Optics Communications 383 (2017) 500–507

Contents lists available at ScienceDirect

Optics Communications

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

Imaging photonic crystals using Fourier plane imaging and Fourier ptychographic microscopy techniques implemented with a computer controlled hemispherical digital condenser

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ARTICLE INFO

Article history:
Received 28 June 2016
Received in revised form
19 August 2016
Accepted 21 September 2016

Keywords:
Optics
Microscopy
Photonic crystals
Phase recovery imaging methods

ABSTRACT

Fourier plane imaging (FPIM) and Fourier ptychographic (FPM) microscopy techniques were used to image photonic crystals. A computer-controlled hemispherical digital condenser provided required sample illumination with variable inclination. Notable improvement in image resolution was obtained with both methods. However, it was determined that the FPM technique cannot surpass the Rayleigh resolution limit when imaging photonic crystals.

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1. Introduction

Microscope condensers permit to increase the image resolution of traditional optical microscopes [1–5]. Illumination of the sample in a traditional optical microscope with a digital condenser increases the image resolution and permits flexible implementation of a variety of microscopy techniques with a single illumination source [6–13]. Digital microscope condensers also permit the implementation of the Fourier ptychographic microscopy (FPM) technique in a traditional optical microscope [7,10,13,15]. FPM combined with a low numerical aperture (NA_o) objective lens with large field of view allows the observation of large-area samples with enhanced resolution, thus resulting in images with increased information content [7]. Fourier plane imaging microscopy (FPIM) [16,17] is a new developed sub-wavelength resolution microscopy technique based on the use of microscope condensers that allows the detection of periodic structures with a period much smaller than the Rayleigh resolution limit $\lambda/(2NA_o)$, where λ is the vacuum-wavelength of the light used for imaging [17–20]. In addition to the traditional camera used to collect the image of the object under observation that is formed in the microscope's real plane (RP), our microscope setup has a second camera for observing the image formed in the Fourier plane (FP) [4,5,11,12,16,17]. FPIM is based on the recent demonstration that FP images may carry more information about the sample than the corresponding RP image [16,17,21]. In this work, we demonstrate for the first time the implementation of the FPIM technique using a hemispherical digital condenser (HDC) [11–14]. A computer-controlled HDC comprising of 64 white-light emitting diodes (LED) uniformly distributed in the internal surface of a hemisphere [12] was used for illuminating the sample with controllable directional light. The hemispherical distribution of LEDs in a HDC is advantageous when compared to a planar array of LEDs [6–10,14,15], because all LEDs in a HDC are at the same distance from the sample, thus resulting in superior illumination uniformity [10–14]. We report experiments dedicated to study the resolution limit achievable by implementing the FPM technique using a HDC. Previous studies using planar digital condensers and samples with non-periodic structures demonstrated that FPM permits to obtain images with resolution well below $\lambda/(2NA_o)$ [7,15]. We also used the FP images of samples containing periodic structures to determine the resolution limit of the HDC-microscope arrangement using Abbe's theory of image formation [18–20]. In contrast to previous results obtained with non-periodic samples, our experiments performed on photonic crystal structures and for this particular case our results

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http://dx.doi.org/10.1016/j.optcom.2016.09.047
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contradicted previously known facts. We also discuss the advantages and disadvantages of FPM and FPIM techniques using HDCs, thus explaining the relationship between the two techniques.

This paper is organized as follows: In Section 2 we describe the samples and the HDC-microscope arrangement used for imaging. In Sections 3 and 4 we present and discuss the results obtained using a HDC for implementing the FPM and FPIM techniques, respectively. Finally, the conclusions of this work are presented in Section 5.

2. Experimental set up and sample fabrication

Fig. 1(a) illustrates the experimental setup used in our experiments. In our experiments we used a Nikon Eclipse Ti inverted microscope. Various objective lenses with different numerical apertures (NA_o) and magnifications were used to image our samples. Two charge-coupled device (CCD) cameras are attached to the microscope for obtaining RP and FP images of the object under observation. A band-pass spectral filter (BPF) centered at $\lambda=450$ nm with a 10 nm bandwidth was inserted after the microscope objective lens. In the experiments described here, the microscope's built-in white-light illumination source was substituted by the HDC, shown in Fig. 1(b).

