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# Photosensitivities in Germanium-doped Planar Waveguides and Dye-doped Polymer Optical Fibres

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**Abstract**

The refractive index of Germanium-doped planar waveguides can be changed when it is exposed to UV light. Furthermore, if the waveguide is bombarded by ions during exposure, a negative index change is obtained. If the waveguide is not bombarded by ions, positive change in index results. In a dye-doped polymer fibre, large index change is obtained due to the photosensitivity effect of the dye, in our case, flourescein. However, the basic material, PMMA, is also photosensitive.

## 1. Introduction

Recently, UV-induced refractive index changes in planar germanosilicate films have shown great promise both for writing buried waveguide grating structures [1] and for direct writing of buried devices [2]. These applications may have a potentially profound impact on the fabrication of planar devices for wavelength division multiplexed (WDM) systems in the 1.55μm wavelength regime.

As the photosensitivity of high temperature germanosilicate glass is relatively small, various techniques including flame brushing [3] and hydrogen loading [4] have been used to enhance this effect. Index changes up to 0.007 have been observed in hydrogen loaded (for two weeks) waveguide structures formed by flame hydrolysis [2]. However, hydrogen loading, in addition to being a long process, introduces unwanted effects, such as transient behaviour during UV writing due to gas out-diffusion, and increased absorption at 1.55μm.

Recently, Germanium-doped waveguides have been fabricated by the Plasma Enchanced Chemicall Vapour Deposition (PECVD) technique. It has been demonstrated that waveguides were photosensitive to the UV light even without hydrogen loading [5]. However, conventional PECVD has a large absorption peak (3-10dB/cm) around 1.55μm due to N-H bonds formed as a result of nitrogen incorporation from the $N_2O$ commonly used as the oxidant for $SiH_4$ [6]. Recently, we have demonstrated that the hollow-cathode PECVD process (HC-PECVD) can be used to fabricate low loss germanium-doped silica waveguides at 1.55μm and this process can also be used to induce large refractive index changes in both the positive and negative directions [7-8]. One the purpose of this paper is to describe the photosensitivity effect of these waveguides.

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On the other hand, photosensitivity in silica optical fibres have attracted considerable attention because it enables fibre gratings to be fabricated. Since these gratings have found extensive applications in optical communications and optical sensing, it would be useful to extend the fabricatin of gratings to polymer optical fibres. This is because polymer fibres are finding increasing interest in short-distance communication systems such as in aeroplanes and motor vehicles. Sadly, no polymer fibre gratings have been reported. In this paper, we study the fundamental issue of photosensitivity in polymer fibres which hopefully would pave a way for us to understand the issues associated with fabrication of gratings in polymer fibres.

## 2. Photosensitivity of Germanium-doped silica waveguides

Ge-doped silica planar waveguides were deposited on 50mm diameter silicon substrates using the Hollow Cathode PECVD method [9] from a mixture of silane and oxygen with addition of germane ($GeH_4$). The germane was premixed with silane before entering the reactor. In order to investigate the effect of ion bombardment on the waveguide properties, two wafers were deposited simultaneously: one wafer was clamped to the top of the electrode in the "face-down" position, while the second wafer was placed face-up, 3mm above the bottom electrode on three small ceramic spacers in the PECVD deposition chamber as shown in Figure 1. This allowed for the level of ion bombardment on the second wafer to be reduced by reducing its voltage from that of the electrodes to the significantly smaller floating potential of the plasma glow. The ions from the electrically neutral plasma glow are accelerated in the plasma sheath by the electric field of the self-developed negative bias voltage on the electrode (~-300V) and impinge on the surface of the top wafer. At the same time the bottom wafer, placed on the ceramic supports and lifted above the plasma sheath, is immersed in the electrically neutral plasma glow where it acquires only a small floating potential (~-30V). This bottom wafer, therefore, receives significantly reduced ion bombardment.

In order to measure the UV photosensitivity, the deposited waveguides were exposed to an ArF excimer laser (193nm) with a total fluence of around $5kJ/cm^2$ and an incident UV power density of $0.34W/cm^2$ (pulse energy $17mJ/cm^2$, repetition rate 20Hz).

The refractive indices of the waveguides were measured using a standard prism coupling technique at 633nm with a measurement repeatability within ±0.0001. This allowed relative changes in refractive indices of around 0.015% to be measured.

In order to measure small thickness changes of the waveguides produced during UV exposure, the samples were patterned with aluminium and the resultant step after UV exposure and mask removal was measured with a surface profilometer. This way relative thickness changes as small as 0.1% could be measured.

