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Wavefront shaping: A powerful and versatile approach for overcoming multiple scattering across multidisciplinary domains: A review article

Abstract
Optical techniques encompass a broad range of applications, as light–matter interactions provide highly sensitive means for probing or manipulating target media. The majority of these approaches depend on ballistic or quasi-ballistic photons to achieve high spatial resolution. However, the intrinsic scattering of light in biological tissues and tissue-mimicking media represents a major limitation, as it severely restricts the penetration depth of non-scattered photons and, consequently, constrains the broader applicability of many optical methods. Furthermore, conventional optical systems are typically designed and fabricated to perform a fixed function or to deliver a predetermined level of performance.

Recent advances in wavefront shaping have revealed that phase distortions induced by scattering media or optical components can be effectively compensated by adaptively optimizing the incident wavefront through iterative algorithms or by exploiting the transmission matrix of the scattering medium. These developments create unprecedented opportunities to realize controlled optical delivery and detection at greater depths, as well as dynamically reconfigurable functionalities, by leveraging scattering media as substitutes for traditional optical components.

This article reviews recent progress in wavefront shaping across multidisciplinary fields, including optical focusing and imaging through scattering media, functionalized optical devices, modulation of mode coupling, and nonlinear effects in multimode fibers, along with a range of multimode fiber-based applications. In addition to outlining the fundamental principles and recent technological advances, the review provides a critical discussion of practical limitations and future development pathways. Collectively, these insights suggest that wavefront shaping has a promising future, with the potential to enable new avenues for noninvasive or minimally invasive optical interactions and precise control deep within biological tissues.

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I. INTRODUCTION

The high sensitivity of optical signals to variations and inhomogeneities within a medium, renders light an exceptionally powerful tool for probing and manipulating target materials. Over recent decades, this sensitivity has been harnessed through the development of numerous advanced optical techniques and instruments, contributing substantially to progress in modern science and technology. Achieving high spatial resolution in most of these approaches depends on the use of ballistic or quasi-ballistic photons, which enable coherent light focusing. This requirement poses little challenge for transparent or weakly scattering samples. In contrast, in thick biological tissues and tissue-mimicking scattering media, photons undergo multiple scattering events as a result of the intrinsically heterogeneous refractive index distribution, thereby significantly complicating coherent light propagation and focusing. As a consequence, the number of ballistic photons decreases exponentially with increasing propagation depth. High-resolution optical focusing and imaging in biological tissues are therefore typically restricted to depths of approximately 1 mm beneath the skin or tissue surface, or are feasible only in weakly scattering samples, where adaptive optics can be employed to correct optical aberrations. At greater depths—beyond one optical transport mean free path—adaptive optics becomes ineffective, as ballistic photons are exceedingly scarce and cannot be readily distinguished from diffusely scattered photons, resulting in the observation of fully developed speckle patterns.

Another biomedical scenario in which optical speckle patterns prevail is light transmission through multimode optical fibers. Optical fibers have been extensively explored for minimally invasive endoscopic imaging, surgical interventions, and optical stimulation in biomedical applications. Among the various fiber types, multimode fibers (MMFs) are often favored because they support thousands of propagation modes within a compact footprint, with diameters as small as tens of micrometers. However, practical applications are constrained by mode dispersion and intermodal interference within MMFs, which give rise to complex speckle patterns analogous to those produced by multiple scattering in thick turbid media.

Beyond biomedical applications, multiple light scattering adversely affects a wide range of optical technologies. In many optical systems, transparent and homogeneous components—such as lenses, mirrors, polarizers, and beam splitters—are preferred to minimize optical losses and preserve functionality. Consequently, stringent requirements are imposed on the refractive index homogeneity and structural uniformity of the materials employed, as even minor irregularities or deformations can result in significant performance degradation. These constraints restrict material selection and substantially increase device cost. Moreover, the strict structural requirements associated with optical components such as waveguides and photonic crystals further limit the available degrees of freedom for light propagation. Collectively, multiple scattering poses a fundamental challenge to several critical optical applications, including the penetration depth of high-resolution optical techniques in biological tissues, the practical utility of multimode fibers, and the design flexibility of optical components.

Given its fundamental significance, overcoming multiple scattering has long been a highly sought-after objective. Historically, this challenge was considered intractable, as both the processes and outcomes of multiple scattering appeared random and prohibitively complex. However, during the 1980s, it became evident that these seemingly stochastic scattering events are in fact deterministic within the speckle decorrelation time window. Building on this insight, Vellekoop and Mosk introduced a transformative approach in 2007 known as wavefront shaping (WFS), whereby scattering-induced optical distortions can be precompensated through iterative optimization of the incident wavefront or by time-reversing the scattered wavefront. Subsequently, optical propagation through complex media was shown to be systematically describable via measurement of the transmission matrix (TM) of the medium, enabling precise manipulation of the incident wavefront to achieve arbitrary desired outputs. Over the past decade, the field of wavefront shaping has progressed rapidly, with several methodologies gaining widespread adoption in research. Notably, WFS has been successfully applied to counteract optical scattering and to realize diffraction-limited focusing at substantial depths within complex scattering media.

