



# **Review Review of Helical Long-Period Fiber Gratings**

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**Abstract**: In this paper, comprehensive remarks are given that focus on the main fabrications and wide applications of helical long-period fiber gratings (HLPGs). Firstly, the techniques of fabricating HLPGs by CO<sub>2</sub> laser, hydrogen–oxygen flame heating, and arc discharge are summarized. Furthermore, the applications of HLPGs are investigated, i.e., orbital angular momentum (OAM) mode converters, all-fiber band-rejection filters, and sensors for measuring physical perturbation of torsion, strain, temperature, curvature, and surrounding refractive index (SRI). Furthermore, several long-period fiber gratings (LPFGs) of near-HLPG structures with periodic refractive index change along the azimuthal direction are introduced. Lastly, the prospects and key challenges for HLPGs are discussed.

**Keywords:** band-rejection filters; fiber optic sensors; long-period fiber gratings; orbital angular momentum

# 1. Introduction

The long-period fiber grating (LPFG) is an optical passive device, which can couple the core mode to the cladding modes transmitted in the same direction. Since Vengsarkar et al. first proposed the photo-induced standard LPFG by ultraviolet laser irradiation [1], LPFGs based on different materials of silica fiber [2], fluoride fiber [3], erbium-doped fiber [4], polymer fiber [5,6], and plastic optical fiber [7] have been reported. Numerous LPFG devices of filters [8–10], couplers [11–13], polarizers [14,15], and sensors [16,17] have also been widely used in fiber communication and sensing fields.

The concept of "helical grating" was first proposed in 1991, and Poole et al. proved a kind of micro-bending grating produced by winding wire around a two-mode fiber [18]. Due to the period of the grating being difficult to control, the development of this fabrication technology is limited. In 2003, Kopp et al. studied a chiral fiber structure which was fabricated by wrapping a thick polymeric rod with a thin rod [19,20]. The next year, remarkable research work on a new type of LPFG, namely, the chiral long-period fiber grating (CLPG), was proposed [21]. Subsequently, a series of researches on the application of the CLPG in optical isolators, polarizers, and sensors were demonstrated [22–25]. Since the CLPG is formed by continuously twisting glass fiber when passing through the miniature heat zone, whereby a periodic structure is generated in the fiber with a helical path, the CLPG is also known as a helical long-period fiber grating (HLPG). Unlike traditional LPFGs induced by UV irradiation, HLPGs have the characteristic of periodic spiral refractive index modulation along the axis direction and do not require the fiber materials to have photosensitive properties. Because of this excellent property, HLPGs implemented in various types of fiber, such as single-mode fiber (SMF) [26-60], two-mode fiber (TMF) [61-65], few-mode fiber (FMF) [66–68], double-clade mode fiber (DCF) [69,70] photonic crystal fiber (PCF) [71–78], multicore fiber (MCF) [79–81] polarization-maintaining fiber (PMF) [82], and dual-hole elliptical core fiber (DEF) [83], have been proposed and demonstrated. At the same time, the types of HLPGs have evolved from a relatively simple spiral structure



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**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). to near-helical structures [30,32,39,60,65]. The fabrications and applications of the HLPGs have also been widely developed. With efforts from corresponding researchers, some outstanding research results regarding LPFGs and HLPGs were summarized [84–86]. In view of the HLPGs receiving continuous increasing interest in recent years, the main fabrications and wide applications deserve comprehensive remarks.

In this paper, the fabrication techniques of HLPG, such as  $CO_2$  laser, hydrogen–oxygen flame heating, and arc discharge are summarized in Section 2. Subsequently, in Section 3, their wide applications on OAM mode converters, special all-fiber band-rejection filters, and sensors of torsion, strain, temperature, curvature, and refractive index are investigated. In addition, several near-HLPG structures are also proposed. Lastly, the discussion and conclusions are given in Section 4.

# 2. Methods of HLPG Fabrication

Unlike the traditional LPFG, HLPGs have the characteristic of periodic spiral refractive index modulation along the axis direction. Figure 1 shows a schematic diagram of a rectangular-core fiber HLPG in which the rectangular core was twisted into a helical path. The periodic spiral refractive index modulation is required to be written into the optical fiber during the preparation process of the HLPG. Ever since Kopp et al. made the first HLPG using a miniature oven, researchers have been exploring the manufacturing technology of HLPGs [21]. Accordingly, various methods for fabricating HLPGs have been reported, such as  $CO_2$  laser, hydrogen–oxygen flame heating, and arc discharge. In this section, the main methods of preparing HLPGs mentioned above are reviewed. Additionally, a comparative table (Table 1) is given at the end of this section to compare the characteristics of the different fabrication techniques.



Figure 1. Schematic diagram of rectangular-core fiber HLPG.

Mechanism	Description
Stress relaxation Fiber structure change	Features: flexible, high quality Shortcomings: expensive
Fiber structure change	Features: wide heating area, uniform heating temperature Shortcomings: difficult to fabricate gratings with a short period
Stress relaxation Fiber structure change	Features: much simpler, low cost Shortcomings: lack of reproducibility and duplicability
-	Mechanism      Stress relaxation      Fiber structure change      Stress relaxation      Fiber structure change

Table 1. Comparative table of the characteristics with different fabrication technologies.

