Nano-optics gets practical

Early-career researchers share their thoughts on how to make use of the ability to manipulate light at the nanoscale.

The advent of nanotechnology has allowed scientists to study light–matter interactions at the nanoscale. A considerable amount of fundamental knowledge has accumulated in the past two decades and the field of nano-optics may now in fact be on the cusp of delivering on practical applications in a variety of areas. This collection of short opinion pieces provides a glimpse of these technological possibilities and a preview of what we might expect.

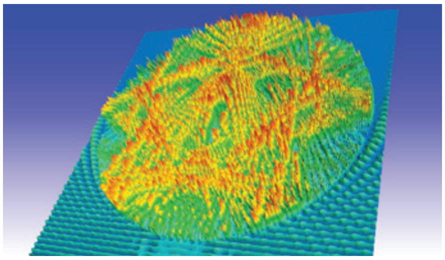
Chaotic energy harvesting

Chaos is a natural phenomenon that affects systems of all scales, from micro-organisms to galaxies. When an infinitesimal perturbation is applied to a chaotic system, the resulting time evolution can diverge exponentially from that of an unperturbed system, which makes it almost impossible to predict the system's future state beyond a specific timescale. This unpredictability defines chaotic behaviour even in the absence of randomness (that is, for systems that are completely deterministic). A case in point is weather forecasting, for which round-off errors in numerical computations of deterministic models are strongly amplified by chaos, thus limiting weather predictability to just a few days. Although controlling such unpredictable dynamics may seem daunting, billions of years of natural evolution have enabled pathways whereby chaos has been turned into a powerful ally. For example, *Cyphochilus* beetles have developed sophisticated camouflage strategies that rely on controlling complex processes of chaotic light scattering to generate brilliant shells that keep predators away.

Understanding and harnessing the chaotic dynamics of light could be essential for devising scalable energy-harvesting systems. Recent theoretical and experimental work has demonstrated how optical resonators, whose shape is suitably deformed to support the chaotic motion of light rays, can store energy from a broadband range of frequencies with unprecedented efficiency[1,2]. The resulting effect is the optical analogue of the Brownian motion of particles in liquid suspensions, wherein irreversible diffusion leads the system towards a uniform concentration of particles. In the optical system, each incoming frequency acts as a 'particle' that undergoes Brownian motion due to the chaotic scattering of light inside the cavity. Chaos leads to the irreversible 'diffusion' of light, which reaches an equilibrium configuration where each electromagnetic frequency becomes equally trapped inside the cavity. Under broadband illumination, the optical cavity absorbs the same quantity of energy from every frequency of the incoming radiation, which leads to dramatic energy build-up. Non-chaotic cavities with classical shapes do not manifest such constructive dynamics, and they can efficiently absorb light only in narrow regions of the spectrum[1]. Chaos, in this respect, provides a natural mechanism for overcoming the intrinsic limitations of these systems.

This chaos-enhanced energy-storage mechanism can in principle enable the design of nanostructures for efficient energy harvesting because it is not limited to any specific scale. For example, by optimizing chaotic light scattering in chaotic cavities made of gold nanoparticles with asymmetric shapes, it has been possible to design an absorber in the visible range that behaves as an almost ideal black-body (>99% energy absorption in the range 300–700 nm under all possible illumination angles). The nanomaterial, which mimics the *Cyphochilus* beetle shell, is completely disordered and fully compatible with standard photovoltaic technology, which makes it cost effective for large-scale fabrication. Prototype solar modules that exploit chaotic harvesting can increase efficiencies by more than 30%[3].

Chaotic energy harvesting could also be a promising approach for thermovoltaic technologies, wherein thermal emission from the Sun is converted into electricity by a heat absorber[4]. A significant drawback of such devices is the fact that heat absorbers — usually carbon nanotubes — are very sensitive to the angle of incident illumination[5]. The chaotic trapping of light, in contrast, takes place at any incidence condition, thus in principle allowing the design of efficient thermovoltaic modules that are not constrained by orientation. ❐



Surface plot showing the electromagnetic energy distribution of a chaotic resonator. Data from ref. 1.

