

Large tunability of intramodal four-wave mixing in optical microfiber

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We report a theoretical and experimental investigation of intramodal four-wave mixing (FWM) in the fundamental mode of optical microfibers, focusing on its dependence on the microfiber diameter in the normal-dispersion regime. We demonstrate that the generated signal wavelength can be widely tuned simply by adjusting the microfiber diameter. Using a picosecond pump at 1064 nm, we generate anti-Stokes signals spanning 717 nm to 960 nm as the microfiber diameter increases from 6.1 μm to 9 μm . This corresponds to a tuning range of approximately 250 nm in the anti-Stokes FWM peak for only a 3 μm change in microfiber diameter, yielding a remarkable maximum frequency detuning as large as 137 THz.

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1. INTRODUCTION

Optical microfibers (OMFs), the uniform-diameter regions of tapered optical fibers [1–3], exhibit a combination of properties that make them highly attractive for nonlinear and waveguide-based photonics. In particular, their strong transverse field confinement enhances Kerr-driven nonlinear effects such as supercontinuum generation [4–6], while their significant evanescent field enables efficient interaction with the surrounding medium. These characteristics have enabled a broad range of applications, including atom trapping [7] and evanescent nonlinear processes such as Brillouin, Raman, and Kerr interactions [8–10]. In addition, OMFs exhibit a strong dependence of chromatic dispersion on their diameter, providing a powerful degree of freedom for engineering phase-matching conditions in nonlinear processes, particularly four-wave mixing (FWM).

Among these nonlinear effects, third-order interactions such as FWM play a central role in the development of parametric light sources, high-repetition-rate pulse generation, photon-pair production, and widely tunable fiber-based optical parametric amplifiers and oscillators (OPA and OPOs) [11–15]. In its intramodal form, FWM can be more generally interpreted as the phase-matched manifestation of spontaneous modulation instability, in which perturbations on a continuous-wave or quasi-continuous-wave pump are exponentially amplified through the interplay of Kerr nonlinearity and dispersion, leading to the generation of widely detuned spectral sidebands [16]. This interpretation is well established in a variety of guided-wave systems [17–19] and has enabled far-detuned frequency conversion in platforms such as chalcogenide microwires [20].

Large-detuning intramodal FWM has been widely studied in

standard fibers under normal dispersion [17, 18], photonic crystal fibers [19], chalcogenide microwires [20], and more recently in graded-index fibers [21]. Related far-detuned sideband generation mechanisms also include intermodal FWM in few-mode graded-index fibers [22] and polarization modulation instability in weakly birefringent fibers [23].

Microfibers can undoubtedly offer benefits for frequency conversion by FWM. Indeed, intramodal FWM offers a particularly flexible route to wavelength conversion, since the phase-matching condition, and thus the generated wavelengths, can be precisely and easily engineered by only tuning the OMF diameter [20, 24, 25]. Moreover, because they are fabricated by tapering standard optical fibers, without any intermediate coupling interface, microfibers can exhibit extremely low insertion losses despite their micrometer-scale dimensions, making them particularly attractive for seamless integration into all-fiber systems. Finally, as demonstrated in this work, a wide tuning range of the FWM signal wavelength can be achieved with only a slight variation of the microfiber diameter. This simple geometrical control provides an efficient route for dispersion engineering, compared with approaches based on more complex waveguide designs such as photonic crystal fibers (PCFs) or photonic integrated circuits (PICs).

In this paper, we thus demonstrate the large tunability of intramodal FWM in the normal-dispersion regime enabled by fourth-order dispersion in an optical microfiber with diameters ranging from 6 to 9 μm with a pumping wavelength at 1064 nm. Our experimental results show widely tunable parametric conversion spanning up to 250 nm, corresponding to a maximum frequency detuning of 137 THz. These observations are in excel-

lent agreement with phase-matching predictions and numerical simulations based on the generalized nonlinear Schrödinger equation (GNLSE). Moreover, the measured energy conversion efficiency reaches up to $\sim 26\%$, highlighting the potential of this platform for microfiber-based optical parametric amplifiers and oscillators, owing to the very low insertion loss (<0.2 dB in the present work) of the entire tapered fiber system.

2. THEORY

The FWM process considered here corresponds to quantum-noise-seeded parametric amplification and is analyzed in the exponential gain regime. Efficient energy transfer requires strict phase matching among the interacting waves [24]. This condition arises from the balance between the linear phase mismatch, governed by waveguide dispersion, and the nonlinear phase shift induced by the Kerr effect.

For intramodal FWM, the phase-matching condition can be written as

$$\Delta\beta = \beta(\omega_s) + \beta(\omega_i) - 2\beta(\omega_p) + 2\gamma P_p = 0, \quad (1)$$

where $\beta(\omega)$ denotes the propagation constant at angular frequency ω , with subscripts p , s , and i referring to the pump, signal, and idler waves, respectively. Here, γ is the nonlinear parameter and P_p is the pump peak power.

