Recent progress of dynamic mode manipulation via acousto-optic interactions in few-mode fiber lasers: mechanism, device and applications

Abstract: The burgeoning advances of spatial mode conversion in few-mode fibers emerge as the investigative hotspot in novel structured light manipulation, in that, high-order modes possess a novel fundamental signature of various intensity profiles and unique polarization distributions, especially orbital angular momentum modes carrying with phase singularity and spiral wave front. Thus, control of spatial mode generation becomes a crucial technique especially in fiber optics, which has been exploited to high capacity space division multiplexing. The acousto-optic interactions in few-mode fibers provide a potential solution to tackle the bottleneck of traditional spatial mode conversion devices. Acousto-optic mode conversion controlled by microwave signals brings tremendous new opportunities in spatial mode generation with fast mode tuning and dynamic switching capabilities. Besides, dynamic mode switching induced by acousto-optic effects contributes an energy modulation inside a laser cavity through nonlinear effects of multi-mode interaction, competition, which endows the fiber laser with new functions and leads to the exploration of new physical mechanism. In this review, we present the recent advances of controlling mode switch and generation employing acousto-optic interactions in few-mode fibers, which includes acousto-optic mechanisms, optical field manipulating devices and novel applications of spatial mode control especially in high-order mode fiber lasers.

Keywords: acousto-optic interactions; dynamic mode manipulation; fiber laser; orbital angular momentum; spatial mode conversion.

1 Introduction

Spatial modes composed by cylindrical vector modes (CVMs), linear polarization (LP) modes and optical vortex modes exhibit special distributions of electrical fields existing stably in optical fibers [1–3]. Given the increasing growth of network traffic, the manifestation of these spatial modes could imply the future communication technology through spatial division multiplexing (SDM) [4–8]. Meanwhile, light beam shaping in spatial domain incorporating fiber laser technique has found diverse applications in optical tweezers [9–11], structured light imaging [12–16], quantum information science [17–20], laser manufacture [21–24] and optical communication [25–28].

Dynamic mode manipulation should be considered during generating spatial high-order modes (HOMs) directly, which can greatly improve the practical utilities of these light sources. Static methods of generating spatial modes in optical fibers can be mainly classified into four categories: mode selective couplers (MSCs) [29–31], photonic lanterns [32–34], long-period gratings (LPGs) [35–38] and fiber Bragg gratings (FBGs) [39–41]. MSC employs tapering fused fibers to demonstrate mode coupling via evanescent field interactions. Combining a single-mode fiber (SMF) and a few-mode fiber (FMF), an MSC is constituted to convert the Gaussian-like fundamental mode to HOMs.
Photonic lanterns are integrated optical components with intriguing ability of generating specific HOMs in different ports. This method of generating HOMs is capable of mode converting with low crosstalk, providing the potential value in SDM system [33]. Periodic refractive index change is applied in fibers to realize mode conversion from forward propagating fundamental mode to forward propagating HOMs in LPGs [35] or backward propagating HOMs in FBGs [39]. These methods can demonstrate high efficiency of mode conversion, but their limited versatility of static generation of spatial modes greatly constrains the application domain of HOM light sources. An effective and widely adaptable solution to generate spatial modes with dynamic switching capability would potentially expand the practical applications of spatial modes.

Acousto-optic mode converters (AOMCs) employ acoustic waves to create acoustically induced fiber gratings (AIFGs), providing a tunable spatial mode generation with high switching speed [43–50]. The pioneered discovery in 1986 that Kim et al. firstly proposed and demonstrated the mode conversion with a frequency shift by a two-mode fiber-based AOMC [43], which has opened a door to novel researches on acousto-optic interactions (AOI) in fibers and various derived components. Among them, the most extensively concerned are tunable filters [51–64], super lattice modulations [65–69], heterodyne vibration detections [70–73], AOI in photonic crystal fibers (PCFs) [74–77], wavelength tunable lasers [78–82], ultrafast fiber lasers based on AOMCs [83–92], vector modes generations [93–97], optical switchers and modulators [98–100], frequency shifters [101–103] and polarization controls [104], as shown in Figure 1. From the development tree of AOMCs, the practical applications well exploit the intriguing properties of dynamic switching and tuning, frequency shifting and mode conversion in AOMC devices. Previously, AOI-based devices for frequency shifting, FBG sideband modulation and tunable filter are the research hotspots. The frequency up-shifting and down-shifting during the mode conversion between fundamental core modes and HOMs provide the possibility of carrying acoustic vibration information for heterodyne detections. The control of microwave radio frequency (RF) signal enables the resonance tunability for dynamic band-reject and band-pass filtering. Later, fiber laser soon found their demand of AOI-based filter device and active modulation technique. Recently, benefit from the new mechanism of the co-effect of acoustic and optical birefringence on the AOMC in an ellipse-core FMF (E-FMF), dynamic mode switching could be demonstrated successfully via frequency shift keying (FSK) technique. The novel AOMC with dynamic mode switching has attracted immense attentions targeting in dynamic optical field tuning for HOM lasers.

**Figure 1:** The development tree of researches based on acousto-optic (AO) interactions in fibers.
spatial mode perturbation for spatial mode locking (ML) mechanism research [112].

In this review, we summarize the new mechanisms of dynamic mode switching based on AOMCs and the applications incorporated with HOM fiber lasers. Firstly, the fundamentals of classical AOMCs and novel dual resonant AOMCs are introduced in Section 2, including the basic mechanism of the AOMC, physical principle of mode switching, and new devices derived from AOMCs. Secondly, dynamic mode switching fiber lasers with continuous-wave (CW) output are described in Section 3. Then, ultrafast fiber lasers incorporating AOMC-based dynamic mode manipulation are specifically commented in Section 4. Mode switching ultrafast fiber lasers possessing complex optical field structures are demonstrated in both spatial and time domains. Furthermore, vortex mode switching dynamics in ML process is introduced and discussed in detail. Finally, the outlook and future challenges of AOMC-based dynamic mode manipulation are discussed in Section 5.

2 Fundamentals of acousto-optic interactions in fibers

2.1 Fundamentals of classical AOMCs

The advanced discovery reported by Brillouin in 1922 that acoustic waves and light waves can interact has led to appreciable frontiers in acousto-optics. In an optical fiber, the acoustic wave can travel along the unjacketed fiber and the AOI is mainly induced by the light diffraction from a moving refractive index periodic modulation.

From a quantum mechanical view, the photon–phonon scattering is deemed as the energy and momentum conservation [50]:

$$\omega' = \omega_0 + \omega_a; k' = k_0 + k_a. \quad (1)$$

(\omega', k') \), (\omega_0, k_0) \) and (\omega_a, k_a) \) are the frequency and the wavenumber of diffracted light, incident light and acoustic wave, respectively, as shown in Figure 2B. In fiber acousto-optics, the practical applications based on acoustically induced refractive index modulation depend on different kinds of acoustic vibrations including longitudinal mode [65–67, 84], torsion mode [113–117] and flexural mode [43, 59, 71, 107–109, 112], as depicted in Table 1.

Longitudinal modes excite acoustic pulses to induce the interlace of medium density, which contributes to the superlattice in FBGs for sideband modulation. The torsion mode of acoustic wave is enabled by exploiting two piezoceramic transducers (PZTs) with inverse vibration directions. Thus, the horn experiences a twisted force with the interlace of clockwise and anticlockwise rotations. The torsion mode of acoustic perturbation exhibits high polarization dependence of mode conversion so that it is widely used in polarization mode generation and filtering. Among these, the flexural mode excites highest coupling efficiency and is capable of mode conversion between co-propagating light modes in optical fibers. Especially employing acoustic modulations in FMFs, the AOIs deliver profound possibilities of generating HOMs and orbital angular momentum (OAM) modes with a high degree of freedom in fast mode switching capability, as shown in Figure 2A. With the control of microwave RF signal (both frequency and amplitude), the acoustic vibration can be modulated with different tuning degrees on AOIs. Therefore, arbitrary mode conversions can be demonstrated via controlling the applied RF modulation, as shown in Figure 2C and D. Previous researches focus on the wavelength tunability of optical filter induced by acousto-optic (AO) effect [53, 57, 59, 62–64, 118, 119]. In recent years, numerous progresses of HOM conversion enabled by the AOMC have been established by a rich variety of theoretical and experimental results [93–97, 105–112, 114, 120].

