Optics Communications 427 (2018) 603–608

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Scanning differential microscopy for characterization of reflecting phase-gradient metasurfaces

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ARTICLE INFO

Keywords:
Heterodyne microscopy
Gradient metasurface
Phase response
Amplitude response

ABSTRACT

Gap-plasmon based phase-gradient metasurfaces operating in reflection are widely used for the realization of diverse flat optical components, ranging from spectropolarimeters to efficient couplers for surface waves. Successful implementation of carefully designed metasurfaces is however often hampered by technological imperfections that could be related to deviations of geometrical parameters of fabricated nanostructures from the designed ones or material properties, such as the metal and/or dielectric susceptibilities, from the handbook data. While the overall performance of fabricated components might indicate the existence of a potential problem, it is very difficult to identify its origin, which, for example, can simply be related to the deviation in only one cell of the metasurface supercell. We suggest exploiting well-developed experimental techniques of scanning differential heterodyne microscopy (SDHM) to characterize fabricated phase-gradient metasurfaces designed to operate in reflection. We further establish that, by carefully measuring the SDHM response of a gradient metasurface, one should be able of detecting small (~5%) amplitude and phase deviations (with respect to the design values) in the optical field reflected by an individual subwavelength-sized cell of the metasurface supercell.

1. Introduction

Metasurfaces have experienced enormous progress over the last years and attracted a great deal of attention due to unprecedented control over optical fields that can be exercised, resulting in extremely diverse functionalities demonstrated already along with several technologically appealing features, such as planar thin-film design [1–9]. Gap-plasmon based phase-gradient metasurfaces operating in reflection represent an important sub-class of metasurfaces, and are widely used for the realization of diverse flat optical components, ranging from spectropolarimeters to efficient couplers for surface waves [10]. Successful implementation of carefully designed metasurfaces is however often hampered by technological imperfections that could be related to deviations of geometrical parameters of fabricated nanostructures from the designed ones or material properties, such as the metal and/or dielectric susceptibilities, from the handbook data [11]. While the overall performance of fabricated components might indicate the existence of a potential problem, it is very difficult to identify its origin, which, for example, can simply be related to the deviation in only one cell of the metasurface supercell. Characterization techniques that would enable differentiating the performances of individual metasurface cells are crucial for further progress in this field, especially towards the implementation of practical flat optical components that have to compete in quality with conventional (and very well developed) optical components.

Several methods for optical characterization of metasurfaces were recently proposed and experimentally tested [12,13], utilizing different physical principles and revealing different limitations in their performance. Spectrally and spatially resolved interferometry using a Mach–Zehnder interferometer with the imaging spectrometer and supercontinuum laser [12] allows one to reach the accuracy of phase characterization of ~0.02 rad within +/−0.5 rad region. At the same time, the reported spatial resolution was only ~50 μm, which is not enough for the performance assessment of individual cells that should be of subwavelength sizes. Another approach, the vortex based interferometric method [13], exploits a specially structured light beam at the wavelength of 633 nm and exhibit the spatial resolution determined by the focused laser beam size of ~6 μm (at the $1/e^2$ intensity level). Both methods [12,13], apart from featuring insufficient spatial resolution for the individual cell assessment, are not stable versus microphonic noises, requiring thereby proper acoustic and vibration isolation.

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Abbreviations: SDHM, Scanning differential heterodyne microscope; SOM, Scanning optical microscope

https://doi.org/10.1016/j.optcom.2018.07.019
Received 18 May 2018; Received in revised form 5 July 2018; Accepted 8 July 2018

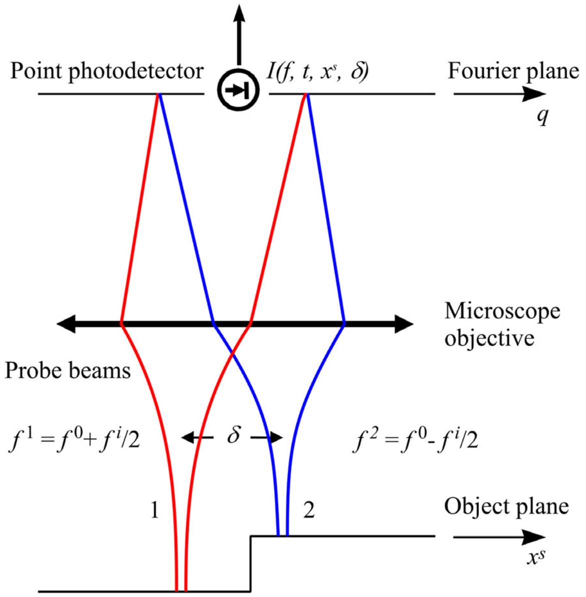

Fig. 1. Schematic SDHM configuration, where f_1 and f_2 — shifted optical frequencies of two probe beams, (1) — red, (2) — blue line, f_0 — unshifted optical frequency, f_i – heterodyne frequency, δ — the distance between the probe beams at the object plane, I — signal from a photodetector.

Scanning differential heterodyne microscopy (SDHM) allows one to accurately compare the phases of two reflected laser beams that are frequency shifted (typically, by an acousto-optic deflector) and focused on a sample surface at close locations (Fig. 1). This characterization technique is capable of detecting sub-nanometre steps in the surface reflection phase and reaching the spatial resolution close to the operating wavelength λ, while also being inherently stable with respect to microphonic noises due to the common-path optical scheme [14]. The SDHM seems therefore very well suited for the characterization of reflective phase-gradient metasurfaces, in general, and gap-plasmon based gradient metasurfaces, in particular. Generally speaking, the SDHM can be considered as the modification of conventional far-field scanning optical microscopy (SOM) with the additional possibility of accurately determining spatial gradients in the phase of reflected optical beams [15–17].

