Romanian Reports in Physics, Vol. 65, No. 3, P. 915–924, 2013

At the 70th Anniversary of Professor Vlad, one team in nonlinear optics

EXPERIMENTAL INVESTIGATION OF THE OUTPUT MODE PROFILE OF SOLITON WAVEGUIDES RECORDED AT 405 NM WAVELENGTH IN LITHIUM NIOBATE

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Received July 8, 2013

Abstract. We have recently shown that soliton waveguides in lithium niobate can be recorded very fast and at very low power levels using 405 nm wavelength. In this paper we analyse the mode profile of soliton waveguides (SWGs) recorded at 405 nm using different external electric fields and different polarizations of the writing beam. We show that there is a beneficial effect in the minimum mode size that can be obtained when recording at this wavelength. This is due to a lower photovoltaic field at 405 nm compared to that at 532 nm wavelength, which is usually used for recording SWGs in lithium niobate.

Key words: soliton waveguides, lithium niobate, photorefractive, integrated optics.

1. INTRODUCTION

Since the first study of self-trapped beams by Chiao et al. [1] there has been an intensive research in this broad domain. Optical solitons are self-trapped beams or optical pulses that do not change their spatial or temporal profile, respectively. They are mathematical solutions to a non-linear Schroedinger equation [2]. In the spatial domain, natural beam diffraction can be compensated by the material non-linearity, generating spatial solitons. Temporal solitons are dispersion compensated light pulses that maintain their temporal shape during propagation. There are also spatio-temporal solitons that are pulses which propagate without modifying their shape in both space and time domains [3, 4]. The latter, so-called “light bullets”, are the ideal way to transport information since dispersion is the main detrimental factor to the maximum bit rate. Recently, theoretical models have been also developed for solitons generated with ultrashort pulses [5, 6].

Spatial solitons exist in many forms – bright, dark, discrete and can be generated experimentally by different physical mechanisms (Kerr, quadratic, photorefractive). A recent review [7] points out the broad family of spatial solitons. Very much work has been done in the domain of photorefractive solitons where the beam localization can be obtained in both transversal directions due to the saturating nature of the photorefractive nonlinearity. They have been observed in different photorefractive materials like SBN [8–11], BSO [12–15] or $LiNbO_3$ (LN) [16–22]. The interest in generation of photorefractive spatial solitons is due to the possibility to maintain a spatially confined propagation with very low light powers (~nW). Also, generation of spatial solitons in some photorefractive materials can create a refractive index profile that remains recorded in the crystal for a long time in the absence of the illumination. The persistence of the refractive index profile inside the material represents what is usually called a soliton waveguide (SWG). This SWG, maintained in the crystal by a space-charge field created by illumination, has a lifetime of the order of the dielectric relaxation time. In lithium niobate, SWG lifetime can be of the order of one year [21, 24]. The term soliton waveguide is usually used in a broader sense to refer to waveguides created by self-trapped beams even if they are not an exact mathematical soliton solution to the propagation equation. In photorefractive materials, quasi steady-state solitons (QSS) can be generated. They can exist only in a finite time interval [9]. The experimental conditions to record SWGs generated by QSS are typically more relaxed. QSS do not depend on the signal to background irradiance ratio and can be generated by input beams with a wide range of transversal diameters. This means that they can be generated without special background illumination, which is usually used when generating bright steady-state solitons. It is important to note that from an applicative point of view it is not so important to have exact soliton solutions for self-trapped propagating beams. Moreover, particular applications may require waveguides with different transversal sizes and shapes. These can be created by modifying the SWG recording parameters [23]. Depending on the signal beam focusing, the recorded SWG can be planar, cylindrical or conical. The waveguide size and shape can also be controlled by exposure time, external voltage, temperature variation or beam polarization.

Recently, we have shown that SWGs can be recorded very fast and at low optical powers in LN, using 405 nm wavelength. The recording process was assisted by an electric field generated using an external voltage [24] or by pyroelectric effect, heating the crystal with several degrees [25]. The low recording time at 405 nm is due to several wavelength dependent properties that favour the recording speed at this wavelength (absorption, photoconductivity, electro-optic coefficients etc.). In this paper we show that the recording at this wavelength has also important influence on the waveguide refractive index profile that determines the transversal mode profile. We analyze the transversal mode profile at 405 nm wavelength for different experimental parameters (external electric field, optical irradiance, and beam polarization). We continue the analysis started in [26] and demonstrate the benefit regarding the transversal mode size when using 405 nm instead of 532 nm wavelength. We analyse the influence of the signal beam polarization on the output transversal mode profile.

