Efficient wavelength conversion with low operation power in a Ta$_2$O$_5$-based micro-ring resonator

CHUNGLUN WU,^1 JEN-YANG HUANG,^1 DING-HSIN OU,^1 TING-WEI LIAO,^1 YI-JEN CHIU,^1 MIN-HSIUNG SHIH,^1,3,4 YUAN-YAO LIN,^1 ANN-KUO CHU,^1 AND CHAO-KUEI LEE^1,2,*

^1Department of Photonics, National Sun Yat-sen University, 70, Lienhe Road, Kaohsiung, Taiwan
^2Department of Physics, National Sun Yat-sen University, 70, Lienhe Road, Kaohsiung, Taiwan
^3Research Center for Applied Sciences, Academia Sinica, 128, Sec. 2, Academic Road, Taipei, Taiwan
^4Department of Photonics, National Chiao Tung University, 1001, Daxue Road, Hsinchu City, Taiwan
*Corresponding author: chuckcklee@yahoo.com

Received 17 July 2017; revised 4 September 2017; accepted 12 September 2017; posted 14 September 2017 (Doc. ID 302655); published 21 November 2017

The Ta$_2$O$_5$-based micro-ring resonator with an unloaded quality factor of 182,000 has been demonstrated to realize efficient nonlinear wavelength generation. The propagation loss of the resonator is 0.5 cm$^{-1}$, and the buildup factor of the ring resonator is estimated to be $\sim$50. With a high buildup factor of the ring structure, the four-wave-mixing (FWM) conversion efficiency of $\sim$30 dB is achieved in the resonator with a pump power of 6 mW. Based on power-dependent FWM results, the nonlinear refractive index of Ta$_2$O$_5$ is estimated to be $1.4 \times 10^{-14}$ cm$^2$/W at a wavelength of $\sim$1550 nm. The demonstration of an enhanced FWM process in the Ta$_2$O$_5$-based micro-ring cavity implies the possibility of realizing FWM-based optical parametric oscillation in a Ta$_2$O$_5$-based micro-ring resonator. © 2017 Optical Society of America

OCIS codes: (230.7370) Waveguides; (230.7405) Wavelength conversion devices; (190.4380) Nonlinear optics, four-wave mixing.

https://doi.org/10.1364/OL.42.004804

Nonlinear optical processes, including wavelength generation [1], optical switching [2], and signal processing [3] by using optical waveguides, have been widely investigated in recent years due to their advantages of small footprint, low cost, and low operation power, compared to the traditional solid-state platform. Particularly, broadband and highly coherent light sources demonstrated by supercontinuum generation or frequency comb generation in the optical waveguides are important for the applications on frequency metrology, optical communications, and optical coherence tomography [4–6]. Recently, lots of large bandgap materials, such as CaF$_2$, Si$_3$N$_4$, Hydex, and AlN, have been utilized to demonstrate chip-scale frequency comb generation by using optical waveguide structures [7–10]. Although these kinds of large bandgap materials show lower optical Kerr coefficients than Si, the two-photon absorption (TPA) free properties enable it to operate at ultrahigh peak intensity without introducing nonlinear losses [11].

To further develop efficient nonlinear waveguide applications, an alternative material, tantalum pentoxide (Ta$_2$O$_5$), was proposed and demonstrated recently. Ta$_2$O$_5$ is a large bandgap material. In addition, it has the nature of loss free from 300 to 8000 nm [12]. Based on previous researches, a low propagation loss of Ta$_2$O$_5$ waveguides and micro-ring resonators has been successfully demonstrated [12–15]. By comparing to Si$_3$N$_4$ and SiO$_2$, Ta$_2$O$_5$ is without hydrogen-related atomic bonding (Si-H or N-H bonds), leading to low absorption in the telecommunications regions [16]. Besides, Ta$_2$O$_5$ shows great performance as a thermal-optical coefficient. The thermal-optical coefficient of Ta$_2$O$_5$ is merely $2 \times 10^{-6}$/K [17], which is much lower than Si$_3$N$_4$ of $3 \times 10^{-5}$/K and Si of $1 \times 10^{-4}$/K [18,19]. It implies that Ta$_2$O$_5$ is suitable to utilize to fabricate temperature-insensitive waveguide devices for optical communications systems. For the nonlinear optical properties of Ta$_2$O$_5$, the strong self-phase modulation (SPM), as well as four-wave-mixing (FWM), has been successfully demonstrated by using the Ta$_2$O$_5$-based straight waveguides [20–23]. In addition, the all-optical switching based on the Kerr effect with a modulation bandwidth up to 12 GHz has been demonstrated by using a Ta$_2$O$_5$-based ring resonator [23]. These aforementioned results all imply that Ta$_2$O$_5$ is indeed suitable to develop nonlinear waveguide devices.