## 2.1. CO<sub>2</sub> Laser Heating Techniques

Davis et al. first proposed a method of fabricating LPFGs by exposing the conventional optical fiber to  $CO_2$  laser pulses in 1998 [87,88], and various gratings based on  $CO_2$  laser fabrication technology were successively reported. In 2004, Oh et al. demonstrated a method to fabricate HLPGs by using a  $CO_2$  laser heating technique [43]. An example of this kind of fabrication method is shown in Figure 2a, whereby the manufacturing system for making the HLPG is composed of a translation stage, a rotation motor, two rotating fiber holders, and a focal lens. The helical refractive index modulation can be written in the fiber by  $CO_2$  laser irradiation when the fiber moving along the axis direction with the actuator

is translated and rotated by the rotation motor at the same time. However, the helical index modulation in the grating is realized by releasing the residual stress, since the fiber is rotated rather than twisted during the fabrication process, which leads to a low refractive index modulation depth [46]. In order to obtain strong resonance coupling, Shin et al. proposed a high-strength coupling of a structure-induced HLPG made by  $CO_2$  processing technology, which was fabricated by twisting a single-mode fiber [46]. The strategy to manufacture the structure-induced HLPG is schematically shown in Figure 2b, whereby the  $CO_2$  laser heats the fiber to a softened state while the two motorized precision rotating fiber holders can twist in opposite directions, thus fabricating the structure-induced HLPG. This grating is formed by twisting fiber into a helical path, and its mechanism can be explained as core-cladding eccentricity [34,89,90].



**Figure 2.** Experimental setup for fabricating HLPGs by (**a**) releasing the residual stress under CO<sub>2</sub> laser irradiation, and (**b**) inducing the structure change under CO<sub>2</sub> laser irradiation.

In [43,46], the power of the CO<sub>2</sub> laser could be controlled accurately and easily by a computer. Since their laser beam was fixed and focused on the fiber with a small spot, the fiber had to be moved to obtain the spiral refractive index modulation. Therefore, a precise and stable mechanical translation stage is required in this device. Zhang et al. proposed a simple and effective method to design HLPGs by using a scanning CO<sub>2</sub> laser [56]. The fiber does not need to move in the axis direction; instead, it is fixed on the stage between the fiber holder and the rotator, and it is twisted at a constant speed by the rotator. In the meantime, the laser system uses a tuning mirror to control the scanning orbit of the laser beam, and the laser beam can also advance along the fiber axis while transversely scanning the fiber. Another method of fabricating HLPGs was proposed, in which the fiber can move along the axis [63]. The laser scanning technology was adopted to ensure uniform heating and fully melting of optical fiber [61,63,69,70,82].

Generally,  $CO_2$  lasers have an output power fluctuation, which leads to poor quality and repeatable performance of the HLPG. Li's group proposed a new method for fabricating HLPGs, which uses a sapphire tube to uniformly heat the optical fiber [33,67,91]. A typical fabrication setup is presented in Figure 3a; unlike the previous method of focusing the laser beam on the surface of optical fiber to fabricate the HLPG, here, a sapphire tube is utilized in place of the lens. When the laser beam irradiates the tube, it can be acted as a miniature oven to uniformly heat the fiber.

 $CO_2$  laser techniques also have some shortcomings, such as unilateral irradiation. The asymmetrical irradiation of the  $CO_2$  laser can produce uneven heating, which affects the quality of the grating. In order to avoid the asymmetrical distribution of the refractive index and bending of the fiber, Li et al. reported a double-sided  $CO_2$  laser manufacturing system to fabricate HLPGs [37]. A schematic example is shown in Figure 3b. In addition, Kong et al. demonstrated a promising technology and successfully fabricated a high-quality HLPG with a commercial fusion splicer [35]. The laser beam of the fusion splicer is split into two paths, which heat the optical fiber on opposite sides at a certain angle to avoid direct irradiation with each other. The fusion splicer also has a real-time feedback system to stabilize the  $CO_2$  laser, which can greatly reduce the power fluctuation and ensure a repeatable heating process.



**Figure 3.** Schematic diagrams for fabricating HLPG by (**a**) using a sapphire tube, and (**b**) using a double-sided  $CO_2$  laser beam.

#### 2.2. Hydrogen–Oxygen Flame Heating Techniques

The hydrogen–oxygen flame heating machine is a kind of high-efficient energy conversion device, which realizes high heating temperatures by electrolyzing water. At present, it is widely used in preparing various optical fiber devices.

Yuan's group demonstrated an HLPG in a dual-hole elliptical core fiber by using the hydrogen–oxygen flame heating technique [83]. A similar example is depicted in Figure 4, where the fabricated setup is composed of a gas generator, a rotator, a fixation, and a translation stage. The fiber is heated by a hydrogen–oxygen flame, which can reach 1300 °C with a computer controlling the gas generator. By means of the heating techniques, a refractive index sensor of the microfluidic chip can be easily fabricated.



Figure 4. Schematic diagram of hydrogen–oxygen flame heating system for fabricating HLPGs.

Fu et al. proposed a high-efficiency fabrication method of HLPGs [31]. The highquality HLPG can be obtained by using a hydrogen–oxygen flame heating system so that the grating can be cut into a series of sections to generate orbital angular momentum modes. An example of such an experimental setup is presented in Figure 5. In the fabrication system, a 1 cm long hydrogen–oxygen flame heat zone is used to heat the fiber, which is fixed on two different translation stages by a holder and the rotation motor. When the two translation stages move along the axial direction, a constant speed difference is maintained between them to avoid fiber bending during the fabrication process. Due to the diameter of the grating decreasing with the increase in velocity difference, their group designed an improved HLPG with different diameters [92].

In addition, an improved hydrogen–oxygen flame heating setup was reported [72,73], which can be used to fabricate inflated HLPGs. The HLPG was prepared in a photonic crystal fiber (PCF) by using an inflation-assisted hydrogen–oxygen flame heating system. During the fabrication process, one end of the PCF was glue-sealed with an air pump to ensure that the air holes of the fiber were connected to the gas chamber. The other end of the PCF was spliced to an SMF to seal the hollow silica channels. To avoid the shrinkage of the hollow silica channels during the heating, the air was inflated into the PCF to apply pressure onto the air-hole.



Figure 5. Schematic diagram of hydrogen-oxygen flame heating system with two translation stages.

