Second-Harmonic Generation in Poled Optical Fibres: Dynamics and Phasematching Techniques

M. E. Fermann[*] L. Li, M. C. Farries and D. N. Payne

Introduction

It has recently been shown that large second-order non-linearities may be induced in optical fibres by an excitation poling technique[1,2]. In this, high-intensity blue light is launched the fibre core. Two-photon absorption then gives rise to the excitation of defect centres, which align in the presence of the dc-field. The process is strongly linked to the generation of $\chi^{(2)}$-gratings from noise[3,4] or by seeding[5] and the formation of Hill-gratings[6,7].

Here we present detailed measurements of the excitation poling dynamics using very strong poling fields ($\leq$150V/μm) and both pulsed and cw blue defect excitation light. The measurements were made using a novel phase-matching technique. It is based on $\chi^{(2)}$-gratings that are generated by the stationary mode-interference pattern of the blue defect excitation light inside a slightly multi-moded fibre when a poling field is applied. These mode-interference gratings (MIGs) are permanent and remain fixed in the fibre after the blue light and the dc-field are switched off. They are easily erasable and may subsequently be rewritten. MIGs may be used for efficient SHG by a correct choice of the pump and SH-modes (a detailed theory of SHG employing MIGs will be given elsewhere[8]). Unlike the gratings described by Hill *et al*[6] MIGs do not require a "standing wave" in the fibre and are thus easily produced. Compared to conventional $\chi^{(2)}$-gratings[3,4,5] MIGs are based on much larger non-linearities and allow phase-matching to be obtained for any infrared design wavelength by an appropriate choice of the defect excitation wavelength.

Compared to modal phase-matching[2] MIGs allow phase-matching to be obtained over longer coherence lengths, since a degree of self-compensation of fibre non-uniformities is provided by the writing process.

Experiment

The poling dynamics were studied using a D-shaped GeO_2-doped fibre with an internal electrode[1]. The fibre had a core area of 5μm^2 and an NA of 0.30. It was elliptical with an aspect ratio of 3:1 and cut-off wavelength of about 1.15μm. The flat side of the fibre allowed an accurate alignment of the internal electrode with the second external electrode. The applied poling field was aligned with the major axis of the fibre core. Typically, a fibre length of 30cm was used, over which the fibre was polarisation preserving. The electrodes were incorporated at the blue light launching end to minimise the negative effect of dispersion.

Defects were excited employing either cw Argon laser light at 488/514.5 nm or pulsed blue light of variable wavelength from a dye laser (6ns pulse width, 30Hz repetition rate). The growth of the second-order non-linearity was measured by launching pulsed infrared light from a Raman-shifted dye laser (6ns pulse-width, 30Hz repetition rate, 10W peak power) into the fibre and monitoring the SH-conversion efficiency as a function of time. The infra-red wavelength was chosen to coincide with a MIG phase-match peak. The polarisation of all lasers was adjustable with compensators. A set of suitable filters and detectors was employed to allow the simultaneous measurement of the infrared, SH and blue light powers. Due to the large sensitivity of the $\chi^{(2)}$-grating structure on the mode-interference pattern, the launching condition were dept constant during the poling process.

CW Excitation Poling

Before using any blue light, the effects of applying only a poling field, and poling field in conjunction with high power infrared light were established. No $\chi^{(2)}$ ($2\omega = \omega + \omega$) could be generated by applying only a dc-field; however, a permanent Pockels-type non-linearity was nevertheless inducable[9]. A poling field in conjunction with high-intensity infrared light (>20W) led to a semi-permanent $\chi^{(2)}$ ($2\omega = \omega + \omega$), which decayed within minutes after switching-off of the poling field.

Figure 1: SH-power as a function of poling field strength and time for a cw defect excitation power of 25mW at 488nm.

