Recent progress in all-fiber ultrafast high-order mode lasers

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Abstract

Ultrafast high-order mode (HOM) lasers are a relatively new class of ultrafast optics. They play a significant role in the fields of scientific research and industrial applications due to the high peak power and unique properties of spatial intensity and polarization distribution. Generation of ultrafast HOM beams in all-fiber systems has become an important research direction. In this paper, all-fiber mode conversion techniques, pulsed HOM laser strategies, and few-mode/multi-mode fiber (FMF/MMF) lasers are reviewed. The main motivation of this review is to highlight recent advances in the field of all-fiber ultrafast HOM lasers, for example, generating different HOM pulses based on fiber mode converters and mode-locking in the FMF/MMF lasers. These results suggest that mode selective coupler can be used as a broad bandwidth mode converter with fast response and HOM can be directly oscillated in the FMF/MMF laser cavity with high stability. In addition, spatiotemporal mode-locking in the FMF/MMF is also involved. It is believed that the development of all-fiber ultrafast HOM lasers will continue to deepen, thus laying a good foundation for future applications.

1. Introduction

In recent years, high-order modes (HOMs) in fibers, including scalar modes, cylindrical vector beams (CVBs) [1], and optical vortex beams (OVBs) [2, 3], have attracted considerable interest due to their potential applications in the fields of optical communication [4–8], particle trapping [9–11], high-dimensional quantum entanglement [12, 13], high resolution imaging [14–16], and material processing [17–19]. The rise of all-fiber pulsed HOM lasers began around 2010 and has become an important research direction due to the high peak power and annular intensity distribution [20, 21]. In regards to laser technology of all-fiber pulsed HOM lasers, the discussion of mode-locked fiber lasers (MLFLs) and mode converters is significant and essential.

MLFLs have developed rapidly over the last few decades due to their unique advantages, such as compact size, low cost, flexibility, high peak power, high quantum efficiency, and high optical quality [22, 23]. In the last few decades, all the studies of fiber lasers have mainly concentrated on fundamental mode in a single mode fiber (SMF). However, its single-pulse energy is limited due to the small fiber core. More recently, there is a strong resurgence of interest in HOM beams because of the unique properties of spatial intensity and polarization distribution [24, 25]. In order to make the most of the potential application value, researchers have proposed many methods to generate and manipulate HOM beams based on all-fiber system, such as mode selective couplers (MSCs) [26–31], few-mode fiber (FMF) gratings [32–42], mode selective photonic lanterns [43–47], offset splicing technique [48], and so on. These early explorations promoted the rapid development of mode converters in the field of ultrafast photonics. Inspired by the study of all-fiber mode converters, researchers have achieved many exciting results, which make this direction flourish.

Quite recently, few-mode/multi-mode fiber (FMF/MMF) lasers are proposed to directly generate HOM beams with high efficiency and have also developed rapidly [49, 50]. Compared with SMF, FMF and MMF support more transverse modes, and have high dispersion and attenuation rate [51]. The mechanisms of laser transmission and amplification in the FMF/MMF are more complicated and need to be explored. And
the versatility of the FMF/MMF lasers, together with the possibility of scaling the pulse energy, make it highly attractive in ultrafast photonics. They also open up new directions in researching multimode non-linear propagation, multi-mode continuum generation, and have potential applications in the fields of high power fiber lasers, random lasers, space-division multiplexing (SDM), multi-dimensional fiber sensors, and so on [49, 50, 52–54]. As mentioned above, a large number of important work have emerged in the field of generating pulsed HOMs. However, there is still a lack of in-depth summary of this aspect.

In this paper, we first introduce the working principles of MSCs and acoustically-induced fiber gratings (AIFGs). Next, we will discuss the experiments of all-fiber ultrafast HOM lasers using MLFLs and mode converters. Subsequently, we will present pulsed HOM lasing in the FMF/MMF laser cavities. Finally, we will outline the future development directions and potential applications of ultrafast HOMs.

2. Fundamental of all-fiber mode converters

The generation and manipulation of HOM beams are a prerequisite for applications. Since 1972 [55], various active and passive methods have been developed to generate CVBs [56–59]. Two decades later, OVBs, also known as orbital angular momentum (OAM) modes, were recognized [60]. Since then, several methods to generate OVBs in free space also have been proposed: spiral phase plates [61], computer generated holograms [62], cylindrical lens pairs [63], spatial light modulators [64], Q-plates [65]. But all the methods proposed in the early days were based on spatial light, they were not all-fiber systems, which was not conducive to the integration of fiber system. Around 2007, all-fiber mode converters began to rise [66–68]. In the above section, some all-fiber mode converters are briefly mentioned, including MSCs, FMF gratings, and mode selective photonic lanterns. In terms of the implementation technologies, MSCs are divided into fused-type [27], side-polished type [29], dual-core type [69, 70], and stress-induced type [71]; FMF gratings can be divided into mechanical long-period gratings (LPGs) [32], CO2 laser written LPGs [33, 34, 72, 73], AIFGs [38, 39] and fiber Bragg gratings (FBGs) [36]. Among these all-fiber mode converters, photonic lanterns are highly integrated devices with high cost and technical difficulty; offset splicing technique has some problems about poor beam quality and lower conversion efficiency; MSCs have high conversion efficiency and mode quality, broad working bandwidth, and easy fabrication; AIFGs have great flexibility and tunability without fiber damage.