It is a common belief that the microring theory is the basic explanation of mode conversion in an AOMC [121]. The flexural acoustic wave (FAW) is utilized to explain the asymmetric vibration induced microbending on fiber medium. The FAW is produced by electrically modulated PZT materials and creates the mode conversion from core fundamental LP_{0,n} mode to high-order LP_{1,n} modes. The lowest FAW mode F_{11} mode propagating on the unjacketed silica fibers induces the periodic density change asymmetric with respect to the direction of acoustic vibration, which can be interpreted by the acoustically induced displacement vector (AIDV) of \ddot{u}. The AIDV-based microbending on the fiber medium leads to the permittivity modification \delta\varepsilon composed of the geometric perturbation of \delta\varepsilon_g and the photon-elastic effect of \delta\varepsilon_p [50, 112]:

$$\delta\varepsilon(x, y, z, t) = \delta\varepsilon_g(x, y, z, t) + \delta\varepsilon_p(z, t). \quad (2)$$

$$u = u_0 \cos(\kappa z - f_a t) \cdot e^{i\delta\varepsilon_g}. \quad (3)$$

\(u\) stands for the value of the AIDV. Since the shape of fiber end facet is a circle, the vibration can be assumed to be along x axis. Thus, \ddot{u} is simplified to be \(u\) along axis x. \(u_0\) and \(f_a\) are the amplitude and the frequency of the AIDV. \(K\) and \(\Lambda\) represent the wave vector and the period of AIFG. \(\Lambda\) depends on the applied RF signal and is expressed by:

$$\Lambda = \sqrt{\frac{\pi C_e R_d}{f_a}}. \quad (4)$$
The schematic diagram and characteristics of a classical acousto-optic mode converter (AOMC).

(A) The diagram of mode switching via acousto-optic effect. (B) The experimental configuration of an AOMC device (Reproduced with permission from Lu et al. [105]). (C) The experimental setup for characterizing the dynamic tunability of the AOMC. BBS: broadband optical source. OSA: optical spectrum analyzer. (D) The schematic of mode controlling by radio frequency (RF) signal modulation. (E) The transmission spectra at different applied RF signal voltages. (F) The variation of resonant center wavelength with the increase of applied RF signal frequency. (G) The transmission spectra at different applied RF signal frequencies. (H) The variation of resonant fundamental mode power with the increase of applied RF signal amplitude.

\[ C_a = 5760 \text{ m/s} \] represents the velocity of acoustic wave propagating on the fiber medium. \( R_f \) stands for the radius of the fiber cladding. Obviously, the dynamic AIFG structure is capable of tunability under the control of applied RF signal. Then the AIDV induced geometric deformation and the photon-elastic effect \( \delta \varepsilon \) of permittivity modifications can be obtained by employing the standard framework of microbending modal:

\[ \delta \varepsilon_g = n_{co} \cdot K^2 \cdot u \cdot x. \]

\[ \delta \varepsilon_p = -\varepsilon^2_{co} p \hat{S} = \varepsilon^2_{co} p \kappa_{0} \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \sin(Kz - f_0 t). \]

\( n_{co} \) is the refractive index of the fiber core. \( \varepsilon_{co} \) is the permittivity of fiber core material. \( p \) and \( \hat{S} \) represent the photoelastic coefficient and the strain tensor, respectively.

To obtain the mode conversion, the phase matching condition should be satisfied and the corresponding mode conversion efficiency can be expressed incorporating electric field distributions of the identified spatial modes of \( E_{0,n}(x, y) \) and \( E_{1,n}(x, y) \) [95]:

\[ L_B = \Lambda_c \cdot (n_{0,n} - n_{1,n})^{-1} = \Lambda. \]

\[ \kappa \propto \frac{\pi}{\Lambda} \sqrt{\frac{E_{0,n}}{\mu_0}} \int E_{0,n}(x, y) \cdot \delta \varepsilon \cdot E_{1,n}(x, y) dx dy. \]

\( L_B \) is the beat-length of between fundamental mode and the targeted HOM. \( \Lambda_c \) is the resonant wavelength. \( n_{0,n} \) and \( n_{1,n} \) are the effective refractive indices of the fundamental mode and HOMs. The AOMC component has the tunability of resonant wavelength shift and intensity modulation. Once the AOMC is fabricated, the only variable to tune the AIFG period is the frequency of the applied RF signal. Figure 2E and F shows the changes of the transmission spectra and the resonant center wavelength of a two-mode-fiber based AOMC at the varying of RF frequency,
Table 1: Summary of the devices based on acousto-optic interactions (AOIs) in fibers with different vibration modes.

<table>
<thead>
<tr>
<th>Acoustic mode</th>
<th>Fiber type</th>
<th>Incorprations</th>
<th>RF frequency</th>
<th>Resonant wavelength</th>
<th>AO length</th>
<th>Mode conversion</th>
<th>Demonstration</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexural mode</td>
<td>TMF –</td>
<td>8 MHz</td>
<td>488 nm</td>
<td>7.5 cm</td>
<td>LP$_{11}$ mode</td>
<td>Frequency shifter</td>
<td>[43]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TMF Two AOMCs</td>
<td>2.51 MHz</td>
<td>1550 nm</td>
<td>4.5 cm</td>
<td>LP$_{11}$ mode</td>
<td>Comb filter</td>
<td>[55]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SMF Taper</td>
<td>1–1.5 MHz</td>
<td>1532–1550 nm</td>
<td>10 cm</td>
<td>Cladding modes</td>
<td>Attenuation filter</td>
<td>[56]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SMF Cuneal transducer</td>
<td>1.95–2.45 MHz</td>
<td>1550 nm</td>
<td>8.3 cm</td>
<td>Cladding modes</td>
<td>Tunable notch filter</td>
<td>[59]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SMF Parallel AOMCs</td>
<td>0.9001–1.066 MHz</td>
<td>1490–1610 nm</td>
<td>10 cm</td>
<td>Cladding modes</td>
<td>Broadband coupler</td>
<td>[61]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SMF SNS structure</td>
<td>2.384 MHz</td>
<td>1527.7 nm</td>
<td>70 cm</td>
<td>Cladding modes</td>
<td>Band-pass filter</td>
<td>[63]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SMF FBG</td>
<td>1.3 MHz</td>
<td>1541.5 nm</td>
<td>1.7 cm</td>
<td>Reflecting modes</td>
<td>Reflection switch</td>
<td>[68]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SMF FBG</td>
<td>1.3 MHz</td>
<td>1541.5 nm</td>
<td>1.7 cm</td>
<td>Cladding modes</td>
<td>FBG phase-matching</td>
<td>[69]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SMF LPG</td>
<td>2.43 MHz</td>
<td>1543.3 nm</td>
<td>20 cm</td>
<td>Cladding modes</td>
<td>Vibration measurement</td>
<td>[71]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SMF Taper</td>
<td>0.9 MHz</td>
<td>1550 nm</td>
<td>4 cm</td>
<td>Cladding modes</td>
<td>Vibration measurement</td>
<td>[72]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PCF –</td>
<td>7.4 MHz</td>
<td>633 nm</td>
<td>48 cm</td>
<td>LP$_{11}$ mode</td>
<td>Birefringence analysis</td>
<td>[76]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SMF MZI</td>
<td>0.91–0.99 MHz</td>
<td>1561.6–1568.9 nm</td>
<td>6 cm</td>
<td>Cladding modes</td>
<td>Tunable laser</td>
<td>[79]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SMF CMG</td>
<td>0.575–2.934 MHz</td>
<td>1641.4–2127.6 nm</td>
<td>24 + 34.3 cm</td>
<td>Cladding modes</td>
<td>Tunable laser</td>
<td>[82]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EDF –</td>
<td>1.2 MHz</td>
<td>1550 nm</td>
<td>8 cm</td>
<td>Cladding modes</td>
<td>Q-switch laser</td>
<td>[83]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SMF Taper</td>
<td>1.23 MHz</td>
<td>1529.5–1532.5 nm</td>
<td>23.7 cm</td>
<td>Cladding modes</td>
<td>Mode-locked laser</td>
<td>[90]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SMF Polarizer</td>
<td>1.039–1.069 MHz</td>
<td>1539–1571 nm</td>
<td>13.5 cm</td>
<td>Cladding modes</td>
<td>Polarization conversion</td>
<td>[92]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TMDCF Orthogonal PZTs</td>
<td>600–900 kHz</td>
<td>1520–1570 nm</td>
<td>30 cm</td>
<td>OAMs</td>
<td>OAM generation</td>
<td>[93]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FMF Orthogonal PZTs</td>
<td>0.8227–0.8289 MHz</td>
<td>633 nm</td>
<td>4 cm</td>
<td>OAMs</td>
<td>OAM generation</td>
<td>[96]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TMF –</td>
<td>2.687/2.746 MHz</td>
<td>1040.8 nm</td>
<td>50 cm</td>
<td>CVBs</td>
<td>CVB generation</td>
<td>[97]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E-FMF FSK</td>
<td>738/753 kHz</td>
<td>1550 nm</td>
<td>25 cm</td>
<td>OAM</td>
<td>OAM switching</td>
<td>[105]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E-FMF FSK</td>
<td>467.21/485.83/752.6/777.3 kHz</td>
<td>1064 nm</td>
<td>14.6/15 cm</td>
<td>LP$<em>{11}$/LP$</em>{21}$ modes</td>
<td>HOM generation</td>
<td>[107]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FMF Taper</td>
<td>824/841 kHz</td>
<td>1572 nm</td>
<td>10 cm</td>
<td>LP$_{21}$ mode</td>
<td>Mode-locked HOM laser</td>
<td>[108]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DCF –</td>
<td>670 kHz</td>
<td>1070 nm</td>
<td>–</td>
<td>LP$_{11}$ mode</td>
<td>High power HOM laser</td>
<td>[109]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E-FMF FSK</td>
<td>726/742 kHz</td>
<td>1532.9/1534.3 nm</td>
<td>25 cm</td>
<td>OAM</td>
<td>OAM switching dynamics</td>
<td>[112]</td>
<td></td>
</tr>
<tr>
<td>Longitudinal mode</td>
<td>SMF FBG</td>
<td>8.02 MHz</td>
<td>1526.5 nm</td>
<td>0.3 cm</td>
<td>Reflecting modes</td>
<td>Super-lattice modulation</td>
<td>[65]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SMF FBG</td>
<td>10/10.7 MHz</td>
<td>1528 nm</td>
<td>0.3/1.2 cm</td>
<td>Reflecting modes</td>
<td>Tunable reflector</td>
<td>[66]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SMF FBG</td>
<td>2.1/2.4/5.6/10 MHz</td>
<td>1550 nm</td>
<td>1 cm</td>
<td>Reflecting modes</td>
<td>Super-lattice modulation</td>
<td>[67]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SMF FBG</td>
<td>1/2.66/5.5 MHz</td>
<td>1543.2 nm</td>
<td>5 cm</td>
<td>Reflecting modes</td>
<td>Q-switch laser</td>
<td>[84]</td>
<td></td>
</tr>
<tr>
<td>Torsion mode</td>
<td>HB-SMF Two shear PZTs</td>
<td>1.337 MHz</td>
<td>1550 nm</td>
<td>60 cm</td>
<td>Polarization modes</td>
<td>Polarization filter</td>
<td>[113]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E-TMF Twisting</td>
<td>3.24/3.4 MHz</td>
<td>1500 nm</td>
<td>25.5 cm</td>
<td>LP$_{11}$ mode</td>
<td>Twist effect analysis</td>
<td>[114]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>HB-SMF PBS</td>
<td>2.638–2.788 MHz</td>
<td>1530–1620 nm</td>
<td>82 cm</td>
<td>Polarization modes</td>
<td>Tunable filter</td>
<td>[115]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>HB-SMF –</td>
<td>1.189 MHz</td>
<td>1320 nm</td>
<td>49.8 cm</td>
<td>Polarization modes</td>
<td>Band rejection filter</td>
<td>[117]</td>
<td></td>
</tr>
</tbody>
</table>

