Research article

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Non-linear interferometry with infrared metasurfaces

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Abstract: The optical elements comprised of sub-diffractive light scatterers, or metasurfaces, hold a promise to reduce the footprint and unfold new functionalities of optical devices. A particular interest is focused on metasurfaces for manipulation of phase and amplitude of light beams. Characterisation of metasurfaces can be performed using interferometry, which, however, may be cumbersome, specifically in the infrared (IR) range. Here, we realise a new method for characterising metasurfaces operating in the telecom IR range using accessible components for visible light. Correlated IR and visible photons are launched into a non-linear interferometer so that the phase profile, imposed by the metasurface on the IR photons, modifies the interference at the visible photon

wavelength. Furthermore, we show that this concept can be used for broadband manipulation of the intensity profile of a visible beam using a single IR metasurface. Our method unfolds the potential of quantum interferometry for the characterization of advanced optical elements.

Keywords: dielectric metasurface; induced coherence; non-linear interferometer; non-local interaction; single photons.

1 Introduction

Planar optical elements based on sub-wavelength light scatterers, referred to as metasurfaces, have gained significant interest over the last few years. They can introduce abrupt local changes in the amplitude, polarization, and phase of a light wave, either actively or passively [1–7]. Stemming from the sub-wavelength size of their constituting parts, they are capable of modifying wavefront profiles with much higher spatial resolution and smaller form factor than conventional diffractive optical elements and spatial light modulators (SLMs) [7–10]. In particular, metasurfaces made of high refractive index dielectric materials benefit from low optical loss, compatibility with industrial fabrication processes (e.g. CMOS), and distinctive resonance behaviour [11, 12]. That is why metasurfaces hold a promise to serve as enabling components for the next generation of optical devices for augmented and virtual reality, microscopy, imaging, optical communications, and many others.

One of the main uses of metasurfaces is the control of the phase profile of a beam. Characterisation of the phase, encoded by such metasurfaces, can be performed e.g. by interferometry [8, 13, 14]. In these experiments, the probe beam, which reflects from (or passes through) the metasurface, is overlapped with a reference beam. The resulting interference pattern reveals the phase distribution imposed by the metasurface onto the incident beam. While interferometric measurements in the visible range are rather straightforward, measurements in the infrared (IR) have

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practical challenges. They are associated with the limited efficiency and tunability, high noise, and high cost of IR light sources and array photodetectors. With the rapid developments and deployment of IR metasurfaces, there is an urgent need for new methods for their accurate characterization.

There is a growing interest in the use of methods of non-linear and quantum optics for studying structured beams. An interesting approach is based on non-linear frequency mixing using the second harmonic generation (SHG) or the sum-frequency generation (SFG) processes. Both methods bring detection from IR to visible range [15–18]. These techniques involve two beams from two IR lasers (SFG) or a split beam of the IR pump (SHG), where one beam is structured while another one is used as a reference. The two beams are then combined at the non-linear crystal so that the resulting SFG or SHG signal carries the information about the phase or amplitude profile of the structured beam. While the method negates the need for the IR array detector, it still requires a relatively powerful pulsed IR-range laser. Furthermore, measurements at different wavelengths require sophisticated tuneable lasers. The use of metasurfaces in quantum optics has also been demonstrated in several recent works [19–23]. They include novel schemes for efficient generation, manipulation, and measurement of entangled states of light.

Here, we develop a new approach for characterisation of metasurfaces, and non-local manipulation of the angular momentum of single photons, based on the non-linear interference of correlated photons, also referred to as *induced coherence* [24, 25]. This method allows assessing the sample properties in the challenging for detection and broadband IR range by using an accessible light source and a photodetector for visible or near-infrared (NIR) light. Earlier, non-linear interferometers have been used for several metrological applications, including IR imaging, spectroscopy, optical coherence tomography, and polarimetry [26–35]. Here we apply it for the characterisation of telecom IR dielectric metasurfaces and revealing fabrication imperfections. We also demonstrate that metasurfaces designed for the telecom IR range can bring their functionality into visible/NIR by generating intensity patterns at a few-photon level in the visible beam.