In this Letter, the Ta$_2$O$_5$-based micro-ring resonator has been fabricated to realize efficient wavelength conversion with low injection power. The waveguide geometry is carefully designed to achieve the minimum phase mismatching of the FWM process. Based on a reflowing process for smoothing the sidewall roughness of Ta$_2$O$_5$-based waveguides, the low propagation loss and record unloaded quality factor of $\sim$1,82,000 in the Ta$_2$O$_5$ ring cavity is successfully demonstrated. By comparing the FWM process of Ta$_2$O$_5$-based waveguides with and without a ring resonator, the nonlinear process is proved to be significantly enhanced by using a micro-ring cavity. Our results indicate that Ta$_2$O$_5$ has great potential in developing FWM-based optical parametric oscillation.

Figure 1(a) shows the geometric structure of a Ta$_2$O$_5$-based micro-ring resonator. The cross section of bus waveguide is set as 700 nm × 700 nm for single mode operation. For achieving zero dispersion at a wavelength around 1550 nm, the
waveguide structure with high confinement is utilized to compensate for material dispersion [24]. Thus, the cross section of the ring cavity is set as 1500 nm x 700 nm. The diameter of the ring resonator is 100 μm, and the gap between the bus and ring waveguides is 700 nm. The simulated group velocity dispersion (GVD) of different waveguide dimensions by using the full-vectorial beam propagation method and bulk Ta2O5 film is shown in Fig. 1(b). The waveguide dimension with 1500 nm x 700 nm is expected to realize an efficient and broadband FWM process due to the minimized dispersion at a wavelength of ~1550 nm. In addition, to increase power coupling between the lensed fiber and waveguide device, the ends of the waveguide are tapered from 700 down to 300 nm at the waveguide facet, where the length of the tapered region is 200 μm.

The fabrication of the Ta2O5-based micro-ring resonator is described in the following steps. First, the Ta2O5 film with a thickness of 700 nm is deposited on a Si/SiO2 wafer by using RF sputtering. The Ta2O5 film is then annealed at 650°C at oxygen environment for compensating the oxygen vacancy of as-grown Ta2O5 film. The optical properties of sputtered grown Ta2O5 film can be referred to in our previous work [15]. Then, the e-beam lithography is utilized to define the pattern of the micro-ring resonator with negative resist (ma-N 2410). After developing the process, the reflow process is applied on the developed resist to decrease the sidewall roughness of resist [25]. The negative resist of ma-N 2410 is served as a hard mask at a dry etching step. The reactive ion etching with CHF3 plasma is utilized to etch Ta2O5 film to form the waveguide structures. Then, the resist is further removed by using oxygen plasma. The top cladding material is SiO2 with a thickness of 2 μm, deposited by using plasma-enhanced chemical vapor deposition. Finally, the device is diced and polished at both facets. The top-view scanning electron microscope (SEM) image of the Ta2O5 ring resonator is shown in Fig. 1(c).

The normalized transmittance spectrum of a Ta2O5-based micro-ring resonator with TE polarization is shown in Fig. 2. The linewidth of the resonant dip at ~1550 nm is ~30 pm, which corresponds to a loaded quality factor of ~50,000. The free spectral range of the fundamental TE mode at ~1550 nm is ~3.39 nm. To further extract the optical information inside the ring resonator, we fit the experimental results using the transmission function of a resonator [26]:

\[
T(\lambda) = 1 - \frac{[1 - \exp(-\alpha L)][1 - t]}{1 - t \exp(-\alpha L)} + 4t \exp(-\alpha L) \sin^2\left(\frac{\pi n_g L}{\lambda}\right),
\]

