All-fibre frequency conversion in long periodically poled silica fibres

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Abstract: Efficient all-fibre frequency doubling of 1.5µm pulsed fibre laser has been demonstrated. 3.6mW of second-harmonic light in fundamental mode was produced by quasi-phase-matching in a 11.5cm long periodically poled germanosilicate fibre. The $\chi^{(2)}$-grating was fabricated by continuous periodic-UV-erasure.

Glass silica fibres are a key element for photonics applications and optical telecommunications. However, because of its inversion symmetry on a macroscopic scale, glass is not naturally an electro-optical material. Therefore, although all-fibre active nonlinear components based on second-order nonlinear effects are highly attractive for fully transparent WDM routers and switches or for all-fibre frequency doubling of fibre laser, they do not seem to be feasible and so far a hybrid solution fibre-nonlinear crystals have been used. Yet, the technique of thermal poling has opened a new prospective as a nonlinear $\chi^{(2)}$ susceptibility (~1 pm/V) have been successfully induced in a variety of glass compositions, germanosilicate fibres and waveguides [1]. Efficient nonlinear optical interactions can be achieved by quasi-phase matching (QPM). This method is used to compensate for the phase mismatch, induced by dispersion, between electromagnetic fields and corresponding driving nonlinear polarizations in nonlinear media. QPM has been successfully implemented in ferroelectric crystals by domain inversion and in poled silica fibres by using both periodic comb electrodes [2] and periodic UV erasure [3,4]. Compared to periodically poled ferroelectric crystals, periodically poled silica fibres, despite having a lower effective nonlinear coefficient (d_{eff}), can offer longer interaction length (L) for the same bandwidth due to the lower chromatic dispersion, and higher damage threshold intensity (I), thus keeping high values for the efficiency factor: $(d_{eff}\ L\ I)^2$. Low propagation losses and low insertion losses provide an additional benefit. Moreover the higher damage threshold makes it possible to exploit higher intensity which makes poled devices particularly suitable for frequency doubling of high power fibre lasers. In this way, even if the nonlinearity is smaller, the previously defined figure of merit attains similar values for both materials. The comparison becomes even more favourable considering the frequency doubling of ultrashort pulses, where LBO or KDP (for high power levels), having a wider bandwidth and $\chi^{(2)}$~1 pm/V are commonly used.

In 1999 we reported efficient frequency doubling in quasi-phase matched germanosilicate optical fibres [2]. Up to 75 mm long $\chi^{(2)}$-gratings were fabricated by thermal poling in vacuum and periodic electrodes defined by standard photolithography on the flat surface of a D-shape fibre. Average conversion efficiency of 21%, defined as the ratio of the second harmonic (SH) power over the pump power, was demonstrated for pump peak powers as high as 4 kW corresponding to normalized conversion efficiency of 5×10^{-3} %/W. Although successful, this technology has some drawbacks which prevent scalability towards higher conversion efficiency. The photolithographic process limits the device length to about 10 cm. Also the quality of the $\chi^{(2)}$-grating might be an issue as the fringe field produced by the comb-electrode might vary the duty cycle and reduce the contrast of the QPM structure.

In this letter we report the first demonstration of all-fibre frequency doubling of a fibre-laser. 3.6 mW of red light in the fundamental mode was obtained by frequency doubling from 1554.8 nm to 777.4 nm in quasi-phase matched periodically poled twin-hole silica fibre. An average conversion efficiency of 2.4% was achieved in a 11.5 cm long device with pump peak power of only 108 W compared to 4 kW used in our previous works [2]. The correspondent conversion efficiency, normalized for the pump power, is $\eta = 2.2\times10^{-2}$ %/W and is the highest ever reported for poled fibres. Moreover the main advance in the $\chi^{(2)}$-grating fabrication, continuous periodic UV erasure, that it is demonstrated here for the first time and does not need amplitude masks will ensure scalability to even longer devices and possibly compensation of fibre non-uniformities in long devices [5].

