Widely tunable polarization maintaining photonic crystal fiber based parametric wavelength conversion

Robert T. Murray,1,∗ Edmund J. R. Kelleher,1 Sergei V. Popov,1
Arnaud Mussot,2 Alexandre Kudlinski,2 and James R. Taylor1

1 Femtosecond Optics Group, Department of Physics,
Imperial College London, Prince Consort Road, London SW7 2BW, UK
2 Laboratoire de Physique des Lasers, Atomes et Molécules (PhLAM), IRCICA, Université
Lille 1, UMR CNRS 8523, 59655 Villeneuve d’Ascq Cedex, France
∗robert.murray10@imperial.ac.uk

Abstract: We report a near-visible parametric wavelength converter comprising a polarization-maintaining photonic crystal fiber (PM-PCF) pumped by a highly versatile diode-seeded master-oscillator power amplifier system based around 1.06 μm. The device is broadly tunable in wavelength (0.74–0.81 μm), pulse duration (0.2–1.5 ns) and repetition rate (1–30 MHz). A maximum anti-Stokes slope conversion efficiency of 14.9% is achieved with corresponding anti-Stokes average output powers of 845 mW, at a wavelength of 0.775 μm.

© 2013 Optical Society of America

OCIS codes: (190.4370) Nonlinear optics, fibers; (190.4380) Nonlinear optics, four-wave mixing.

References and links

#187833 - $15.00 USD  Received 27 Mar 2013; revised 5 May 2013; accepted 8 May 2013; published 25 Jun 2013
(C) 2013 OSA 1 July 2013 | Vol. 21, No. 13 | DOI:10.1364/OE.21.015826 | OPTICS EXPRESS 15826
1. Introduction

Parametric wavelength conversion in optical fibers is an attractive route to generating coherent radiation at otherwise difficult to reach wavelengths across the electromagnetic spectrum. The use of scalar degenerate four-wave mixing (FWM) in photonic crystal fibers (PCFs) can lead to the production of widely spaced sidebands (>100 THz) from the pump wavelength [1, 2], at frequency separations defined by the dispersive properties of the waveguide [3].

The ability to engineer the dispersion of PCF’s to aid efficient FWM at target design wavelengths, coupled with readily available high power laser pump sources and amplifiers based around 1.06 μm, has led to the demonstration of parametric generation extending from the red [4–6] to the mid-infrared [7]. Fibre optic parametric oscillator (FOPO) devices have also been demonstrated, offering benefits such as lower thresholds than devices that use a single pass geometry [8, 9]. While all-fiber oscillator configurations have also been reported [10, 11], technical issues such as unwanted nonlinearities in the cavity passive fiber limit achievable power levels.

Recently, fiber devices based on FWM have found practical applications in coherent-anti
Stokes Raman spectroscopy (CARS), where pairs of synchronized and spectrally narrow pulses across the visible are required [12–16]. Parametric systems could also prove a useful source for stimulated emission depletion (STED) microscopy, where picosecond pulsed visible wavelength radiation, that can be readily synchronized to an external clock, is needed. Alternative laser architectures delivering wide-band radiation covering the near-infrared are available, such as bulk optical parametric oscillators (OPOs) and Ti:Sapphire solid-state lasers [17, 18]. These systems, however, are often restricted in terms of repetition rate and pulse duration tunability.

Most parametric devices make use of scalar degenerate FWM, but vectorial FWM processes, such as cross phase modulation instability (XPMI) and polarization modulation instability (PMI) can also be exploited [19–21]. In scalar FWM, the pump, Stokes and anti-Stokes photons lie in the same polarization axes, whereas for XPMI and PMI the photons can propagate in different axes, and will efficiently interact provided phasematching conditions are satisfied. The use of polarization-maintaining (PM) PCF over conventional PCF opens up potential avenues for additional spectral tunability of parametric devices [22, 23], due to the high levels of birefringence that PM-PCFs exhibit, the space of phasematched wavelength pairs is increased by switching the input polarization of the pump [21]. Furthermore, the fabrication and adoption of PM-PCF for use in parametric converters is important for enhanced stability and improved source performance; it is widely known that fully PM systems have superior environmental stability when compared to their non-PM counterparts [24].

