1332

Photorefractive Damage Removal in annealed-proton-exchanged $LiNbO_3$ Channel Waveguides

Elaine E. Robertson and Robert W. Eason

Optoelectronics Research Centre and Department of Physics, University of Southampton, UK.

Yoshiatsu Yokoo

HOYA Corporation, Tokyo, Japan

Peter J. Chandler

School of Mathematical and Physical Sciences, University of Sussex, UK.

Abstract

Ion beam implantation has been used as a post processing technique to dramatically reduce the photorefractive effect in lithium niobate channel waveguides. The waveguides were fabricated by proton exchange and then annealed. 1.0 MeV H^+ ions were then implanted over the existing channel waveguides and the output characteristics from the waveguides were examined. Highly stable single mode outputs were observed with the waveguides retaining up to 95% of their original transmission. It is thought that this decrease in photorefractive susceptibility can be explained by the implant changing the defect structure and hence photovoltaic properties of the material.

Submitted to Appl. Phys. Lett.

Nov. '96

Lithium Niobate is an attractive material to use in waveguide device applications due to its large electro-optic and acousto-optic coefficients[1]. When doped with rare earth ions, for example neodymium, it has also been successfully used for lasing applications[2]. The major factor which has limited such use, however, is the photorefractive effect, which induces optical degradation in both bulk and waveguide devices, where, in the latter, it is particularly detrimental due to the high intensities inherent in such geometries. This limitation effectively restricts the use of lithium niobate waveguides to near infra-red wavelengths and low intensity operation.

The photorefractive effect, which was originally referred to as "optical damage", was discovered in the 1960's when it was observed that if a laser beam was focused into crystals of $LiNbO_3$ or $LiTaO_3$ it was severely distorted[3]. The effect was attributed to charge carrier migration between light and dark regions, under non-uniform illumination[4]. The resultant space charge field can then modify the local refractive index via the electro-optic effect. In $LiNbO_3$ the photorefractive effect severely restricts the crystal's usefulness in device applications and it is highly desirable for the effect to be reduced, or ideally, eradicated when being used for such purposes.

It has been shown that proton exchanged (PE) $LiNbO_3$ channel waveguides are less susceptible to photorefractive damage than annealed proton exchanged (APE) guides[5]. This is partly due to a decrease in the electro-optic coefficient in PE guides which is generally not desirable as it reduces the material's capacity for non-linear applications such as second harmonic generation. It is also due to a decrease in dark conductivity induced by the annealing process. It has also been shown , that the introduction of MgO doping to APE $LiNbO_3$ channel waveguides reduces photorefractive damage by a factor of two[6]; due, it is thought, to a decrease in the photovoltaic current density. Although this is a successful method for reducing

photorefractive damage in APE $LiNbO_3$ waveguides, damage is still present and is sufficiently high to restrict the intensity used in such devices. Further reduction is therefore clearly desirable.

Ion beam implantation (IBI) is an established technique used to fabricate waveguides in many optical materials. IBI waveguides are fabricated by bombarding the material with high energy H^+ or He^+ ions which penetrate a distance of typically 5-25μm depending on their energy. Initially, they interact electronically with the lattice, causing nominally no damage. Once they slow down, however, they undergo nuclear collisions, forming a damaged layer with a refractive index lower than that of the bulk material thus creating the conditions for optical waveguiding. From experiments done on IBI $Sr_xBa_{1-x}Nb_2O_6$ (SBN) waveguides previously, it was shown that as well as creating waveguides within the material, the implant also changed the material chemically[7]. For SBN, IBI has a chemically reducing effect which changes the impurity ion oxidation state ratio (thought to be Ce^{3+}/Ce^{4+} in SBN) while simultaneously increasing the conductivity within the waveguide.

This paper reports how ion beam implantation has been used as a post processing technique in order to dramatically reduce photorefractive damage in APE $LiNbO_3$ channel waveguides.

