



University of Southampton  
*Optoelectronics Research Centre*

Paper number: 1736

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## **>20%-efficient frequency doubling of 1532 nm nanosecond pulses in quasi-phase-matched germanosilicate optical fibres**

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### **Abstract**

**We fabricated second-order nonlinear gratings in D-shaped germanosilicate fibres using thermal poling and periodic electrodes defined by standard photolithography. These gratings, up to 75 mm long, have been used for efficient quasi-phase-matched frequency doubling of 1.532  $\mu\text{m}$  nanosecond pulses from a high power erbium-doped fibre amplifier. Average second harmonic powers as high as 6.8 mW and peak powers greater than 1.2 kW at 766 nm have been generated with average and peak conversion efficiencies as high as 21% and 30% respectively.**

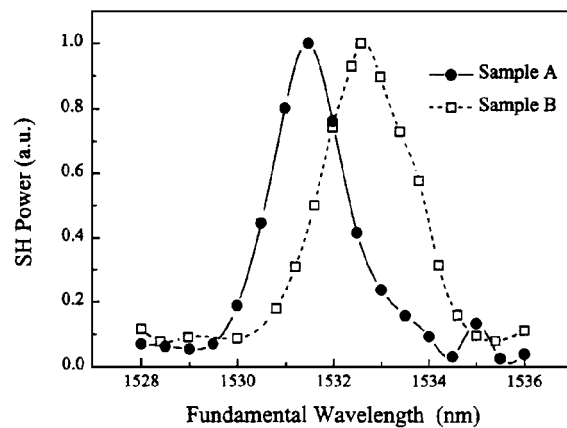
Since its proposal [1] quasi-phase-matching (QPM) has been implemented in many materials and several configurations to achieve efficient nonlinear optical interactions. QPM has several advantages over other traditional techniques (e.g. birefringent and modal phase-matching) used to compensate for the phase-mismatch, induced by dispersion, between electromagnetic fields and corresponding nonlinear driving polarizations in a nonlinear medium. QPM allows one to access new wavelengths, higher efficiencies, non-critical interaction geometries and it provides flexibility and new possibilities for phase-matching, especially in materials where the birefringence is not high enough to compensate for the dispersion and where modal phase-matching is not desirable in order to avoid the generation of light in higher order modes. For example the development of electric-field techniques for periodic poling of ferroelectrics materials, such as lithium niobate [2], has produced a wide range of efficient devices for second-order nonlinear optical frequency conversion, in both bulk and waveguide form. Semiconductor [3] and polymeric [4] materials have also been patterned for QPM interactions. However it is strongly desirable to improve the QPM technology and extend it to other nonlinear

materials of widespread use in optical applications.

Silica and other glasses are particularly attractive since they are dominant materials in information technology and in the development of fibre laser sources. They offer high transparency, low cost, high optical damage threshold, and straightforward integrability; moreover the rare-earth doping of glass fibres has allowed the development of important laser devices, such as the erbium doped fibre amplifiers and more recently high power continuous wave (cw) and pulsed fiber lasers. Unfortunately the inversion symmetry of the glass matrix prevents frequency conversion of coherent radiation through second order parametric processes. The recent discovery that poling techniques [5] can produce a permanent and large second-order nonlinearity in silica has recently made it possible to implement QPM in glass [6] and glass waveguide/fibres [7,8]. Periodically poled glass waveguide/fibres are ideal for a wide range of QPM processes, such as frequency conversion of fibre lasers, difference frequency generation as a means for frequency conversion of telecommunication wavelengths, generation of correlated photon pairs via parametric processes for quantum cryptography, and cascading of second-order nonlinearities to produce equivalent third order effects - self and cross phase modulation- for all-optical switching.