When cw-Argon light was launched into the fibre, the poling field induced a permanent $\chi^{(2)}$ ($2\omega = \omega + \omega$). The relative induced $\chi^{(2)}$ as a function of time and applied poling field strength for a launched cw-Argon light power of 25mW at 480nm is shown in Figure 1. No saturation of $\chi^{(2)}$ with the applied poling field strength is observed. The induced non-linearity was bleachable when launching only blue light into the fibre. An optimum blue light intensity of only about I_{opt} = 6mW/μm^2 was observed to result in the highest SH conversion efficiency. For blue light intensities $<I_{opt}$ the SH-conversion efficiency was proportional to approximately $\sqrt{I}$. For intensities $>I_{opt}$, The SH-conversion

---

[*] Institute fur Allgemeine Elektrotechnik und Elektronik Technische Universitat Wien, Gusshausstrasse 27/359, A-1040 Wien, Austria.

efficiency was observed to decrease. A maximum SH-conversion efficiency of 1% was obtained for an infrared pump power of only 150W in a 6cm coherence length for an estimated[8] maximum induced $\chi^{(2)}$ of about 5×10^{-10} esu, which is about 5 times smaller than the value of $\chi^{(2)}$ for KDP. Extrapolating the results from Figure 1 to possible poling fields at the dielectric breakdown limit of GeO_2-SiO_2 glass of about 700V/μm, as achievable with an optimised electrode design[10], a maximum $\chi^{(2)}$ equal to that of KDP should be achievable. This would result in a SH conversion efficiency of >10% when using MIGs for phase-matching.

Figure 2: SH-Power as a function of time for a range of pulsed defect excitation powers at 480nm and a poling field of 140V/μm.

Pulsed Excitation Poling

The writing and bleaching characteristics of pulsed excitation poling were very similar to cw excitation poling with the exception that a weak permanent $\chi^{(2)}$ $(2\omega = \omega + \omega)$ was inducable when using only pulsed blue light and no poling field. The so generated $\chi^{(2)}$ was about 7 times smaller than induced by simultaneously applying a poling field of 140V/μm. Note that a peak intensity of about 0.2GW/cm^2 is required to start the writing process, which is about one order of magnitude smaller than required for conventional $\chi^{(2)}$-gratings[3,4,5]. The difference may be due to the fact that here it involves coherent two-photon absorption, rather than coherent three-photon absorption[7] as in the conventional writing process. The intensity and time dependence of the relative induced $\chi^{(2)}$ as a function of time and pulsed blue light power at 480 nm for an applied poling field of 140V/μm is shown in Figure 2. The functional intensity-dependence is the same as for cw-excitation poling, but no saturation was detected. As in the cw case defect excitation light at a wavelength of about 480nm was found to give rise to the highest non-linearities, indicating that two-photon absorption via the 240nm absorption band of oxygen deficient germanosilicate glass lies at the root of the process. The bleaching dynamics are displayed in Figure 3. In this, a fibre previously unexposed to high-intensity blue light was poled, then bleached and finally re-poled. It was observed that the fibre is polable and bleachable an unlimited number of times without an effect on the magnitude of the induced $\chi^{(2)}$ and the poling rates. Note that previous measurements of poling dynamics[1] were carried out with much smaller poling fields in highly multi-moded fibres, where an accurate control of the modal intensity distribution inside the fibre and a separation of the contributions to $\chi^{(2)}$ from defect excitation and excitation poling was not possible.

Figure 3: Writing and bleaching characteristics of pulsed excitation poling for a defect excitation power of 40W at 480nm and a poling field of 140V/μm. Note the enhancement of the contribution to the SH-power from electric-field-induced SHG after poling the fiber. It may be explained by a refractive-index grating that accompanies the $\chi^{(2)}$-grating writing process.

Conclusions

In conclusion we have demonstrated a novel efficient phase-matching technique for SHG in optical fibres. The dynamic of cw and pulsed excitation poling were studied and the contributions to the second-order nonlinearity from the poling field, the defect excitation light and the infrared read-out light separated. Efficient SH-generators in fibre form may be predicted as a result of these measurements.

References

1. Bergot, M. V., Farries, M. C., Fermann, M. E., Li, L., Poyntz-Wright, L. J., Russell, P. St. J. and Smithson, A., " "Generation of permanent optically-induced second-order non-linearities in optical fibres by poling", Opt. Lett., Vol. 13, 1988, pp. 592–594.
2. Fermann, M. E., Li, L., Farries, M. C. and Payne, D. N., "Frequency-doubling by modal phase-matching in poled optical fibres", Elect. Lett. Vol. 24, 1988, pp. 894–895.
3. Margulis, W. and Osterberg, U., " J. Opt. Soc. Am., Vol. B5, 1988, pp. 312.
4. Farries, M. C., "Second-harmonic generation in an optical fibre by self- written $\chi^{(2)}$-grating M. C. Farries, P. St. J. Russell, M. E. Fermann, D. N. Payne Elect. Lett., Vol. 23, 1987, pp. 322–324.

