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Frequency-Doubling by Modal Phase Matching in Poled Optical Fibres

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Abstract

We induce a permanent second-order non-linearity in phosphorus and germania doped optical fibres via simultaneous excitation and orientation of defect centres. Modal phase-matching is used for frequency-doubling of 1.208μm radiation and we investigate the effect of non-uniform non-linearities on the second-harmonic conversion efficiency.

Introduction

It is now well known that the transmission of high-intensity light for a period of time can cause an optical fibre to develop a second-order non-linearity ($\chi^{(2)}_{111}$), which enables it to generate frequency-doubled radiation[1]. The effect is thought to be due to the creation of defect centres in the glass by a multi-photon process[2]. The defects are then aligned by a small internally generated DC-field[3] which results from mixing of the optical waves via $\chi^{(3)}$. We have recently shown that the magnitude of the induced second-order non-linearity can be considerably enhanced by creating the defect centres directly using intense blue radiation, and aligning them with a large external DC-field applied transversally across the fibre[4]. We investigate here the effect of non-uniform non-linearities on the SH-conversion efficiency obtained by modal phase-matching. We then demonstrate a conversion efficiency of 0.05% using optical input powers of only 40W. Finally, we show that a $\chi^{(2)}$ induced by poling may be modified by subsequent application of strong DC-electric fields.

Theory

Poling of optical fibres with an external DC-field leads to the formation of a permanent second-order non-linearity, $\chi^{(2)}_{pol}$, which is oriented parallel to the unit vector u_{DC} along the direction of the poling field. When high intensity light is launched into the fibre, frequency-doubled light is generated along u_{DC} with an conversion efficiency which is given by

$$\eta = \sqrt{\mu_0}\frac{\omega^2 z^2}{2cn(2\omega)\varepsilon(\omega)} \left[\bar{\chi}^{(2)}O\right]^2 \frac{P^\omega}{A} \,\mathrm{sinc}^2\left[\frac{(k^{2\omega}-2k^\omega)z}{2}\right], \qquad (1)$$

where z=fibre length, k=wave vector at frequency ω, P=optical power, c=velocity of light, n=refractive index, ε=dielectric constant and $\bar{\chi}^{(2)}$ is the second-order non-linearity averaged over the equivalent core area A. We define the overlap integral as

$$O = \frac{\sqrt{A}}{\bar{\chi}^{(2)}}\int_{-\infty}^{\infty} \chi^{(2)}_{111}(e_{sh}(2\omega))_1^{*}(e_f(\omega))_1^{2}da, \qquad (2)$$

where $(e_{sh}(2\omega))_1$, $(e_f(\omega))_1$ are the normalised modal field distributions of the SH and fundamental waves along the direction of u_{DC}. A fundamental wave propagating in the LP_{01} mode may thus generate a SH-wave only in a LP_{0n} mode (for a radially uniform $\chi^{(2)}$). The value of the overlap integral between the LP_{01} and LP_{02} mode was calculated as a function of V-value of the fundamental mode and is plotted in Fig. 1. In this we solved the eigenvalue equation in the weak guidance approximation for both modes and assumed both a uniform $\chi^{(2)}$ and a $\chi^{(2)}$ present only in the fibre core. The effect of dispersion led to relative errors of less than 5% and was neglected in this calculation. It may be seen that the two overlap integrals differ significantly only close to cut-off of the higher-order mode. At large V-values all optical power is confined to the fibre core and no difference is observed.

Launching high intensity light into a poled fibre and also applying a DC-electric field across the fibre core, one then produces two effects: i) SHG via $\chi^{(2)}{}_{pol}$ and ii) the usual non-permanent electric-field-induced second-harmonic generation (ESHG), which is caused by a mixing between the optical and DC-field via $\chi^{(3)}(2\omega=\omega+\omega+0)$. This allows the comparison of the SH-signal due to the two processes. When a DC-field along u_{DC} is applied to a poled fibre, the observed SH-signal is proportional to

$$S_{tot} \sim \left[(\chi^{(2)}_{pol} |O_1|) \pm (\chi^{(3)}_{1111} E_{DC} |O_2|) \right]^2 \tag{3}$$

where O_1, O_2 denote the respective overlap integrals. O_1 is calculated assuming a step-profile $\chi^{(2)}$, since only the core is doped and no non-linearity may be introduced in the pure silica cladding. O_2 is calculated assuming a uniform $\chi^{(3)}E_{DC}$. A DC-field parallel to the orientation of the defect centres (given by the poling field) adds to the SH-signal and an anti-parallel DC-field reduces the SH-signal.