A specially designed twin-hole germano-silicate fibre was fabricated for this work. The fibre has an outer diameter of 125 µm, to facilitate splicing with standard telecom fibre. It has also two holes of 50 µm diameter running parallel to the core and separated by 10 µm, allowing for two wire electrodes to be inserted in the holes. Since, in poled fibres, the nonlinearity extends typically for few microns in the glass close to the surface in contact with the positive electrode, the ~ 3 µm diameter core is deliberately placed closer to one of the holes in order to maximize the overlap between core and nonlinearity itself. The edge to edge separation between the closest hole and the core is 2 µm. The cladding is made in fused silica glass (Hearasil by Heraeus quarzglas) and the fibre is designed to be single mode at 1550 nm. The NA is 0.28 corresponding to a maximum germanium concentration of 16.8%mol. The high NA is chosen because of the higher confinement of the mode that yields to both higher power density of the fundamental mode and better overlap between fundamental and SH mode. These factors contribute to an efficient frequency conversion.

For poling, gold plated tungsten wires having 25 μm in diameters were inserted in the two holes. The poled area, defined by the region where the electrodes overlapped, was 13 cm long. Poling was carried out in air by heating the fibres to 250°C for 30 minutes with 4kV applied. Cooling down to room temperature occurred in few seconds as the heater was physically removed from under the fibre. After poling the wires were removed from the samples and the devices spliced to standard telecom fibre (SFM28).

The $\chi^{(2)}$-grating for quasi-phase matching were fabricated by local erasure of the nonlinearity through exposure to UV light. This technique is referred to as periodic UV erasure. For the first time, taking advantage of the continuous Bragg-grating writing system [6], no amplitude mask was used. Instead the periodic nonlinearity was created step by step, by focusing the 5 mW output from a frequency doubled Ar^{+}-laser (λ=244 nm, spot size $2\omega_0$= 15 μm x 350 μm) on the core of the poled fibre and translated along it. During the movement, the UV light was flashed intermittently in synchronization with the translation stage. QPM period of 42.400 μm was written in the fibre devices, aiming for frequency conversion between LP^{ω}_{01} −−> $LP^{2\omega}_{01}$ fundamental modes. The UV laser fluence experienced by the fibre core was 7.14 J/cm^2. The duty-cycle of the intermittent UV beam was chosen to be 20% in order to compensate for the erasure due to the tails of the Gaussian spot and to have about 50% duty-cycle on the actual nonlinear profile. The step by step method we adopted for the $\chi^{(2)}$-grating fabrication possesses some key advantages over the use of periodic comb electrodes or amplitude mask for UV erasure. First of all it ensures scalability to much longer length. Up to 1 m long devices are expected to be feasible, being limited only by the travel range of the translation stage and by the uniformity of the fibre itself along the length. Small variations in the effective index along the fibre might severely limit the conversion efficiency for they introduce phase errors among the interacting SH waves preventing their constructive interference. On the other hand the flexibility offered by a direct writing technique enables in principle to locally adapt the period of QPM grating to compensate for fibre non-uniformities. Furthermore, by dosing the fluence of the UV beam, it is possible to tailor the amount of nonlinearity to be erased.

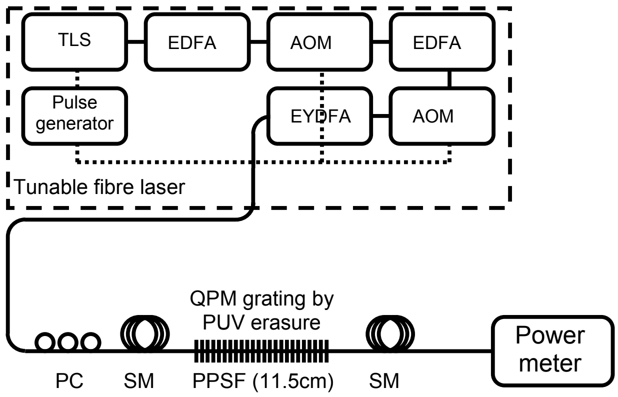

Figure 1. Schematic of the diode seeded tunable fibre laser and of the all-fibre frequency doubling system based on periodically poled silica fibre (PPSF): TLS-tunable laser seed, EDFA-Erbium doped fibre amplifier, AOM-acousto-optic modulator, EYDFA-Erbium Ytterbium doped fibre amplifier, PC-polarization controller, SM standard telecom single mode optical fibre. The grating for quasi phase matching (QPM) in the PPSF was 11.5 cm long and was fabricated by continuous writing periodic UV erasure (PUV).