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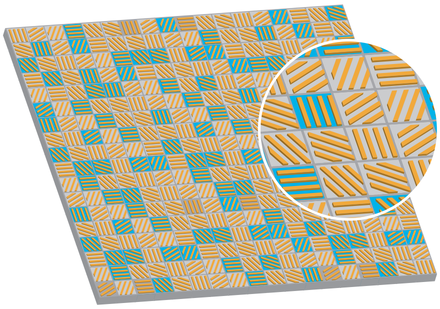
Metasurfaces for informed optics

Nanophotonics is often seen as a bridge between nanoscale electronics and high-bandwidth photonics. However, recent advances are beginning to reveal another way in which nanophotonics can impact information technology: as a means of transforming the data encoded by optical signals.

Typical optical elements are already capable of mathematical manipulation, such as the Fourier transform performed by a lens. In communication technology, we often want to perform more complex, real-time transformations to make a given signal better suited to a specific task or further electronic manipulation. Such dynamic transformations are currently the domain of adaptive optics, in which these tasks are performed using spatial light modulators or deformable mirrors. Such optical elements are, however, too bulky for incorporation into compact platforms, and their large pixel sizes limit the resolution at which they can manipulate a wavefront.

Adaptive optics hinges on the ability to control the amplitude, phase and polarization of light. This capability



Reconfigurable metasurface with individual pixels that consist of subwavelength gratings on top of a phase-change layer in either metallic (silver) or insulating (blue) state.

may be achieved using two-dimensional metasurfaces, in which the scattered light from engineered nanostructures can be carefully manipulated[6]. Recent results have provided a layout by which metasurfaces can perform complex signal processing, such as convolution, differentiation and integration[7]. Adaptive metasurfaces that incorporate phase-change materials[8,9] could allow for even more advanced optical manipulations, such as aberration correction for deep-tissue imaging[10] and, in principle, any general linear optical transformation.

Adaptive metasurfaces may provide new hardware for information optics, but it is how these tools are implemented and integrated that will ultimately dictate their technological success. As recently proposed by David Miller, the sequential use of dynamic elements that control phase and amplitude is sufficient to decompose an optical signal without any *a priori* information through an optical analogue of singular value decomposition[11]. This algorithmic approach can achieve optimal coupling between sources and receivers, which is an important problem in communication systems. For example, it could be used to isolate the numerous communication channels in a multimode optical fibre while reducing alignment tolerances. This phase and amplitude engineering could be realized by exploiting the collective effects of dielectric or metallic scatterers on a metasurface[12].

Similar algorithmic approaches may help to expand the range of optical signal processing in other fields, such as imaging and sensing. For example, optical transformations akin to singular value decomposition could be designed to discriminate between spectral signatures of specific gases. Thus, rather than using a high-resolution spectrometer to separate gas signals from an environmental background, a metasurface filter could project spectral signals matching specific analytes to distinct pixels of a photodetector array. To improve the signal-to-noise ratio, transformations that exploit natural correlations between energy, momentum and polarization distributions in the optical field could be used to decouple — and thus optimize — resolution and throughput[13]. Ultimately, however, the most attractive feature of adaptive metasurfaces is their potential use for low-cost devices where size matters most, such as *in vivo* biomedical monitoring and remote sensing. ❐

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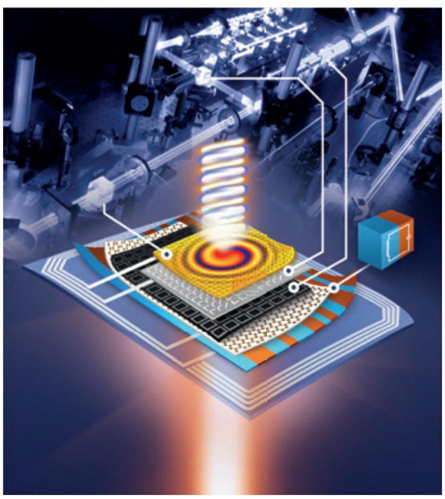
Optical metasurfaces for the real world

In the seventeenth century, Christian Huygens proposed an intuitive explanation for the gradual phase accumulation observed during light propagation in bulk materials: the wavefront of light at time $t + \Delta t$ is given by the envelope of spherical wavelets emanating from every point on the wavefront at time t. This wave-like description of light, which at the time was essential for explaining the effects of reflection and refraction, is still helpful today for illustrating the optical response of a new type of artificial interface — metasurfaces. Acting as subwavelength light converters with controllable optical responses, metasurfaces consist of of two-dimensional arrangements of modular subwavelength resonators, each individually designed to trap and release light in line with Huygens's principle. It is therefore possible to engineer the local surface impedance without relying on simple propagation, by modifying the phase, amplitude and polarization of light that passes through or is reflected from a metasurface[14].



