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Review

Review on Principal and Applications of Temporal and Spatial Beam Shaping for Ultrafast Pulsed Laser

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Abstract: Ultrafast or ultrashort pulsed lasers have become integral in numerous industrial applications due to their high precision, non-thermal interaction with materials, and ability to induce nonlinear absorption. These characteristics have expanded their use in microfabrication, semiconductor processing, automotive engineering, and biomedical fields. Temporal pulse shaping reduces laser pulse durations, often to shorter timescales than many physical and chemical processes, enabling greater control. Meanwhile, spatial shaping improves efficiency and precision in micro- and nanofabrication and biomedical applications. Advances in optical parametric amplifiers (OPAs) and chirped-pulse amplifiers (CPAs) have allowed for more refined temporal and spatial shaping, ensuring the preservation of high peak power while achieving ultrashort pulse durations. Additionally, spatial light modulators (SLMs) have facilitated sophisticated beam shaping, which, when combined with ultrafast lasers, supports applications like computer-generated holography and nanoscale fabrication. These developments underscore the growing utility and versatility of ultrafast lasers in both research and industrial contexts.

Keywords: ultrashort laser; ultrafast laser; temporal beam shaping; spatial beam shaping

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1. Introduction

Ultrafast pulsed lasers are universally functionalized for precision microfabrication and processing metals, semiconductors, ceramics, polymers, and composite materials. Their short pulse duration minimizes heat-affected zones, high resolution, and submicron accuracy [1–5]. Applications include cutting, drilling, surface texturing, engraving, and thin-film patterning in the automotive, aerospace, electronics, and microelectronics manufacturing industries. Ultrafast pulsed lasers are a type of laser system that emits pulses of extremely short duration, typically on the order of femtoseconds (10^{-15} s) to picoseconds (10^{-12} s). Because these lasers produce pulses shorter than the time scales of many physical and chemical processes, the laser's interaction with matter can be precisely controlled, facilitating applications in various fields of science, engineering, medicine, and technology [1–9]. Recently, new temporal, spatial, and spatio-temporal techniques for ultrafast pulsed lasers have been reported. In particular, ultrafast pulse shaping in super-resolution imaging, nanofabrication, quantum information processing, materials science, and optical communications, as shown in Figure 1, has attracted much attention [2,4,5,10–12].

Material processing using femtosecond lasers, as discussed by experts like Stoian, Baumert, Lu, and Sanner, focuses on the precise interaction between ultrafast laser pulses and materials [13–16]. The ultrafast nature of femtosecond pulses allows for material modifications such as ablation or structural changes without heating the material to a significant extent. This results in minimal thermal damage, a crucial advantage in fields like micromachining and bioengineering. The high peak intensity of femtosecond pulses can induce nonlinear absorption processes, allowing energy to be absorbed even in materials that are transparent to the laser's wavelength under normal circumstances [13–16].

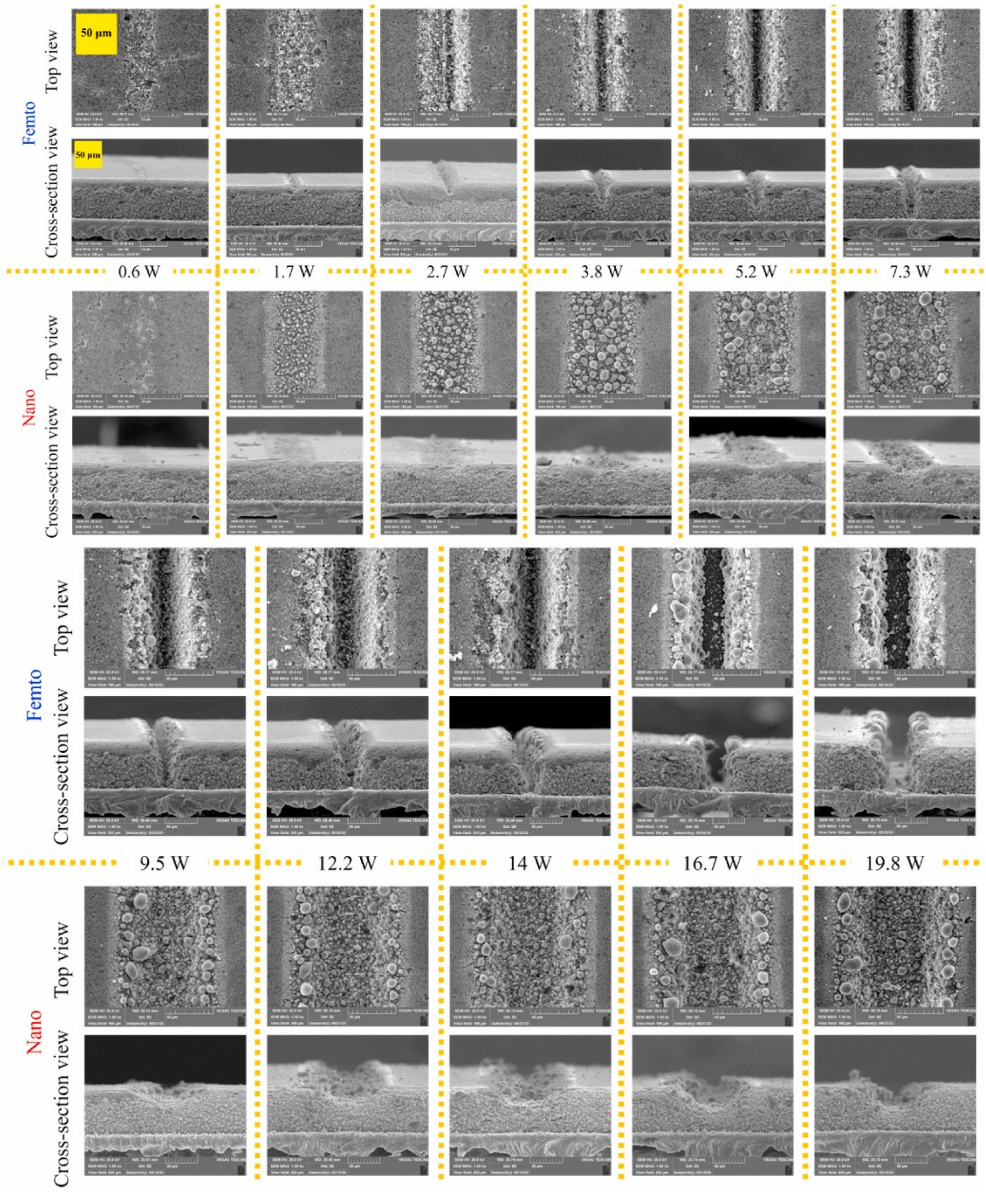


Figure 1. Material processing by an ultrafast laser and comparison with a nanosecond laser [1].

Shin et al. explored and compared the nanosecond lasers with ultrashort pulsed lasers for cost, heat effect, and precision, and Wang et al. explained the principles of nonlinear electron–photon interactions in crystalline by a femtosecond pulse train of multiple pulses [1,2]. Due to these non-thermal processes, the ultrashort laser has many advantages in fabricating state-of-the-art nano-features. Wang et al. and Soleimani et al. reported the fabrication of nano-wires and crystalline Sapphire cutting, which demonstrated the advantages of a non-thermal process in no limited material process [3,4].