We generate correlated photon pairs in a non-linear crystal with one photon in the visible/NIR range (signal), and the correlated one in the telecom IR range (idler), via Spontaneous Parametric Down Conversion (SPDC) [24, 25]. The photons are then launched into a balanced Michelson interferometer, where they are split by a dichroic beamsplitter. The telecom IR photons interact with the metasurface under test, while visible/NIR and pump photons are

reflected by a plane mirror. All the photons are then sent back to the non-linear crystal, where the pump generates photon pairs, identical and coherent with those launched into the interferometer. The state-vectors of the photon pairs created in the first and the second passes of the pump through the crystal interfere. The interference leads to the modulation of the intensity of the detected visible photons. The phase governing the modulation depends on the phases of all the three participating photons: signal, idler, and pump. Thus, from the observation of the interference pattern of the signal (visible/NIR) photons, we can infer the information about the phase induced by the metasurface on the idler (telecom IR) photons. We can then assess the quality of the fabricated metasurface for verification of the design and tracing the fabrication accuracy.

The same setup can be used for characterisation of metasurfaces at different wavelengths with a change of the phase-matching conditions in the non-linear crystal, for example, by changing the crystal temperature. This is a practical and economical advantage of our experiment with respect to the alternative non-linear methods [15–18], which would require the use of expensive tuneable lasers.

Another exciting feature of our experiment is that a single metasurface in the IR range can ‘virtually’ shape the visible beam at the few-photon level at multiple wavelengths. This is achieved by tuning the wavelength of the pump beam, while the wavelength of the probing IR photons is fixed to match the range of the optimal performance of the metasurface. In general, the tunability of the method is limited only by the transparency and phase matching conditions of the non-linear crystal. Thus our method opens up the possibility to expand the range of operations of metasurfaces designed for IR into the visible spectral range avoiding undesired absorption losses.

To prove our concept, we characterize metasurfaces designed to produce vortex and Laguerre–Gaussian beams at telecom IR. We then show that the method allows generating annular and doughnut-shaped beams in the visible/NIR range using silicon metasurfaces operating at the telecom IR wavelengths [36]. We also demonstrate the intensity modulation of the beam at visible and NIR wavelengths using a single metasurface designed for telecom IR.

2 Results and discussions

2.1 Metasurface design

Our metasurfaces are made of silicon (Si) nanocylinders of 650 nm height, which are fabricated on top of an optically

Figure 1: (A) A unit cell of metasurface consisting of Si cylinder and SiO₂ + Al + semi-infinite SiO₂ substrate. (B) The dependence of the acquired phase and reflection of a regular array of Si cylinders with 650 nm period on the cylinder diameter.

thick aluminium layer, acting as a mirror, on a SiO₂ substrate. The nanostructures are separated from the mirror by a 500 nm SiO₂ dielectric spacer (see Figure 1A). The phase retardation induced by Si cylinders of different diameters (from 200 to 400 nm) at the operational wavelength of 1550 nm is calculated, assuming that they form a regular array with a period of 650 nm (see Section 4 for details on the numerical simulations). This range of diameters provides the required $0-2\pi$ range in the phase retardation to allow mapping of any desired wavefront while keeping reflectivity values above 85% (see Figure 1B).

Based on these results, we design and fabricate metasurfaces to generate complex beam profiles with desired azimuthal and radial variations. To do so, we map the phase distribution of the incident beam, which we assume to be a plane wave impinging normally to the metasurface, to the phase profile of the desired beam. We start by generating vortex beams, for which, ignoring the polarization, the transverse field distribution can be described as $E(r, \varphi) = F_m(r) \exp[i l \varphi]$. There are two factors in this expression. The first factor, $\exp[i l \varphi]$, defines the azimuthal variation of the beam, characterized by the azimuthal index l (sometimes referred to as the topological charge or the angular momentum of the beam) and the azimuthal angle φ . The second factor, $F_m(r)$, accounts for the radial variation, and it is determined by the radial index m . Besides the vortex beam, we also apply our technique to generate a Laguerre–Gaussian beam and, finally, a different class of beams, which we refer to as *annular beams*, where the intensity distribution within the rings is given as $I(r, \varphi)$, with r and φ being the polar coordinates. In these beams, the azimuthal order is zero, and the radial part is different from that of usual vortex beams [36].