Expanding $\beta(\omega)$ in a Taylor series around the pump frequency yields an explicit dispersion-dependent phase-matching condition:

$$\Delta\beta = \beta_2\Omega^2 + \frac{1}{12}\beta_4\Omega^4 + \dots + 2\gamma P_p = 0, \quad (2)$$

where $\Omega = \omega_s - \omega_p$ is the frequency detuning, and $\beta_k = \frac{\partial^k \beta}{\partial \omega^k} \big|_{\omega_p}$ are the dispersion coefficients. This expression shows that phase matching depends only on even-order dispersion terms, and can therefore be primarily engineered through the second- (β_2) and fourth-order (β_4) dispersion coefficients.

In the steady-state regime, the corresponding parametric gain is given by the standard expression [24]

$$g = \text{Re} \left[\sqrt{(\gamma P_p)^2 - (\Delta\beta/2)^2} \right], \quad (3)$$

which highlights the competition between nonlinear gain and residual phase mismatch.

To determine the range of OMF diameters relevant for four-wave mixing (FWM), we first model the evolution of the dispersion parameters as a function of fiber diameter. The data shown in Fig. 1 are obtained by starting from SMF-28 fiber and uniformly scaling down both the core and cladding dimensions, while preserving the refractive index contrast between core and cladding.

Figure 1(a) shows the group-velocity dispersion (GVD) parameter β_2 as a function of wavelength and fiber diameter, covering the range from sub-micron OMFs (~ 500 nm) to standard SMF-28 cladding dimensions ($125 \mu\text{m}$). The zero-dispersion wavelengths (ZDW), defined by $\beta_2 = 0$, are indicated by solid white curves. Figure 1(b) similarly presents the fourth-order dispersion coefficient β_4 over the same parameter space. At the pump wavelength $\lambda_p = 1064$ nm, Fig. 1(a) reveals two fiber diameters, $0.86 \mu\text{m}$ and $6.57 \mu\text{m}$, at which the dispersion crosses zero. Between these two ZDWs, the dispersion is anomalous, while normal dispersion occurs outside this interval. Using these dispersion data, the parametric gain g is computed from

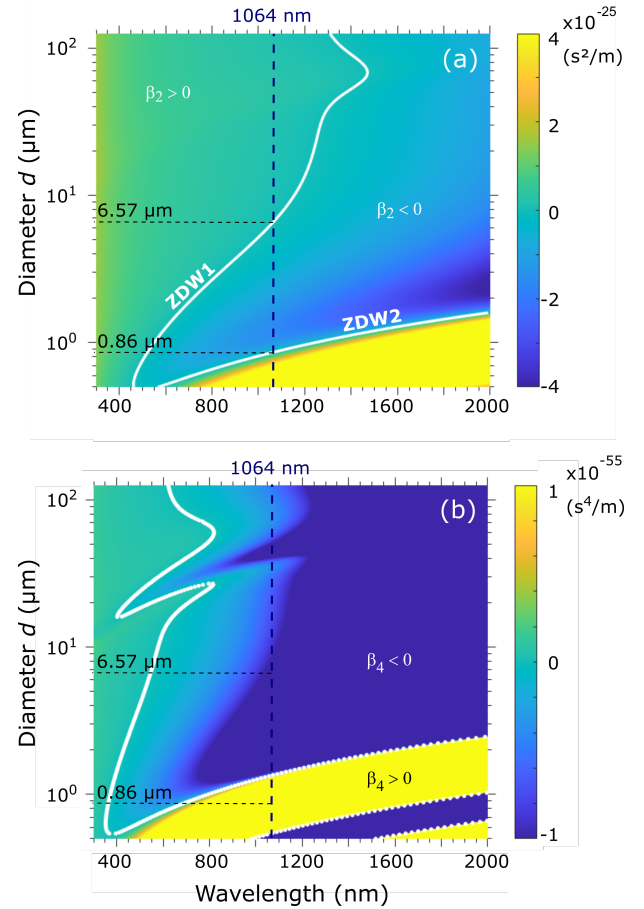


Fig. 1. (a) Second-order dispersion parameter β_2 ($\text{s}^2 \cdot \text{m}^{-1}$) and (b) fourth-order dispersion β_4 ($\text{s}^4 \cdot \text{m}^{-1}$) as functions of wavelength and outer fiber diameter. The solid white curves indicate (a) the zero-dispersion wavelengths (ZDW), defined by $\beta_2 = 0 \text{ s}^2 \cdot \text{m}^{-1}$, and (b) the threshold $\beta_4 = 0 \text{ s}^4 \cdot \text{m}^{-1}$. In (a)–(b), the vertical dashed blue line marks the pump wavelength, while the horizontal dashed lines indicate the two OMF diameters for which the ZDW coincides with the pump wavelength.

Eq. (3) and is shown in Fig. 2(a). The map is restricted to the anti-Stokes wavelength range [700 nm, 1064 nm], fiber diameters [0.5 μm , 20 μm], and assumes a pump peak power of $P_p = 4$ kW for illustration.