2. EXPERIMENTAL SETUP

The experimental setup is similar to that used in [24] and it is shown in Fig. 1. The crystal used is a piece ($8.2 \times 5.5 \times 2$ mm^3) from a congruent commercially available z-cut LN wafer. A voltage source was used to apply a high voltage on the crystal in order to create an electric field in the direction of the crystal *c*-axis. We used as light source for SWGs recording a 405 nm laser diode with an elliptical beam shape. The signal beam is focused on the input face of the LN sample with the lens L1 (focal length = 7.5 cm) to an input beam spot of ~ 10 µm × 12 µm at FWHM. Light propagation is along the 5.5 mm direction of the LN sample. Using two polarisers (P1 and P2), the beam power is modified while keeping the desired polarization of the signal beam. The background irradiance, given by the ambient laboratory light, is of the order of 1µW/cm^2.

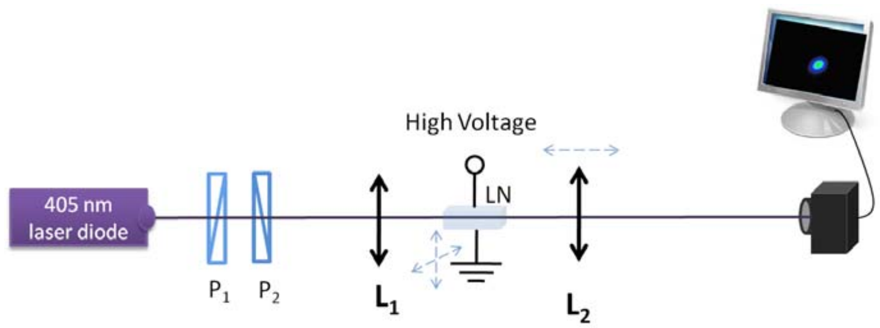

Fig. 1 – Experimental setup for SWG recording.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1. ANALYSIS OF THE TRANSVERSAL MODE PROFILE DURING SWG RECORDING

We have recorded several SWGs for different external electric fields (E), keeping constant the signal beam irradiance on the input face of the LN crystal. The signal beam has irradiance of the order of 1 W/cm^2 on the input face of the crystal. This irradiance level is 6 orders of magnitude higher than the background irradiance. This means that only QSS can be generated [9]. The evolution of the mode size (FWHM) is shown in Fig. 2 for low E (~7kV/cm – Fig. 2a) and high E (~34 kV/cm – Fig. 2b), and for an extraordinary polarization (e-pol) of the signal beam. As expected there is a stronger and faster confinement on the *c*-axis direction (vertical direction).

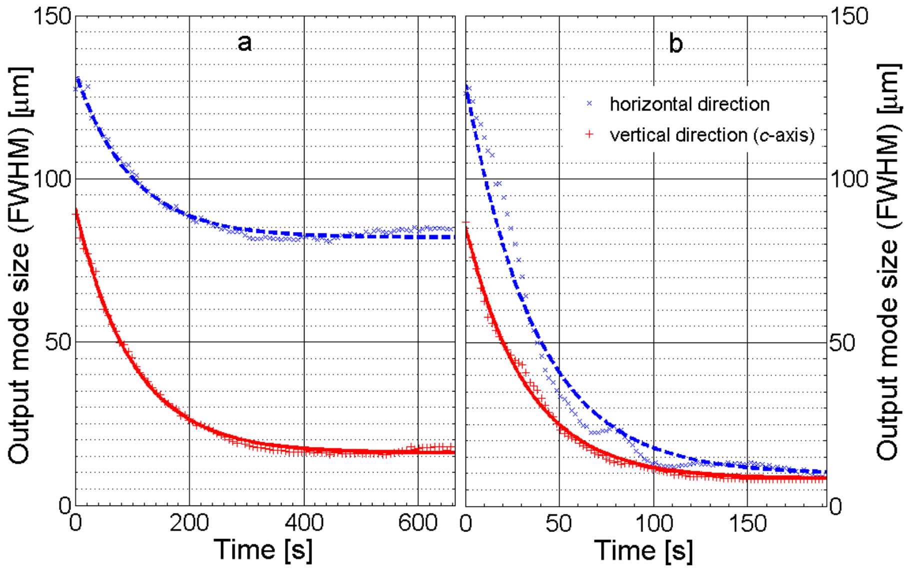

Fig. 2 – Output mode size evolution during SWG recording with e-pol, with:
a) $E \sim$ 7kV/cm; b) $E \sim$ 34 kV/cm.

