Efficient frequency doubling of 1.5 μm femtosecond laser pulses in quasi-phase-matched optical fibres

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Abstract

Second-order nonlinear gratings in optical fibres have been produced for efficient quasi-phase-matched frequency conversion around 1.5 μm. Periodic poling was achieved by defining a patterned electrode on a D-shape fibre via standard lithography and applying high voltage (4-5 kV) at elevated temperature (270-280ºC). This fabrication technique has allowed to produce gratings uniform over 7.5 cm, as indicated by the shape and the bandwidth of the phase-matching curve. By frequency doubling ~100 fs pulses in a grating ~4 cm long and with a period of 57.15 μm, ~1.05 mW average power at 768 nm has been generated, with an average conversion efficiency ~1.2%.

Optical glass waveguides (including their fibre form) play a key role in information technology and in the development of fibre laser sources. Low loss silica waveguides are used to produce a variety of optical integrated elements, such as optical splitters, filters and routers. On the other hand 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. However the inversion symmetry of the glass matrix implies that the second order nonlinear susceptibility ($\chi^{(2)}$) is zero, which prevents linear electro-optic effect and frequency conversion of coherent radiation through second order parametric processes.

At the beginning of the ‘90s Myers and coworkers proposed thermal poling to produce a permanent and large $\chi^{(2)}$ in glass [1]. More recently periodic poling of silica based glass waveguide/fibres has produced $\chi^{(2)}$ patterns for quasi-phase-matching (QPM) of second order nonlinear optical processes [2-4]. Silica, as well as other glasses, can offer high transparency, low cost, high optical damage threshold and straightforward integrability, thus ensuring widespread use of periodically poled devices based on poled glass. For example QPM glass waveguide/fibres could be exploited for difference frequency generation as a means for frequency conversion of telecommunication wavelengths, which will be an essential function in the future WDM networks, where it is desirable to route from the incoming channel wavelength to any other allowed channel wavelengths [5]. Another application could be the generation of correlated photon pairs via parametric processes for quantum cryptography [6].Cascading of second-order nonlinearities [7] in QPM glass waveguide/fibre structures could also be employed to produce equivalent third order effects - self and cross phase modulation, e.g. all optical switching.

Despite of all the aforesaid potential applications, so far periodically poled glass fibres (PPGF) or waveguides (PPGWV) have been used for QPM second harmonic generation (QPM-SHG) to the blue in cw [3,4] and pulsed regime [8]. Apart from the obvious general advantages indicated before (low loss, high optical damage threshold, etc.) PPGF and PPGWV compare favourably with nonlinear crystal waveguides, such as $LiNbO_3$. In fact, as pointed out in our previous work, despite the lower nonlinearity (~10X) the lower dispersion allows longer interaction lengths (~10X) for the same acceptance bandwidth, thus achieving comparable efficiencies without compromising the frequency stability. In particular, PPGF has great potential for frequency conversion of short pulses. In ref.8 we have doubled ~2 picosecond pulses obtaining ~80 μW of blue light with an average efficiency of ~0.22% using 1.8cm long $\chi^{(2)}$ grating and with a period of 25 μm. Here we report on the fabrication of $\chi^{(2)}$ fibre gratings for QPM-

SHG of ~1.5 μm with controlled characteristics over lengths up to 7.5 cm. We have used these gratings for frequency conversion in the femtosecond regime. Average SH powers ~1.05mW with ~1.2% average conversion efficiency have been generated using ~100fs laser pulses, with the potential of increasing these values at least one order of magnitude for the same levels of fundamental powers. The results contained in this paper indicate that PPGF can become a competitive alternative to nonlinear crystals, such as periodically poled lithium niobate, for frequency conversion of high peak power Q-switched and mode-locked sources, such as high power pulsed fibre lasers [9,10].

The fabrication technique used to produce the PPGF for the doubling experiments is the same as described in ref.8. An initial patterned aluminum electrode was fabricated on the plane face of a D-fibre using standard planar lithography and subsequently the fibre was carefully placed in a high vacuum chamber for thermal poling [1] performed by applying high voltage (5kV) at elevated temperature (275°C). Several D-shape silica fibres with a GeO_2 doped core and same numerical aperture (NA) of 0.191, were used in the experiments. The core radii were 3, 3.12, 3.32, and 3.45 μm.

For all the measurements the fundamental and SH light were coupled, respectively in and out of the fibre, using 20X microscope objectives. The linear polarization of the fundamental could be rotated via a half-wave plate at 1.5 μm. The output SH light was detected using a calibrated silicon photodiode after additional filters transmitting at 0.7-0.8 μm and cutting 1.5 μm. No significant additional optical loss due to grating fabrication (periodic poling) was observed in the PPGF used in the experiements with respect to untreated fibres.