Intramodal phase matching can occur in three distinct dispersion regimes [17]. First, when the pump wavelength is far from the zero-dispersion wavelength (ZDW), phase matching occurs in the conventional scalar FWM regime in the anomalous-dispersion region ($\beta_2 < 0$). In this case, the frequency detuning Ω is typically small and only weakly influenced by higher-order dispersion terms such as β_4 [26]. This regime corresponds to the central gain region between the two ZDW diameters shown in Fig. 2(a).

Second, when the pump wavelength is close to a ZDW, phase matching can be achieved in the normal-dispersion regime ($\beta_2 > 0$) provided that higher-order dispersion, in particular a negative fourth-order term ($\beta_4 < 0$), compensates the phase mismatch. This regime is observed in Figs. 1(a)–(b) for OMF diameters near and above $6.57 \mu\text{m}$ and leads to large-frequency detunings, as reflected in Fig. 2(a).

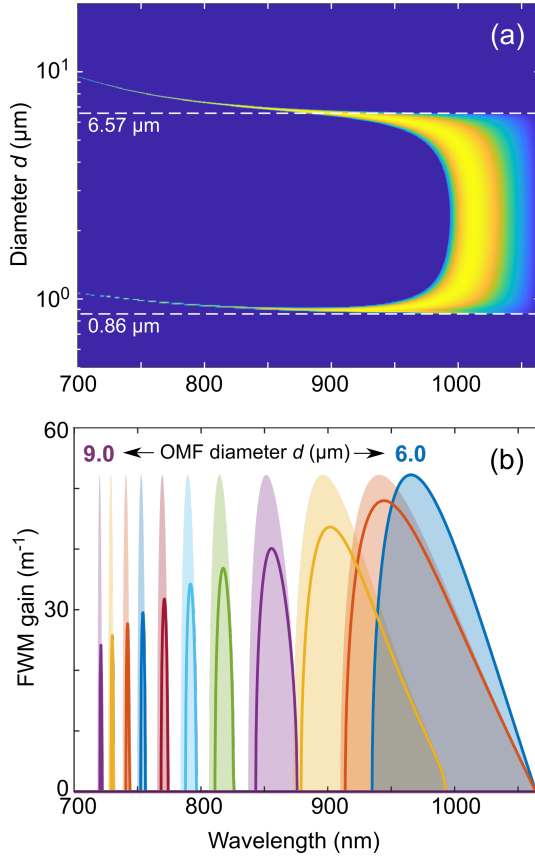


Fig. 2. (a) Normalized parametric gain as a function of wavelength and OMF diameter. The horizontal dashed white lines indicate the two diameters at which the zero-dispersion wavelength (ZDW) coincides with the 1064-nm pump wavelength. (b) FWM gain bands as a function of microfiber diameter. The solid curves correspond to a fixed pump peak power of 4 kW, while the filled curves show the gain spectra obtained when the pump power is adjusted to maintain a constant maximum gain. The OMF diameter is varied from 6 to 9 μm in steps of 0.3 μm .

Finally, phase matching can also occur in the anomalous dispersion regime when β_2 is small but a sufficiently large positive β_4 term dominates the higher-order dispersion balance. This situation arises for OMF diameters near and slightly above 0.86 μm , and can produce both small- and large-detuning solutions, consistent with the multiple gain features observed in Fig. 2(a).

Based on these analytical predictions, OMF diameters in the range 6–9 μm provide a particularly favorable operating window, offering broadband tunability of the FWM gain from 965.5 nm down to 720.2 nm. Beyond spectral flexibility, this regime also offers several practical advantages compared to sub-micron diameters near 0.9 μm , including improved mechanical robustness, higher optical damage threshold, better confinement of the fundamental mode, and enhanced energy-conversion efficiency [17].

The FWM gain landscape shown in Fig. 2(a) depends on the OMF diameter both through dispersion engineering (Fig. 1) and through nonlinear scaling via the coefficient γ [see Eqs. (2)–(3)]. As the diameter increases from 6 to 9 μm , the effective mode area increases from approximately 14 μm^2 to 32 μm^2 , leading to a reduction in γ and therefore a decrease in the FWM gain

at fixed pump power. Since the gain also depends on pump power, we computed the wavelength of maximum anti-Stokes gain as a function of OMF diameter under two conditions: fixed pump peak power and pump power adjusted to maintain a constant maximum gain. The latter approach is consistent with the experimental operating regime, in which the pump power is adjusted to maintain a nearly constant FWM peak intensity while remaining below the threshold for cascaded FWM. In this regime, the first-order sideband is not yet sufficiently strong to seed subsequent FWM generation stages. This operating condition makes it possible to observe the decrease in the spectral linewidth of the FWM peaks with increasing OMF diameter, a trend that would be obscured in the cascaded FWM regime due to the spectral broadening of the first-order FWM peaks.