The refractive index and thickness in the UV-exposed and unexposed areas of Ge-doped ion-bombarded and non ion-bombarded wafers are shown in Figure 2. It is seen that the refractive index increases after UV exposure for the non ion-bombarded waveguides and decreases for the ion-bombarded waveguides, both accompanied by a decrease and increase in thickness, respectively. It is interesting, however, to note the difference in the relative thickness changes accompanying the refractive index changes in both cases. For ion-bombarded waveguides, a relative decrease in refractive index of 0.21% is accompanied by a relative increase in thickness of 0.91%, while for non ion-bombarded waveguides, a relative increase in refractive index of only 0.086% is accompanied by a relative decrease in thickness of 3.5%. This effect points to the difference in mechanisms underlying the refractive index changes in both cases.

## 3. Photosensitivity in Polymer Optical Fibres

The basic polymer material of the optical fibre is PMMA. The refractive index of the core is raised by doping it with an appropriate amount of TFEMA [10]. To induce the photosensitivity effect in the fibre in visible wavelengths, we added fluorescein (170ppm). The fibre has two identical cores each with a diameter of 3μm and the core to core spacing 10μm. The single mode cut-off wavelength is 780nm. The maximum absorption wavelength of the fluorescein is 496nm.

The experimental set-up for the photosensitivity experiment is shown in Figure 3. The Ar-laser launches an optical power at certain visible wavelength into one of the cores of the fibre to induce the photosensitivity effect. To observe this effect, a He-Ne laser of output power 1mW at 633nm is launched equally into both cores via a defocussing lens. Since the fibre cut-off wavelength is at 780nm, care must be taken to launch this 633nm He-Ne light into the cores so that fundamental mode only is excited. The fibre length is 15cm which is much shorter than the coupling length between the two cores. Thus there is negligible coupling. A stable and uniform output far field interference fringe pattern can be obtained. The fringe shift of this pattern is recorded as a function of time for different Ar pump powers. The fringe shift is in turn converted into phase shift.

The photo-induced phase shift requires a long build-up time but it remains relatively permanent even after the pump power is removed. Figure 4 shows the measurement of this type of photosensitivity as a function of pump power exposure time at 514nm. The experiment was carried out in two steps: (1) the Ar pump at power 0.36mW was launched into the fibre for 9 minutes, and then (2) the Ar pump power was increased to 1.08mW and the fibre was illuminated for 53 minutes. It can be seen that the phase shift during step 1 changes rapidly while in step 2 it tends to saturate. This saturation indicates that the active dye molecules have been depleted. In this experiment, a total phase shift of $15\pi$ is obtained. The fibre length was 14.5cm which means that the induced refractive index changes is $3.3\times10^{-5}$. During the course of this experiment, if we increased the pump power to 10mW, we noticed that the fringe shift had a rapid response to the applied pump power with a build-up time about 0.1ms but it also disappeared when the pump power was removed. This is obviously is due to the third order nonlinear effect and/or thermal effect of the dopant.

So far, the pump power was launched axially into the fibre cores. Another experiment was done where the pump illuminated the fibre transversely as shown in Figure 5. The pump source now is an OPO which generates short pulses of 5ns in width and the pulse repetition rate 10Hz. Three illumination wavelengths have been used: 325nm, 280nm and 248nm. In these experiements, the photosensitivity depends on the orientation of the twin-core with respect to the illumination light. Figures 6 and 7 show the phase shifts as a function of the product pulse energy-exposure time for different cases. Since the wavelengths are in the UV range, the photosensitivity increases with the decrease of illumination wavelength as expected.

## 4. Conclusions

Photosensitivity is obtained in Ge-doped planar waveguides under UV exposure due to the change of Ge-ion density. Negative index change in the waveguide is due to the ion bombardment in the deposition chamber of the PECVD process. Positive index change can be obtained without ion bombardment.

Photosensitivity in dye-doped polymer optical fibre can be obtained through two processes. When the illumination light is launched into the fibre axially, the dye-dopant gives rise to a large index change in the visible wavelength range. However, when the fibre is illuminated from the side by a UV beam, large index change is also obtained but this photosensitivity is due to the basic fibre material PMMA.