Ultrafast pulsed lasers typically emit optical pulses ranging from a few femtoseconds to a few picoseconds. Such short pulse widths are achieved using mode-locking techniques in which the laser cavity is actively or passively modulated to generate ultrafast pulses. Despite short pulse widths, ultrafast pulsed lasers can achieve high peak powers. This high peak power is advantageous for inducing nonlinear optical effects such as multiphoton absorption and harmonic generation and for material processing applications that require intense laser irradiation [11,13–16].

Temporal and spatial pulse modulation provides many useful analytical tools. Zhao et al. reported the effects of inter-pulse delay on the quantitative analysis of femtosecond–nanosecond double-pulsed laser-induced breakdown spectroscopy as a way of temporal modulation of ultrashort pulsed laser, and Mendez-Lopez et al. studied spatially resolved characterization of plasma induced by femtosecond laser [11,12]. Carpene et al. reported an experimental setup for the characterization of magnetization vector by means of the pump–probe technique, which is widely used for temporal pulsed modulation [17]. In addition, Feist et al. developed a transmission electron microscope driven by photoemission, which opened a new era of TEM [18].

Ultrafast pulsed lasers typically exhibit excellent pulse-to-pulse stability and repeatability. This is essential for applications requiring precise control of laser parameters, such as laser microfabrication, time-resolved spectroscopy, and multiphoton imaging. Due to their ultrafast pulse duration, ultrafast pulsed lasers can ablate materials with minimal thermal damage to the surroundings. This non-thermal ablation process is advantageous for processing thermally sensitive materials such as polymers, biological tissues, and semiconductor substrates [4–6]. In particular, micro or nanostructures on the surface can be used to fabricate optical devices such as microlens arrays and diffractive optical elements, and they can be measured by optical coherence tomography (OCT), as shown in Figure 2 [19]. Zhu et al. reported various applications of nanostructures fabricated by ultrafast pulsed laser and provided the technical prospects and potential usage by temporal and spatial beam modulations [6]. Chasys et al. reported the detailed development of an OCT system for laser texturing [19]. OCT using a femtosecond laser is an advanced imaging technology primarily used in medical diagnostics, especially in ophthalmology, to capture detailed cross-sectional images of biological tissues. The femtosecond laser enhances OCT by offering high-precision ultrafast pulses and minimal thermal damage, which improves imaging resolution and reduces tissue disruption [19].

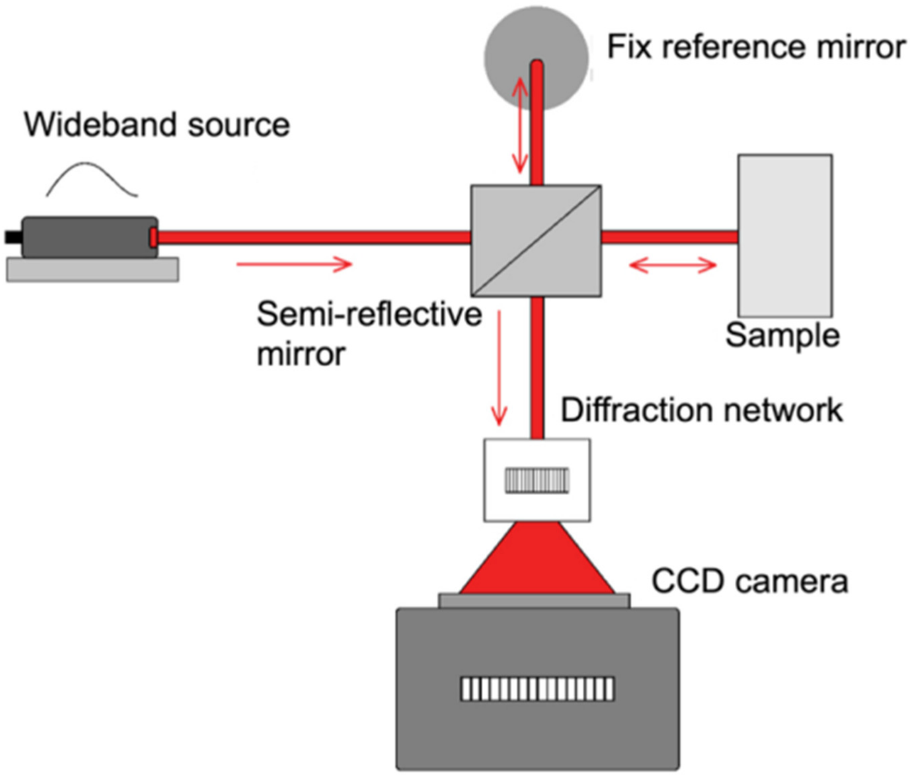


Figure 2. Schematic of OCT [19].

Ultrafast pulsed lasers can achieve very high peak powers despite short pulse durations. This high peak power enables efficient nonlinear optical processes and parametric processes. These nonlinear effects are essential for microfabrication, materials processing, and nonlinear microscopy applications [1–7]. Ultrafast femtosecond or picosecond pulse durations allow precise spatial and temporal control of laser–material interactions. This precision enables high-resolution imaging, microscale processing with submicron precision, and selective material ablation without damaging the surrounding area. In areas like laser eye surgery and microsurgery, ultrafast pulses allow precise tissue removal with minimal collateral damage [1–10].

Ultrafast pulsed lasers are used in many biomedical applications. Compared to long pulse lasers, ultrafast pulsed lasers can achieve ultrahigh peak powers for complete ionization of all materials and often exhibit broadband optical spectra [1,4,5]. With short pulse durations corresponding to wide frequency bandwidths, broadband spectra enable efficient nonlinear optical processes and facilitate applications such as OCT and spectroscopy [1–5,19]. OCT is an imaging technique for measuring the dimensions of objects, and lateral point OCT measurements can provide the depth of various layers of material in many applications, as shown in Figure 2 [19].

Temporal or spatial pulse shaping is essential in many applications. The short time width of an ultrafast pulse corresponds to an ultrafast coherence length in the frequency domain. This property allows precise temporal localization of laser energy and enables high-resolution imaging and spectroscopy techniques with depth discrimination, such as optical coherence tomography and multiphoton microscopy [8–11,20–23].

Zhang et al. extensively studied spatial beam shaping using an ultrashort pulsed laser [20]. They used diffractive optical elements to reshape the Gaussian beam profile for a flat top distribution. Bourquard et al. reported the effect of temporal shaping of femtosecond laser pulses on laser ablation of aluminum and boron and found the increase with a saturation of ion emission at long delays or long pulse durations result from an interaction between the shaped laser pulse and the expanding matter after the onset of the plasma [21].

