

Enhanced four-wave mixing in $\text{Nb}_2\text{CT}_x\text{-ZnO}$ deposited on tapered fibers for 1- μm wavelength applications

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This study examines four-wave mixing (FWM) enhancement in tapered optical fibers operating at 1- μm wavelength, achieved by depositing an $\text{Nb}_2\text{CT}_x\text{-ZnO}$ composite onto the fiber surface. Tapers with waist diameters of 30 μm , 40 μm , and 50 μm were fabricated using the flame-brush technique. The composite coating significantly boosted the nonlinear response, with the 30 μm taper showing the greatest improvement, a 22.5% increase in FWM conversion efficiency. The generated idler wave remained stable throughout a 60-minute test. These results advance the development of efficient, compact nonlinear photonic devices for applications in the 1 μm spectral band.

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1. Introduction

Among the various nonlinear effects observed in optical materials, particularly within optical fibers, four-wave mixing (FWM) stands out as a versatile process with significant implications for numerous applications in optical communications, sensing, and quantum technologies. Optical fibers, capable of confining light over long distances and possessing inherent nonlinear properties, serve as an ideal medium for exploring and utilizing these nonlinear interactions. Four-wave mixing is a third-order nonlinear optical process resulting from the Kerr nonlinearity inherent in optical fibers. Its nonlinearity appears as an intensity-dependent refractive index, which leads to the interaction of two or more light waves propagating in the fiber and the generation of new frequencies. The fundamental principle of FWM involves the interaction of photons from the input waves, creating photons at new frequencies while conserving energy. A key condition called phase matching must be met for this process to occur efficiently. Phase matching ensures that the generated wave constructively interferes with the interacting waves during propagation [1–3].

Furthermore, FWM plays a crucial role in generating supercontinuum light, which has an extensive spectral bandwidth and finds applications in various fields, including optical coherence tomography and metrology [4,5]. Notably, FWM has also become an essential tool in quantum photonics, enabling the creation of entangled photon pairs and squeezed light [6–8], which are fundamental resources for quantum communication and

computation [9–11]. Four-wave mixing has garnered significant attention due to its potential to develop compact and efficient photonic devices [9,12,13]. Research has demonstrated the use of FWM for wavelength conversion in silicon photonic waveguides and micro-ring resonators operating near this wavelength. For example, FWM can be achieved at a wavelength around 2 μm . Additionally, studies have reported high conversion efficiencies in silicon carbide ring resonators at wavelengths around 1550 nm [14,15]. However, there are only a few reports on FWM in the 1- μm region.

Various methods have been reported for generating FWM, typically using highly nonlinear fibers [12,16,17]. While this approach is convenient, it does not offer a compact system. Tapered optical fibers, on the other hand, provide several compelling advantages. The tapering process, which involves reducing the fiber's diameter over a certain length, significantly increases the optical intensity within the tapered region for a given input power. This higher intensity directly leads to a stronger nonlinear response, making tapered fibers ideal for enhancing nonlinear interactions, such as FWM. As a result, efficient wavelength conversion and other FWM-based functions can be achieved with relatively low input powers in these structures [3,18,19]. The phase-sensitive nature of FWM also allows its use in phase-sensitive amplification, offering the potential for low-noise amplification of optical signals. Additionally, manipulating the fiber's diameter through tapering enables the creation of compact and versatile photonic devices.

FWM generation can be enhanced by introducing

$\text{Nb}_2\text{CT}_x\text{-ZnO}$, which further increases the nonlinearity. Using $\text{Nb}_2\text{CT}_x\text{-ZnO}$ composites in tapered optical fibers for 1- μm wavelength, it offers significant advantages by synergistically combining their unique nonlinear optical properties with enhanced light-matter interaction. Nb_2CT_x MXenes provide a high third-order nonlinear susceptibility ($\chi^{(3)}$), strong near-infrared extinction, and broadband saturable absorption, ensuring robust interaction with the 1 μm pump light. Complementarily, Zinc Oxide (ZnO) offers crucial transparency at 1- μm , minimizing linear losses while contributing its own significant and tunable $\chi^{(3)}$ through doping and defect engineering [20,21]. This composite benefits from potential synergistic enhancements, such as charge or energy transfer at the interface, which can further enhance the overall nonlinear response, as demonstrated in other MXene heterostructures [22]. The tapered fiber geometry, especially with smaller waist diameters, is critical as it maximizes the evanescent field overlap, thereby intensifying the interaction between the optical field and the composite material and significantly enhancing the FWM conversion efficiency [3,23,24].