Standard procedures were used to fabricate the APE waveguides. Firstly an aluminium mask was deposited onto a wafer of x-cut $LiNbO_3$ which was then immersed in benzoic acid at 200°C for 5 minutes and annealed in air at 200°C to 400°C for 40-50 minutes. The wafer was 5cm long and was cut into 1cm × 1cm samples. Implants ranging from 0.2×10^{16} ions cm^{-2} to 2×10^{16} ions cm^{-2} were carried out; all were implanted at liquid nitrogen temperature and 1.0 MeV H^+ ions were used. One sample was kept aside as a reference sample. The channel waveguides previously created by APE were 3μm deep but the energy of the H^+ ions was

sufficiently high that the damaged layer was formed at a depth of ≈10μm, hence no additional structural damage would be expected to the existing channels. It is important to clarify at this point that the waveguides examined in this paper are the APE channel waveguides and not the additional IBI planar ones.

To evaluate any changes in the photorefractive effect in the post-implanted channel waveguides, a basic set up was employed. Extraordinarily polarised He-Ne light was focused into the waveguides using a ×20 objective. The exiting light was collected using a ×10 objective and imaged onto a power meter. Two separate experiments were used to quantify the effects in the waveguides; firstly, the power out of the guide was examined as a function of the input power to determine the optical damage threshold of each sample and secondly the output power was monitored as a function of time. Figure 1 shows power out against power in results for each sample. A trend can be seen clearly; as the implant dose increases, the power at which the waveguide saturates also increases until, for an implant of 1×10^{16} ions cm^{-2} no saturation is observed. This implies that these waveguides have a dramatically increased resistance to photorefractive damage for incident powers of up to 16mW (an output power of 1mW corresponds to a guided wave intensity of $\approx2\times10^{5}$ W cm^{-2}).

Figure 2 shows the time dependent transmission characteristics for each sample. It can be seen how the unimplanted sample and the sample with the low implant suffer from a large depletion in output while the sample with the high implant dose retains about 95% of its initial transmission. Both figures 1 and 2 imply that the effect of the IBI is to dramatically increase the resistance of APE $LiNbO_3$ channel waveguides to the photorefractive effect.

The proton-exchange and annealing process was carried out at the HOYA Corporation in Japan. The APE waveguides were sent with one section of the aluminium mask remaining in the centre of the wafer for easy identification of the channel waveguides. Before any of the

implants were done, the remaining aluminium was removed using standard etching procedures. After the etching, however, it was observed that the surface of the wafer appeared darker in the region where the residual aluminium layer had remained after the proton exchange. No aluminium remained on the top surface as a scan was taken showing complete removal. It is suspected that this staining may be due to the $LiNbO_3$ being reduced by the presence of the aluminium creating oxygen vacancies within the $LiNbO_3$. The regions in which this happened, however, were adjacent to the APE channels only. From experiments conducted looking at the mode profiles from Al modified and non-modified regions it became apparent that this modification was playing an important role in the reduction of the photorefractive effect in the $LiNbO_3$ channel waveguides. Figure 3 shows the mode profiles for 4 different regions in the wafers studied; profile (a) is from the reference sample , in a region where there was no Al modification. It can be see that the guide is extremely photorefractive being unable to confine the light efficiently and is clearly multimode. Profile (b) is from the same sample but is from a modified region- again it can be seen that the guide is very photorefractive and the light is not well confined. Profile (c) however shows a dramatic improvement in comparison to (a) and (b). This profile is taken from the implant with 2×10^{16} ions cm^{-2} in the region with no Al modification. The output here was still multimode, however the light confinement has been improved dramatically. Finally, if we look at profile (d) which is from the same sample though in an Al modified region, it can be seen that the output is clearly single mode and the light is well confined. This result demonstrates how the combined effects of the implantation and the suspected aluminium induced reduction are required for the most dramatic increase in resistance to photorefractive damage, with the former having the more profound effect (seen by comparing profiles (a) and (c) which only show the effects of the implantation.)

Optically induced change in the refractive index in $LiNbO_3$, Δn, via the electro-optic effect, is described by

$$\Delta n = -\frac{n_e^{\,3} r_{33}}{2} E_{sc} \qquad (1)$$

where n_e is the extra-ordinary refractive index, r_{33} is the electro-optic coefficient and E_{sc} is the internal space charge field. The observed increase in resistance to photorefractive damage could be explained by either a reduction in r_{33} or E_{sc}. The former mechanism, which does result in a lower photorefractive susceptibility, is undesirable as it also reduces the crystal's potential application in waveguide devices such as modulators. Although a direct measurement of the electro-optic coefficient has not been performed we have previously implanted lithium niobate planar waveguides by IBI which were found to have retained the photorefractive effect demonstrating they were still electro-optic. The latter mechanism, a reduction in the space charge field, E_{sc}, is an alternative explanation which would also explain an increased resistance to the photorefractive effect.

