Poled glass optical communication devices

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Abstract

A review of electro-optic and nonlinear optical devices based on poled glass will be presented, including recent developments and potential applications.

Invited paper at ECOC 97
Edinburgh 22-25 September 1997.

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Abstract: A review of electro-optic and nonlinear optical devices based on poled glass will be presented, including recent developments and potential applications.

Optical glass waveguides play a key role in information technology because of their excellent optical properties, including low loss, and low fabrication costs. The availability of low-loss silica fibres has led to a revolution in optical communications and low-loss silica waveguides are used to produce a variety of optical integrated elements, such as optical splitters, filters and routers. However the inversion symmetry of the glass matrix implies that the second-order nonlinearity (SON) is zero, which prevents linear electro-optic effect and frequency conversion of coherent radiation through second-order parametric processes. The development of a practical SON in silica and related materials would add electro-optic modulators and switches, electrically tunable Bragg gratings and frequency converters to the list of active fibre and waveguide components. Also other potential devices for spectral inversion, all-optical switching through cascading of nonlinearities and up and down conversion could be realized. Transparency, low dielectric constants, low dispersion, high optical damage threshold, low cost, straightforward integrability with silicon and fibre networks would ensure widespread use of these devices.

From the beginning of the 90's several techniques have been demonstrated to produce a permanent and large SON in several glasses [1-7]. These include thermal poling of silica [1], corona poling of sputtered Corning 7059 onto Pyrex substrate [2], electron beam implantation in silica [3], thermal poling of tellurite glass [4], thermal poling of sol-gel substrate [5], corona poling of sol-gel processed silica films doped with organic azo dye [6] and UV-excited poling of germanosilicate glass [7]. Levels of SON of order 1pm/V [1-5], which corresponds to an electro-optic coefficient (r) and a nonlinear coefficient (d) of ~0.5pm/V, have been achieved, with some indications that even higher values of d ~100pm/V [6] and r ~6pm/V [7] may be possible. From a device point of view, a comprehensive and critical analysis of the potential of poled glass should include other important features, such as stability of the SON, possibility of making low-loss waveguides or fibre structures, spatial extension and position of the SON (e.g. optimization of overlap integral), integration of particular electrode structures (e.g. travelling-wave configuration for electro-optic modulation), polarization insensitive behaviour.

A few research groups have been making efforts to demonstrate the feasibility of devices based on poled glass. In particular, electro-optic modulation and second harmonic generation in waveguide and fibre geometries and electro-optic tuning of Bragg gratings have already been demonstrated. Here we review recent results in this research area, including the contribution from our group, and we will indicate other potential applications of poled glass to optical communication.

Linear electro-optic modulation in an optical fibre was first demonstrated by Li and Payne [8]. They used a twin-hole fibre, poled at room temperature using internal liquid electrodes. The value of the reported electro-optic coefficient (r) was ~0.002pm/V. Thermal poling techniques have produced 0.1÷1pm/V and electro-optic modulation was reported in thermally poled fibres [9,10] and waveguides [11,12]. More recently Long et al. [13] have demonstrated a half-wave drive voltage of 75V for a 12cm active length in a thermally poled D-shape fibre. The corresponding electro-optic coefficient was 0.3pm/V and did not show any decay at room temperature (at 90°C the decay was ~10% over ~40days). Abe et al. [12] reported a 2x2 electro-optic switch in an integrated Mach-Zehnder interferometer constructed with thermally poled GeO_2-SiO_2 channel waveguides on a silicon substrate. The high switching voltage of 1.7kV was due to the relatively low r~0.02pm/V.

Using a twin-hole fibre with a core containing about 15% GeO_2 and internal electrodes (similar scheme as ref.8) and by applying 4.5kV at room temperature for 30 minutes we have recently produced an electro-optic coefficient of ~0.04pm/V (half-wave voltage at 633nm of about 350V over 20cm interaction length - measured also in a Mach-Zehnder configuration using a KD*P modulator as reference). No significant improvement was observed when the fibre was thermally poled with the same voltage at 270°C. The value of the electro-optic coefficient is ~20 times higher than in ref.8 but ~20 times lower than in ref.7 where Fujiwara and coworkers reported about 0.9pm/V using 800V poling voltage at room temperature on a similar fibre structure. The significant difference in these results on the twin hole-fibre poled via internal electrodes may be due to composition of the fibre core and cladding as well as geometrical factors. In addition ref.7 reported that when the electric-field poling was assisted by UV irradiation the electro-optic coefficient increased up to 6pm/V. With the same fibre structure the same group demonstrated electrical tuning of a Bragg grating of 0.01nm for 1V/μm and a corresponding intensity modulation of 10dB for 300V applied voltage. These results have not been yet confirmed by other groups and more recent studies [14] show that the SON associated with UV poling suffers degradation.