TMF: two-mode fiber; PCF: photonic crystal fiber; TMDCF: two-mode dispersion compensation fiber; E-FMF: ellipse-core FMF; HB-SMF: high-birefringence SMF; DCF: double-cladding fiber (core/cladding: 15/130); SNS: single-mode fiber-none core fiber-single mode fiber; CMG: core mode blocker; FSK: frequency shift keying; PBS: polarization beam splitter; CVB: cylindrical vector beam; OVB: optical vortex beam.
respectively. From Eq. (8), the mode conversion efficiency can be controlled by changing the RF signal amplitude. It is worth noting that the intensity modulation has different stages at increasing the applied RF signal voltage, as depicted in Figure 2G and H. When the voltage is at the low regions, the LP01 mode power decreases with the increase of the applied voltage, indicating that the energy converted to HOM is increasing. The experimental result shows that when the voltage is over the threshold (∼90 Vpp), the conversion efficiency declines with the increase of the applied voltage due to over-coupling effect.

2.2 Mechanisms of dual-resonant AOMC for dynamic mode switching

The classical AOMC has a single resonance of mode conversion between adjacent order modes, for instance, only one resonant wavelength for mode conversion from fundamental LP01 mode to LP11 mode. Recently, a new AO mode conversion with dual resonance employing a slightly ellipse fiber has been proposed [105]. The irregularity of the fiber induces the HOM degeneration and creates the dual resonance of the AOMC.

A slight ellipticity of the silica fiber in the AOMC induces the co-effect of optical and acoustic birefringence. Firstly, the radius of the fiber cladding is degenerated into a long axis and a short axis. Secondly, the ellipticity causes the acoustic birefringence. Figure 3B shows the elliptic-fiber-based AOMC setup and the corresponding fiber end facet model. The acoustic vibration should consider an orthogonal decomposition:

\[
\Lambda = \begin{bmatrix} \Lambda_x \ \\ \Lambda_y \end{bmatrix} = \begin{bmatrix} \frac{\pi C_a R_l \cdot (f_a)^{-1}}{b} \\
\frac{\pi C_a R_l \cdot (f_a)^{-1}}{a} \end{bmatrix},
\]

\[\varepsilon_0 (x, y) \rightarrow \varepsilon \cdot (x - y) \cos (x - u_x, y - u_y).\]  

\[u_x = u_0 \cos (K_Z - f_a t) \cdot e^{i \delta e_x},\]  

\[u_y = u_0 \cos (K_Z - f_a t) \cdot e^{i \delta e_y}.\]

\[
\delta \varepsilon = \begin{bmatrix} \delta e_x^x \\
\delta e_y^y \end{bmatrix} = \begin{bmatrix} n_0 K^2 u_x \cdot x \\
n_0 K^2 u_y \cdot y \end{bmatrix}.
\]

Finally, the ellipticity of the fiber core enables a degeneration of HOMs. Thus, the mode conversion between LP01 mode and LP11 mode has two components and the efficiency can be modified into:

\[
x(z) = \begin{bmatrix} \kappa_z \varepsilon_x^x \\
\kappa_z \varepsilon_y^y \end{bmatrix} = \kappa \begin{bmatrix} -\sin \beta \cdot \sin \alpha \cdot e^{i \delta e} + \cos \beta \cdot \cos \alpha \cdot e^{i \delta e} \\
-\sin \beta \cdot \cos \alpha \cdot e^{i \delta e} + \cos \beta \cdot \sin \alpha \cdot e^{i \delta e} \end{bmatrix} = \kappa \begin{bmatrix} \cos \beta \cdot e^{i \delta e} \\
\sin \beta \cdot e^{i \delta e} \end{bmatrix}.
\]

The dual-resonant transmission spectra combined of both LP11a mode and LP11b mode patterns at different resonant wavelengths in Figure 3C well confirms a simultaneous orthogonal HOM generation. By setting the frequencies appropriately, the two mode conversions can be coincident at a same resonant wavelength. Furthermore, the dynamic mode switching can be demonstrated by employing the electrically alternated applied frequency via the FSK technique, as depicted in Figure 3A. The beat-lengths between fundamental mode and HOMs are calculated by a finite element method (Comsol Multiphysics). From Figure 3D, the ellipticity \( E = \arctan (x/y) \) of the fiber determines the strength of the birefringence and further controls the wavelength separation \( \Delta \lambda \). In Figure 3E, the wavelength separation declines as the decrease of the ellipticity. It well indicates a great possibility of the dual-resonant spectrum shaping or the wideband discrimination of HOM generation.

The mode switching time is an important performance of the mode switchable AOMC. The switching time is mainly deemed as the propagating time of the acoustic flexural wave during the AO coupling region [95]:

\[\tau = L / (\pi \cdot R_d \cdot (f_a)^{1/2}).\]

\( L \) is the length of the AO coupling region. Figure 3F shows the experimental configuration of AOMC switching time measuring. The experimental results depicted in Figure 3G indicate the switching speed of two orthogonal HOMs reaches 4.3 kHz. The speed of mode switching is not fast enough for the application in optical communication (generation GHz level). However, such a fast tuning property enables possibilities in optical field tuning for broadening the flexibility of laser manufacturing, stimulated emission depletion microscopy (STED) and particle manipulation.

