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1529

Highly efficient second harmonic and sum frequency generation of nanosecond pulses in a cascaded erbium doped fibre:PPLN source

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Abstract

By combining erbium doped fibre sources based on a large mode-area design and periodically poled lithium niobate we have obtained single pass conversion efficiencies of up to 83% (energy efficiency) for second harmonic generation into the near-IR (768nm) and 34% for sum frequency generation into the green (512nm) for ns

pulses using first order quasi phase-matching. Pulse energies in excess of 80μJ of second harmonic have been obtained from systems pumped by a single laser diode.

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Recent developments in optical-fibre-based sources, resulting in higher peak powers, coupled with "engineered" nonlinear optical materials such as periodically poled lithium niobate (PPLN) are opening the way for a whole new class of practical nonlinear optical devices. These will exploit the combination of the large optical nonlinearity of PPLN [1] and the high peak powers available from advanced fibre designs such as cladding-pumping, large-mode-area fibres, ring-doping, etc.[2,3]. They will be diode pumped, with the simplicity, flexibility and ruggedness of fibre sources, and have the wide wavelength coverage provided by parametric nonlinear processes. Recently such a combination has been used to frequency-double the output of femtosecond erbium fibre lasers with up to 25% efficiency[5], and using the second harmonic, to pump an Optical Parametric Generator (OPG)[6]. However, for many applications, e.g. pumping of nanosecond Optical Parametric Oscillators (OPOs), pulses with greater energies are required, for which diode-pumped, large mode-area erbium doped fibre amplifiers (LA-EDFA) and lasers are ideally suited[2].

Here we report record single-pass energy conversion efficiencies for PPLN of 83% and 34% for second (768nm) and third (512nm) harmonic generation respectively using 2-50 nanosecond pulses generated with practical erbium-doped fibre systems. Second harmonic pulse energies as high as 80 μJ have been obtained. These energies are suitable for pumping a PPLN OPO for which thresholds in the 10μJ range have been reported[1]. The tunability of the erbium device is an important asset, which should allow broad tuning (over more than 10nm) of the second harmonic, using a multigrating PPLN sample[7]. With such a tunable pump, and again a multigrating PPLN sample for the OPO, continuous tuning of the OPO could then be achieved at a fixed PPLN temperature, as demonstrated for a picosecond Ti:Sapphire-pumped PPLN OPO[8]. This promises a very practical source, tuning from 1-5μm.

Two different fibre pulse sources were used for the frequency mixing experiments. The first was a diode-seeded amplifier-cascade employing large-mode-area, single-mode erbium-doped fibre in which 1 mW level square pulses of duration 1-10 ns (generated from a directly modulated DFB diode laser operating at 1536nm) could be amplified to produce peak powers in the range 0.1-100 kW at repetition rates of between 1kHz and 100kHz [3]. [Clearly one could replace the current argon ion/Ti-sapphire pump, delivering 1W, by a MOPA system to yield pulse powers of up to

30kW]. The second source used in these experiments was a simple MOPA-pumped, Q-switched fibre laser once again based on a LA-EDFA [4]. The cavity comprised a bulk acousto-optic modulator (the Q-switch was operated on zeroth-order), a high reflector and the 96% output coupling provided by the Fresnel reflection from the fibre end-face. The laser could be tuned in the range 1530-1560nm by rotation of an intracavity filter (1nm bandpass). The laser produced 45 ns pulses of energies up to 180 μJ at a repetition rate of 200 Hz with a corresponding peak power of 3.6 kW. Both laser sources produced linearly-polarized, diffraction-limited output with bandwidths (0.01nm for the amplifier-cascade, 0.15nm for the Q-switched laser) much less than the 0.5nm acceptance bandwidth of the PPLN sample.

For these experiments several PPLN crystals were fabricated in 0.5mm thick z-cut lithium niobate by electrical poling. The samples were mounted in temperature-controlled oven assemblies to allow temperature tuning of the phase-matching condition. Sample 1, an uncoated sample, designed for second harmonic generation at wavelengths around 1536nm, had a period of 18.05 μm, and was 16mm long. Sample 2, had a period of 6.5μm, which phase-matches sum-frequency-mixing between the fundamental and the second harmonic to produce green light at 512nm. For some of the experiments using the Q-switched LA-EDFA source, a number of which were performed at a later date, we used 20mm long samples, some coated with MgF_2:silica and some polished at Brewster's angle to give higher throughput. Measurements on the samples indicate an effective nonlinear coefficient of 16pm/V, approaching the maximum possible value.