2.1. Principle and experimental results of MSCs

MSCs are composed of a SMF and a FMF, and the schematic of MSCs is shown in figure 1(a). According to the coupled-mode theory [75], efficient mode conversion in fibers needs to meet the phase-matching condition [27–30]. In general, the propagating constant of LP01 mode in SMF is larger than that of LP11 (LP21) mode in FMF. In order to make their propagating constants equal, the fiber diameter of SMF needs to be pre-tapered. And then, two dissimilar optical fibers are twisted, stretched and fused together by weakly fused technique so that their fiber claddings are very close to each other and the shape of coupler cross-section remains unchanged. This is essential for the complete power transfer between the modes in SMF and FMF [27]. The expected output beams are typically scalar modes, such as LP11, LP21 modes. Scalar modes are degenerated by vector modes which have similar propagation constants. OAM modes can be produced by combining different vector modes with a π/2 phase shift [74], as shown in figure 1(b).

According to the experimental results, the SMF was pre-tapered, then carefully aligned with the FMF and fused together using the flame brushing technique [24, 27, 76]. By precisely controlling the phase matching condition during the manufacturing process, researchers fabricated a mass of MSCs with low loss and broad bandwidth. The measured excess loss of the LP11 MSCs is less than 0.5 dB and the working bandwidth is more than 60 nm [24]. Figure 2(a) shows the experimental setup used to measure the mode patterns. PC1 is used to adjust the polarization of the input light. PC2 is used as a rotator and a flat slab to control the generation of OVBs and CVBs. The principle is to change the symmetric fiber structure and mode propagation constants by adjusting the rotating angle and pressure. OVBs are generated when it leads to a π/2 phase shift between two vector modes [49]. Similarly, CVBs also can be generated by adjusting PC2, which makes all the vector modes coupled to a specific vector mode [33, 77].

Far-field intensity patterns of output beams are shown as figures 2(b) and (c). When the FMF is not deformed, the output beam is LP11 or LP21 mode. By adjusting PC2, OVBs can be obtained with annular intensity profiles and topological charges. The interference patterns of the donut-shaped beams with a coherent gaussian beam indicate that the topological charges are ±1 and ±2, as shown in figure 2(b). CVBs with different polarization states also can be excited. Figure 2(c) shows the spatial distribution of CVBs. The polarization states of the donut-shaped mode patterns can be determined by a polarizer. Radially polarized beam is TM01 mode and azimuthally polarized beam is TE01 mode.
Figure 1. (a) Schematic of MSCs. LP$_{01}$ mode in the SMF is expected to be converted at coupling region, the excited LP$_{11}$ (LP$_{21}$) mode will propagate along the FMF. (b) The relationship between vector modes and OAM modes [74].

Figure 2. (a) Experimental setup used to measure the mode patterns. (b) Output LP$_{11}$ mode, LP$_{21}$ mode and corresponding OAM modes from the end of FMF at 1550 nm. (c) Output TM$_{01}$ mode, TE$_{01}$ mode and mode patterns with rotation of a polarizer. The white double-headed arrows indicate the polarization orientation. PC: polarization controller; BS: beam splitter.
Figure 3. Experimental results of MSCs at 1064 nm. The first column: LP_{11}, LP_{21}, LP_{02}, and LP_{31} modes. The corresponding OVBs and CVBs are on the right, including OAM_{±1} and OAM_{±2} modes, TM_{01} and TE_{01} modes [78].

Similarly, in the 1.0 \( \mu \)m band, MSCs can also perform effective mode conversion with low loss and high mode quality [78]. According to the experimental results, SMFs (core/cladding diameters are 6.2/125 \( \mu \)m) were pre-tapered to 102, 79, 52 \( \mu \)m, and then fused with FMF (core/cladding diameters are 18.5/125 \( \mu \)m), respectively. As can be seen from the first column of figure 3, LP_{11}, LP_{21}, LP_{02} modes were successfully excited. The measured conversion efficiencies were 94.2\%, 86\%, 26.1\%, insertion losses were 0.26, 1.3, 3.1 dB, respectively. Similarly, corresponding OVBs and CVBs also can be stimulated by adjusting PC. Bending loss method was used to measure the purity of HOMs due to the high bending loss of HOMs, and the purity was more than 93\%.