2.3 Higher-order orthogonal mode switching using cascaded AOMCs

Generally, the AOMC only conducts the mode conversion between two spatial modes with adjacent azimuthal numbers, on account of the phase-matching condition [122, 123]. However, higher-order modes have the demand...
in diverse applications with the requirements of more in-
tensity centers or higher topological cores. To realize the
mode coupling between two modes with nonadjacent
azimuthal numbers, cascading two independent AIFGs
shows great simplicity and high efficiency, as shown in
Figure 4A. The cascaded AOMCs incorporate two AO cou-
plings for constructing two stages of the mode conversions.
Besides, both the AOMCs are electrically dominant by the
identified RF signals so that the mode coupling from the
fundamental mode to several HOMs (LP11a/b, LP21a/b)
located at a certain resonant wavelength is capable of
dynamic control [107].

Due to the co-effect of acoustic and optic birefringence,
the simulated wavelength separation between two LP11
(LP21) modes is 2(18) nm in Figure 4B and C. The two
resonances of the orthogonal HOMs under a certain
frequency have a wavelength interval of 32(25) nm for two
LP11 (LP21) modes. For simplifying the con-
figuration, the cascaded AOMCs can only exploit one frequency (f11a/b), as
shown in Figure 4D. In the con-
figuration, the unjacketed
fi-
ber region is divided into two parts with different di-
ameters by hydro-
fl
uoric acid (HF) etching with different
times. According to Eq. (4), the period of the AIFG is
determined by the radius of the
fi-
ber when acoustic fre-
quency is
fi-
exed. By carefully controlling the diameters of
region I and region II, the AIFG periods can satisfy the
phase matching conditions of LP01–LP11 and LP11–LP21
mode conversion under same applied RF signal, respec-
tively. Therefore, the two AO coupling regions share the
same acoustic wave. As shown in Figure 4E, by applying

Figure 3: The dual resonance of acousto-optic interactions (AOIs) in an ellipse-core FMF (E-FMF) with co-effect of acoustic and optic
birefringence.

(A) The schematic diagram of the dual-resonant acousto-optic mode converter (AOMC) and the mode switching mechanism. (B) The model of
acoustic and optic birefringence from the view of fiber end face. (C) The dual-resonant transmission spectra at different RF signals
incorporating orthogonal LP11 mode patterns. (D) The simulated results of orthogonal LP11 mode conversions with different ellipticities of the
fiber. (E) The resonant wavelength interval change at the variation of the ellipticity. (A–E are reproduced with permission from Lu et al. [112]).
(F) The setup diagram of intensity modulator based on an acoustically induced fiber grating (AIFG). TL: tunable laser; MS: mode stripper; RF:
radio frequency; PD: photoelectric detector; OSC: oscilloscope. (G) The experimental measurement of switching time between different mode
(f1: 738.0 kHz; f2: 753.0 kHz) (F and G are reproduced with permission from Lu et al. [105]).
the frequency (481.5 kHz) on the PZT, the AOMCs can demonstrate the mode conversion from LP$_{01}$ mode to LP$_{21}$ mode at 1060 nm.

Figure 4F is the schematic diagram of a multiple-level intensity modulator (MLIM) based on the cascaded AOMCs. The mode stripper (MS) ensures a pure fundamental mode into the cascaded AOMCs and the light can be converted to HOMs. Then, the generated HOMs are attenuated in the SMF while the remaining LP$_{01}$ mode propagates through the SMF and is recorded by the oscilloscope (OSC). With cascading AOMCs, different mode conversions are dynamically controlled. The intensity modulator of multiple level can be fabricated by employing different mode conversion efficiencies, as shown in Figure 4G. The experimental switching time from LP$_{01}$ to LP$_{21a}$ (LP$_{21b}$) mode is 0.195 (0.155) ms.

Higher-order modes can be obtained by employing cascaded AOMCs with dynamic control of separate RF signals. The method of cascaded AOMCs benefits from the simple configuration. However, it requires different RF signal generators which increase the cost and complexity of the control system. The method that exploits single RF signal exhibits a compact size for easy integration. But this device lacks the robustness due to the requirement of HF corrosion for fiber diameter control. To date, cascading AOMCs is shown to be the most effective all-fiber method for generating higher-order modes with dynamic flexibility. But the challenge remains how to improve the switching speed with high conversion efficiency.

2.4 CVM and OAM generations via cascaded AOMCs with orthogonal vibration

Vector light beams possess doughnut-like light field distributions and anisotropic polarization profiles which have found diverse applications in both scientific researches and industrial designs. Traditional all-fiber method of generating vector modes especially OAM modes incorporates linear polarized HOM conversion and the subsequent light field tuning via changing polarization state and phase difference in FMFs [29]. Due to the inherent birefringence of silica fibers, the light field tuning requires accurate manual adjustment of the polarization controller (PC) which increases the difficulty of the demonstration. Fortunately, cascaded AOMCs are capable of active modulation with accurate phase difference profit from the microwave RF signal control. Figure 5A delivers the configuration of extracavity vector mode manipulation via cascaded AOMCs. The cascaded AOMCs consist of two PZTs with orthogonal vibration directions and a horn-like transducer. Here, the x-vibration PZT ($f = 0.8289 \text{ MHz}$) and the y-vibration PZT ($f = 0.8227 \text{ MHz}$) demonstrate the mode conversions from the linear polarized $HE_{11}$ mode to $TM_{01}$ mode and $TE_{01}$ mode.
respectively. The corresponding mode patterns of radially polarized $TM_{01}$ mode and azimuth polarized $TE_{01}$ mode without and with a polarizer are depicted in Figure 5B and C, respectively. In this experiment, the utilized FMF possesses a circular morphological structure and relatively large core-cladding refractive index difference so that the eigen vector modes ($TM_{01}$, $TE_{01}$, and $HE_{odd/even}^{21}$, that is, the CVMs) can be degenerated from LP$_{11}$ mode. By applying different RF signals on the PZT, the certain cylindrical vector beam (CVB) can be generated.

Moreover, when the applied RF signals employ the same frequency of 0.8270 MHz, the two PZTs enable the $HE_{even}^{21}$ mode and $HE_{odd}^{21}$ mode due to the orthogonal vibration. Dexterously, setting a phase difference of ±$\pi/2$ between RF$_1$ (applied on the $x$-vibration PZT) and RF$_2$ (applied on the $y$-vibration PZT) creates a phase shift of ±$\pi/2$ on the generated $HE_{even}^{21}$ mode and $HE_{odd}^{21}$ mode. Thus, the corresponding ±1-order OAM modes are generated. The ±1-order optical vortex mode patterns and the corresponding off-axial and coaxial interference patterns are shown in Figure 5D and E, respectively.

The orthogonal vibration cascaded AOMC components provide a new pathway for inducing phase difference and lead to the capability of generating the CVBs and the OAMs with different topological cores. This configuration possesses more compact size and more simple generation of vector modes. However, the cascaded AOMCs are unable of avoiding using several RF signals which increases the complexity of the control system. Besides, this method depends on the eigen modes conversion so that it is restricted to the generation bandwidth. Although the dynamic switching of different vector modes is not reported in the demonstration, incorporating the FSK technique can simply realize the dynamic altering between CVBs and OAMs.

2.5 Low-frequency shifter based on AOMC for microvibration heterodyne detection

Heterodyne detection, as an optical coherent detection method, has provided a new strategy in high-order harmonic light generating [124], imaging based on nano-clusters and nanocrystals [125], spectroscopy scanning tunneling [126], and gravitational waves detection [127]. An optical heterodyne configuration employs photo-mixing

![Figure 5: The experimental setup and results of cylindrical vector beams (CVBs) and orbital angular momentums (OAMs) generation based on orthogonal vibration cascaded acoustically induced fiber gratings (AIFGs).](image-url)
technique, resulting in a down-conversion of probe signal frequency from a high value to a lower, easily measurable one [128]. Thus, the optical frequency shifter creates a high-quality frequency shift on the local oscillator signal. However, it is generally challenging for fabricating a single acousto-optic modulator (AOM) through the frequency shift of several hundred kHz. The traditional bulk AOMs like Bragg cell [129] and integrated structure [130], demand precise alignment and high diffraction efficiency. Besides, the performance of these methods for heterodyne detection is restricted by the signal-to-signal beating interference (SSBI) [131].

