Towards ideal focusing of diffused light via optical wavefront shaping

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Multiple scattering can significantly scramble the amplitude and phase profile of an optical field. It obscures subtle observations but only speckle patterns can be seen, unlike the ballistic regime where the information or the optical field can be identified with limited distortions. Efficient optical manipulation including information transmission and precise focusing is therefore obstructed as light travels deep into turbid media such as fog, turbid fluids, and biological tissues.[1] Overcoming such seemingly notorious phenomena has long been desired in many scenarios yet considered highly challenging until the emergence of wavefront shaping (WFS).[2,3] The basic idea of this technology is to redirect the multiply scattered photons to the spatiotemporal coordinate(s) of interest such as optical focusing [Figs. 1(a) and 1(b)],

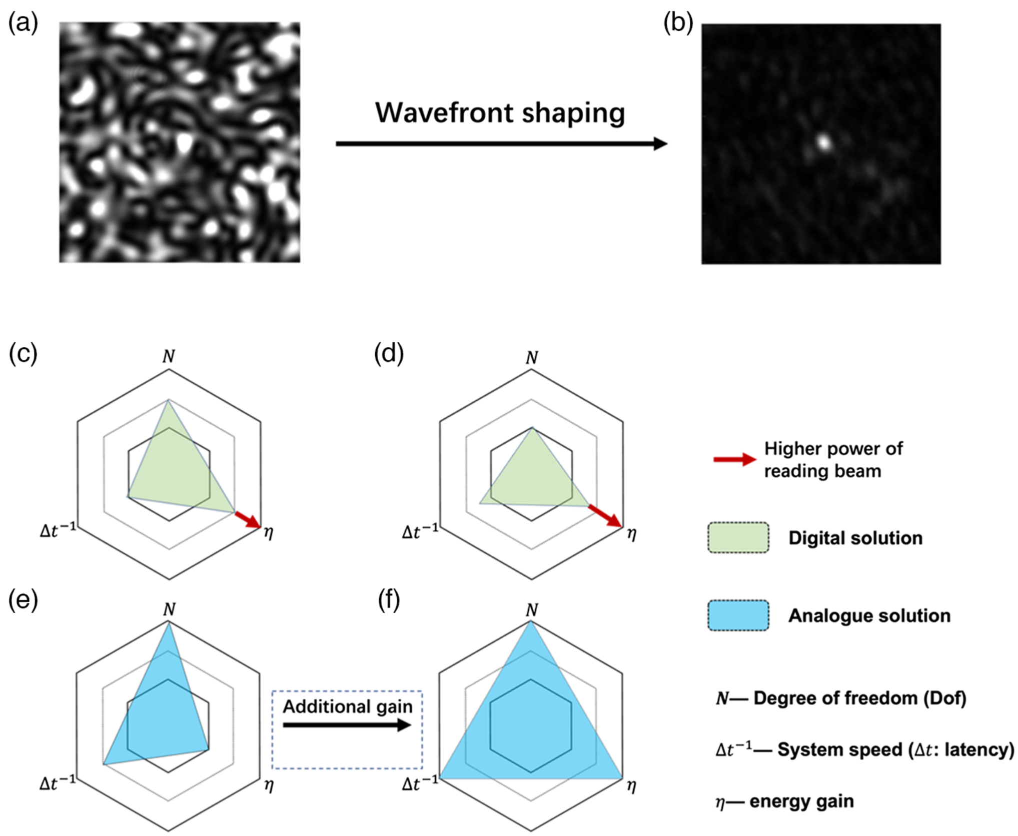

Fig. 1 (a), (b) An example of light intensity profiles before and after wavefront shaping. (c), (d) Performance metrics for an exampled DOPC system[4]: (c) more DoF ($\sim 10^6$) accompanied with longer latency ($\Delta t \sim 5.4$ ms) and higher gain; (d) less DoF ($\sim 10^5$) accompanied with shorter latency ($\Delta t \sim 1$ ms) and lower gain. The energy gain (theoretically > 1) can be increased by scaling up the power of the reading beam (red arrow). (e), (f) Performance metrics for an exampled AOPC system[5] : (e) DoF (can be up to 10^{10} – 10^{11}) and latency ($\Delta t \sim$ tens of microseconds) with energy gain $<10^{-3}$; (f) With additional gain enabled by the new setup, HGHS-WFS, energy gain and latency can be improved to 1.05 and 10 μs, respectively.