The space charge field, E_{sc}, for intensities above 100 W cm^{-2} is given by[8]

$$E_{sc} = \frac{\kappa}{a}\left(I_{ir}\right)^{1-\frac{1}{n}} \qquad (2)$$

where n is an integer greater than 1, κ is the Glass constant (related to the strength of the photovoltaic current) and a is a constant given by

$$a = \left(\frac{e}{h\nu}\right)\mu\tau_0\phi \qquad (3)$$

(e is electronic charge, hν is the photon energy, μ is the electron mobility, τ_0 is the carrier lifetime and ϕ is the quantum efficiency) . Since κ is expressed as[9]

$$\kappa = \frac{e}{h\nu}\phi L \qquad (4)$$

where L is the mean distance travelled by the excited charge carrier along the c-axis. Substituting (2),(3) and (4) into (1) we get

$$\Delta n = \frac{n_e^{\,3} r_{33}}{2}\frac{L}{\mu\tau_0}\left(I_{ir}\right)^{1-\frac{1}{n}} \qquad (5)$$

It can be seen from equation (5) that if the mean distance, L, travelled by the charge carrier can be reduced, then one would also expect a decrease in the optically induced refractive index change.

It is known that during the IBI process, when the H^+ ions interact electronically with the lattice, they have sufficient energy to displace individual atoms and to liberate holes and electrons creating colour centres[10]. Explicitly, the implant can change the defect structure of the material by introducing new donor/acceptor sites in the crystal. An increased density of donors/acceptors can lead to the liberated charge carriers travelling a shorter distance before they are retrapped, hence reducing L, and therefore, via (4), the photovoltaic current. In reference 6, it is reported that by doping $LiNbO_3$ with MgO, the photorefractive susceptibility can be decreased. This is explained by a decrease in the photovoltaic current due to the dopant

altering the defect structure of the crystal. It appears that both the IBI process and the MgO doping process reduce the photorefractive susceptibility in a similar manner.

Although no direct measurement was made of the photovoltaic current a simple experiment was performed to investigate the effect of the defect structure on the photorefractive properties. It is known that some of the defect sites created by the implant can be removed by annealing the sample. The IBI waveguide was annealed in air for 40 minutes at 250°C after which the output from the waveguide was again monitored. It was noticed that although the annealed IBI treated waveguides were still not as photorefractive as the untreated ones, they displayed a more unstable multimode output, suggesting that the removal of the defects does indeed increase the material's susceptibility to the photorefractive effect. Although this provides an explanation of the role the IBI has on reducing the photorefractive susceptibility of the APE $LiNbO_3$, as yet, it is still unclear what role the aluminium plays in reducing the effect.

In summary, we have managed to dramatically reduce the photorefractive susceptibility of APE channel waveguides in $LiNbO_3$ by implanting H^+ ions into pre existing waveguides. It is thought that the implant is altering the defect structure which in turn reduces the photovoltaic current. This reduction in the photovoltaic current results in a smaller space charge field being induced across the waveguide hence lowering the optically induced refractive index change.

References.

1. M. Abouelleil, F. Leonberger, J. Am. Ceram. Soc., 72 (8), 1311, 1989

2. E. Lallier, J.P.Pocholle, M.Papuchon, C. Grezebesset, E. Pelletier, M.De Micheli, M.J. Li, Q. He, D.B. Ostrowsky, Elec. Lett., 25 (22), 1491, 1989

3. A. Ashkin, G.D. Boyd, J.M. Dziedzic, R.G. Smith, A.A. Ballman, H.J. Levinstein, K. Nassau, Appl. Phys. Lett., 9, 72, 1966

