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SECOND HARMONIC GENERATION IN AN OPTICAL FIBRE BY SELF WRITTEN $\chi^{(2)}$ GRATING

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Abstract

Measurements of the effective length and wavelength selectivity of a second order susceptibility grating written into a fibre are reported. A weak non-phase matched second harmonic signal at 532nm is generated by the allowed quadrupole polarisation. This signal initiates the self-writing of an axially periodic pattern of defect centres in the fibre which lead to the growth of a $\chi^{(2)}$ grating. Phase-matching is achieved automatically because the enhanced $\chi^{(2)}$ is written periodically into the fibre at spatial locations where the second harmonic signal is the highest and is in phase with the pump. One particular $\chi^{(2)}$ grating extends over 12cm of fibre and has a bandwidth of 0.24nm.

1. Introduction

Second-harmonic generation (SHG) by an electric-dipole process is normally forbidden in a fused-silica fibre for two reasons: (a) silica possesses a centro-symmetric structure and (b) it is difficult to achieve a phase-matching condition. Despite this, however, SHG of a Nd:YAG laser operating at 1.06μm has been recently reported[1,2] with efficiencies of around 1%. The second-harmonic (SH) signal was observed to grow exponentially over a period of ten hours. We report here similar efficiencies for SHG, together with experimental evidence that the effect is due to the existence of a spatially periodic 2nd-order nonlinear susceptibility ($\chi^{(2)}$) in the fibre. Our hypotheses and experimental results are further supported by a coupled-wave theory in which it is shown that the phase-matching condition can be satisfied by the $\chi^{(2)}$ grating vector.

2. Physical Mechanism

In silica optical fibres very weak SHG occurs at high pump intensities owing to a nonlinear electric quadrupole susceptibility[3]. For a pump wavelength λ_p of 1.064μm the coherence length Λ_c between the pump and the SH at 532nm is approximately 30μm as a result of both material and waveguide dispersion. This gives rise to a 30μm periodic intensity pattern of SHG (green) light along the fibre as energy is interchanged between pump and SH generated light.

In certain fibres with SiO_2 cores doped with a GeO_2 and P_2O_5, semi-permanent colour centres can be created by short wavelength radiation[4]. These are known to form dipole centres which we postulate give rise to enhanced second-order nonlinear susceptibility. If this is the case, phase matching will be automatically achieved because the colour centres which enhance $\chi^{(2)}$ will be written periodically into the fibre at spatial locations where the green light intensity is highest, i.e. where the pump and second-harmonic signal are in phase. At points where the pump and SH are out of

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phase few colour centres are generated. This results in reduced $\chi^{(2)}$ and hence no destructive interference between existing generated green light and the second-order polarisation due to the nonlinear process.

The rate of formation of colour centres is slow at 532nm, but it increases rapidly with the intensity. Thus it takes time to create the spatial grating in $\chi^{(2)}$ within the fibre and this gives rise to the observed rapid growth of SH light.

3. Coupled Wave Analysis

We assume that the self-written $\chi^{(2)}$ is sinusoidally modulated with distance x along the fibre at a period equal to the coherence length Λ_c of the SH polarisation at $\lambda_p = \lambda_{po}$ (the writing wavelength). This gives an electric polarisation:

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$$P = \varepsilon_o(E_p\chi_p + E_s\chi_s) + \varepsilon_o\ \chi^{(2)}\ [1 + M^{(2)}\cos Kx]E^2 \qquad (1)$$

where $E = E_p + E_s$, $K = 2\pi/\Lambda_c$, $M^{(2)}$ is the modulation strength of the grating, χ_p and χ_s are the susceptibilities at the pump (ω_p) and SH (ω_s) frequencies, and E_p and E_s the corresponding electric fields. Using a coupled-wave approach[2], the SH intensity at x = L in the fibre, for an initial pump amplitude $A_p(0)$, takes the form:

$$|A_s(L)|^2 = \{A_p(0)\ \kappa^{(2)}\ M^{(2)}\ L\}^2\ \mathrm{sinc}^2(\nu_g L/2) \qquad (2)$$

in the absence of pump depletion, and

$$|A_s(L)|^2 = 2A_p^2(0)\ \tanh^2\{\kappa^{(2)}\ M^{(2)}\ L/\sqrt{2}\} \qquad (3)$$

including pump depletion for exact phase matching. The various parameters are $\nu_g = (\Delta\lambda_p/\lambda_{po})\nu^{(2)}$, $\nu^{(2)} = k_s - 2k_p$ and $\kappa^{(2)} = A_p(0)k_p\chi^{(2)}/N_p^2$, where λ_{po} is the wavelength for exact phase matching, ν_g the grating dephasing parameter, $\nu^{(2)}$ the SH dephasing parameter and $\chi^{(2)}$ the SH coupling constant. For conversion efficiencies less than about 5%, Eqn. (2) shows that the FWHM bandwidth of the resonance is $\Delta\lambda_{p\frac{1}{2}} = 4\sqrt{2}\ \lambda_{po}/\nu^{(2)}L$. Eqn. (3) shows that the peak conversion efficiency to the SH is approximately quadratic with x for $\kappa^{(2)}M^{(2)}x \ll 1$. However, much more significant is that the $\chi^{(2)}$ grating potentially yields efficiencies approaching 100% for large enough L, as is commensurate with phase-matching.

4. Experiment

Mode-locked, Q-switched pulses of <100psec duration and peak powers of 10kW from a Nd:YAG laser at 1.064μm were launched into a variety of single-mode fibres. Very weak second and third harmonic generation was observed in several. However to date growth in SHG has only been observed in a silica fibre with the core and cladding doped with <1% P_2O_5 and the core doped with 15% GeO_2. The SH signal grew with time from 100pW to 50W over a period of 10 hours.

