Visible, duration–bandwidth tuneable source based on adiabatic Raman compression and frequency upconversion in PPKTP

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Abstract

We demonstrate a wavelength, bandwidth and pulse duration tuneable picosecond source operating around 772 nm. The source utilises quasi-phase-matched second harmonic generation in a periodically poled KTP crystal and optical seeding of an erbium fibre amplifier using adiabatic Raman compression of directly modulated 10 GHz pulses at 1544 nm. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Practical visible sources based on fibre lasers and frequency upconversion in periodically poled materials require control of wavelength stability, line width and high peak powers. Previous research has demonstrated that with PPLN, high peak powers are achievable and up to 85% efficient second harmonic generation (SHG) of a large core fibre source is possible [1]. It has also been demonstrated that with PPKTP, much more relaxed requirements on the temperature stabilization of the crystal are needed and damage thresholds of the material are significantly higher than in PPLN.

Up to 44% conversion efficiency at 1540 nm was achieved using 50 ps to 2 ns pulses from directly gain switched DFB lasers as a seed source for high power erbium amplifiers [2]. Development of the seeding sources with pulse-bandwidth tuneability can allow bandwidth and peak power optimisation of the specific quasi-phase-matched non-linear frequency conversion in periodically poled materials. In this paper we propose and demonstrate the use of an optical, fibre based, pulse compressor as a seed source for frequency doubling in PPKTP, with duration tuneability from 1 to 10 ps and wavelength, bandwidth and repetition rate as selectable characteristics. Applications of this novel source include replacing Ti:Sapphire systems and source for upconversion into the ultra-violet for lithography use.

The two main approaches to the compression of pulses to picosecond and sub-picosecond durations

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in optical fibre are high order soliton effect compression and adiabatic pulse compression. For sub-picosecond chirped pulse compression in the normal dispersion region of optical fibre, stimulated Raman scattering and third-order group-velocity dispersion (GVD) \( \beta_3 \) limit the efficiency of compression. In the anomalous dispersion region, soliton effect compression offers the advantage of achieving high compression factors in short lengths of fibre, although self-Raman scattering may be problematic. For instance, 1.1 ps pulses have been compressed to 18 fs using 11 m of fibre [3]. In this scheme the increase in pulse compression factor can lead to degradation of the solitons through shedding of their pulse energy as dispersive waves and through self-Raman effects and non-linear mixing [4]. This drawback can be eliminated using adiabatic soliton compression which takes place in the fibre lengths significantly longer than the characteristic soliton period but can lead to an increase in the distributed fibre loss. The use of a dispersion decreasing fibre, which compensates for distributed fibre loss by adjusting soliton power requirements [5], was first suggested by Tajima [6]. Analogous to adiabatic amplification, the technique can be used for pulse compression with the compression factor determined by the ratio of the input to output dispersion. As an alternative, the use of step-like [7] and comb-like [8] dispersion profiled fibre composites successfully demonstrated high compression factors and femtosecond pulse generation [9]. High compression ratios have been obtained using seed sources based on electro-absorption modulators (EAMs) which provide soliton like inputs [10] with some compromise in duration and wavelength flexibility.

Unlike fibre composite adiabatic compressors, adiabatic soliton compression via Raman amplification provides a source of high peak power pulses that are wavelength, duration and bandwidth tunable. Distributed Raman amplification was originally proposed by and Hasegawa for soliton transmission to overcome distributed fibre loss [11] and was later experimentally verified [12]. The technique of synchronous Raman amplification of solitons has also been shown to give rise to high pulse compression of 2 ps to 300 fs via adiabatic amplification [13]. With the availability of the new family of efficient and compact cascaded fibre Raman pump lasers a counter-propagating pump and signal configuration has become possible. This configuration supports fundamental solitons of a wide range of pulse durations, with a tuneable compression ratio limited only by gain saturation and high order non-linear effects, providing greater input and output pulse duration flexibility compared to the aforementioned compression methods [14]. These sources can be effectively employed in non-linear frequency conversion using periodically poled materials when high optical peak powers, controllable bandwidths and wavelength diversity are required. The only wavelength restriction of the technique is that while the Raman gain of the silica fibre may be accessed and utilised within any part of the transmissive region of silica from 1.0 to 2.0 \( \mu \)m, providing an appropriate pump source is available, soliton adiabatic compression is limited to the wavelength region of the gain fibre where dispersion is anomalous, which with conventional silica based fibre is for wavelengths greater than 1.3 \( \mu \)m.