According to the core radius the period for the periodic poling was chosen for QPM-SHG of a given wavelength. Fig.1 shows the QPM-SHG experimental fundamental wavelengths for 8 sets of different combinations core radius-period. These points were obtained by using a synchronously pumped lithium triborate optical parametric oscillator (LBO-OPO) as tunable fundamental source. In the same figure we also report the theoretical curves (grating period versus QPM fundamental wavelength) for the different fibres (different core radii) used in the experiments. It is clear from this figure that a small error in evaluating the core radius results in a consistent change of the QPM wavelength for a given period. The same applies to the numerical aperture. In fact ~1-2 % errors in evaluating the NA or core radius would result in 10nm QPM wavelength error for a given period. This indicates that the design and the measurements of the fibre parameters are critical for QPM applications at around 1.5μm. However fig.1 shows good agreement between theoretical predictions and experiments, indicating that it is possible to predict accurately the QPM points by controlling both fibre and grating fabrication.

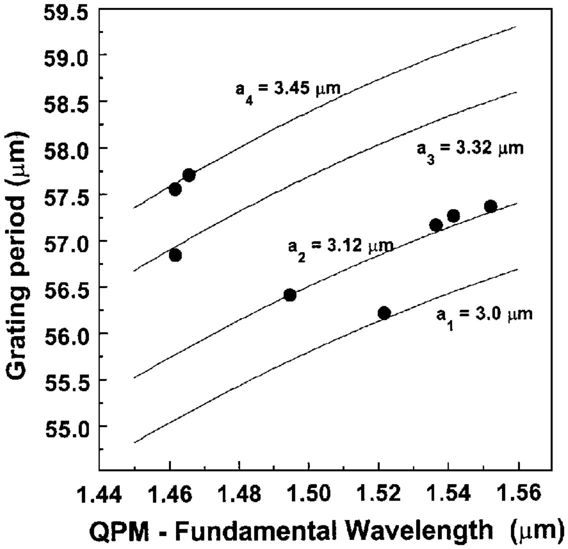

Fig. 1. Period of $\chi^{(2)}$ grating as a function of QPM fundamental wavelength for different core radii. The numerical aperture of the fibre is 0.191. The points are experimental data while the continuous lines are theoretical curves.

To assess the quality of the gratings we have performed SHG measurements in cw using an amplified tunable diode laser, so that the QPM curve (SH power versus fundamental wavelength) is not affected by the bandwidth of the ~100fs pulses delivered by the LBO-OPO. Fig. 2 shows a typical result for a grating 7.5cm long with a period of 57.35 μm in a fibre with 3.12 μm core radius. The normalized conversion efficiency with repect to the

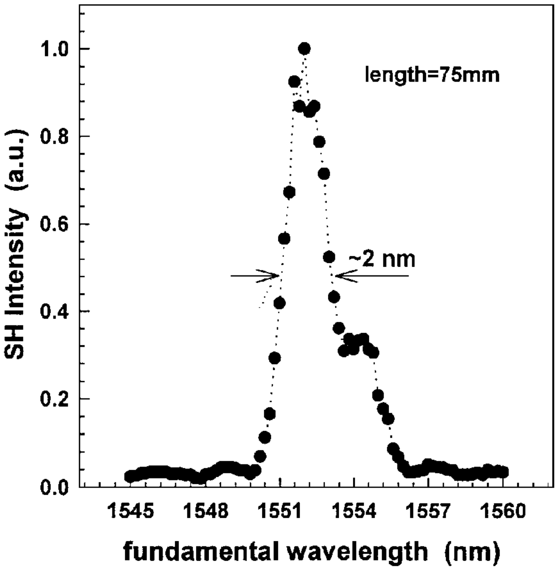

Fig. 2. QPM curve (normalized conversion efficiency as a function of fundamental wavelength) for a $\chi^{(2)}$ grating 7.5 cm long with period of 57.35 μm. The numerical aperture and the core radius of the fibre are 0.191 and 3.12 μm respectively. The bandwidth is close to the theoretical value for a uniform grating with the same length.

fundamental power was ~$1.5 \cdot 10^{-3}$ %/W. The shape of the QPM curve is close to the expected sinc^2 behaviour and its bandwidth of ~2nm is the same as for a transform limited grating, thus indicating that the grating is quite uniform over the whole length. The side lobe is probably the result of small effective refractive index variation along the propagation distance. When the fundamental light was polarized orthogonally to the poling direction the conversion efficiency was reduced of ~7 times. In fact the polarization dependence of the SH efficiency is not only due to intrinsic reasons (tensorial nature of the nonlinear coefficient) but also to the birefringence (different QPM wavelength for different set of polarizations).