For a better understanding of the mechanism behind the SON induced by applying an electric-field at room temperature with and without UV light irradiation, we have been preparing very thin polished samples (from 30 to 100μm thick), cut from a graded-index VAD preform containing 17%GeO_2. The samples were then subjected to a strong electric-field, more than 100kV/mm, which is to our knowledge among the highest electric-field applied to bulk silica. Several electrode geometries were considered. An example of the layout of UV assisted electric-field poling is shown in fig.1. The thin germanosilicate sample was placed between two electrodes (evaporated or pressed against) and from the anode side the sample could also be exposed to intense UV light (up to 150mJ/cm^2 from a 193 ArF laser pulsing at 10Hz). Part of the light at an angle of 45° reflected onto the cathode electrode back into the sample (the sample absorption was ~30dB/mm at 193nm). The poled sample was then removed and tested for second harmonic generation (SHG) using a Q-switched and mode-locked Nd:YAG laser. When a sample 30÷35μm thick was used and 4kV applied between the electrodes we could not detect any SH in the regions between the electrodes without UV irradiation. However the regions UV irradiated for about 25minutes (150mJ/cm^2, 10Hz) while the voltage was applied showed SHG. The dependence of the SH intensity as a function of the incident angle (Maker's oscillation) for a TM polarized input fundamental light is shown in fig.2. In the same figure is also represented the theoretical behaviour expected for a 32 μm thick layer, uniformly poled over the entire thickness. The value of the d_{33} nonlinear coefficient was found to be ~0.1pm/V (a quartz plate was used as reference sample). Although more experiments have to be carried out, several conclusions can be drawn. The UV irradiation certainly contributes to an increase in the SON of germanosilicate layers subjected to a strong electric field. Moreover the SON was induced over the entire 30÷35μm sample thickness (see Maker's fringes), in contrast to the ~5μm nonlinear layer induced by thermal poling where a depleted region of ions [15] (sodium) is formed under the anode surface. Other results and developments regarding these studies will be presented at the Conference.

Our effort is also concentrated in developing quasi-phase-matching (QPM) structures in optical fibre and waveguide for second order nonlinear optical process, such as SHG, parametric amplification and oscillation, frequency conversion and cascading of second order nonlinearities. Frequency conversion of telecommunication wavelengths will be an essential function in the WDM networks, where it is desirable to route from the incoming channel wavelength to any other allowed channel wavelengths [16]. The difference frequency generation between a relatively strong and chosen pump wavelength and the wavelength of a given channel can generate the wavelength of another given channel. Because of energy conservation the sum of the frequencies of the two channels (e.g. 1508 and 1500nm) has to be equal to the pump frequency (752nm). The same technique could be used for spectral inversion at the mid point of long fibre links to compensate for the delay due to dispersion between the spectral components of a communication signal. Another application could be the generation of correlated photon pairs via parametric processes for quantum crypotography [17]. These QPM fibre structures could also be employed for cascading of second order nonlinearities [18] to produce equivalent third order effects - self and cross phase modulation. These Kerr like effects can be exploited for all optical switching. Apart from the obvious advantages indicated before (integrability, low loss,...) poled glass fibres and waveguides compare favourably with the nonlinear crystal waveguides used for second order nonlinear processes. In fact, despite the lower nonlinearity (about 10X) the lower dispersion allows longer interaction lengths (10X) for the same acceptance bandwidth, thus achieving comparable efficiencies without compromising the frequency stability.

Ti:Sapphire laser, we have moved to fabricate periodically poled fibres for SHG at around 1.5microns. Fig.4 shows the required period as a function of the fundamental wavelength for different fibre parameters, i.e. core radius and numerical aperture. It is clear from these curves that a small error in evaluating the fibre parameters may lead to significant deviation from the estimated QPM period or wavelength. The same graph can be used in the case of near-degeneracy frequency conversion or parametric down-conversion at around 1.5µm (pump in the 700-800nm region). Fig.5 shows a typical phase matching curve (SH power against fundamental wavelength) for a fabricated grating with a period of 57.5µm and a length of 7.5cm. The bandwidth and the shape of the curve indicate the good uniformity of the grating over the entire length. Experiments are in progress to use such gratings for SHG and parametric processes. We will report on them at the Conference.

VP and FS acknowledge Pirelli Cavi S.p.a. (Italy) for their fellowship and studentship respectively. GB thanks DRA Malvern for his studentship. We would also like to thank P.De Sandro and L.Dong (Southampton) for fabricating the fibres, D.Richardson and D.Taverner (Southampton) for help in the 1.5µm experiment, L.Reekie and S. Pissadakis for help in the UV assisted E-field poling experiments.

