Thermo-Optical Modulation of PPLN Crystal for Tunable Poisson Spot Array

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***Abstract*—Lithium Niobate is a ferroelectric material with interesting physical properties. In particular, Periodically Poled Lithium Niobate (PPLN) crystals have been used in diverse applications, such as non-linear optics or microlens array fabrication. In this work, we used a PPLN crystal having hexagonal reversed polarization domains, disposed on a square array of 200 μm period. We applied a temperature gradient to the PPLN and simultaneously observed it with a lensless incoherent holographic microscope. We observed that the phase of the inverse polarization domains varied depending on the temperature applied. Therefore, we induced a thermo-optical modulation of the PPLN crystal. We further analysed the behaviour of the PPLN, propagating the complex field beyond the crystal and plotting its intensity. We found that an elongated bright spot was formed at the centre of each hexagonal reversed polarization domain, due to diffraction. Given their shape and the nature of the phenomenon, these intensity spots are similar to Poisson spots. The intensity of the spots depended on the phase of the PPLN (hence, on the temperature applied). Therefore, we were able to generate a tunable Poisson spot array by controlling the temperature of the PPLN.**

***Index Terms*—Periodically poled lithium niobate, PPLN, thermo-optical modulation, poisson spot, lensless incoherent holography.**

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I. Introduction

Lithium Niobate (LN) is a ferroelectric crystal widely used for several optics and optoelectronics applications. Its optical properties make it a fundamental element for electro-optical modulators in fibre-optic communication systems [1], [2] and non-linear optics devices [3], [4]. LN also presents interesting physical properties. Its high spontaneous polarization at room temperature, for example, has been explored for investigating its effects on cells [5]. LN also exhibits pyroelectricity, that is the change of spontaneous polarization caused by a temperature variation, according to $\Delta P = p_i \Delta T$, where ΔP is the coefficient of the polarization vector, p_i is the pyroelectric coefficient and ΔT is the temperature variation [6]. In [7], [8], the electric field activated by the application of a thermal stimulus was used to print polymer 2D and 3D structures in a nozzle-free configuration. The polarization orientation of the LN crystal can be reversed by the application of an external electric field [9]. Periodically poled LN (PPLN) crystals can be obtained selectively reversing the polarization of the material by means of a periodically patterned mask [10]. These functionalised crystals have been exploited for the generation of tunable terahertz waves [11] or for electrically controlled Bragg-diffraction gratings [12]. PPLN crystals were used to fabricate microlens arrays through the pyroelectric-generated self-assembling of thin films (of liquid or polymer) deposited onto the crystal surface [13], [14] and for the non-contact trapping of cells or particles immersed in it [15], [16]. PPLN crystals were also used to realize flexible optical illuminators combining the electro-optical tunability and the Talbot effect [17]. Due to the periodicity of the reversed polarization domains, the PPLN produced different kind of diffraction patterns in the near field when illuminated with a collimated laser beam. Specifically, different illumination patterns were obtained by controlling the voltage applied between the crystal faces, that is, by tuning the phase-step of the PPLN.

In this work, we induce a thermo-optical modulation of the phase of a PPLN crystal. We demonstrate that it is possible to control the phase profile of the inverse polarization domains of the PPLN applying a temperature gradient. Simultaneously illuminating this phase array by an LED, we observe an intensity spot at the centre of each hexagonal-shaped domain. The intensity spot varies depending on the phase (hence, on the temperature gradient). These intensity spots are due to diffraction, and they can be considered Poisson spots. The Poisson spot (also called spot of Arago) is the interference spot that is formed at the centre of an opaque disc's shadow when the disc is illuminated by a collimated beam.

For the observation of the phase modulation of the PPLN crystal and the subsequent rise of the Poisson spot behind the reversed polarization hexagonal domains, we implemented a lensless incoherent holography set-up [18]. This system allows us to observe a wide portion of the PPLN, as its field of view is almost equal to the size of the camera sensor. Besides, it allows the reconstruction of the complex field and its propagation, from a single image recording of the sample. This permits to record a video of the sample during the application of the temperature gradient and to reconstruct *a posteriori* the phase map of the PPLN and the intensity of the light transmitted. The modulation of the phase mask array enables the tunability of the spots. In fact, during the application of the temperature gradient, we observed an increase of the intensity at the center of the beam by a factor ∽3.