It can be seen from Fig. 2 that there is a time interval when the mode size has a minimum value. This time interval was exceeded in our experiments on SWGs recording in order to have a more detailed analysis of the evolution process. For the corresponding recording parameters the time interval is not critical. For $E \sim$ 34kV/cm it is at least 10 s, as shown in Fig. 2b.

The refractive index change that defines the waveguide profile is given by:

$$\Delta n = -\frac{1}{2} n^3 r_{eff} E_{SC}, \tag{1}$$

where n is the unperturbed refractive index of the crystal, r_{eff} is the effective electro-optic coefficient dependent on light polarization and direction, and E_{SC} is the space-charge field created by illumination. The waveguide profile size and shape is determined by the final spatial dependence of the space-charge field at the end of the recording. The recorded space-charge field is mainly influenced by charge diffusion, photovoltaic field and external voltage. A maximum refractive index change can be obtained when E_{SC} reaches E-E_{PV}, where E_{PV} is the value of the photovoltaic field at saturation. For low E, the mode size on the output face of the crystal cannot reach the mode size on the crystal's input face and the confinement occurs predominantly only in the vertical direction. For high E, the influence of the photovoltaic field is well compensated and a strong confinement occurs on both transversal directions.

The temporal evolutions of the output mode size for the SWGs recorded with ordinary polarization (o-pol) of the signal beam are shown in Fig. 3, in a similar manner to that used in the Fig. 2. One can observe a slower recording process and a larger mode diameter when using an o-pol signal beam. The consequences of using o-pol signal beam are discussed in detail in Section 3.2.

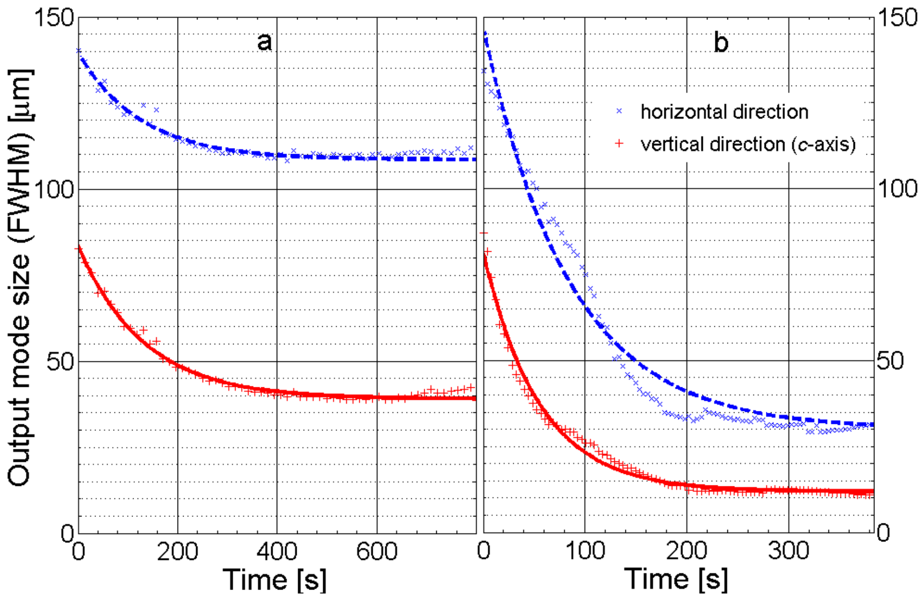

Fig. 3 – Output mode size evolution during SWG recording with o-pol, with:
a) E ~ 7kV/cm; b) E ~ 34 kV/cm.

