Tuneable far-detuned intramodal Four-Wave Mixing via diameter control of optical microfibres

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ABSTRACT

We present a theoretical and experimental study of the spontaneous intramodal four-wave mixing process in the normal dispersion regime of optical microfibers in the fundamental mode. We show that the wavelength of the generated signal can be tuned over a wide range by precisely adjusting the microfiber diameter.

Keywords: optical microfiber, far detuned four-wave mixing, waveguide dispersion control

1. INTRODUCTION

An optical microfiber corresponds to the uniform diameter portion obtained during the stretching of a standard optical fiber [1,2]. It exhibits several important optical properties, such as enhanced nonlinear effects due to field confinement, a wide evanescent field interacting with the external environment, a high damage threshold, low injection losses, and the possibility of multimodal interactions. In this work, we exploit the property of adapting the chromatic dispersion of the microfiber simply by modifying its diameter. This control allows us to influence linear and nonlinear dispersion-dependent processes, notably four-wave mixing (FWM) [3]. Our work thus focuses on spontaneous intramodal FWM in the normal dispersion regime, for which the wavelength of the generated signal can be finely controlled by the microfiber diameter over a wide spectral range, up to a spectral shift of 137 THz. Significant spectral shifts have already been reported in the literature, but in other types of fibers [4–6].

2. THEORY

The FWM process requires strict phase matching between the interacting waves to be effective. The phase matching condition for intramodal FWM, including linear and nonlinear contributions, is written as follows [7]:

$$\Delta\beta = \beta_s(\omega_s) + \beta_i(\omega_i) - 2\beta_p(\omega_p) + 2\gamma P_p = \beta_2\Omega^2 + \frac{1}{12}\beta_4\Omega^4 + \cdots + 2\gamma P_p = 0 \qquad (1)$$

where β_2 and β_4 are the second and fourth order dispersion terms, Ω the spectral mismatch between the pump and the signal generated by FWM, γ the nonlinear parameter, and P_p the peak power of the pump. In normal dispersion regime ($\beta_2 > 0$) and close to a zero-dispersion wavelength (ZDW defined by $\beta_2 = 0$), phase matching is made possible by a negative β_4 term (see Eq. (1)), which can then induce a large spectral mismatch Ω. The evolution of the parameters β_2 and β_4 as a function of wavelength and fiber outer diameter allows us to identify the microfiber diameters for which the dispersion conditions (close to a ZDW, with $\beta_2 \geq 0$, $\beta_4 < 0$) are favorable for a wide spectral shift for a 1064 nm pump (ZDW at 1064 nm, notably for a diameter of 6.57 µm). To predict the wavelength range of the signal generated by FWM, we model, by varying the microfiber diameter, the amplitude parametric gain profile defined by the relation

$$g = Re\left(\sqrt{\left(\gamma P_p\right)^2 - \left(\frac{\Delta\beta}{2}\right)^2}\right) \qquad (2)$$

The theoretical parametric gain (Figure 1(a)) obtained for a pump at 1064 nm (peak power of 5 kW) shows that microfiber diameters between 6 and 9 µm offer a wide tunability of the FWM-generated signal from approximately 960 nm down to 720 nm. We therefore used this range of microfiber diameter variation in this work.

