Four-Wave Mixing UV Generation in Optical Microfibers

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ABSTRACT

UV generation via four-wave-mixing (FWM) in optical microfibres (OMFs) was demonstrated. This was achieved by exploiting the tailorable dispersion of the OMF in order to phase match the propagation constant of the four frequencies involved in the FWM process. In order to satisfy the frequency requirement for FWM, a Master Oscillator Power Amplifier (MOPA) working at the telecom C-band was connected to a periodically poled silica fibre (PPSF), producing a fundamental frequency (FF) at 1550.3 nm and a second harmonic (SH) frequency at 775.2 nm. A by-product of this second harmonic generation is the generation of a signal at the third harmonic (TH) frequency of 516.7 nm via degenerate FWM. This then allows the generation of the fourth harmonic (FH) at 387.6 nm and the fifth harmonic (5H) at 310nm via degenerate and nondegenerate FWM in the OMF.The output of the PPSF was connected to a pure silica core fibre which was being tapered using the modified flame brushing technique from an initial diameter of 125 μm to 0.5 μm. While no signal at any UV wavelength was initially observed, as the OMF diameter reached the correct phase matching diameters, signals at 387.6 nm appeared. Signals at 310 nm also appeared although it is not phase matched, as the small difference in the propagation constant is bridged by other nonlinear processes such as self-phase and cross phase modulation.

Keywords: Nonlinear optics; Parametric processes; Four-wave mixing; Optical microfibers

1. INTRODUCTION

Ultraviolet (UV) generation has traditionally relied on crystals and gases to allow frequency conversion from longer wavelengths [1-10]. These methods involve the use of nonlinear crystals such as KTP, KDP, sapphire, K2Al2B2O7, potassium pentaborate (KB5), the exploitation of nonlinear processes in waveguides such as photonic crystal fibers or the use of hybrid schemes employing both waveguides and nonlinear crystals [1-7]. Fiberized UV generation in optical fibers typically involve the use of gas-filled hollow core microstructured fibers, or otherwise exploit nonlinear processes such as supercontinuum generation to generate a broad spectrum which extends down to the UV wavelength region [8-15].

It was also suggested that efficient generation of UV wavelengths is possible by exploiting the tailorable dispersion characteristics of optical microfibers (OMFs) to achieve phase matching for intermodal third harmonic generation [16,17]. This allows narrowband UV generation in a fully fiberized system to be constructed, which is not possible in previous UV generation schemes. However, it was shown recently that the variations in the diameter from intrinsic frozen-in surface waves effectively limit the efficiency of such processes to < 1 % [18]. Here, we show that an alternative method of manufacturing a fully fiberized narrowband UV source in optical microfibers is possible by employing four wave mixing.

2. PHASE MATCHING CONDITIONS

Four wave mixing (FWM) is a parametric nonlinear process whereby two 'pump' photons are annihilated and converted into two 'new' photons, called the idler and signal, at different wavelengths via the Kerr nonlinearity of a medium [19]. There are two conditions for efficient FWM, namely, the energy conservation condition and the phase matching condition, which can be written as,

$$\omega_1 + \omega_2 = \omega_3 + \omega_4 \tag{1}$$

$$\beta_1 + \beta_2 = \beta_3 + \beta_4 . \tag{2}$$

where ωj and βj are the frequency and wave vector of the photon j, respectively, and subscripts 1,2,3 and 4 indicate the four interacting wavelengths. Here, wavelengths which are harmonics of a fundamental frequency (FF) at 1.55 µm are selected; namely, λ = 1.55 µm, 0.775 µm, 0.517 µm, 0.387 µm and 0.310 µm. A subset combination of these five wavelengths automatically satisfy condition (1) for both degenerate FWM (DFWM, ω1 = ω2) and non-degenerate FWM (NDFWM, ω1 ≠ ω2), thereby allowing UV generation to take place.

Condition (2) is satisfied by tailoring the dispersion of the OMF by varying the OMF diameter to achieve phase matching. This is depicted for the fourth harmonic wavelength (FH) 0.387 µm in figure 1a and the fifth harmonic wavelength (5H) 0.310 µm in figure 1b for the relevant FWM schemes. From figure 1, it can be seen that there are four phase matching diameters for the FH, while 5H is not phase matched. The phase matching diameter for 387 nm is summarized in Table 1. It is worth noting that while the signal at the 5H is not phase matched, there is a very small difference in the relevant propagation constant which may be 'bridged' by other nonlinear effects such as self-phase modulation (SPM) and cross phase modulation (XPM). Therefore, while the 5H wavelength is not explicitly phase matched, it may still be possible to generate a signal at this wavelength.