PATRICE GENEVET/SIMTECH AND STEPHANE HUSSER

Artist's rendition of a lab-on-a-surface circuit, comprising a stack of subwavelength optical layers individually addressed by an electric signal.

This concept has been intensely investigated over the past few years, and has resulted in a variety of devices that are ultrathin compared with the wavelength of the incoming light, including 60-nm-thin lenses[15,16]. By combining several optical functionalities at an interface, or assembling a few of these layers, it might be possible to create ultrathin components that can control light with higher efficiency or perform sophisticated mathematical operations on the wavefront[7].

To become practical, however, this technology must overcome a number of challenges during its transition from laboratory to industry. The metasurface-based devices reported so far are limited in terms of practical use because of their low light throughput, large chromatic aberrations, and narrow tunability and reconfigurability. These issues must be addressed at the most fundamental and technological level by, for example, choosing materials with the most suitable properties, or leveraging the near-field coupling mechanism between neighbouring resonators or using nanostructures that operate on several modes. Pushing this technology towards real-world applications at visible wavelengths brings yet more challenges: metallic nanostructures experience plasmonic responses at these frequencies, which makes metasurfaces lossy and difficult to design. To cope successfully with these problems, other types of low-loss optical resonator, such as dielectric or group III–V semiconductors, are currently being investigated[17].

Considering the time and effort required to cover large areas with elements of nanometre-scale spatial resolution, it could be reasonably contended that the traditional refractive approach is better suited for making everyday components. But because the fabrication process of metasurfaces is planar, it can be integrated with other cost-effective large-scale manufacturing techniques, such as microchip manufacturing, nanoimprinting, injection moulding, soft lithography, and laser-assisted and directed self-assembly lithography[18,19]. As an emerging technology conceived for patterning features measuring tens of nanometres over large areas at rates of metres-per-minute, roll-to-roll nanoimprinting can replicate billions of identical nanodevices on various types of substrate. By combining this technology with reconfigurable nanofabrication on curved surfaces, it might be possible to deliver creative solutions for the on-demand, roll-to-roll manufacturing of metasurfaces.

Going beyond refractive and diffractive technology, the metasurface approach has the potential to transform and perhaps revolutionize the field of optics; we have only just begun to scratch the surface of its capabilities[20]. However, if this technology is to have a realistic chance of impacting our way of life, we must develop devices tailored for specific large-scale applications. Exciting prospects can be envisioned, such as at the intersection between metasurfaces and wearable devices or two-dimensional and stretchable electronics. Metasurfaces can also be expected to play a pervasive role in imaging and sensing. ❐

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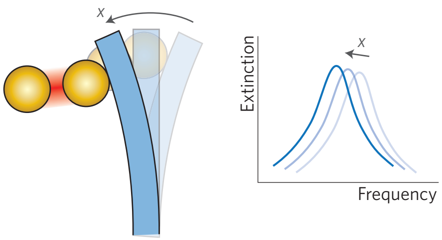
Plasmons in motion

The optical response of a plasmonic system can depend strongly on the displacements of its constituent nanoscale objects. This property makes it possible to establish an extremely strong coupling between light and nanomechanical motion, which can be exploited in two ways. First, optical properties can be finely tuned by mechanical motion. This is used, for example, to create metamaterials with a reconfigurable response[21]. Second, plasmonic fields can generate strong mechanical forces, such as those exploited in nano-optical tweezers[22]. Through these interactions, surface plasmons can be coupled to micro- and nanomechanical resonators[23], which are widely used as compact force- and mass-sensors[24]. Plasmon–mechanical coupling offers new ways to actuate nanomechanical resonators and to transduce their motion to a measurable optical signal with high sensitivity and low power.