In micromachining, the application of conventional deposition techniques for the elaboration of various materials such as diamond-like carbon oxides, nitrides, and quasicrystals, the advantages of laser beams are maximized by flat-top laser beams such as Tailored beam forming is often used. In the deep femtosecond range, using strong electro-optical phase modulation and subsequent compression of the continuous-wave laser, its applications are not limited to high-field laser–matter interactions. Still, they are used in ultrafast time-resolved spectroscopy, optical clocks, nonlinear microscopy, optical communications, and more [24]. As earlier studied by Rebane et al., interferometric processing of laser by ultrafast signal demonstrated that spatial beam modulation can be conducted for nanoscale texturing [25]. As Weiber and Ackermann et al. reported in their review article, ultrafast pulse shaping enabled optical waveforms and control of phase, amplitude, and polarization by temporal and spatial modulation [24,25].

Ultrafast pulsed lasers have applications in a variety of fields, including materials microfabrication and processing, nonlinear optical imaging and spectroscopy, ultrafast spectroscopy and dynamics, laser micro- and nanofabrication, medical imaging and surgery, quantum technology, femtosecond laser direct writing, ultrafast optical switching, signal processing, and more. Overall, ultrafast pulsed lasers are versatile tools that enable precise, efficient, and versatile laser processing across various disciplines, driving advances in science, engineering, medicine, and technology [1–11,26,27].

2. Advantages of Ultrafast Pulsed Lasers

As summarized in Table 1, the ultrafast pulsed laser has many advantages in various applications. Ultrafast pulsed lasers offer several advantages over conventional continuous waves and long pulse lasers due to their unique time characteristics, including extremely short pulse durations in the femtosecond and picosecond order. These advantages have made them indispensable tools in a wide range of scientific, industrial, and medical applications [4–7]. By using powerful ultrashort pulse lasers, laser energy is stored via nonlinear absorption and non-thermal processes [4]. The pulse–lattice interaction time is much shorter than the heat transfer time to the lattice, so the pulse ends before any thermal or structural effects occur. Zhu et al. and Moreno-Madariaga et al. reported many non-thermal ablation processes by ultrafast pulsed laser for cleaning paints and fiber-reinforced polymers and nanostructure fabrication [6,7].

Table 1. Selected applications of ultrashort pulsed laser in various fields.

Applications	Target	Processing Parameters	Results	Ref.
Nonthermal Ablation	Sapphire	300 fs deep UV (206 nm), IR (1030 nm) laser pulses	Achieved surface roughness < 100 nm; enhanced microstructuring with less thermal damage.	[4]
CO_2 Electroreduction	Copper electrodes	50 fs, 1030 nm, varying scan speeds (10–100 mm/s)	Enhanced C2+ selectivity by modifying surface morphology; significant porous microstructures.	[5]
Surface Micro/Nanostructuring	Metals, polymers	Parameters adjusted for LIPSS, periodic arrays, and 3D structures	Applications in optics, biomedicine, and electronics; improved anti-reflective and sensing properties.	[6]
Paint Removal on Maritime Surfaces	Glass-fiber-reinforced plastic	<400 fs, 1040 nm, pulse energy < 40 μJ	Effective removal without substrate damage; reduced surface wettability compared to sanding.	[7]
Cataract Surgery Analysis	Intraocular lenses (IOLs)	Comparison of conventional vs. femtosecond laser-assisted surgery	Improved IOL alignment and reduced decentration in FLACS group, but visual acuity unaffected.	[8]
Biomedical	Tissues	Femtosecond pulses for selective ablation	Precise tissue removal with minimal thermal damage	[9]
Spectroscopy	CO_2 and O_2 in flames	24 fs pulses, filamentation-based supercontinuum fab.	High-accuracy thermometry in laminar flames up to 2220 K; multiplex Raman spectroscopy possible.	[10]

Ultrafast pulsed lasers can ablate materials with minimal thermal damage to the surroundings [3,4]. The short pulse duration limits energy deposition to a small spatial and temporal volume, resulting in fast energy absorption and minimal thermal diffusion. This non-thermal ablation process is vital for delicate materials and biological tissues where thermal damage must be avoided. Ultrafast pulsed lasers are often called “cold” because of their ultrafast pulse duration and non-thermal ablation characteristics. Ultrafast pulsed lasers can process and treat materials without creating large heat-affected zones or inducing thermal stresses. This capability is advantageous for processing thermally sensitive materials such as polymers, biological tissues, antifouling paint washes, fiber-reinforced polymers, etc. [3–9].

The precision and control offered by ultrafast pulsed laser processing often obviate the need for post-processing steps such as polishing, cleaning, and surface preparation. This not only saves time and resources in manufacturing but also minimizes the risk of defects or contamination of the processed material [10–12]. Ultrafast pulsed lasers demonstrate broad material compatibility, enabling them to process a wide range of materials, including metals, semiconductors, ceramics, polymers, and biological tissue. This versatility positions them as a valuable tool in various industries, including aerospace, automotive, electronics, biomedical, and cultural heritage preservation [6–12]. In applications such as biomedicine, surface micro/nanostructures, drug delivery systems, biosensors, and artificial organs, ultrafast lasers can be used as state-of-the-art technology [6–12]. Calvarese et al. reviewed recent developments in femtosecond laser ablation, focusing on its expanding biomedical applications, including hard tissue surgeries and the development of endoscopic probes for image-guided microsurgery [9].

Ultrafast pulsed lasers enable multiphoton imaging and spectroscopic techniques to provide high-resolution, three-dimensional imaging of biological tissues and materials [6,28]. These techniques provide deeper tissue penetration, reduced photodamage, and improved contrast, making them indispensable in biomedical research, neuroscience, and drug discovery [9,22,23,29–32]. Overall, the advantages of ultrafast pulsed lasers derive from their unique temporal characteristics, which enable accurate, efficient, and versatile laser processing across a wide range of applications. As technology advances and ultrafast pulse durations become even shorter and more accessible, these lasers' potential applications and benefits continue to expand. Radmilovic et al. explored the interactions between ultrashort laser pulses and hemoglobin, revealing the formation of a stable fluorescent photoproduct that can be used for precise micropatterning and real-time tracking of erythrocytes, with potential applications in biomedical imaging and diagnostics [32].

Rabitz, Gerber, and Feurer pioneered the developments and major steps in pulse shaping techniques by focusing on optimizing laser pulses for various applications like adaptive matter interaction, femtochemistry, and spectroscopy. These techniques allow precise control over the temporal profile of ultrafast laser pulses, typically in the femtosecond range. Key advances include the use of Fourier-transform pulse shaping and acousto-optic programmable dispersive filters, which enable the manipulation of pulse phases and amplitudes. These approaches have led to significant progress in optimizing interactions between laser pulses and matter by shaping the laser's time-domain characteristics, resulting in more efficient and targeted outcomes in experiments [33].

3. Temporal and Spatial Beam Shaping in Ultrashort Pulsed Lasers

3.1. Principles of Beam Shaping

Temporal and spatial beam shaping in ultrafast pulsed lasers are essential techniques for controlling laser pulses' temporal and spatial characteristics, respectively. These shaping methods allow precise manipulation of pulse duration, temporal profile, beam profile, and intensity distribution, providing versatility and control for various applications. Mendez-Lopez, Carpene, and Feist reported that spatially and temporally shaped ultrafast lasers can be used for spectroscopy and nanoscale fabrication imaging [12–14]. Temporal and spatial beam shaping techniques for ultrafast pulsed lasers allow precise control of pulse characteristics and beam profiles, enabling advances in such fields as ultrafast optics, laser materials processing, biomedical imaging, and optical communications [2,9,19]. Researchers and engineers can optimize laser performance and achieve desired results in numerous applications by tuning the temporal and spatial characteristics of laser pulses. Calvarese et al. reviewed advancements in femtosecond laser ablation, highlighting its potential for precise, minimally invasive surgeries beyond ophthalmology, including hard tissue ablation in dental and orthopedic applications, and explored the development of image-guided endoscopic probes to enhance real-time diagnostics and targeted microsurgeries [9].