Wavefront shaping further enables the purposeful exploitation of scattering to realize functionalities that are unattainable using purely ballistic light. For instance, WFS has been employed to transform scattering media into reconfigurable functional elements, including linear operators, polarization controllers, and optical beam splitters, thereby opening new possibilities for innovative optical computing architectures. Additionally, WFS has been utilized to regulate mode coupling and enhance light–matter interaction efficiency, allowing optimization of output light characteristics, such as improved or dynamically modulated information transmission and communication through strongly scattering environments. Importantly, wavefront shaping also offers compelling strategies to mitigate the intrinsic mode dispersion in multimode fibers, with the potential to significantly advance fiber-based endoscopy and optical communication technologies. To elucidate the contributions of wavefront shaping to these diverse fields, this review first introduces the fundamental concepts of multiple scattering and the operating principles of WFS, followed by a comprehensive discussion of recent advances in optical focusing, imaging, and manipulation through and within scattering media, functionalized optical devices, and light control and modulation in multimode fibers for a wide range of applications.

II. PRINCIPLE

Optical scattering in disordered media

Light propagation within structurally disordered media differs fundamentally from propagation in homogeneous environments such as air, pure water, or transparent glass. To describe the resulting strong scattering behaviour, a variety of theoretical models have been developed. When light propagates over distances shorter than the transport mean free path (TMFP), it retains ballistic or quasi-ballistic characteristics, meaning that information transfer between the object and the image remains one-to-one and spatially localized. In contrast, beyond the TMFP, light propagation becomes predominantly random and diffusive, such that a single image point receives contributions from multiple source points, and vice versa. As a consequence, the point spread function of a diffusive optical system assumes a random form, converting originally ordered information into seemingly random intensity distributions known as speckle patterns.

Although complex, this transformation remains deterministic within the speckle correlation time. For a static scattering medium, even one exhibiting strong scattering, the output optical field produced by a given input field remains invariant under identical boundary and conjugation conditions. However, when these conditions change due to internal dynamics or external perturbations, the input–output relationship rapidly decorrelates. Prior to temporal decorrelation, there exists a limited spatial regime in which the output field undergoes translation or tilt in response to corresponding changes in the input field, a phenomenon known as the optical memory effect (ME). Within the range of the memory effect, imaging through scattering media can be achieved using linear transformations; however, the achievable field of view (FOV) is typically restricted, on the order of ~10 mm × 10 mm. Increasing medium thickness further reduces the effective memory effect range and, consequently, the FOV, posing a significant barrier to practical implementation. As a result, accurately estimating the medium's response to the incident optical field is essential for retrieving information encoded within scattered outputs. Rigorous theoretical treatments of scattering models have been presented by Rotter et al. and in earlier foundational studies.

Wavefront shaping via transmission matrix engineering and feedback-based optimization

To model the scattering process, speckle patterns can be regarded as the result of interference among a large number of independent optical paths, or equivalently, as the superposition of their corresponding electric fields. As illustrated in Figure 1C, the cumulative effect of all scattering events linking each input and output channel can be encapsulated within a complex transmission matrix (TM). In this framework, the optical field at each output channel (the m-th element of the output vector **Y**) is expressed as a weighted linear combination of the input channels (the n-th elements of the input vector **X**), such that $y_m = \sum_n t_{mn} x_n$, or equivalently **Y** = **T X**, where **T** denotes the TM composed of complex-valued elements t_{mn}. By appropriately manipulating this matrix, the information embedded within the disordered medium can be systematically extracted, enabling both physical insight and practical engineering applications. Consequently, accurate measurement of the TM is of central importance. To this end, two primary classes of approaches—analytical and statistical—have been developed and extensively investigated. For analytical approaches, transmission matrix determination relies on optical interference. In one strategy, an internal reference pattern is superimposed on the wavefront modulator and combined with probing wavefronts through phase-shifting operations. In an alternative approach, an external reference beam is introduced to interfere with the output speckle field, enabling holographic recording of the complex field. The second major class of transmission matrix measurement methods is based on statistical inference, largely guided by Bayesian frameworks. These statistical approaches typically require a greater number of measurements to achieve accurate estimation of the transmission matrix elements.

Once the transmission matrix has been measured, the output wavefront can be engineered with high flexibility, either at a global or local level. Global control is typically achieved through singular value decomposition, whereby analysis of the eigenvectors of $T^{\dagger}T$(with †denoting the conjugate transpose) enables comprehensive control over energy transport—often referred to as eigenchannels—as well as polarization states through the scattering medium. In contrast, local control allows the output light to be confined into user-defined spatial patterns, such as single- or multi-point optical foci, achieved through inversion of the transmission matrix or by directly adjusting the phase and/or amplitude of the incident field based on the matrix elements. As a result, tailored input wavefronts can be simultaneously generated to focus light onto arbitrary positions on the detection plane. This capability readily enables raster scanning across the detection plane, thereby making imaging through scattering media practically achievable.