All-fiber mode conversion incorporating frequency shift provides a potential solution to eliminate such difficulties effectively without the expense of carrier and sideband suppression ratios [132]. The MSC is used for exciting HOMs and removing the SSBI effect in the FMF without the sacrifice of spectral efficiency [131–133], while the AOMC is to reconvert the HOMs back to fundamental mode with an upshifted frequency amount equal to the acoustic frequency ($f_a$) [43]. Figure 6A shows the all-fiber heterodyne detection with or without the FBG based on mode conversion frequency shifter (MCFS), marked as scheme (A) and scheme (B), respectively. To ensure the carrier signal a good temporal stability, two arms should have the same optical path [72]. Figure 6B and C shows the transmission spectrum and the RF signal of the MCFS, respectively. From the experimental proof, this all-fiber MCFS possesses high performance of pure frequency shift. Compared with free-space devices, it exhibits higher stability for converting microwave information through mode conversion. From Figure 6D, scheme (B) configuration significantly improves the performance of measurement sensitivity than scheme (A). Moreover, Figure 6E indicates that the vibration information can be detected more efficiently by using all-fiber FBG heterodyne system. The vibration amplitude of the PZT firstly increases with the increase of the resonant frequencies and then decreases in general as the driving frequency increases. From Figure 6F and the inset of Figure 6E, scheme (B) is excellent to increase the measurement sensitivity of heterodyne microvibration detection.

Figure 6: The mode conversion frequency shifter (MCFS) based heterodyne detection system of micro vibration measurement. (A) Setup diagram of all fiber (A) or all-fiber FBG (B) heterodyne detection based on the MCFS. NLL: narrow linewidth laser; PC: polarization controller; RF: radio frequency; OC: optical circulator; VS: vibration source; SP: splice point between single-mode fiber (SMF) and few-mode fiber (FMF); BPD: balanced photoelectric detector; OSC: oscilloscope. (B) Transmission spectrum of the MCFS. (C) The RF signal of the MCFS. (D) Demodulated vibration waveform. (E) Demodulated amplitude as a function of the driving voltage when $f_v = 50$ kHz. (F) Demodulated amplitude as a function of driving frequency ($U_v = 2.5$ Vpp) (Reproduced with permission from Zhang et al. [132]).
polarization-maintaining fibers (PMFs) is a promising solution in the scheme.

3 Dynamic mode switching CW fiber lasers

HOM fiber lasers have attracted tremendous attentions and become a new research hotspot in fiber laser physics in recent years [29, 96, 134–139]. Incorporating fiber laser oscillation and mode conversion outside the laser cavity is the common way to generate HOM laser beams with easy implementation and simple configuration [35, 94, 108]. However, this method is restricted to the low efficiency of HOM laser stimulation. Intracavity mode converters enable the HOM oscillations in the laser cavity, which provides a high-purity HOM laser output [29, 105, 109, 112, 134–136, 140]. Besides, mode switchable AOMCs enable flexible tunability in spatial degree of freedom to the fiber laser and contribute to wider applications.

3.1 Cylindrical vector laser enabled by intracavity AOMC

Cylindrical vector light has the advantage of tight focusing due to its intriguing polarization distribution. For example, the radially polarized TM01 mode enables a strong longitudinal electric field component under the focus of a high numerical aperture. Simultaneously its focal spot is far smaller than that of uniformly polarized beam. Such the unique property brings up a broad application prospect in material processing, optical tweezers, excited surface plasma and high-resolution imaging. To create the cylindrical vector light source, an intracavity AOMC is utilized in a linear fiber laser cavity, as shown in Figure 7A. The laser cavity configuration is strictly polarization controlled by employing PMF-based components. The AOMC exhibits triplet resonances of mode conversions from the fundamental mode to the CVMs of TE01, HE21 and TM01 under an unpolarized broadband light source, as shown in Figure 7B. After polarization control and RF signal setting, the AOMC can convert fundamental mode to TM01 mode at a high efficiency of 99%, as depicted in Figure 7C. The laser cavity mirror is provided by the FBG reflection and fiber end-face Fresnel reflection. Therefore, the laser oscillates at a narrow bandwidth, as exhibited in Figure 7D. Figure 7E delivers the experimental results of the mode patterns of TM01 mode without and with a polarizer (Reprinted with permission from Carrion-Higuera et al. [97]).
Yb-doped fibers. In addition, the reflection efficiency of the fiber end-face is quite low so that the laser threshold is quite high (100 mW). A pair of FBGs is expected to decline the laser threshold and may decrease the difficulty of laser oscillation. Although the laser output power is moderate (mW-level, lower than general high-power laser output of kW-level), this laser cavity design provides a significant pioneered work for high-power CVB lasers.

3.2 Dynamic mode switching vortex laser

It leads to numerous varieties of theoretical and experimental researches of OAM that the pioneered works discover optical vortex carrying topological phase singularity and spiral wave front [1, 4, 93, 141–143]. Previous reports on vortex fiber lasers are static generations, that is, the OAM beams with different topological cores are generated separately via manual adjustments [144, 145]. To extend the flexibility of vortex fiber lasers, dual-resonant AOMC is employed to convert a switchable OAM laser beam [105].

Figure 8A shows the diagram of the mode switchable laser cavity that consists of SMF part and FMF part. High-purity HOMs operate in the laser cavity as follows. Here, the AOMC enables the mode conversions of LP$_{01}$–LP$_{11a}$ and LP$_{01}$–LP$_{11b}$ by applying different RF signals. The HOMs reflected by the cavity mirror are reconverted to LP$_{01}$ mode.
by an AOMC and propagate into the SMF cavity. But the LP$_{01}$ mode is reconverted to HOMs and dissipated in the splice point before propagating into the SMF cavity. Figure 8C and D presents the CW output with the slope efficiency of $\sim 18.2\%$.

The PC-based optical field tuning technique is employed to obtain the vortex mode switching, as shown in Figure 8B. The generated orthogonal HOMs are firstly rotated at 45° and then a phase difference of $\pi/2$ ("$\pi$") is obtained by adjusting the stress of the PC appropriately. Finally, the LP$_{11a}$ mode and LP$_{11b}$ mode are adjusted to be the corresponding $-1$-order OAM mode and $+1$-order OAM mode [105, 112]:

$$\begin{align*}
\text{LP}_{11a}(\text{adj}) &= \text{TM}_{01} - \text{HE}_{21}^{\text{odd}} - i\text{HE}_{21}^{\text{even}} = \text{OAM}_{-1}, \\
\text{LP}_{11b}(\text{adj}) &= \text{TM}_{01} - \text{HE}_{21}^{\text{odd}} + i\text{TE}_{01} + i\text{HE}_{21}^{\text{even}} = \text{OAM}_{+1}.
\end{align*}
$$

(15)

Once the laser cavity and PC state is adjusted appropriately, the mode switching of OAMs can be demonstrated only by altering the applied RF signal frequency via FSK technique. The corresponding mode patterns of $+1$-order OAM and $-1$-order OAM generation processes are shown in Figure 8E and F, respectively.

To date, this is the first report of a fiber laser with dynamic switchable OAM modes by using an intracavity AOMC. This configuration exhibits the advantage of OAM switching via electric controlling rather than manual adjusting. Therefore, the dynamic switching of OAM modes has a high speed up to 4 kHz. Such a switching OAM light source with different topological cores has the great potentials in diverse scientific researches and industry fields, for example, dynamic optical tweezers and flexible STED imaging. Initially, such an OAM-switchable fiber laser is expected to be a promising light source in mode division multiplexing system for OAM communication. However, the switching speed is restricted to the construction time of the AIFG, which needs to be improved for high-speed optical communication.

### 3.3 High-power agile mode fiber laser with AOMC

The development of high-power fiber lasers has promoted the applications in strong physics research, materials processing, and laser manufacturing [146–149]. Recent years, the HOM high-power lasers have attracted extensive attentions due to their unique intensity, polarization and phase distribution [150, 151]. It is a common belief that the mode instability (MI) has become the most important constraint to increase the power of high-power lasers. The foundation of eliminating or reducing the mode instability is to explore the dynamic coupling mechanism of HOMs in high-power lasers. Introducing mode switching into high-power lasers is a significant method to study the dynamic mode coupling mechanism [109].

The experimental configuration of a high-power agile mode fiber laser with intracavity mode switchable AOMC is shown in Figure 9A. Figure 9B shows an obvious result that the output laser beam alters from LP$_{01}$ mode to LP$_{11}$ mode at the applied RF signal frequency of 670.0 kHz. The corresponding center wavelength shifts from 1070.48 to 1070.07 nm, which matches well with the LP$_{01}$ and LP$_{11}$ reflection peaks of the few-mode fiber Bragg grating (FM-FBG).