One example of temporal pulse shaping is the pump–probe technique, which can extract the time dependence of individual projections with subpicosecond resolution [17]. This method is widely used to study the time evolution of searches for specific physical phenomena. Temporal beam shaping controls the temporal profile of an ultrafast laser pulse. This operation is crucial to optimize the interaction between the laser and the material, to control nonlinear optical effects, and to obtain the desired processing results [18,34–38]. Feist et al. presented the development of an ultrafast transmission electron microscope (UTEM) driven by a laser-triggered field emitter, achieving femtosecond temporal resolution with a high-coherence electron beam, enabling new capabilities in imaging, diffraction, and spectroscopy of nanoscale dynamics [18].

Chirped-pulse compression techniques, such as the use of grating pairs and prism compressors, are the most commonly used techniques employed to reduce pulse duration while maintaining high peak power. This process is critical to achieving the ultrafast pulse widths needed for many applications, such as high-resolution microscopy and laser materials processing, as shown in Figure 3 [27,34–37]. Ge et al. presented a burst-mode chirped pulse amplification system using an Yb-doped fiber laser seeded by a multi-soliton bunch, achieving high-power femtosecond pulses with enhanced flexibility in burst repetition rates for applications like material processing and nonlinear microscopy [27]. Dansette et al. explored the influence of group delay dispersion (GDD) and higher-order dispersion on second harmonic generation (SHG) using chirped femtosecond laser pulses, demonstrating that small amounts of chirp can significantly impact conversion efficiency and beam quality, highlighting the need for precise control of dispersion to achieve high-efficiency SHG [35].

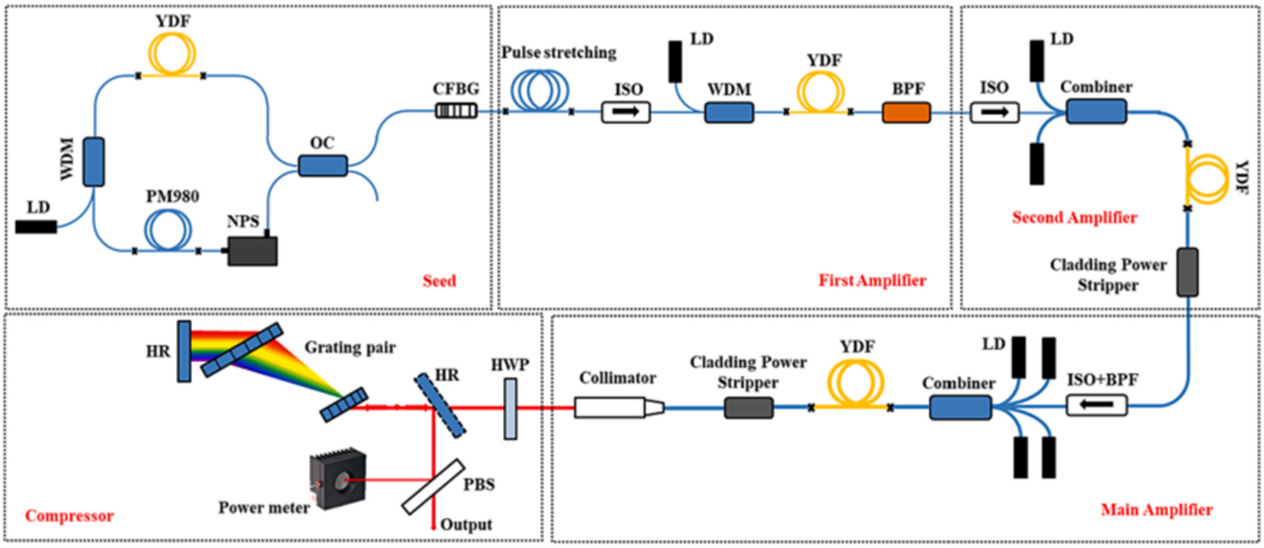


Figure 3. Schematic of the proposed CPA system. OC, coupler; NPS, nonlinear phase shifter [27].

Optical parametric amplifiers (OPAs) allow for more sophisticated pulse shaping; the development of OPAs has provided the opportunity to obtain tunable ultrashort laser pulses over a variety of spectral ranges, thus making OPAs a versatile tool for generating femtosecond pulses over a wide wavelength range [29,38–41]. A variety of micro-ripples have been formed using OPA lasers tuned to various wavelengths [41]. Kozich et al. presented a high-energy optical parametric amplifier system pumped by a 1030 nm Yb/KGW laser, which generates tunable femtosecond pulses in the mid-infrared range, achieving high pulse energy and efficiency using negatively chirped pump pulses or transform-limited pump pulses for applications in femtosecond infrared experiments [39]. Guo et al. demonstrated a broadband femtosecond optical parametric amplification system using a YCOB crystal, achieving amplification in the near-infrared region at near-critical wavelength degeneracy, which results in high gain bandwidth and energy efficiency, making it suitable for generating ultrashort, high-intensity pulses [40].

Spatial light modulators (SLMs) are another advanced technology in beam shaping. Recently, femtosecond lasers and SLMs have been combined to enable computer-generated holograms and micro/nanoscale fabrication [42–44]. SLMs are primarily used for spatial beam shaping but can also be used for temporal pulse shaping. By applying a spatially varying phase pattern to the incident laser pulse, SLMs can manipulate the pulse's spectral phase and temporal profile. This technique allows for highly accurate, versatile, and programmable pulse shaping [42–47]. Hasegawa et al. demonstrated a holographic femtosecond laser processing method using a ferroelectric liquid-crystal-on-silicon spatial light modulator with 6.3 kHz pulse-to-pulse spatial light modulation, enabling high-speed reconfiguration of computer-generated holograms (CGHs) with binary phase masks for efficient and precise laser material processing applications [42]. Kuang et al. presented a high-throughput femtosecond laser processing technique using a spatial light modulator to create diffractive multi-beam patterns with computer-generated holograms, achieving efficient and precise surface micro-structuring on materials like silicon and Ti6Al4V with significantly increased throughput [46]. Jesacher et al. discussed a method for parallel direct laser writing in three dimensions that minimizes chromatic aberration by designing holograms with reduced diffractive power, enabling high-precision fabrication of photonic devices and nanostructures in materials like diamond, fused silica, and lithium niobate [48].

Table 2 summarizes applications of pulse shaping technologies for various fields of science and engineering.

Table 2. Applications of pulse shaping techniques and key characteristics.