Besides being investigated from a theoretical point of view [19], [20], Poisson spot has been used for different applications, such as measurement of surface corrugation [21], astronomy [22], or particle imaging velocimetry [23]. Poisson spots formed illuminating an array of opaque discs have been used for the fabrication of microtube arrays through diffraction lithography [24], [25], [26]. For this specific application, the possibility to modulate the Poisson spot array and switching the spots on and off applying a temperature gradient onto the LN crystal would open the way for a fine controlling of the geometrical characteristics of the fabricated microtube array.

II. Materials and Methods

A. Periodically Poled Lithium Niobate

The sample used in this work is a 500 µm thick, optically polished, z-cut LN crystal. The PPLN was obtained through electric field poling [9], [10]: an external electric field higher than the coercive field of the material (∽21 kV/mm) was applied between the crystal sides, to reverse its spontaneous polarization. The periodical pattern of reversed polarization domains was achieved through the use of a photolithographic mask. The pattern consists of hexagonal domains of internal diameter 100 µm disposed on a square array, having 200 µm period in both x and y directions. The PPLN obtained is shown in Fig. 1.

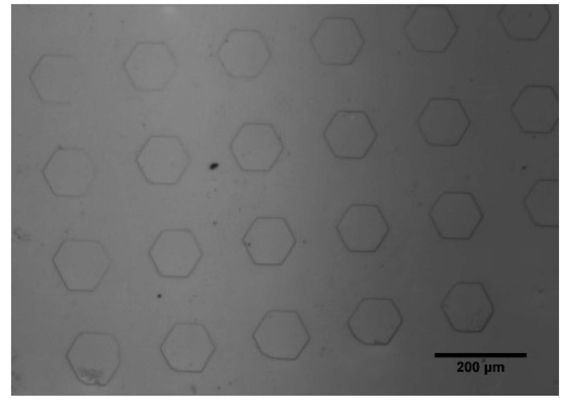

Fig. 1. The PPLN observed with an optical microscope, after being heated up to 100 °C. The internal diameter of the hexagonal domains is 100 µm, while their period is 200 µm.

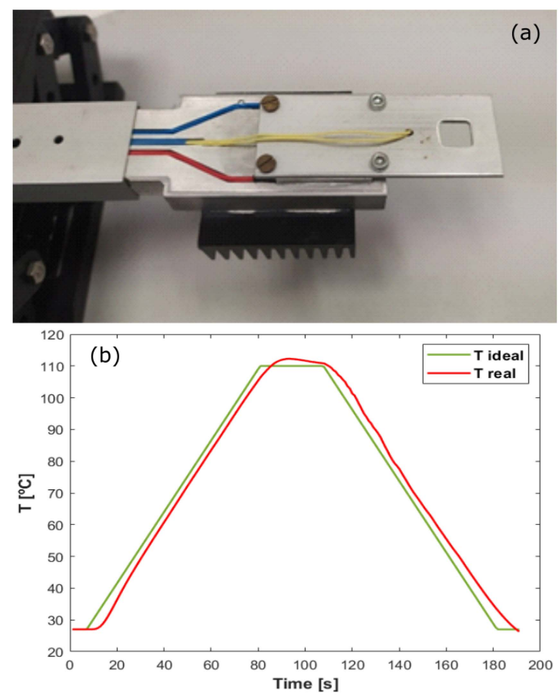

Fig. 2. (a) The thermal device used to apply the temperature gradient to the PPLN. The square window permits the real time observation of the sample in transmission mode. (b) The ideal and the real temperature curve applied.

B. Temperature Gradient

A temperature gradient was applied to the PPLN, through a customized device whose functioning is based on a Peltier cell. The thermal device is shown in Fig. 2(a). The square window permits the observation in transmission mode. The device is controlled by a customized software that permits to set the temperature gradient and to follow the measured temperature in real time. The PPLN is placed onto a glass microscope slide and this is put onto the thermal device. The PPLN is heated up following a ramp from 27 °C to 110 °C (with a temperature changing rate of ∽1 °C/s) and subsequently cooled down to 27 °C (with a temperature changing rate of ∽-1 °C/s). The ideal temperature and the real temperature sensed are shown in Fig. 2(b). We set a plateau of 30 seconds at 110 °C in the controlling software, to let the device reach the maximum temperature and stabilise before going down. This temperature gradient provokes a change in the refractive index of the material. Hence, a thermo-optical modulation of the PPLN is induced. Compared to the classic electrical modulation, the thermo-optical modulation has the advantage of being an electrodeless method, thus avoiding the application of high external voltages. The electrical modulation would be preferable just in those cases where high speed modulation is needed.