The phase profiles of all these beams are shown in Figure 2A, C, E and G. To fabricate the metasurfaces, we use Electron Beam Lithography (EBL) followed by Reactive Ion Etching (RIE), as detailed in Section 4. The corresponding

SEM images of the fabricated samples are shown in Figure 2B, D, F and H.

2.2 Non-linear interferometer

We use non-linear interferometry to, first, characterize the response of telecom IR metasurfaces using visible/NIR light and, second, to generate complex beams in the broad visible/NIR range using the same telecom IR metasurface. The scheme of the non-linear interferometer setup is shown in Figure 3 (see Section 4 for the detailed schematics and description).

The frequency-non-degenerate SPDC occurs in the non-linear crystal, where the phase-matching condition is chosen in such a way that the wavelengths of signal (detected) and idler (probe) photons are in the visible/NIR and telecom IR range, respectively [28–33]. The photons are sent into the interferometer, where they are separated by a dichroic mirror DM. Signal and pump photons are reflected by the reference mirror M and the idler photon is reflected by the metasurface under study. The confocal three-lens system in each arm of the interferometer projects photons on the metasurface and the reference mirror [33]. The reflected pump passes through the crystal for the second time and, with some probability, generates another pair of photons, which is identical and coherent with those launched initially into the interferometer.

When one cannot *in-principle* distinguish if the photon pairs were generated in the first or in the second pass of the pump through the non-linear crystal, the interference is observed. This interference is associated with the effect of induced coherence without induced emission, discovered by Zou, Wang, and Mandel [24, 25]. We emphasize here that this effect is associated with the interference of probability amplitudes (wavefunctions) of down-converted pairs, rather than

Figure 2: Theoretically calculated phase distributions and SEM images for metasurfaces producing: (A) and (B) annular beam (structure 1), (C) and (D) vortex with topological charge $l = 2$, $m = 2$ (structure 2), (E) and (F) Laguerre–Gaussian beam with $l = 2$, $m = 1$ (structure 3), (G) and (H) vortex with topological charge $l = 6$, $m = 1$ (structure 4).

Figure 3: The schematic of the non-linear interferometer. Arrows indicate the interfering photons; dashed lines show the paths of the photons. The laser (green arrow) generates a signal (visible, orange arrow) and idler (IR, red arrow) photons in the non-linear crystal. Photons are split by a dichroic mirror (DM). Pump and signal photons are reflected by a mirror (M); idler photons are reflected by a sample under study. The interference of visible photons is detected by a camera as a function of displacement Z of mirror M or metasurface itself. Properties of the metasurface in the IR range are inferred from the interference of photons in the visible range. The beams are shifted for clarity.

with the interference of real fields. The intensity dependence observed at the signal photon wavelength is given by [30, 31]:

$$I_s \propto (1 + |r_i| |\tau_i|^2 |\mu(\Delta t)| \cos(\varphi_i + \varphi_s - \varphi_p)) \quad (1a)$$

$$|\mu(\Delta t)| = 2\pi \int_0^\infty d\Omega |S(\Omega)| e^{-i\Omega\Delta t}, |\mu(0)| = 1, \quad (1b)$$

where τ_i is the amplitude transmission coefficient of idler photons in the interferometer; r_i is the amplitude reflection coefficient of idler photons by sample surfaces; $|\mu(\Delta t)|$ is the normalized first-order correlation function of the SPDC field; $\varphi_{s,i,p}$ are the phases acquired by the signal, idler and pump photons respectively; Δt is the time delay between signal and idler photons in the interferometer; $|S(\Omega)|$ is the spectrum of SPDC photons; Ω is the frequency detuning. From Equation (1a) it follows that losses and phase changes experienced by idler photons due to interaction with the metasurface are revealed in the interference pattern of the signal photons. Hence, the observed non-linear interference allows retrieving information about the metasurface properties at the idler photon wavelength (telecom IR in this case) by measuring the interference pattern for signal photons only (visible or NIR in this case), i.e. direct detection of idler photons is not required. While, in this particular case, we use this technique to study the spatial distribution of the phase imparted by the metasurface, one can envision scenarios in which modulation of the polarization or amplitude are studied using the same concept.