4. F.S.Chen, J. Appl. Phys., 40 (8), 3389, 1972

5. T.Fujiwara, X. Cao, R. Srivastava, R.V. Ramaswamy, Appl. Phys. Lett., 61 (7), 743, 1992

6. S.Steinberg, R. Göring, T. Hennig, A. Rasch, Optics Lett., 20 (7), 683, 1995

7. E.E.Robertson, R.W.Eason, M. Kazcmarek, P.J. Chandler, X. Huang, Optics Lett. 21 (9), 641, 1996

8. T. Fujiwara, R. Srivastava, X. Cao, R.V. Ramaswamy, Optics Lett., 18 (5), 346, 1996

9. R. Grousson, M. Henry, S. Mallick, S.L. Xu, J. Appl., Phys., 56, 839, 1984

10. P. D. Townsend, P.J. Chandler and L.Zhang, *Optical Effects of Ion Implantation,* Cambridge University Press, Cambridge (1994)

Figure 1 Waveguide transmission (uncorrected for launch efficiency and other losses) for IBI APE $LiNbO_3$ channel waveguides for different ion implant doses.

Figure 2 Time dependent transmission through IBI APE $LiNbO_3$

Figure 3 Mode profiles of (a) unimplanted waveguide, no Al modification, (b) unimplanted waveguide, Al modification present, (c) implanted waveguide, no Al modification and (d) implanted waveguide, Al modification present, at exit face of channel waveguides.

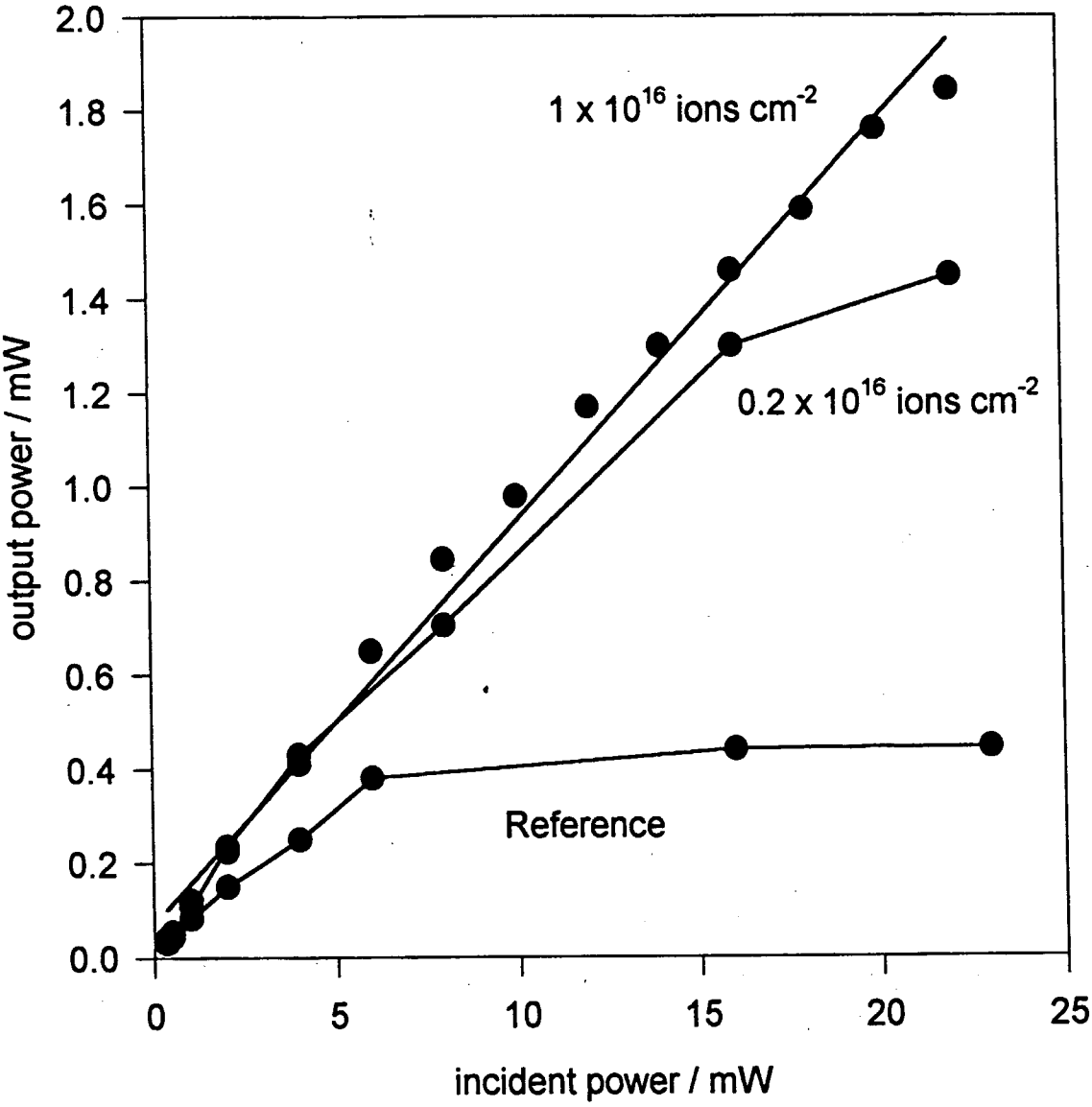
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
output power / mW
0
5
10
15
20
25
incident power / mW
1 x 10^16 ions cm^-2
0.2 x 10^16 ions cm^-2
Reference