A non-fundamental (\( N \neq 1 \)) soliton launched into the Raman compression fibre will dissipate energy during propagation, via dispersive waves, and adopt an \( N = 1 \) soliton sech\(^2\) intensity profile. Energy shed by the pulse in this manner reduces the peak to pedestal ratio leading to deterioration in the quality of the compressed output pulse, although pedestals can be reduced by employing non-linear optical loop mirror configurations and or non-linear polarization rotation techniques. As a guide to the power requirement to use at launch into the compressor an \( N = 1 \) soliton pulse train of sech\(^2\) pulses should have an average power \( P_{av} \)

\[
P_{av} = R \frac{2}{1.763} P_1 T_{FWMH}
\]

where \( R \) is the repetition rate and \( T_{FWMH} \) the pulse duration. The peak power \( P_1 \) of an \( N = 1 \) soliton is related to the GVD parameter \( \beta_2 \) and the non-linearity coefficient \( \gamma \) as

\[
P_1 = \frac{3.11|\beta_2|}{\gamma T_{FWMH}^2}
\]
For non-linear frequency upconversion in periodically poled crystals a quasi-phase-matching bandwidth of the process needs to be taken into account. The bandwidth is dependent on the poling period, length of the crystal, fundamental wavelength and the dispersion of the refractive index of the material [15]. To achieve the maximum conversion efficiency, the quasi-phase-matching bandwidth of the periodically poled crystal need to be matched with that of the source, while keeping the highest peak power possible. As follows from Eqs. (1) and (2), the adiabatic soliton compressor allows an elegant and efficient way of the adjustment of the output pulse duration and hence the bandwidth of the source directly by varying the pump power level of the Raman compressor.

2. Experiment and results

Our experimental configuration of a duration tuneable pulse source that employs adiabatic compression in a Raman amplifier to generate 772 nm, 10 GHz repetition rate pulses via frequency doubling with a periodically poled KTP crystal is shown in Fig. 1.

An external cavity laser diode, set to 1544 nm, with a fibre coupled output power of 6 dBm, was used as the seed source for adiabatic pulse compression. Near sech² shape pulses of 9 ps duration were generated using an experimental EAM driven at 10 GHz with appropriate post-modulator chirp compensation using 140 m of dispersion compensating fibre. The modulator provided an extinction of at least 20 dB and the insertion loss of the EAM was compensated with a 22 dBm EDFA pre-amplifier giving 2.3 dBm power post-filter into the Yb:Er amplifier, the characteristics of this experimental EAM have been previously detailed [16] and commercial devices operating at up to 40 GHz are now available from many suppliers. Before launching in the Raman adiabatic compressor, the pulses were further amplified in a Yb:Er power amplifier and tuneable band pass filers were employed to minimise the residual amplified spontaneous emission.

The Raman gain fibre consisted of a 21.5 km, single stage, dispersion shifted fibre (DSF) with a dispersion of 3.8 ps/nm km at 1.55 µm. A counter-propagating pump and signal geometry was employed utilising optical circulators. A cascaded fibre Raman laser with up to 1.07 W power at 1455 nm post-launch circulator was used as a pump source.