To confirm the establishment of a $\chi^{(2)}$ grating, the wavelength dependence of SHG was measured. Pulses from a tunable Raman-shifted dye laser of 6ns duration and peak powers of 1kW were launched into fibre with a previously burnt-in $\chi^{(2)}$ grating. The pump was tuned over 4nm, giving a measured $\Delta\lambda_{p\frac{1}{2}}$ of 0.24nm for the SH signal, as shown by the experimental points in Figure 1. The same behaviour resulted when the fibre was pumped from the other end. A best fit of Eqn. (2) to the experimental data occurs at an effective grating length L of 12cm, with $\nu^{(2)} = 2\pi/\Lambda_c = 0.207\mu m^{-1}$. Side-scatter measurements nearer the input end of the grating region gave significantly broader linewidths as one would expect from Eqn. (2).

Figure 1 shows that the largest discrepancies between experiment and theory occur in the side-lobes. This is likely to be linked to non-uniformities in grating phase (and to a lesser extent $M^{(2)}$ and $\chi^{(2)}$) along the fibre. Such variations are an inevitable consequence of the self-writing process, and a more elaborate theory is at present being developed to deal with these effects[5]. Their presence is confirmed in Figure 2, where a side-scatter measurement of the SH intensity is plotted as a function of distance from the fibre end. The pump light was launched from the opposite end of the fibre. It can be appreciated that about 90% of the conversion is occuring in the last 15cm, which agrees quite well with our best-fit value of 12cm.

A variety of different phenomena are likely to contribute to these axial non-uniformities in grating properties, such as the manifestly non-linear x-dependence of the growing SH signal, the 40GHz bandwidth of the pump pulses, group velocity walk-off between pump and SH, and pump depletion due to stimulated Raman or Brillouin scattering. The efficiency of SHG -as distinct from the writing process - will level off at very high pump powers owing to competing non-linear processes such as the two just mentioned.

Finally, an estimate of the product $\chi^{(2)}M^{(2)}$, the modulation depth of $\chi^{(2)}$, can be made if we take our result of 0.5% conversion efficiency at $\lambda_p = \lambda_{po}$ and compare it with the peak value given by Eqn. (2). For the fibre spot-size diameter of 5μm, $\lambda_{po} = 1.064\mu m$, and a peak pulse power of 10kW, 0.5% conversion occurs if $\chi^{(2)}M^{(2)} = 2.75.10^{-16}$ m/V. From Eqn. (9), 60% conversion would be achieved if a grating of this strength were uniform over 1.7m of fibre.

5. Conclusions

We have confirmed experimentally that 1% efficient second-harmonic generation is possible in an optical fibre. We postulate that the mechanism is due to the generation of a grating of colour centres which enhance the second-order susceptibility. The grating period is matched to the coherence length between pump and SH waves. Confirmation of the grating model is provided by our measurements of the operating bandwidth as 0.24nm.

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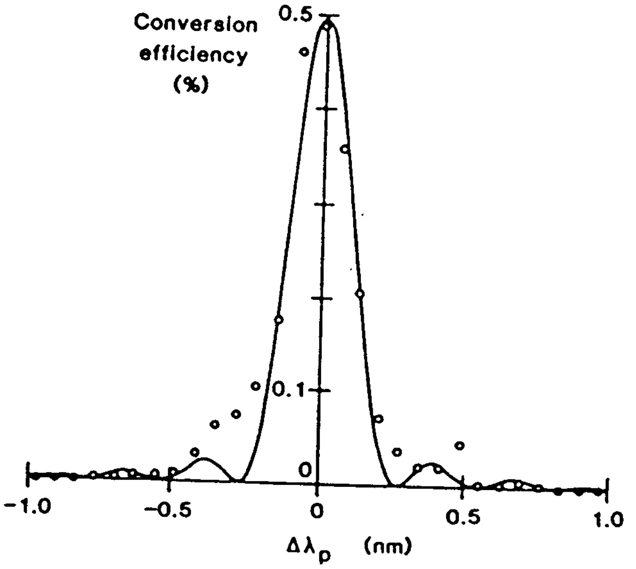

Fig.1 Wavelength dependence of SH conversion for deviations of pump wavelength from 1.064um.

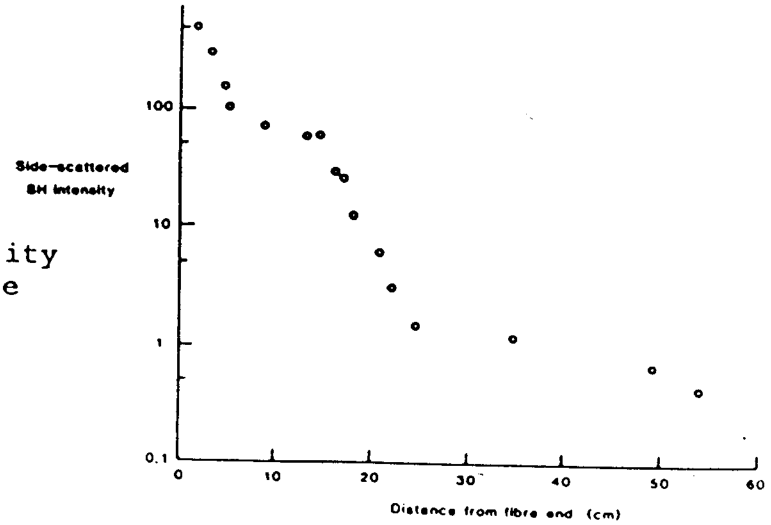

Fig.2 Measured SH intensity as a function of distance from fibre end.