Except 1.5 and 1.0 \( \mu \)m, in the visible wavelengths, MSCs can also perform effective mode conversion. The same weakly fused technique was employed to fabricate the visible wavelength MSCs. According to the experimental results, SMFs (core/cladding diameters are 6.2/125 \( \mu \)m) were pre-tapered to 122, 112, and 110 \( \mu \)m, and then fused with FMF (core/cladding diameters are 10/125 \( \mu \)m, NA = 0.23), respectively. As can be seen from figure 4, the 450, 520, and 638 nm LP_{11} mode were successfully excited [79]. The measured conversion efficiencies were around 94.5\%, 72.5\%, and 50\%, insertion losses were 0.3, 1.9, and 3 dB, respectively. The LP_{11} mode purity was more than 98\%. The results show the MSCs have high mode conversion efficiency and mode purity. By adjusting the PC to remove the degeneracy of LP_{11} mode, the two-lobed linearly polarized mode can be converted into donut-shaped OVBs and CVBs. Such MSCs can be used in visible-wavelength all-fiber vortex lasers [80, 81]. The visible donut-shaped beams can be an optical source for stimulated emission depletion microscopy [82, 83].

To verify the MSCs with a broad bandwidth and high conversion efficiency, the transmission spectra of the output SMF and FMF ports were observed from 430 nm to 1600 nm by an optical spectrum analyzer (OSA), as shown in figure 5. The central wavelengths at the FMF output port are around 450 nm, 520 nm, 638 nm, 980 nm, 1064 nm, and 1550 nm. The mode converters have a contrast of 15 dB at the resonance wavelengths. It is indicated that the conversion efficiency is more than 95\%. The spectrum fringes in the FMF port are caused by the interference between the degenerated vector modes of LP_{11} mode. LP_{11} mode is degenerated by four vector modes with similar propagation constants, including TE_{01}, TM_{01}, HE_{21}^{odd}, and HE_{21}^{even}. The purity of the LP_{11} mode was estimated to be 90\% at all resonance wavelengths, which was measured by tight bend approach [27]. The power extinction ratio indicates the mode purity.

2.2. Principle and experimental results of AIFGs
AIFGs employ acoustic waves in the optical fiber via acousto-optic effect to produce periodic refractive index modulation. Based on micro-bending model, the periodic index modulation creates the so-called
acoustically induced LPG. The AIFG is formed within the optical fiber, which can convert the fundamental core mode to the high-order core mode or cladding mode. Besides, the AIFG-based mode converter has the advantages in tunable mode coupling and filtering [38, 84–87]. The acoustic waves are generated by Piezoelectric transducer (PZT) with electrically controlled system. The controlling signal (mainly sine wave or square wave) is firstly amplified by a high-frequency voltage amplifier and transformed to acoustic vibration through PZT. Furthermore, the silica horn is employed to amplify the acoustic vibration and convert it from longitudinal mode to transverse mode. Finally, the flexural acoustic wave propagates along the unjacketed fiber and creates the AIFG. So, by changing the frequency and amplitude of applied signal, one can simply change the period and efficiency of AIFG. By means of the simple structure, wide wavelength tuning range, fast response speed, low insertion loss cost, AIFGs have a wide range of applications in optical fiber communication, optical fiber lasers and optical fiber sensing.

According to the acousto-optic effect of wave guide mode coupling theory, the mode conversion via AIFG needs to satisfy phase matching conditions. The phase matching condition of LP_{01}-LP_{11} core modes in AIFG is \( L_B = \Lambda \), that is the beat length of LP_{01}-LP_{11} core modes should equal to the period of AIFG. Here the beat length can be expressed as \( L_B = \lambda / (n_1 - n_2) \), where \( \lambda \) is the transmission wavelength of light, \( n_1 \) is the
effective refractive index of fundamental mode, $n_2$ is the effective refractive index of $LP_{11}$ mode. The period of AIFG is $\Lambda = 2\pi / k = \sqrt{\pi r_{cl} C_f / f}$, $r_{cl}$ is the diameter of optical fiber cladding, $C_f$ is the propagation speed of acoustic waves in silica fibers, $f$ is the frequency of applied signal [88].

The experiment device is shown in figure 6(a). In the experiment, a FMF (fiber core/cladding diameters are 18.5/125 µm) was employed to fabricate the AIFG-based mode converter. The transmission performance of the AIFG is shown in figure 6(b). When the frequency of the signal generator is 742.0 kHz, an AIFG with a period of 1234 µm is produced and a dual-resonance has been observed due to the ellipticity of the silica fiber. The two resonant peaks exhibit the mode conversion from $LP_{01}$ mode to $LP_{11a}$ mode and $LP_{11b}$ mode. Due to the tunability of AIFG, the resonant peaks can be shifted via changing the applied frequency. As shown in figure 6(c), the mode switching at a certain wavelength is realized by employing the altering of two corresponding frequencies.

### 3. Ultrafast HOM lasers based on mode converters

In the early days, pulsed HOM lasers were generated from solid-state lasers and emitted to free space [20, 21]. Thanks to the development of all-fiber mode converters, researchers have proposed various kinds of techniques to generate ultrafast HOM lasers in all-fiber systems. As mentioned above, MLFLs exhibit the advantages of broad bandwidth, high peak power, compact structure, excellent beam quality, high stability, long lifespan and so on [89, 90]. OVBs have many interesting characteristics, such as helical phase front, carrying OAM, central singularities, orthogonality, various polarization distribution, doughnut spatial structure and so on [3, 6]. Here, a simple and effective method of generating ultrafast HOM lasers with high peak power and doughnut spatial structure is to combine MLFLs and mode converters [77, 91–96]. Such all-fiber ultrafast HOM lasers have the advantages of ultrafast fiber laser and optical vortex at the same time.