#### 2.3. Arc Discharge Heating Techniques

Poole et al. first reported an LPFG induced by arc discharge heating technology [62]. Owing to its flexibility and simplicity, the arc discharge heating technology has attracted wide attention in the fabrication of LPFGs [93]. Within arc discharge technology, several methods have been proposed, including the use of a fusion splicer and ignition coil [94].

In 2017, Sun et al. confirmed the method of preparing an HLPG with arc discharge heating technology [48]. An automatic arc processing is realized by writing a designed program in a commercial fusion splicer. Because each component of the fusion splicer can be easily controlled by programming, this technology has high flexibility. In addition, due to the special high-precision motorized translation stages and rotation motors in the fusion splicer, the fabricated HLPG has good co-axiality. Figure 6 shows a partially enlarged view of a commercial fusion splicer (Fujikura (Tokyo, Japan) FSM-100P). In the fusion splicer, the electrodes are fixed, and two holders can move along the fiber axis driven by the translation stages.



**Figure 6.** HLPG fabrication system based on arc discharge heating technology of commercial fusion splicer (Fujikura (Tokyo, Japan) FSM-100P).

The use of a commercial fusion splicer improved the manufacturing quality and writing efficiency of HLPG. The discharge time, discharge current, speeds of translation stage, and the rotating motors can be independently set through the program in the fusion splicer. By changing the corresponding parameters of the program, the HLPG can be conveniently and flexibly prepared. Li et al. presented a HLPG by twisting an all-solid photonic bandgap fiber [74], which was prepared by a splicer machine (Fujikura (Tokyo, Japan) FSM-100P+). Dang's group investigated the sensing characteristics of an HLPG with two resonant peaks [26,27], where the grating was fabricated using the same type of machine.

Zhu et al. fabricated a novel helical taper structure in PMF using an electric-arc discharge method [95]. This structure can enhance the coupling between different modes

and is used to improve the torsion sensitivity. It is implemented in three manufacturing steps by using the selected user-defined program in a fusion splicer (Ericsson (Stockholm, Sweden) FSU-995PM). The first step is to make the optical fiber thinner without rotation. Subsequently, stretching and twisting are simultaneously carried out, such that a helical taper structure is fabricated on the waist of the taper. Lastly, the structure is shaped with a small current and short-time discharge.

It is worth noting that, although HLPGs made by commercial welding machines are relatively perfect, there are also some shortcomings. On the one hand, the translation stages of the machine are ultra-precise, and the moving distance is often limited. This method is not feasible when the HLPG needs a long coupling distance or when manufacturing multiple grating structures. On the other hand, such commercial machines are always expensive, which increases the manufacturing cost. An arc discharge system based on an ignition coil is usually another option.

Yuan et al. fabricated an HLPG with low cost and high efficiency by using selfconstructed arc discharge equipment [40,41]. An example of the fabrication system is schematically shown in Figure 7a. The main components of the fabrication equipment include an arc discharge system, a translation stage, and a pair of rotators. HLPGs with different off-axis spiral radii can be prepared by adjusting the height of two rotators in the fabrication. The details of the partial fabrication system are shown in Figure 7b. Compared with the commercial welding machine, this self-constructed arc discharge equipment has a longer preparation space, which is convenient for accurately preparing cascade grating structures in the fiber.



**Figure 7.** (**a**) Schematic diagram of the off-axis HLPG fabrication system, and (**b**) details of partial fabrication system.

#### 3. Applications

## 3.1. OAM Mode Converters

OAM beams have been widely used in the fields of optical manipulation, optical fiber communications, and optical detection [96–99]. The methods of generating OAM modes based on free-space coupling and LPFGs were previously reported [100–105]. Because a spiral twist has the ability to control the dispersion, loss, and polarization of light transmitted in the optical fiber, OAM converters based on HLPGs have attracted much attention.

### 3.1.1. OAM Mode Converters Based on Helical PCFs

Wong et al., for the first time, demonstrated the excitation of OAM modes utilizing a twisting solid-core PCF [76]. Due to the helical lattice of hollow channels, part of the axial momentum in the fiber was transferred to the azimuth direction. However, it was difficult to observe the OAM modes in the experiment. Subsequently, many kinds of OAM mode converters were proposed by helically twisting various PCFs.

By twisting a PCF with a three-bladed Y-shaped core, Xi et al. proposed a kind of HLPG that can preserve the OAM modes of the same order [78], enabling an increase in the capacity of optical telecommunications. In an all-fiber optical communication system, high-order OAM generators can enhance data transmission capacity. In 2018, Fu et al. studied high-order OAMs. OAM<sub>+5</sub> and OAM<sub>+6</sub> were produced by twisting a solid-core hexagonal PCF [71]. To achieve a high-quality OAM generator, the effect of the twist length and the twist rate on the leaky cladding resonance of the grating was investigated. Compared with the maximum coupling efficiency of -5 dB in [78], the helical PCF sample had a coupling efficiency greater than -20 dB, as shown in Figure 8a. Figure 8b–g show the simulated beam profiles, measured beam profiles, and measured interference patterns with different wavelengths.



**Figure 8.** (a) Transmission spectrum and polarization-dependent loss (PDL) of the helical PCF; (b,e) simulated beam profiles, (c,f) measured beam profiles, and (d,g) measured interference patterns of the OAM<sub>+6</sub> mode. Reprinted with permission from [71] © The Optical Society.

In 2019, a novel twist-direction-dependent high-order OAM generator was proposed [72]. An inflated helical PCF was used to investigate the effect of the air holes on the transmission spectrum. As shown in Figure 9, four types of HLPG with different twists rates were experimentally investigated. Figure 9a,b show that the transmission dips of the helical PCF (HPCF) had some distinct splits. The benefit of the inflated helical PCF (IHPCF) is that the shrink of the air holes was avoided. Perfect transmission dips were obtained, as shown in Figure 9c,d. The experiment also found that OAM<sub>+6</sub> and OAM<sub>-6</sub> modes can be generated by twisting the inflated helical PCF in a clockwise and anticlockwise manner, respectively. Additionally, to solve the problem of the generation and transmission of OAM beams, a twisted Yb<sup>3+</sup>-doped three-core microstructure fiber amplifier was developed [106]. The experimental results showed that the transmission modes at 1064 nm can carry one-, two-, and three-order OAM under different coupling cases, and the 1064 nm laser can be amplified due to the doped material Yb<sup>3+</sup>. This provides a potential method to combine the doped materials with a helical fiber to generate and amplify the OAM.