Category	Application	Pulse Characteristics	Key Findings	Ref.
Laser Diagnostics	Thermometry in Combustion Systems	Chirped femtosecond CARS pulses	Demonstrated high-precision temperature measurements (±3%) in turbulent flames; expanded dynamic range up to 2300 K.	[37,43]
Material Fragmentation	Molecular fragmentation control	Chirped femtosecond laser pulses	Enhanced specific fragmentation pathways in n-propyl benzene; chirp direction significantly influences fragmentation yield.	[34]
Second Harmonic Generation (SHG)	Visible laser pulse generation	Chirped femtosecond pulses	SHG efficiency is highly sensitive to chirp and group delay dispersion; asymmetric effects for positively vs. negatively chirped pulses.	[45]
Mode-Locked Lasers	High-energy pulse generation	Passively mode-locked ultralong fiber	Generated sub-200 fs pulses in a 25.2 km fiber laser system, enabling high-energy outputs suitable for low-repetition applications like spectroscopy.	[36]
Fiber Laser Amplification	Chirped pulse amplification systems	Burst-mode Yb-fiber laser	Delivered high-energy femtosecond pulses with flexible soliton bunching, enabling efficient high-power laser applications.	[27]
Electron Microscopy	Ultrafast electron microscopy	Femtosecond-resolution electron beam	Developed highly coherent 200 fs electron pulses for nanoscale structural dynamics studies in material science and biology.	[18]

3.2. Temporal Beam Shaping

The Fourier-transform pulse shaping technique utilizes spectral phase modulation to shape the time profile of a laser pulse [20–23]. Complex time profiles can be synthesized by modulating the spectral phase through a dispersive element and applying an inverse Fourier transform. This technique allows precise pulse duration and chirp control, facilitating applications such as ultrafast spectroscopy and pulse compression, as shown in Figure 4 [21–23]. The time–bandwidth product is fundamental in characterizing ultrafast pulsed lasers and represents a trade-off between pulse duration and spectral bandwidth. In the context of ultrafast pulsed lasers, which emit optical pulses of extremely short durations on the order of femtoseconds or picoseconds, the time–bandwidth product plays a crucial role in understanding the temporal and spectral properties of these pulses [23,29–31].

Gunaratne is one of the first pioneers who investigated the effects of bandwidth and phase shaping on femtosecond laser-induced breakdown spectroscopy. Gunaratne et al. demonstrated that broader bandwidths lead to lower LIBS thresholds and that phase control can enhance efficiency, making it a promising tool for precise material analysis and micromachining [23]. Lopez-Ripa demonstrated the characterization of ultrashort laser pulses across the visible to near-infrared spectrum using the amplitude swing technique, highlighting its flexibility in operating over different spectral ranges without significant modifications and introducing a differential evolution algorithm for efficient pulse retrieval [29].

The Fourier's uncertainty principle, a cornerstone of the Fourier-transform pulse shaping technique, sets a fundamental limit to the simultaneous determination of the temporal and spectral characteristics of a pulse. This principle, which states that the product of the pulse time–bandwidth and spectral bandwidth is bounded by a constant, is key to understanding the technique's theoretical underpinnings. Therefore, the technique's focus on minimizing the time–bandwidth product is essential to achieving conversion-limited pulses with the narrowest possible pulse duration and spectral bandwidth. Achieving a low time–bandwidth product in ultrafast pulsed lasers is desirable for several reasons, including pulse compression, nonlinear optical effects, high-resolution spectroscopy, and non-ultrafast dynamics [23,32,45,49].

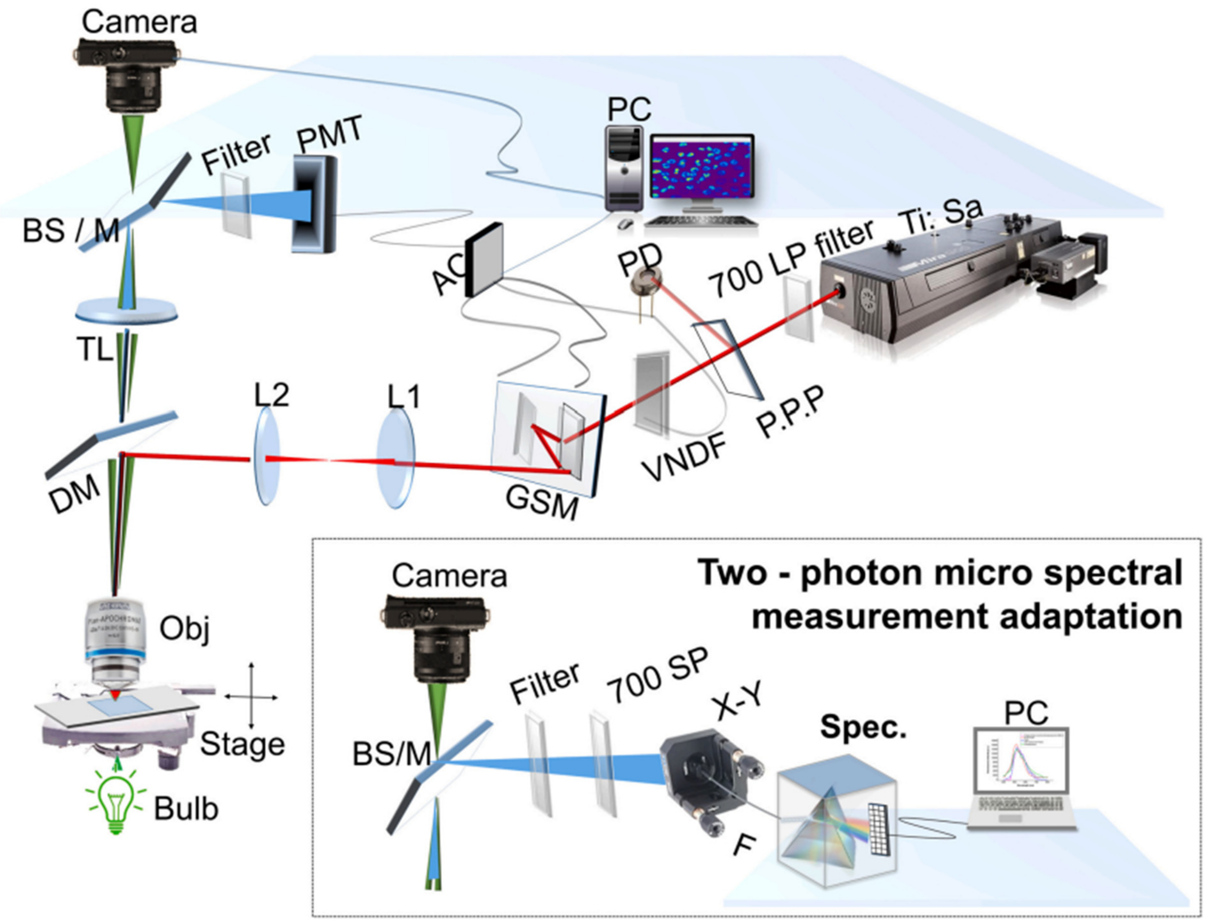


Figure 4. Schematic 3D drawing of the home-built TPEF microscope with specific adaptations for in situ emission spectra measurement [22].