In the first experiments we measured the single-pass SHG conversion efficiency in sample 1 using the amplifier-cascade source. The fundamental output, which was in the lowest order transverse mode, was focused to a 29µm spot radius in the sample, corresponding to a ratio l/b (crystal length/confocal parameter) of 2.1, close to the optimum focusing condition. The internal SHG efficiency was determined for various peak powers and pulse shapes. The pulse shape was a function of pulse duration and repetition rate because of gain saturation effects in the amplifier cascade. A typical plot of SHG conversion versus pulse peak power is shown in figure 1 for 10nsec pulses (width of base) at a repetition rate of 14kHz. The energy conversion efficiency (SH pulse energy/ total pulse energy) was 83%, obtained at a peak pulse power of 1.4kW (internal peak intensity, at beam centre, of 104MW/cm^2). This record single-pass conversion efficiency for PPLN is in part due to the absence of low power wings in the pulse shape, so that high conversion efficiency occurs over the entire pulse. The roll off at higher peak powers observed in Fig.1 was found to be due to parametric down conversion of SHG photons back to wavelengths around the fundamental. The uncoated crystal faces provided feedback for this parametric oscillation. This is illustrated in Fig.2 showing the throughput spectrum around 1536nm as observed via a spectrum analyzer as a function of peak power. A symmetric feature of 8 nm spectral bandwidth is found to develop around the spectrum of the residual fundamental at peak powers of 1.4 kW and above. Note that the spectrum in fig 2b does not give a quantitative representation of the spectal wings as these were less well launched into the fibre input of the spectrum analyzer. A separate estimate of the power in the wings was consistent with the reduced SH power.

Having obtained high SHG conversion efficiency from the EDFA cascade source we examined the performance obtainable using two PPLN samples to obtain efficient sum-frequency generation into the green (512nm) at the third harmonic of the fundamental. This was achieved by setting an appropriate SHG conversion efficiency (theoretically around 66% for maximum conversion efficiency, i.e. equal numbers of second harmonic and fundamental photons) at sample 1 and relaying the SH beam and the residual pump into sample 2 via two (uncoated) focusing lenses. The focusing into Sample 2 was optimized to give the maximum green power. A plot of the achieved internal energy conversion efficiency as a function of total internal peak power is shown in Fig.3 for the experimentally determined optimum ratio of fundamental to second harmonic (26:74 in practice). From Fig.3 it is seen that internal conversion efficiencies as high as 34% are readily achieved with what is in reality a far from optimal system. Substantially higher conversion efficiencies should be achievable by appropriate coating of the PPLN samples and ancillary optics, and optimisation of the spot sizes of the two mixing beams in the second crystal. Alternatively, PPLN offers the possiblity of fabricating the two gratings consecutively within the same sample allowing for considerable simplification of the system.

Finally, we investigated the pulse energy conversion to SHG and THG using the more practical, all solid-state source, MOPA-pumped, Q-switch source. In our initial experiments using PPLN samples 1 and 2 and the Q-switch laser operating at reduced output we obtained maximum (internal) energy SH conversion efficiencies of 62% for 45ns, 50μJ fundamental pulses. A maximum THG conversion efficiency of 15% was obtained. The reduced efficiency relative to the EDFA-cascade result is mainly due to the Gaussian temporal profile of the fundamental pulses which gives low SH conversion in the pulse wings. In later experiments using the AR coated SH crystals previously described and with the Q-switch laser optimised to give increased output pulse energies we have obtained external SH pulse energies in excess of 80μJ for 45ns, 180μJ fundamental pulses. The reduced efficiency in this instance we attribute to pulse shape effects since the fundamental q-switch pulses develop a significant pulse tail at these high energies.

In conclusion, we have shown that the combination of nanosecond pulses from LA-EDFA systems and PPLN provides a versatile means of nonlinear optical frequency conversion. We have demonstrated substantial harmonic conversion into the near-IR and visible. The results show that the stability, high quality and versatile performance characteristics achieved with erbium doped fibre systems are suitable for efficient wavelength translation via PPLN, opening up new device performance opportunities in the visible and near IR.