Typically, the key parameters for PCF-based parametric devices include, but are by no means limited to: spectral tuning range, spectral linewidth, repetition rate, pulse duration, peak and average power. It is often the case that the optimization of one parameter will restrict the flexibility of others. One such example of this is the use of fixed repetition rate mode-locked fiber oscillators as seed sources to generate the short pulses for subsequent amplification and parametric conversion. Although generating high power and short duration pulses, the output is often restricted in wavelength, duration and repetition rate tunability. The use of semiconductor diode lasers, either gain switched [9] or amplitude modulated, provides an alternative route to greater flexibility in the radiation produced in the parametric conversion process.

In this paper, we report a parametric conversion-based device which has a highly tunable spectral output (0.74–0.81 μm), repetition rate (1–30 MHz) and pulse duration (0.2–1.5 ns). This is, to the best of our knowledge, the first example of a widely tunable sub-ns external cavity laser diode (ECLD) based pump system used for parametric conversion to the near-visible. Our results highlight the flexibility of employing a semiconductor based device as the seed source. In addition, system robustness and a compact footprint are intrinsic advantages of this approach. The manuscript is presented as follows: Section 2 introduces the pump source and its characteristics and Section 3 demonstrates the use of the pump for widely tunable parametric wavelength conversion into the near visible.

2. Highly tunable pump source

Tuning the spectral output of a parametric wavelength converter or oscillator can be achieved through a variety of techniques; these include temperature tuning of the nonlinear conversion medium [25], dispersion tuning of the oscillator cavity [26], rotation of the polarization of the pump from the fast to slow axis [1, 2], and the most commonly used technique of tuning the pump wavelength [2]. Of these, tuning of the pump wavelength offers the potential for the highest degree of tunability.

Figure 1 is a schematic outlining the components of the compact, fully fiberized pump source used. The seed cavity consisted of a fiber pigtailed semiconductor amplifier centered around 1.06 μm (LD), a fiber polarization controller (PC) and a stress controlled tunable fiber Bragg grating (TBFG). The TBFG was tunable from 1.055–1.075 μm and had a constant spectral...
linewidth of 0.07 nm across its whole tuning range. Figure 2(a) shows the spectral output of the seed laser before the amplification stage at wavelengths across the spectral range of the ECLD. The increase in amplified spontaneous emission (ASE) with increasing wavelength was due to the peak of the gain of the semiconductor amplifier being situated around 1.055 μm.

The continuous-wave output of the seed cavity was then modulated using a 10 GHz fiber-coupled Mach-Zehnder amplitude modulator (MZAM). A DC bias voltage supply provided a π voltage of approximately 14 V for maximum extinction of the light from the seed cavity, as monitored at the tap coupler (TAP). An electrical pulse generator was used to modulate the MZAM at pulse durations selectable from 0.3-2 ns and repetition rates ranging from 1-30 MHz. Figure 2(b) shows the range in pump pulse durations possible by adjusting the electrical drive pulses across the MZAM, with the optical full-width half maximum (FWHM) durations highlighted in the inset, measured using a 50 GHz fast oscilloscope and fast photodiode. The pulse shapes closely match that of the electrical drive pulses out of the RF pulse generator. The use of active modulation has the additional benefit of easy synchronization to an external clock if necessary.

The pulses were then amplified in the two ytterbium doped amplifiers (YDFA 1 and 2) to peak powers up to several kilowatts. A tunable band pass filter (TBPF) was employed between the two amplifiers to suppress ASE. Figure 2(c) shows the amplified spectral output measured after the isolator (ISO). The increase in ASE as the wavelength increases above 1.07 μm or decreases below 1.06 μm was due to the power amplifier being operated outside its specified bandwidth of 1.06-1.07 μm. The ASE contributed less than 2% of the total pump energy from 1055–1070 nm, increasing to 5% at a pump wavelength of 1075 nm. The pulses experienced no spectral broadening effects within the amplifier stage, accumulating only a low-level ASE pedestal.

