Dynamic metasurfaces for 3D imaging (3D-META)

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ABSTRACT

An entirely new principle for beam steering of relevance to 3D imaging with lidar micro-sensors has been studied. Using MEMS to tune the electromagnetic properties of gap surface plasmon metasurfaces, wide angle switching of 15 degrees and a diffraction efficiency of 50% have been demonstrated. The proposed platform thereby has several advantages over current state of the art lidar technologies based on MEMS micromirrors, gratings and phased arrays.

Keywords: lidar; metasurfaces; MEMS.

1. INTRODUCTION

Three-dimensional (3D) imaging technologies are essential for the digitalization of a wide range of industrial processes. They are for instance a prerequisite for many fully autonomous systems within transportation (e.g. autonomous vehicles), logistics (e.g. space estimation), production-line manufacturing (e.g. process characterization) and characterization systems (e.g. measurement of ocean amplitudes from ship or satellite). Among 3D imaging technologies, lidar (light imaging and ranging) is considered as one of the most promising. Lidar typically relies on scanning a pulsed laser (UV, VIS or NIR depending on application) over a desired field of view where distances are measured through a time-of-flight measurement relying on the detection of backscattered light.

A significant challenge within lidar systems is achieving sufficient scanning angle while ensuring high resolution, cost-effectiveness, small size and efficiency. Three common methods of beam scanning are (i) mechanically tilting a mirror to steer a laser beam, (ii) mechanically tilting a grating or tuning the wavelength of incident light and (iii) phased laser arrays or spatial light modulators (SLMs). Each of these have inherent limitations that need to be addressed (as discussed in the next section).

In order to overcome the challenges involved in lidar imaging we propose and demonstrate an entirely new platform relying on *dynamic metasurfaces* for beam steering. Metasurfaces consist of arrays of simple subwavelength nanostructures (e.g. plasmonic or dielectric bricks, discs or pillars) arranged on a surface which act as designer point sources for the reflected/transmitted light in a similar manner to Huygen's principle for constructing wavefronts [5]. They have been shown to offer full control over phase, intensity, polarization and dispersion, i.e. all the degrees of freedom of the field, thus making it possible to revolutionize optical sensor development by saving space, weight and cost. In the context of lidar sensors we demonstrate that dynamic metasurfaces have dramatic advantages in terms of scanning angle, efficiency and switching rates.

2. STATE OF THE ART

Precision lidar requires fine beam-steering control over wide angle range (e.g. 10° - 120°) and typically relies on large and expensive solutions such as stepper motors or phased laser arrays. Integrated MEMS technologies are compact and cost-effective but typically lead to a trade-off between scanning angle range and precision: Resonant MEMS micro-mirrors lead to large scanning angles with low angular precision, whereas non-resonant MEMS mirrors have the advantage that they can be controlled to scan with high precision but only over small angle ranges [3] (typically 1° - 5° for size and stiffness properties of relevance to lidar).

Gratings have a low theoretical diffraction efficiency of only 40.5% (in the case of binary gratings [2]), making more powerful lasers necessary for their utilization. If the beam steering is achieved by modulating the wavelength of the laser, this also adds significant cost to the system.

Conventional phased laser arrays and SLMs are manufactured with large periodicities between the source elements in comparison to the NIR wavelengths relevant for lidar, thereby limiting their resolution and efficiency. A promising new development in this context is the utilization of metasurface structures in liquid crystal SLMs which allows for sub-wavelength periodicities [1]. However, SLMs based on liquid crystals offer slow response speeds, limiting the frame rate of the image capture process.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

Our project uses an entirely new principle for beam steering by combining MEMS actuation with a gap surface plasmon (GSP) metasurface-based grating shown in **Fig.** 1). GSP resonances are excited between Au nanoparticles structured on the top plane and a non-structured Au backplane [5]. These resonances are used to impose a desired phase delay distribution onto the reflected light. The amplitude of reflected phase delay depends on the geometrical parameters of the structure: Tailoring the lateral dimensions of the structure allows for point-wise control of the phase over the surface. In our design, the distance t_s between the structured and non-structured gold surface can be modulated by a thin-film piezo MEMS membrane, thus allowing the switchable reflected light between different diffraction orders of the metasurface grating upon small MEMS deflections. If the reflected beam is then e.g. sent to a micromirror with smaller tilting angles, this arrangement allows for precise beam steering over large angles.

Our proposed platform has the following advantages:

- **Large deflection angles from small MEMS displacements.** Basing the current MEMS design on our earlier non-resonant MEMS micromirror architecture [3,4] we expect a factor 10 improvement of deflection angle is achievable in the GSP metasurface arrangement relative to simply deflecting the micromirror.
- **High deflection efficiency.** GSP metasurfaces in literature have achieved experimental efficiencies between 60-80% [2, 5], while the theoretical limit for binary gratings is 40.5% [6].