The potential of a second-order nonlinear medium in fibre form is best highlighted in all-fibre devices. A tunable fibre laser (1535-1562), narrow linewidth (~15 pm) single polarization, with 10 ns pulses operating at 100 kHz, was frequency doubled with a periodically poled device directly spliced to the output of the laser. The schematic of this all-fibre frequency doubled laser is shown in Fig.1. The laser delivered a maximum peak power of ~200 W within the acceptance bandwidth ($\Delta\lambda_{FWHM}$=1.4 nm) of the periodically poled device. Further growth of the peak power is prevented by four wave mixing that spread the power to a broader range of wavelength outside the bandwidth of the poled devices. The splice loss, between the standard single-mode telecom fibre and the twin-hole fibre, is about 3dB, due mainly to NA mismatch. It is possible to reduce this though with tapered or buffer fibres.

The device is first characterized by examining the wavelength tuning profile (Fig.2a). The acceptance bandwidth, measured at FWHM, is 1.4 nm for a device length of 11.5 cm. The agreement with theoretical predictions is remarkable and does show that the whole length of the device is used in the frequency conversion process. It is also a direct proof of the good quality of the $\chi^{(2)}$-grating fabricated by our continuous writing method.

At a pump peak power of 108 W, corresponding to an average pump power of 148 mW, a maximum average conversion efficiency of 2.4% was obtained. 3.6 mW of red light in the fundamental mode was produced by the periodically poled fibre device after frequency doubling from 1554 nm to 777.4 nm. The quadratic dependence of the SH power against the pump power and the corresponding linear relationship between the conversion efficiency and the pump power are shown in Fig.2b.

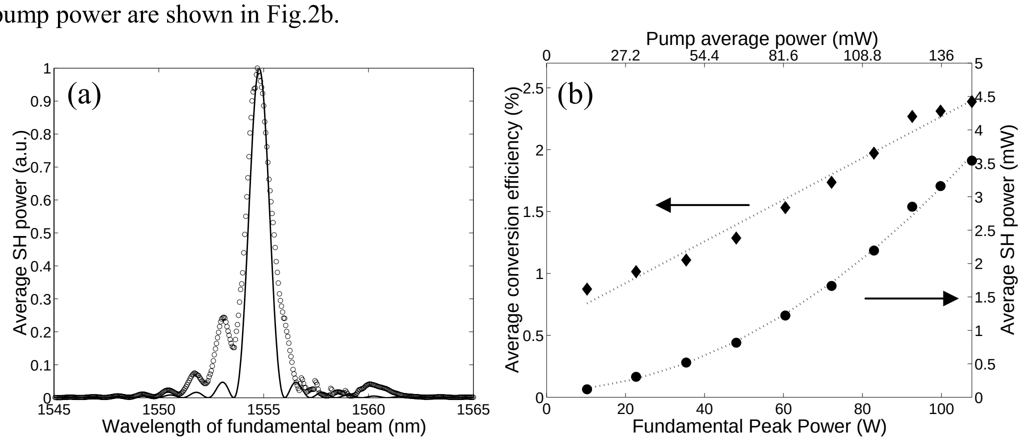

Figure 2a. Wavelength tuning profile of the 11.5 cm long periodically poled fibre device. (circles) experimental data and (solid line) theoretical predictions. The acceptance bandwidth of the device is 1.4 nm at FWHM.

Figure 2b. (circles) Quadratic dependence of the SH average power (right axis) versus the pump power and (dotted line) fit to the experimental data. (Diamonds) correspondent average conversion efficiency (left axis) versus pump average power is shown. (dotted line) linear fit to the experimental data. The wavelength of the fundamental is 1554 nm.

In conclusion we demonstrated an all-fibre frequency doubled laser using 11.5 cm long periodically poled fibres. Efficiency of 2.4% was obtained with pump peak power of about 100 W. Given the linear relationship holding between the pump peak power and conversion efficiency, we expect ~50% efficiency for frequency doubling of laser sources delivering 2 kW of peak power. The results presented here were made possible by a new method for the fabrication of the periodically poled fibre devices based on continuous periodic UV erasure.

References

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