It should be noted that instabilities in the scattering medium or the optical system can substantially compromise the validity of a measured transmission matrix and, consequently, the effectiveness of the corresponding modulated wavefront. In such situations, the input–output relationship becomes relaxed, rendering adaptive modulation necessary and motivating the use of feedback-based optimization strategies. A variety of optimization algorithms have been developed for this purpose, including evolutionary algorithms, artificial intelligence–based methods, and hybrid combinations thereof, which can dynamically update modulation patterns while accounting for variations in feedback signals. When stronger perturbations are present, such as in dynamically evolving media, optimization approaches incorporating physical priors have demonstrated greater efficiency by quantitatively estimating errors in the optimized wavefront for optical focusing. This represents a significant improvement over earlier methods, in which the number of spatial light modulator (SLM) pixels requiring correction was largely determined empirically. Furthermore, learning-based wavefront optimization techniques offer additional adaptability by decomposing motion into sequences of quasi-stationary states for iterative phase modulation. Collectively, these methods complement transmission matrix–based approaches and have achieved robust light focusing with enhanced resilience to noise.

It is also important to recognize that transmission matrix–based methods inherently assume linearity in the system under investigation. By contrast, although feedback-based optimization algorithms may be less effective for channel decomposition or rapid focus scanning, they offer greater adaptability and versatility, particularly in regimes where nonlinear effects or excitation-dependent responses dominate the detected signals from scattering systems.

Wavefront shaping via optical phase conjugation

The wavefront shaping approaches discussed above typically require continuous acquisition and updating of feedback signals, with a single optimization procedure often necessitating thousands or even millions of measurements. In the absence of advanced electronic control, such methods are poorly suited to compensate for the rapid optical field fluctuations induced by dynamic scattering media, such as *in vivo* biological tissues, where speckle decorrelation can occur on millisecond timescales and becomes increasingly rapid with depth. A robust alternative to address this challenge is optical phase conjugation (OPC), which focuses on direct manipulation of the scattered optical field rather than precompensating the incident wavefront. The first demonstration of OPC through a ground glass diffuser dates back to the 1960s. Following nearly five decades of subsequent development, this concept has been successfully extended to counteract volumetric scattering in biological tissues and even in living organisms.

In essence, optical phase conjugation operates by time-reversing the scattering process. The scattered optical field is first recorded and then phase conjugated using a phase conjugate mirror (PCM). The resulting phase-conjugated field subsequently propagates backward through the scattering medium, retracing the original optical paths in reverse and ultimately refocusing at the initial point of incidence. This implementation enables effective reversal of scattering and refocusing of light using only a single measurement, thereby facilitating rapid wavefront shaping and enabling successful *in vivo* demonstrations of high-speed optical control. The core component, the PCM, was initially realized using analog photorefractive materials and later implemented digitally using interference-based recording, typically involving a digital camera pixel-wise aligned with a spatial light modulator (SLM) at the same optical plane. Both implementations offer fast response times on the order of milliseconds; however, digital optical phase conjugation (DOPC) is not constrained by theoretical limits on maximum reflectivity and is compatible with both continuous-wave and pulsed laser sources. When combined with corrections for minor optical misalignments and intrinsic SLM surface curvature, DOPC delivers significantly enhanced performance. These advantages have established DOPC as a widely adopted approach for addressing optical scattering in dynamic environments and optogenetic applications.

OPTICAL FOCUSING AND IMAGING WITH WAVEFRONT SHAPING

Since its introduction in 2007, the capability of wavefront shaping techniques to operate effectively in the presence of strong scattering—particularly in terms of focusing efficiency and optimization speed—has improved substantially. These advances have been driven by parallel developments in wavefront modulation hardware and optimization algorithms. As a result, wavefront shaping has enabled a broad range of applications, most notably optical focusing and imaging within scattering media.

Direct probing or direct access to the optical field inside a scattering medium is generally infeasible due to the diffusive nature of light propagation. Consequently, to realize wavefront shaping at depth in a noninvasive or minimally invasive fashion, the use of internal guide stars is essential. These guide stars provide in situ feedback that enables accurate estimation and control of the optical field within the sample.

In optical phase conjugation–based wavefront shaping, optical focusing can be accomplished using a single measurement by directing the phase-conjugated light back toward the original internal guide star. One of the earliest implementations of this concept was time-reversed ultrasonically encoded (TRUE) optical focusing, which employs ultrasonic modulation based on the acousto-optic effect to serve as an internal guide star. In this approach, only photons that are frequency-shifted by the ultrasound modulation frequency contribute to hologram formation at the phase conjugate mirror, ensuring that the reconstructed phase-conjugated wave converges precisely at the original ultrasound focal region. Because ultrasound experiences approximately three orders of magnitude less scattering than light in biological tissues, this technique enables acoustic-resolution optical focusing at substantial depths.

More recently, TRUE focusing has been successfully extended to optogenetic modulation of neural activity in acute mouse brain slices with thicknesses approaching 800 μm. Nevertheless, the achievable resolution of this method is fundamentally limited by the size of the ultrasound focus, which is significantly larger than the optical wavelength. To overcome this limitation, time reversal of variance-encoded light was introduced, enabling speckle-scale lateral resolution (~5 μm) by assigning distinct variance signatures to individual spatial modes within the scattering medium. Beyond ultrasonic mediation, optical perturbations induced by moving absorbers have also been exploited to guide time reversal in a strategy known as time-reversed adapted perturbation (TRAP). To enable precise and remote control of perturbation motion in TRAP-based focusing, externally actuated magnetic particles have been proposed as noninvasive internal guide stars. Alternatively, localized perturbations in the diffusive light field can be generated in situ by destroying microbubbles using a focused ultrasound beam, yielding optical focal spots with sizes on the order of ~2 μm, as dictated by the microbubble dimensions. Collectively, these approaches facilitate high-resolution and high-specificity optical focusing and imaging deep within tissue, thereby enabling advanced biomedical applications such as optogenetics and photothermal therapy.