As such our project has aimed to combine the best of existing lidar micro-sensor techniques in a novel platform which avoids their respective pitfalls.

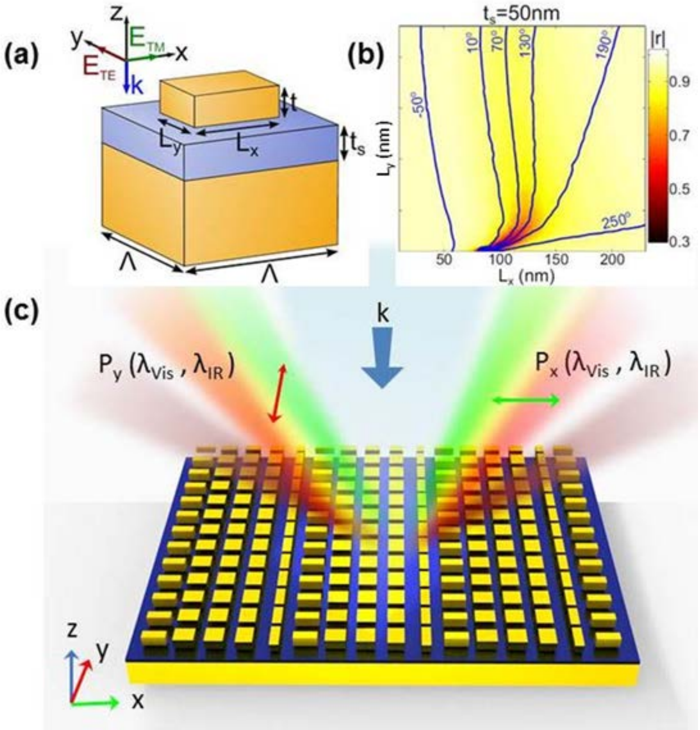

Fig. *1 (a) Unit cell consisting of plasmonic nano-brick placed above a conductive back plane with a gap in between (blue layer, which could be a dielectric or air). (b) The colour plot shows the reflection amplitude and the lines show the relative phase addition to the reflected field for a given spacer thickness* t_S. *(c) A phase gradient in the x-direction is created by varying the nano-brick dimensions. The reflection angle of the normally incident field is determined by this gradient and the incoming polarization.*

4. PROJECT RESULTS

Metasurfaces comprising gold rectangles were produced at SDU on glass slides using electron beam lithography, see Fig. 2. The glass slides were then mounted on gold plated MEMS mirrors at SINTEF. The mounting was done in a cleanroom environment to avoid particles between the mirror and metasurface. White light interferometry was used to verify that the gap between the gold nanostructures and the MEMS mirror was smaller than the displacement available by the mirror. After wirebonding, the devices were tested and the minimum gap was measured by observing the interference pattern generated by reflections from the glass surface and the gold mirror. The nanostructures protrude 50 nm above the glass surface. Most of the assembled devices reached a minimum gap size of around 300 nm to 500 nm, with a few reaching gap sizes from 100 nm to 200 nm. These gap size measurements have considerable uncertainty, ± 40 nm, due to the wavelengths of light used in the measurements. The residual gap is most likely due to stray particles caught between the mirror and glass slide.

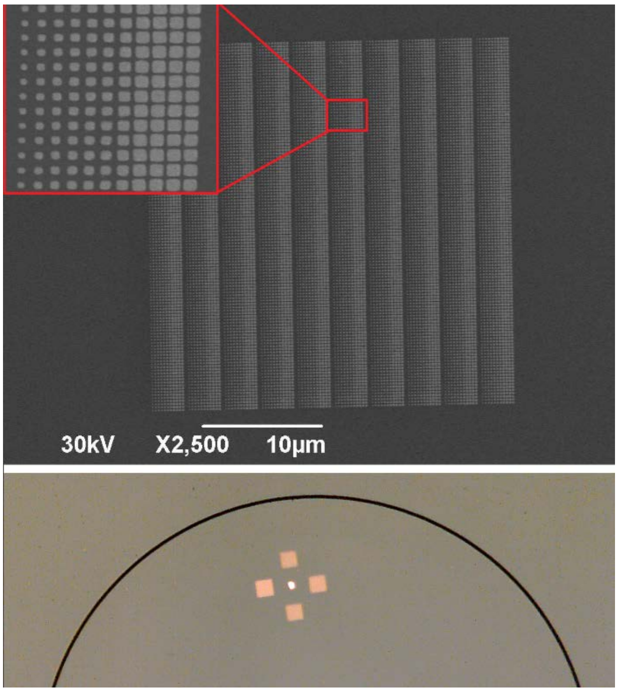

Fig. 2. *Above: SEM image of the metasurface blazed grating, the inset shows a close up of the individual gold rectangles. Below: Microscope image of the metasurface mounted above a gold coated MEMS mirror.*