Figure 2(b) shows the resulting gain spectra for a fixed pump peak power of 4 kW (solid curves), where the peak amplitude decreases with increasing diameter. The filled curves correspond to spectra computed with a pump power adjusted to maintain a constant maximum gain. Over the 6–9 μm diameter range, the required pump power, shown in figure 3(a), increases approximately linearly from 4 kW to about 8.7 kW. The solid curves in Fig. 3(b) show the evolution of the wavelength associated with the maximum FWM gain under three conditions: constant-gain operation (green dashed curve), and fixed pump powers of 4 kW (blue curve) and 8 kW (red curve). The corresponding sensitivity of the FWM wavelength to diameter variations, defined as $\Delta\lambda/\Delta d$ and obtained from the derivative of these curves, is shown by the dashed curves in Fig. 3(b). It reaches a maximum of approximately $-150 \text{ nm}/\mu\text{m}$ at an OMF diameter of 6.6 μm , highlighting the strong geometric tunability of the system.

Although the present work was carried out using a pump source at 1064 nm, it is nevertheless interesting to investigate the dependence of the FWM spectral shift on the pump wavelength. Figure 4(a) shows the evolution of the OMF diameter d_{ZDW} corresponding to the zero-dispersion wavelength (blue crosses, left vertical axis). To normalize the data and facilitate comparison, all calculations were performed using a constant pump peak power of 4 kW and a diameter increment of 1 μm relative to d_{ZDW} for each pump wavelength ranging from 700 nm to 1100 nm. The pump wavelength range was limited to 1100 nm because the OMF diameter d_{ZDW} increases significantly at longer wavelengths. The red dots (right vertical axis) represent the spectral shift between the FWM peak wavelength obtained for the OMF diameter d_{ZDW} and that obtained for the larger diameter $d = d_{\text{ZDW}} + 1 \mu\text{m}$. The vertical line indicates the pump wavelength of 1064 nm used in this work. It can be seen that, for this pump wavelength, d_{ZDW} is approximately 6.6 μm , in agreement with the value reported previously, and that the spectral shift between the diameters of 6.6 μm and 7.6 μm is approximately 122 nm. Of particular interest, Fig. 4(a) clearly shows that a pump wavelength of approximately 850 nm would maximize the spectral shift, reaching about 157 nm for a OMF diameter variation of 1 μm . The corresponding OMF diameter at the zero-dispersion wavelength is approximately $d_{\text{ZDW}} = 3.1 \mu\text{m}$. Figure 4(b) presents the corresponding frequency shift, expressed in THz, under the same conditions as in Fig. 4(a). It represents the maximum frequency detuning $\Delta\nu = \nu_{\text{FWM}} - \nu_{\text{pump}}$ of the FWM signal generated by the largest-diameter OMF from the pump. A maximum frequency shift exceeding 310 THz is predicted for a pump wavelength of 700 nm.

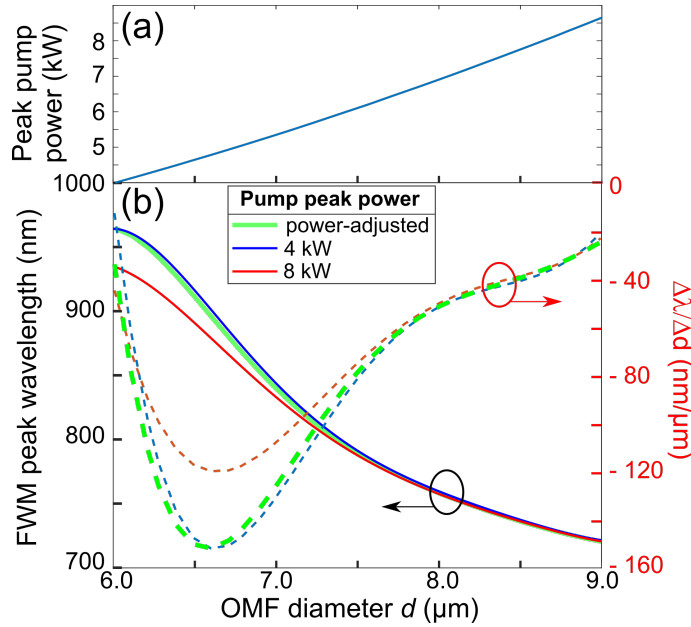


Fig. 3. (a) Evolution of the peak pump power to maintain constant the theoretical FWM gain (figure 2(b)). (b) Solid curves: evolution of the wavelength corresponding to the maximum anti-Stokes FWM peak as a function of the microfiber diameter and for a pump power of 4 kW (blue curve), 8 kW (red curve) and pump-power-adjusted curve (green curve - increase of the pump power approximately linearly from 4 kW to about 8.7 kW, as shown by the curve in the inset (a) above). Dashed curves: corresponding sensitivity of the FWM signal wavelength to variations in the OMF diameter.