For pre -compensation-based wavefront shaping approaches, including transmission matrix engineering and iterative optimization, photoacoustic (PA) signals have emerged as highly effective internal guide stars for assessing localized photon flux within scattering media. In this modality, short laser pulses induce a photothermal response in the sample, generating photoacoustic waves that can be detected externally using an ultrasound transducer. PA-guided wavefront shaping has been successfully implemented in both iterative optimization schemes and transmission matrix–based frameworks, enabling non-invasive optical focusing and imaging at appreciable depths. However, the achievable focusing resolution in these approaches is fundamentally constrained by the size of the acoustic focal region of the transducer, which typically encompasses multiple optical speckle grains within the PA guide star volume.

To overcome this limitation, sub-acoustic optical focusing has been demonstrated by exploiting the Gaussian spatial sensitivity variations of the ultrasound transducer along the acoustic axis in conjunction with genetic optimization algorithms. Furthermore, nonlinear PA feedback based on the Grueneisen relaxation effect has been introduced as an internal guide star for iterative wavefront optimization, enabling light to be focused onto a single optical speckle grain (Figure 2D). In addition to PA-based strategies, ultrasonically mediated light—leveraging the same acousto-optic mechanism employed in TRUE focusing—has been utilized as an internal guide star. This ultrasonically encoded light provides noninvasive feedback suitable for both iterative wavefront shaping and direct phase conjugation, thereby enabling effective optical focusing within strongly scattering media.

Wavefront shaping is not strictly limited to the use of physical guide stars. Recent studies have introduced model-based wavefront shaping strategies that eliminate the need for an explicit guide star, provided that the refractive index distribution of the sample is known. In this framework, a virtual guide star is assumed at an arbitrary target position beyond the scattering medium, and the corresponding incident wavefront is numerically calculated and subsequently implemented experimentally using a spatial light modulator to achieve optical refocusing. Despite its conceptual elegance, this approach remains challenging to implement in practice, particularly for biological tissues, where refractive index distributions are complex and dynamically varying.

To address these limitations, an image-guided wavefront shaping method enabling guide star–free incoherent imaging has also been reported. This strategy employs generalized image-based metrics as iterative feedback, effectively using the object itself as an implicit guide star to reconstruct hidden structures. Such guide star–free wavefront shaping approaches hold significant promise for non-invasive imaging applications, including endoscopic modalities.

FUNCTIONALIZED DEVICES ENABLED BY WAVEFRONT SHAPING

A scattering medium disrupts the spatial and temporal distribution of light, effectively scrambling an incident wavefront. Nevertheless, as discussed earlier, this apparent randomness is fundamentally deterministic, and the behavior of a complex scattering system can be accurately described using a transmission matrix that maps the relationship between input and output optical fields. By appropriately exciting a carefully designed combination of input modes through a spatial light modulator, a desired output field can be generated. Consequently, with the aid of wavefront shaping, an optical scattering medium can be repurposed to perform specific or multifunctional operations, effectively acting as a programmable or functional optical device.

Scattering Optical Components

Early wavefront shaping studies primarily aimed to counteract wavefront scrambling in order to achieve optical focusing behind scattering media, effectively treating the medium as a scattering lens in the far field. This capability has been extensively addressed in previous sections. In the near-field regime, however, a scattering medium can likewise function as a scattering lens capable of producing subwavelength optical foci. When near-field scanning optical microscopy (NSOM) is employed to record optical patterns in the near field, the resulting speckle size can reach subwavelength dimensions. By contrast, speckle grains observed in the far field are typically on the order of the optical wavelength.

Using a conventional NSOM system, the near-field transmission matrix can be experimentally measured. The linear mapping between the incident far-field wavefront and the scattered near-field output enables coherent control of the near-field optical distribution at arbitrary spatial locations. As a result, optical foci with full widths at half maximum as small as 165 nm have been demonstrated, corresponding to approximately one-quarter of the incident wavelength (633 nm). Beyond serving as a standalone scattering lens, such scattering media can also be integrated with conventional lenses to further enhance focusing resolution.

Beyond enhanced lensing performance, wavefront shaping–assisted scattering media offer significant potential for multidimensional control of light, including manipulation of wavelength and polarization degrees of freedom. In conventional optical systems, individual optical components are typically employed to modify specific properties of light. By contrast, in scattering optics, a scattering medium can be engineered to function as a desired optical element only when its transmission matrix encodes the relevant functional relationship. For example, to configure a scattering medium as a polarization-selective device—such as a dynamically tunable waveplate—the polarization-dependent relationship between the input and output fields must be characterized.

Once the polarization-resolved transmission matrix is measured, optimized focal spots with orthogonal polarization states (p and s) can be generated at the same spatial location by displaying the appropriate modulation patterns on a spatial light modulator. Furthermore, selectively shifting the phase of the p-polarized focus while maintaining the phase of the s-polarized component enables continuous transformation of the focal polarization state from linear to circular. In this configuration, the scattering medium effectively functions as a reconfigurable polarization control element capable of generating arbitrary polarization states without any mechanical movement. Analogously, when the wavelength-dependent transmission matrix is measured, the same scattering medium can be repurposed to operate as a spectral analyzer.