At first, researchers used FBG and offset splice in MLFLs for the generation of HOM beams. In 2014, a team from the City University of Hong Kong, Jiangli Dong and Kin Seng Chiang experimentally demonstrated a passively MLFL that incorporated a two-mode FBG for transverse-mode selection, and stable picosecond pulses for both the $LP_{01}$ and $LP_{11}$ modes were generated [97]. In 2015, B. Sun et al proposed and demonstrated a radially polarized MLFL through the use of a figure-8 cavity in combination with cascade FBGs, the transverse mode pulses with width tunable from 2.8 to 23 ns [98]. In 2016, researchers from University of Science and Technology of China demonstrated a passively MLFL emitting a radially polarized beam by using offset splicing method and few-mode FBG, the emitted mode-locked pulses have a duration...
Table 1. Summary of mode-locked fiber lasers with mode converters.

| Mode converters          | Principle | $\lambda$/nm | $\Delta\lambda$/nm | $\tau$/ns | $P_{ave}$/mW | $\Delta\tau$ | Reference |
|--------------------------|-----------|---------------|---------------------|-----------|--------------|-------------|-----------|
| Mode selective coupler   | FMF       | 1547.4        | 56.5                | 95        | 5.6 mW       | 143 fs      | [24]      |
|                          | TMF       | 1556.3        | 3.2                 | 86        | 3.5 mW       | 17 ns       | [76]      |
|                          | TMF       | 1042.3        | 1.5                 | 90        | 5.2 mW       | 53.7 ns     | [94]      |
| FMF LPG                  | AIFG      | 1560          | 10                  | 95        | —            | 384 fs      | [104]     |
|                          | AIFG      | —             | 1533                | 0.08      | 30 mW        | ~ 80 μs     | [114]     |
|                          | LI-LPG$^a$ | ~1550        | 0.15                | 99        | 25 mW        | 6 ns        | [41]      |
|                          | M-LPG$^b$ | NPR          | 1564                | 8         | 0.74 mW      | 398 fs      | [115]     |
| Offset splicing          | FBG       | SESAM         | 1553.1              | 0.2       | 0.32 mW      | 20 ps       | [97]      |
|                          | FBG       | —             | 1547.5              | 0.2       | 99           | 13.2 mW     | 2 ns      | [100]     |
|                          | TM-FBG    | CNT-SA        | 1550.5              | 0.34      | —            | 6.87 ps     | [92]      |
|                          | FBG       | SESAM         | 1551.5              | 0.02      | 1.25 mW      | 56.8 ps     | [116]     |

$^a$LI-LPG, laser inscription LPG.
$^b$M-LPG, mechanical LPG.

of dozens of picosecond [99, 100]. Around 2016, MSCs have been found to have excellent broad bandwidth mode conversion property and can be used to generate ultrafast CVBs and OVBs with fast response [101]. Since then, generation of ultrafast HOM lasers using MSCs has been intensively investigated. For example, researchers from Shanghai University proposed a method to generate femtosecond CVBs and OVBs in all-fiber MLFLs using MSCs in 2017 [77, 24]. At the same year, another group of researchers from Nanjing University of Posts and Telecommunications also demonstrated a passively MLFL with a figure-8 cavity, which generated pulsed CVBs based on a MSC [76, 102]. One year later, the same group further revealed its broadband mode conversion at 1 μm and applied it to fiber lasers [94, 103]. Subsequently, LPGs were employed in MLFLs as mode converter to produce pulsed HOMs. In 2018, researchers from Northwestern Polytechnical University, proposed a method for generation of femtosecond optical vortex pulse in a two-mode fiber based on an AIFG [104]. At the same year, researchers from University of Science and Technology of China proposed and demonstrated an actively MLFL producing optical vortex pulses with high efficiency and a tunable repetition rate. In this case, a two-mode LPG was introduced in the cavity as a mode converter with high mode conversion efficiency and low insertion loss [41]. Unlike the MSCs mentioned above, in 2019, the same teams from Shanghai University and Nanjing University of Posts and Telecommunications proposed a mode-locked all-fiber laser emitting two-color high-order transverse mode [95] and a passively MLFL with a symmetric two-mode fiber coupler for CVB generation [105], respectively. Besides the optical devices mentioned above, another method that should be mentioned is half cavity lasers, which can be controlled to generate ultrafast OVBs from a MLFL [106].

With the recent progress in fiber lasers and mode converters outlined above, researches have yielded a mass of important results, but more efforts are still needed to extend the operating wavelength of HOM fiber laser to 2.0 μm or visible wavelength, and develop its applications. Interestingly, in the development process of all-fiber ultrafast HOM lasers based on mode converters, various types of continuous wave (CW) HOM lasers are also developing rapidly, and they promote each other. CW HOM lasers, such as multi-wavelength, narrow linewidth, wavelength tunable, and wavelength switchable HOM lasers also have important applications in mode division multiplexing and sensing system [72, 74, 80, 107–113].