Images of the input mode profile, initial output mode profile, and minimum mode profile during SWG recording are shown in Fig. 4, corresponding to the recording processes from the Fig. 2. The profiles shown in Fig. 4c and Fig. 4d correspond to initial moments of time, t = 0 s, from Fig. 2a and Fig. 2b. The profiles shown in Fig. 4e and Fig. 4f correspond to minimum mode sizes on the vertical direction at t ~ 570 s from Fig. 2a and t ~190 s from Fig. 2b.

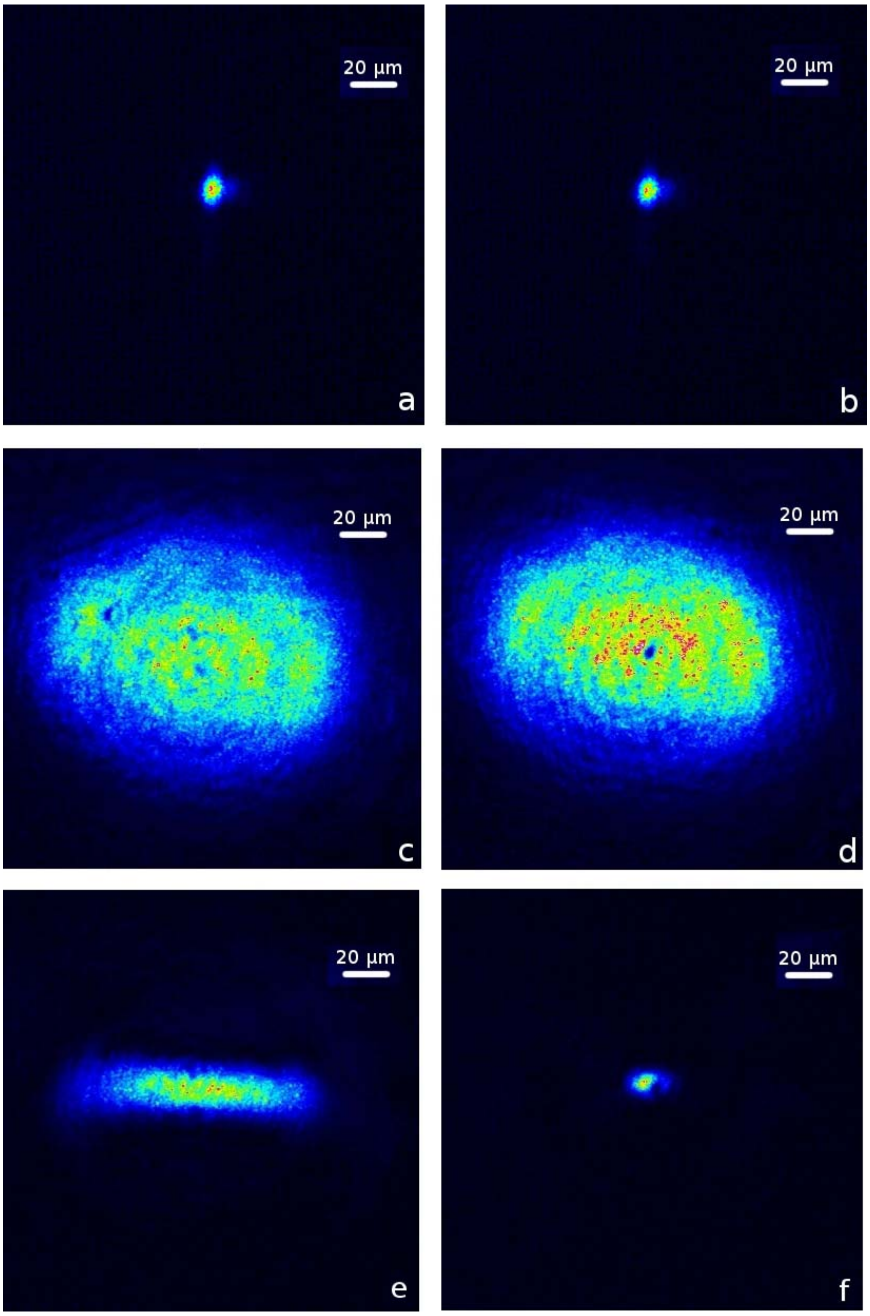

Fig. 4 – Input mode profile (a, b), initial output mode profile (c, d) and minimum output mode profile (e, f), when recording SWGs with $E \sim 7$ kV/cm (a, c, e) and $E \sim 34$ kV/cm (b, d, f).