Wavefront shaping–assisted scattering media can also be configured to function as optical circuits or beam splitters by incorporating multiple independent input channels. For example, Huisman *et al.* demonstrated programmable optical beam splitters using a layer of dry white paint in conjunction with wavefront shaping techniques. Two independent input beams were directed through the scattering layer to generate two enhanced focal spots at the output. Importantly, the relative intensity distribution between these spots could be continuously tuned by introducing a phase offset to either input beam. This principle has since been extended to realize multiport optical circuits and to enable precise control of quantum interference phenomena, highlighting the versatility of scattering media as reconfigurable optical elements when combined with wavefront shaping.

In a further innovative application, scattering media have been exploited as dynamic three-dimensional (3D) holographic display elements. Three-dimensional holographic displays represent a disruptive technology for next-generation display systems, enabling the reconstruction of dynamic volumetric scenes. Conventional holographic displays based on refractive optics are typically constrained to relatively small image sizes and limited viewing angles, primarily due to the restricted number of controllable modes available on wavefront modulators. These limitations prevent achievement of the high space–bandwidth product—defined as the product of the active aperture and viewing angle—required for large-scale, wide-angle holographic displays. This quantity, also referred to as étendue, remains constant for a single wavefront modulator when a lens-based configuration is used.

The introduction of a scattering medium fundamentally alters this constraint. Multiple scattering disrupts the ordered mapping between the input field on the wavefront modulator and the output field forming the holographic image, thereby breaking the conventional étendue limitation. Once this scrambled input–output relationship is characterized using transmission matrix approaches, the desired volumetric display can be reconstructed by displaying a precalculated modulation pattern on the spatial light modulator, resulting in substantially increased viewing angles and image sizes. Yu *et al.* demonstrated that the product of viewing angle and image size could be enhanced by a factor of approximately 2,600 through the incorporation of two holographic diffusers, compared with a configuration employing a single wavefront modulator. Two characters (“3D”), each composed of 15 focal points, were rendered on distinct output planes, spanning a large display volume while preserving high spatial resolution, with individual focal spots as small as 1 μm.

Reconfigurable Optical Computing Units

It is important to note that, in the scattering-based optical components discussed above, only a limited number of output channels are typically utilized, corresponding to the use of only a few rows of the transmission matrix. In contrast, a scattering medium inherently possesses a high-dimensional transmission matrix, and the absence of symmetry within such systems further increases its effective rank. By exploiting a larger set of output channels, a scattering medium can therefore be configured to perform significantly more complex operations, including functioning as a general linear operator, as proposed by Matthès *et al.* through the optimization of input–output projectors.

The underlying procedure can be summarized as follows. First, the complex-valued transmission matrix of the scattering medium is retrieved without interferometric measurements by employing a phase retrieval algorithm. Subsequently, a mixed-integer convex optimization solver is applied to determine an approximate input mode that minimizes the discrepancy between the target operator and the experimentally measured operator. Finally, once the optimal input mode is computed and implemented on a digital micromirror device (DMD) to perform optical analog computation, the scattering medium effectively realizes the desired linear operation, such as a Fourier transform operator. More recently, Yu *et al.* demonstrated that a single scattering medium, when combined with wavefront shaping, can be configured to perform fundamental optical logic operations. These findings highlight the substantial potential of scattering media empowered by wavefront shaping as a platform for developing reconfigurable optical computing units.

MODULATION OF MULTIMODE FIBERS VIA WAVEFRONT SHAPING

This section reviews wavefront shaping–based optical modulation in multimode fibers (MMFs), encompassing both linear and nonlinear regimes. The distinction between these regimes is determined by whether nonlinear optical processes are involved. Specifically, in the nonlinear regime, intrinsic effects within MMFs—such as stimulated Raman scattering and four-wave mixing—can be actively controlled through wavefront shaping. Furthermore, owing to the flexibility and small core diameters of MMFs, the integration of wavefront shaping techniques has enabled a range of distinctive and innovative implementations. In the final part of this section, two representative application areas—optical endoscopic imaging and optical tweezers—are discussed to illustrate the practical impact of these approaches.

Linear Modulation

When nonlinear optical processes are absent within a multimode fiber, the relationship between the input and output fields can be accurately described using a linear transmission matrix model. Within this framework, controlled focusing and raster scanning of the focal spot across the measured field of view can be achieved. This capability has enabled the development of multimode fiber endoscopes, through which *in vivo* imaging of neurons and blood cells in the mouse brain has been successfully demonstrated.

Moreover, the capacity to transform arbitrary spatial modes into well-defined focal spots at designated positions effectively allows a spatial light modulator–integrated multimode fiber to function as a mode sorter. By applying optimized phase masks, light coupled into specific spatial modes—including Fourier modes, Laguerre–Gaussian modes, random bases, and optical angular momentum states—can be selectively sorted through the multimode fiber.