Although both Nb_2CT_x MXenes and Zinc Oxide (ZnO) nanomaterials have notable nonlinear optical (NLO) potential, there is a lack of direct research on FWM generation in $\text{Nb}_2\text{CT}_x\text{-ZnO}$ composites, especially in the 1- μm wavelength range, indicating significant inherent limitations. At 1 μm , the metallic nature and high conductivity of Nb_2CT_x can cause substantial linear absorption, which dissipates pump and signal energy and reduces the optical interaction length, a key factor for FWM efficiency. Additionally, Nb_2CT_x 's poor stability in oxygen-rich environments [21,22] makes it susceptible to oxidation, degrading its structural integrity and optical properties over time, which directly affects the consistency of FWM generation. To overcome these limitations, Nb_2CT_x is combined with ZnO to form a composite of $\text{Nb}_2\text{CT}_x\text{-ZnO}$.

This work generates FWM in tapered optical fibers at the 1- μm wavelength. The nonlinear optical effect was enhanced using tapered fibers, which were fabricated via flame brushing, thereby concentrating light intensity in their reduced-diameter regions. FWM was further enhanced by introducing $\text{Nb}_2\text{CT}_x\text{-ZnO}$ at the tapered region. The experimental setup utilizes two tunable continuous-wave laser sources, which are amplified by a ytterbium-doped fiber amplifier (YDFA). The effect of different tapered fiber waist diameters (30 μm , 40 μm , and 50 μm) was investigated, along with the FWM conversion efficiency and its stability.

2. Experimental setup

This section presents the fabrication of tapered fibers and the corresponding setup configuration.

2.1. Fabrication of tapered fiber

The tapered optical fiber was fabricated using the

flame brushing method, a versatile and well-established technique for creating tapered optical fibers with controlled profiles and low insertion losses [25,26]. This method involves heating a specific section of an optical fiber to its softening point while applying a controlled pulling force to stretch the fiber, thereby reducing its diameter in the heated zone [23]. Moving the heat source, typically a flame, along the fiber as it is stretched enables the formation of a tapered region with precise shapes, including a uniform waist and transition zones [3]. In this experiment, the optical fiber used was Corning HI-1060, a specialty fiber designed for operation at wavelengths of approximately 1- μm . The flame brushing setup employed a two-stage pulling system to control the tapering process. Two motorized translation stages held the optical fiber at its ends [4,27,28]. During the process, these stages moved apart, applying tensile force to stretch the heated section and decrease its diameter. The two-stage pulling process provided precise control over the taper profile. The first stage involved a faster pulling rate over a longer distance to form the initial taper transitions. The second stage involved a slower pulling rate over a shorter distance to achieve the final waist diameter and length with greater accuracy [27]. This multi-stage approach helps minimize optical losses and produce the specific adiabatic taper shape needed for efficient light propagation in nonlinear interactions [3,17,25].

An oxy-butane flame was used in this process, providing sufficient heat to soften the silica glass of the optical fiber, allowing it to be stretched and drawn into a tapered region. The flow rates of oxygen and butane gases were carefully regulated to ensure a stable flame with the appropriate temperature and size for uniform heating of the tapered fiber segment [3,25,26]. Maintaining a consistent flame is crucial for achieving a smooth and uniform taper profile, minimizing scattering losses, and ensuring efficient light transmission through the tapered fiber. A motion controller played an essential role in the experimental setup by precisely controlling the movement of the oxy-butane flame. The flame was mounted on a motorized stage programmed to move back and forth along the tapered fiber section, while the pulling stages simultaneously stretched the fiber. This controlled movement, known as flame brushing, ensures that heat is applied uniformly over a specific length of the fiber, resulting in a uniform waist diameter and controlled taper transitions. The motion controller enabled the precise setting of parameters, including the flame speed, the length of the brushing region along the fiber, and the duration of the heating cycle. These parameters are critical for achieving the desired length and tapered profile [15,27]. Three tapered fibers with waist diameters of 30 μm , 40 μm , and 50 μm were fabricated, exhibiting insertion losses of 3.2 dB, 3.5 dB, and 3.3 dB, respectively. Subsequently, the $\text{Nb}_2\text{CT}_x\text{-ZnO}$ composite was deposited onto the tapered region via the drop-casting method. Following the coating process, the insertion loss increased by approximately 1 dB for all tapered fibers. The measured loss remained nearly constant over the investigated power range, indicating negligible power-dependent absorption.

Therefore, the observed enhancement in FWM performance can be attributed primarily to the increased nonlinear interaction provided by the $\text{Nb}_2\text{CT}_x\text{-ZnO}$ composite rather than to any power-dependent transmission effect.