where \(T(\lambda)\) is normalized transmittance at a given wavelength, \(\alpha\) is propagation loss inside the ring cavity, \(L\) is the circumference of the ring cavity, \(t\) is the transmission coefficient between the ring and bus waveguides, and \(n_g\) is the group index. The fitting curve shows good agreement with the experimental results, and the loss coefficient of the ring cavity is 0.5 cm\(^{-1}\). Such low propagation loss inside the ring cavity indicates the unloaded quality factor of ~1,82,000. It is a current record of the unloaded quality factor for the Ta2O5-based micro-ring resonator [14,27].

To demonstrate wavelength conversion in a Ta2O5-based micro-ring resonator, a two-beam excitation system shown in Fig. 3 is applied. The tunable laser amplified by an erbium-doped fiber amplifier is served as a pump beam, and the distributed-feedback laser diode with lower output power is regarded as a signal beam. The optical bandpass filters are utilized to eliminate amplified spontaneous emission so that the noise level can be decreased as low as ~75 dBm. The polarization of pump and signal beams is controlled as TE polarization, and the two beams are combined by using a 3 dB coupler. The optical beams are injected into devices by using lensed fiber with a mode diameter of 2 μm, and the output optical beams are analyzed by an optical spectrum analyzer. The wavelengths are precisely set as adjacent resonant wavelengths of the ring resonator so that the maximum FWM conversion can be realized in the Ta2O5-based micro-ring resonator.

The output optical spectrum of the Ta2O5-based micro-ring resonator under two beam injections is shown in Fig. 4. The wavelengths of the pump and signal beams are set as 1556.562 and 1560.002 nm, respectively. The pump/signal wavelengths are carefully aligned to the resonant wavelengths of the resonator, and the polarizations of the two beams is controlled as TE polarization. As shown in the optical spectrum, the FWM process-induced new optical wavelengths are observed at 1553.146 and 1563.456 nm. The wavelengths of

![Fig. 1.](image1.png)

![Fig. 2.](image2.png)
The conversion efficiency of the FWM process is defined by the power ratio of signal power to idler power. In the present case, the conversion efficiency of −30 dB is experimentally obtained in the resonator. The conversion efficiency (η) of the FWM process in the all-pass type ring resonator is described by [28]

$$\eta \equiv \frac{P^{\text{out}}}{P^{\text{in}}} = \left| \frac{2\pi n_2 P_p L_{\text{eff}}}{\lambda A_{\text{eff}}} \right|^2 F^4$$

$$F = \frac{\sigma}{1 - \tau \exp(-\alpha L/2 + j\Delta kL)}$$

$$L_{\text{eff}}^2 = L^2 \exp(-\alpha L) \left( 1 - \exp(-\alpha L + j\Delta kL) \right)^2,$$

(2)

where $n_2$ is the nonlinear refractive index of Ta$_2$O$_5$, $P_p$ is the coupled pump power in the bus waveguide, $\lambda_p$ is the pump wavelength, $A_{\text{eff}} \sim 0.92 \, \mu\text{m}^2$ is the effective area of the resonator, and $F$ is the buildup factor under the resonance condition. The buildup factor of the ring cavity represents optical power magnification at resonance in the ring resonator by comparing to that of in the bus waveguide [28]. The buildup factor is influenced by the propagation constant ($k$), the loss coefficient of the ring cavity ($\alpha$), and the coupling ($\sigma$) and transmission coefficient ($\tau$) of the directional coupler. In the present resonator, the buildup factor is as high as 50 at resonance. In addition, $L_{\text{eff}}$ is the effective propagation length for the ring resonator. $L_{\text{eff}}$ is influenced by the loss coefficient of the ring cavity, circumference, and linear phase mismatch of interacting four waves ($\Delta k = 2\Delta k - \Delta k$) [29]. For the present case, the linear phase mismatch is merely −0.0018 cm$^{-1}$ due to the small wavelength difference between the pump and signal, as well as the near zero dispersion designed waveguide structure. By using Eq. (2), the nonlinear refractive index of Ta$_2$O$_5$ can be estimated according to the experimental results. Figure 4(b) shows the estimated nonlinear refractive index of Ta$_2$O$_5$ with different coupled pump powers, and the nonlinear refractive index of Ta$_2$O$_5$ at ~1550 nm is estimated to be $1.4 \times 10^{-14}$ cm$^2$/W for the pump power below than 6 mW. The nonlinear refractive index of Ta$_2$O$_5$ is higher than other large bandgap materials (for instance, Si$_3$N$_4$, Hydex, ZnO, and AlN) [10,30,31], which indicates that Ta$_2$O$_5$ has great potential in developing nonlinear waveguide applications with low power consumption.