A mechanical resonator coupled to a plasmon resonance essentially forms a cavity-optomechanical system[25]. A simple example is a plasmonic dimer antenna, which consists of two metallic particles, one of which is attached to a small mechanical resonator. The plasmon resonance frequency shift induced by the displacement of the mechanical resonator is an indicator of the strength of the optomechanical coupling. A point-dipole approximation estimates that this coupling parameter can be as large as ~3 THz per nanometre of displacement for



Plasmonic optomechanical system in which a mechanical resonator mediates the interparticle separation and therefore the resonance frequency of the plasmonic dimer nanoantenna.

40-nm-diameter gold particles placed 60 nm apart. Similarly, the dispersion of surface plasmons excited with 600 nm light in a 30-nm-wide gap between two silver surfaces is shifted by ~5 THz for a change in gap width of 1 nm. These frequency shifts are at least an order of magnitude larger than in any other dielectric system[25], and they also determine the force exerted by each photon on the resonator. In other geometries, plasmonic optomechanical coupling can take alternative guises, such as pronounced changes of radiative linewidth or local field distribution.

The sensitivity of a resonant transducer depends not only on the coupling strength, but also on the optical quality factor of the resonator. Unavoidable losses usually result in modest quality factors for plasmonic systems. However, the large optical bandwidth conversely allows straightforward frequency-matching between source and system, as well as the ability to address many resonators simultaneously[26]. Indeed, challenges in nanomechanical sensing are nowadays focused on the massively parallel readout of resonators in large arrays[24]. In this sense, the efficient coupling of plasmons to free-space radiation makes the plasmonic transduction of motion extremely appealing. Importantly, the deep-subwavelength size of plasmonic transducers means that the dimensions of the mechanical system can be reduced to tens of nanometres, without incurring a penalty in coupling strength.

The implications of plasmonic optomechanics go beyond mechanical sensing. The possibility to miniaturize and integrate arrays of plasmonic optomechanical systems can lead to the fabrication of nano-optomechanical metamaterials, in which many acoustic and optical degrees of freedom can interact strongly. Recent proof-of-principle demonstrations have also shown the possibility to study thermoplasmonic effects[27]. Moreover, the presence of metals in plasmonic devices provides another interesting direction for future investigations: the use of plasmon–mechanical interactions for electro-optic modulation at extremely low voltages[28] and efficient, broadband conversion between electrical and optical signals. ❐

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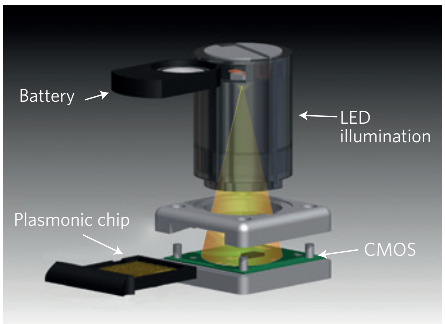
Chasing the ideal biosensor

New healthcare initiatives such as personalized medicine, global healthcare, point-of-care and early disease diagnostics demand breakthrough developments in biosensors. The recent Ebola epidemic, for example, clearly illustrates how the rapid detection and surveillance of infectious pathogens remains a significant challenge in resource-limited settings. In such cases, it should be possible to screen suspected patients rapidly using a minimal amount of biofluid, preferably outside of existing hospital support. Unfortunately, today's biosensors are unsuitable for decentralized and personalized patient control in the field because they are costly, bulky and require several days for a trained laboratory professional, working in a relatively advanced infrastructure, to obtain a result.

Surface plasmon resonance sensors — already considered to be the gold standard for label-free biosensing — can meet the requirements for next-generation biosensor technologies. In particular, metallic nanostructures with defined shapes and arrangements whose dimensions are smaller than the wavelength of light are fuelling significant excitement in the field. This is because of their unique ability to scatter and absorb light with efficiencies many orders of magnitude larger than dielectric nanoparticles and dye molecules, as well as their ability to confine and enhance electromagnetic radiation at the nanometre



A handheld plasmonic biosensor for high-throughput, point-of-care diagnostics. Image reproduced from ref. 33, 2014 Nature Publishing Group.

scale. Metallic nanoparticles are, for example, already being used in pregnancy tests and photothermal ablation therapy for cancer treatment[29].