When raising the pump power, the output power increases with good stability of LP$_{11}$ mode pattern, as depicted in Figure 9C. The maximum output powers of 6.06 and 5.85 W at LP$_{01}$ and LP$_{11}$ mode lasing are obtained with a slope efficiency of $\sim 48.16$ and $\sim 46.58\%$, respectively. Benefit from the dynamic tunability of the AOMC, the agile mode high-power laser is capable of generation of high-power laser beam with controllable proportion of HOMs. The output beam profiles under different modulation frequencies are shown in Figure 9D. Figure 9E and F shows the stability of the lasing wavelength and intensity in the mode switchable high-power laser. Although the laser output just reaches several Watts, this demonstration has profound implication for introducing HOM control in high-power fiber lasers. The capability of demonstrating the high-power laser with versatile HOM beam profiles could find potential applications in material processing, light field manipulation.

### 3.4 Brillouin fiber laser employing AOMCs

The pioneered discovery of the nonlinear effect of stimulated Brillouin scattering (SBS) generated in optical fibers contributes to Brillouin lasers with good line-width compression characteristics [153–155], which has found its implications in coherent communication. Brillouin lasers have their unique property of Brillouin frequency shift toward distributed optical fiber sensing, for instance, the Brillouin optical time domain meter (BOTDR) [156, 157]. Moreover, Brillouin lasers exhibit a high signal-to-noise ratio (SNR), showing the promising values in practical applications with low noise requirement [158, 159]. However, Brillouin lasers have their restrictions of high pumping threshold and low output power. Fortunately, Brillouin Erbium (Er)-doped fiber laser (BEFL) emerges to tackle the bottleneck in the conventional Brillouin lasers [160]. BEFL exploits stimulated radiation of the Er-doped
fiber for generating high laser energy at 1550 nm to free the threshold limit of the seed laser.

To date, previous works mainly focus on compressing the line width of the BEFLs through shortening the cavity length and fabricating BEFLs with multiwavelength output. Few works of Brillouin lasers with HOMs output has been reported. Heng et al. have demonstrated the Brillouin lasers with switchable HOMs by using MSCs [161]. However, the mode conversion purity should be further improved because the out-of-cavity mode conversion exhibits low efficiency. Wang et al. employ the photonic lanterns for HOMs generation in Brillouin lasers [162], but the linewidth is restricted to the long cavity length. Recently, a dynamic mode switchable Brillouin fiber laser based on an AIFG provides a new pathway for generating a Brillouin HOM beam with low threshold and narrow linewidth [163].

The dynamic switch of HOM output is enabled by the AOMC incorporating an MSC. The tunable laser source (TLS) serves as Brillouin pump while the 980 nm pump is utilized to decline the Brillouin threshold, as shown in Figure 10A. From Figure 10B, the spatial mode evolution of light propagating in the laser cavity obviously exhibits the generation mechanism of Brillouin lasing. Firstly, the LP$_{01}$ mode generated by TLS is amplified by the EDFA and then converted to LP$_{11}$ mode by the MSC. Meanwhile, the SBS is generated in the FMF by energy accumulation as the Brillouin threshold. The Brillouin laser beam propagates as a counterclockwise direction in the laser cavity so that it is reconverted to LP$_{01}$ mode when passing through the MSC from the FMF port. Finally, the LP$_{01}$ mode Brillouin laser beam propagates into the AOMC through the circulator and is converted to LP$_{11}$ mode with a frequency shift. Figure 10C and D shows the Brillouin laser output under a Brillouin pump (BP) power of 10 mW and the Brillouin output spectra of both LP$_{11}$ mode and LP$_{01}$ mode, respectively. The lasing wavelength of the output spectrum is dynamically controlled by modulating the applied RF signal on the AOMC.

The intracavity AOMC-based Brillouin fiber laser not only has the advantage of emitting ultranarrow bandwidth laser beams, but also possesses the superiority of dynamic switching of the output spatial modes. The HOM Brillouin laser with dynamic tunability is promising in high-sensitivity interferometers which can be found in fiber sensing strategy. Furthermore, benefit from the wavelength...
tuning property of the AOMC, Brillouin laser can oscillate at different resonant wavelengths by exploiting synchronous control of the BP and the applied RF signal frequency. Wavelength tunability can greatly extend the practical applications of the Brillouin laser. A narrow band filter is expected to ensure that 980 nm-pump light excites the Brillouin lasing efficiently. Thus, the Brillouin lasing threshold is reduced and the length of the FMF can be declined for generating a narrower linewidth. Besides, the wavelength tuning property of the AOMC needs to be promoted for continuously adjusting the lasing wavelength of the Brillouin laser.

4 Ultrafast mode switching fiber lasers

HOM fiber lasers with CW outputs possess unique symmetry of intensity distribution, polarization property and phase profile [164] and have found their applications in advanced optical communication [165], particle manipulation [166] and nanoscale imaging [167, 168]. Nevertheless, ultrafast fiber lasers employing ML techniques have their unique properties of ultrahigh peak power, ultrashort pulse duration. Recent years have seen the fast developments and widespread applications of HOM ultrafast fiber lasers [169, 170]. Surprisingly, the HOM oscillation in a mode-locked laser cavity exhibits more interesting phenomena and intriguing properties due to the nonlinear interactions on the ultrafast time scale [171].

4.1 Ultrafast higher-order modes switching using AOMCs

To date, AOMC has been well proved to be an efficient method to produce CVBs and vortex beams [94, 96, 105]. Except for the direct generation of vector beams, transverse-mode switching using an AOMC is attracting more attentions. Naturally, mode conversion process of the AOMC can be controlled, and the mode switching between fundamental mode (LP_{01} mode) and HOMs contributes to more possibilities of light field manipulation. Currently, AOMC combined with FM-FBGs is the most common way to excite a specific HOM [109]. However, this method is not suitable for generating higher order modes, for instance, LP_{21} mode. This is because of the relatively low efficiency for the excitation of LP_{21} mode in FM-FBGs. In addition,
owing to the narrow-band reflective peaks of the FM-FBG, mode switching of ultrashort pulse cannot be realized.

HOMs switching of ultrashort pulse is demonstrated by using a cascading mode converter incorporating an MSC and an AOMC [108]. From Figure 11A, the mode conversion process has two steps. Firstly, the fundamental mode emitted from the laser source is coupled to linearly polarized LP_{11} mode by using the MSC, and then LP_{11} mode is converted to LP_{21} mode in the AIFG region. In Figure 11B, the mode conversion of LP_{21} mode is achieved at 1570 nm when the driven frequency is adjusted to 830 kHz. In the experiment, the FMF is etched by HF (40%, 30 min) under the room temperature, and the corresponding fiber diameter is reduced to 88 μm. As shown in Figure 11C, the visibility of the resonant peak reaches ~10 dB, which implies the mode coupling efficiency is 90 %.

A real-time mode switching of ultrashort pulses can be obtained by dynamic modulation of the period of the AIFG. The ultrashort pulse is delivered from a home-made ML Er-doped fiber laser, as shown in Figure 11D [172]. The formation of the ML pulse is based on the nonlinear polarization rotation (NPR) effect. Figure 11E–G shows the properties of the soliton ML laser. The output laser mode is modulated between LP_{11} mode and LP_{21} mode by altering the RF signal, as shown in Figure 11H. The result shows a mode switching between LP_{11} mode and LP_{21} mode. However, HOM conversion efficiency still requires to be improved. Besides, HOM generation employs the MSC to demonstrate the mode conversion from LP_{01} mode to LP_{11} mode. Therefore, HOMs can be switched between LP_{11} mode and LP_{21} mode.

It is found that extra-cavity AOMCs can also demonstrate the OAM generations from a fundamental mode ultrafast pulsed laser [91, 136]. Figure 12A and B (Figure 12C and D) delivers the experimental configuration and the corresponding results of femtosecond (picosecond) pulsed OAM generation, respectively. These configurations exploit the similar strategy for generating OAM pulses by utilizing AOMCs. The experimental proofs well demonstrate the great ability of generating OAMs efficiently. It is worth noting that the optical frequencies of the reference light and interference light should be equal in an OAM detection system via interference method. However, the AO effect induces a frequency shift. Generally, there are two methods for ensuring the frequencies of the reference light and interference light equal. One is to add a same RF signal to the reference light through a phase modulator, as depicted in the configurations of Figure 12A and C. The other method is to divide the converted OAM beam into two parts: one is regarded as the interference light; another is regarded as the reference light after splicing to an SMF [105].

---

**Figure 11:** Ultrafast high-order mode (HOM) fiber laser employing cascaded mode selective couplers (MSC) and acousto-optic mode converter (AOMC).