**Figure 9.** Transmission spectra of the (**a**) clockwise-twisted HPCF, (**b**) anticlockwise-twisted HPCF, (**c**) clockwise-twisted IHPCF, and (**d**) anticlockwise-twisted IHPCF with different twist rates. Reprinted with permission from [72] © The Optical Society.

### 3.1.2. OAM Mode Converters Based on Single-Helix HLPG

In 2008, Alexeyev et al. theoretically analyzed the generation and conversion of OAM modes in a helical core fiber [107]. Subsequently, the mode coupling in the single-helix HLPG was analyzed by coupled-mode theory [89,90]. In 2013, Xu et al. theoretically studied the interactions of OAM and spin angular momentum in the grating [108]. In 2018, Fu et al. experimentally demonstrated an all-fiber OAM mode converter by twisting a standard SMF [31]. The OAM<sub>+1</sub> mode was generated, and its purity and conversion efficiency were 91% and 87%, respectively. The OAM modes were detected by using a space-free interference method. Figure 10 shows the beam profiles and interference patterns. The OAM modes can be generated within a large wavelength range by changing the pitch of the HLPG; thus, this approach has potential application in all-fiber optical communication.

Furthermore, other OAM mode converters based on HLPG fabrication in SMF have been reported. Ren's group proposed a novel method to fabricate an HLPG [36]. The OAM<sub>+1</sub> and OAM<sub>-1</sub> modes can be generated by axis-offset twisting SMF in a right-hand and left-hand manner. Results showed that the OAM modes can be easily and repeatedly fabricated. Using an SMF, Zhu et al. successfully demonstrated a DC-sampled HLPG, and they first reported the generation of multi-channel OAM modes using only one HLPG [58]. This allows potential application to multi-wavelength OAM generators. Moreover, based on helical refractive-index modulation induced in SMF, Bai et al. presented a wavelengthtunable OAM generator [28]. When the HLPG is under an applied torsion strain, the wavelength of the generated OAM modes can be tuned linearly. To improve the quality of OAM vortex beams, Ren et al. proposed a high-quality OAM generator by using a real-time monitor and control system [45].

In addition to the SMF–HLPG, other single-helix HLPGs have been used to generate the OAM modes. Zhao et al. proposed a method of generating all-fiber high-order OAM using a multimode fiber [67]. They demonstrated an all-fiber OAM generator, which can turn the fundamental mode into second OAM modes by twisting a few-mode fiber. By twisting the few-mode fiber, Zhang et al. reported a polarization-independent OAM generator [109]. When light with different polarization states enters into the HLPG, the helical phases can be successfully excited. An ultra-broadband OAM mode converter based on HLPG inscribed in a two-mode fiber was achieved [64]. The bandwidth of the converter can be tuned with increases of the twist rate and temperature. In addition, multiple OAM modes were realized in a four-mode fiber [66]. By using two consecutively

cascaded HLPGs fabricated in a four-mode fiber, the first- and the second-order OAM modes are generated simultaneously.



**Figure 10.** (a) Schematic diagram of the experimental setup for detecting the OAM modes; (b) beam profile and (c) interference pattern of  $OAM_{+1}$  mode at a wavelength of 1586; (d) beam profile and (e) interference pattern of  $OAM_{+1}$  mode at a wavelength of 1530. © (2021) IEEE. Reprinted, with permission, from [31].

# 3.2. All-Fiber Band-Rejection Filters

Compared with fiber Bragg gratings (FBGs), the LPFG has a bandwidth of several tens nanometers, which can be used as a band-rejection filter [8–10]. Several special all-fiber band-rejection filters based on HLPG have been reported.

Shin et al. demonstrated a bandwidth-tunable all-fiber band-rejection filter, consisting of an HLPG pair with opposite helicities [47]. With an applied torsion strain, the bandwidth of the proposed device was tuned more than 14 nm at the rejection level of 15 dB. Based on two successively-cascaded HLPGs, Li's group proposed a unique flat-top band-rejection filter [33]. The two HLPGs were fabricated by CO<sub>2</sub> laser with opposite helicity. Moreover, in order to avoid spectral interferences, there was no separation between the HLPGs. The fine flat-top filter had a bandwidth of ~13 nm at 0.5 dB and ~15 nm at 1 dB. The proposed consecutively cascaded structure can be used as a circular polarizer, which turns the polarization light from a left-circular to a right-circular mode. Then, an all-fiber circular polarization filter is realized [59]. Later, based on reflective HLPGs, an enhanced flat-top band-rejection filter was reported [110]. The filter also utilized two consecutively cascaded HLPGs work in the reflective direction, the incident light passes through the structure twice. Thus, the filter has a strongly enhanced rejection depth of 34 dB, and the bandwidth is 15 nm at the rejection level of 2 dB.

Generally speaking, the spectra of HLPG-based filters strongly depend on the polarization state of the incident light. To solve this problem, a polarization-insensitive flat-top band-rejection filter was produced [111]. The proposed filter is based on the combination of two cascaded HLPGs and a cladding-mode stripper, where the stripper is acted on by an oil region. When the cladding modes generated in the first grating pass this area, they can be quickly stripped off the cladding. The transmission spectra of only one HLPG and of two successively cascaded HLPGs with and without an oil region are shown in Figure 11a. Results showed that, due to the existence of the cladding-mode stripper, a polarization-insensitive flat-top filter was obtained. It had a bandwidth of ~14 nm at 1 dB and a rejection depth of ~17 dB. The spectrum of the polarization-dependent loss (PDL) is shown in Figure 11b.