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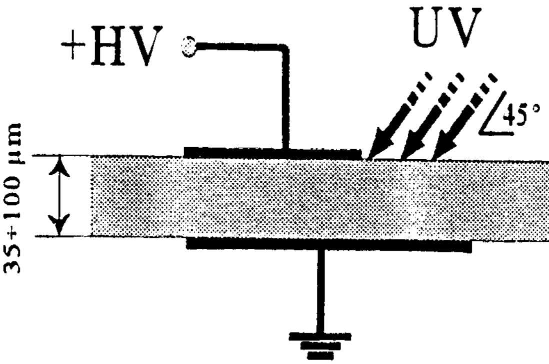

Fig.1 UV assisted E-field poling set-up.

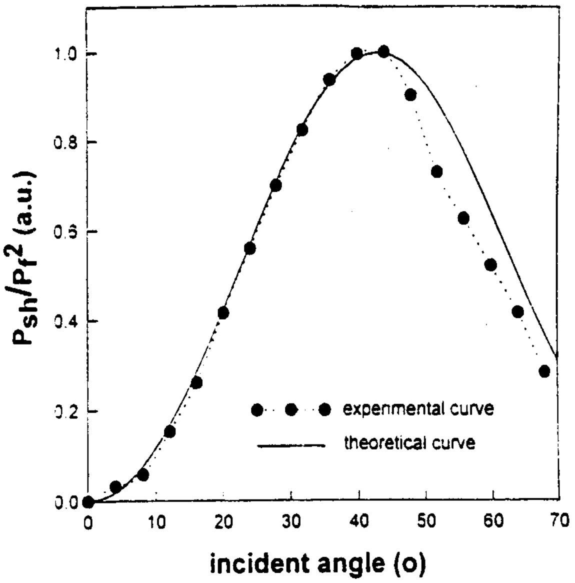

Fig.2 Maker's oscillation of UV-E-field poled sample. The continuous line represents a theoretical curve for a sample 32μm thick, uniformly poled.

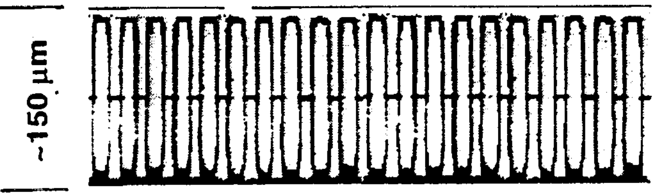

Fig.3 Electrode pattern on the plane face of the D-fibre.

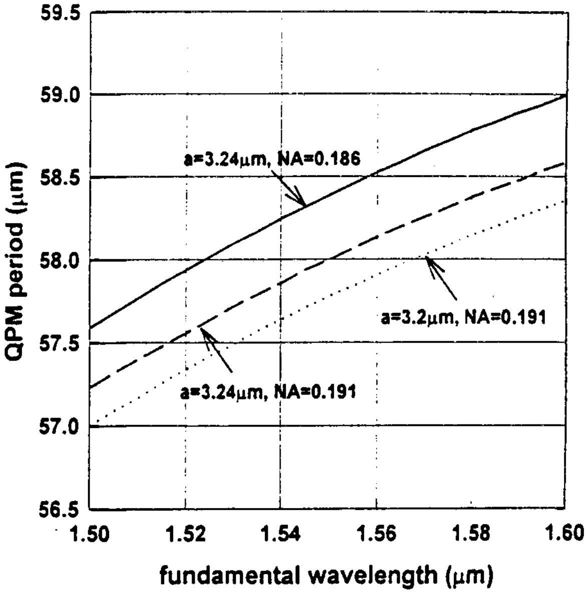

Fig.4 Period of SON grating as a function of fundamental wavelength for QPM-SHG of ~1.5μm (a = *core radius*, *NA* = *numerical aperture*).

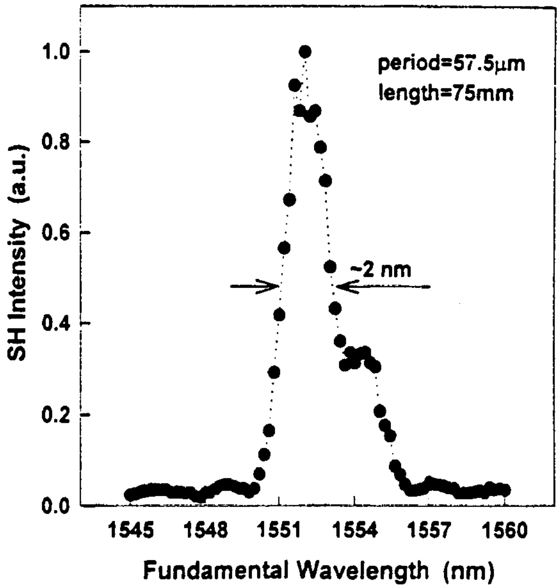

Fig.5 QPM curve of a grating for ~1.5μm.