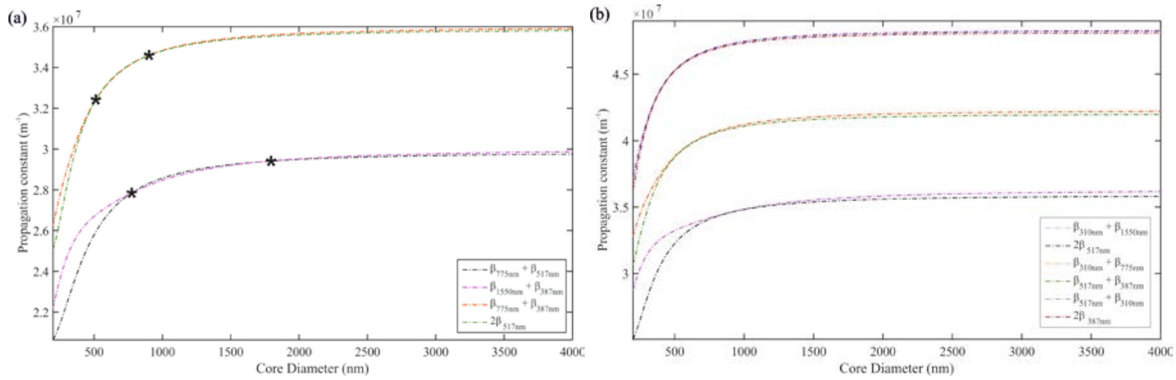

Figure 1. Evolution of the propagation constants or propagation constant with varying OMF diameter for FWM involving (a) 387 nm and (b) 310 nm. The phase matching diameter is indicated by (*)

Table 1. Phase matching diameter for the generation at 387 nm.

FWM scheme and type	Interacting Wavelengths (μm)		Phase matching diameter (μm)	
	Pump	Idler / Signal	d_1	d_2
Non-degenerate FWM	0.775	1.550	1.719	0.790
	0.517	0.387		
Degenerate FWM	0.517	0.775	0.872	0.530
		0.387		

3. EXPERIMENTAL VERIFICATION

An experimental verification was undertaken with a tunable seed laser at the telecom C-band at 1.550 µm connected to a Master Oscillator Power Amplifier (MOPA) producing pulses with a duration of τ = 5 ns, duty cycle f = 200 kHz and average powers Pav = 300 – 800 mW, corresponding to peak powers of Ppeak = 300 – 800 W. The output of the MOPA is then connected to a polarization controller (PC) before being spliced to a periodically poled silica fiber (PPSF, total loss α = 1.7 dB), producing a signal at the second harmonic (SH) wavelength of 0.775 µm via quasi-phase matched second harmonic generation (SHG) [20], as shown in figure 2. As the MOPA is quite noisy, the output average power was limited to Pav ~ 400 mW to avoid pump depletion and other undesirable nonlinear effects.

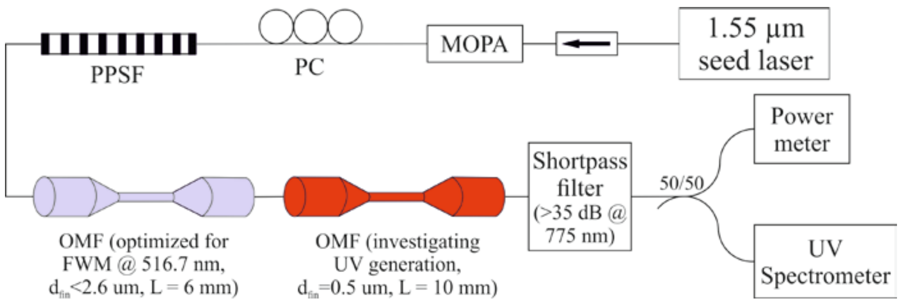

Figure 2. Experimental verification of UV generation via four wave mixing in optical microfibers. Here, MOPA is Master Oscillator Power Amplifier, PC is polarization controller, PPSF is periodically poled silica fiber, and OMF is optical microfiber.

A by-product of the SHG process is the generation of the third harmonic wavelength (TH) at 0.517 µm via non-phase matched sum-frequency generation. As FWM typically requires a relatively strong signal at the pump wavelength, the output at this wavelength is parametrically amplified with an OMF as described in [21]. The output from the first OMF is then connected to a shortpass filter (α1.550µm > 90 dB), and the output spectrum is shown in figure 3.