**Figure 11.** (a) Transmission spectrum of the first HLPG and the successively cascaded HLPGs with and without an oil region; (b) measurement results of PDL and transmission spectrum of the successively cascaded HLPGs. Reprinted from [111] Copyright (2021), with permission from Elsevier.

Additionally, Li's group presented a method for the fabrication of multichannel HLPGs using a phase-only sampling approach [57]. Three-channel and nine-channel HLPGs were proposed and experimentally demonstrated, which can be used as multichannel filters. Ren et al. proposed an approach to realize a broad bandwidth rejection filter based on the analysis dual-resonance principle around the dispersion turning point [112]. They analyzed this effect on the transmission spectra of the double-cascaded HLPGs and the chirped HLPGs, whose period changes along the fiber axis. Results showed that it is possible to realize a flat-top broadband rejection filter using this method.

## 3.3. Sensing Applications

Over the past few decades, optical fiber sensors have been widely applied because of their outstanding advantages. LPFG-based sensors have been widely used in industry, chemistry, biomedicine, and civil engineering applications [113–117]. Compared with the conventional LPFG, the HLPG has periodic helical index modulation, which shows excellent torsion sensing performance. Furthermore, the versatile applications of the HLPG in measuring the surrounding physical perturbations of strain, temperature, curvature, and SRI have attracted much attention. Here, we provide a comprehensive description.

## 3.3.1. Torsion Sensors

Due to the inherent modulation of the spiral refractive index, HLPGs can be used for torsion sensing, especially for detecting torsion direction and torsion rates. Shin et al. made an HLPG by twisting a PCF under  $CO_2$  laser irradiation [75]. When responding to external torsion stress, the resonant peaks of the proposed device had a tuning ability exceeding 18 nm. Since the length of the torsion region was not given in the paper, the torsion rate could not be calculated. Moreover, Zhang et al. developed a bidirectional torsion sensor based on cascading two identical HLPGs [55]. When the applied torsion direction was opposite to the twisting direction, the torsion sensitivity could reach up to 0.115 nm·m/rad. However, when the applied torsion direction was the same as the twisting direction, the torsion sensitivity decreased.

A torsion sensor with high sensitivity was fabricated using an HLPG written in twomode fiber [63]. As shown in Figure 12b, the resonance wavelength of the grating shifted linearly, and the sensitivity was as high as 0.47 nm/(rad/m). Moreover, Zhang et al. compared the torsion characteristics of conventional LPFG with those of an HLPG written in the same SMF. Figure 12a shows that the SMF–HLPG had a higher torsion sensitivity than the SMF–LPFG. This may have been due to the advantages of the helical structure, and the period of the HLPG could be easily reduced or enlarged with the applied co-direction or contra-direction torsion.



**Figure 12.** (a) The dependence of resonance wavelength on the twist rate of the SMF–LPFG and SMF–HLPG; (b) the dependence of resonance wavelength on the twist rate of the TMF–HLPG. © (2021) IEEE. Reprinted, with permission, from [63].

Furthermore, Sun et al. reported a potential twist stress sensor based on an arcinduced HLPG [48]. Its resonance wavelength changed monotonically with a sensitivity of -46.46 nm/(rad/mm). The tuning properties of the transmission spectrum were investigated by mechanically twisting a laser-induced HLPG in [35]. When the twist angle varied from  $-360^{\circ}$  to  $+360^{\circ}$ , the wavelength tuned about 49 nm with a high sensitivity of 0.307 nm·m·rad<sup>-1</sup>. Zhao et al. proposed a method to improve the torsion sensitivity of HLPG by reducing the diameter of the grating [92]. When the grating diameter was reduced from 109 µm to 85 µm, the torsion sensitivity could be significantly enhanced from -245.80 to -942.77 nm/(rad/mm). A summary of the presented torsion sensors with their comparative information is listed in Table 2.

Fabrication	Fiber	Sensitivity	Range	Ref.
CO <sub>2</sub> laser	PCF	_	$-540^\circ$ to $540^\circ$	[75]
$CO_2$ laser	SMF	115 nm/(rad/mm)	$-5\pi/2$ to $5\pi/2$ (rad/m)	[55]
$CO_2$ laser	TMF	470 nm/(rad/mm)	-30 to 30 (rad/m)	[63]
Arc discharge	SMF	-46.46 nm/(rad/mm)	-100 to 100 (rad/m)	[48]
$CO_2$ laser	SMF	307 nm/(rad/mm)	-80 to $80$ (rad/m)	[35]
Hydrogen–oxygen flame	SMF	-942.77 nm/(rad/mm)	-40 to 40 (rad/m)	[92]

Table 2. Comparative table of HLPGs for torsion measurement.

# 3.3.2. Strain Sensors

When a strain is applied to the HLPG, the tension-induced photoelastic effect and the change of the period lead to a shift of the resonance wavelength in the transmission spectrum. Therefore, HLPGs are widely used as strain sensors.

By twisting a solid-core PCF, a mechanical strain sensor based on an HLPG was successfully realized [77]. With the applied axial tension from 0 to 1700  $\mu\epsilon$ , the resonance wavelength linearly shifted to a shorter wavelength with a strain sensitivity of 1.18 pm· $\mu\epsilon^{-1}$ . Fu et al. also proposed a strain sensor based on helical PCF [73]. Results showed that the strain sensor was independent of the air-hole diameter of the PCF, whereby the helical PCFs with different air-hole diameters of 2.9 and 3.6  $\mu$ m achieved sensitivities of 3.20 and 3.18 pm/ $\mu\epsilon$ , respectively. Furthermore, Li et al. presented a kind of HLPG which was fabricated by twisting an all-solid photonic bandgap fiber with a few periods [74]. As shown in Figure 13, the response of the resonance wavelength to the applied external strain under different torsion angles was studied. Such a strain sensor exhibited a linear

relationship between resonance wavelength and axial strain in the wide range of 0 to  $3696 \ \mu\epsilon$ .