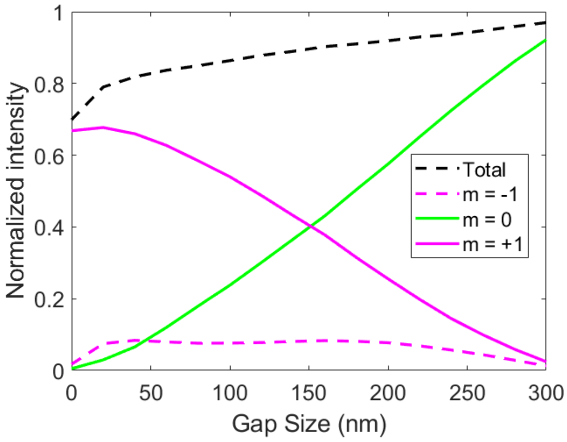

Fig. 3. *Simulated intensities of reflected diffraction orders as a function of gap size between metasurface and gold mirror under 800-nm-wavelength incident light. For the simulations a 20nm silica dielectric cover layer has been assumed on top of the Au nanoparticles, and zero gap spacing corresponds to the MEMS Au plate being in contact with this cover.*

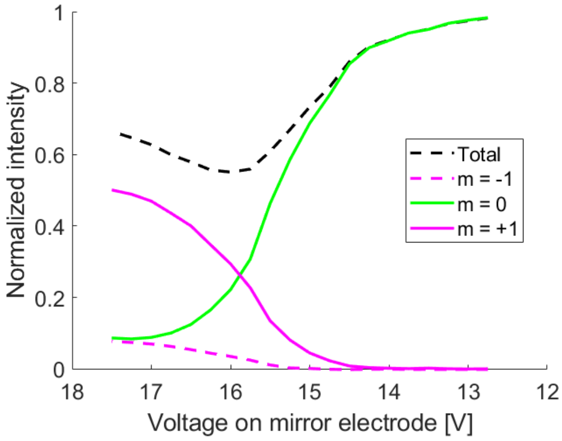

Fig. 4. *Measured intensities of reflected diffraction orders as a function of the voltage applied on the mirror electrodes, changing the gap size, under800-nm incident light.*

The optical response from one of the samples measured to achieve around 100 nm gap size was characterized at SDU, and the initial measurements are presented here. When the device is off (gap size larger than 300nm), all light is reflected into the specular direction (m = 0), while applying a voltage on the mirror electrodes changes the gap, resulting in some of the incident light to be reflected in the m = 1 and m = -1 diffraction orders, which lie 15 degrees to either side of the specular direction. This angle is determined by the wavelength of the light and the grating period (in this case 800 nm and 3 um, respectively). Thus the angle can be chosen when designing the metasurface.

Fig. 3 shows the simulated intensity of the reflected diffraction orders as a function of gap size, calculated using commercially available software COMSOL Multiphysics (v 5.5). Bringing the metasurface into close vicinity of the gold backplane switches the beam angle from the $m = 0$ diffraction order entirely to the $m = +1$ order. Fig. 4 shows the measured intensity of the reflected diffraction orders for an assembled device as a function of the voltage applied to the MEMS mirror electrodes, which changes the gap size. The maximum intensity measured in the m = +1 diffraction order was 50%, which agrees well with the simulated efficiency for a gap size of around 100 nm. Hence the MEMS-metasurface device successfully switches the beam angle between 0 and 15 degrees.

Even with the larger than intended gap spacing this is already significantly better than the theoretical efficiency limit for a binary grating at 40.5% [6] which will have similar fabrication costs to the metasurfaces due to the number of production steps involved. From Fig. 3 and [5] we expect that achieving a smaller gap size could give efficiencies above 60%.

5. FUTURE PROJECT VISION

5.1. Technology Scaling

Having demonstrated the principle of beam switching based on our MEMS GSP metasurface platform, the setup is currently at Technology Readiness Level (TRL) 3. In order to reach TRL 5-7 and thereby validate, demonstrate and prototype in relevant 3D-imaging application environments, the main steps required are

- **Component design**
  Further design of the component is needed to realize beam scanning based on the current beam switching device. We envision adding an inexpensive conventional micromirror to provide scanning, while the MEMS-metasurface device acts to "gear" the incidence angle onto it.

