Near Field Transmission of Ordered Arrays of Sub-Wavelength Holes Fabricated in Lithium Niobate by Femtosecond Laser Writing.

Jorge Barrio, Jorge Lamela, Airán Ródenas, Daniel Jaque, Ginés Lifante, Francisco Jaque
Departamento Física de Materiales, F. Ciencias, Universidad Autónoma de Madrid, 28049 Madrid, Spain
e.mail: daniel.jaque@uam.es
Guangyong Zhou, and Min Gu
Centre for Micro-Photonics and Centre for Ultrahigh-bandwidth Devices for Optical Systems, Faculty of Engineering and Industrial Sciences, P. O. Box 218, Hawthorn, Victoria 3122, Australia.
mgu@swin.edu.au

***Abstract*— In this work direct femtosecond laser ablation of ordered arrays of sub-λ/4 (80-200 nm) holes in $LiNbO_3$ crystals is presented. The near field transmission properties of the fabricated arrays of sub-micrometric holes have been investigated by means of Near Field Scanning Microscopy. We have found a rich variety of phenomena all of them in agreement with beam propagation simulations. We have found that the near field intensity distribution created by the fabricated arrays could lead, under certain conditions, to intensity enhancements in excess of 50%, behaving as efficient near field lenses.**

Keywords: femtosecond ablation, SNOM, sub-wavelength

I. INTRODUCTION

The possibility of creating controlled periodic nanostructures at the surface of ferroelectric nonlinear lithium niobate (LN) crystals is nowadays attracting much attention because of its numerous applications including the fabrication of two-dimensional (2D) photonic crystals [1], micro-diffraction elements [2], 2D photonic crystals [3], and novel focusing structures when combined with metallic coatings [4]. Among the different techniques capable of controlled surface structuring in LN crystals at the sub-micrometric scale (such as focused ion beam milling, ion beam enhanced etching, or mask assisted plasma etching), femtosecond laser ablation (FLA) is of special relevance because its simplicity, reduced processing times and absence of sample preparation requirements [5]. Nevertheless, for most of the above mentioned applications (especially those involving visible light control) reduced hole sizes are required. The possibility of using high-NA (NA > 1) optics has been already demonstrated in several materials (including glasses and self-assembled monolayers) [6,7], but its potential application in LN crystals for beating the 200 nm limit is still unexplored. In addition to the above mentioned practical applications, the creation of sub-200 nm surface structures in a high refractive-index nonlinear medium such as LN (n ~ 2.2 - 2.4) is also interesting from a fundamental point of view since they could open the avenue novel fundamental effects, such as extraordinarily high transmission or polarization-sensitivity effects [8].

In this work we report on the femtosecond laser fabrication of orders arrays of sub-λ/4 holes in a LN crystal by multi-pulse ablation, with a full control over the hole diameter in the 80-200 nm range. We demonstrate that the presence of the fabricated nano-holes strongly modulates the near-field optical transmission of the LN surface. We show that the near-field transmitted intensity almost vanishes at hole´s central position, whereas a significant near-field enhancement is produced at its surroundings. The increment observed in the near field intensity in the surroundings of the nano-holes has been found to be weak for single nano-holes but of relevance in the case of ordered arrays of nanoholes. By comparing the measured and FDTD simulated NSOM images we found nanometric surface relief in combination with cooperative multiple-scattering as the key factors for the optical contrast mechanisms.

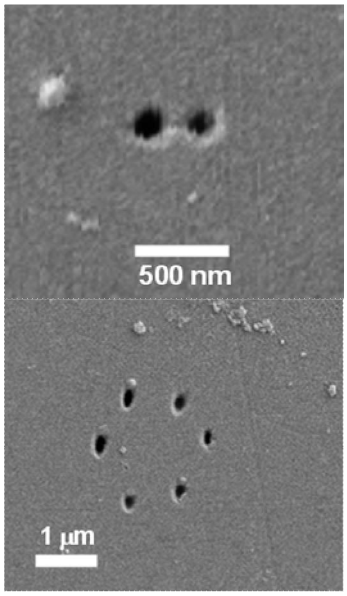

Fig 1.- Ordered arrays of nano-holes fabricated in LN by fs laser ablation.

II. EXPERIMENTAL

The LN samples used in this work were 0.5x1x10 mm^3 prisms in both x-cut and z-cut orientation. Femtosecond laser ablation was done by using a Spitfire (Spectra Physics) regenerative amplifier generating ~150 fs laser, linearly polarized pulses at 800 nm wavelength, with a 1 kHz repetition rate. The laser beam was focused onto the LN surface by using an oil immersion Olympus PlanAPO 60X TIRFM microscope objective with a numerical aperture (NA) of 1.45. The size of the ablated nano-holes was controlled by a careful adjust of the irradiation energy. The NSOM image was obtained with a Nanonics near-field microscope (MultiView 200 TM) working in non-contact tapping mode using a visible 532 nm continuous wave laser for back illumination of the sample and a ~100 nm aperture fibre for near-field collection. The fibre was kept at a constant separation of ≈20 nm above the LN surface.