**Figure 13.** Wavelength shifts of the HLPG with increasing strain; the insets are the transmission spectra of the HLPG with different torsion angles. Reprinted with permission from [74] © The Optical Society.

Li et al. realized strain measurement using an HLPG fabricated in a SMF [37]. According to the experimental results, the fabricated HLPG had a strain sensitivity of 6.4 pm/ $\mu\epsilon$ , and it could measure strain and temperature concurrently. In addition, the simultaneous measurement of strain and torsion was realized by using a cascaded HLPG, for which the grating was fabricated with different molten state duration times [51]. The sensing device could discriminate strain and torsion in the range of  $-240^{\circ}$  to  $240^{\circ}$  and 0 to  $1744 \ \mu\epsilon$ . Moreover, Zhang et al. presented a strain sensor with high sensitivity by making a helical structure in a multicore fiber [79]. In the strain range of 0 to  $250 \ \mu\epsilon$ , the linear strain sensitivities of the two wavelengths reached  $-61.13 \ \text{pm}/\mu\epsilon$  and  $-37.44 \ \text{pm}/\mu\epsilon$ , respectively. A summary of the presented strain sensors with their comparative information is listed in Table 3.

Table 3. Comparative table of HLPGs for strain measurement.

Fabrication	Fiber	Sensitivity	Range	Ref.
CO <sub>2</sub> laser	PCF	1.18 pm/με	0 to 1700 με	[77]
Hydrogen–oxygen flame	PCF	3.2 pm/με	0 to 2100 με	[73]
Arc discharge	PCF	—1.84 pm/με	0 to 3696 με	[74]
$CO_2$ laser	SMF	6.4 pm/με	0 to 450 με	[37]
CO <sub>2</sub> laser	SMF	$0.420 \text{ nm/m}\varepsilon$	0 to 1744 με	[51]
$CO_2$ laser	MCF	—61.13 pm/με	0 to 250 με	[79]

#### 3.3.3. Temperature Sensors

HLPG sensors for temperature measurement have been widely studied in scientific research and industrial production. The thermal characteristics of HLPGs fabricated in an SMF by indirect CO<sub>2</sub> laser irradiation were investigated in [50]. The achieved temperature sensitivity was 49.2 pm/°C in the range of 20 °C to 120 °C. Using two cascaded HLPGs with opposite helicities, Li's group realized temperature measuring [118]. According to the experimental results, the maximum temperature responsivity of the resonant dip was 58.8 pm/°C.

Excellent performance of a temperature sensor was realized by using a residualstress-induced HLPG [38]. The sensor had a high sensitivity of 132.8 pm/°C, and it could measure from room temperature to 900 °C. In order to improve the sensitivity of temperature sensing, Yuan et al. proposed an ultra-high-sensitivity temperature sensor based on a urethane acrylate-coated off-axis HLPG [41]. Because urethane acrylate has a high thermo-optic coefficient and the refractive index is close to the cladding of SMF, the resonant wavelength had a high sensitivity to the temperature change. As shown in Figure 14, the resonant wavelength shift drifted rapidly when the temperature changed in the range of 25.0 °C to 25.5 °C. With the temperature rise and fall, the sensitivity could reach -108.69 nm/°C and 113.23 nm/°C.



**Figure 14.** (a) Transmission spectra of the ultrasensitive temperature sensor with various temperatures; (b) the dependence of resonant wavelength on the temperature. Reprinted from [41] Copyright (2021), with permission from Elsevier.

In practical applications, fiber optic sensors are often affected by factors such as vibration and torsion. At that time, multiparameter measurement is often necessary. A power-interrogated sensor was demonstrated for simultaneous measurement of temperature and torsion [52]. The sensor was manufactured by using a pair of HLPGs with opposite helicity, which could act as both interrogating and sensing elements. Zhang et al. also proposed a sensor to realize the multiparameter measurement of temperature and torsion [80]. The sensor was based on an HLPG fabricated in a multicore fiber by a CO<sub>2</sub> laser splicing system. The temperature sensitivities for two-wavelength dips were 40 pm/°C and 54 pm/°C. Another method to measure temperature without the cross-impact of twisting was demonstrated [27]. Two resonance peaks were obtained in the transmission spectrum of the HLPG. Their temperature sensitivities were 45 and 72 pm/°C, and one of them was insensitive to torsion. Thus, it could be used to measure the temperature and twist simultaneously. A summary of the presented temperature sensors with their comparative information is listed in Table 4.

Fabrication	Fiber	Sensitivity	Range	Ref.
CO <sub>2</sub> laser	SMF	49.2 pm/°C	20 to 120 $^\circ C$	[50]
CO <sub>2</sub> laser	SMF	58.8 pm/°C	20 to 100 °C	[118]
Hydrogen–oxygen flame	SMF	132.8 pm/°C	25 to 900 °C	[38]
Arc discharge	SMF	113.23 nm/°C	25 to 25.5 °C	[41]
$CO_2$ laser	SMF	41 pm/°C	20 to 150 °C	[52]
CO <sub>2</sub> laser	MCF	54 pm/°C	25 to 95 °C	[80]
Arc discharge	SMF	72 pm/°C	60 to 120 °C	[27]

Table 4. Comparative table of HLPGs for temperature measurement.

#### 3.3.4. Curvature Sensors

Curvature sensors are widely used in the field of structural monitoring because they can sense the shape and deformation of structures. Yuan et al. measured the bending response using an arc-discharge-induced off-axis HLPG [40]. Using an experimental setup composed of a micrometer and a steel ruler, curvatures of 1.22 m<sup>-1</sup> to 5.49 m<sup>-1</sup> were applied on the grating. Meanwhile, the resonant wavelength was shifted with a sensitivity of -6.765 nm/m<sup>-1</sup>. Employing the same structure of an off-axis HLPG but induced by a CO<sub>2</sub> laser, He's group investigated the performance of bending sensing [49]. When

the bending curvature was from 1.96 to 5.19 m<sup>-1</sup>, the bending sensitivity could reach  $-9.25 \text{ nm/m}^{-1}$ .