Polarization scrambling in multimode fibers represents another significant challenge, arising from unavoidable fabrication imperfections and external perturbations. However, this issue can be effectively mitigated through precise control of the phase of the incident beam. Notably, mode coupling within multimode fibers—often regarded as a drawback—can instead be leveraged as an advantage for polarization control, as it provides a sufficiently large set of degrees of freedom to independently manipulate the polarization state at each output channel. By shaping the incident wavefront using a polarization-resolved transmission matrix, the polarization of the output can be actively tuned in a manner that is independent of the input polarization.

Nonlinear Modulation

Beyond the linear regime, spatiotemporal nonlinear effects in multimode fibers—particularly graded-index multimode fibers (GRIN-MMFs)—have attracted considerable interest for both fundamental studies and practical applications. In addition to their high energy-handling capability, GRIN-MMFs exhibit two distinctive characteristics: (1) reduced modal dispersion, whereby interactions among fiber modes are preserved over relatively long propagation distances, even in high-energy ultrafast regimes; and (2) spatial self-imaging, in which the beam width and intensity undergo periodic oscillations along the fiber, accompanied by longitudinal modulation of the refractive index induced by the Kerr effect.

When driven by high-power ultrafast pulses, GRIN-MMFs support a rich variety of nonlinear phenomena, including graded-index soliton formation, spatiotemporal instabilities, self-beam cleaning, and supercontinuum generation. Traditionally, control over these nonlinear dynamics has been achieved through manual adjustment of the coupling conditions between the input lens and the fiber. To enable more flexible and precise control, wavefront shaping can be employed to tailor the incident beam using a spatial light modulator, thereby allowing customization and dynamic regulation of nonlinear interactions within the fiber.

In the linear regime, the transmission matrix plays a central role in describing and controlling the input–output relationship of a multimode fiber. However, its applicability diminishes markedly when nonlinear optical effects become significant, necessitating modulation strategies that do not rely on linearity assumptions. To address this challenge, deep learning and optimization-based algorithms have been increasingly employed to harness and control nonlinear dynamics in multimode fibers.

For instance, deep neural networks (DNNs) have been trained to map a desired target spectrum to the corresponding input intensity distribution at the fiber entrance. Using such an approach, frequency conversion within a multimode fiber can be effectively achieved. The intensity patterns displayed on the spatial light modulator, as predicted by a well-trained network, yield experimentally generated Raman scattering and supercontinuum spectra that closely match the target spectral profiles. In parallel, adaptive optimization methods, such as genetic algorithms, have been demonstrated to steer nonlinear processes toward versatile spectral control. By iteratively evolving the phase patterns applied to the spatial light modulator, enhancements of specific nonlinear features—such as a sixfold increase in the four-wave mixing peak at 518 nm have been realized, along with wavelength-selective excitation of fundamental modes induced by stimulated Raman scattering. These techniques further enable flexible spectral manipulation, including controlled shifting or suppression of anti-Stokes components.

In more complex systems, such as multidimensional fiber lasers, nonlinear effects can likewise be managed by optimizing the input wavefront using appropriately defined cost functions. For example, under quasi-continuous-wave operation, the speckled output of a fiber laser can be reshaped into a Gaussian beam profile. Wavefront shaping has also been shown to facilitate mode locking, allowing precise control over pulse excitation, pulse duration, and the generation of multiple pulses. Collectively, these studies demonstrate the feasibility and versatility of wavefront shaping–assisted multimode fibers for nonlinear optical control. Although nonlinear excitation driven by pump fields involves complex underlying physical mechanisms, relevant physical information is implicitly encoded in the optimized wavefronts or modal distributions during the learning and optimization processes. This intrinsic adaptability significantly broadens the applicability of wavefront shaping across both linear and nonlinear optical regimes.

Multimode Fiber–Based Applications

Optical Endoscopic Imaging

Endoscopes are extensively employed in the medical diagnosis and treatment of internal tissues and organs. Implementations based on wavefront shaping–enabled multimode fibers offer the possibility of extreme probe miniaturization, with diameters below 100 μm, while alleviating the pixelation artifacts commonly encountered in fiber-bundle–based systems. As discussed earlier, calibration of the transmission matrix of a multimode fiber enables arbitrary light focusing and raster scanning at the distal fiber end. When these scanning foci are directed onto fluorescent markers positioned beyond the fiber tip, the resulting fluorescence emission from each focal point can be collected through the same fiber and processed to reconstruct an image.

This capability readily extends to *in vivo* imaging applications, as the compact form factor of multimode fibers is well suited for minimally invasive access to deep tissue regions. For instance, Piestun and colleagues demonstrated a single–multimode fiber endoscope and subsequently introduced an advanced endomicroscope design for imaging neural activity in biological specimens. Furthermore, in 2018, Cizmár and co-workers reported the first demonstration of *in vivo* deep-brain imaging using multimode fiber endoscopy, achieving subcellular spatial resolution.

Considerable efforts have been devoted not only to enhancing the spatial resolution and frame rate of multimode fiber–based endoscopes to support *in vivo* experimentation, but also to extending their working distance and field of view in order to improve practicality for real-world applications. For example, a recently reported far-field endoscopic system employing two multimode fibers—one for illumination and the other for signal collection—enabled reflectance imaging of distant macroscopic objects. In this configuration, the field of view scales linearly with the working distance, which can extend from tens to hundreds of millimeters. Using this approach, far-field imaging of three-dimensional natural scenes, such as a sweet pepper and a mechanical clock, was demonstrated. With further optimization, this technique holds promise for organ- or tissue-scale imaging applications. Moreover, the incorporation of time-of-flight information enables depth perception in macroscopic three-dimensional scenes, further expanding the capabilities of multimode fiber–based endoscopic imaging.