- **Silicon and MEMS process development**:
  Developing an integrated process for fabricating both the metasurfaces and MEMS will be necessary for improving performance, reducing cost, and miniaturizing the devices.

- **Partnering with systems design expertise in lidar systems**:
  A partnership with expertise in building lidar systems will be necessary to develop our sensor element into relevant demonstrator and prototype systems.

- **Involving end-users**: Involving technical experts from end-users in the automotive industry such as Volvo or Waymo can provide valuable input for the development stages.

5.2. Project Synergies and Outreach

Our strategy towards reinforcing our consortium with the above mentioned additional organizations will involve

- Disseminating our results at the ATTRACT conference and other channels. We hope to come in contact with researchers with common interest in 3D-imaging lidar imaging and dynamic metasurfaces.
- Using existing network with sensor systems expertise from our existing portfolio of sensor development at both SINTEF Microsystems and Nanotechnology and Centre for Nano Optics at SDU.
- Requesting meetings with industrial end-users (such as Volvo and Waymo) where we offer to demonstrate our beam steering device fabricated during Phase 1 of ATTRACT. The goal of such meetings will be to get valuable end-user feedback and invite them to participate in an advisory role for the further development.

5.3. Technology application and demonstration cases

Our MEMS GSP metasurface platform targets the Horizon 2020 objective "Smart, green and integrated transport" by enabling efficient, sensitive, cost-effective and small beam steering (lidar) sensors. By adoption in existing lidar applications our MEMS-metasurface platform can reduce size, weight and cost and will benefit European society and its citizens in terms of more effective transportation, logistics, production and monitoring systems. To this end we aim to make demonstration cases of 3D-imaging based on our MEMS-metasurface platform, first in a laboratory environment (TRL4), then in relevant environment (TRL 5-6) (e.g. automotive or drone application). Furthermore, the MEMS-metasurface platform can be envisioned to a wide range of other applications where switchable optical properties are desired. In the bigger picture, we believe that exploration of industrial applications for metasurfaces will be important for European industrial competitiveness and job creation. Although Europe is a significant player in metasurface research it is rivalled by the heavy involvement of Asia and North-America. Industrially relevant research now will allow European industry to take the future lead in the competitive photonics sensor industry, which will likely be heavily impacted by metasurface wavefront engineering – and in particular sensors which enable dynamic modulation of these.

5.4. Technology commercialization

Our device is fabricated using cost-effective standard silicon processing tools, meaning that up-scaling towards an industrial product would follow a similar path as for many other optical MEMS components utilized today (e.g. MEMS diffractive optical elements). In particular the following steps are involved:

- Development of a fully integrated production process for optimized MEMS-metasurface devices.

- Miniaturize and optimize the electronics and system surrounding the device.

- Transfer the production to larger Si fabs (when seeking the high volume market). At SINTEF MiNaLab we have state of the art (NorFab) facilities for small to medium scale silicon micro-and nano production of optical MEMS components (up to around 100k devices annually).

We have extensive experience with commercializing optical MEMS technology: Technology developed by SINTEF MiNaLab has in the past lead to start-ups such as Gassecure (acquired by Dräger for approximately 50 M€ in 2015), poLight, Tunable and Sensibel. In a longer perspective, we would typically look to set up a spin-off company which would be able to attract private and governmental funding.

5.5. Envisioned risks

The core risks of Phase 2 relate to process development and enabling satisfactory beam scanning. Developing an integrated process for the devices means integrating nanopatterning into the MEMS fabrication line. One particular challenge at our MEMS fab facilities relates to contamination rules prohibiting top down nanopatterning of gold-covered substrates. The problem will be solved by patterning gold through a lift-off process instead. An alternative is to perform parts of the fabrication externally.

Achieving satisfactory beam scanning performance will be achieved through the development of more advanced metasurface design at SDU and the addition of an inexpensive micromirror component. Risk in this aspect will be mitigated by early involvement of necessary expertise in systems designs and end-user applications: See Sec. .5.1-5.2 Fortunately, we already have existing collaborations with strong research groups in sensor development and are confident we can find the right people.

5.6. Liaison with Student Teams and Socio-Economic Study

We can involve students at SDU Campus in Odense for volunteer MSc. projects involving ideas and prototyping inspired by the MEMS-metasurface platform we are developing for the societal challenges of smart, green and integrated transport. This can be integrated in existing educational programmes related with nano optics. Furthermore, we are open to provide relevant information from our consortium to the socio-economic study of the ATTRACT initiative and ecosystem.

6. ACKNOWLEDGEMENT

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