Figure 1

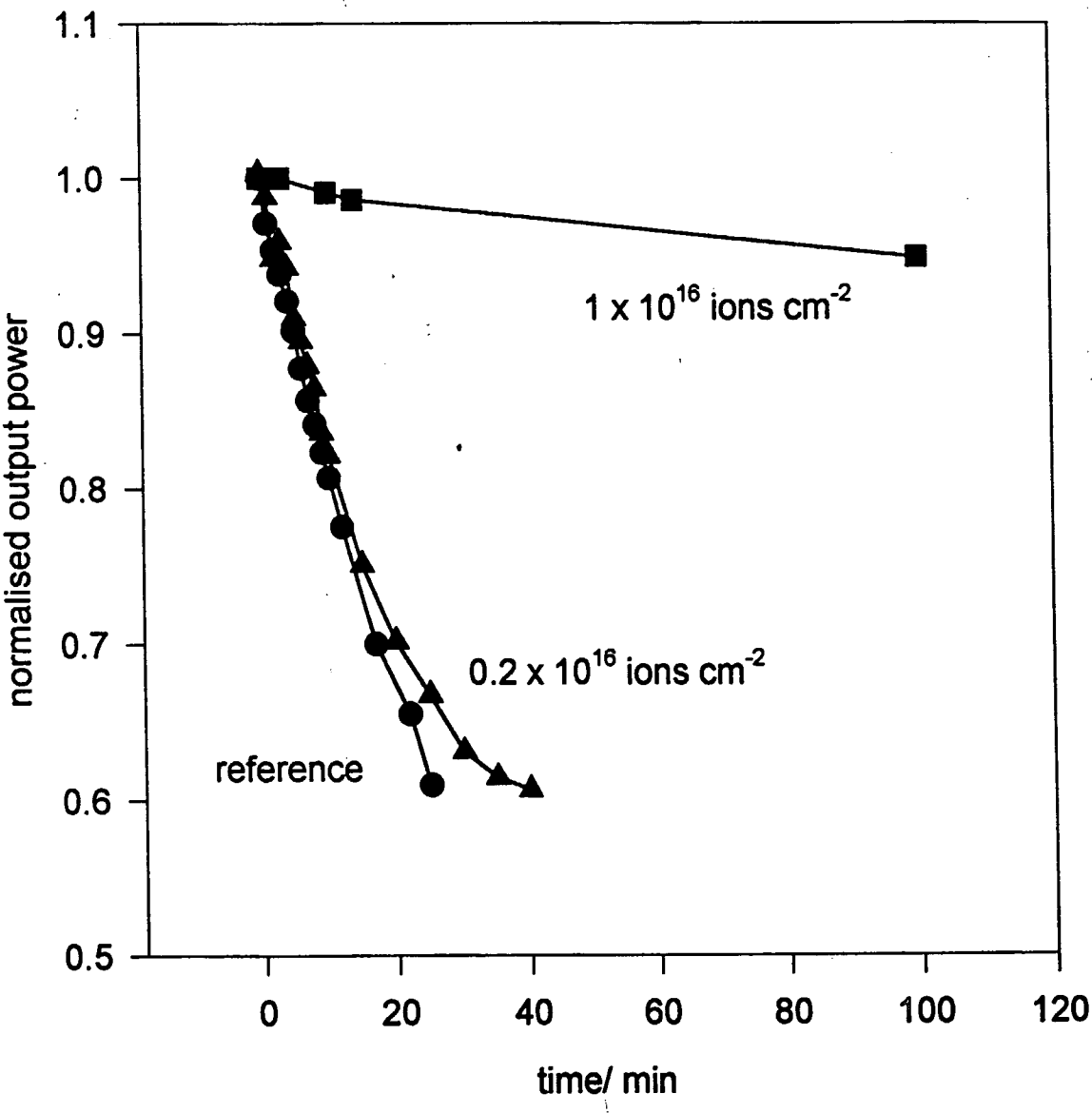
1.1
1.0
0.9
0.8
0.7
0.6
0.5
normalised output power
1 x 10^16 ions cm^-2
0.2 x 10^16 ions cm^-2
reference
0
20
40
60
80
100
120
time/ min