Caceres-Pablo et al. introduced a novel ultralong passively mode-locked ring fiber laser architecture, utilizing Raman amplification to generate femtosecond pulses in ring resonators up to 25.2 km, achieving sub-200 fs pulses and ultra-low repetition rates of 20 kHz, making it suitable for high-energy pulse applications [36]. Bourquard et al. investigated the effects of temporal pulse shaping on aluminum and boron ablation plumes generated by ultrashort laser pulses, showing that shaping increases ion emission and reduces nanoparticle production, with implications for optimizing plasma composition and nanoparticle generation in material processing [21].

A typical method of temporal pulse shaping is a chirped pulse, where the spectral component of the pulse is frequency spread. Pulse compression techniques, such as dispersive elements like gratings or prisms, can compress such chirped pulses to shorter durations while conserving energy. The practical benefits of achieving a low time–bandwidth product are evident in this context, as it is essential to achieve high compression ratios and minimize distortion during compression [21–23,29–32]. Salgado-Remacha et al. demonstrated the single-step self-compression of ultrashort pulses to below 20 fs using all-fiber supercontinuum generation, with numerical simulations confirming the role of resonant dispersive waves as a key indicator of optimal pulse compression [32].

Ultrafast pulses with broad spectral bandwidths are essential for inducing nonlinear optical effects such as self-phase modulation, four-wave mixing, and supercontinuum generation. A low time–bandwidth product ensures that the pulse duration is sufficiently short to drive these nonlinear processes efficiently [23,29–32]. In spectroscopic applications, narrowband laser pulses with short durations are desirable for achieving high spectral resolution and minimizing broadening effects. A low time–bandwidth product indicates that the laser pulse is close to transform-limited, allowing for precise spectral measurements [23,29–32,45,49]. In ultrafast science, where processes occur on femtosecond or picosecond time scales, ultrafast pulsed lasers with low time–bandwidth products are crucial for studying fast dynamics with high temporal resolution [33]. The ability to generate transform-limited pulses facilitates accurate time-resolved measurements of ultrafast phenomena [45,50–52].

Achieving a low time–bandwidth product in ultrafast pulsed lasers requires careful design of the laser system, optimizing pulse shaping techniques, and minimizing dispersion effects [20–23]. By reducing the time–bandwidth product, researchers and engineers can generate ultrafast pulses with high temporal and spectral purity, enabling ultrafast optics, laser spectroscopy, material processing, and biomedical imaging advancements. Table 3 summarizes current technologies in use by temporal pulse modulation.

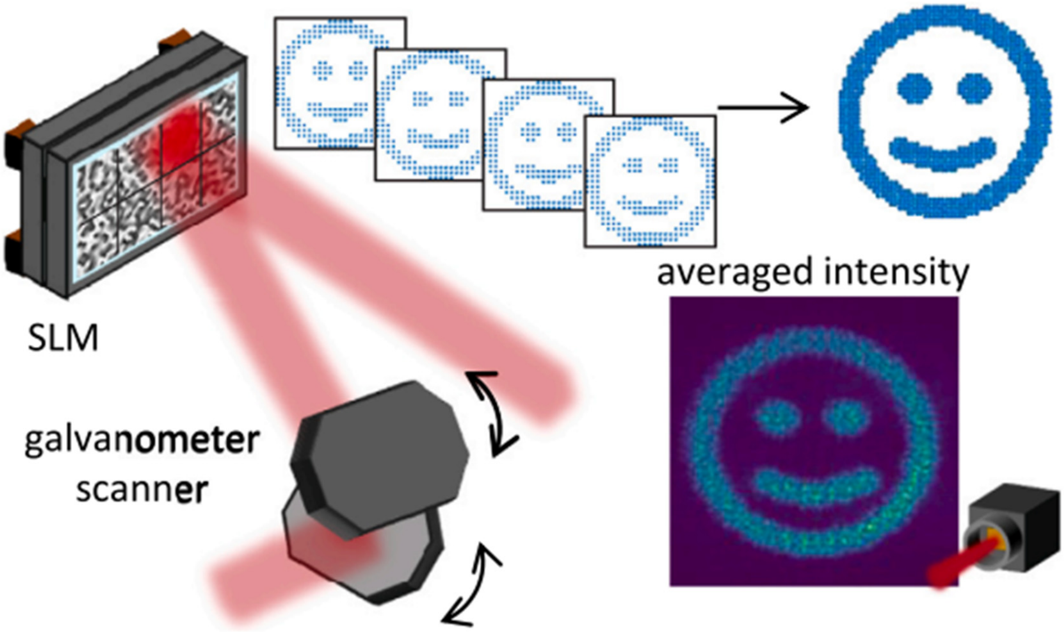
Table 3. Temporal pulse shaping technologies in use.

Key Technology	Applications	Pulse Characteristics	Key Findings	Ref.
Temporal Pulse Shaping	Plasma Excitation and Nanoparticle Generation	Double pulses, chirped femtosecond pulses	Enhanced control of ionization and nanoparticle formation in ablation plumes; saturation effects observed.	[21]
Laser-Induced Breakdown Spectroscopy	Metallic Sample Analysis	Chirped and phase-shaped pulses	Reduced ablation threshold and improved elemental detection at low fluences.	[21,23]
Ultrashort Pulse Characterization	Amplitude Swing Technique	Tunable pulses in the VIS-NIR range	Developed flexible amplitude modulation for robust diagnostics across visible and infrared spectra.	[27,45]
Pulse Compression	Sub-20 fs Pulse Compression	Supercontinuum generation in highly nonlinear fibers	Achieved compression to 17 fs; simplified all-fiber setup for high-quality outputs.	[32]
Second Harmonic Generation	Quantum Dot Nanostructures	Linearly modulated refractive index in QD crystals	Improved SHG efficiency; minimized walk-off effects with optimized chirping.	[45,49]
Pulse Reconstruction	Asymmetric FROG Setup	Chirped second harmonic generation	Enhanced unambiguous reconstruction of ultrashort pulse phase and intensity.	[32,45,49]

3.3. Spatial Beam Shaping

Spatial beam shaping involves controlling the spatial profile and intensity distribution of laser beams. This manipulation is crucial for optimizing laser delivery, improving processing efficiency, and achieving desired beam characteristics. Diffractive optical element is a technique mainly used for spatial beam shaping [31,42–47,53,54]. Kuang et al. demonstrated high-throughput diffractive multi-beam femtosecond laser processing, and Karosas et al. investigated fused silica-based phase diffractive optical elements using femtosecond lasers [46,55].

As shown in Figure 5, SLMs can also be used for spatial beam shaping by applying spatially varying phase patterns to incident laser beams. By dynamically controlling the phase distribution across the beam, SLMs can generate tailored intensity distributions and beam shapes. This technique enables adaptive beam shaping for applications such as laser microfabrication and optical trapping [56]. Diffractive optical elements (DOEs) are microstructured optical components that diffract incident laser beams into desired intensity patterns. By designing appropriate phase profiles on DOEs, ultrafast pulsed laser beams can be shaped into complex spatial profiles, such as Gaussian-to-flat-top profiles or multiple focal spots. DOEs are widely used in applications such as laser material processing and microscopy [55–58]. Ackemann et al. presented a high-speed speckle averaging method for phase-only beam shaping in laser materials processing, using a galvanometer scanner to scan a laser beam over a spatial light modulator, effectively reducing speckle noise and improving beam shaping efficiency and quality for ultrashort pulsed laser applications [26].