We already suggested [7] that, compared to crystal waveguides, periodically poled silica fibres (PPSF) despite having a lower effective nonlinear coefficient ( $d_{\text{eff}}$ ) can offer longer interaction length ( $L$ ) for the same bandwidth and higher damage intensity threshold ( $I$ ), thus keeping high values for the efficiency-factor  $d_{\text{eff}}^2 L^2 I$ . In particular the large value of the bandwidth-interaction length product, due to low dispersion, makes PPSF suitable for frequency conversion of short pulses (picosecond and even femtosecond) where low group velocity mismatch between interacting pulses at different frequencies is desirable. In a previous report we frequency doubled the output at around 1.5  $\mu\text{m}$  from an optical parametric oscillator delivering  $\sim 100$  fs pulses [8]. The average second harmonic power and efficiency achieved were limited by low values of the effective nonlinear coefficient, group velocity mismatch effects (short interaction length) and higher order nonlinear effects. It was clear that great improvements could be obtained by optimizing the effective nonlinear coefficient but also that longer pulses of correspondingly narrower spectral bandwidth were needed to use the whole 75 mm grating.

In this letter we present average second harmonic powers and efficiencies as high as 6.8 mW and 21% respectively, achieved in improved gratings using as fundamental source a high power erbium fibre amplifier delivering nanosecond pulses at around 1.5  $\mu\text{m}$ . The results of this work represent the highest efficiencies achieved in an optical fibre for second-order nonlinear processes and compare well with those obtained using periodically poled ferroelectrics [9]. We believe they also put PPSF in the position to be considered as serious competitor to other periodically poled materials for frequency conversion of high peak power Q-switched and mode-locked sources, in particular high power pulsed fibre lasers [10] where an integrated frequency doubled all-fibre source would be very attractive.



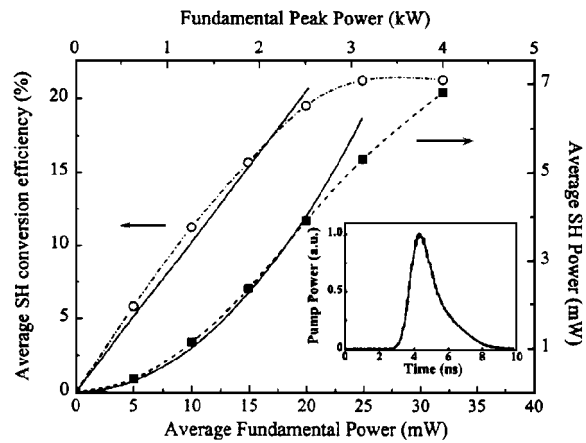
**Fig. 1. QPM curves (Second harmonic power as a function of fundamental wavelength) for sample A (period of 56.45  $\mu\text{m}$  and length of 75mm) and sample B (period of 56.5  $\mu\text{m}$  and length of 60mm). The numerical aperture and the core radius of the fibre are 0.191 and 3  $\mu\text{m}$  respectively. The bandwidths compare well with the theoretical values for uniform gratings with the same length.**

The PPSF samples were fabricated as described in reference 7. The D-shaped fibre had numerical aperture of 0.191, core diameter of 6  $\mu\text{m}$ , outer diameter of 300  $\mu\text{m}$  and initial flat surface/core distance of 15  $\mu\text{m}$ . Preliminary etching reduced the flat surface/core distance to 5  $\mu\text{m}$ , so that after poling the nonlinear layer under the anodic surface includes the core region. The patterned aluminum anode (positive electrode during poling) was fabricated on the plane face of the D-shaped fibre using standard planar lithography. According to the measurements of QPM wavelength versus fibre parameters (NA and core radius) previously reported [8], periods of 56.45 and 56.5  $\mu\text{m}$  were chosen for frequency doubling within the 1530-1540 nm optimum range of tunability of the fundamental fiber amplifier source. Subsequently the patterned fibre was placed in a high vacuum chamber for thermal poling performed by applying 3-4 kV voltage at 270-280  $^{\circ}\text{C}$  for 10-20 minutes.