2.3 IR metasurfaces characterized by visible light

We first calibrate our setup by substituting the metasurface with the mirror. The measured visibility of the interference pattern constitutes $V = 63 \pm 1.4\%$ (see Supplementary Figure S1). Next, we introduce the metasurfaces in our interferometer. Altogether we have characterized four different metasurfaces numbered as follows: (1) the annular beam structure (Figure 2A and B), (2) the vortex structure with topological charge $l = 2$, $m = 2$ (Figure 2C and D), (3) the Laguerre–Gauss structure with $l = 2$, $m = 1$ (Figure 2E and F), and (4) the vortex structure with topological charge $l = 6$, $m = 1$ (Figure 2G and H).

We perform a fine scan of the phase in the interferometer (see Section 4) and observe the modification of the interference pattern, as the light illuminating the sample acquires different phases, see the animation.

First, we analyse the intensity distribution for the metasurfaces producing vortex and Laguerre–Gauss beams. The summary of our results is shown at Figure 4. Figure 4A, C, and E show theoretical calculations of the intensity distributions of interference patterns at the telecom IR range ($1.5 \mu\text{m}$), for which the metasurfaces are designed. The calculated profiles are obtained considering the interference of the telecom IR beam, modified by the metasurface, with the Gaussian beam. Figure 4B, D, and F show the experimental interference patterns measured at the NIR (810 nm). As we can see from Figure 4, the patterns contain several radial beams, which correspond to the topological charge induced by the metasurface, while the degree of their chirality corresponds to the radial index. For the case of metasurfaces fabricated to produce vortex beam (structures 2 and 4), we infer, that the topological charges l induced by the metasurface are $l = 2$ and $l = 6$, and radial indexes $m = 2$ and $m = 1$, respectively. We also obtain topological charge $l = 2$ and radial index $m = 1$ for the Laguerre–Gauss structure (structure 3).

Our results reveal several peculiar features of the fabricated metasurfaces. First is the phase step-like gradients (see Figure 4D), which are related to discretization and the rounding up ($\sim 5 \text{ nm}$) of the phase to cylinder diameter mapping in the lithography process. Second, the phase non-uniformity at the edge of the structure in Figure 4F is due to different levels of EBL exposure doses required to produce cylinders of the same size at the edge and the centre of the metasurface. We verified these conclusions by performing scanning electron microscopy (SEM) imaging of the metasurfaces (see Supplementary Figure S2). Our results indicate relatively high deviation of the sizes of the

Figure 4: Calculated at 1550 nm and measured at 810 nm interference patterns for (A) and (B) vortex structure with topological charge $l = 2$, $m = 2$ (structure 2), (C) and (D) Laguerre–Gauss structure with $l = 2$, $m = 1$ (structure 3), (E) and (F) vortex beam structure with topological charge $l = 6$, $m = 1$ (structure 4).

cylinders at the edge of the metasurface from the targeted sizes. Thus we show that our method can indeed reveal the fabrication irregularities in the studied metasurfaces.

Next, we analyse the intensity distribution in the case of annular beam shaping metasurface, see Figure 5A and B. We analyse two cases: when the phase acquired in the interferometer is equal to $2\pi m$ and when it is equal to $\pi + 2\pi m$. We take the cross-cut from the experimental intensity plot, measured at 810 nm (red), and normalise it to the spatial intensity distribution of the signal photons at this wavelength measured without interference (IR arm of the interferometer is blocked) (see Supplementary Figure S3). The obtained result is compared with the theoretically calculated intensity distribution of the metasurface at 1550 nm (black), see Figure 5E and F. For all the cases, the nearly perfect agreement between our

experiments and the theory shows that (1) our technique can indeed be used for characterizing IR metasurfaces using light sources and detectors for the visible range and (2) the fabricated metasurfaces are of acceptable quality.

2.4 Shaping the visible light beams at different wavelengths by a single metasurface

Another exciting feature of our experiment is that a single metasurface designed for the specific IR wavelength can be used to shape visible/NIR beams (at a few photon level) at multiple wavelengths. In our experiment described above, we design a metasurface for a specific telecom IR wavelength and show that it is possible to use it to shape a NIR

Figure 5: Intensity distribution for annular beam structure (structure 1).