The typical SDHM configuration contains a modified Mach–Zehnder common-path interferometer with an optical frequency shift introduced in the interferometric arms, and exploits coherent registration of the two reflected (frequency-shifted) optical beams at the Fourier plane (Fig. 1). The SDHM has already been successfully applied for the characterization of integrated optical channel waveguides [17], channel plasmon waveguides [18] and diffraction gratings [19], but its use and potential as an experimental tool for the characterization of phase-gradient metasurfaces has so far not been considered. While the idea of using the SDHM for the metasurface characterization is straightforward, one should first properly analyse the SDHM response in the case of reflective phase-gradient metasurfaces before embarking on the corresponding experimental investigations. In this work, we discuss in detail the possibility of SDHM application for the gradient metasurface characterization. The analysis is made on the basis of analytical considerations and numerical calculations of the SDHM optical responses for different parameters of probing laser beams and the reflecting phase-gradient metasurface configuration. The paper is organized as follows. Section 2 is devoted to establishing the basics of the SDHM response that makes it easier to understand the SDHM response when characterizing phase-gradient metasurfaces, which is calculated and presented in Section 3. In Section 4, we summarize the results obtained and offer our conclusions.

2. SDHM response

The basics of the SDHM operation (Fig1) has already been discussed at length in previous publications [15,17], so that we can simply reiterate the main SDHM features: (*i*) the common-path optical interferometric microscopy with coherent optical detection, which involves two probe beams with the intermediate (heterodyne) frequency shift: f_i ~0.1–4 MHz, (*ii*) the distance δ between the probe beams in the object plane (typically ~0.1–4 μm) can conveniently be adjusted by varying the frequency shift, (*iii*) the object is located at the front focal plane of the objective with the point-like photodetector positioned at the Fourier plane of the objective, and (*iv*) the phase and amplitude response determined by the sample reflectivity is detected at the intermediate frequency f_i. Overall, these features ensure rather reliable and robust optical characterization of the sample reflectivity via registration of both phase and amplitude components of the differential optical response.

Within the thin phase-amplitude screen approximation [15,16], the output current of the point photodetector (coherent registration scheme) at the centre of the objective Fourier plane contains both amplitude and phase information directly related to the amplitude and phase of a complex response function [15,17]:

$$D(x_s,\delta) = L(x_s,-\delta/2)\cdot L^*(x_s,\delta/2), \quad \text{with}$$
$$L(x_s,\delta) = B\cdot\int_{-\infty}^{\infty} h(x)\cdot r(x-\delta-x_s)dx, \tag{1}$$

where x_s is the scanning coordinate, $h(x)$ is the optical field amplitude distribution of a probe beam at the object (sample) plane, $r(x) = R(x)\exp[i\phi(x)]$ is the complex reflection coefficient of the sample, and B is the normalization constant. The phase of the SDHM response is determined by the phase difference between the two probe (frequency-shifted) beams, which is in turn related to the difference in the reflection phase of two adjacent sample areas illuminated by the focused probe beams (Fig. 1). The distance between the two adjacent probed areas producing the phase response is thereby set by the distance δ between the two (focused) probe beams, which can be characterized at the sample surface by Gaussian distributions (Fig. 2a) with a half width w at $1/e^2$ intensity:

$$h(x) = E(x) = E_0\exp\left[-\frac{(x\pm 0.5\delta)^2}{w^2}\right]. \tag{2}$$

The SDHM phase response, $\phi(x_s,\delta) = \arg(D(x_s,\delta))$, is therefore related to the gradient of the sample phase reflectivity, generally increasing with the probe beam separation δ. The SDHM amplitude response, $|D(x_s,\delta)| = abs(D(x_s,\delta))$, also depends on the parameter δ, but its nature is rather similar to that of the conventional SOM, at least for small values of δ.

These features of the SDHM response are illustrated with the phase and amplitude dependencies calculated using the above formulae for two basic phase objects — a purely phase step (Fig. 2b) and ridge (Fig. 2c) with the phase increment $\Delta\varphi = 60°$. For the phase step, it is seen that, when the distance δ between two probe beams is larger than the beam width $2w$, the phase response maximum $\varphi(0)$ is equal to the interrogated phase step $\Delta\varphi = 60°$ (Fig. 2b). When the distance δ becomes smaller than the beam width $2w$, the phase response maximum $\varphi(0)$ becomes progressively smaller, depending nonlinearly on the ratio $\delta/2w$. As expected, the amplitude response resembles the SOM response, while being influenced by the parameter δ. Both amplitude and phase responses, when considered as spatial amplitude and phase dependencies, take up the width of $2w+\delta$, so that it is approximately equal to parameter δ for large beam separations and to the beam width $2w$in case of smaller separations. The phase ridge (Fig. 2c) can be treated as a sum of two opposite phase steps, whose distance should be compared to the width of $2w+\delta$, separating thereby the regime of pure superposition of step responses for wide (width > $2w+\delta$) ridges from the regime of destructive interference of step responses for narrow ridges. It should be noted that the beam separation δ provides an additional (as compared