Wang's group studied the bending characteristics of HLPGs made in different types of optical fiber. Using a twisted SMF, a high-sensitivity HLPG sensor was realized [56]. Due to the advantage of a helical structure in the fiber, the proposed sensor had higher bending sensitivity. When the curvature was increased to more than  $2.1 \text{ m}^{-1}$ , a sensitivity of 12.62 nm/m<sup>-1</sup> was obtained. Later, they also studied the bending characteristics of an HLPG which was written in a twisted two-mode fiber [61]. Results showed that the resonant wavelength of the sensor was linear with curvature, and the bending sensitivity was 12.409 nm/m<sup>-1</sup>. Subsequently, an HLPG was fabricated by twisting a double-clad fiber with a CO<sub>2</sub> laser [69]. The fabricated HLPG was found to have a response to the curvature with a maximum bending sensitivity of 18.122 nm/m<sup>-1</sup>. As shown in Figure 15a, when the curvature increased, the grating contrast decreased gradually. This may have been due to the photoelastic effect caused by bending, which led to asymmetric index variation in the fiber. In addition, the sensor could overcome the dependence of the bending characteristics on the bending directions, as shown in Figure 15b. A summary of the presented curvature sensors with their comparative information is listed in Table 5.



**Figure 15.** (a) The transmission spectra of the HLPH change with curvature; the inset shows that the dependence of resonant wavelength and grating contrast on the curvature; (b) bending response in different directions. © (2021) IEEE. Reprinted, with permission, from [69].

Fabrication	Fiber	Sensitivity	Range	Ref.
Arc discharge	SMF	$-6.765 \text{ nm/m}^{-1}$	1.22 to $5.49$ m <sup>-1</sup>	[40]
$CO_2$ laser	SMF	$-9.25  \mathrm{nm}/\mathrm{m}^{-1}$	1.96 to $5.19$ m <sup>-1</sup>	[49]
$CO_2$ laser	SMF	$12.62 \text{ nm}/\text{m}^{-1}$	$2.1 \text{ to } 6.0 \text{ m}^{-1}$	[56]
$CO_2$ laser	TMF	$12.409 \text{ nm}/\text{m}^{-1}$	$0 \text{ to } 5.0 \text{ m}^{-1}$	[61]
CO <sub>2</sub> laser	DCF	$18.122 \text{ nm/m}^{-1}$	$4.0 \text{ to } 6.0 \text{ m}^{-1}$	[69]

Table 5. Comparative table of HLPGs for curvature measurement.

3.3.5. Surrounding Refractive Index (SRI) Sensors

SRI measurement is crucial in the chemical engineering [119–121] and biomedical fields [122,123]. An SRI sensor based on a screw-shaped HLPG was fabricated by means of a femtosecond laser system [29]. The refractive index sensitivity of the screw-shaped HLPG was approximately 48–51 nm/RIU in the range of 0–70% glycerin concentration. Although the HLPG produced by the femtosecond laser system used single-path scanning, it took a longer time than that produced by  $CO_2$  laser.

Wang et al. fabricated an HLPG written in a thinned fiber using a  $CO_2$  laser [91]. The unique HLPG could realize the temperature-insensitive measurement of SRI. However, results showed that the response of wavelength separation to the change in SRI was low. Then, Shen et al. reported an SRI sensor based on HLPG with a maximum sensitivity of 816 nm/RIU, which was written in a multicore fiber with a  $CO_2$  laser [81]. When the sensor was used to measure the change of SRI, it exhibited little crosstalk with the changes in

curvature and surrounding temperature. Sensors with high sensitivity and multiparameter measurement have always been the research focus in the field of optical fiber sensing. By using an HLPG, Xu et al. not only realized the highly sensitive measurement of SRI, but also achieved the simultaneous measurement of SRI and temperature. [54]. An HLPG with resonance at first and second diffraction orders was presented. As shown in Figure 16a, the high diffraction order mode of <sup>2</sup>LP<sub>16</sub> had a high SRI response and a sensitivity of 2493 nm/RIU in the range of 1.445 to 1.460. However, the first diffraction order mode of <sup>1</sup>LP<sub>12</sub> was insensitive to SRI, but responsive to temperature. Therefore, this sensor could measure temperature and SRI simultaneously. The dependence of wavelength shifts of some first and second diffraction order modes on SRI is shown in Figure 16b.



**Figure 16.** (a) Transmission spectrum growth of the HLPG with a period of 640 μm when the refractive index was changed; (b) dependence of wavelength shift of some first and second diffraction order modes on refractive index. Reprinted with permission from [54] © The Optical Society.

Using a polarization-maintaining fiber, Jiang et al. proposed an SRI sensor, whose sensitivity could reach -7248.6 nm/RIU in the refractive index range of 1.4470 to 1.4600 [82]. Generally, the reported SRI sensor of the HLPG tended to have high sensitivity only when the SRI was greater than 1.40. Yuan et al. demonstrated an SRI sensor for microfluidic chips, which was fabricated by twisting a dual-hole elliptical core fiber [83]. Experimental results indicated that the sensitivity of the internal and external sensing channel of the grating could reach 584 nm/RIU and 1108.8 nm/RIU in the refractive index range of 1.385 to 1.405.

