gas environment. By selecting robust sealing methods, advanced coatings, or specialized purification routines, one can maintain the necessary cleanliness inside the fiber, thus preserving both the longevity and the performance of gas-filled hollow-core lasers.

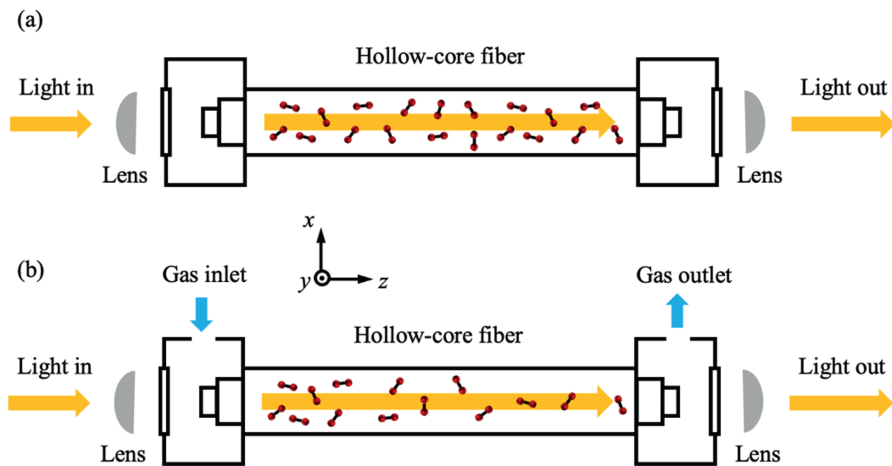


Figure 12.
(a) Sealed and (b) flowing gas laser system.

5.4 Pumping configurations

Depending on the chosen gas, the pumping mechanism for a hollow-core fiber laser may differ greatly from standard diode or fiber-coupled pumps.

5.4.1 Optical pumping

A solid-state or fiber laser at a convenient wavelength can inject photons into the hollow core, exciting the gas atoms or molecules to higher energy levels. Efficient coupling and mode matching between the pump beam and the hollow-core fiber mode are essential.

Figure 13 shows different optical pumping techniques used in laser systems, including flashlamp pumping (a), semiconductor laser diode pumping (b), and laser diode array pumping (c) [14]. While these methods are commonly employed in solid-state and fiber lasers, similar principles can be applied to gas-filled hollow-core fiber lasers for efficient energy transfer. In **Figure 13(a)**, a flashlamp surrounds a solid-state laser rod, providing broadband optical excitation. While effective for high-energy pulsed lasers, this method is inefficient for gas-filled hollow-core fibers, as it lacks the spectral selectivity needed for targeted gas excitation. **Figure 13(b)** depicts a semiconductor laser diode pumping an erbium-doped silica fiber, a configuration that ensures precise wavelength control and high coupling efficiency. This method is particularly relevant for hollow-core fiber lasers, where careful selection of the pump wavelength can optimize gas-phase excitation and stimulated emission. **Figure 13(c)** presents a laser diode array pumping a Nd:YVO₄ laser rod, a strategy useful for achieving higher power densities and uniform energy distribution. For hollow-core fiber lasers, similar diode arrays can be employed to excite Raman-active gases or drive nonlinear processes efficiently.

While diode-based pumping offers greater efficiency, stability, and wavelength selectivity compared to flashlamp pumping, challenges remain in mode matching the pump light with the hollow-core fiber mode. Improper alignment or spectral mismatch can lead to inefficient energy transfer and higher lasing thresholds. Furthermore, in gas-filled hollow-core fiber systems, the pressure and composition of