2.2. Experimental setup for FWM generation at 1 μm wavelength

The experimental setup for studying FWM in a tapered optical fiber, operating within the 1- μm wavelength range, uses two tunable continuous-wave laser sources for the pump and signal waves, as shown in Fig. 1. The output of each laser is combined with a 3-dB optical coupler to ensure simultaneous propagation of the signals. A YDFA then amplifies this combined signal to boost the optical output power. To prevent back reflections, the amplified signal passes through an optical isolator before being launched into the tapered optical fiber, where the FWM process takes place. The output spectrum from the tapered fiber was analyzed with an optical spectrum analyzer (OSA). An optical attenuator is placed before the OSA to protect it from high-power input.

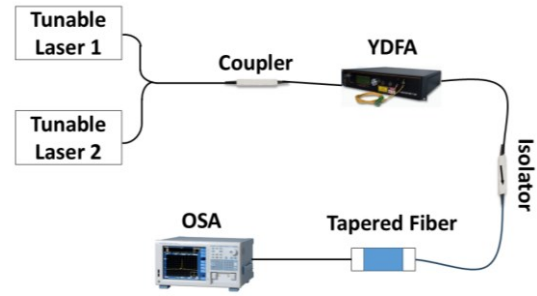


Fig. 1. The schematic diagram for generating the FWM effect using a tapered fiber (YDFA: ytterbium-doped fiber amplifier; OSA: optical spectrum analyzer) (colour online)

3. Results and discussion

Firstly, the FWM was generated using a tapered fiber with different waist diameters (30 μm , 40 μm , and 50 μm). The signal λ_1 and signal λ_2 wavelengths were 1049.73 nm and 1050.29 nm, respectively, resulting in the generation of two new idler wavelengths: λ_3 at 1049.14 nm and λ_4 at 1050.86 nm. The conversion efficiency for each tapered fiber was measured. Fig. 2 shows two scenarios for the FWM using a tapered fiber without and with $\text{Nb}_2\text{CT}_x\text{-ZnO}$.