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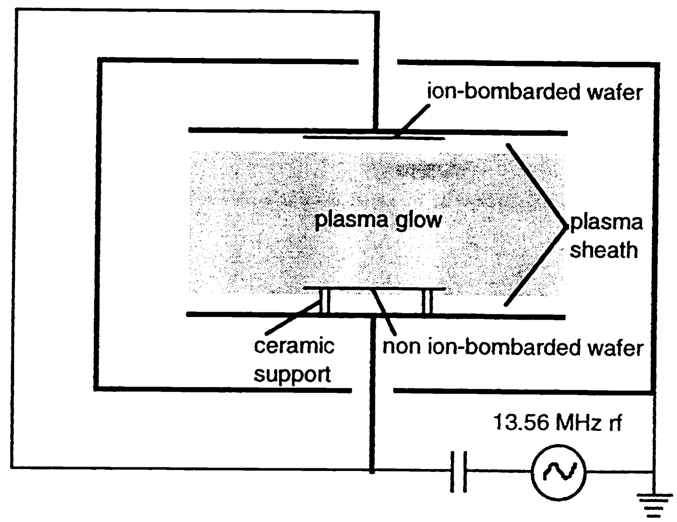


Figure 1- Schematic of dual wafer deposition in HC-PECVD system

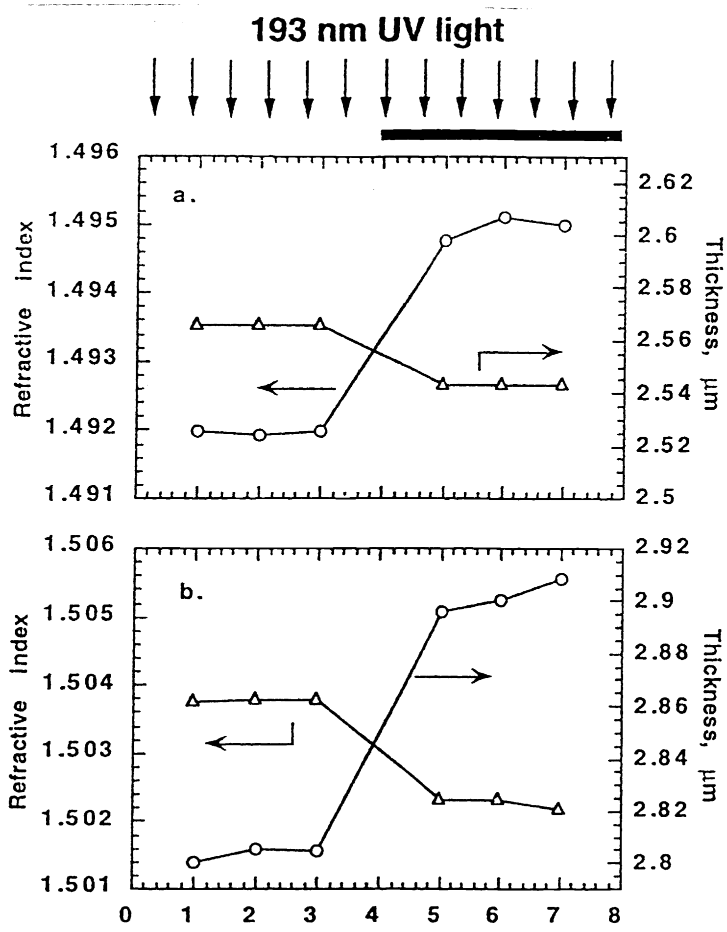


Figure 2 - Refracefactive index and thickness in UV-exposed and unexposed areas of Samples for (a) ion-bombarded and (b) non ion-bombarded Ge-doped waveguides