Figure 5(a) shows the power-dependent FWM process in Ta$_2$O$_5$ waveguides with and without a ring resonator. The two cases are the Ta$_2$O$_5$-based micro-ring resonator (red square) and the Ta$_2$O$_5$-based channel waveguide (blue triangle). For the resonator, the maximum conversion efficiency of −30 dB is achieved for the coupled pump power of merely 6 mW. In contrast, the maximum conversion efficiency of −49 dB is obtained for the channel waveguide case. In addition, the pump power as high as 40 mW is required, and the waveguide length should be as long as 12.6 mm. Based on Eq. (2), the simulated conversion efficiency of the Ta$_2$O$_5$-based micro-ring resonator with different coupling coefficients is shown in Fig. 5(b). The maximal conversion efficiency of −27 dB can be theoretically achieved with the critical coupling coefficient of ~0.1262. The experimentally obtained FWM conversion efficiency of −30 dB is close to the simulated maximal conversion efficiency, indicating that the fabrication of the directional coupler in the Ta$_2$O$_5$-based micro-ring resonator approaches to the optimized design.

In reviewing previous work on the degenerate FWM in the ring resonator with several thousands of quality factors among different optical materials [28,32,33], the present Ta$_2$O$_5$-based
micro-ring resonator shows great performance of FWM conversion efficiency and low operation power. In addition, Ta$_2$O$_5$ has no concern on TPA- and TPA-induced free-carrier absorption issues due to the large bandgap property. It implies that the higher FWM conversion efficiency can be further achieved by increasing the injecting power. Although the frequency comb generation has not yet been observed in the present resonator, Ta$_2$O$_5$ with superior optical nonlinearity among a lot of large bandgap materials is still worth utilizing to develop nonlinear waveguide applications. The loss coefficient in the present Ta$_2$O$_5$ ring cavity is still too high to accumulate optical power to demonstrate frequency comb generation. Therefore, the high-order FWM process is difficult to be observed. Based on the formula of threshold oscillation power [34], the threshold power of $\sim$153 mW is estimated for the present resonator. Nevertheless, once the fabrication process of the Ta$_2$O$_5$-based micro-ring resonator has been optimized by various aspects (E-beam lithography, reflow process, dry etching process, and annealing), the ultralow propagation loss of the Ta$_2$O$_5$-based ring resonator is expected to show outstanding performance on the optical parametric oscillation.

In conclusion, the Ta$_2$O$_5$-based micro-ring resonator with a record unloaded quality factor of $\sim$1, 82, 000 has been successfully fabricated. The high conversion efficiency of $\sim$30 dB is achieved in the resonator with pump power merely 6 mW. With the numerical simulation on FWM conversion efficiency in the Ta$_2$O$_5$-based ring resonator, the maximum conversion efficiency of $\sim$27 dB can be obtained in the present resonator with critical coupling condition, implying that the present devices have almost optimized coupling configuration. By comparing the conversion efficiency between the Ta$_2$O$_5$-based ring resonator and straight waveguide structure, the conversion efficiency of the ring resonator is higher than that of the straight waveguide with the magnitude of 50 dB under the same injection pump power. Our primary results on a FWM process in a Ta$_2$O$_5$ ring resonator indicate that Ta$_2$O$_5$ indeed has great potential in developing chip-scale optical parametric oscillators.

**Funding.** Ministry of Science and Technology, Taiwan (MOST) (MOST 104-2112-M-110-012-MY2, MOST 104-2811-M-110-017, MOST 105-2811-M-110-024, MOST 106-2112-M-110-006-MY3).

**REFERENCES**