In Fig. 4 are shown two different types of shape that can be obtained by varying the external field. It is important to note that we can have a good vertical confinement even for low E (7kV/cm). The elliptical mode profile shown in Fig. 4e suggests that the corresponding waveguide can be useful for coupling beams from laser diodes, which usually have an elliptical shape. The confinement when using such a low E demonstrates that the photovoltaic field is of this order of magnitude or even lower. This is an important advantage when using 405 nm wavelength, since at 532 nm the photovoltaic field is significantly higher. To check this, we made an experiment of recording a SWG using an e-pol beam at 532 nm wavelength, and $E \sim 40$ kV/cm. The beam irradiance on the input face was of the order of 1000 W/cm^2, 3 orders of magnitude higher than that used at 405 nm. This was necessary to have an acceptable recording time. The time evolution of the mode size is shown in Fig. 5 until the moment when the propagation becomes unstable. Besides the fact that the recording process is much slower and very unstable, the beam cannot reach a good confinement on both transversal directions.

Even if the transversal mode size for a particular waveguide is increasing with the guided wavelength, the large value in Fig. 5 (~90 µm on horizontal direction comparing with ~9 µm at 405 nm in Fig. 2b) cannot be attributed to the wavelength change and suggests a significant waveguide profile difference. As one can see in Eq.(1), the waveguide profile is also affected by the electro-optic coefficient and the refractive index which slightly decrease at 532 nm, but the main influence is due to the increase of E_{PV}. At 532 nm, E_{PV} has a sub-linear dependence on the irradiance, increasing with $I^{0.5\text{-}0.6}$, for I in the range (30 – 9000) W/cm^2 [27].

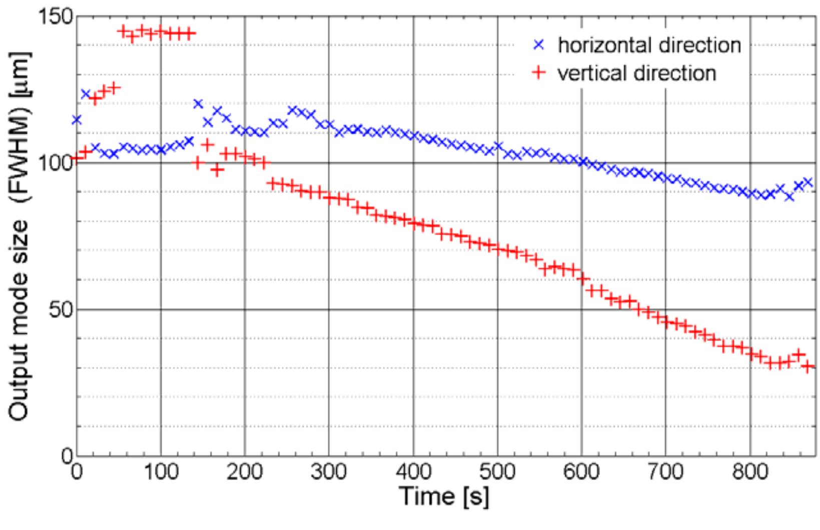

Fig. 5 – Output mode size evolution for SWG recording using e-pol at 532 nm wavelength with $E \sim 40$ kV/cm.

For an acceptable recording time at 532 nm we have to use an increased irradiance since the recording process is much slower at this wavelength. This increases the photovoltaic field and creates a weaker refractive index contrast for the recorded SWG. When the irradiance is low, the photovoltaic field is nearly constant. This is confirmed by the minimum transversal mode size which is not significantly modifying for increasing irradiance when recording SWG at 405 nm at low I [25]. When recording SWGs at 532 nm and constant E, we showed that the output transversal mode size on the horizontal direction is significantly increasing with the irradiance, for I in the range (100–2 500) W/cm^2 [25].

3.2. THE INFLUENCE OF THE SIGNAL BEAM POLARIZATION ON THE TRANSVERSAL MODE SIZE

We have recorded SWGs using both e-pol and o-pol at 405 nm using an irradiance of ~3 W/cm^2 and varying the external field. The minimum transversal mode size on the output face of the crystal was determined for both horizontal and vertical directions and is shown in Fig. 6. After recording the SWGs with o-pol, we used low intensity e-pol beams to propagate through the recorded SWGs and we acquired the mode size on the output face of the crystal.