The reason why the HLPG can realize refractive index sensing is that the effective refractive index of the cladding modes depends on the SRI. Thus, the SRI sensor is mostly used to measure the SRI change in the material surrounding the grating. However, the transmission spectra depend not only on the coupling efficiency between the core mode and cladding modes, but also on the length of the grating [124]. Since the effective length of the HLPG is determined by the length immersed in the SRI, the transmission spectrum is influenced by the height of the SRI. In this way, another type of sensor, i.e., a liquid-level sensor, was realized [44]. A summary of the presented SRI sensors with their comparative information is listed in Table 6.

Fabrication	Fiber	Sensitivity	Range	Ref.
Femtosecond laser	SMF	51 nm/RIU	0% to 70%	[29]
CO <sub>2</sub> laser	SMF	29.34 nm/RIU	1.333 to 1.379	[91]
CO <sub>2</sub> laser	MCF	816 nm/RIU	1.400 to 1.440	[81]
$CO_2$ laser	SMF	2493 nm/RIU	1.445 to 1.460	[54]
$CO_2$ laser	PMF	-7248.6 nm/RIU	1.447 to 1.460	[82]
Hydrogen–oxygen flame	DEF	1108.8 nm/RIU	1.385 to 1.405	[83]

Table 6. Comparative table of HLPGs for SRI measurement.

# 3.4. Near-HLPG Structures

HLPGs are characterized by a helical structure and spiral refractive index modulation along the fiber axis direction. Recently, some special LPFGs have been reported. Although their refractive index has no continuous helical modulation along the fiber axis, it changes periodically in the azimuthal direction. Because these unique LPFGs tend to have properties similar to those of HLPGs, they were named near-HLPG structures [32].

Deng et al. proposed a new fabrication method of a pre-twisted LPFG to measure torsion sensing [30]. The pre-twisted LPFG was fabricated by periodically creating screw-type deformations in an SMF under  $CO_2$  laser irradiation. The device displayed good torsion sensing performance and could measure torsion rate and twist direction simultaneously. Using a similar approach, an ultra LPFG used to measure torsional characteristics was fabricated [60].

An orthogonal LPFG was demonstrated, which can directly excite the OAM [65]. The grating was manufactured by  $CO_2$  laser exposure in the orthogonal direction of the SMF. As shown in Figure 17, when one-side exposure was completed, the processed fiber was rotated by 90° to expose the other side of the fiber. In this case, the rotation direction of the fiber can be clockwise or counterclockwise. After exposure, the helical phase is induced in the grating, and the chirality is determined by the rotation direction of the fiber. According to the experimental results, +1 and -1 order OAM were observed in the orthogonal LPFG with different chirality.



**Figure 17.** Schematic diagram of formation principle of orthogonal LPFG: (**a**) the first exposure step; (**b**) the second exposure step; (**c**) schematic diagram of exposure combination of orthogonal LPFG with clockwise and counterclockwise chirality; (**d**) interference patterns between the coupled OAM and co-axis Gaussian beams. Reprinted with permission from [65] © The Optical Society.

Yuan's group also studied these special types of grating structures. A kind of near-HLPG was developed, which was applied to torsion and temperature sensors [32]. The grating was fabricated by spirally writing a groove in the four sides of an SMF with a high-frequency pulsed  $CO_2$  laser. One local helix grating contained four grooves, of which two adjacent ones were orthogonal. Due to the low linear birefringence in the device, the correlation between the transmission spectrum and the polarization states was reduced. Moreover, a spring-shaped LPFG was fabricated utilizing  $CO_2$  laser irradiation [39]. An SMF was polished in four directions, of which the polishing areas in the clockwise direction and any two adjacent polished areas were partially coincidental in the vertical direction. The asymmetric fiber structure led to a deviation between the geometric center and core at different positions. With an applied strain, the light in the fiber core suffered a great change in the optical path, leading to a significant shift in resonant wavelength.

# 4. Discussions and Conclusions

In summary, the research progress related to preparations and applications of HLPG was reviewed in this paper. Based on the heating technologies of  $CO_2$  laser, hydrogen-oxygen flame, and arc discharge, the fabrications of HLPG have a tendency of repeatability, high quality, and low cost. In addition to twisting the fiber along the coaxial axis under a constant period, the off-axis or variable period methods have provided a design for HLPG fabrications. In particular, the emergence of the near-HLPG has provided much greater fabrication flexibility, and it is an excellent candidate for optical communications and sensing applications.

The HLPGs have widely been used in the applications of OAM mode converters, all-fiber band-rejection filters, and optic sensing. Unlike OAM mode converters based on LPFGs, HLPGs can directly excite OAM modes without any auxiliary accessories. Recently, the realization of multichannel HLPGs and the simultaneous generation of different-order OAM modes has highlighted the great prospect of HLPGs in wavelength-division multiplex devices of both fiber sensing and communication systems. In addition, due to its inherent spiral structure, the HLPG has shown excellent performance in optic sensing, especially in detecting torsion directions and torsion rates. It is believed that the incorporation of functional materials with HLPG will provide a potential application in biochemical detection.

HLPGs have undergone rapid development in terms of fabrication and application, but there are still some challenges. In terms of grating preparation, due to the fiber needing to be heated continuously in the preparation process of a twisted structure, it is susceptible to environmental factors such as vibration, especially during the processing of special optical fibers. Although this effect can be greatly reduced during the fabrication of the near-HLPG, some new methods need to be explored to facilitate the fabrication of helical structures with high quality in more types of fibers. Another problem to be solved is the transmission of OAM modes. To the best of our knowledge, at present, the experimentally reported OAM modes belong to the cladding mode, with some of them even belonging to the high-order cladding mode. Since the cladding mode in optical fibers suffers from high attenuation and cannot be transmitted over long distances, the application of OAM modes in the field of optical communication can rarely be moved from the laboratory to practical applications. In addition, it is worth noting that the measurement of surrounding physical perturbation can be realized using an HLPG, which is especially sensitive to bending and torsion. However, this sensitive sensing property can cause instability in the OAM mode when the HLPG is used in optical communication. Thus, some advanced packaging techniques are strongly demanded.

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