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by modulating or shaping the wavefront. Note that this commentary will particularly focus on the realizations based on optical phase conjugation (OPC) that essentially time-reverses the aforementioned scattering process via two stages: 1) the writing stage, in which a phase conjugated mirror (PCM) records the hologram interfered between a reference beam and the induced scattered light from a source and then both beams are turned off; 2) the reading stage, in which a third beam, namely reading beam, is modulated by the PCM, generating a wavefront conjugated copy of the original scattered light that traces back through the scattering medium and sequentially back to the origin of the source.

Depending on the characteristics of the PCM, there are two versions of OPC, digital and analogue OPC (i.e., DOPC and AOPC), whose key elements of PCM are a spatial light modulator (SLM) coupled with a conjugated camera and a photorefractive crystal (PRC), respectively. Nevertheless, intrinsic tradeoffs arise among the system speed, energy gain, and degree-of-freedom (DoF) control of the shaping unit [Figs. 1(c)–1(e)]. In DOPC, due to the functionality of the SLM, the increase of the DoF often leads to slower system speed, and vice versa. For example, in an identical DOPC system[4] [Figs. 1(c) and 1(d)], more DoF ($\sim 10^6$) is usually associated with larger latency ($\Delta t \sim 5.4$ ms), and less DoF ($\sim 10^5$) with lower latency ($\Delta t \sim 1$ ms). Yet, such compromise has been tolerated, thanks to an easy realization for increasing the energy gain (the power ratio between the corrected wavefront and that of the detected scattered wavefront) by raising the power of the reading beam. Reflectivity on an order of 10^{-1} for SLM makes it possible to achieve an energy gain larger than unity by merely increasing the power of the to-be-modulated wavefront illuminating the SLM (below the damage threshold of the SLM) in the reading stage. The DOPC solution has therefore gained wide visibility in wavefront shaping.[6–9] Comparably, in AOPC, the DoF and system speed are physically determined by the PRC but are weakly coupled: the DoF of PRC can reach $10^{10} - 10^{11}$ with holographic materials,[10] which is four to five orders more than that of digital SLM; the response time can be refined by selecting proper material and enhancing the illumination intensity.[5] Note that although the tradeoff between DoF and system speed can be avoided, the energy gain in AOPC is rather low, e.g., $<10^{-3}$ [Fig. 1(e)],[5,11] which is essentially limited by low nonlinear conjugation reflectivity of PRC ($\sim 10^{-3}$). This has considerably impeded wider advances of the approach.

Encouragingly, a very recent study by Cheng et al., from L.V. Wang's group at Caltech, termed high-gain and high-speed wavefront shaping (HGHS-WFS), returned AOPC to the community's attention.[5] This study technically evades the intrinsic drawback of PRC (i.e., low reflectivity) while introducing the concept of stimulated emission light amplification into the AOPC. Gain modules are added between the scattering medium and the PRC, so that both the scattered light before going into the PRC (in the writing stage) and the modulated wavefront out from the PRC (in the reading stage) can be effectively amplified. By doing so, even though the PRC still suffers from low reflectivity, its incident and outgoing components can be extraordinarily scaled up. The energy gain consequently approaches unity, which is about one thousand times of the gain obtained in previously reported AOPCs.[5,10–12] To further enhance the energy gain, the authors also demonstrated how to improve the reflectivity of the PRC, such as increasing the power of the reference and reading beams illuminating the PRC, applying external electric field across the PRC as well as the adoption of a four-wave mixing (FWM) mode. In particular, it is the first time for the FWM mode to be integrated in AOPC, in which the scattered and reference beams are continuously on throughout the period of writing and reading stages. Such intervention not only improves the OPC reflectivity but also accelerates the system speed to $\sim 10\ \mu s$ with $\sim 10^6$ DoF. Such phenomenal features ensure its high-gain and high-speed ability to overcome strong scattering and achieve effective optical focusing through thick and dynamic scattering media, such as a 4-mm thick chicken breast slice and a living mouse ear.

As demonstrated in this study, the most featured drawback, i.e., low energy gain, of AOPC system can be addressed with stimulated emission light amplification and multidimensionally improved reflectivity of the PRC. Equipped with the inherent fast response speed and large DoF of PRC, least tradeoff in controlling diffused light via wavefront shaping has been achieved [Fig. 1(f)]. Although further engineering is needed, the study removes one of the largest obstacles for optical wavefront shaping towards practical applications in biomedicine, such as optogenetics, microsurgery, and photodynamic therapy.

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