Following Eqs. (1) and (2), a DSF was chosen, as opposed to standard telecommunications fibre (STF). The lower dispersion of the DSF as

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Fig. 1. Experimental configuration of the pulse duration selectable, frequency doubled source. PC – polarization controller, EAM – electro-absorption modulator, DSF – dispersion shifted fibre, DCF – dispersion compensating fibre, TBPF – tuneable band pass filter.
compared to that of the STF, 3.8 and 16 ps/nm km respectively, reduces the launch power requirement of the 9 ps $N = 1$ soliton pulse train to 120 mW peak power and 13 mW average power compared to 530 and 54 mW respectively for STF. Such power level was readily achievable and used with the Yb:Er amplifier deployed. Additionally, as the output soliton pulse duration is dependent on the GVD $\beta_2$ of the gain fibre, the use of the DSF allowed us to obtain output pulse durations around half of those of STF for the same amplifier’s gain.

As indicated in Eq. (2) the soliton pulse duration $T_{\text{FWHM}}$ is inversely proportional to the peak power $P_0$. In the adiabatic compression regime the output pulse duration, and hence the compression factor, is proportional to the net gain which is in turn controlled by the Raman pump power. In our experiment, the counter-propagating pump geometry provided a low exponential gain over the fibre length that was of the order of the soliton period as required for adiabatic soliton compression [5]. The increasing Raman gain towards the output was proportional to the pump power providing the soliton compression along the fibre and increased with the reducing soliton period. The typical small signal Raman gain at the pump end of the fibre was around 2 dB/km, at 1.07 W post-circulator pump power level. Not accounting for the pump saturation, the adiabatic regime was maintained with the gain coefficient of under 1.1 over the 100 m of soliton period and resulted in 0.93 ps pulses at the output of the compressor.

The $N = 1$ soliton pulses were extracted via an optical circulator and were amplified in a 28 dBm EDFA. Pre-amplifier dispersion compensation was arranged to compensate for the pulse broadening in the Yb:Er power amplifier and post-compressor STF. Fig. 2 shows the variation of output pulse duration and corresponding peak power, after the adiabatic Raman compressor and the subsequent Yb:Er power amplifier as a function of post-circulator Raman pump power at 1455 nm. The adiabatically compressed pulses were transform-limited solitons with an optical intensity peak to pedestal ratio of at least 23 dB measured using non-collinear second harmonic autocorrelation technique (SHG-AC), which was in good agreement with the adiabatic soliton model [5]. Additional pulse compression occurred in the output DCF and Yb:Er power amplifier, leading to a decrease in pulse duration from 0.93 to 0.73 ps at maximum Raman pump power of 1.07 W. We attribute this to high order soliton effect compression in the short length, high gain amplifier’s fibre.

The optimised 1544 nm Raman soliton compressor was used as a fundamental source for SHG in periodically poled KTP. A 0.6 cm long PPKTP sample was poled with a 23.2 μm period, 50:50 domain duty cycle, and was temperature stabilized at 68°C for the optimal first-order quasi-phase-matched SHG at 1544 nm. It should be noted that the PPKTP crystal can be temperature tuned at 0.083 nm/°C for maximum quasi-phase-matched SHG at other wavelengths, with temperatures in excess of 200°C possible. The adiabatic Raman soliton compressor has also be demonstrated producing sub-picosecond pulses over the wavelength range 1536–1560 nm with the use of an external cavity tuneable laser as a seed source [17]. The quasi-phase-matching bandwidth of the crystal is directly proportional to the polling period [18], at 1544 nm, the phase-matching bandwidth of the 0.6 cm crystal was 2.6 nm which corresponded to the spectral bandwidth of a 0.96 ps soliton pulse. At this pulse duration the walk-off distance of 0.8 cm was longer than the physical length of the
adiabatic soliton compressor would alleviate the non-linear process arising from high peak powers in the final amplifier and the additional losses involved could be compensated with increased amplification, however the demonstrated flexibility in choice of output pulse duration would be negated.

3. Conclusions

In conclusion, we have demonstrated a novel, duration and bandwidth tuneable, Raman adiabatic pulse compressor which was successfully used for frequency upconversion in periodically poled KTP. The output pulse duration could be tuned within 0.73–9 ps range and was determined by the Raman pump power. The source allows selection of repetition rate and wavelength and can be used as a seeding source for a high power fibre amplifier and efficient second harmonic generation in periodically poled crystals.

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