3. EXPERIMENT

Our OMFs were fabricated by tapering standard SMF-28 silica fiber using the well-established heat-brush technique [1, 9, 27]. Each tapered fiber comprises a uniform-waist section (the OMF) of 138 mm in length (Fig. 5(a)). The transition regions on both sides are 30 mm long and share the same geometric profile, differing only in the minimum waist diameter (Fig. 5(b)). This design ensures adiabatic guidance of the fundamental LP_{01} mode across all diameters by maintaining the local taper angle $\Omega(r)$ (Fig. 5(a)) below the critical threshold for mode coupling [28, 29]. Under this condition, coupling from the fundamental LP_{01} mode to higher-order modes, typically those with the same azimuthal symmetry LP_{0m} , is strongly suppressed, thereby minimizing insertion loss and enabling adiabatic transitions. The fabricated fibers exhibit insertion losses below 0.2 dB at 1550 nm. These low losses, primarily associated with the taper transitions, confirm adiabatic behavior for the fundamental mode at 1550 nm and, by extension, at 1064 nm. After fabrication, the OMFs are stored in hermetic enclosures to prevent contamination by dust. In the following, fiber system refers to the complete structure comprising the OMF waist, both taper transitions, and the input/output standard fiber sections, each limited to ~ 30 cm to minimize their contribution to the nonlinear output spectrum (Fig. 5(a)).

Scanning electron microscope (SEM) measurements on several samples show that the fabricated OMF diameters deviate from their target values by approximately 2% (i.e., ≈ 200 nm over the 6–9 μm range). According to the sensitivity curve in

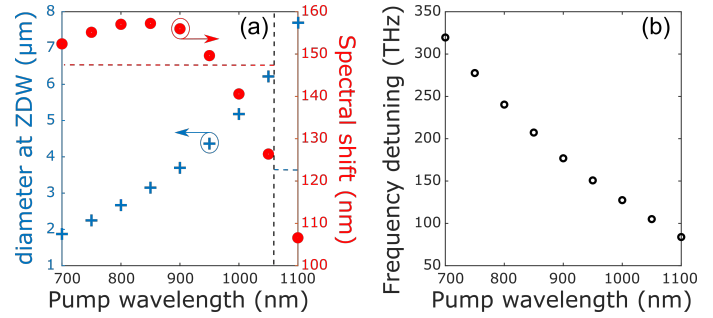


Fig. 4. (a) Dependence on the pump wavelength of the microfiber diameter d_{ZDW} corresponding to the zero-dispersion wavelength (blue crosses, left vertical axis), and of the spectral shift between the FWM peak wavelengths obtained for the diameters d_{ZDW} and $d = d_{ZDW} + 1 \mu\text{m}$ (red dots, right vertical axis). (b) Dependence on the pump wavelength of the maximum frequency detuning between the pump and the generated FWM signal.

Fig. 3(b) (dashed lines), such deviations induce a shift in the FWM peak wavelength of about 6 nm for a 6 μm diameter and 4 nm for a 9 μm diameter, reaching up to ~ 30 nm near 6.6 μm where the sensitivity is maximal. These values are taken as the uncertainty on the experimentally measured FWM peak wavelengths.

The experimental setup employs a pump laser delivering 42-ps pulses at a wavelength of 1064 nm with a repetition rate of 200 kHz (EKSPLA ATLANTIC-5). The incident beam passes through a half-wave plate to control the input polarization, since the FWM peak amplitude is polarization dependent and can be optimized through appropriate adjustment. The output spectra are recorded using an optical spectrum analyzer (Yokogawa AQ6373) covering the 350–1200 nm range, enabling access to the high-frequency spectral components. An imaging system is used at the fiber output to verify single-mode (LP_{01}) propagation in the linear regime and to identify, in the nonlinear regime, spectral signatures associated with intermodal FWM and polarization instability arising in the standard fiber sections.

Figure 6(a) presents the output spectra of the fiber system for different OMF diameters. The spectral components near the pump wavelength (1000–1100 nm) include the silica Raman peak at 13.2 THz, intermodal FWM products, and polarization modulation instability (PMI) sidebands. These components may originate from the standard fiber sections, as confirmed by dedicated measurements, but may also potentially arise from the transition regions and the OMF itself concerning PMI. As the FWM peak power is optimized by adjusting the input coupling conditions and the orientation of the half-wave plate, these vectorial nonlinear processes may occur with different efficiencies from one experiment to another, explaining the variations in the spectral signatures of these processes.

In contrast, the intramodal FWM peaks are clearly observed, shifting away from the pump and becoming spectrally narrower as the OMF diameter increases, in agreement with theoretical predictions. Experimentally, the anti-Stokes FWM peaks span wavelengths from 960 nm to 717 nm, corresponding to a tunability of 243 nm. The largest frequency detuning, obtained for an OMF diameter of 9 μm , reaches 137 THz.