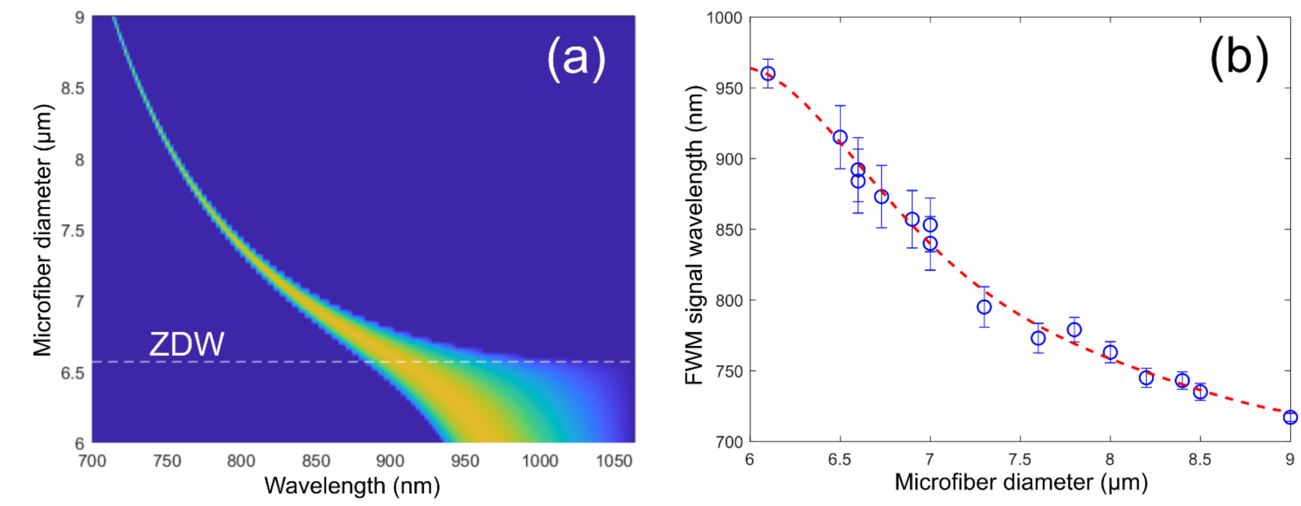

Figure 1: (a) 2D profile of the theoretical parametric amplitude gain (Eq. (2)) as a function of the microfiber diameter (between 6 and 9 µm), for Pp = 5 kW. (b) Evolution as a function of microfiber diameter of the wavelengths of the experimental FWM peaks (blue circles) compared to the theoretical values (red dashed curve).

3. EXPERIMENTS

The microfibers were fabricated by drawing a standard fiber (SMF28) using the heat and brush technique [8]. They have identical lengths of 138 mm, connected to the standard fiber by 30 mm long transitions (Figure 2(a)), and exhibit a controlled geometric profile to ensure their adiabaticity for the fundamental mode. Post-drawing losses are kept below 0.2 dB at 1550 nm. Regarding the experimental setup, the pump source used is an Nd:YAG laser emitting 42 ps pulses at 1064 nm with a repetition rate of 200 kHz. The experimental measurements (Figure 1(b)) of the wavelengths of the anti-Stokes FWM peaks (blue circles) are in good agreement with the theoretical data (red dashed curve). Note that the theoretical values have been weighted by the pump power (between 5 kW and 11 kW) in order to take into account the increase in experimental pump power to obtain FWM peaks of comparable power observed before the FWM cascade phenomenon.

4. NUMERICAL SIMULATIONS

To more closely approximate experimental conditions than theoretical gains (taking into account, for example, phase self-modulation, the Raman effect, transitions, etc.), the field propagation in the fiber system (including standard fibers, transitions, and microfiber – see Figure 2(a)) was modeled using the generalized nonlinear Schrödinger equation (GNLSE), which accounts for dispersion and nonlinear Kerr and Raman effects. We then compare the spectrum at the output of the microfiber alone, the microfiber and the two transitions, the microfiber + transitions and the standard fibers before and after the transitions. These numerical simulations show that transitions do not influence the FWM spectrum, more specifically its spectral width, confirming the uniformity of the microfiber diameter. They also show that standard fibers before and after transitions only increase the Raman and SPM components in the output spectra due to an obvious longer silica fiber length. These observations explain the good agreement between experiment and modeling, particularly in terms of FWM peak width, as shown as an example in Figure 2(b).

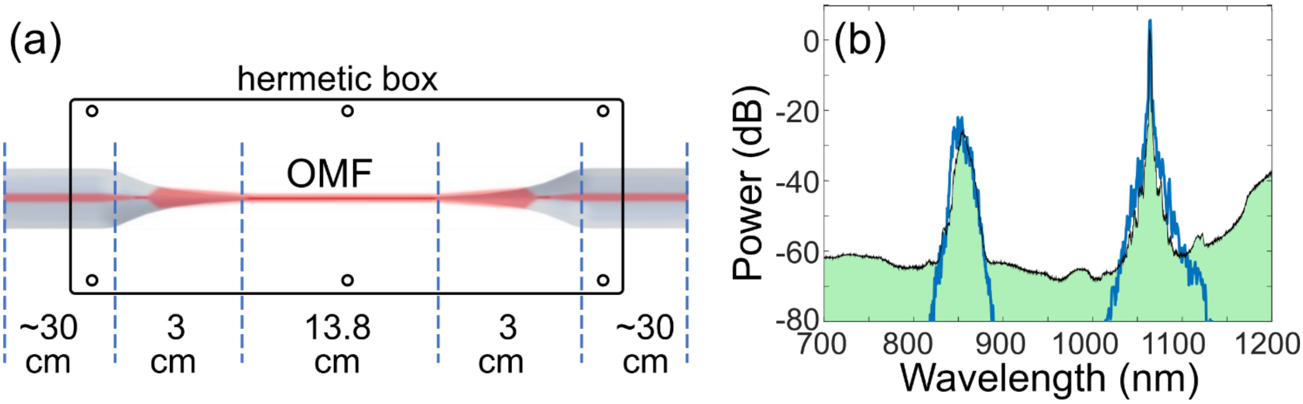

Figure 2: (a) geometry of the optical microfiber system used in this work. The red curve schematically represents the propagation of the fundamental mode in the waveguide. (b) Comparison of the numerical (blue curve) and experimental (filled green curve) spectra for a microfiber diameter of 6.85 µm.

5. CONCLUSION

We have demonstrated an intramodal FWM tunability of over 250 nm in microfibers with diameters between 6 and 9 µm, with a maximum frequency detuning of 137 THz. These results, in good agreement with theory and numerical simulations, pave the way for fully fiber-based, tunable parametric sources, photon pair generators, and optical amplifiers.

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