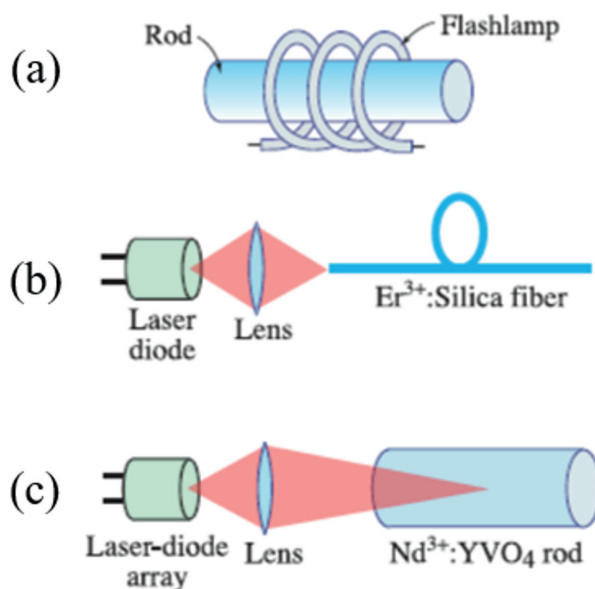


Figure 13. Examples of optical pumping are: (a) Flash lamps, (b) semiconductor laser diodes, and (c) an array of laser diodes [14].

the gas medium must be carefully optimized to ensure efficient absorption of pump photons and minimized quenching effects.

5.4.2 Electrical or RF discharge

Common in traditional gas lasers like CO₂ or excimers, electrical or RF discharges can excite the gas within the hollow fiber. This approach often demands specialized electrode configurations or waveguides that do not inadvertently spoil the optical mode.

Figure 14 shows two electrical pumping techniques used for exciting gases in hollow-core fiber lasers and traditional gas lasers: direct current (DC) discharge (a) and RF discharge (b) [14]. These methods provide an alternative to optical pumping by using electrical energy to ionize the gas molecules, leading to collisional excitation and population inversion necessary for laser action. In **Figure 14(a)**, a DC discharge system is depicted, where an applied voltage between the cathode and anode generates an electric field inside the hollow-core fiber. This field accelerates free electrons, which then collide with gas molecules, transferring energy and enabling stimulated emission at specific wavelengths. DC discharge excitation is commonly used in CO₂ lasers and other molecular gas lasers but requires precisely aligned electrodes to avoid interfering with the optical mode inside the fiber. **Figure 14(b)** shows an RF discharge system, where an alternating current (AC) field at radio frequencies is applied via an external electrode wrapped around the hollow-core fiber. RF discharges eliminate the need for physical electrodes inside the fiber, reducing potential optical losses and contamination caused by electrode degradation. This method is particularly useful for excimer lasers, UV gas lasers, and hollow-core fiber-based plasma generation, as it allows for more uniform excitation and longer operational lifetimes.

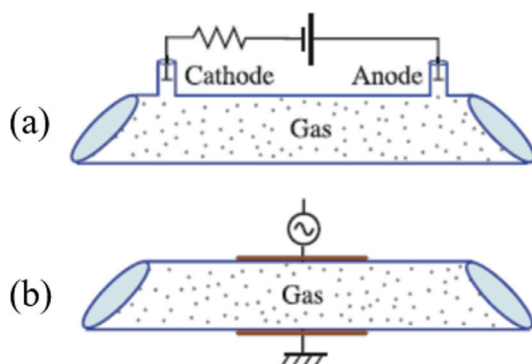


Figure 14. Examples of electrical pumping are: (a) Direct current and (b) radio frequency (RF) discharges [14].

While electrical pumping offers precise control over excitation energy, it presents engineering challenges in maintaining stable plasma conditions, avoiding discharge instabilities, and preventing unintended optical losses. Electrode placement, discharge uniformity, and heat dissipation must be carefully managed to ensure efficient and stable lasing. Additionally, compared to optical pumping, electrical discharges may introduce additional noise or fluctuations, requiring advanced cavity designs or feedback stabilization techniques. Electrical and RF discharge pumping methods expand the operational flexibility of hollow-core fiber lasers, enabling access to new lasing wavelengths and enhanced plasma-based nonlinear interactions.

5.4.3 Hybrid pumping

Combining a discharge with optical pumping can help maintain a steady population inversion while also offering finer control over the gain medium's spatial and temporal properties.