Experiment and Results

We used a polarisation preserving D-shaped fibre with a built-in electrode[4], which allowed the application of very large transverse DC-electric fields up to 200V/μm. The fibre was doped with 13 mole percent GeO_2 and 0.5 mole percent P_2O_5. It had an elliptical core with an aspect ratio of 2:1, an effective core area of $1.6*10^{-11}m^2$ and was 20cm long. The fibre was double-moded at the wavelength of operation (λ=1.208μm), so as to allow phase-matching between the fundamental wave in the lowest-order mode and the SH in the third-order mode. Care was therefore taken to launch the fundamental mode only. A cw Argon laser operating at 488nm was used as the defect excitation source and a pulsed tunable Raman-shifted dye-laser was employed for probing the SHG characteristics.

Prior to poling the fibre ESHG with an applied DC-electric field of 125V/μm was measured. In contrast with previous observations[5], we did not induce any $\chi^{(2)}_{pol}$ by an electric field alone, i.e. the SH-power was only present with the electric field on and dropped immediately to a constant base value, governed by quadrupole effects, after the DC-field was switched off. For our fibre the SH-wave was phase-matched to the fundamental wave at 1.208μm, where the fundamental wave was in the LP_{01} mode and the SH in the LP_{02} mode. Using an infra-red input power of 40W a maximum conversion efficiency of 0.002% was observed. From (2) and neglecting the ellipticity of the fibre, the overlap integral was calculated as O_2=11%.

Subsequently, the fibre was poled by launching 400mW of Argon laser light into the fibre for 10min and simultaneously aligning the excited defect centres with an applied field of 100V/μm. The resulting dipole non-linearity led to phase-matched SH generation again at 1.208μm where the modes were the same as observed for ESHG. Fig.2 is a measurement of the SH power as a function of pump wavelength for a constant pump power. The half-width of the phase-match peak is about 1nm, from which we calculate that the minimum coherence length for in-phase propagation of the fundamental and SH-wave is about 1.5cm, which is limited by very small diameter fluctuations along the fibre. A maximum SH conversion efficiency of 0.05% was observed with a pump power of 40W. The low efficiency is a direct result of the relatively low optical input power used and the low overlap integral between the fundamental and the LP_{02} mode, which was estimated to be approximately O_1=15%.

A comparison of the observed SH conversion efficiency and the overlap integrals in the poled and unpoled fibre shows that $\chi^{(2)}{}_{pol}/\chi^{(3)}E_{DC} \approx (3.3\pm1)$. Permanent poling of the fibre by aligning defect centres is thus more efficient for SHG than semi-permanent poling by very strong DC-fields in defect-free fibres. To confirm this we also applied an external field to the poled fibre, which was either parallel or antiparallel to the field used in the poling process, thus either increasing or decreasing the total SH-signal as shown in Fig.3. From these measurements we estimate that $\chi^{(2)}{}_{pol}/\chi^{(3)}E_{DC} \approx (5\pm1)$. This is in good agreement with the value given above. The discrepancy between the two results may indicate that ESHG and SHG by poling are not purely additive. We also calculated the SH-conversion efficiency using (1). In this we assumed a coherence length of 1.5cm and the value of $\chi^{(3)} = 2.75*10^{-22}(m/V)^2$, which was converted into our notation from measurements of the intensity-dependent refractive index[5] at 1.06μm. Taking the ratio $\chi^{(2)}{}_{pol}/\chi^{(3)}E_{DC}=3.3$, the theoretical conversion efficiency is then about a factor of two smaller than measured, which is within the stated error margins.