For the QPM pulsed experiments involving 100fs pulses at 82MHz from the LBO-OPO we opted to use shorter gratings, essentially for two main reasons. The first reason is related to the limitations imposed by the group velocity mismatch (GVM) between fundamental and SH pulses interacting along the grating [8]. This is shown in fig.3 where the GVM and the QPM bandwidth (which is in first-order approximation inversely proportional to GVM) are plotted as functions of fundamental wavelength. The optimum grating length (which represents a good trade-off between high efficiency and low SH pulse distortion and lengthening due to GVM) turns out to be of the order of 1cm for 100 fs pulses. This length is about one order of magnitude greater than those allowed in $LiNbO_3$. The second limitation on the grating length is due to higher-order optical processes, associated to self-phase modulation (SPM), group velocity dispersion (GVD), etc. The influence of these effects on the SHG is discussed in detail elsewhere [11]. Here we say that these effects are very sensitive to the grating length and they put severe limits on the distance between the input fibre edge and the beginning of the grating to achieve high efficiencies and nearly quadratic behavior for the SH power as a function of the fundamental power. Our choice for the grating length and for its distance from the input and output fibre edges were ~4cm and ~1cm respectively. Since the actual grating length is longer than the optimum (1 cm) we expect to produce SH pulses with longer duration than the fundamental pulses and to be in a quasi-linear growth regime for the SH power versus interaction length (rather than quadratic). When a fibre with NA = 0.191, core radius = 3.12 μm, grating period = 57.15μm was used as frequency doubler we were able to produce average SH powers up to ~1.05mW with an average conversion efficiency ~1.2%. Fig. 4 shows the average SH power as a function of

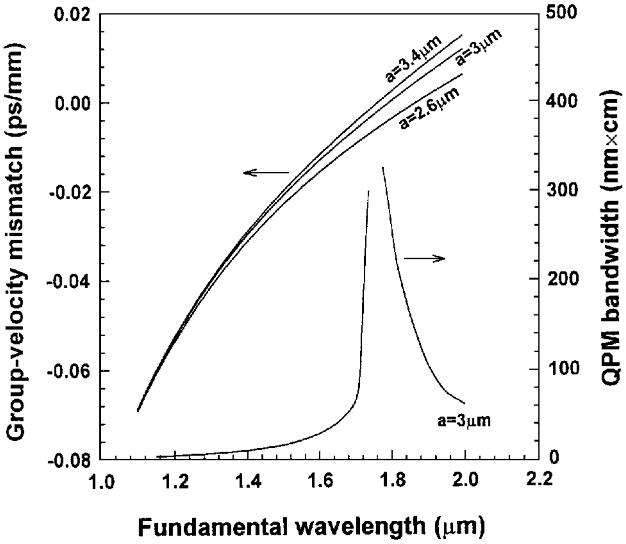

Fig.3. Group velocity mismatch and QPM bandwidth as functions of fundamental wavelength. The numerical aperture of the fibre is 0.191 and the core radius (a) is indicated in the figure.

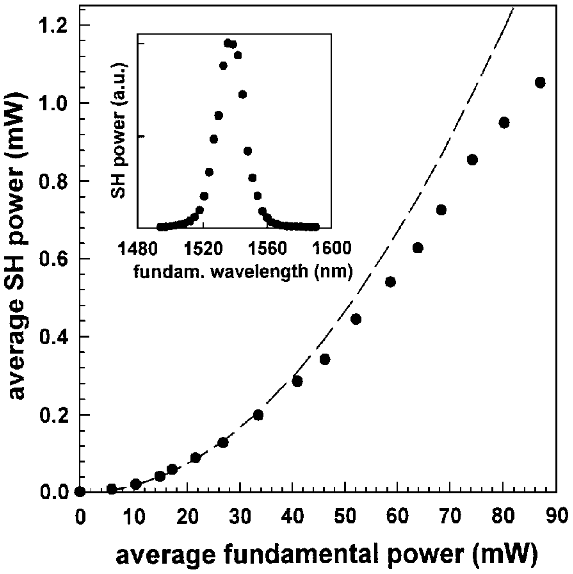

Fig.4. Average SH power as a function of average fundamental power for the QPM-SHG of 107fs pulses at 1537nm. The dashed curve represents the quadratic behaviour which fits the experimental points at fundamental powers below 30mW. The inset is the QPM curve obtained with 107fs pulses at low power in order to avoid higher order effects due to SPM, GVD, etc.

fundamental power for the QPM wavelength of 1537nm. There is a small deviation, due to higher order effects (SPM, GVD, etc.), at high fundamental power (>30mW) from the quadratic behaviour (dashed line) at low fundamental power (<30mW). The inset of the same figure shows the QPM curve obtained using the LBO-OPO. The bandwidth of this curve reflects the ~20nm bandwidth of ~107fs fundamental pulses at this wavelength.

In conclusion we have reported for the first time to our knowledge SHG of 1.5 μm in a periodically poled glass fibre. These results indicate great potential for this novel nonlinear medium in frequency conversion of high power lasers, especially of short pulses (picosecond and even femtosecond regime). Taking account that the effective nonlinear coefficient is still 5-10 times below the theoretical value estimated from measurements on uniformly poled fibres [4], conversion efficiencies and output SH powers of tens of % and tens of mW respectively should be achievable in the near future by optimizing the fabrication of the grating. Moreover we intend to use the same gratings for frequency conversion of high power longer pulses, e.g. picosecond and Q-switched, so that the good quality longer gratings reported in this letter could be already used for achieving higher efficiencies.

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