The fundamental source used in the experiment is a diode-seeded erbium doped amplifier chain based around a large mode area doped fibre [10]. The source was seeded by an external cavity laser, externally modulated with a fast electro-optic amplitude modulator to produce 5 ns square pulses at a user definable repetition rate and whose wavelength could be continuously tuned from 1530 to 1560 nm. The maximum average output power from the amplifier was 100 mW. The pulse energy, peak power and precise pulse shape were pulse repetition rate dependent. For the repetition rate range 1-4 kHz used in these experiments the output pulse duration (see inset Fig.2) was 2 ns (the pulse shortening and shaping relative to the seed pulses was due to gain saturation effects within the chain). The maximum achievable peak power (at 1 KHz) was 30 kW. The optical launch efficiency from the source into our PPSF samples (lens coupling) was 35%.

To assess the quality of the gratings we initially performed second harmonic measurements in the low power regime to avoid saturation and higher order nonlinear effects. Typical QPM curves (SH power versus fundamental wavelength) are shown in fig.1 for the sample with period of 56.45  $\mu\text{m}$  (sample A) and the sample with period of 56.5  $\mu\text{m}$  (sample B). The gratings were 75 and 60 mm long for sample A and B respectively. The bandwidths of the QPM curves compare favourably with the expected values for perfect gratings of the same length, thus indicating that the whole grating length is contributing to the nonlinear interaction.

Figure 2 shows the second-harmonic power and efficiency as functions of fundamental power for  $\sim 2$  ns pulses at 4 kHz (see inset Fig.2) at the QPM wavelength of 1531.5 nm. The maximum average second harmonic power generated in the fundamental mode  $\text{LP}_{01}$  was 6.8 mW with 21% average conversion efficiency. It is evident that there is a roll-off at high power levels with respect to the quadratic behavior (linear for the efficiency) at low power levels. This is probably due to high order nonlinear effects (the influence of these effects on the second harmonic generation is discussed in



**Fig. 2. Average SH power and conversion efficiency as functions of average fundamental power for the QPM-SHG of 2 ns pulses at 1531.5 nm and at 4 kHz for sample A. The solid curve represents the quadratic behaviour (linear behaviour in efficiency) which fits the experimental points at fundamental powers below 20 mW. The inset represents the fundamental pulse shape.**

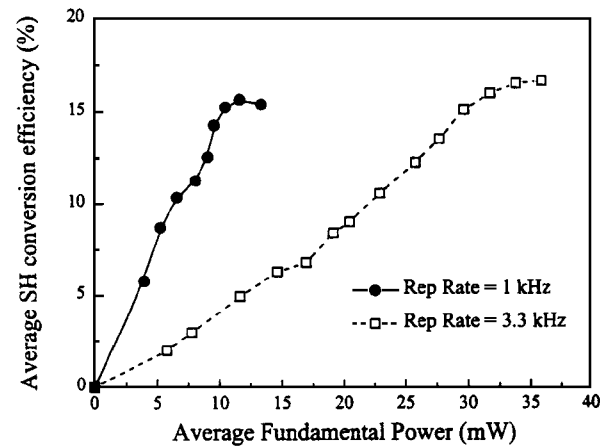
detail elsewhere [11] ) and is consistent with the experimental observation that at high power levels the second harmonic pulse is of similar duration to the fundamental pulse rather than being shorter (e.g. in the low depletion regime and assuming gaussian-shape pulses the reduction factor would be  $\sqrt{2}$ ).