C. Lensless Incoherent Holography

For the observation of the sample, we built a lensless incoherent holographic microscope [18]. A scheme of the

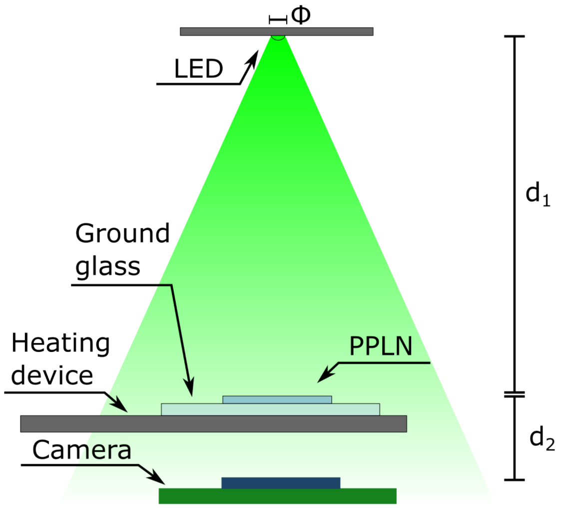

Fig. 3. A scheme of the lensless incoherent holographic microscope used for the real time observation of the PPLN sample during the application of the thermal stimulus.

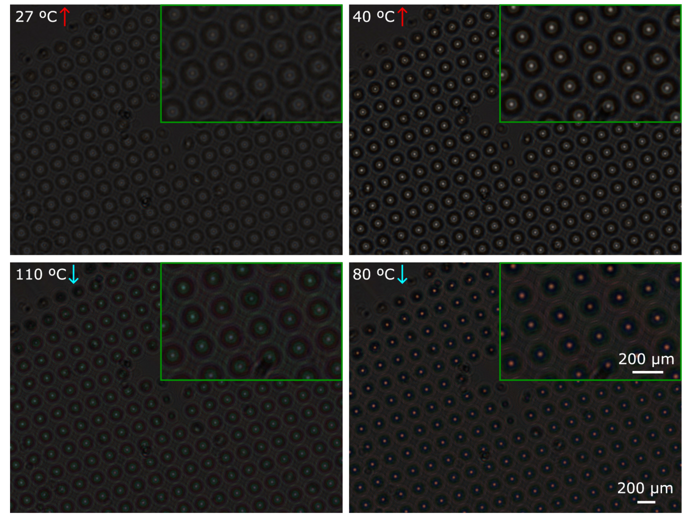

Fig. 4. Some frames of the video of the PPLN at different temperatures, recorded with the lensless incoherent holographic microscope. The insets show a zoom on some hexagonal domains.

set-up is shown in Fig. 3. The sample is simultaneously illuminated by three fibre-coupled LEDs (central wavelengths $\lambda = [455, 530, 617]$ nm) and the diffraction pattern is directly registered by a CMOS camera (Alvium 1800 U-1240c). A video of the sample is recorded during the temperature gradient, with a frame rate of 0.5 frames/s. Through a phase-retrieval approach (denoted as "Method 2" in [18]), the complex field of the sample is reconstructed. This allows to reconstruct, in a post-processing stage, the phase map of the PPLN changing over temperature. Through the propagation of the complex field of the sample, we obtained the intensity of the light transmitted by the PPLN. Therefore, extracting this information at different time points, we were able to analyse the effect of the thermo-optical modulation of the PPLN on the transmitted light.

Differently from lensless coherent holography [27], [28], in this system, the distance between the illumination and the sample (d_1) must be set much higher than the distance between the sample and the sensor (d_2). This is because the aperture, Φ, that is illuminated by the incoherent source, is scaled down by a factor $M = d_1/d_2$ at the sensor plane. Setting $M \gg 1$ (i.e. $d_1 \gg d_2$), the incoherent illumination through Φ can be considered as coherent illumination for each individual object of the sample. In our case, the distance between the sample (PPLN) and the camera sensor is limited by the thickness of the heating device and the ground glass. Moreover, the heating device could not be located too close to the sensor, as the high temperature could damage the camera. To avoid this problem, we finally had $d_2 \backsim 4.5$ mm. The distance between the LED and the sample had to be set consequently. Typical values of M are greater than 40. Setting $d_1 \backsim 175$ mm, we have $M \backsim 39$. Therefore, at the sample plane, the width of each point scatterer is $\phi = \Phi/M \backsim 5$ μm (being $\Phi = 20$ μm).