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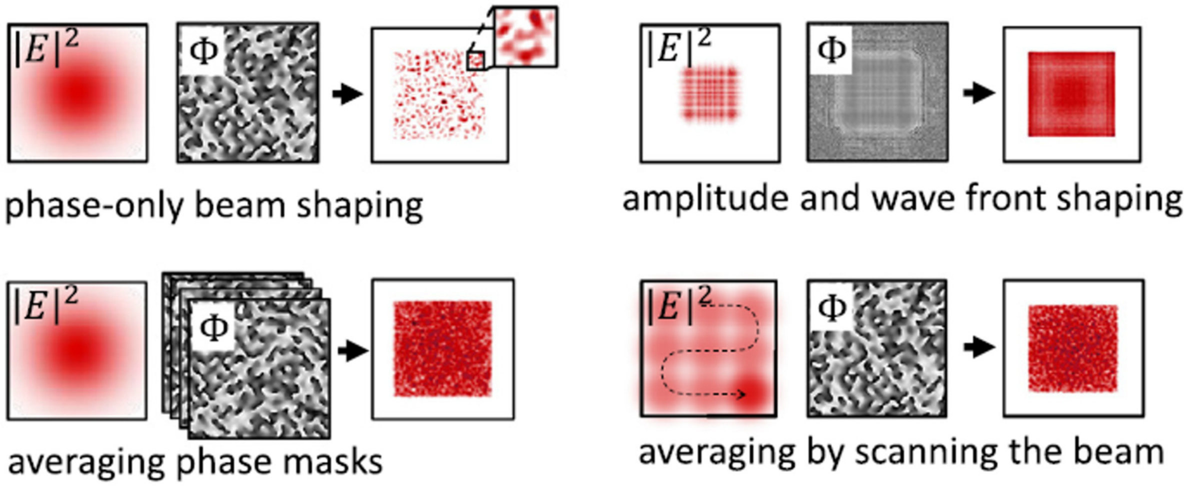

(**b**)

Figure 5. (**a**) SLM for spatial beam shaping. (**b**) Methods for phase-only beam shaping [26].

Axicon lenses are conical lenses that can transform Gaussian laser beams into Bessel beams with a narrow central lobe and extended depth of focus. This beam-shaping technique is proper in applications requiring long propagation distances or precise control of the focal volume, such as laser microfabrication and optical tweezers [57,58]. Dudutis et al. demonstrated the use of laser-fabricated axicons for generating high-quality Bessel beams, which are effectively applied to glass dicing, with enhanced performance achieved through axicon tilt operation that improves glass separation quality and dicing efficiency [58].

Various methods exist to homogenize the spatial intensity distribution of ultrafast pulsed laser beams. These techniques aim to produce uniform intensity profiles across the beam cross-section, ensuring consistent processing results. Examples include microlens arrays, diffractive diffusers, and fly's eye condensers [26,59]. Bischoff et al. presented a method for generating laser-induced periodic surface structures on borosilicate and soda-lime glasses using a less expensive picosecond-pulsed laser system, optimizing scanning strategies to achieve high-quality, metal-like, and dielectric-like nanostructures for industrial applications [59].

Holographic Optical Elements (HOEs) exploit holographic techniques to shape ultrafast pulsed laser beams. They can generate intricate light patterns by recording interference patterns of reference and object beams. This method enables the creation of tailored beam shapes for specific applications, such as optical trapping or laser material processing [24,25,60,61].

Beam homogenization techniques are used to homogenize the spatial intensity distribution of ultrafast pulsed laser beams. These techniques aim to produce uniform intensity profiles across the beam cross-section, ensuring consistent processing results. Examples include microlens arrays, diffractive diffusers, and fly's eye condensers [26,62,63]. Bieda et al. demonstrated that well-defined periodic patterns with pitches smaller than 1 micron can be achieved by microlens array [63].

Wavefront shaping techniques manipulate the phase and polarization of ultrafast pulsed laser beams to achieve desired focusing or propagation characteristics. Adaptive optics systems, for instance, can dynamically adjust the phase of the incident beam using deformable mirrors, compensating for optical aberrations and optimizing beam quality [64–67]. Dement'ev et al. experimentally demonstrated wavefront reconstruction using geometric-optical reflection, employing femtosecond laser pulses, and showed that the approach offered achromatic wavefront reconstruction, which differs from traditional holographic methods by avoiding diffraction and enabling reconstruction with wide-spectrum radiation [65]. A summary of spatial beam shaping is presented in Table 4.

Table 4. Summary of spatial beam shaping.

Key Techniques/Methods	Application	Results/Findings	Ref.
Spatial light modulation with binary phase masks	Holographic FS Laser Processing	Improved precision in beam shaping and real-time holographic processing	[20,42]
Spatial light modulator with computer-generated holograms	High-Throughput Diffractive Multi-Beam Processing	Enhanced throughput by >1 order of magnitude; demonstrated precise micro-structuring	[42,46]
Femtosecond laser with spatial light modulator for beam division	Parallel Microstructuring	High degree of parallelism; feature sizes down to a few microns	[47]
Phase-only beam shaping with spot arrays	Uniform Material Ablation with Spot Arrays	Uniform surface ablation; increased ablation efficiency by a factor of 2	[54]
Direct femtosecond laser writing	Phase-Diffractive Optical Elements in Fused Silica	Achieved 97% diffraction efficiency for Bragg gratings and high-quality Fresnel lenses	[55]
Galvanometer scanner with spatial light modulator	High-Speed Speckle Averaging for Phase-Only Beam Shaping	Reduced speckle noise; near-perfect uniformity in intensity profiles for laser ablation	[52,68]

4. Applications of Ultrafast Pulsed Laser Beam Shaping

Ultrafast pulsed lasers have revolutionized numerous fields of science, engineering, medicine, and technology due to their unique temporal characteristics, including extremely short pulse durations on the order of femtoseconds or picoseconds. These lasers find applications across various disciplines, enabling precise, efficient, and versatile laser processing [65,66]. Sahoo et al. reviewed the use of ultrashort pulse laser patterning on zirconia to enhance adhesion to resin-matrix cement in dentistry, concluding that this technique increases bond strength and avoids surface defects compared to traditional methods [67–69]. Rodriguez et al. presented a 6-degree-of-freedom robot-assisted laser ablation system for automated paint removal on complex 3D surfaces using ultrashort pulse lasers, demonstrating improved precision and efficiency in processing curved geometries while minimizing surface damage [70]. Outon et al. investigated the corrosion behavior of nanostructured ferritic stainless steel treated with Laser-Induced Periodic Surface Structures generated by ultrashort laser pulses, demonstrating that the treatment enhances corrosion resistance while maintaining surface brightness [71].

Ultrafast pulsed lasers enable advanced nonlinear optical imaging and spectroscopy techniques, such as two-photon microscopy, second-harmonic generation imaging, and coherent anti-Stokes Raman spectroscopy. These techniques offer high-resolution, three-dimensional imaging of biological tissues, cells, and materials with deep tissue penetration, reduced photodamage, and enhanced contrast [71–77]. As an example, Hadjichristov et al. investigated the laser-induced photodegradation of optically transparent polymers, specifically polymethyl methacrylate and polystyrene, using two-photon Raman-resonant laser irradiation [43].