Different mode converters have different properties, such as central wavelength ($\lambda_c$), 3 dB bandwidth ($\Delta\lambda$), conversion efficiency ($\tau$), average output power ($P_{ave}$), and pulse duration ($\Delta\tau$). The properties of MLFLs with mode converters are summarized, as illustrated in table 1. The fiber types they use are mainly two-mode fiber (TMF) and four-mode fiber (FMF). The main mode-locking mechanisms are non-linear polarization rotation (NPR), non-linear amplifying loop mirror (NALM), semiconductor saturable absorption mirror (SESAM), Mach–Zehnder intensity modulator (MZIM) and carbon nanotube based saturable absorber (CNT-SA). It can be clearly seen that MSCs have a wider working bandwidth, which makes the pulse duration narrower.

3.1. Ultrafast optical vortex lasers with MSCs

It is a simple method to generate ultrashort OVB pulses by mode conversion of fundamental mode pulses. But ultrashort pulses have high peak power and broadband spectrum, so a high damage threshold and broad operation bandwidth are required for mode converters. MSCs meet the requirements and can be embedded into laser cavities. Therefore, it is preferred to generate femtosecond OVB pulses based on MLFL and MSCs.

A typical experimental setup of generating OVB pulses by using MSCs is shown in figure 7. The fiber cavity was composed of a 980/1550 nm WDM coupler, a MSC, a 0.4 m heavily doped erbium-doped fiber (EDF) (LIEKKEI, ER80-8/125), a polarization-dependent isolator (PD-ISO), a 1.5 m dispersion compensating...
Figure 7. Schematic of mode-locked fiber lasers with MSC [24]. WDM: wavelength division multiplexing coupler; EDF: erbium-doped fiber; PC: polarization controller; PD-ISO: polarization-dependent isolator; DCF: dispersion compensating fiber; FROG: frequency-resolved optical gating; OSC: oscilloscope; OSA: optical spectrum analyzer; CCD: charge coupled device, infrared camera.

fiber (DCF) (THORLABS, DCF38), and a optical coupler. All the components of the laser cavity were connected by standard SMF, and the total length of SMF was 4 m. The group velocity dispersion of EDF, DCF and SMF were $-20 \text{ ps}^2 \text{ km}^{-1}, 50.35 \text{ ps}^2 \text{ km}^{-1}, -23 \text{ ps}^2 \text{ km}^{-1}$, respectively. The net cavity dispersion was 0.015 ps$^2$. Two PCs and PD-ISO in the cavity were used as the mode-locking device. The signal of Output 2 was used to monitor the working state of fiber laser. The output port of MSC was connected to an OSA (YOKOGAWA, AQ6370C), a 1 GHz oscilloscope (Tektronix, MSO 4104), and a commercial frequency-resolved optical gating (FROG, Mesa Photonics) to observe and analyze the pulse spectrum, the time domain waveform, and the pulse duration. A infrared camera was used to record the mode field distribution of pulsed OVBs.

The fused MSCs were verified effectively when acting as broadband mode converter. The intra-cavity PCs were carefully adjusted for ensuring the mode-locking operation. Figure 8(a) shows the output pulsed spectrum when using a LP$_{11}$ mode coupler. Typically, the 3-dB bandwidth was 56.5 nm owing to the net positive dispersion in the cavity [22], and the central wavelength was 1547.4 nm. Figure 8(b) shows the pulsed spectrum of Output 1 when using a LP$_{21}$ mode coupler. The central wavelength was 1545.0 nm, with a 3-dB bandwidth of 67.6 nm. Pulse spectral width and pulse duration depend on the dispersion of the laser cavity. When the LP$_{11}$ mode coupler was switched to LP$_{21}$ mode coupler, the total length of laser cavity changed, resulting in a change in the total net dispersion of the cavity, so their pulse durations and spectral widths were different. LP$_{11}$ mode, LP$_{21}$ mode, and corresponding OAM modes were observed by a infrared camera, as shown in figures 8(c) and (d). The interference patterns indicate that topological charges of vortices were 1, 2, respectively. The clockwise and counter-clockwise spiral interference patterns show that femtosecond OAM$_{\pm 1}$ and OAM$_{\pm 2}$ modes were successfully obtained. These results suggest that MSC can be used as a broadband mode converter with fast response.