To estimate the effective nonlinear coefficient and the peak value of the SH conversion efficiency from fig.2 we recall here the time dependent expression for the conversion efficiency. In a waveguide geometry, in the low fundamental depletion regime and when the walk-off between SH and fundamental pulses is negligible, the time dependent SH conversion efficiency  $\eta_{2T}(t)$  can be expressed as (x and y are the coordinates perpendicular to the direction of propagation and  $f_{\omega}(x,y)$  and  $f_{2\omega}(x,y)$  are the normalized fundamental and SH mode profiles respectively):

$$\eta_{2T}(t) = \frac{2 T^2 d_{eff}^2}{n_{2T} n_T^2 g_o c_o^3} \frac{P_T(t)}{A_{OVL}} L^2 \text{sinc}^2 \left( \frac{\Delta k L}{2} \right) \quad (1)$$

$$d_{eff} = \frac{1}{m B} \frac{\left| \int_{\text{mm}} f_T^2(x,y) d(x,y) f_{2T}^*(x,y) dx dy \right|}{\left| \int_{\text{mm}} f_T^2(x,y) f_{2T}^*(x,y) dx dy \right|}, \quad A_{OVL} = \frac{1}{\left| \int_{\text{mm}} f_T^2(x,y) f_{2T}^*(x,y) dx dy \right|^2}$$

where  $T$  is the fundamental frequency,  $P_T(t)$  is the time dependent fundamental power,  $d(x,y)$  is the spatial distribution of the nonlinear coefficient (along the direction of propagation  $z$  the nonlinear coefficient is supposed to be  $\pm 0$  modulated),  $d_{eff}$  is the effective nonlinear coefficient which depends on the  $m$ -th QPM order and includes the overlap between poled region and interacting modes,  $L$  is the grating length,  $n_{2T}$  and  $n_T$  are the effective refractive indices at frequency  $2T$  and  $T$  respectively,  $g_o$  the dielectric constant in vacuum,  $c_o$  the speed of light in vacuum,  $A_{OVL}$  is an equivalent area which depends on the overlap integral between the interacting fields and  $\Delta k = k(2T) - 2k(T) = 2(T/c_o)(n_{2T} - n_T)$  is the wave-vector mismatch. From the detailed pulse shape data obtained at the 20 mW average fundamental power data point shown in Fig.2 (where the behaviour is still linear in efficiency) and by averaging the conversion efficiency over the pulse shape we estimate the effective nonlinear coefficient (which includes the overlap between the poled layer and the interacting modes and the  $1/B$  factor of first order QPM) to be 0.014 pm/V for sample A. Correspondingly we also estimate that efficiencies exceeding 30% were achieved at the peak of the pulse for peak fundamental powers of  $\sim 2.5$  kW.



**Fig. 3. Average SH conversion efficiency as a function of average fundamental power for the QPM-SHG of 2 ns pulses at 1532.7 nm for sample B at 1kHz and 3.3 kHz.**

Figure 3 shows the conversion efficiency versus pump power for the second shorter grating ( $L=6\text{cm}$ ), sample B, at the QPM wavelength of 1532.7 nm for two different repetition rates. From these curves and using the expression for the SH conversion efficiency given above, up to the point where the quadratic behaviour is maintained, one can estimate that peak SH powers exceeding 1.2 kW were generated for ~4.5 kW peak fundamental power. This data and that shown in Fig.2 for grating A indicate that the two samples have approximately the same effective nonlinearity, highlighting the reproducibility of our poling process.

In conclusion we have reported efficient frequency doubling of 1532 nm radiation in an all-fibre system based on a high power fibre amplifier and a periodically poled silica fibre. The efficiencies and the second harmonic powers obtained suggest that PPSF is a mature medium for frequency conversion of high power laser sources, in particular fibre lasers. The nonlinear grating and the effective nonlinear coefficient are still far from the optimum (it is estimated that  $d_{\text{eff}}$  can be improved 4-6 times in such a fibre) and further improvements, including fibre design and poling optimization, will reduce the power levels necessary to obtain useful conversion efficiencies. Other wavelength ranges (e.g. doubling of 0.8-1  $\mu\text{m}$  sources) and other second-order processes (e.g. difference frequency generation and parametric downconversion) will be the subject of further experiments.

V. Pruneri acknowledges Pirelli Cavi for his Fellowship, G. Bonfrate acknowledges DERA Malvern for his studentship. This work was supported in part by EPSRIT Grant No. 20029 (ACQUIRE).

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