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Periodically poled silica fibre: an emerging nonlinear medium for optical frequency conversion

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Abstract

Record second-harmonic efficiencies exceeding 20% and parametric fluorescence have been demonstrated in periodically poled silica fibres (PPSF). The achieved performances set PPSF as a highly competitive material with respect to some of the more traditional nonlinear crystal waveguides. We will review some current material and device research in the field, highlighting the potential applications in several areas such as frequency conversion of high power fibre lasers, optical telecommunication, and quantum technology.

Summary

Since its proposal quasi-phase-matching (QPM) has been implemented in many materials (including lithium niobate, semiconductors, and polymers) and several configurations to achieve efficient second-order nonlinear optical interactions. 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. Periodic poling of silica fibres, using thermal poling to produce a permanent and large second-order nonlinearity [1], exploits the potential of the QPM technology to extend the possibility of efficient frequency conversion to materials which have a widespread use in optical applications and offers several advantages. Silica and other glasses exhibit high transparency, low cost, high optical damage threshold, and straightforward integrability; moreover the rare-earth doping and the photosensitivity of glass fibres and waveguides have allowed the development of important devices, such as the Er-doped fibre amplifier/lasers and Bragg gratings.

Combining all the aforesaid properties, it is natural to consider periodically poled silica fibre (PPSF) and waveguide (PPSWV) ideal for a wide range of QPM processes, such as frequency conversion of fibre lasers, difference frequency generation for telecommunication wavelengths routing, generation of correlated photon pairs via parametric fluorescence for quantum cryptography and avalanche photodiodes characterization, and cascading of second-order nonlinearities to produce equivalent third order effects - self and cross phase modulation- for all-optical switching.

Compared to more traditional crystal waveguides, periodically poled silica fibres (PPSF), despite having a lower effective nonlinear coefficient (d_{eff}), offer longer interaction length (L) for the same bandwidth (due to a lower dispersion), higher damage intensity threshold (I), lower loss (α) and refractive index (n) thus keeping high values for the efficiency-factor ($d_{eff}^2L^2I)/(\alpha\ n^3$). In particular the large value of the bandwidth-interaction length product 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.

Recent results include second-harmonic generation (SHG) with record efficiencies in an all-fibre system based on a high power erbium doped fibre amplifier and PPSF [2] and the first demonstration of parametric fluorescence (PF) at around 1.5 µm in an optical fibre [3].

The PPSF samples used in the experiments were fabricated in a D-shaped fibre as previously described [4], using standard planar lithography to define the patterned Al electrode and thermal poling in high vacuum to induce the periodic nonlinearity. For the D-shaped fibre used (numerical aperture of ~0.19, core diameter of 6 µm) typical QPM periods were ranging from 56 to 57_µm for SHG and PF at around 1.5 µm. The fabricated gratings, up to 7.5 cm long, showed a nearly transform limited nonlinear response (revealed by the QPM curve: normalised SHG intensity against fundamental wavelength).

In the doubling experiments average powers as high as ~7 mW and peak powers greater than 1.2 kW at 766 nm have been generated with average and peak conversion efficiencies exceeding 20% and 30% respectively. These results represent the highest efficiencies achieved in an optical fibre for second-order nonlinear processes and compare well with those obtained using periodically poled ferroelectrics. We believe they also put PPSF in the position to be considered as serious competitor to other periodically poled materials for frequeny doubling of high peak power Q-switched and mode-locked sources, in particular high power pulsed fibre lasers where an integrated frequency doubled all-fibre source would be very attractive.

The achieved SH efficiencies were promising for parametric fluorescence considering that, in the low conversion efficiency regime, the parametric gain is of the same order as the SH efficiency. By pumping with 300 mW from a cw Ti:Sapphire laser (766 nm) we obtained a photon production rate of ~150 MHz at around 1.5 µm and gain bandwidth ~100 nm. These results are already very promising for the realization of reliable all-fibre single photon sources for quantum cryptography systems and metrology applications.

Besides the research on fibre poling for QPM frequency conversion we have made some effort in studying the time evolution of the second-order nonlinearity in thin fused silica samples (~0.1 mm thick), in order to gain a deeper understanding of the process in the fibres, given the similar geometrical conditions [5]. In fact for greater thicknesses ($0.1 mm) the value of the nonlinearity seems to scale inversely with sample thickness, suggesting that the undepleted part of the sample plays a significant role in the poling process (although the conductivity of the depleted region is smaller than that of the undepleted region our experiments indicate that part of the external voltage may drop on the undepleted layer and that the conductivity of the depleted region is dependent on the electric field - as one would expect given the values close to breakdown). For sample thicknesses of ~0.1 mm, a comparison between thermal poling of silica in air and in vacuum was carried out. The results indicate that the second-order susceptibility and thickness of the nonlinear layer as well as their time evolution are highly dependent on the surrounding poling atmosphere. In the vacuum case a charge distribution (under the anode) more complex and broader than that for the air case was also revealed by laser induced pressure pulse measurements. A multiple charge carrier model, involving the motion of Na^+, H^+/H_3O^+, oxygen and electrons, can explain the formation and evolution of the depletion region under the anode.

The nonlinear QPM gratings produced so far and their effective nonlinear coefficient are still far from the optimum (it is estimated that d_{eff} can be improved 4-6 times in such a fibre) and further improvements, including fibre design and poling optimization, will lead to higher conversion efficiencies and lower power level requirements to achieve useful performance. These improvements will ensure the use of PPSF as nonlinear medium for real world applications, such as frequency conversion of high power fibre lasers, optical telecommunication, and quantum technology (in fact for single photon sources for quantum cryptography and metrology the performances obtained in our experiments are already sufficient).

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