(A) The experimental configuration of the cascading mode converter. VA: voltage amplifier. (B) The simulated mode effective indices and beat-length with LP_{11} and LP_{21} modes. (C) Transmission spectrum of the cascading mode converter for LP_{21} mode generation. (D) The experimental setup of the homemade mode locking (ML) fiber laser. (E) ML laser spectrum (blue curve), and the transmission spectrum of the acoustically induced fiber grating (AIFG) (black curve). (F) Pulse train of the ML laser output. (G) Autocorrection measurement of the ML pulse. (H) Real-time switching between LP_{11} and LP_{21} modes (Reproduced with permission from Shi et al. [108]).
Ultrashort laser pulse with switchable HOMs has great potentials in industrial applications due to its output robustness and simple configuration. However, extra-cavity HOM generation has the restriction of mode conversion efficiency because the HOM does not participate in the laser oscillation. The extra-cavity mode conversion of ML pulses is unable to modulate the nonlinear effects in the laser cavity oscillation. In fact, the AOMC is an effective active modulator for dynamically controlling the laser oscillation especially the ML fiber laser. The mode conversion in CW laser only influence the energy distribution of each mode for laser oscillation. However, the dynamic mode manipulation in a ML fiber laser affects the mode competition on both the spatial domain and time domain in the laser oscillation process. There exist more interesting phenomena of nonlinear effects in the ML laser cavity.

4.2 Wavelength tunable mode-locked fiber laser via AOMC

Taking advantage of the spectral tunability, wavelength tunable fiber laser has been proved as a potential seed laser source benefiting numerous applications in optical communication [173], optical sensing [174], materials processing [175], spectroscopy [176] and signal processing [177]. Generally, a tunable spectral filter is required to achieve the lasing wavelength tuning ability such as Fabry–Perot interferometer (FPI) [178, 179], Mach–Zehnder interferometer (MZI) [180], graphene-coated filter [181], chirped FBG [182], W-shape LPG [183] and fiber birefringence filter [184, 185]. Recently, an NPR strategy incorporating intracavity polarizer and intrinsic fiber birefringence has been reported to enable a wide spectral tuning range [186]. These tuning methods are mainly the passive means...
with great depends on laser operation, which are restricted to the tuning range and the response time. Fortunately, AOMC has emerged as an active spectral modulator to contribute the wideband continuous tunability [78, 82, 187]. Huang et al. have demonstrated tunable fiber lasers employing AIFG-based MZI and incorporating AIFG and a tapered fiber [79, 80, 188]. They also utilize the AIFG filter to generate wavelength tunable vector lasers, which yields extensive attentions in fiber laser researches [92]. Recently, the spectral filtering of a wavelength tunable bandpass filter (TBPF) employing fiber core modes conversion has been proved to exhibit an ultralow optical loss and becomes a new strategy of spectral tuning. Especially, the core mode conversion-based filter incorporating an MSC and an AOMC is capable of simultaneous wide tuning range and fast active response [189].

The configuration of this TBPF is shown in Figure 13A. To generate a highly efficient bandpass filtering property, the resonant wavelengths require fine precise matching. Due to the wideband property of the MSC, the wavelength tunable range of the TBPF can obtain hundreds of nanometers [190–192]. The bandpass property of the TBPF is shown in Figure 13C. AOMCs have been used as filters based on the condition of phase matching [193]. To carry out the wavelength tunable ML fiber laser, the TBPF is employed in the laser cavity providing a tunable filtering mechanism. In addition, the TBPF also plays a role of a splitter in the passive ML fiber laser, as shown in Figure 13C. Figure 13D–F presents the output properties of the ML fiber laser. The TBPF-based ML laser exhibits great wavelength tunability with precise active positioning benefiting from the dynamic control of AOMC. This band-pass filter has the advantage of high conversion efficiency and low loss because of employing core mode conversion inside the FMF. Based on the dynamic wavelength tunability of the AOMC, the ML fiber laser is capable of oscillating at different wavelengths. Thus, an intracavity TBPF-based ML fiber laser has more flexible wavelength tuning characteristics than a wavelength tunable ML laser through manual gain adjustment.

4.3 Vortex mode switching dynamics in an ML fiber laser

Transient dynamic process in a ML fiber laser delivers the landscapes of the ultrafast pulse evolution. In a ML fiber laser, the ML state is established on the ultrashort transient time scale. The ML fiber laser experiences a series of instabilities before the ultimate ML state [194–201].

Figure 13: Mode locking (ML) wavelength tunable fiber laser.
(A) Structure of the tunable bandpass filter (TBPF) and modal light in different parts of the TBPF. (B) The transmission spectra of the TBPF at different applied frequencies. (C) The experimental configuration of the tunable ML fiber laser. WDM: wavelength division multiplexer; EDF: erbium-doped fiber; PI-ISO, polarization-independent isolator; SWCNT, single-walled carbon nanotube. (D) The laser spectra with wavelength tunability via controlling the radio frequency (RF) frequency. (E) Pulse trains of the wavelength-tunable ML laser. (F) The measurement of pulse width (Reproduced with permission from Cheng et al. [189]).
Specifically, the energy oscillation depends on the light wave interactions through nonlinearity, dispersion, intracavity gain and loss and contributes to the ultimate ML formation [202]. Although extensive theoretical literatures on ML dynamics have been investigated, the experiments have more restrictions and are always limited by the measurements only utilizing fast photoelectric detectors (PDs).

Conventional PDs are incapable of capturing ultrafast dynamic process with high resolution and sensitivity due to the restrictions of (1) the narrow electric-bandwidths; (2) the time for reading out the data from sensor arrays and (3) the fundamental compromise between sensitivity and frame rate [203]. The recently developed time-stretched dispersion Fourier transform (TS-DFT) method provides an elegant way for exploring the ultrafast dynamics [204–219], as shown in Table 2.

The experimental demonstrations of real-time observation of spectral evolution dynamics in ML lasers are enabled by controlling the pump switch. Generally, the pump switch is demonstrated by employing a chopper or just turning on the pump laser and is suitable for the observation of ML formation through pump injection. However, pump injection switch is incapable of obtaining the intracavity perturbation and variation of the ML state. Recently the mode switching capability of the dual-resonant AOMC has been proved to obtain the real-time observation of intracavity pulse evolution among different ML vortex modes [112].

Figure 14A shows the experimental setup of the narrow-linewidth vortex ML fiber laser. To explore the mode switching dynamic process of the vortex mode switching ML fiber laser, the observation of the vortex mode switching has been demonstrated by the real-time OSC. Figure 14B exhibits the whole process of the pulse evolution during the vortex mode switching. There exist obvious laser strike regions in every vortex mode switching process.

Figure 14C and D depicts the detailed information of interesting instabilities at the laser strike regions of different vortex mode switching processes. When detuned from the stable vortex ML state, the laser experiences a ML collapse phase. As the cavity energy accumulates, there exist large laser spikes, that is, relaxation oscillation. Due to the spatial mode interaction, the laser spikes exhibit irregular fluctuation type rather than conventional raising style. To be specific, the spatial mode competition leads to an energy coupling between different spatial modes. Therefore, the corresponding laser spikes exhibit envelope fluctuation due to the undulant energy accumulation. Vortex mode switching between different order modes experiences a more complex process due to a large interval of effective refractive index, which takes more time to recover the pulse amplitude than that of same order vortex modes.

To further explore the dynamic process of vortex switching, a TS-DFT method has been employed to demonstrate the real-time observation of the single-shot spectrum evolution. Figure 14E shows the experimental result of the wavelength red shift in the vortex mode switching process from OAM_{1+1} mode to OAM_{0-1} mode. Firstly, the laser remains a stable ML state at OAM_{1+1} mode. When the RF signal is applied on the AOMC component, the stable ML state of OAM_{1+1} starts to quiet down and collapses to the initial quantum state, which exhibits ultralow power. Afterward there emerge some small laser spikes mainly originated from relaxation oscillation. When the laser cavity energy accumulates enough, a dominant laser spike appears. Then, the lasing wavelength experiences a shifting phase determined by the spatial mode conversion from OAM_{1+1} mode to OAM_{0-1} mode. AOMC-based switching strategy provides a higher degree of regulatory freedom and enables the intracavity energy dynamic perturbation. Therefore, it is considered as a new regulatory mechanism to achieve more abundant ML dynamics observations.

Table 2: The dynamics observations in mode locking (ML) fiber lasers via dispersion Fourier transform (DFT) method.

