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382

Second Harmonic Generation in Optical Fibres

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Abstract

The mechanism and properties of high conversion efficiency second harmonic generation in optical fibres is reviewed.

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Introduction

There has been much interest in second harmonic generation (SHG) in optical fibres [1-13] since Osterberg and Margulis [1] reported a conversion efficiency of 0.5% and demonstrated dye laser pumping. Further work has achieved conversion efficiencies in excess of 10%. The phenomenon has stimulated particular interest in view of the classical theory that there is no second order nonlinearity in an isotropic medium such as fused silica. The results reported clearly indicate the generation of non-inversion symmetry in the fibre as a result of optical excitation. There have been earlier observations [14] of shg in fibres but it is not clear if these arise from quadrupole nonlinearities, Raman related 4 wave mixing or optically written gratings. In this paper we review SHG due to optical modification of the fibre.

Production of a SHG fibre.

The first technique[1] for production of a phase matching $\chi^{(2)}$ grating in a fibre is to launch intense (>10kW) radiation at 1064nm into a fibre for 8-10 hours. The second harmonic intensity builds up from an initial few pW to greater than 10W. This technique only works for large pump intensities which often leads to optical damage of the fibre.

The second technique[3], following further understanding of the process, involves seeding the fibre with second harmonic (generated in a crystal) which is coherent with the pump radiation. With pump powers as low as 1kW we have found that the fibre reaches saturation after 10 minutes. When the crystal is removed, strong SHG occurs in the fibre.

Mechanism

There is general agreement[2,3,5] that SHG in fibres results from the creation of a permanent periodic structure of defect related dipoles as shown in Fig 1. The periodic structure is produced by a poling dc electric field generated by the 3rd order nonlinear mixing of the pump and seed waves. The field direction and hence the dipoles varys periodically as the relative phase of the pump and seed waves changes along the fibre due to dispersion. The grating period, which is approximately 30μm for conversion at 1064nm, exactly matches the coherence length of the SHG process. Measurements of the conversion efficiency with wavelength in prepared fibre support the idea of a permanent periodic structure[2]. It has also been shown[10] that the peak conversion wavelength may be shifted by changing the effective period of the grating through stretching the fibre or using birefringent fibre. The SHG in the fibre has been shown to be coherent with SHG independently from a crystal when pumped with the same laser [21].

Defects

There is a high defect centre concentration associated with the SHG grating in the fibre. We have measured increased attenuation of 10 dB/m at 532nm due to colour centres produced during grating formation[12]. We have also measured a broad ESR trace associated with the optically written grating (Fig 2). The ESR spectrum is much broader than that usually associated with glass defects, and shows a symmetry characteristic of a crystal rather than a glass. It has has been observed, in measurements of the Raman spectra of fibres suitable for SHG, that the peaks in the defect signal are more pronounced[4]. Annealing some fibres before writing increases the conversion efficiency by 10×. This may be due to residual stress birefringence in the fibre or an increase in the number of available defect centres.

Experiments with non-periodic external electrodes [15,16,20] have shown that a large $\chi^{(2)}$ can be permanently induced in a fibre when a large field is applied to it in the presence of light in the blue region of the spectrum (Fig 3). The wavelength dependence indicates that germania defects are being created by a two-photon process [19]. In the preparation of SHG fibres the exciting light is supplied by the seed and the third harmonics of the pump and seed. To date, SHG has been achieved with 647nm, 1064nm, and 1.319nm all of which have harmonics in the uv-blue. It has been suggested [17] that 4th harmonic generation at 266nm by mixing pump and seed will excited defects by a single photon process.

There is strong evidence [3,5] to suggest that the periodic dipole alignment is a dynamic process. The generated second harmonic will continually interact with the pump field to rewrite the grating. The grating has been bleached by a variety of blue/green wavelengths.

The effect of fibre material on second harmonic generation.

Dopants.	Treatment.	efficiency.	Pump power	Ref.
P, Ge	non seeded	3-5%	20KW at 1064nm	1,2,3
0.5-2% P, Ge	seeded	1-2.%	1-20KW	2,3,8
P,Ge (HiBi)	annealed	13%	1KW	9
P,Ge (HiBi)	not annealed	0.5%		9
P, Ge		0.24%	230W (ml)	11
2% P, Ge	sm 532nm seeded	0.03%	3.5KW	3
2% P, Ge	sm 532nm un seeded	0%	3.5KW	3
Ge	seeded	0.1%	>1KW	8,18
Ge	non seeded	0%	>1KW	8,18
Ge	multimode	0.05	200mW	8
Ge P F	sm 900nm	1.5%	90mW average	8
P		0.04%		9
Al		0.18%		9
SiO_2 only	seeded or not	$0-10^{-4}$%		7,8,18
Ge		10^{-4}%	720W at 647nm	13
Ge, P	seeded	0.005%	520 W at 1319nm	12

The highest conversion efficiency is obtained when pump and sh are maintained in the same polarisation in a Bow-Tie fibre which has been annealed at 700 ^{o}C. It is seen in that weak SHG by permanent grating formation occurs in un-doped phosphorus doped silica fibres which do not contain germania. However strong conversion only occurs if either germania or aluminium are present as codopants. The build up of a $\chi^{(2)}$ grating without seeding when the initial SH is a few pW only occurs in phosphorus germania doped fibres which are at least two-moded at 532nm. This indicates that the quadrupole nonlinearity is responsible for the initial SHG.