III. RESULTS AND DISCUSSION

Figure 1 shows an example of two simple arrays (consisting of two and six nanoholes) fabricated at the surface of the LN sample. The particular experimental conditions used for this structure lead to nano-holes with an average size well below 200 nm. As it can be seen fs laser writing well allows for surface relief with a spatial control in the nanometric scale with a complete absence of extended damage regions.

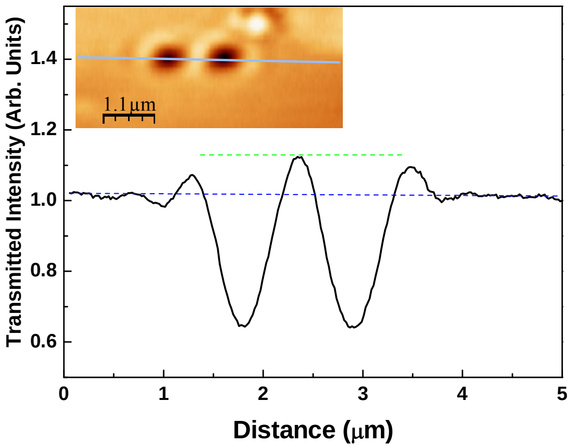

Fig 2.- Inset shows the SNOM transmission image obtained from a pair of nano-holes separated 1 μm. Black line corresponds to the intensity profile as obtained along the scan direction indicated in the inset. Blue and red dashed lines indicate the background and enhanced intensity, respectively.

Once the structures were fabricated then the near field transmission was characterized by SNOM measurements. Some results are summarized in Figure 2. In this Figure we show as an inset the near field transmission image obtained for a pair of nano-holes separated 1 μm. In this Figure it is clear that the near field intensity is strongly reduced at the centre of both holes. This is compensated by a near field increment in the hole's surroundings, in accordance to previous experimental and theoretical works [9]. The most relevant result can be appreciated in the intensity profile shown by the black line. In this profile it is clear that the near field intensity is enhanced in the region between holes (see the different intensity levels indicated by the blue and red lines). This effect can be understood in terms of the constructive overlap between the scattering filed distributions created by each hole, denoting a cooperative scattering phenomenon. The validity of this assumption was checked by numerical simulations, that have shown an excellent agreement from both the qualitative and quantitative point of view.

We have found that when the number of scattering centers is increased (as in the array shown at the bottom of Fig.1) the Near Field enhancement induced between these sub-wavelength scattering centers is increases even further, reaching a total amplification at the middle of the structure exceeding 40% in respect to the background intensity.

IV. CONCLUSIONS

We have fabricated ordered arrays of sub-wavelength scattering centers in Lithium Niobate crystals by femtosecond laser ablation. The Near Field Optical images of the obtained structures denote the presence of cooperative scattering. We state at this point that the fabricated structures emerge as very promising structures for their use as potential lenses in the Near Field.

ACKNOWLEDGMENT (HEADING 5)

This work has been supported by the Spanish Ministerio de Educación y Ciencia (MAT2004-0334 and MAT2007-64686), by the Universidad Autónoma de Madrid and Comunidad Autónoma de Madrid (projects MICROSERES-CM and CCG07-UAM/MAT-1861), and by the Australian Research Council (ARC) Centre of Excellence for Ultrahigh-bandwidth Devices for Optical Systems (CUDOS, No. CE0348259), and ARC Discovery grant (No. DP0665868).

REFERENCES

[1] S. Diziain, J. Amet, F.I. Baida, and P.M. Bernal. Appl. Phys. Lett. **93**, 261103 (2008).

[2] G.A. Torchia, C. Méndez, I. Arias, L. Roso, A. Ródenas, D. Jaque. Appl. Phys. B. **83**, 559 (2006).

[3] K. Kokkonen, M. Kaivola, S. Benchabane, A. Khelif, and V. Laude. Appl. Phys. Lett. **91**, 083517 (2007).

[4] M. Merano, G. Boyer, A. Trisorio, G. Chériaux, and G. Mourou. Opt. Lett. **32**, 2239 (2007).

[5] F. Korte, J. Serbin, J. Koch, A. Egbert, C. Fallnich, A. Ostendorf and B. N. Chichkov. Appl. Phys. A. **77**, 229 (2003).

[6] Y.V. White, X. Li, Z. Sikorski, L.M. Davis and W. Hofmeister. Opt. Express **16**, 14411 (2008).

[7] N. Hartmann, S. Franzka, J. Koch, A. Ostendorf and B. N. Chichkov. Appl. Phys. Lett. **92**, 223111 (2008).

[8] A. Battula, S. Chen, Y. Lu, R. J. Knize and K. Reinhardt. Opt. Lett. **32**, 2692 (2007).

[9] A. Ródenas et al, Appl. Phys. Lett. **95**, 181103 (2009)