3. Parametric wavelength conversion

3.1. Polarization-maintaining photonic crystal fiber

For efficient parametric generation, a fiber was designed with low normal dispersion at pump wavelengths around 1.06 μm to facilitate large frequency shifts into the near visible phase-matched through negative higher-order dispersion. The fiber thus had zero dispersion wavelengths of 1.108 μm and 1.112 μm for the fast and slow axes respectively, and a calculated group birefringence of 0.5 × 10⁻⁴. The fiber had a loss of 10.1 dB/km at 0.775 μm and 7.1 dB/km at 1.06 μm. The calculated nonlinear coefficient was 7.1 W⁻¹km⁻¹ at 1.06 μm and 10.1 W⁻¹km⁻¹ at 0.775 μm. The manufacturing process was also tailored to suppress longitudinal dispersion fluctuations that adversely affect the phasematching conditions [21, 27]. The fiber was also designed to be single mode over the wavelength region of interest.
Fig. 2. Time and spectral domain pump source characteristics. (a) Wavelength tuning of the seed oscillator. (b) Temporal tuning of the seed oscillator. (c) Wavelength tuning of the amplified seed oscillator, at average output powers of 20 W.

The scalar degenerate FWM phasematching curves for the PM-PCF can be seen in Fig. 3(a), calculated from the scanning electron microscope image in Fig. 3(b). The red and blue curves correspond to phasematched components along the fast and slow axes of the fiber, respectively. This can be seen more clearly on the inset to Fig. 3(a), and shows the potential of over 70 nm of tuning in the sideband wavelengths for 20 nm of tuning in the pump wavelength.

A 3 m length of the PM-PCF was used – this length was chosen to balance the effects of maximised parametric amplification and the onset of competing nonlinear spectral broadening. Optimal PCF length-scales for efficient pulse-pumped FWM are typically less than 1 m [5, 6] (depending on the exact pump conditions), to limit temporal walk-off of pump and anti-Stokes waves and to prevent the growth of competing nonlinearities, such as Raman scattering and self phase modulation (SPM). Here, the slightly longer length was chosen to increase the nonlinear-length product to allow the device to operate over a broader range of parameters, both in terms of repetition rate and pulse duration. This length was determined through an experimental cut back, and optimized for a repetition rate of 15 MHz and pump pulse duration of 1 ns. These values correspond to the centre of the pump parameter space, ensuring device performance is maintained at each extrema. An increase of peak power will cause a decrease in the corresponding optimal length, and a decrease in peak power an increase in the optimal length.

3.2. Highly tunable anti-Stokes output

The pump pulses were coupled into the PM-PCF with coupling efficiencies exceeding 70%. Figure 4(a) shows the anti-Stokes spectral output whilst tuning the pump wavelength in 2 nm steps. The output power of the device was limited to below 100 mW in each of the spectra by limiting the pump power, in order to maintain the anti-Stokes spectral linewidth at or below 0.3 nm. The red and blue curves correspond to pumping the fast and slow axes of the fiber respectively, achieved by rotating the plane of polarization of the pump with a half wave plate between the principle axes of the fiber. The calculated and experimentally measured phase-matched wavelengths were in good agreement, as can be seen in the inset of Fig. 3(a). The output was linearly polarized as would be expected from using a linearly polarized pump, and the scalar nature of the FWM process under investigation.

When the pump power was increased to higher levels, the parametric output experienced significant spectral broadening. This broadening typically started when the anti-Stokes output power exceeded 100 mW. This process is highlighted in Fig. 4(b), which shows the spectrum...
of the parametric signal at increasing output powers. The origin of this broadening lies in the pump itself broadening through SPM as it propagates through the PM-PCF. Before the onset of SPM, the pump remains spectrally narrow on propagation through the PM-PCF and so the produced parametric signal is also spectrally narrow. With increasing power, the pump begins to rapidly broaden through the PM-PCF and this broadening is transferred to the parametric sideband.