<table>
<thead>
<tr>
<th>Laser type</th>
<th>Switch mode</th>
<th>Method</th>
<th>Dynamics</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ML fiber laser</td>
<td>Pump switch</td>
<td>DFT</td>
<td>Rogue wave formation</td>
<td>[207]</td>
</tr>
<tr>
<td>Soliton fiber laser</td>
<td>Pump switch</td>
<td>DFT</td>
<td>Q-switch and ML build-up</td>
<td>[208]</td>
</tr>
<tr>
<td>DS fiber laser</td>
<td>Pump switch</td>
<td>DFT</td>
<td>DS molecules build-up</td>
<td>[213]</td>
</tr>
<tr>
<td>DS fiber laser</td>
<td>Pump switch</td>
<td>DFT + time lens</td>
<td>DS break-up and collisions</td>
<td>[212]</td>
</tr>
<tr>
<td>Soliton fiber laser</td>
<td>Pump switch</td>
<td>DFT</td>
<td>Soliton explosions</td>
<td>[218]</td>
</tr>
<tr>
<td>Soliton fiber laser</td>
<td>Pump switch</td>
<td>DFT</td>
<td>Soliton triplets vibrating</td>
<td>[219]</td>
</tr>
<tr>
<td>Bidirectional soliton laser</td>
<td>Pump switch</td>
<td>DFT</td>
<td>Bidirectional soliton build-up</td>
<td>[214]</td>
</tr>
<tr>
<td>Narrow-linewidth ML laser</td>
<td>AOIs</td>
<td>DFT</td>
<td>Vortex mode switching</td>
<td>[112]</td>
</tr>
</tbody>
</table>


Figure 14: The experimental setup and real-time observation of vortex mode switching in a mode-locked fiber laser.
(A) The schematic diagram of vortex mode switching fiber laser setup. OSA: optical spectrum analyzer; PC: polarization controller; MS: mode stripper. (B) The real-time information of mode switching dynamic processes among three vortex modes ($\text{OAM}_0$, $\text{OAM}_{-1}$ and $\text{OAM}_{+1}$). The detailed information of the strike regions named as I (C) and II (D). (E) The whole spectrum evolution of vortex mode switching dynamics obtained by time-stretched dispersion Fourier transform (TS-DFT) technique (Reproduced with permission from Lu et al. [112]).
5 Conclusions and perspectives

Toward spatial mode conversion, various investigations of AOIs in FMFs have constructed the dynamic control by microwave RF signal modulation, which provides a new degree of freedom in HOMs and OAMs generation. Benefiting from the dynamic tunability of AOMCs, switching topological charges of OAM modes, heterodyne detections, HOM fiber lasers, Brillouin lasers, ultrafast tunable lasers as well as ML dynamics are summarized in this review with exhibition of Figure 15. To date, dynamic fiber gratings based on the AOI has been the intensive research hotspot in recent years. It involves that how to achieve the resonant response spectrum from narrow bandwidth to wideband conversion, from single resonance of mode conversion to dual resonances with mode switching, from low efficiency to deep resonant peaks via cascading AOMCs with the development of AOMCs.

However, what is the future of the AOMC? How to explore the new mechanisms and practical applications of the AOI in optical fibers? Compared to static mode converters of other schemes, AOIs take advantages of the intriguing properties of fast switching and frequency shifting. The dynamic mode manipulation based on AOMCs exhibits promising values in future researches of AOIs in optical fibers.

This review is aimed to discuss and excite the further interest of the AOI in fibers. Potential research topics of AOMCs include as follows:

1. AOIs are enabled by applying microwave RF signals on the PZTs for controlling the light propagation. Note that the microwave signal also travels along the optical fibers with the modulation of the light wave. The microwave signal that carries information may be demodulated from the output light wave signal. Moreover, operating microwave signal on the transducer in a soliton ML cavity enhances the nonlinear interactions between microwave signal and ultrashort soliton pulses. There may emerge microwave spectrum purifying for generating high-quality microwave signal toward various applications. The underlying mechanism of nonlinear interactions between microwave signal and optical solitons on both the time scale and spatial scale also attracts intensive attentions and will open a new future of AOIs.

2. The dynamic evolutions of AO modulation in fibers lead to a new way for figuring out the effect of AOIs, especially in ultrafast ML lasers. Thanks to the development of TS-DFT technique, ultrafast dynamic process can be observed from a real-time view. ML process exhibits complex mechanism from quantum initial state to ultimate ML state. From now on, researchers have investigated theoretically and experimentally on fundamental mode ML dynamics. However, multiple spatial modes interact in the ML laser cavity show more interesting phenomena in the ML process. By introducing the dynamic control of spatial mode conversion, AOMCs can provide new possibilities on revealing the spatial mode evolution mechanism (even spatiotemporal ML) in HOM ML lasers.

3. Vector mode field has attracted numerous attentions due to its intriguing properties of donut-type intensity profiles and unique polarization distributions. AOMCs possess the flexibility of mode switching, which provides a high degree of freedom in light manipulation. For example, the STED system requires a fundamental mode source for stimulation and a vector mode source for depletion. The AOMC is capable of the integration for stimulation and a vector mode source for depletion. The AOMC is capable of the integration for stimulation and depletion sources and contributes to super-diffraction imaging. Optical tweezers incorporating OAM modes lead to particle manipulation including optical catching, moving and even rotation. AOMCs provide the fast switch of OAMs with different topological charges, which can lead to high degree of flexibility in microparticle operations. For example, the switch of OAM light between “+1 order” and “−1 order” may control the particle to rotate between clockwise and counterclockwise.

4. From the practical point of view, AOIs can control the mode conversion with different conversion efficiencies,
which can be utilized in device tests. For example, FM-FBG is now a very useful fiber device in HOM fiber optics, especially employed in fiber laser configurations. Conventionally, only reflecting wavelengths of different mode resonances in an FM-FBG are measured spectrally by using an off-set technique. The off-set technique only ensures that HOMs are generated but the proportions of each HOM are out of control. However, the unknown reflectivity of each spatial mode makes FM-FBGs restricted to broad applications. AOMC has the possibility of generating certain proportion of multi-HOMs by controlling the mode conversion efficiency dynamically. The controllable HOM source is promising for characterizing the reflection efficiencies of the FM-FBG component.

(5) AOMC has been proved to be employed in high power laser front constructions. Conventional in-line fiber devices like LPGs and MSCs depend on the inner refractive index modulation or evanescent field coupling, which are incapable of resisting high temperature created by high-power laser propagation in the fiber. However, AOMIs exploit external fiber vibration to control the light propagation without any physical damage of the optical fiber. Therefore, AOMC is quite promising in high-power laser science with agile mode switching capability.

However, the AOIs in optical fibers also have the following challenges:

(1) AO effects exploit acoustic vibrations on optical fibers, which introduces vibration perturbations in the fiber system. The dynamic tunability of light-ultrasound interaction also introduces dynamic variation characteristics in an AOMC. Compared to passive components such as LPGs and MSCs, AOMCs have more complexity in practical uses. Obviously, the environmental vibrations (close to the applied vibration on the AOMC) may disorder the acoustic wave and decrease the mode conversion efficiency.

(2) AOMC device, as an active modulator, requires a modulation unit of modulation signal (microwave RF wave, usually company with a voltage amplifier) to provide the active control. These additional parts may limit the device size for the integration of the fiber system. Besides, according to the theory of the AOIs in fibers, a highly efficient mode conversion needs a several-centimeter length of the AOI region. To reduce the size of the AOMC, one straightforward way is to decline the fiber diameter by HF etching method. With a small diameter of fiber cladding, the vibration efficiency will be improved so that the mode conversion requires short coupling region length. However, decreasing the fiber diameter also reduces the robustness of the AOMC device.

Indeed, the mechanisms and applications of AOIs in optical fibers, especially in special fibers such as FMFs, MMFs, PCFs, ring-core fibers, rare-earth-doped fibers, double-cladding fibers, still require further explorations, not limited to the above suggestions. It is believed that the transformation of scientific researches of AOIs in optical fibers into industrial applications will benefit the future fiber optics.

Acknowledgments: Xianglong Zeng acknowledges the Program for Professor of Special Appointment (Eastern Scholar) at Shanghai Institutions of Higher Learning.

Author contribution: All the authors have accepted responsibility for the entire content of this submitted manuscript and approved submission.

Research funding: National Natural Science Foundation of China (NSFC) (91750108, 61635006); Science and Technology Commission of Shanghai Municipality (STCSM) (20JC145700, 16520720900); 111 Project (D20031); National Key Research and Development Program of China (2018YFB1801800).

Conflict of interest statement: The authors declare no conflicts of interest regarding this article.

References