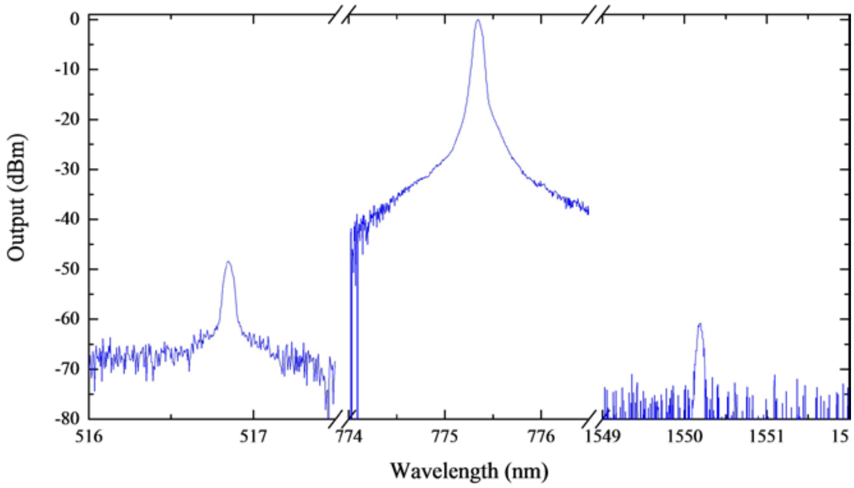

Figure 3. Output spectrum after the first optical microfiber designed to boost the power at 0.517 µm after a shortpass filter designed to have a loss at 1.550 µm of α1.550µm > 90 dB.

The shortpass filter is then replaced with one with a larger loss at the SH and TH wavelengths, which is then connected to a broadband 3-dB coupler [22], with one end of the coupler connected to a power meter (Thorlabs S130C) and the other end connected to a UV spectrometer (Ocean Optics UV4000). A length of Sumitomo Z-Fiber (10 mm) was then cleaned and tapered whilst the high power source is turned on by using the modified flame brushing method, with the tapering profile carefully controlled to minimize losses [23]. The polarization of the MOPA is periodically altered in order to correct for thermal drift and maximize the power at the SH wavelength. The Z-Fiber was employed here as it has a pure silica core, and therefore does not exhibit any significant absorption features between 0.3 – 0.4 µm [24]. The evolution of the signals at around the FH and 5H wavelengths are recorded whilst the fiber is tapered, as shown in figure 4 and figure 5, respectively. It should be noted that the spectrometer is sensitive to visible light, which is manifested in a relatively large background in the spectrum, and is not manifested in any peaks in the UV wavelength region.

From figure 4, it can be seen that as the OMF is close to the phase matching diameter at 1.72 µm, the signal at the FH wavelength increases suddenly. This is then reduced as the fiber is tapered further, as the OMF diameter increasingly goes away from the phase matching diameter. However, close to the second phase matching diameter at 0.8 µm, the output at the FH increases abruptly again, simultaneously with an increase in the background spectrum, attributed to phase matched parametric amplification at the TH wavelength. The output signal then oscillates as the OMF is tapered further, with the signal finally growing weaker at a diameter dOMF < 0.6 µm. As can be seen in the spectrum in figure 4b, only a narrowband increase in the signal is seen, consistent with phase matched FWM processes. The small side lobe which can be observed is due to other nonlinear effects which are currently being investigated.

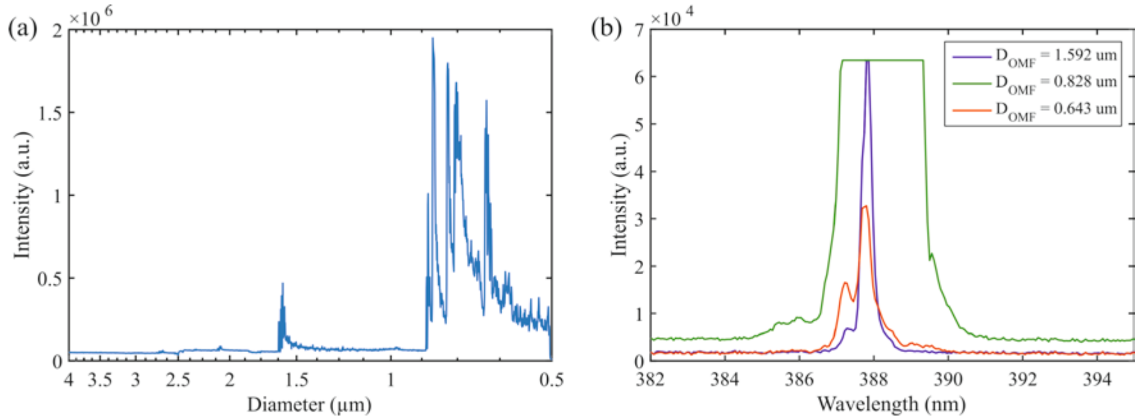

Figure 4. (a) Evolution of the signal at around 0.387 µm with diameter whilst tapering. (b) The spectrum at around 0.387 µm.