III. Results

With the set-up described in the previous section, we recorded a video of the surface of the sample during the application of the temperature gradient. Fig. 4 reports some frames of the video captured. The insets show a zoom on a small portion, for a more detailed visualization of a limited number of hexagonal domains. The corresponding temperature is indicated, along with an arrow that indicates if the frame corresponds to the heating stage (red up arrow) or the cooling stage (blue down arrow). From the raw data captured, it is possible to note an array of spots, whose intensity changes over time (so, over the applied temperature). This phenomenon is analysed more deeply in the following sections.

A. Phase Modulation of PPLN

The first step was the calculation of the phase map of the sample. We extracted the information of the green channel of the camera. From the datasheet of the camera, we know that the data of the green channel has negligible contribution from the blue and red LEDs. We processed one every ten frames of the captured video. Each frame was processed with the phase-retrieval approach described in [18]. The complex field was estimated at -9 mm from the sensor (considering negative distances as opposite to the light propagation direction) for a better estimation of the object support. Then, it was propagated to the sample plane. Due to thermal expansion at high temperatures, the distance between the sample and the sensor slightly changes during the temperature gradient. If this effect was not taken into account and the sample was always reconstructed at the same depth, we would have obtained slightly defocused reconstructions. To avoid such imperfections, the retrieved complex amplitude was refocused into the best sample plane. Additionally, a lateral displacement of the PPLN occurred, probably due to the formation of an air layer between the thermal device and the sample. Therefore, we also compensated for the lateral displacement between one processed frame and the following one.

The focused phase map of the PPLN is shown in Fig. 5. Specifically, in Fig. 5(a), we show the phase map of the PPLN at four different time points (so, four different temperatures). In