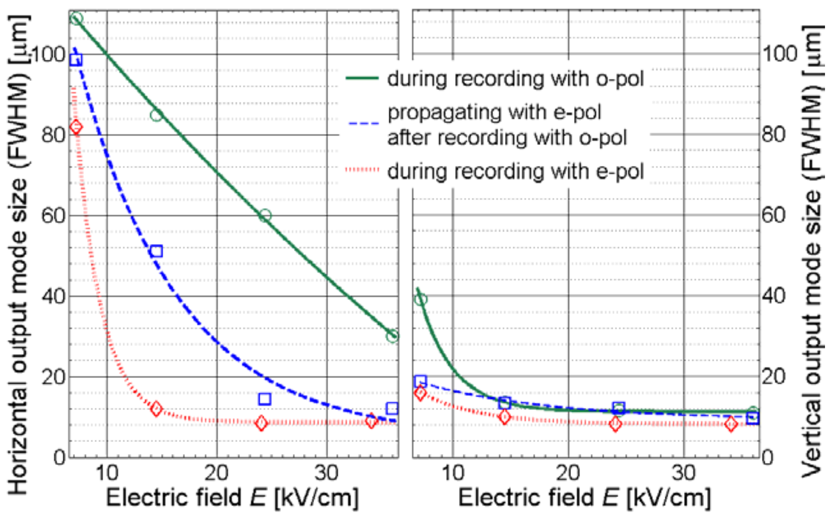

Fig. 6 – Minimum transversal mode size on the output face during recording with e-pol and o-pol and the mode size for propagating e-pol beams through SWGs recorded with o-pol light.

At a first view, the recording with o-pol beams seems to be detrimental compared to the recording with e-pol beams. This is due to the fact that the electro-optic coefficient is ~3 times lower for o-pol [28]. Even if the refractive index is slightly higher for o-pol [22], the difference introduced by the electro-optic coefficient still results in a ~3 times weaker refractive index modification for the same space-charge field. However, when using e-pol beams to propagate through SWGs recorded with o-pol, the beam confinement is better and the size of the vertical mode size is nearly the same as for SWGs recorded with e-pol. Note that the time moment for reaching the minimum mode size on horizontal direction can be different than the time moment for the minimum mode size on vertical direction. This can be seen in Fig. 3b, where the horizontal mode size has a minimum size in the interval 320–355 s and the vertical mode size has a minimum size in the interval 370–380 s. Also, since our SWGs are recorded to analyse the evolution process, the recording process of the SWGs exceeded the moment when the mode size has the minimum size. This is why there is a bigger difference when comparing the minimum output mode size between SWGs recorded with e-pol and propagating beams with e-pol through SWGs recorded with o-pol.

At 532 nm, it was observed that SWGs recorded with o-pol can guide better IR beams at 1550 nm than SWGs recorded with e-pol [24, 29]. This was attributed to a lower E_{PV} when the recording process was done with an o-pol signal beam. E_{PV} influences the waveguide profile during the recording process only, by contributing to the space-charge field. A lower value of E_{PV} for o-pol can create a larger space-charge field, which is then exploited by an e-pol beam that benefits of a larger electro-optic coefficient. In principle, this is also true at 405 nm wavelength. However, since E_{PV} is low at 405 nm wavelength, the difference between SWGs recorded using e-pol or o-pol beams is less important.

4. CONCLUSIONS

We have experimentally analysed the mode profile of SWGs recorded at 405 nm. When recording SWGs at 405 nm we benefit not only on a very fast recording time and low optical power, but also on a smaller mode size for a lower external field. This is due to the smaller photovoltaic field at 405 nm in contrast to that at 532 nm wavelength. When using 405 nm wavelength, a smaller applied voltage is required in order to have a good beam confinement. We have also analysed the influence of the beam polarization on the minimum attainable SWG mode size. In principle, it is better to record waveguides with o-pol light. At 405 nm wavelength, due to the low photovoltaic field for any beam polarization, there is not a significant difference in the profiles of SWGs recorded with e-pol or o-pol light.

Acknowledgements. This work has been supported by the project PN 09 39 and by the project UEFISCDI Partnerships 3/2012 “Bio-Nano-Photo”.

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