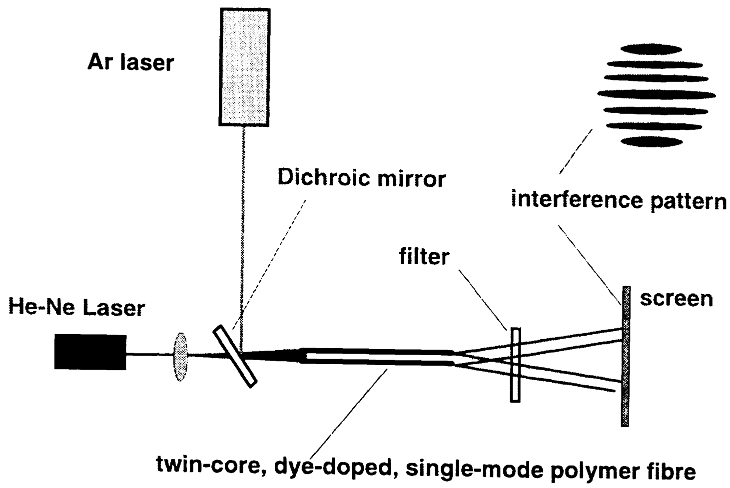


Figure 3 - Photosensitivity study of dye-doped polymer fibre

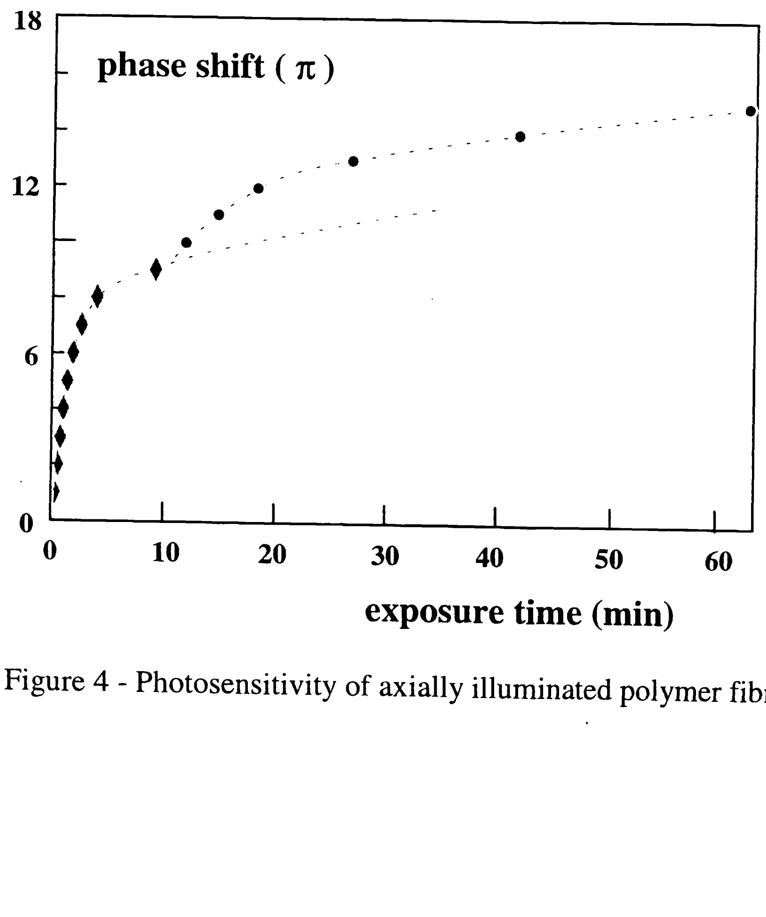


Figure 4 - Photosensitivity of axially illuminated polymer fibre

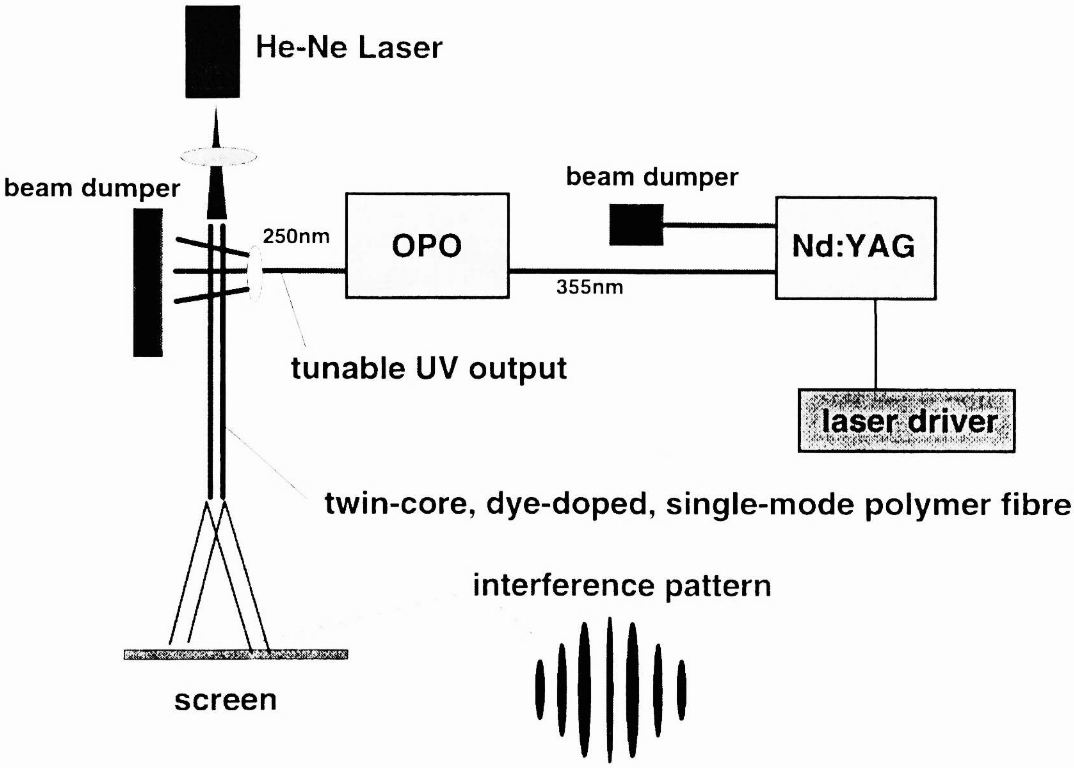


Figure 5 - Side illumination of dye-doped twin core polymer fibre