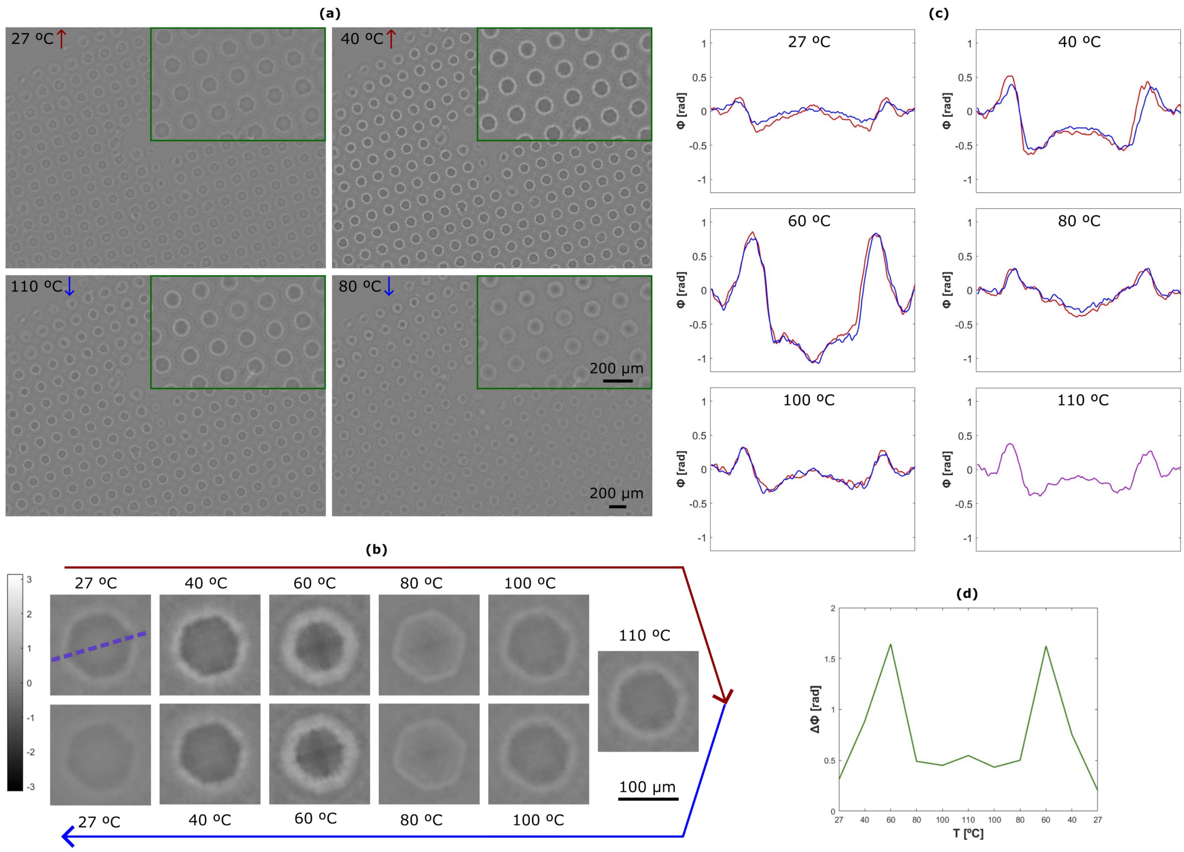

Fig. 5. Phase map of the PPLN. In (a), the whole phase maps reconstructed from the PPLN captured at four different temperatures. The insets show an enlarged portion of the phase map for each temperature. In (b), the phase maps of a single hexagon reconstructed every ten frames of the video. The scale bar on the left represents the value of the phase in radians. (c) The phase profile along the purple line of the first hexagon of (b) at the different temperatures. For each temperature, the phase profile during the heating stage is the red curve, while the phase during the cooling stage is the blue curve. (d) The phase step of the hexagon (difference between the phase of its edge and that of its inner part) during the whole temperature gradient.

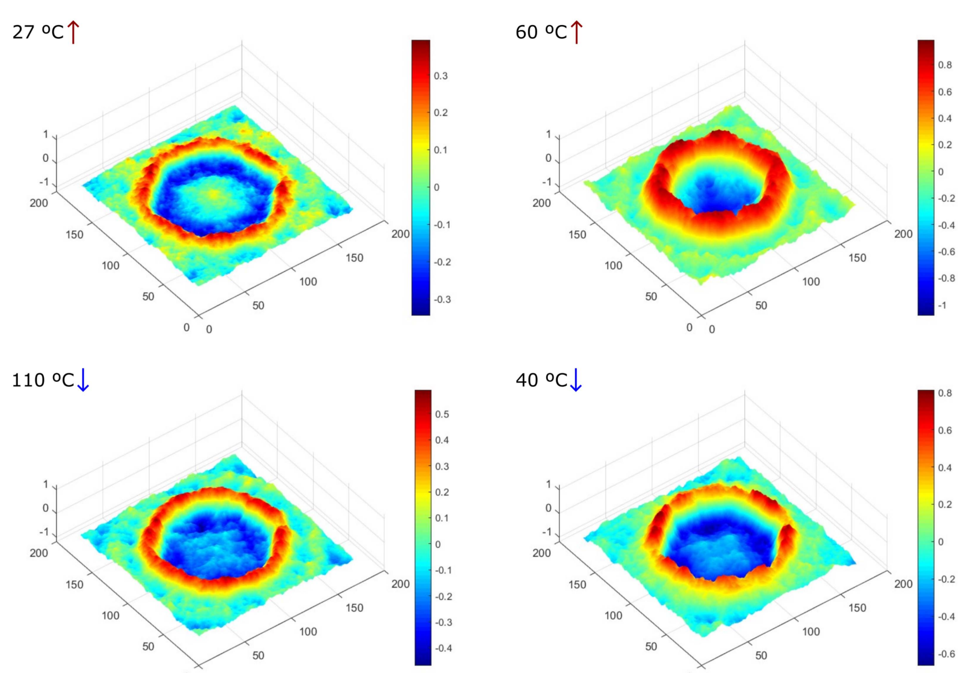

Fig. 6. 3D representation of the phase map of a single hexagon at four different temperatures. Note that the range of the scale bar of the phase (in radians) is different for each frame.