(A) and (B) Interferograms obtained at 810 nm when the phase in interferometer is equal to (A) $\pi + 2\pi n$ and (B) $2\pi n$. (C) and (D) Interferograms obtained at 760 nm when the phase in interferometer is equal to (C) $\pi + 2\pi n$ and (D) $2\pi n$. (E) and (F) Cross-cuts of the obtained interferograms at 810 nm (red) and 760 nm (green) compared with theoretical intensity distribution at 1550 nm (black).

light beam at 810 nm. Here, by tuning the pump wavelength and adjusting the phase-matching conditions in the crystal, we keep the wavelength of idler photons at the operation wavelength of the metasurface while tuning the wavelength of the signal photon to visible (760 nm). Thus, the same metasurface “virtually” shapes the visible/NIR light at multiple wavelengths, which is limited only by the transparency range of non-linear crystal and requirements of phase-matching conditions.

We demonstrate this idea with the metasurface designed for annular beams. We change the detected wavelength of the signal photon from 810 to 760 nm by shifting the pump wavelength from 532 to 514 nm and adjusting the phase-matching conditions by changing the temperature of the non-linear crystal. We measure the intensity distribution for phase differences $2\pi n$ and $\pi + 2\pi n$ in the interferometer, see Figure 5C, D. The small feature in the centre of the interferogram appears due to the subtraction of the background noise (containing residuals of

the pump) from the original data. As in the previous case, we normalise the cross-cuts of the experimental data to the spatial intensity distribution of signal photons (see Supplementary Figure S3), and then compare the obtained results (green) with theoretically calculated distributions for 1550 nm (black), see Figure 5E and F. Based on the comparison presented in Figure 5E and F the results measured at 810 nm (red) and at the tuned wavelength of 760 nm (green) are found to be in good agreement with each other and with theoretically calculated intensity distributions for 1550 nm (black). From here, we can conclude that using our method, metasurfaces designed for telecom IR can indeed be used for beam shaping at multiple wavelengths in the visible/NIR range. Interestingly, the intensity distribution in the visible/NIR beams can also be manipulated by shifting either the metasurface or the mirror for signal or pump photons along the interferometer arms, allowing, for example, to transform a high-intensity region to a low-intensity one, see panels A–D in Figure 5.

Figure 6: Experimental setup.

The tuneable continuous-wave (cw) laser, injected through a dichroic mirror D_1 , is used as a pump source for the PPLN crystal. The visible and IR photons are separated into different channels by a dichroic beamsplitter D_2 . The visible and pump photons are reflected by the mirror M , while the IR photons are reflected by the metasurface. The metasurface is mounted on the motorized XYZ translator for the coarse and the piezo stage for the fine movement of the sample. The interference of signal photons is detected by a standard visible light CMOS camera (Thorlabs). The signal is filtered by the notch (NF) and bandpass (BP) filters. XY axis corresponds to the surface plane of the sample.

3 Conclusions

We have demonstrated a technique for characterising metasurfaces designed to operate in the telecom IR range using only visible/NIR range sources and detectors. The concept is based on the non-linear interference of correlated photons. It can be extended to other frequency ranges by simple adjustment of the non-linear crystal, thus negating the need for tuneable lasers. We show that our method reveals irregularities in the fabricated metasurfaces, which can find direct applications for quality assurance (QA) and quality control (QC) of the fabrication processes.

Furthermore, we have shown that the same approach can be used to modulate the intensity of a visible/NIR beams across multiple wavelengths using a single metasurface designed to operate in the telecom IR. Though we have shifted the wavelength of the signal photon, the idler photon still stays within the optimal operation range of the metasurface. This method can be used for beam shaping at different wavelengths in the visible/NIR range using a single metasurface. It may open exciting opportunities for dynamic optical manipulation in time-varying optical traps and low-light microscopy using low-loss and easy to fabricate IR-optimized metasurfaces.