Figure 5 shows that the evolution of the 5H signal follows a similar trend to that of the FH. However, the background spectrum is larger as the UV spectrometer is more sensitive to visible light at this wavelength range. This is seen in the increase in background for dOMF ~ 1.0 µm and dOMF ~ 0.83 µm, which do not correspond to any narrowband signal in the spectrum in figure 5b. Interestingly, however, a signal can be discerned corresponding to narrowband signal generation for dOMF ~ 0.66 µm and dOMF ~ 0.52 µm, despite not being phase matched. This is due to, (a) the signal at the FH wavelength being sufficiently intense for FWM to occur, (b) higher effective nonlinearity due to the smaller diameter and (c) the small 'gap' in the propagation constants being 'bridged' by other nonlinear effects such as SPM and XPM. However, as it is not phase matched, the signal at the 5H is quite weak as compared to the signal at the FH.

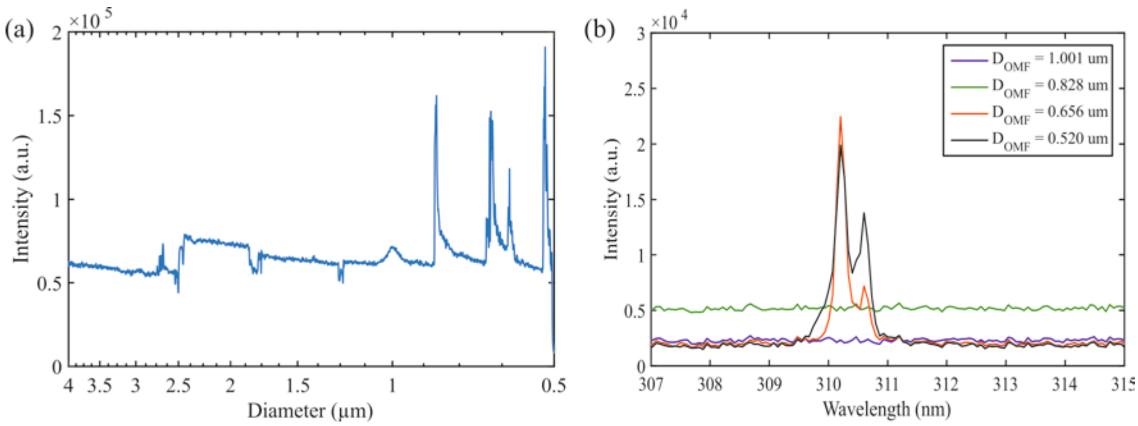

Figure 5. (a) Evolution of the signal at the fifth harmonic (5H) around 0.310 µm with diameter whilst tapering. (b) The spectrum at around 0.310 µm.

4. CONCLUSION

In conclusion, we have demonstrated the possibility of using OMFs to generate narrowband UV wavelengths via four wave mixing. This is done by exploiting the tailorable dispersion characteristics of the OMF to achieve phase matching. A 1.55 µm MOPA source working in conjunction with a PPSF to produce a SH signal at 0.775 µm was employed to investigate the possibility of UV generation in OMFs. This is done first by amplifying the TH wavelength at 0.517 µm with one OMF before tapering 10 mm of Z-Fiber whilst the MOPA is turned on. As the OMF diameter approximates the first phase matching diameter at dOMF ~ 1.72 µm, a signal at the FH can be seen, which then is reduced as the

OMF is tapered further. This same behaviour is seen at the second phase matching diameter at dOMF ~ 0.8 µm. A signal at the 5H wavelength of 0.310 µm can also be observed at dOMF ~ 0.66 µm and dOMF ~ 0.52 µm, despite not being phase matched. This is due to the fact that the small gap in the propagation constants is bridged by other nonlinear effects such as SPM and XPM. We have therefore conclusively demonstrated the possibility of employing FWM for UV generation in OMFs.

5. FUNDING INFORMATION

This work has been supported by two research grants by the Engineering and Physical Sciences Research Council (EPSRC), grant numbers: EP/L01243X/1 and EP/I035307/1. All data supporting this study are openly available from the University of Southampton repository at http://dx.doi.org/10.5258/SOTON/389375

6. ACKNOWLEDGEMENTS

The authors would like to thank Oleksandr Tarasenko and Walter Margulis from Acreo fiberlab who manufactured the fiber used for the PPSF as well as Peter Kazansky, Francesca Parmigiani, James Wilkinson, Senthil Ganapathy and Kyle Bottrill at the Optoelectronics Research Centre of the University of Southampton for access to the necessary technical facilities and insightful discussions.

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