Conclusion

In conclusion we have shown that poling of optical fibres gives rise to large permanent second-order non-linearities. This may be used for efficient SHG by employing modal phase-matching between symmetric fibre modes. Coherence lengths of 1.5cm have been demonstrated between different fibre modes and SH-conversion efficiencies of 0.05% have been obtained with optical input powers of 40W. By developing more efficient phase-matching techniques involving grating structures, we project that SHG conversion efficiencies of several percent may be reached at input powers of 100W, a level obtainable with Q-switched fibre lasers.

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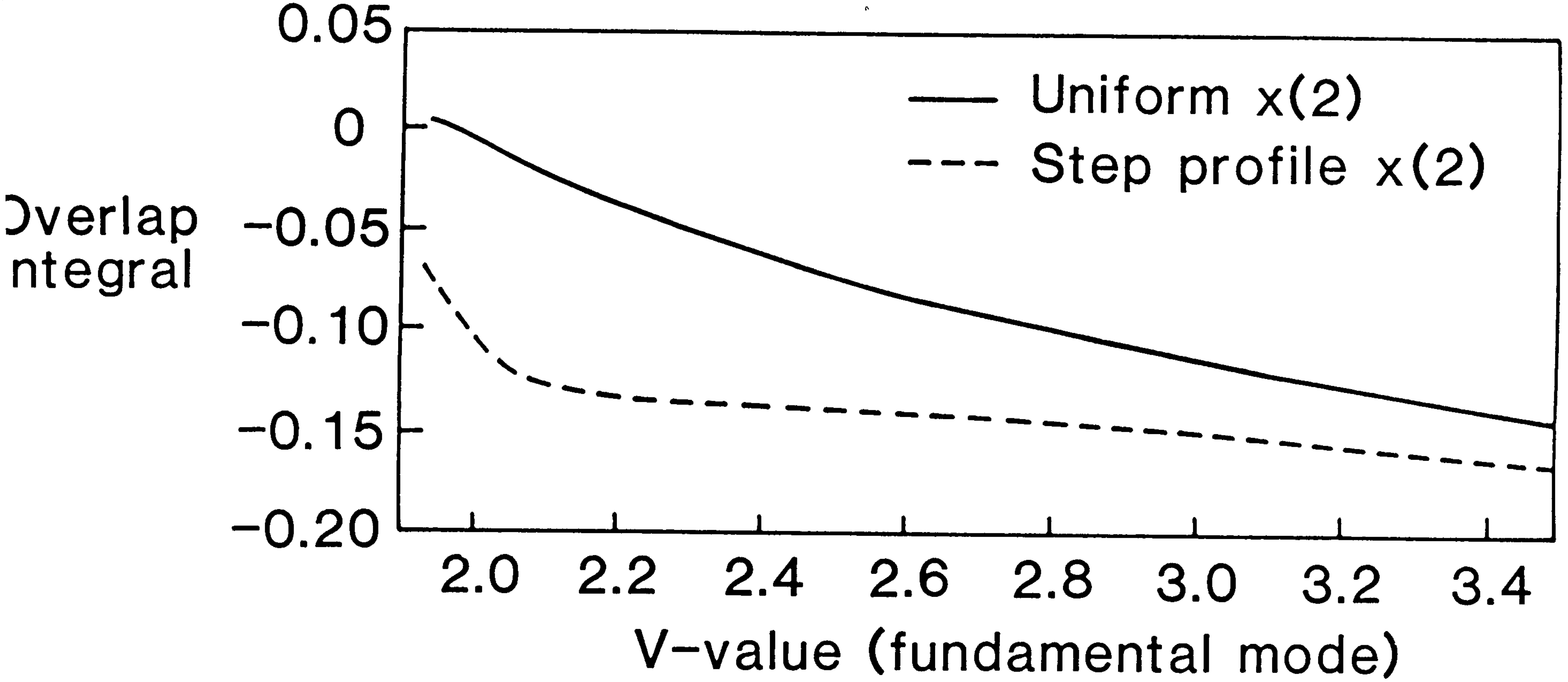
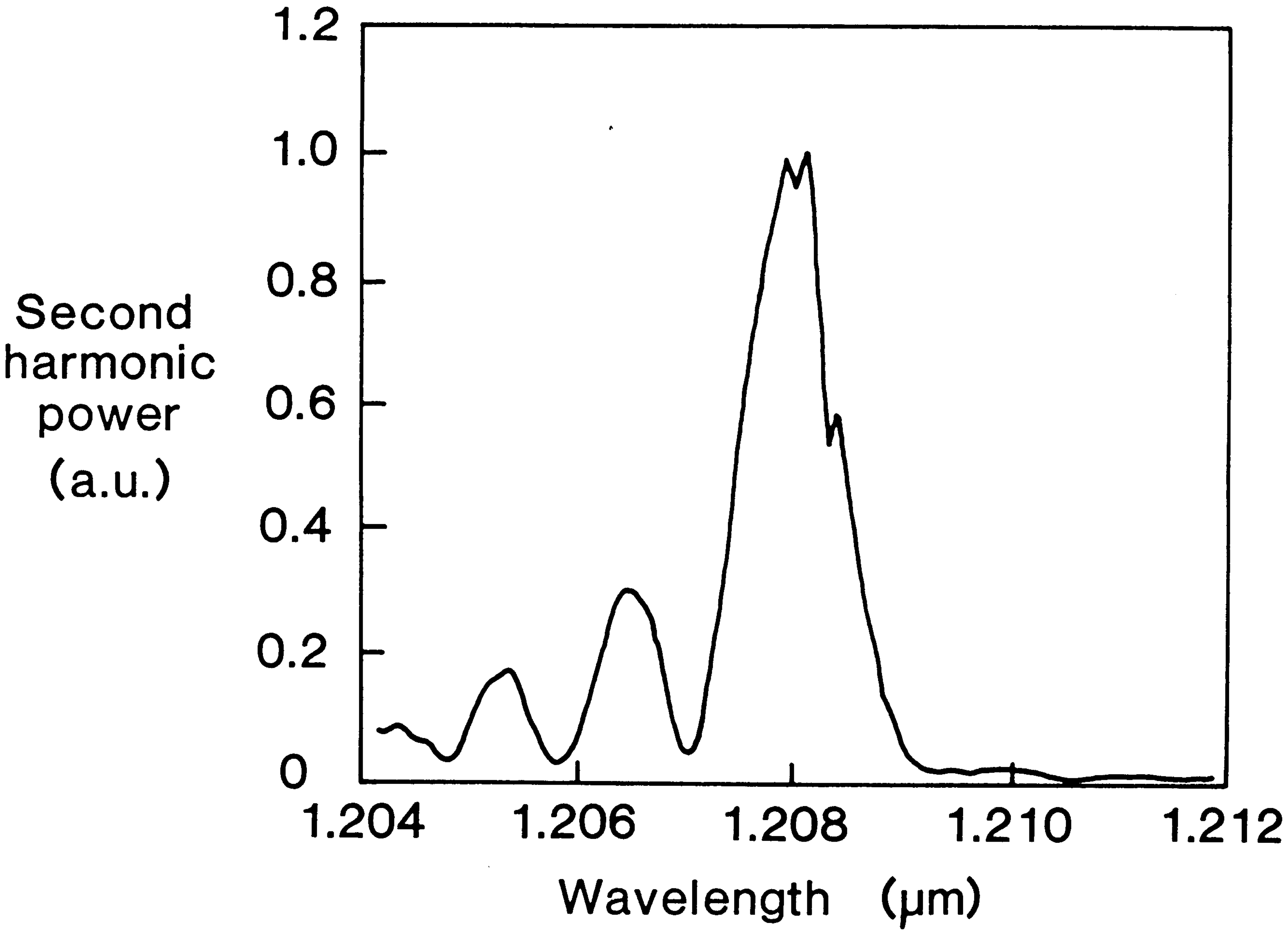
Figure Captions