5.5 Fundamental advantages for hollow-core laser systems

Hollow-core laser systems offer a range of compelling benefits over traditional solid-core fibers. One key advantage arises from the minimal overlap between the optical mode and any solid medium, substantially reducing nonlinear effects such as self-phase modulation or stimulated Brillouin scattering. By confining most of the light to an air or vacuum region, hollow-core fibers can sustain higher power levels and more efficiently deliver ultrafast laser pulses. This geometry also increases the damage threshold, permitting higher peak powers and pulse energies—attributes essential for applications involving femtosecond or picosecond pulses. In addition, the hollow-core design provides unique flexibility in dispersion engineering, allowing for precise manipulation of group velocity dispersion (GVD) that benefits mode-locked lasers and custom pulse shaping. Another distinctive feature is that the core can be filled with various gases or even liquids, enabling advanced nonlinear processes, frequency conversion, or direct gain. This versatility paves the way for a new class of hybrid laser systems that combine fiber guidance with gas-phase phenomena, such as stimulated Raman scattering and high harmonic generation, thereby expanding both the operational wavelength range and the power handling capabilities of fiber lasers.

5.6 Outlook for gas-filled hollow-core fiber lasers

Ongoing research in gas-filled hollow-core fiber lasers continues to expand the technological possibilities in several significant ways. One key endeavor involves reducing losses through the development of new anti-resonant and hybrid-lattice fiber designs, which promise lower attenuation and make gas-phase lasing feasible at both higher energies and longer fiber lengths. Another promising direction focuses on creating multifunctional fibers that can simultaneously deliver the pump beam, provide the resonant cavity, and accommodate the gas medium, culminating in an integrated, all-in-one photonic device. Researchers are also pursuing advanced diagnostics and control techniques, such as real-time monitoring of gas pressure and composition, along with active feedback mechanisms. These approaches allow for dynamic tuning of the laser output, potentially resulting in reconfigurable systems that can adapt on-the-fly to different operational requirements.

Together, these developments underline the remarkable versatility offered by filling hollow-core fibers with gases, moving well beyond the more traditional idea of doping glass to achieve optical gain. By exploiting the molecular and atomic transitions of a wide variety of gases, one can access spectral regions that remain largely out of reach for conventional solid-core fiber lasers. Although challenges persist—particularly regarding the stability and reliability of high-power operation over extended periods—gas-filled hollow-core fiber lasers are reshaping the conventional limits of fiber photonics, merging the benefits of gas lasers with the practical advantages of fiber-based architectures.

6. Hollow-core fiber laser applications

6.1 Ultrashort pulse generation and delivery

Hollow-core fibers have proven exceptionally valuable in the realm of ultrafast optics, particularly for pulse compression and delivery at high intensities.

1. **Pulse compression:** Researchers have leveraged gas-filled hollow-core fibers to perform nonlinear spectral broadening followed by dispersion compensation, achieving compression of high-energy pulses down to few-cycle durations. This process is often referred to as a “hollow-core fiber compressor.”
2. **High-power delivery:** Delivering ultrashort pulses through conventional fibers can lead to rapid pulse distortion or damage. Hollow-core fibers mitigate these issues, enabling stable transport of femtosecond pulses with minimal temporal broadening.
3. **Biomedical imaging:** In optical coherence tomography (OCT) and multiphoton microscopy, ultrafast pulses can enhance imaging depth and resolution. Hollow-core fiber-based delivery systems offer improved signal fidelity and reduced sample heating.

6.2 Industrial laser processing

Industrial applications of lasers—such as cutting, drilling, and marking—require high average power, often in the multi-kilowatt regime. Fiber lasers are favored for

their compact footprint and robustness, but typical solid-core fibers can suffer from thermal management challenges and nonlinear distortions at very high-power levels.

1. Metal processing and welding: Hollow-core fiber lasers can maintain beam quality at elevated powers, improving the precision of welding, cutting, and micro-machining processes. The reduced nonlinearities also enhance the consistency of the beam shape over long distances.
2. Ablation and surface treatment: For processes like laser ablation or surface texturing that rely on short or ultrashort pulses, hollow-core fibers expand the accessible pulse energies without risking fiber damage.
3. Pulse shaping: Some industrial tasks benefit from customized temporal and spatial pulse profiles. Hollow-core lasers can integrate additional control elements, such as gas-based nonlinearities or adjustable dispersion, to fine-tune pulses in situ.