3.2. Dynamic mode-switchable laser based on AIFG
To apply the AIFG-based switchable mode converter into laser field, a linear cavity is demonstrated as depicted in figure 9(a). A two-dimensional (2D) material of Sb$_2$Te$_3$ was used as a SA to achieve mode locking in the laser cavity. The intracavity AIFG played the role of spatial mode switching. The pulsed LP$_{11\alpha}$ mode and LP$_{11\beta}$ mode were achieved at the frequencies of 753.0 and 738.0 kHz, respectively. The results of this mode switching pulsed laser are exhibited in figure 9(b). The output spectra of this fiber laser have narrow bandwidths due to the wavelength selection of the FBG. The pulse trains show stable mode locking states of both LP$_{11\alpha}$ mode and LP$_{11\beta}$ mode. The slope efficiencies of laser output with LP$_{11\alpha}$ mode and LP$_{11\beta}$ mode were measured to be 11.3% and 11.7%. The pulse widths of LP$_{11\alpha}$ mode and LP$_{11\beta}$ mode pulses were 20 ns [117, 114]. It is confirmed that the spatial mode switching was achieved by incorporating a dual-resonant AIFG in the MLFL. The results have great implications in the study of spatial mode-locking mechanisms and ultrashort laser applications.
Figure 8. Spectra of pulsed (a) LP_{11} mode and (b) LP_{21} mode in output 1 when the fiber laser is running at the state of mode-locking. CCD images of far-field intensity distribution of output 1. Intensity profiles of the (c) LP_{11} mode and (d) LP_{21} mode and corresponding OAM mode patterns and spiral interferograms.

Figure 9. (a) Experimental setup of ultrafast HOM laser generation based on AIFG \cite{117}. (b) Experimental results of ultrafast HOM laser generation based on AIFG. Output optical spectra (left), pulse trains (middle), and slope efficiency (right) of LP_{11\alpha} mode (top) and LP_{11\beta} mode (bottom).
4. All-fiber FMF/MMF lasers

In order to generate HOM lasers efficiently and overcome the bandwidth limitation of mode conversion, researchers try to make HOM directly oscillate in laser cavities. This kind of all-fiber FMF/MMF lasers not only can generate HOM pulses, but also can provide a new platform to research multimode non-linear propagation, multimode solitons, multimode continuum generation, high-power lasers, random lasers, and so on [50]. In the early days, researchers worked on novel optical fibers used to generate/guide HOM beams. In 2009, Ramachandran et al from Technical University of Denmark proposed a class of optical fibers in which CVBs can be generated and maintained with exceptional modal purity [118]. The next year, Nicholson from OFS Laboratories demonstrated the first HOM, EDF amplifier [119]. Since 2011, researchers from University of Southampton have done some important works on HOM lasers. For example, J. M. O. Daniel et al described a simple technique for mode selection in a MMF laser [120], Y. Jung et al presented a multimode amplifier and a spatial mode switchable, wavelength tunable fiber laser [121, 122]. Researchers from University of Jena demonstrated a fiber based polarization filter for radially and azimuthally polarized light [123], and a compact Raman all-fiber oscillator for CVB generation [124]. In 2011, P. Uebel et al from University of Erlangen–Nuremberg demonstrated an azimuthally polarizing photonic crystal fiber with a central gold nanowire to support a low-loss azimuthally polarized mode [125]. Recently, Y. Jung et al have been working on the development of SDM components including optical isolators, circulators, gain flattening filters, WDM couplers, switches, few mode microfiber couplers, and so on [126–128]. These achievements have laid a foundation for the development of all-fiber HOM lasers.

Furthermore, researchers began to study optical pulse propagations in graded-index (GRIN) MMFs and MMF lasers. In 2015, a team from Cornell University discovered spatiotemporal non-linear effects, spatiotemporal dispersive waves, and spatiotemporal dynamics of optical pulse propagations in GRIN MMFs owing to its low dispersion and unique non-linear dynamics [129–131]. In the next year, they revealed self-organized instability, spatiotemporal characterization of supercontinuum extending, and Kerr self-cleaning of femtosecond-pulsed beams in GRIN MMFs [132–134]. Meanwhile, researches from University of Burgundy and University of Brescia found that MMFs support a rich and complex mix of spatiotemporal non-linear phenomena [135]. And researches from University of Central Florida further revealed multimode solitons in FMF [136]. After that, more and more exciting results have been achieved, including optical solitons in MMF [52, 136], multimode supercontinuum generation [137], spatiotemporal modulation instability [132], beam self-cleaning [134, 138], spatial self-imaging [139], and so on. But all the MMF lasers are CW, coherent superposition of longitudinal and transverse modes in a MMF laser to form ultrashort pulses has received little attention. In 2017, the same team from Cornell University, Wright et al proposed and experimentally demonstrated spatiotemporal mode-locking in MMF lasers, and ultrashort pulses were generated by locking multiple transverse and longitudinal modes [50]. Since then, more and more researchers have begun to study pulsed MMF lasers. In 2018 and 2019, another group of researchers from Tsinghua University further observed soliton molecules and multiple-soliton in spatiotemporal mode-locked MMF lasers [52, 140]. Here, another MMF laser that should be mentioned is that a team from Shanghai Jiao Tong University reported a high-power mode-locking operation of a multimode thulium fiber laser at 2 µm with a SESAM as the modulator [141]. Such high-power mode-locking operation of MMFs including both temporal and spatial dynamics will improve our understanding of spatiotemporal dynamics of multi-dimensional pulses.