As discussed above, the pump power is intentionally maintained below the threshold for cascaded FWM, ensuring oper-

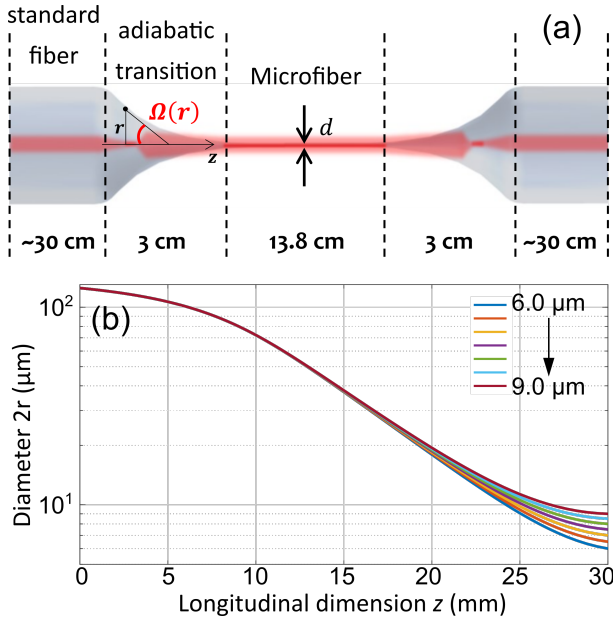


Fig. 5. (a) Schematic and geometry of the tapered optical fiber system used in this work. The local taper angle is defined as $\Omega(r) = \frac{dr(z)}{dz}$. The red profile illustrates the propagation of the fundamental mode along the entire structure. (b) Evolution of the fiber diameter ($2r$) along the taper transitions (vertical logarithmic scale) for OMF waist diameters ranging from 6 to 9 μm in 0.5 μm steps.

ation in the single-sideband regime. Under these conditions of limited input pump power, the energy conversion efficiency (ECE) from the pump to the anti-Stokes sideband is estimated to be 0.1%–1%, comparable to values reported for intramodal FWM in silica fibers [30]. For higher pump powers, as shown by figure 6(b), ECE values of up to 26% were achieved. However, these higher efficiencies are accompanied by significant spectral broadening of the FWM peak.

In the present OMF system, an additional limiting factor may arise from residual non-uniformities of the waist diameter, which induce variations in the local dispersion profile and thus in the parametric gain, reducing the overall conversion efficiency. Despite these limitations, the measured intramodal FWM efficiencies remain lower than those typically reported for intermodal FWM processes [31]. Nevertheless, the achieved conversion efficiency is sufficient for the realization of microfiber-based optical parametric oscillators, owing to the very low insertion loss of the tapered microfiber device. In a resonant configuration, even a modest single-pass parametric gain can overcome cavity losses, enabling oscillation and providing significant enhancement of the generated sideband power through multiple round trips.

Figure 6(c) summarizes the experimentally measured anti-Stokes FWM wavelengths as a function of OMF diameter (red circles). The error bars account for the uncertainty in the actual fiber diameter relative to the target value, estimated from the dashed curves in Fig. 3(b), with a maximum deviation of 200 nm. The solid green curve corresponds to the pump-power-adjusted theoretical prediction from Fig. 3(b). This curve is obtained independently of any fitting to the experimental data and serves as a predictive model, showing excellent agreement with the measurements.