Acknowledgements

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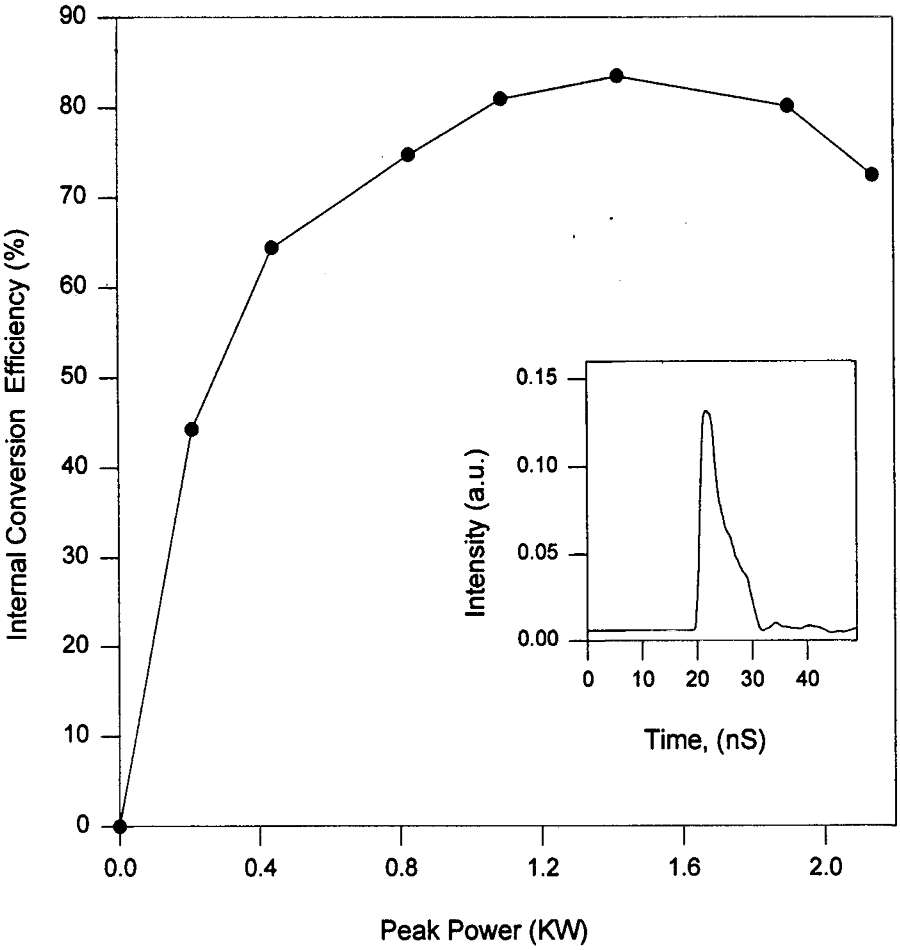
Fig.1 Internal SHG energy conversion efficiency for pulses from EDFA cascade source. Inset. Fundamental pulse shape.

Fig.2 Spectral output around 1536nm (a) before and (b) after exit face of PPLN for a peak power of ≈1.8kW, showing the parametric down conversion of SHG photons at high peak powers (>1.4kW).

Fig.3 Internal THG conversion efficieny for pulses from EDFA cascade souce as a function of internal second harmonic peak power. The ratio of the fundamental to the second harmonic power was (26:74).

Figure 1



Internal Conversion Efficiency (%)
90
80
70
60
50
40
30
20
10
0
0.0
0.4
0.8
1.2
1.6
2.0
Peak Power (KW)
Intensity (a.u.)
0.15
0.10
0.05
0.00
0
10
20
30
40
Time, (nS)