Competing nonlinear effects

High conversion efficiencies can only be achieved if competing nonlinear effects are minimised[11]. In many observations of SHG in fibres in which optical powers of the order of 10 kW were used the interaction length is severely limited by self-phase modulation and possibly stimulated Brillouin and Raman generation. A typical laser linewidth of 8 GHz FWHM will generate an effective grating length of 40cm at low powers. However, the effective length will be reduce by a factor of 2 for 100ps pulses of 800 W peak powers. Considering the quadratic length dependence of SHG, a considerable depletion in conversion efficiency occurs. By poorly mode-locking the laser such that the pulse width is greater than 500ps and keeping the peak power to 1KW we are able to obtain grating lengths of 30cm and hence high conversion efficiencies (Fig 4).

Conclusions.

The efficiency of SHG in optical fibres is within an order of magnitude of competing with crystals. The fibre design and writing process are understood and have been optimised to produce greater than 10% conversion efficiency. There remains much work to be done to understand the material change in a fibre from an isotropic glass to a material capable of efficient second harmonic conversion.

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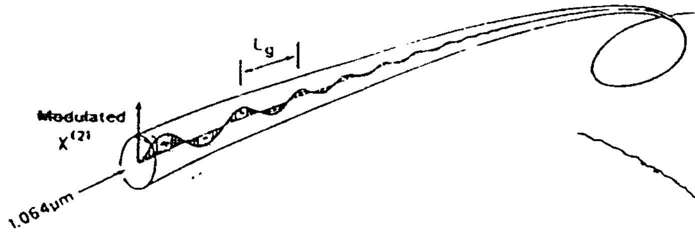


fig 1. $\chi^{(2)}$ grating in a fibre.

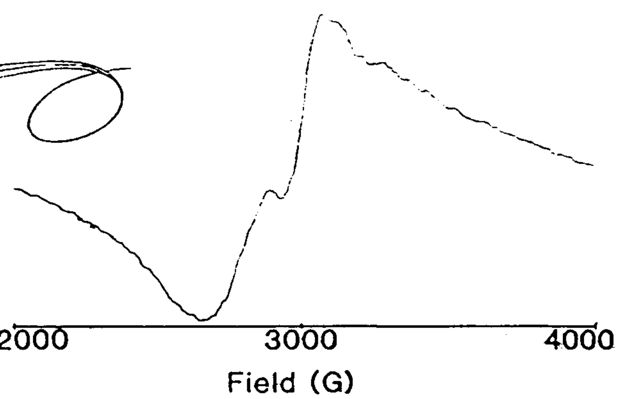
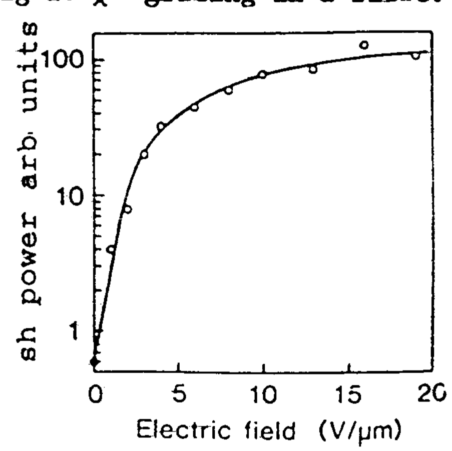


fig2. ESR spectra of prepared shg fibre.



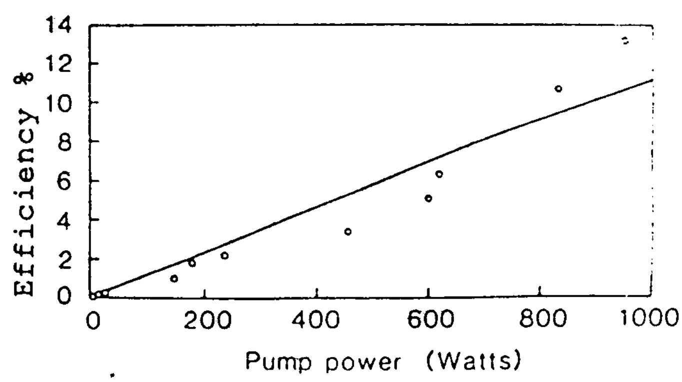


fig 3. Shg in externally poled fibre. fig 4. Efficient shg in a fibre.