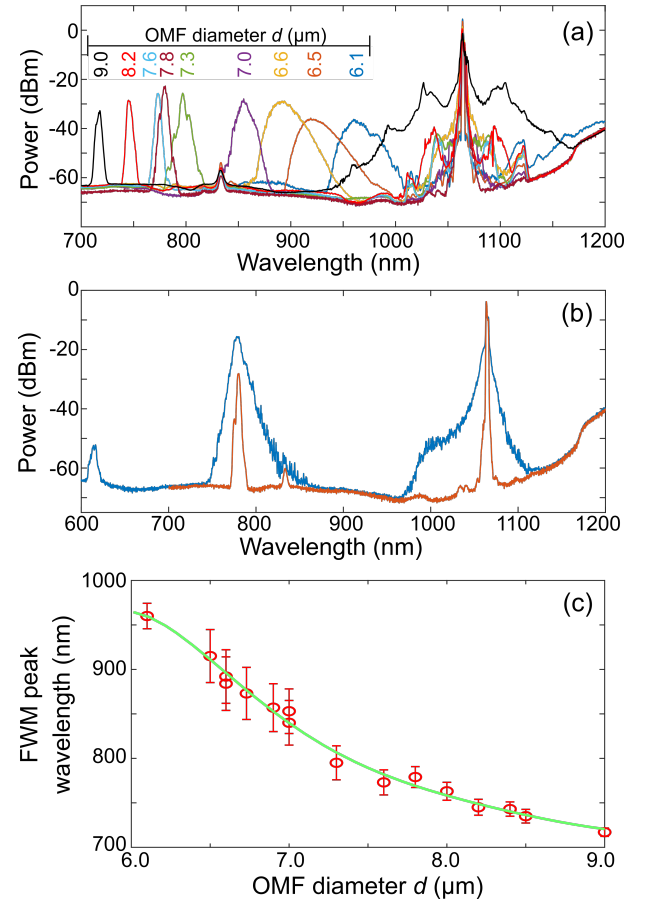


Fig. 6. (a) Experimental output FWM spectra of the fiber system as a function of OMF diameter from 6.1 to 9 μm . The corresponding input pump peak powers are 5, 6, 7.7, 10.7, 16.7, 14, 17, 15.4, and 26 kW, respectively. (b) Comparison of the output spectra obtained for a 7.8 μm -diameter OMF at two input peak pump powers of approximately 17 kW and 21 kW. (c) FWM peak wavelength as a function of the OMF diameter. Red circles represent the experimental data, and the solid green curve shows the theoretical power-adjusted curve from Fig. 3(a).

It can be observed in Fig. 6(a) that the FWM peaks are reversed for OMF diameters of 7.6 μm and 7.8 μm . This is clearly due to a discrepancy between the target diameter and the fabricated diameter. This inversion is also clearly visible in Fig. 6(c). Furthermore, Fig. 6(c) shows that the theoretical curve (solid green line) intersects the error bars associated with these diameters, indicating that the diameter deviation remains within the estimated 200 nm. Nevertheless, the wavelength separation between the FWM peaks obtained for OMF diameters of 6.6 and 7.6 μm is approximately 118 nm, in good agreement with the theoretically predicted value of 122 nm obtained in the previous theory section.

Concerning the non-monotonic dependence of the pump power on the OMF diameter (see the caption of Fig. 6(a)), this behavior may have several origins. It may result from the fact that the system is not operating at a strictly constant gain, as evidenced by the varying amplitudes of the FWM peaks shown in Fig. 6(a). It may also arise from the presence of different nonlinear phenomena in the vicinity of the pump wavelength, such as intermodal FWM and polarization modulation insta-

bility (PMI), which, depending on the coupling conditions into the standard fiber and the input polarization state, can extract varying amounts of energy from the pump. The significant spectral broadening clearly observed around the pump wavelength for the 9 μm OMF diameter is consistent with the occurrence of additional nonlinear processes, which can deplete the pump energy and may explain the relatively high peak pump power of 26 kW required in this case. This may also contribute to the deviation of the pump power dependence on the OMF diameter from the linear behavior predicted by the theoretical model. Finally, from a general perspective, fluctuations in the pump power may also result from residual diameter variations along the length of the OMFs, which can differ from one microfiber to another and consequently affect the average gain. Nevertheless, despite these fluctuations, the overall trend remains an increase in power with increasing OMF diameter.

4. NUMERICAL SIMULATIONS

To closely reproduce the experimental conditions, we model light propagation in the fiber system using the generalized nonlinear Schrödinger equation (GNLSE), which includes dispersion, Kerr nonlinearity, and Raman response, and is solved using the standard split-step Fourier method [24]. The simulated system reproduces the full experimental architecture: two standard fiber sections, two taper transitions with the geometry shown in Fig. 5(b), and the OMF waist, enabling a quantitative assessment of each segment's contribution to the output spectra. The model accounts for longitudinal variations of both dispersion and nonlinear parameters induced by the changing fiber diameter. In particular, the nonlinear coefficient γ varies from approximately 14 $\text{W}^{-1}\text{km}^{-1}$ to 6 $\text{W}^{-1}\text{km}^{-1}$ for OMF diameters ranging from 6 to 9 μm , respectively. The spatial evolution of γ across the taper transitions is also included through the corresponding variation of the effective mode area.

As a representative case, we consider an OMF with a diameter of 7 μm . The results are shown in Fig. 7(a) for a pump peak power of 9 kW, chosen to reproduce the experimental operating point just below the onset of cascading at the output of the fiber system. This value can be compared with 5.3 kW used for the power-adjusted theoretical curve in Fig. 6(c) and the experimentally estimated peak power of approximately 10.7 kW.

For the OMF alone (Fig. 7(a), spectrum i), the simulation shows efficient FWM generation and the onset of cascaded processes, with the peak near 690 nm corresponding to the second-order FWM, and negligible Raman contribution. Including the input and output taper transitions (spectrum ii) leads to a slight reduction in FWM gain and a marginal suppression of cascading, without noticeable spectral broadening due to the short length of these sections. Adding the input standard fiber section before the taper (spectrum iii) significantly enhances Raman scattering and self-phase modulation (SPM), owing to the increased nonlinear interaction length. Finally, including the output standard fiber section (spectrum iv) further strengthens the Raman background, without otherwise altering the main spectral features.