Ultrafast pulsed lasers are indispensable for studying ultrafast dynamics and processes in physics, chemistry, and materials science. Techniques such as pump–probe spectroscopy, time-resolved fluorescence spectroscopy, and transient absorption spectroscopy use ultrafast laser pulses for probing and manipulating molecular, electronic, and structural dynamics on femtosecond to picosecond time scales [71].

Ultrafast pulsed lasers enable micro- and nano-fabrication techniques with sub-diffraction-limited resolution. Applications include the fabrication of micro-optical elements, photonic devices, microfluidic systems, nanostructures, and lab-on-a-chip devices for photonics, optoelectronics, biotechnology, and nanotechnology applications [78–87].

In medicine, ultrafast pulsed lasers are used for advanced medical imaging techniques such as OCT in Figure 2 and multiphoton microscopy. This allows for high-resolution, non-invasive imaging of biological tissues with subcellular detail. In laser surgery, ultrafast pulsed lasers enable precise tissue ablation, minimally invasive procedures, and therapeutic treatments with reduced collateral damage and faster healing [88–92].

Ultrafast pulsed lasers play a crucial role in quantum technologies such as quantum computing, quantum communication, and quantum cryptography. They generate and manipulate quantum states of light, create entangled photon pairs, and implement quantum gates and operations [53,93–95]. These applications highlight ultrafast pulsed lasers' versatility, precision, and efficiency across diverse fields of science, engineering, medicine, and technology. As technology advances and ultrafast pulse durations become even shorter and more accessible, the potential applications and benefits of these lasers continue to expand.

5. Limitations of Beam Shaping in Ultrafast Pulsed Laser

While beam shaping in ultrafast pulsed lasers offers significant advantages, it also comes with certain limitations. Implementing beam shaping techniques often requires specialized optics, such as SLMs, DOEs, or HOEs. These components can be expensive and may require complex alignment and calibration procedures, increasing the overall cost and complexity of the laser system [12–18,54–60].

Some beam shaping methods, such as those involving diffractive or refractive elements, can introduce losses in the laser beam, reducing energy efficiency. For ultrafast pulsed lasers, minimizing energy losses is crucial to maintaining high peak powers and achieving desired material processing effects. Beam shaping elements, particularly those used for spatial modulation, can introduce dispersion and aberrations into the laser beam. These effects may distort ultrafast pulses' temporal and spatial profiles, compromising the quality and precision of laser processing applications. Certain beam shaping techniques, such as grating-based pulse stretching/compression, can alter the temporal profile of ultrafast laser pulses. Lens dispersions up to the second order are considered to obtain easy-to-use formulas. Using this formulation, we designed a refractive–diffractive triplet for near-infrared femtosecond laser pulses. While this may be desirable for specific applications, it can also introduce pulse broadening or temporal chirping, affecting the interaction dynamics with materials [96–103]. Amako et al. presented a baseline design scheme for refractive–diffractive hybrid lenses aimed at focusing ultrashort laser pulses while minimizing space–time distortions, demonstrating the ability of such lenses to correct both chromatic and temporal aberrations [96]. Grunwald explored techniques for spatio-temporal beam shaping and the characterization of ultrashort pulse lasers, focusing on the use of thin-film micro-optics and autocorrelation methods to achieve high-resolution spatial mapping and pulse characterization [97].

Some beam shaping methods may have inherent limitations in terms of the range of beam profiles that can be generated or the flexibility to adapt to different processing requirements. This lack of versatility can restrict the applicability of beam-shaping techniques in diverse laser processing tasks. Beam-shaping components, especially those based on phase modulation or interference effects, can be sensitive to environmental factors such as temperature variations, mechanical vibrations, and air turbulence. These external influences may degrade the performance and stability of beam-shaping systems, necessitating careful environmental control [104–108].

Scaling beam-shaping techniques to high-power or industrial-grade ultrafast pulsed laser systems can pose challenges. Factors such as thermal management, optical damage thresholds, and scalability of beam-shaping elements may limit their practical implementation in large-scale laser processing setups. Addressing these limitations requires ongoing research and development efforts to enhance beam-shaping techniques' efficiency and robustness in ultrafast pulsed lasers, thereby unlocking their full potential for a wide range of applications.

6. Conclusions

In this paper, we reviewed the current literature on the modulation of ultrafast laser beams through temporal and spatial modulation. Ultrafast laser beam shaping presents numerous advantages for scientific, industrial, and medical applications. By enabling precise control over the spatial, temporal, and spectral characteristics of ultrafast laser pulses, beam shaping significantly improves the performance and efficiency of laser-based processes.

Ultrafast laser beam shaping enables the precise distribution of laser energy in specific patterns or focal regions, facilitating high-precision material processing while minimizing damage to surrounding areas. By focusing the energy more accurately, beam shaping enhances the interaction between the laser and the target material, thereby increasing the efficiency of processes such as micromachining and laser surgery.

Beam shaping can significantly reduce the heat-affected zone and minimize thermal damage during material ablation, resulting in cleaner cuts and improved quality in applications such as semiconductor manufacturing, 3D microfabrication, and laser-based texturing. By tailoring the pulse shape, users can optimize energy transfer to the material, enhancing processing speed while maintaining high precision. These capabilities make ultrafast lasers particularly well suited for high-throughput industrial applications.

Beam shaping can improve the efficiency of nonlinear processes such as harmonic generation and multiphoton excitation, which is critical for applications like biological imaging (e.g., multiphoton microscopy) and optical communication systems. In high-intensity scenarios, beam shaping plays a key role in controlling laser filamentation caused by nonlinear self-focusing, making it particularly useful in fields such as atmospheric science and laser-guided lightning protection.

Temporal shaping of ultrafast pulses, ranging from femtoseconds to picoseconds, allows precise control over the interaction duration with materials or biological tissues, minimizing damage and optimizing therapeutic outcomes in medical laser applications.

By adjusting the pulse chirp (frequency variation over time), energy deposition can be enhanced, improving the efficiency of specific laser-based processes. In microscopy, beam shaping enhances both resolution and contrast, particularly in advanced techniques like structured illumination microscopy and holographic imaging. Optimized pulse shapes also boost the efficiency of multiphoton excitation, leading to improved signal-to-noise ratios in biological imaging and fluorescence techniques.

In optical communication systems, ultrafast lasers with shaped beams enable faster and more efficient data transmission by minimizing pulse overlap and interference. Similarly, in adaptive optics, shaping laser wavefronts compensates for optical aberrations, enhancing the precision of laser-guided systems and improving the imaging quality of telescopes.

In conclusion, ultrafast laser beam shaping enhances precision, efficiency, and control across a wide range of laser-based applications, driving advancements in science, industry, and healthcare. The ability to fine-tune the spatial, temporal, and spectral properties of ultrafast laser pulses makes beam shaping highly adaptable for diverse applications, including medical diagnostics, surgical procedures, laser welding, and micromachining.

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