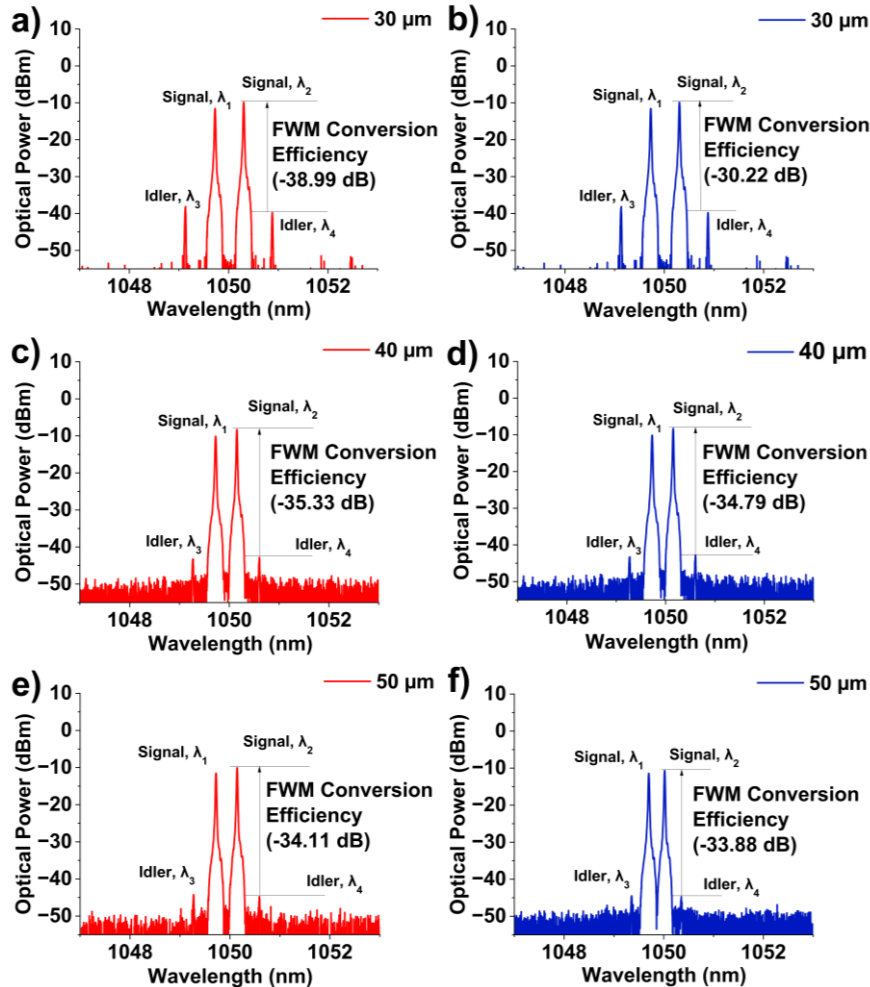


Fig. 2. Optical spectrum of FWM using (a) 30 μm without $\text{Nb}_2\text{CT}_x\text{-ZnO}$, (b) 30 μm with $\text{Nb}_2\text{CT}_x\text{-ZnO}$, (c) 40 μm without $\text{Nb}_2\text{CT}_x\text{-ZnO}$, (d) 40 μm with $\text{Nb}_2\text{CT}_x\text{-ZnO}$, (e) 50 μm without $\text{Nb}_2\text{CT}_x\text{-ZnO}$, and (f) 50 μm with $\text{Nb}_2\text{CT}_x\text{-ZnO}$ (colour online)

The calculated conversion efficiencies varied among the different tapered diameters, and the results were tabulated in Table 1.

Table 1. Conversion efficiency for 30 μm , 40 μm , 50 μm tapered fibers

Waist Diameter	Without Nb ₂ CT _x -ZnO (dB)	With Nb ₂ CT _x -ZnO (dB)	Conversion Efficiency Improvement
30 μm	-38.99	-30.22	22.5%
40 μm	-35.33	-34.79	1.53%
50 μm	-34.11	-33.88	0.67%

From the table, tapered fiber with 30 μm waist diameter showed conversion efficiencies of -38.99 dB (without Nb₂CT_x-ZnO) and -30.22 dB (with Nb₂CT_x-ZnO), which shows enhancement of around 22.5%. Tapered fiber with 40 μm waist diameter exhibited conversion efficiency of -35.33 dB (without Nb₂CT_x-ZnO) and -34.79 dB (with Nb₂CT_x-ZnO), thus showing 1.53% improvement. Furthermore, tapered fiber with 50 μm waist diameter shows 0.67% improvement from -34.11 dB (without Nb₂CT_x-ZnO) to -33.88 dB (with Nb₂CT_x-ZnO). The deposition of Nb₂CT_x-ZnO materials enhanced the conversion efficiencies, with the tapered fiber at 30 μm waist diameter showing the best conversion efficiency. It

implies that the intensity will be higher for a narrower waist, contributing to high FWM effect.

In Fig. 3, stability tests conducted over 60 minutes showed optical power fluctuations in the FWM output. The tapered fiber with a 30 μm waist diameter exhibited fluctuations of 0.844 dB (without Nb₂CT_x-ZnO) and 0.822 dB (with Nb₂CT_x-ZnO). The 40 μm waist diameter fiber displayed fluctuations of 0.795 dB (without Nb₂CT_x-ZnO) and 0.561 dB (with Nb₂CT_x-ZnO). The 50 μm waist diameter fiber demonstrated fluctuations of 0.533 dB (without Nb₂CT_x-ZnO) and 0.864 dB (with Nb₂CT_x-ZnO). These findings indicate that the FWM signal generated by the tapered fibers remains stable throughout the test period, with variations depending on the fiber's waist diameter and deposited material. Additionally, to assess the performance of the Nb₂CT_x-ZnO-coated tapered fiber, the FWM characteristics were compared with the previously reported systems operating in the 1- μm wavelength region. Achieving efficient FWM at 1- μm remains challenging because phase-matching conditions are not readily satisfied in conventional optical fibers. Therefore, earlier studies typically employed advanced fiber designs, such as double-cladding fibers and photonic crystal fibers (PCFs) or relied on high-power pump sources. Table 2 presents a comparison of the performance of these reported FWM systems with that achieved in the present work.