Each of the sixty four LEDs comprising the HDC can be turned ON/OFF independently. This can be verified in Fig. 1(b), where we show only LEDs turned ON in row 1 and 3. The numerical apertures corresponding to each of the four LED circular rows of the HDC, starting from the smallest inclination are $NA_c=0.58$, 0.73, 0.89, and 0.97 [12] respectively. The HDC was placed directly on the top of the sample (Fig. 1(a)). The HDC was centered in the area of interest of the sample and this was confirmed by acquiring the corresponding FP image. A representative emission spectrum of one white LED from the HDC is shown in Fig. 1(c). The peak emission occurs at $\lambda\sim450$ nm, while a weaker but broader secondary emission peak occurs at $\lambda\sim570$ nm. Since, 450 nm is the predominant emission wavelength, we assumed $\lambda\sim450$ nm for all calculations in this work. The investigated sample consists of photonic crystals with periodic structures made of Chromium (Cr) pillars arranged in a rectangular lattice-symmetry. In our sample layout design we used pillar diameter is $d=p_x/2$ to obtain a quantitative evaluation of the resolution of the real plane (RP) images. Two different periodicities, p_x and p_y, in two orthogonal directions were fabricated. This dual periodicity was intentionally chosen to demonstrate the effectiveness of FPM technique. Two different samples were fabricated: one with periodicities $p_x=500$ nm, $p_y=300$ nm and another with periodicities $p_x=600$ nm, $p_y=270$ nm. Details of the sample fabrication can be found in [12]. Briefly, the Cr lattices were defined by first spin-coating a layer of poly-methyl-methacrylate (PMMA) over a 150 μm thick glass cover-slip. This layer acts as the patterning resist for the electron beam lithography step. Methyl-isobutyl-ketone: isopropanol solution was used to develop the PMMA exposed to the electron beam, thereby forming holes in the PMMA layer arranged in a rectangular lattice pattern. A 15 nm thick Cr layer was then deposited on top of the PMMA layer using an electron beam deposition system. Cr fills in the holes in the square lattice arrangement previously revealed. Finally, the sample was sonicated in acetone to dissolve the PMMA layer, thus leaving only the periodic structure formed by Cr pillars.

3. Implementation of FPM using a HDC

The minimum observable period (p_{min}) in a traditional optical microscope using a condenser with a numerical aperture $NA_c \leq NA_o$ is given by the following equation [2,4,11,16]:

$$p_{\min} \approx \frac{\lambda}{NA_o + NA_c} \tag{1}$$

when $NA_o=NA_c$, Eq. (1) gives the Rayleigh resolution limit. Eq. (1) can be obtained assuming that a sample containing periodic features is illuminated by a coherent monochromatic plane wave

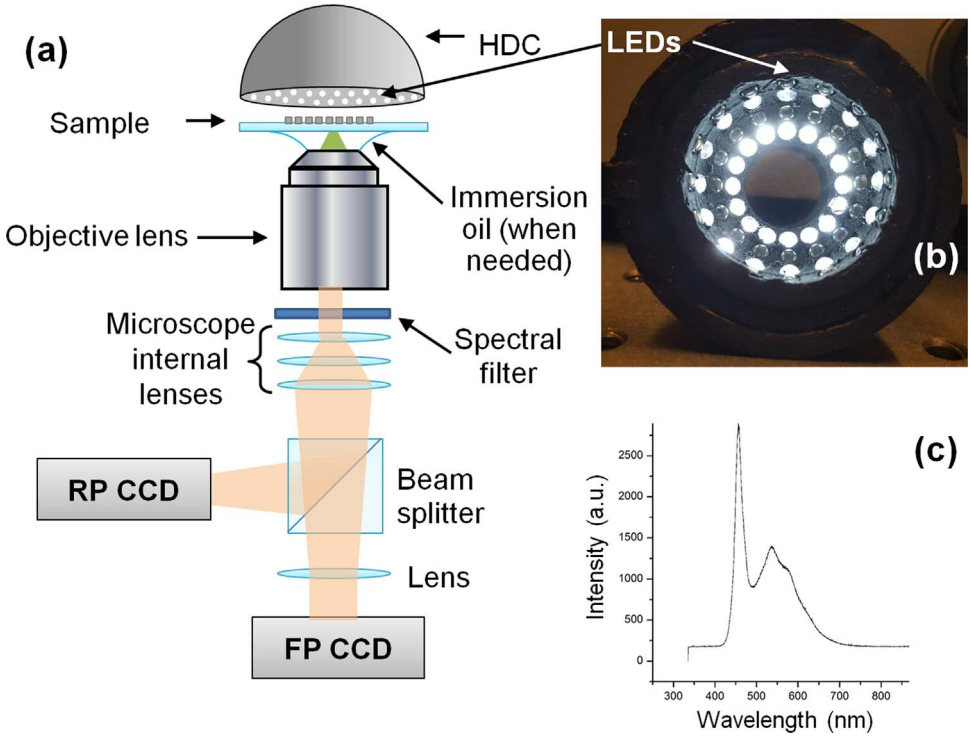

Fig. 1. (a) Schematic illustration of our experimental setup, (b) photograph of the HDC, (c) Emission spectrum of a single LED.

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