Compared with MMF, FMF supports only few HOMs, so FMF lasers can achieve single HOM lasing and the output mode fields have higher quality [49]. Around 2018, researchers began to explore that HOM direct oscillation of FMF lasers [142–145]. For example, researches from Nankai University proposed a multimode oscillation Q-switched fiber laser with a FMF cavity [146]. In 2019, a team from Nanjing University of Posts and Telecommunications experimentally demonstrated an all-FMF passively mode-locked figure-8 cavity laser and an all-FMF mode-locked ring laser [147, 148]. To give readers a clearer understanding of the recent progress of mode-locking in FMF/MMF, table 2 lists some crucial experimental results which were generated directly from mode-locked or Q-switched FMF/MMF laser cavities without mode conversion. The fiber types are mainly step index (STIN) and GRIN FMF/MMF. The mode-locking mechanisms are similar to conventional lasers, including NPR, SESAM, SA, and non-linear optical loop mirror (NOLM). It is noted that the output performances of generated HOM beams are still not satisfactory, and need to be further developed. For example, the output powers are low, the pulse durations are not narrow enough. Relevant research hasn’t been formed yet, so there is still a long way to go in this field.

A typical experimental setup of pulsed HOM all-FMF ring cavity fiber laser is shown in figure 10 [49]. The fiber laser consisted of a 1.9 m FM-EDF (Dcore = 6 µm, Dring = 17.5 µm) [151] and a 6.7 m FMF. All the devices in the laser cavity were made of FMF. The mode of pump light was converted to LP_{11} mode by a 980 nm MSC. HOM pump light was injected into the laser cavity through a 980/1550 nm FMF-WDM.
Table 2. Summary of mode-locking in FMF/MMF lasers.

| Fiber types | Principle | $\lambda$/nm | $\Delta\lambda$/nm | $P_{ave}$/mW | $\Delta\tau$/µs | Reference |
|-------------|-----------|--------------|-------------------|--------------|----------------|-----------|
| FMF         | STIN NPR+SA          | 1595.98      | 0.1               | 7            | 21 µs         | [49]      |
|             | GRIN SESAM          | ~1550        | --                | --           | 6.2 µs        | [146]     |
|             | GRIN SESAM          | 1055.98      | 0.19              | 13.24 mW     | 2.67 µs       | [149]     |
|             | STIN CNT-SA         | 1595.6       | 0.33              | 700 µW       | 34 ns         | [148]     |
|             | STIN NOLM           | ~1548        | ~0.2              | 280 µW       | 9.3 ns        | [147]     |
| MMF         | GRIN NPR            | ~1040        | --                | ~800 W       | ~4 ps         | [50]      |
|             | GRIN NPR            | ~1033        | ~0.3              | ~500 mW      | ~6 ps         | [52]      |
|             | GRIN SESAM          | ~2000        | --                | >10 kW       | ~30 ps        | [141]     |
|             | GRIN SESAM          | ~1064        | 4                 | --           | ~10 ps        | [150]     |

Figure 10. Schematic of pulsed LP$_{11}$ mode all-FMF ring laser [49]. LD: laser diode; MSC: mode selective coupler; FMF-WDM: few-mode fiber wavelength division multiplexer; FM-EDF: few mode erbium-doped fiber; PD-ISO: polarization dependent isolator; PC: polarization controller; OSA: optical spectrum analyzer; OSC: oscilloscope; CCD: charge coupled device, infrared camera; CNT-SA: carbon nanotube saturable absorber.

The SA was made of carbon nanotube (CNT), which was dispersed in polyvinyl alcohol film, and then sandwiched between two optical ferrules. Two PCs were employed in the laser cavity to adjust the polarization state. The all-FMF PD-ISO was not only used to ensure unidirectional operation, but also formed a NPR mechanism when combined with the two PCs [152]. Both the CNT-SA and the NPR technique were applied to achieve the stable Q-switched mode locking operation in the FMF laser [153]. A FMF-FMF coupler with power splitting ratio of 90:10 was used to extract the LP$_{11}$ mode power out of the FMF cavity. The time domain waveform was analyzed by an oscilloscope (Tektronix, MSO4104). The output spectra were analyzed by an OSA (YOKOGAWA, AQ6370C). The far-field intensity distributions of output signals were recorded by a CCD camera (InGaAs camera, Model C10633-23 from Hamamatsu Photonics).

The self-started Q-switching state occurred when the pump power was between 180 mW to 500 mW. The output spectrum and waveform of Q-switched HOM pulses were recorded when the pump power was set to 400 mW, as shown in figures 11(a) and (b). The output central wavelength was 1595.98 nm, with a 3-dB bandwidth of 0.1 nm. And the 3-dB pulse duration of output pulses was measured to be 21 µs. Pulsed CVBs were excited by adjusting PC3. Figure 11(c) shows the mode patterns of the output pulsed beams. A polarizer was used to determine the polarization states of the donut-shaped mode patterns. The far-field images present uniform TM$_{0,1}$ and TE$_{0,1}$ mode distributions, confirming that pulsed CVBs with high purity were achieved.