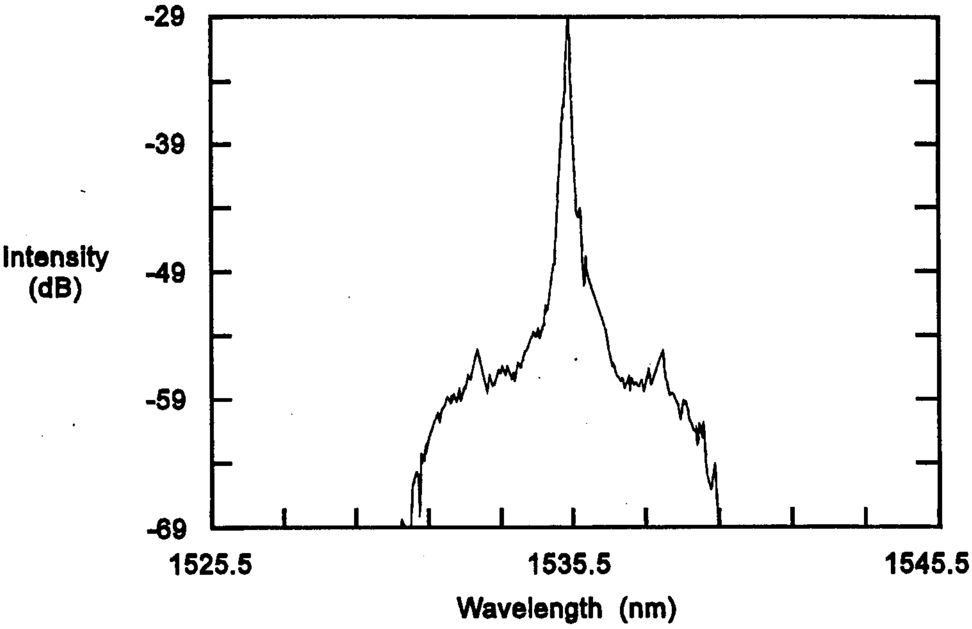


Figure 2b

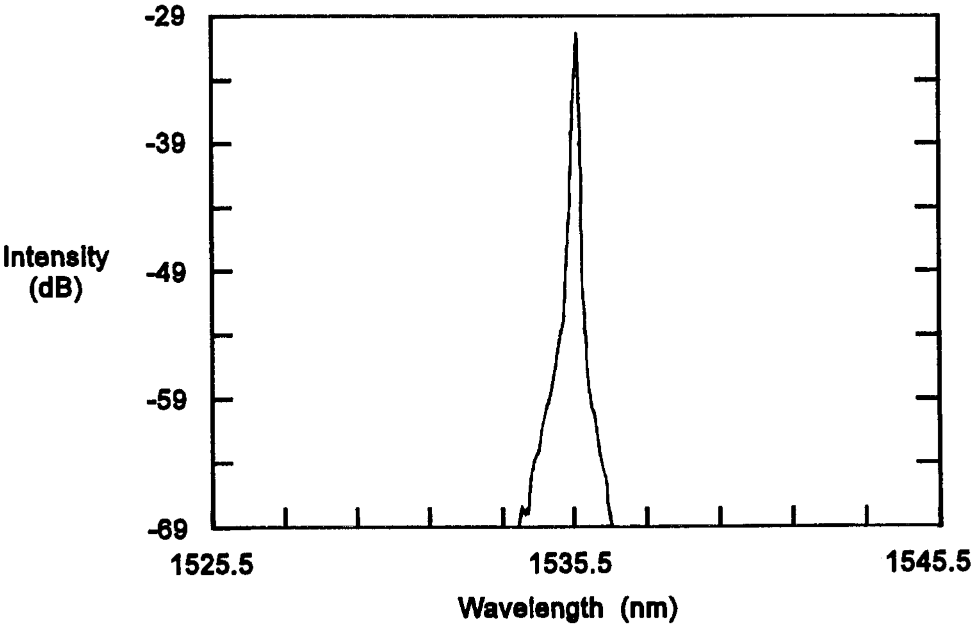
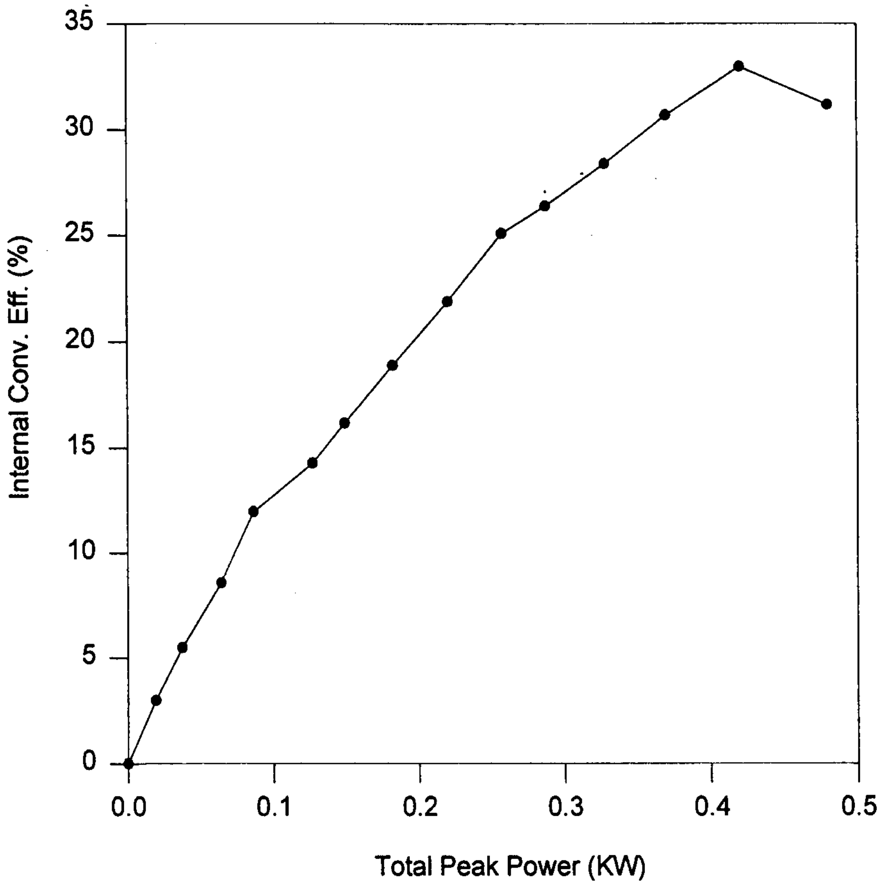


Figure 2a

Figure 3


35
30
25
20
15
10
5
0
Internal Conv. Eff. (%)
0.0
0.1
0.2
0.3
0.4
0.5
Total Peak Power (KW)