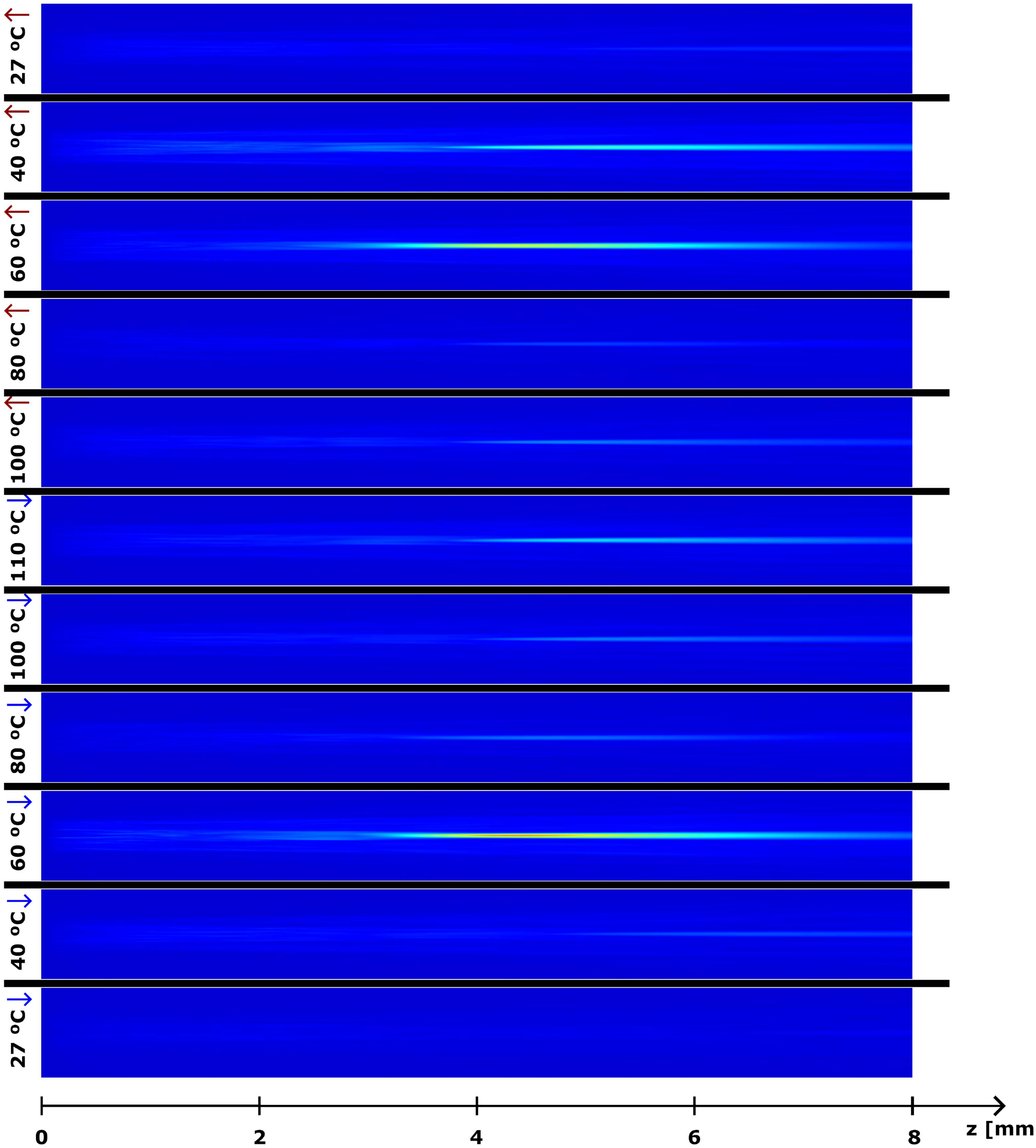

Fig. 7. The intensity from 0 to 8 mm behind a single hexagon at different temperatures of the thermal stimulus. We observe the formation of a bright spot at the centre of the hexagon, whose intensity changes during the temperature gradient.

Fig. 5(b), we focus onto the phase map of a single hexagon, showing how it changes along all the temperature gradient applied to the sample. We can notice that the phase map of the single hexagon at a given temperature in the heating stage is almost equal to the phase map at the same temperature in the cooling stage. This is more evident from Fig. 5(c). Here, the phase profile along the purple line shown in the first hexagon of Fig. 5(b) is plotted. For each specific temperature, the phase profiles during the heating (in red) and cooling (in blue) stages are compared in the same plot. In Fig. 5(d), the phase step of the single hexagon during the entire temperature gradient applied to the PPLN crystal is reported. The phase step is calculated as the difference between the average phase of the edge of the hexagon and average phase of its inner part. As expected from Fig. 5(c), the behaviour is symmetric in the heating and cooling stages, with respect to the maximum temperature. The phase step is minimum at 27 °C, it reaches its maximum value at 60 °C and then rapidly decreases. It remains approximately constant between 80 °C and 110 °C and follows a symmetrical trend during cooling. In Fig. 6, the phase map of the single