Despite their promise, the multimode fiber–based endoscopic techniques described above generally require prior calibration of the fiber and rely on the assumption of a mechanically rigid endoscope, with negligible deformation due to bending or twisting. To overcome this limitation, recent studies have explored the development of flexible multimode fiber endoscopes, in which the use of graded-index fibers reduces sensitivity to bending-induced perturbations. An alternative strategy involves *in situ* calibration of the multimode fiber using measurements acquired solely at the proximal end. Although conceptually attractive, such configurations remain technically demanding to implement. More recently, Li *et al.* proposed a simplified approach that leverages optical memory effects in structures with arbitrary geometries to efficiently estimate the transmission matrix, albeit with reduced accuracy. Multimode fiber–based endoscopes are also capable of integrating fluorescence and photoacoustic imaging modalities, enabling dual-modality imaging within a single ultrathin probe. A hybrid photoacoustic–fluorescence endomicroscope typically incorporates a multimode fiber for fluorescence excitation and collection, alongside a single-mode fiber dedicated to photoacoustic signal detection. Imaging results of red blood cells and fluorescent particles, demonstrate the feasibility and effectiveness of this compact hybrid configuration.

Optical Tweezers

Optical manipulation of biological systems using light-induced forces enables *in vivo* intervention without direct physical contact, thereby minimizing mechanical damage to living organisms. In this context, holographic optical tweezers can be implemented within biological tissues, where tightly focused laser beams generated through wavefront shaping permit precise manipulation of microscopic objects at depth. The compact form factor of multimode fibers further extends the operational depth of holographic optical tweezers while maintaining minimal invasiveness.

For instance, following characterization of the complex light propagation through a multimode fiber, individual microbeads can be selectively manipulated, or multiple particles—up to 16 microbeads on a single focal plane—can be simultaneously controlled by dynamically adjusting multifocal intensity distributions. A key limitation in multimode fiber–based optical tweezers, however, arises from the relatively low numerical aperture of standard multimode fibers, which restricts axial trapping capability because the axial gradient force is insufficient to counteract radiation pressure. To overcome this constraint, Leite *et al.* developed a soft-glass step-index multimode fiber with a numerical aperture increased to 0.96. The resulting high-quality output beam enables stable optical trapping in both lateral and axial dimensions, allowing particles to be confined into three-dimensional configurations, such as cubic arrays.

III. DISCUSSIONS AND PERSPECTIVES

Multiple light scattering has long been regarded as a fundamental limitation that degrades the performance of optical systems. This article has reviewed the emergence and rapid evolution of wavefront shaping techniques, which have opened numerous promising pathways for mitigating, controlling, or even exploiting multiple scattering to recover and enhance optical system performance. Before concluding, several additional points warrant further discussion and clarification.

As noted in the Introduction, wavefront shaping shares conceptual foundations with adaptive optics, a field with a longer history and a similar overarching objective: to enhance the transmission and/or reception of light in the presence of optical distortions. In both cases, spatial inhomogeneities in the refractive index constitute the primary source of aberrations. However, the severity of these distortions differs markedly between the two regimes, leading to fundamental differences in achievable performance. In adaptive optics, phase distortions are typically weak and can be efficiently represented using Zernike polynomials as a basis set, with low-order modes—generally up to the 20th–30th order—being sufficient to describe the dominant wavefront aberrations.

In contrast, wavefront shaping operates in regimes of substantially increased turbidity and severe wavefront distortion, where light undergoes multiple scattering events. Under such conditions, the number of modes required to characterize the input–output relationship of a scattering medium becomes exceedingly large. Specifically, the number of independent incident modes scales as $N = 2\pi A/\lambda^2$, where Adenotes the surface area of the medium and $\lambda$is the wavelength of light. Given that imaging inherently acts as a low-pass filtering process—where high spatial frequency information is lost and the number of sensor pixels is finite—it is practically infeasible to measure and control all scattering modes. Although wavefront shaping corrections involving several million modes have been demonstrated, this level of control remains far from complete. Consequently, current wavefront shaping implementations yield only a very small effective Strehl ratio, with the majority of optical energy residing in the background speckle rather than the corrected focus.

Nevertheless, multiple scattering does not imply an insurmountable loss of optical functionality. Although the Strehl ratio is of limited relevance in this regime, the optical intensity at a targeted focal region can be enhanced by factors as large as 10^5. Such substantial enhancement provides adequate contrast for a wide range of applications, including imaging, sensing, stimulation, therapeutic interventions, and information delivery, and may fundamentally transform the use of light for high-resolution operations at depth.

A further distinctive—and somewhat paradoxical—feature of wavefront shaping lies in the vast number of orthogonal modes generated through multiple scattering. Rather than being purely detrimental, this high modal diversity enables functionalities that are unattainable with conventional optical components. Traditional elements based on refraction or diffraction are typically engineered for specific, fixed purposes. In contrast, wavefront shaping leverages the complex mode mixing induced by multiple scattering to couple incident light into a multitude of output channels, which can be selectively accessed and reconfigured to realize a broad range of optical functions.

