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Digital resonant laser printing: Bridging nanophotonic science and consumer products

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ABSTRACT

Nanophotonics research relies heavily on state-of-the-art and costly nano and microfabrication technologies. While such technologies are fairly mature, their implementation in large-scale manufacturing of photonic devices is not straightforward. This is a major roadblock for integrating nanophotonic functionalities, such as flat optics or high definition, ink-free color printing, into real life applications. In particular, optical metasurfaces – nanoscale textured surfaces with engineered optical properties – hold great potential for a myriad of such applications. Digital laser printing has recently been introduced as a low-cost lithography solution, which allows the fabrication of high-resolution features on optical substrates. By exploiting resonant opto-thermal modification of individual nanoscale elements, laser printing can achieve nanometer-sized resolution. In addition, the concept of digital resonant laser printing at the nanoscale supports mass-customization and may therefore convert nanophotonic science into everyday consumer products.

Photonic science drives our colorful world from medieval stained glass to interactive smart screens. Current technological breakthroughs, such as virtual and augmented reality and quantum computers, rely on manipulating light in a desired fashion. Enabled by nano and microfabrication technologies, nanophotonics research offers the ultimate control of light with the help of nanoscale metallic or dielectric structures. One example is functional metasurfaces [1,2] with structured meta-atoms, which use either plasmonic or high-index dielectric materials for, e.g., color generation [3–5], flat optics [6], or invisibility cloaking [7]. Metasurfaces rely on the ability to precisely control its individual meta-atoms, including material and morphology composition, geometry, orientation, and the mutual position of all meta-atoms. By full spatial control over light, metasurfaces allow for engineering scattering spectra as well as the optical wave-front. Metasurfaces are commonly realized by complex nanofabrication techniques for master origination. This is an obstacle to reach consumer products.

A digital resonant laser printing (DRLP) technique was recently developed as a flexible post-writing technology for mass-customization of optical meta-surfaces [8–10] (Fig. 1). Strong on-resonance energy absorption under pulsed laser irradiation locally elevates the lattice temperature of individual meta-atoms in an ultra-short time scale [11]. This was demonstrated for both plasmonic [12–14], and high-index dielectric meta-surfaces [9]. In the DRLP process, rapid melting allows for surface-energy-driven morphology changes and sintering/annealing [15] of individual meta-atoms with associated modification of amplitude, phase and polarization of the reflected and transmitted light from the metasurface. Combined with the use of large-area metasurface templates [16,17], DRLP is a promising approach for low-cost customized photonic devices with subwavelength elements for applications in areas such as holograms, anti-counterfeit and virtual reality.

Metal surfaces have already been successfully modified [18] and colourized with femto and picosecond laser pulses [19,20] or CO_2 lasers [21]. High-density information storage has also been explored by laser heating of gold nanorods dispersed in layered polymers [22]. Further immediate applications of DRLP include fabrication of flat lenses (metalenses) with large numerical aperture

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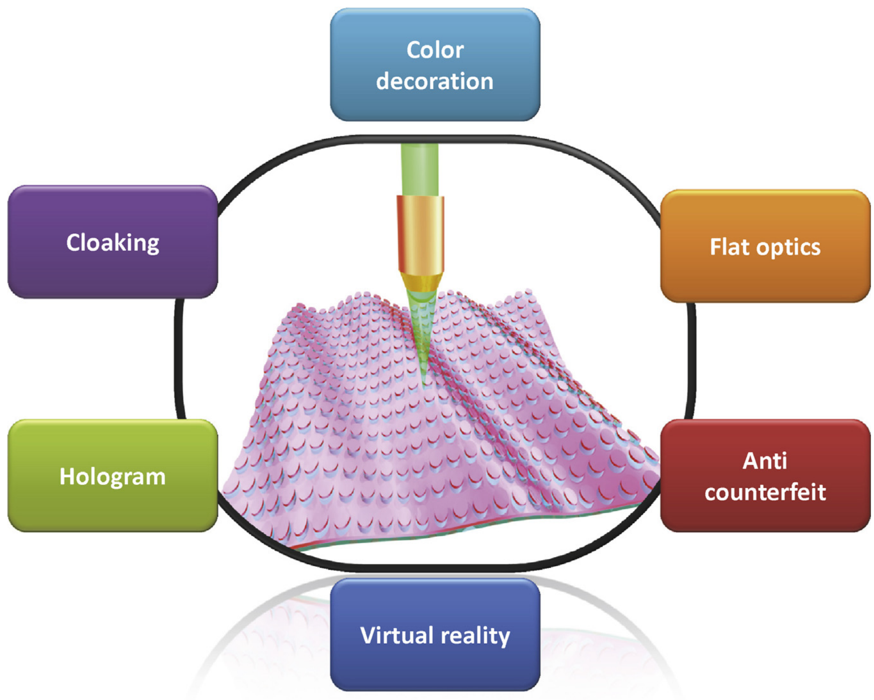