Figures 7(b–c) compare numerical and experimental spectra for two OMF diameters. Overall, the agreement is very good: the linewidths of the pump, FWM peaks, and Raman features are accurately reproduced. The main discrepancy appears in the central wavelength of the FWM peak in Fig. 7(b). The observed shift of approximately 18 nm corresponds to an estimated OMF diameter deviation of about 150 nm, consistent with the maximum fabrication uncertainty of 200 nm. For an OMF diameter

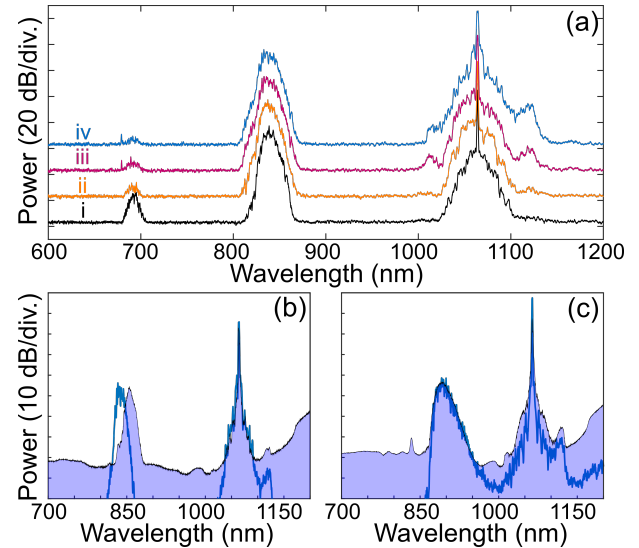


Fig. 7. (a) Numerical spectra for the microfiber alone with 7 μm of diameter (spectrum i), the microfiber including the taper transitions (spectrum ii), the microfiber with transitions and the input standard fiber (spectrum iii), and the complete fiber system including both input and output standard fibers (spectrum iv). (b–c) Comparison of numerical (solid curves) and experimental (filled curves) spectra for microfiber diameters of (b) 7 μm and (c) 6.6 μm .

of 6.6 μm and a pump peak power of 7 kW (to be compared with 4.8 kW used for the power-adjusted curve in Fig. 6(c) and 7.7 kW in the experiment), the simulated and measured spectra show excellent agreement in both spectral position and linewidth, as shown in Fig. 7(c). Although only representative examples are shown in Figure 7(b–c), a similar level of agreement is obtained for all other diameters, including the extreme values, within the specified fabrication uncertainty.

These results demonstrate that intramodal FWM provides a sensitive, non-destructive diagnostic for accurately determining OMF diameter and its uniformity, particularly in regimes where Brillouin-based techniques are no longer effective [27].

It is necessary to discuss the differences between theoretical, numerical, and experimental powers. The theoretical powers are chosen to achieve good agreement between the theoretical and experimental FWM peak wavelengths, as shown in Fig. 6, particularly for the smallest OMF diameter, where the FWM wavelength is highly sensitive to the pump power, as illustrated in Fig. 3(b) (solid curves). The discrepancy between theoretical and numerical powers is straightforward to interpret. Physical effects such as self-phase modulation (SPM), and to a lesser extent stimulated Raman scattering, are included in the numerical model but not in the theoretical model; these effects reduce the effective peak power available for the FWM process. In addition, the theoretical model assumes steady-state operation and neglects short-pulse dynamics, pump depletion, and FWM cascading processes. As a result, higher pump power is required in the numerical model to reproduce the same FWM signal wavelength.

Regarding the difference between experimental and numerical peak powers, the numerical values are lower than the experimental ones. Moreover, the experimental peak powers do not increase linearly with the OMF diameter (see caption of Fig. 6)

as in the numerical case (see figure 3(a)), and instead exhibit noticeable variations. These two observations can be attributed to non-uniformities in the OMF diameter along the fiber length, which reduce FWM efficiency and contribute to the observed peak-power fluctuations among different OMFs. Such rapid and random diameter variations were observed in SEM measurements and were estimated to be no greater than 4% relative to the mean diameter.

5. CONCLUSION

We have demonstrated intramodal FWM in highly nonlinear tapered optical microfibers, achieving a remarkable tunability of 250 nm for a diameter variation of only 3 μm . This performance is obtained using microfibers with relatively large diameters in the range of 6–9 μm . The experimental results show excellent agreement with theoretical predictions and numerical simulations based on the generalized nonlinear Schrödinger equation, which incorporates both dispersion and nonlinear effects. The simulations accurately reproduce the measured FWM peak positions, linewidths, and amplitude trends, confirming the dominant role of microfiber diameter and higher-order dispersion in governing phase matching and FWM gain.

Embedding such microfibers into an optical cavity could further narrow the FWM spectral features, enhancing spectral coherence and conversion efficiency, and enabling the realization of an all-fiber optical parametric oscillator. Overall, the combination of precise microfiber fabrication, predictive modeling, and experimental validation highlights the strong potential of this platform for tunable parametric sources, on-demand photon-pair generation, and widely tunable optical parametric amplification and oscillation fully integrated within fiber systems.

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conflict of interest. The authors declare that they have no conflicts of interest. related to this article.

Data Availability. The data that support the findings of this study are available from the corresponding author upon reasonable request.

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