Nanohole-perforated metallic films that support extraordinary optical transmission (EOT) are highly promising plasmonic structures for biosensing[30]. The resonance condition of EOT is very sensitive to the optical refractive index of the environment near the surface of the device. The nanoholes can be functionalized with biomolecules to provide biospecificity; when target analytes bind to them the effective refractive index of the medium increases and the EOT spectrum redshifts. The magnitude of this spectral shift is proportional to the amount of molecules bound to the sensor surface. This enables quantitative refractometric biosensing, which has been successfully used, for example, to detect live pseudo-Ebola viruses at medically relevant concentrations[31]. Furthermore, coherent interference between the propagating and evanescent modes of the nanoholes can be used to excite ultrasharp asymmetric Fano resonances, which offers the possibility to detect single monolayers of biomolecules with the naked eye[32].

Compared with conventional surface plasmon resonance sensors, the nanohole array eliminates the need for a prism to excite plasmons, thus enabling the excitation and detection of the EOT signal in the same optical path. In many cases, the use of gratings to couple the far-field light source to the surface plasmon modes significantly simplifies the optical requirements of the system and reduces the sensor footprint, thereby increasing its ability to detect multiple analytes simultaneously. Recently, researchers integrated a plasmonic protein microarray with a lens-free on-chip microscope to create a compact, handheld and high-throughput biosensor that uses a low-cost LED source and a CMOS camera for operation[33]. Such new sensors could be particularly desirable for screening large numbers of disease biomarkers for the early identification of infections and point-of-care applications.

Plasmonic biosensors have evolved quickly in recent years. Further significant innovations are expected in the future, given the advances in low-cost and large-area nanofabrication methods, the use of alternative materials, and the integration of plasmonics with nano/microscale fluidic and electromechanical systems. ❒

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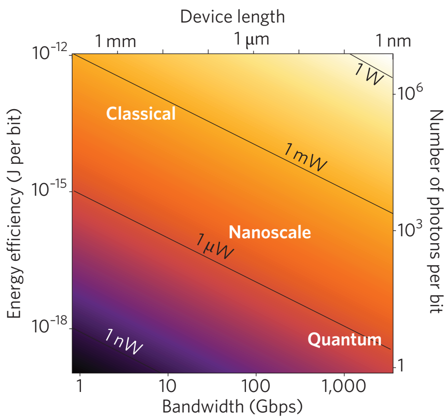
Plasmon modulators

The performance of today's computing devices is increasingly limited by two issues: the inability of input–output rates to keep pace with the ability of computing cores to process logic; and the high energy required to send a bit of information. Large data bandwidth and low power consumption can, however, be achieved using photonic interconnects, and the path to practical applications involves implementing optical connections; first between server boards, then between cores, and potentially intra-cores.

For such future links, the electric-to-optical conversion of data can be achieved by either modulating the light source directly or using an electro-optic modulator (EOM) — a three-terminal device that resembles a transistor with an optical source and drain, and an electrical gate that modulates the refractive index of the optical propagating mode. For EOMs, the objective is to fabricate subwavelength devices without sacrificing performance. A compact areal footprint is vital because it implies small electrical capacitance, which results in a low energy-per-bit ratio and high modulation speed. There is, however, a difference of around three orders of magnitude in the wavelength of telecommunications photons and the electrons of the active material, which leads to a weak light–matter interaction. This fundamental limit impedes device miniaturization unless modulation efficiency is compromised. With today's technologies, powering just tens of optoelectronic devices at relatively low data rates requires milliwatts of optical power. A second challenge for EOMs is the choice of modulation mechanism and the subsequent integration of active material into manufacturing processes. To this end, researchers have recently showed strong tunable optical modulation using free carriers in silicon[34] and indium tin oxide[35], quantum-confined Stark effects in germanium[36] and permittivity-tuning in graphene[37]. For example, researchers have used indium tin oxide and hybrid plasmonics to fabricate modulators that are around 100 times more efficient than previous approaches[35].



Technological regimes and limits of electro-optic modulators.