Fig. 1. Digital resonant laser printing holds potential for large-scale processing of optical metasurfaces, with the potential to levitate nanophotonics to new levels where it may enter a myriad of real-life applications.

[23] without use of expensive and time-consuming electron-beam lithography. Laser-written large-area metasurfaces can also be implemented in solar cells and photodetectors to increase performance without the concomitant dramatic increase in price.

Besides the significant benefits in applied research, DRLP also opens new avenues in fundamental research in nanophotonics. In addition to morphological changes of plasmonic nanostructures [24–26], DRLP allows for changing the crystallinity of the meta-atom material. Nanosecond laser pulses can change silicon meta-atoms from amorphous to crystalline [27], which is accompanied by a large change in the refractive index. This phase change is reversible [28], allowing for rewritable metasurfaces – a topic currently being pursued with more traditional phase-change materials [29]. Fabrication of meta-atoms made from alloys is an alternative approach. Targeting only one of the materials with the laser, the meta-atom composition, and thereby the optical response, can be gradually controlled. Multimaterial meta-atom designs are largely unexplored, but have potential for realizing hyperbolic metasurfaces [30] for quantum-information applications [31].

Looking beyond photonics, we anticipate application wherein the nanoscale manipulation of the structure or constituents of a compound is desired. As an example, the resonant nature of DRLP can be used in polymer welding for expanding the material selection from traditional absorbing polymers [32] or polymer-metal composites [33] to non-absorbing or additive-free counterparts. This allows for polymer welding without toxic elements, important for e.g. bio-medical applications [34]. Localized de-alloying of solid solution alloys – selective corrosion of one or more elements of alloys – can be realized in fraction of seconds by DRLP (contrasting slow chemical methods [35]). Likewise, pre-defined porous substance with extremely high surface area and low refractive index can be realized. The former can be profound for applications in catalysis [36] and surface chemistry [37], while the latter is highly desired e.g. for anti-reflective coatings in solar cells [38]. The high temperature in DRLP can also be exploited to locally oxidize or nitridize metals to locally functionalize otherwise passive films. For instance, localized oxidation of titanium via DRLP can be used to construct smart surfaces where the wettability can be tailored on the nanoscale: Pure titanium is hydrophilic, while DRLP-written titanium oxide areas are hydrophobic. Such surfaces can find application as anti-icing (icephobic) surfaces among others [39].

Post-processing large areas of nanostructures is highly desirable for adaptable and low-cost applications, which can have a strong impact on the industrialization of these devices. The diversity of the nanophotonic products naturally requests the development of efficient, universal and high-quality technologies, which should also be ready for the production-chain in industry. With the sub-diffraction-limited precision and the ultrafast feature, high-performance DRLP may be a game-changer in enabling, controlling, and enhancing the nowadays nanophotonic devices as well as other fundamental and functional applications.

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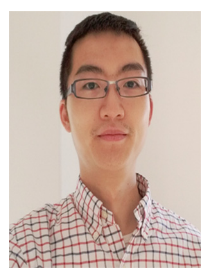

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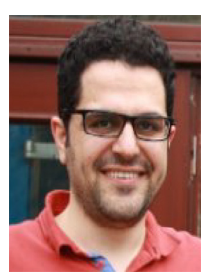

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