The transmission matrix of a scattering medium can be characterized across multiple optical degrees of freedom, including polarization, wavelength, spatial frequency, and angular momentum. Thus, multiple scattering—which initially appears as an irreversible scrambling of information into random speckle patterns—can instead be harnessed to sense, manipulate, and control these degrees of freedom, enabling a wide range of functionalities. Demonstrated examples include waveplates, spectrometers, near-field lenses, holographic displays and sensors, and orbital angular momentum demultiplexers. This paradigm stands in sharp contrast to conventional optical components, which must be precisely designed and fabricated to perform specific, fixed functions.

Furthermore, because the calibration and operation of wavefront shaping–based systems can be conducted under well-defined or application-optimized conditions, challenges related to medium stability and calibration time can be treated as design trade-offs, balanced against system complexity and cost. Recent advances, such as the introduction of metasurfaces and liquid-crystal geometric-phase diffusers, have been proposed to significantly reduce calibration time. Collectively, these developments suggest that practical and impactful applications of wavefront shaping—particularly in static or moderately dynamic environments—are approaching realization.

For bioimaging applications, further advances are required to fully exploit the potential of wavefront shaping. Because the overarching objective is non-invasive or minimally invasive *in vivo* imaging at substantial tissue depths, wavefront shaping systems must be carefully optimized to accommodate intrinsic biological constraints that cannot be relaxed. Several critical challenges remain.

First, living tissues are inherently dynamic, leading to temporal randomization of the transmission matrix. As a result, transmission matrix measurement or iterative optimization must be completed within the speckle decorrelation time of the tissue, which is on the order of milliseconds for many organs. Second, to enable rapid measurements, single-shot approaches—such as those based on Shack–Hartmann wavefront sensing—are often preferred. However, for deep-tissue imaging, Shack–Hartmann sensors are ineffective, as their operating principles fail when only speckle fields are available. Third, rapid acquisition of signals originating from deep tissue typically suffers from low signal-to-noise ratios, posing significant challenges for reliable calibration and optimization. Finally, the spatially heterogeneous distribution of cells and subcellular structures within biological tissue necessitates distinct wavefront corrections across different fields of view, further complicating the realization of fast imaging within the limited speckle decorrelation time.

Innovations in wavefront shaping have naturally concentrated on overcoming these challenges. To enable faster measurements and more efficient wavefront control, researchers have actively incorporated advances in optical hardware and control technologies. For example, wavefront modulators have evolved from liquid-crystal–on–silicon spatial light modulators to faster alternatives such as microelectromechanical system mirrors, digital micromirror devices, and micromechanical grating light valve technologies, driven by the need to match or exceed the rapid speckle decorrelation times characteristic of living biological tissues.

To further enhance spatial resolution and signal-to-noise ratios at depth *in vivo*, wavefront shaping has been extended to longer excitation wavelengths and combined with multiphoton microscopy. It should be noted that many of these advanced implementations have so far been demonstrated primarily at the proof-of-concept level. Nonetheless, sustained progress in integrating, refining, and scaling these approaches toward robust performance in realistic *in vivo* settings is expected to catalyze a second wave of development in wavefront shaping. Such advances have the potential to significantly reshape biomedical optical research and clinical practice at the tissue scale.

IV. Conclusions

Over the past fifteen years (2007–2022), the field of wavefront shaping has undergone rapid and transformative development across nearly all technological dimensions. The initial demonstration of generating a bright optical focus through scattering media was soon followed by image transmission through turbid environments based on the transmission matrix framework. Subsequent integration with internal guide stars—such as ultrasonically encoded light and photoacoustic emission—has enabled the creation of reference beacons at arbitrary locations deep within biological tissue using holographic techniques. Concurrently, substantial efforts have been directed toward accelerating measurement schemes and expanding the effective field of view.

To date, wavefront shaping represents the most promising—albeit still imperfect—approach for achieving noninvasive or minimally invasive optical-resolution functionality at significant tissue depths, where conventional methods fail due to the scarcity of ballistic or quasi-ballistic photons. Under such extreme scattering conditions, precise wavefront measurement and control are both essential and technically demanding. Despite these challenges, the rapid and sustained progress across multiple facets of wavefront shaping is highly encouraging. This advancement has been driven in part by the adaptation and further development of foundational concepts from related disciplines, including adaptive optics in astronomy, random matrix theory, and time-reversal techniques in acoustics. Moreover, ongoing advances in optimization algorithms and the increasing incorporation of deep learning are expected to play a pivotal role in enabling faster and more efficient wavefront shaping implementations.

Reflecting on both past achievements and future prospects, wavefront shaping holds significant promise for opening new avenues in noninvasive or minimally invasive optical interactions and for achieving precise control deep within biological tissues. The exceptionally high degrees of freedom afforded by multiple scattering and wavefront shaping also present unprecedented opportunities for the development of novel optical devices based on a single, generic or customized scattering medium—devices that may surpass the performance of traditional optical components. At present, the field stands at a critical juncture, transitioning from proof-of-principle demonstrations toward practical, real-world applications, with many exciting developments anticipated in the years ahead.

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