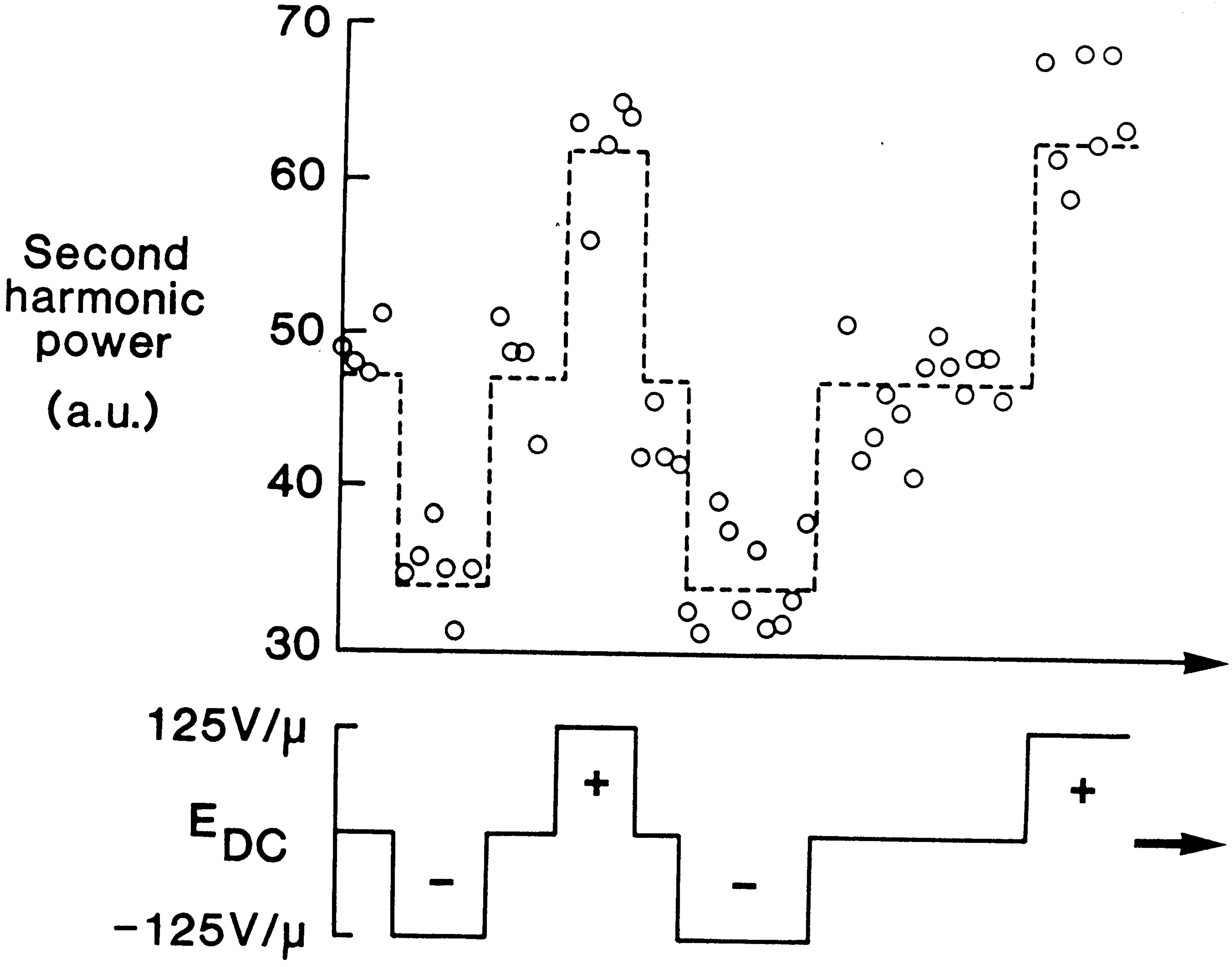
1) Field overlap integral for the LP_{01}/LP_{02} modes as a function of V-value of the fundamental mode. Both a uniform and a step profile $\chi^{(2)}$ are assumed

2) SH-power as a function of wavelength around the phase-match peak

3) Effect on SH-power when a strong DC-field is applied to a poled fibre


0.05
0
-0.05
-0.10
-0.15
-0.20
Ɔverlap
ntegral
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
V-value (fundamental mode)
Uniform x(2)
Step profile x(2)


Second harmonic power (a.u.)
1.2
1.0
0.8
0.6
0.4
0.2
0
1.204
1.206
1.208
1.210
1.212
Wavelength (µm)


Second harmonic power (a.u.)
70
60
50
40
30
125V/μ
E_{DC}
−125V/μ
−
+
−
+