6.3 Telecommunications and data transmission

While the telecommunications sector is historically reliant on solid-core fibers, hollow-core fibers are attracting attention for next-generation data links. The lower nonlinearity and potential for lower latency (due to the faster speed of light in air compared to glass) make hollow-core fibers interesting for:

1. Latency-sensitive networks: Hollow-core fibers have slightly faster group velocities than silica, potentially reducing latency in data transmission. Although the difference is small, high-frequency trading and data-center communications may benefit from any fractional latency decrease.
2. High-power signal delivery: In certain specialty telecom links—e.g., distributing high-power pump light—hollow-core designs mitigate nonlinear effects that degrade signal quality in conventional fibers.
3. Terahertz and mid-infrared transmissions: Researchers are exploring hollow-core fibers that guide mid-infrared wavelengths effectively for free-space optical communication or molecular spectroscopy. Such developments could form the basis of advanced communication channels in niche applications.

6.4 Sensing and spectroscopy

The hollow core of these fibers can be exploited to probe gases or liquids directly within the fiber length, acting as an extended interaction region for spectroscopic measurements.

1. Gas sensing: By flowing target gases through the fiber, one can measure trace species absorption over a long path length, significantly enhancing sensitivity. Laser-based photoacoustic or Raman techniques can be integrated, leveraging the waveguiding properties for improved signal collection.
2. Distributed sensing: Hollow-core fibers can also support distributed sensing schemes, such as distributed Brillouin or Rayleigh scattering methods, though

the design must account for the unique cladding structure and minimal core-cladding interaction.

3. Chemical and biological detection: With appropriate surface functionalization or doping of the inner walls, hollow-core fibers may be used to detect specific chemical or biological analytes. The reduced background interference from the solid medium can lead to sharper spectral features and higher signal-to-noise ratios.

6.5 Medical instrumentation

In medical settings, lasers are used for diagnostic imaging, surgical procedures, and therapeutic applications. Hollow-core fiber lasers may offer advantages in scenarios requiring precise beam shaping or high peak powers at the tissue interface.

1. Surgical cutting and drilling: High-intensity beams can be delivered through flexible catheters without the risk of thermal damage to the fiber itself, offering more robust surgical tools.
2. Endoscopic imaging: Minimizing nonlinear distortion and maintaining high pulse fidelity can improve imaging modalities like multiphoton endoscopy, providing deeper, clearer tissue views.
3. Photoactivation and photodynamic therapy: Laser systems for activating light-sensitive drugs may benefit from wavelength-tunable hollow-core designs, particularly if the lasers are delivering mid-IR or UV pulses that are challenging to handle in solid-core fibers.

6.6 Future outlook in applications

Continued advances in hollow-core fiber design and fabrication promise an expansion of laser applications:

1. Quantum communications: Low-loss hollow-core fibers for single-photon transmission or entangled photon distribution may reduce decoherence, especially in the mid-infrared region.
2. High-field physics: Experiments that demand extremely high intensities, such as attosecond pulse generation or electron acceleration, can benefit from the lower nonlinear distortions achievable in hollow-core systems.
3. Space and defense: Hollow-core fibers potentially offer robust power delivery and resilience in harsh environments, including high-radiation areas or in vacuum conditions.

7. Conclusions

Hollow-core fiber lasers stand at the convergence of precise optical engineering and innovative photonic designs. By guiding light through air or vacuum rather than

a solid silica core, these systems unlock distinct advantages: reduced nonlinearities, higher damage thresholds, and unprecedented design flexibility. From ultrafast pulse delivery and industrial processing to specialized sensing and advanced telecommunications, hollow-core fiber lasers are demonstrating a revolutionary influence across multiple sectors.

Numerous challenges remain, particularly in scaling manufacturing capabilities to produce hollow-core fibers with both ultralow loss and robust mechanical properties. The ongoing refinement of anti-resonant and photonic bandgap structures—alongside novel hybrid designs—suggests that future generations of hollow-core fibers will enable performance characteristics once deemed unattainable, such as multi-kW single-mode beams, sub-single-cycle pulses with minimal dispersion, and extremely sensitive spectroscopic detection.

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Conflict of interest


The authors declare no conflict of interest.

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