Despite fundamental physical challenges, such as the diffraction limit of light and the weak light–matter interaction, encouraging opportunities for the realization of high-performance EOMs are beginning to emerge; the light–matter interaction can be enhanced by increasing the optical field intensity and/or the density of states overlapping with the switching material. One realistic approach is to increase the optical field density by employing devices that operate without resonance effects (slot[38] or plasmonic waveguides[35]), while also increasing the optical density of states through the use of low-quality-factor resonators. (High-quality-factor resonators are not a viable option because they have slow modulation speeds due to long photon lifetimes[34].) Furthermore, the ability of metallic surfaces to confine electromagnetic fields in nanoscale spots can be exploited to overcome the diffraction limit of light and thus optimize electrical connections, which facilitates heat dissipation. Such EOMs have wavelength-scale dimensions (~1 μm), low power consumption (<1 fJ bit^{-1}), fast response times (>100 Gbit s^{-1}) and operate spectrally across a broad wavelength range. In these devices, the required optical power level is reduced from ~1 mW ('classical') to ~1 μW ('nanoscale') — a technological leap that should save 10^3 photons per bit per device.

In the ultimate physical limit, an EOM would behave as a capacitive switching element (comprising either a single quantum dot or an atom) that would be driven by a single electron charge consuming only 160 zJ bit^{-1}. These devices would be working in the 'quantum' regime (1–10 photons per bit), and could be electrically driven at frequencies of around 1,000 Gbit s^{-1}. Before getting there, however, we will need to achieve better strategies for enhancing the light–matter interaction by concentrating light into tighter spots, and address the issue of losses due to photon–electron mode mismatching and incompatibilities linked to light polarization effects. ❒

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Colouring at the nanoscale

Nicky Dean

The increasing miniaturization and resolution of consumer electronics poses quandaries for generating colour in imaging devices, which plasmonic nanostructures may be able to overcome.

Digital cameras are getting smaller and producing better quality images all the time. A large part of this success is down to advances in the technology behind the image sensor, which now have pixels that are just a few micrometres in size. But the current technology uses colour filters based on dyes and this approach may not withstand further shrinking because of the way the sensor handles colour information. The drive towards ever higher resolution displays is hampered by similar concerns, as pixel sizes shrink and screen sizes grow. Fortunately, plasmonic colour pixels could offer a solution for both of these technologies.

Typical digital cameras use either CCD (charge-coupled device) or CMOS (complementary metal–oxide–semiconductor) imager arrays to turn the incoming light into electrical signals. CMOS arrays are an example of active-pixel arrays, in which each pixel contains a photodetector with an active amplifier. They are more common than CCDs for regular consumer electronics, as they tend to be cheaper and consume less electricity. But regardless of which system is employed, the pixel array can only record intensity information — any knowledge of the wavelength or polarization of the light is lost once it is absorbed by the imager. To produce colour images, an array of colour filters is placed over the imager. Each colour filter in the array records intensity information within a given wavelength range, covering red, green and blue (RGB), and assigns a specific colour to each pixel. Finally, computational algorithms process the light intensity information for each colour channel into a full-colour image.

Figure 1 | An image captured using a commercial CMOS camera but with a plasmonic colour filter array instead of the standard dye-based one, after full computational reconstruction and signal processing. Reproduced with permission from ref. 12, © 2013 American Chemical Society.

Ordinarily these colour-filter arrays are fabricated using dye-doped polymers, with each dye individually tailored for each colour channel. But as the size of the pixel shrinks, this approach becomes increasingly plagued by problems. First, the spacing between the colour array and the imager (which lies at the bottom of the structure) becomes smaller, meaning that the filters become less efficient at collecting and guiding light down to the photodetector. Second, crosstalk between adjacent pixels caused by scattering becomes a bigger proportion of the total signal, causing colour information to be muddied and lost in the final image. Moreover, the fabrication of the dye filter requires numerous processing steps and becomes more prone to imperfections and inefficiencies as the dimensions of the pixels shrink, especially with pixels now at the wavelength scale.

A plasmon has a resonant frequency that depends on the metal used and on the particulars of the nanostructured features on the surface. Early attempts at exploiting plasmonics for colour pixels came in 2001 and used subwavelength grid nanostructures fabricated on top of CMOS active-pixel sensors (with lateral dimension of 0.18 μm) for imaging in