As mentioned above, research in the field of ultrafast FMF/MMF lasers has achieved some great results, but it is still in its infancy. Our understanding of spatiotemporal mode-locking in FMF/MMF lasers is only the tip of the iceberg and needs further study. SA is a key component of Q-switched and mode-locked techniques [154]. Compared with other SAs, 2D materials show potential advantages (e.g. low loss, wide operation wavelengths, fast saturation recovery, high-damage threshold, easy to fabricate) as SAs using in pulsed lasers [155]. Some 2D materials based SA like graphene [89], CH$_3$NH$_3$PbI$_3$ perovskite nanosheets...
Figure 11. (a) Output optical spectrum of pulsed all-FMF laser. (b) Single pulse envelope of pulse trains. (c) Far-field intensity distribution of TM\textsubscript{01} (top) and TE\textsubscript{01} (bottom) modes with rotation of a polarizer [49].

[156], phosphorene quantum dot [157], black phosphorus [158, 159] and few-layer bismuthene [160] have been explored in traditional lasers. They provide valuable and perspective overviews on the saturable absorption performances in pulsed laser generation and can be used in all-fiber FMF/MMF lasers.

In addition, optical solitons are stable localized wave packets that can propagate over a long distance without distortion. The formation of optical solitons is a result of the mutual interaction among the dispersion, non-linearity, gain saturation, and gain bandwidth filtering [161, 162]. Temporal optical solitons and spatial solitons have been investigated in different physical systems. But spatiotemporal solitons operation in FMF/MMF lasers have not yet been explored. Some related soliton dynamics in HOM lasers need investigation. Such as, vector multi-soliton operation [163], vector dissipative solitons [164], Sub-200 fs soliton [165], noise-like square-wave pulses [166]. It can be anticipated that FMF/MMF lasers will be a powerful platform for the study of spatiotemporal solitons in the future.

5. Conclusions and perspectives

In this review, we have summarized some common all-fiber mode converters, especially introduced the working principles of MSCs and AIFGs in detail. MSCs can be used as a broad bandwidth mode converter with fast response at 1.5 \( \mu \text{m} \), 1 \( \mu \text{m} \), and visible wavelengths. AIFGs have great flexibility and tunability, and can be used in a dynamic mode-switchable laser. Moreover, recent progress of ultrafast HOM lasers based on MLFLs and mode converters are summarized. We also have proposed and experimentally demonstrated the generation of ultrafast HOM lasers based on MLFLs and MSCs. Furthermore, recent progress of mode-locking in FMF/MMF are summarized. As an example, we have shown a Q-switched all-FMF ring HOM laser with an output of pulsed CVBs. Over the past decade, with the efforts of many researchers, a series of important results in the field of all-fiber ultrafast HOM lasers have been achieved, and they have gradually become a very hot research topic.

As future perspective, several challenging and important aspects may be considered to further develop the all-fiber ultrafast HOM lasers. First, the industrialization of specialty fibers and FMF/MMF components is a great start. HOMs require specialty fibers for generation, transmission, and amplification. A number of research institutes have begun to design and produce HOM guide fibers, gain fibers, and FMF/MMF components including HOM couplers, WDM couplers, isolators, circulators, filters, switches, and so on. These basic devices are crucial for the development of HOM lasers and SDM systems.
Second, new methods of all-fiber HOM generation or converters still need to be explored. Current research has mainly focused on MSCs, LPGs, FBGs, photonic lanterns, and so on. Novel types of optical fiber devices for HOM generation with high quality, high efficiency, high stability and broad bandwidth should be fully considered.

Third, performances of all-fiber ultrafast HOM lasers will continue to improve. Mature mode locking technology and mode conversion technology have contributed to the development of this field. The development of MLFLs and all-fiber mode converters will continue to drive its progress.

Fourth, mechanisms and techniques of pulsed all-fiber FMF/MMF lasers will be deeply studied. Spatiotemporal mode-locking mechanisms and soliton dynamics in FMF/MMF lasers are interesting. New analytical methods and techniques need to be further developed to improve the pulsed laser output performances, for instance, the output power, pulse energy, single pulse peak power, and pulse duration. 2D materials with strong non-linear properties may sufficiently speed up this process.

Fifth, more efforts are still needed to develop its applications. The development of all-fiber ultrafast HOM lasers continues to evolve and impact many fields. For example, optical vortex induction via light–matter interaction [167], such ultrafast HOM lasers can be used to fabricate a chiral nano-structure originated by angular momentum transfer of the optical vortex to a material [18]. The donut-shaped beams can be an optical source for stimulated emission depletion microscopy with superresoluation [79]. They have promising applications in the biomedical field like optical bioimaging [21]. Large mold field diameter in MMF lasers makes it a candidate for high power fiber laser delivering. Besides, the long-term stability of these HOM lasers should also be further exploited. The operating wavelengths of HOM fiber lasers are still needed to extend to near-infrared, mid-infrared and visible wavelengths. We believe that related researches will gradually develop from scientific research to practical industrial applications, which will give an innovation in the fields of optics, biomedicine, and national defense.

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