Our method can be extended beyond the telecom IR spectral ranges. With the appropriate choice of the non-linear crystal, it can be further extended up to mid-, far-IR and THz ranges [37, 38]. Furthermore, a similar concept can be realised in the high-gain parametric down-conversion, allowing the manipulation of the intensity of relatively bright beams [39]. It also has practical appeal for QC and QA in the scalable manufacturing of flat optics. We believe that the method might be useful for the development of novel quantum-inspired imaging techniques, bringing

together capabilities in quantum optics and nanophotonics for developing new devices and methods.

4 Experimental section

4.1 Numerical simulations

To compute the reflectivity and the phase accumulation provided by the metasurface elements, we simulated a single unit cell using periodic boundary conditions along with the transverse directions and normally-incident plane wave excitation. Perfectly matched layers (PMLs) are used above the Si cylinders and in the SiO_2 layer (thus considered semi-infinite in our simulations). The diameter of cylinders was varied from 200 to 400 nm while keeping a constant period of 650 nm. Amorphous silicon material parameters used in the simulations correspond to those measured by ellipsometry on our deposited films, closely following those reported in the literature [40]. All simulations were performed using a Finite Difference Time Domain-based commercial solver (Lumerical FDTD), targeting an optimal performance at 1550 nm wavelength.

4.2 Experimental realization

The detailed schematics of the non-linear interferometry setup is presented in Figure 6. In the experiment, we use the tuneable continuous wave (CW) laser (C-WAVE Hubner Photonics) (see Figure 6). The pump passes through the single mode fibre resulting in the Gaussian spatial intensity profile for the best focussing. The polarization of the pump after propagation through the fibre is controlled by quarter- and half-waveplates. The pump at 532 nm produces SPDC photons at 810 nm (signal) and 1550 nm (idler) wavelengths in the periodically polled lithium niobate (PPLN) crystal with the length of 10 mm and with 7.5 μm poling period, heated at 70 °C. To produce the signal photons at 760 nm and keep the idler at 1550 nm, we tune the pump wavelength to 514 nm and adjust the phase-matching conditions by changing the poling period to 6.81 μm and setting the temperature of PPLN crystal at 79 °C. The generated SPDC photons are

separated into different arms of the interferometer by a dichroic mirror D_2 (Semrock): visible/NIR and pump photons travel in one arm, and telecom IR photons travel in another arm. In each arm of the interferometer, we insert the three-lens system to achieve the required spatial resolution of the phase mapping. The system consists of three BK7 lenses, where the first two lenses F_1 and F_2 have $f_{1,2} = 75$ mm focal lengths, and the lens F_3 has $f_3 = 5$ mm. The system provides a spatial resolution of $12.4 \mu\text{m}$ (see Supplementary Figure S4). It is constrained by geometrical configuration of our setup and represents the trade-off between the best resolution and the field of view that covers the whole metasurface (see Supplementary for more details). Then, all the beams are reflected in the crystal: visible/NIR beams by the reference mirror and the telecom IR beam by the metasurface. The reflected pump beam generates another pair of SPDC photons. Their interference pattern in the visible/NIR range is observed by a standard CMOS camera (Thorlabs CS2100M-USB) with a pixel size of $5.04 \mu\text{m}$.

The sample is mounted onto a motorized XYZ translation stage (Thorlabs) and unidirectional piezo stage. The XY translation allows us to image different areas of the sample. The coarse Z translation allows for balancing interferometer arms. The piezo stage provides fine-tuning along the Z direction. The optimal position is found at the point which corresponds to the highest interference visibility, defined as $V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{A}{y_0}$, where A is the amplitude of modulation for interference pattern, and y_0 is the base signal without interference. Then, the sample is scanned in a step of ~ 20 nm with the piezo stage. Each position of the piezo stage is related to a phase image of the structure. The typical acquisition time for one image is 300 ms. To analyse the data and compare it with theoretical predictions, we offset the reference visibility (obtained with the mirror in the IR arm), which represents the best result achievable in a given configuration. We subtract the intensity at the minima of the intensity dependence for reference measurements from the corresponding values obtained with the metasurfaces. This value is obtained from the fit of reference non-linear interference (see Supplementary Figure S1) as the difference between the baseline signal y_0 and amplitude of modulation A . Then we infer the intensity distribution introduced by the IR metasurface to the visible/NIR beams.

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