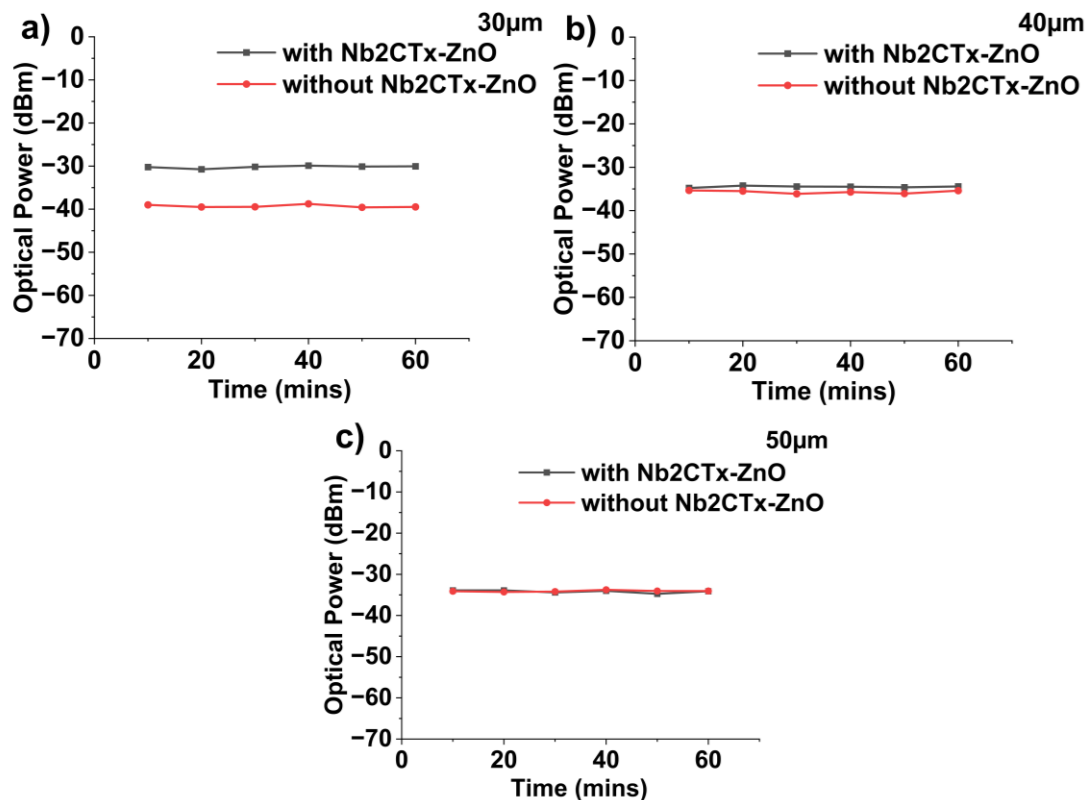


Fig. 3. a) Optical power fluctuations for 30 μm , b) optical power fluctuations for 40 μm waist, and c) optical power fluctuations for 50 μm waist diameters (colour online)

Table 2. Performance comparison of nonlinear material-based FWM at 1-μm

Type of fiber	Materials	Efficiency (%)	Interaction length	Wavelength (nm)	Ref.
Large-core hybrid PCF	Uncoated hybrid silica structure	17	2 m	1064	[16]
Endlessly single-mode large-mode-area PCF	Uncoated silica structure	30	50 cm	1064	[24]
Tapered fiber	Nb ₂ CT _x -ZnO	22.5	1.5 cm	1050.8	This work

As shown in Table 2, conventional uncoated fiber setups require long interaction lengths, ranging from 50 cm up to 2 m, to generate FWM signals. This is because pure silica glass has a relatively low nonlinear response. While these standard fibers can achieve good conversion efficiency, the long lengths make the devices bulky. In contrast, the presented system introduces a highly nonlinear Nb₂CT_x-ZnO composite coating directly onto a 30 μm fiber taper waist. This material deposition successfully concentrates the light intensity in the narrow waist region, leading to a strong nonlinear response over a very short interaction length of only 1.5 cm. By applying this composite coating, the FWM conversion efficiency significantly increases from an uncoated baseline of -38.99 dB to an enhanced value of -30.22 dB. This represents a 22.5% conversion efficiency improvement in the decibel power ratio. The coating combines the high third-order nonlinearity of the MXene with the good transparency of ZnO at 1-μm. This approach offers a reliable and highly compact design for wavelength conversion and signal processing devices within the 1-μm band.

4. Conclusion

This study successfully demonstrated that Nb₂CT_x-ZnO-deposited tapered fibers significantly enhance the FWM efficiency in the 1-μm wavelength range, specifically for a 30-μm waist diameter. The generation of new idler wavelengths (1049.14 nm and 1050.86 nm) from pump (1049.73 nm) and signal (1050.29 nm) wavelengths was observed. The application of Nb₂CT_x-ZnO materials influenced conversion efficiencies, with the tapered fiber at 30 μm showing an increase from -38.99 dB to -30.22 dB. Stability tests confirmed the consistent generation of FWM signals, and the highest conversion efficiency was achieved with a 0.58 nm pump-signal spacing. This work contributes to understanding nonlinear optical properties in tapered fibers, which is crucial for developing compact and efficient 1-μm photonic devices. The advantages of FWM in the 1-μm range include its relevance for high-power fiber lasers, material processing, and integrated photonic circuits, enabling applications such as wavelength conversion, optical parametric amplification, and quantum photonics.

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