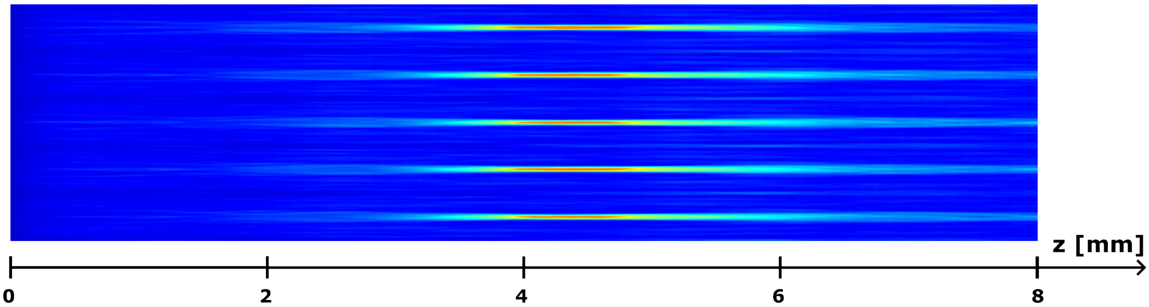

Fig. 8. The intensity propagation of five hexagonal reversed polarization domains, at 60 °C (cooling stage).

hexagon at four different temperatures are shown in a pseudo-3D representation, with the height representing the phase value.

B. Tunable Poisson Spots

From the phase maps reconstructed at different temperatures, we propagated the complex field and evaluated its intensity. The results are shown in Fig. 7: we observe an elongated bright spot at the centre of the hexagonal domain, that is formed ∽3 or ∽4 mm after the PPLN plane, depending on the temperature. The formation of the bright spot is due to diffraction. This is similar to the so-called Poisson spot, that is the bright spot observed at the centre of the shadow behind an opaque disc, when this is illuminated with a collimated laser beam. Interestingly, in our case the intensity and shape of this bright spot varies depending on the temperature. This is because, as we saw before, the phase of the hexagonal reverse polarization domain changes with the temperature applied to the PPLN crystal. The effect is weak at 27 °C and maximum at 60 °C. This means that we can modulate the Poisson spot array controlling the temperature applied to the crystal.

Finally, in Fig. 8, we show the intensity behind five hexagonal reversed polarization domains at 60 °C, during the cooling stage. If we compare this image with the intensity of a single hexagon at 60 °C (Fig. 7), we see that the bright spots of the hexagon array are shorter in depth. This effect could be due to the interference between the light diffracted by each hexagon.

IV. Conclusion

In this work, we have demonstrated the formation of a tunable intensity spot array similar to Poisson spots, behind a PPLN crystal. We used a PPLN with hexagonal shaped reversed polarization domains, disposed on a square array having 200 µm period. We applied a temperature gradient to the crystal, composed of a ramp up from 27 °C to 110 °C and subsequent ramp down to 27 °C. By means of a lensless incoherent holographic microscope, we were able to observe the PPLN during the thermal stimulus and later reconstruct its phase map at the different temperatures. We demonstrated that we were able to induce a thermo-optical modulation of the PPLN without using external electrodes but just employing the intrinsic properties of the PPLN. In fact, the phase profile of the hexagonal reversed polarization domains changed depending on the temperature. The behaviour is symmetrical in the heating and cooling stages, being the phase step minimum at 27 °C and maximum at 60 °C for both stages. Once the PPLN was quantitatively characterised, we propagated the field behind the crystal and we analysed its intensity. We found that an elongated bright spot is formed behind the centre of each polarization reversed domain, due to diffraction. Given their axial shape and their nature, these spots are similar to the so called Poisson spots. The intensity of each spot varied depending on the temperature applied on the crystal. Therefore, we demonstrated the formation of a tunable Poisson spot array by thermo-optical modulation of the PPLN crystal. The system used for the experiments reported can be reused multiple times and could be easily integrated on microfluidic platforms and lab-on-chip systems.

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