5. Stolen, R. H. and Tom, H. W. K., "Self-organised phase-matched second-harmonic generation in optical fibres", Opt. Lett., Vol. 12, 1987, pp. 585–587.
6. Hill, K. O., Fujii, Y., Johnson, D. C. and Kawasaki, B. S., "Photosensitivity in optical fibre waveguide : application to reflection filter fabrication", Appl. Phys. Lett., Vol. 32, 1978, pp. 647–649.
7. Lawandy, N. M., Submitted to J. Opt. Soc., Am. B.
8. Fermann, M. E., Farries, M. C., Russell, P. St. J. and Poyntz-Wright, L. J., "Tunable holographic second-harmonic generations in high-birefringence optical fibres", Opt. Lett., Vol. 13, 1988, pp. 282–284.
9. Li, L. and Payne, D. N., "Permanently-induced linear electro-optic effect in silica optical fibres", Proceedings IGWO '90, Houston, USA, Technical Digest Vol. 4, Paper TuAA2-2, pp. 130–133, February 1989.
10. Haberl, F., Submitted to Elect. Lets.

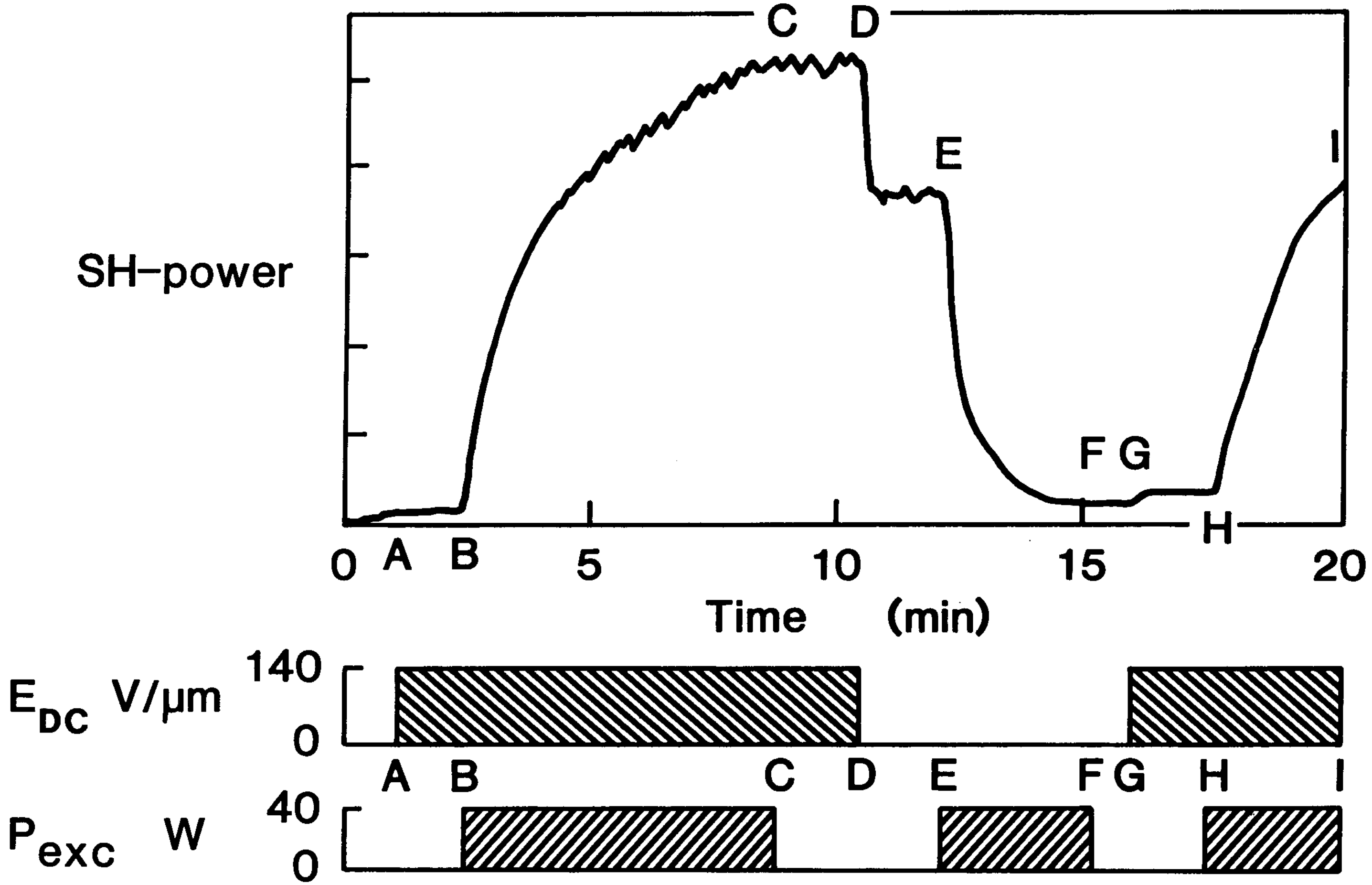


Fig 3

19.0
to
8.0

399 Fig 3

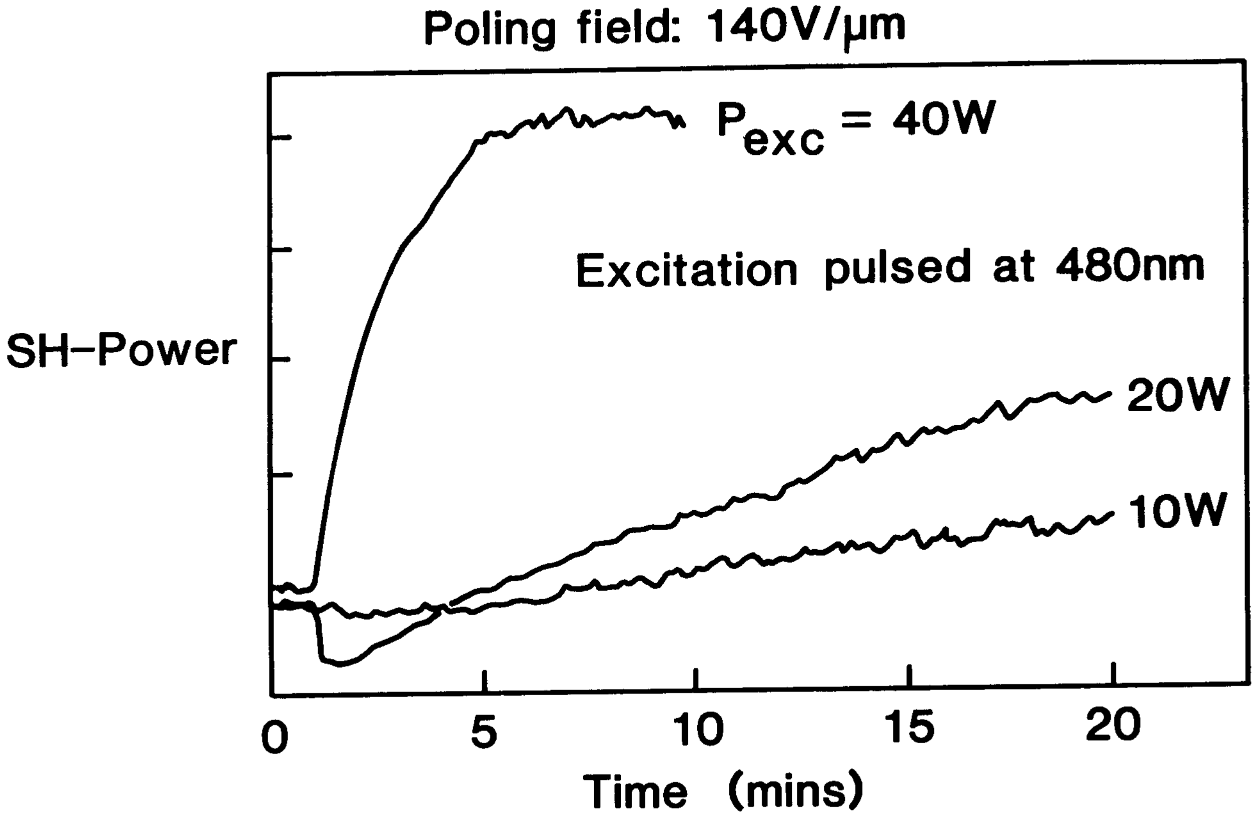
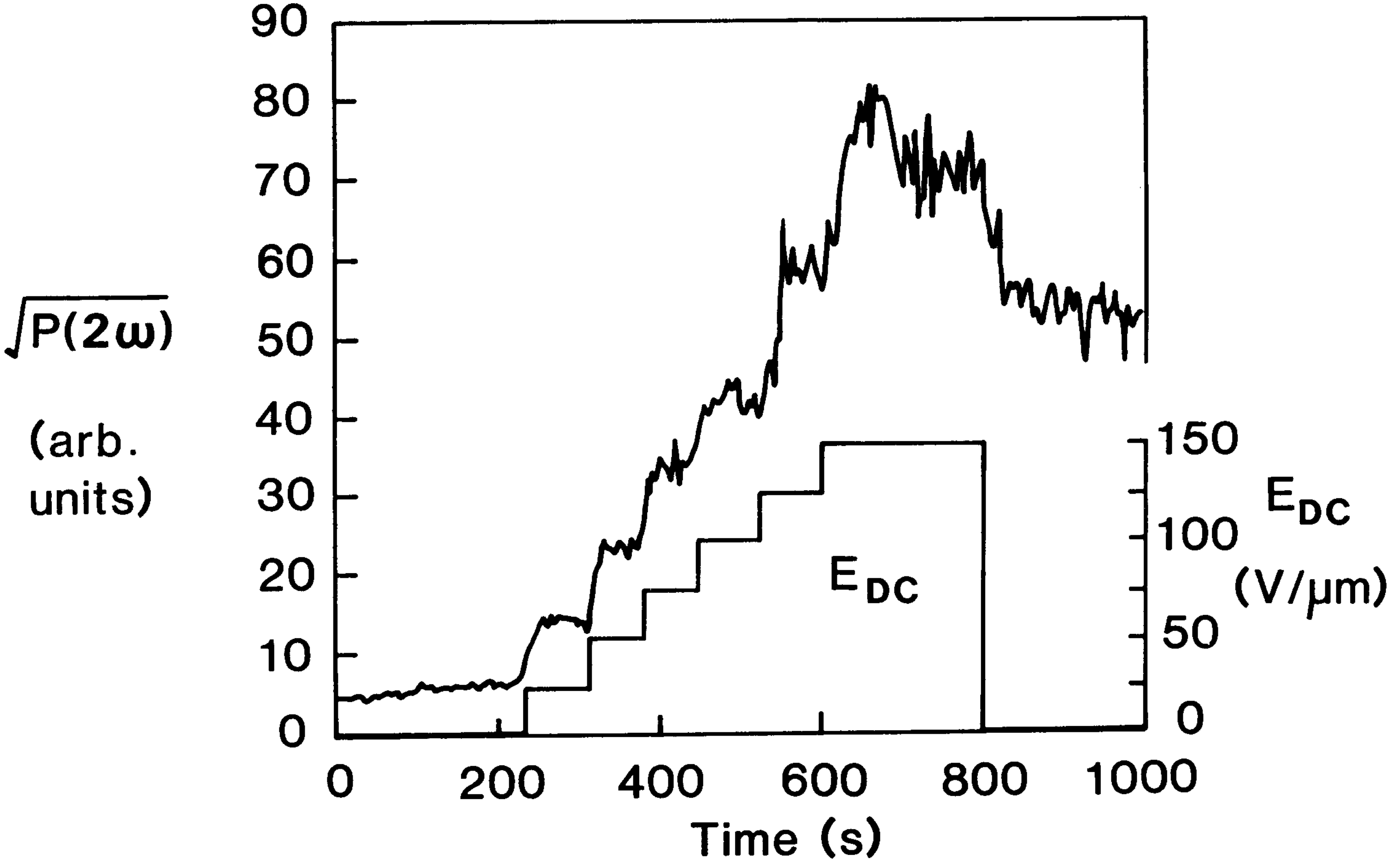


Fig 2

16.5
to
8.0

399 fig 2

399 fig 1



19.0 to 8.0

Fig 1