This SPM induced pump broadening is shown in the inset of Fig. 4(b). The grey curve corresponds to the pump at the input of the PM-PCF at an average power of 20 W (peak power of 3.3 kW), and the black curve the pump after propagation through the PM-PCF. The pump shows clear signs of SPM induced broadening after propagating through the PM-PCF. This SPM broadening of the pump is transferred to the anti-Stokes sideband as the pump power increases, and the characteristic dip in the peak of the anti-Stokes signal is indeed seen to become more evident as the power is increased.

Figure 5(a) shows the average anti-Stokes output power of the device measured at the output of the PM-PCF, plotted against the average pump power measured at the face of the PM-PCF. The corresponding slope efficiencies of the device are shown in the legend. Pumping at 1.065 µm, leads to the greatest slope efficiency of 14.9%. Moving the pump wavelength 10 nm further into the normal dispersion region, as in the case of the 1.055 µm pump, leads to a lower conversion efficiency. We attribute this decrease to two separate effects. Moving further away from the zero dispersion wavelength results in the phasematching conditions becoming more stringent, and hence results in lower conversion efficiencies. The other was a result of operating the two fiber amplifiers in the amplifier stage out of their specified bandwidths of 1.06-1.07 µm, resulting in higher levels of residual ASE. This increased amount of ASE can be observed in Fig. 2(c). When pumping at 1.075 µm, we expected to see an increase in the conversion efficiency due to being closer to the zero dispersion wavelength for the fiber, but a decrease due to operating out of the amplifiers specified bands – a slope efficiency of 10.9% agrees with these observations.

It should be noted that the conversion efficiencies were based on a pump systems with the following parameters: a 15 MHz repetition rate; and 0.3 ns pump pulse duration. Despite the large range of pump parameters, these values can be taken as typical for the full range of operation of the parametric device.
Fig. 4. Anti-Stokes spectral output of the device, pumping with 0.3 ns pulses at 20 MHz. (a) Highly tunable spectral output - blue is axis 1 and red axis 2. (b) Pump self phase modulation induced parametric broadening effects. Legend shows the anti-Stokes output power. Inset shows amplified pump before (grey) and after (black) propagation through the PM-PCF.

Fig. 5. (a) Anti-Stokes output power slope efficiency curves. (b) Tuning of anti-stokes pulse duration.

3.3. Temporal tuning of anti-Stokes output

Tuning the duration of the anti-Stokes signal was readily achieved due to the flexible format of the pump system employed here. Figure 5(b) shows a range of anti-Stokes output pulse durations, for a fixed pump repetition rate of 5 MHz, with output powers up to 500 mW. The duration was tuned by directly tuning the pump pulse duration, parametric shaping results in a slightly shorter anti-Stokes pulse compared to the input pump pulse. This arises from the relative peak intensity across the duration of the pump pulse. The wings of the pump pulse do not have sufficient intensity to be efficiently converted to the anti-Stokes wavelength, with only the central part of the pump pulse contributing to the parametric process, resulting in a temporally shorter anti-Stokes pulse.
4. Conclusions

We have demonstrated a near-visible parametric wavelength converter, realised by pumping a PM-PCF with a highly versatile sub-ns amplitude modulated ECLD fiber amplified seed. The device provides a convenient source of radiation in the 0.74-0.81 μm wavelength range, at pulse durations tunable from 0.2–1.5 ns and repetition rates of 1–30 MHz. Slope conversion efficiencies of 14.9% were achieved with corresponding average output powers of 845 mW at a output wavelength of 0.775 μm. The spectral linewidth of the near-visible parametric sideband was found to increase significantly with output power, with broadening attributed to SPM on the pump. This offers the potential of accessing femtosecond-scale pulses through re-compression of the chirped anti-Stokes pulses. We anticipate that this source will prove a useful tool, in particular, for biophotonic applications.