Figure 2

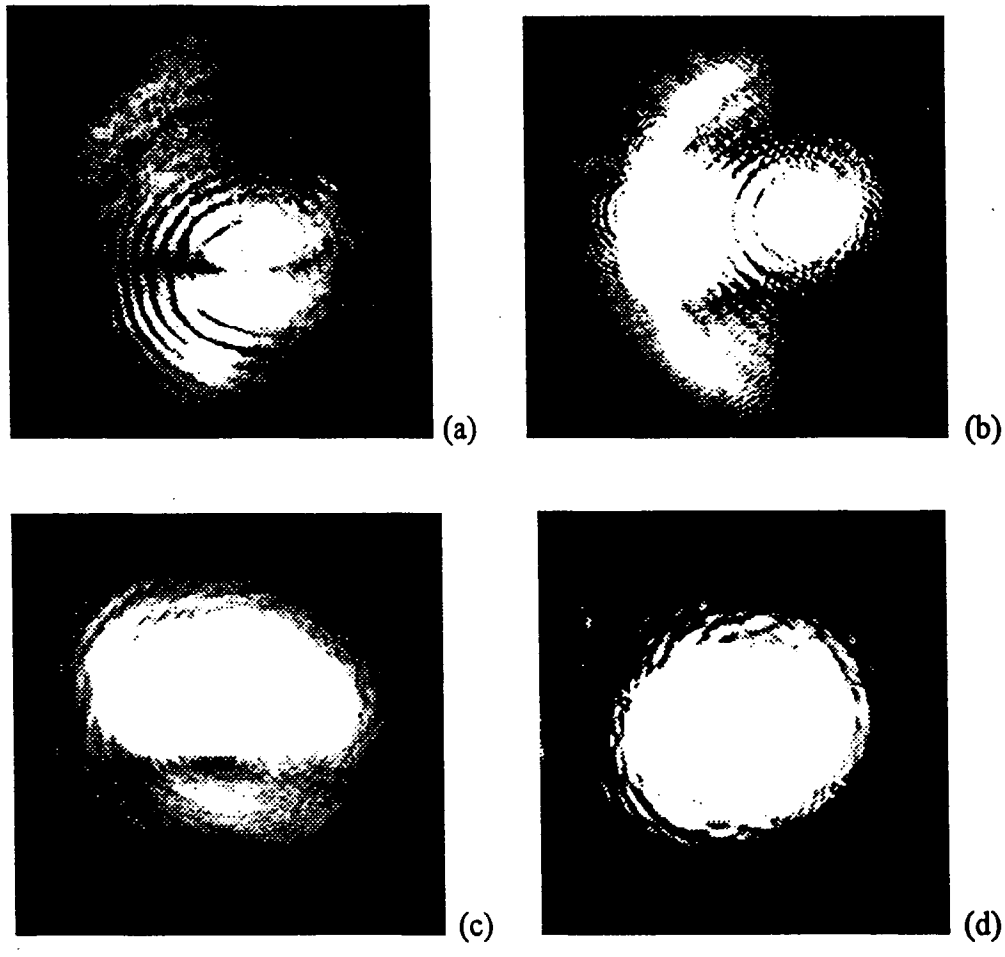

Figure 3