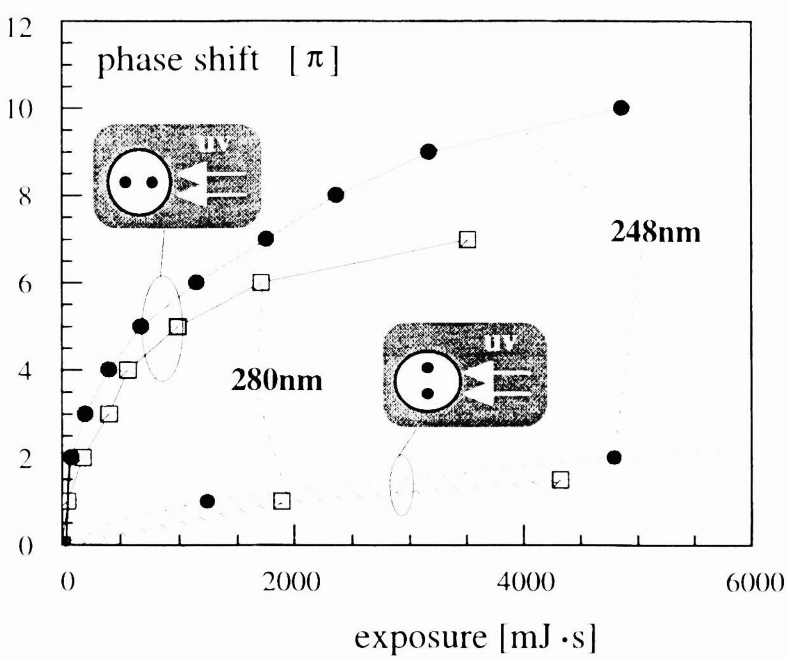


Figure 6 - Photosensitivity of fluorescein-doped polymer fibre
with illumination wavelengths 248nm and 280nm

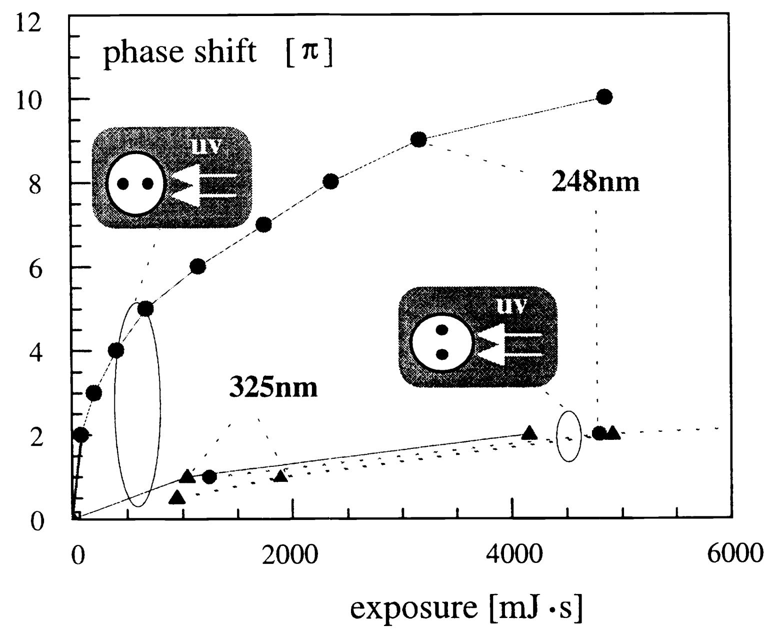


Figure 7 - Photosensitivity of fluorescein-doped polymer fibre with illumination wavelengths 248 and 325nm