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High-Q titanium dioxide micro-ring resonators for integrated nonlinear photonics

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Abstract: We report on the nonlinear characterizations of the titanium dioxide micro-ring resonators (TiO$_2$ MRRs). By utilizing optimized fabrication processes, high quality factors (Q ~ 1.4 x 10$^5$) doubling that of the previous work are achieved here for TiO$_2$ MRRs with high-confinement TiO$_2$ waveguides. The four-wave mixing (FWM) experiment results with low and high signal power demonstrate that, the fabricated TiO$_2$ MRRs can perform broadband (~40 nm) wavelength conversion and cascaded FWMs. These achievements pave the way for key nonlinear photonic applications with TiO$_2$ waveguides and provide an efficient platform for various integrated photonic devices.

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1. Introduction

Titanium dioxide (TiO$_2$) has been attracting increasing attention of the integrated photonics community and utilized for optical sensors [1], athermal photonic devices [2,3], visible photonics [4], meta-surfaces [5,6], and nonlinear photonics [7–10]. These applications are benefited by TiO$_2$'s ultra-broad transparency window from visible to mid-infrared wavelengths (from 0.4 to 10 µm), negative thermo-optic coefficient (TOC), relatively large linear and nonlinear indices ($n_0 = 2.31$, $n_2 = 2.3 \times 10^{-18}$ m$^2$/W [10]) as well as large bandgap (>3eV) [11–14]. For integrated nonlinear photonics, while silicon (Si) and silicon nitride (SiN) waveguides are the main workhorse, TiO$_2$ may be a promising alternative in the cases where the nonlinear effect is restrained by the nonlinear losses present in Si having a small bandgap (1.12 eV [15]) and the nonlinear energy efficiency is limited by SiN’s small linear and nonlinear indices ($n_0 = 2.0$, $n_2 = 2.5 \times 10^{-19}$ m$^2$/W [16]). Besides, the fabrication processes for TiO$_2$ waveguides are potentially compatible with the mature Si-based CMOS technologies, regarding that TiO$_2$ has been already intensively investigated in the integrated electronics (ICs) [17], which makes it stand out among many other emerging nonlinear photonics platforms like chalcogenide glasses [18] and gallium phosphide [19,20].

Indeed, various nonlinear optical effects including spectral broadening [7], third-harmonic generation [8], supercontinuum generation [9], and degenerated four-wave mixing (FWM) [10] have been recently demonstrated within TiO$_2$ waveguides, which illuminate the promising prospects of TiO$_2$ as an integrated photonics platform. However, to the best of our knowledge, the nonlinear characterizations of the TiO$_2$ micro-ring resonators (MRRs) are still absent, which are essential for many nonlinear applications [21–26]. Furthermore, most of the presented TiO$_2$ MRRs only provided relative low quality factors (Qs) around the wavelength of 1550 nm (e.g., 2 x 10$^4$ [27], 8.9 x 10$^4$ [28] and 7.4 x 10$^4$ [10]), which will limit the nonlinear enhancement in the resonator. Though the lift-off fabrication process can produce high-Q TiO$_2$ MRRs (2 x 10$^5$ [13], 1.55 x 10$^5$ [2]), unfortunately, it inherently limits the reachable thickness of the TiO$_2$ micro/nano-waveguide (e.g., 265 nm [13] or 60 nm [2]). We have also demonstrated high-Q...
TiO$_2$ MRRs (1.1 × 10$^5$) by using a bottom-up fabrication method [29]. However, the bottom-up method inevitably produces a big distance between the MRR and the bus waveguide as well as an inversely trapezoidal waveguide profile, which will pose additional complexity to the design of TiO$_2$ nonlinear devices and, what’s more, the TiO$_2$ thickness was also not very thick (250 nm) in that work. Actually, a TiO$_2$ waveguide with moderate thickness not only gives a weak confinement and thus weak nonlinear interaction, but also restrains the bandwidth of the nonlinear interactions and some key nonlinear effects like the frequency comb generation in which the low dispersion or anomalous dispersion is necessary.

In the work presented here, by utilizing an optimized fabrication flow, the TiO$_2$ MRRs with a thick TiO$_2$ waveguide (thickness of 360 nm) are fabricated and exhibit high intrinsic Qs up to ∼1.4 × 10$^5$, which is about double of our previous work [10]. The high Q yields a large power enhancement factor ($\mathcal{F}E^2$) of ∼15, meaning that the light field intensity and the nonlinear interactions can be greatly enhanced in the resonant cavity [21,30]. The FWM experiments with a low signal power or a high signal power are performed in the fabricated TiO$_2$ MRRs. With a pump power of 40 mW, the FWM with a conversion efficiency (CE) of −31 dB is achieved in the MRR having a perimeter of 0.857 mm, which is greatly enhanced compared to the 4-mm-long bus waveguide (−49.6 dB). Within the thick TiO$_2$ waveguide, the low dispersion also results in a broad FWM 3-dB bandwidth of ∼40 nm. Under strong signals, the cascaded FWMs can be observed and, what’s more, no degradation has been found during the characterizations even when the continuous-wave (CW) power go up to ∼2 W, which evidence the capability of handling high CW powers of our fabricated TiO$_2$ waveguides.

2. Fabrication and linear characterization of the TiO$_2$ MRRs

The TiO$_2$ MRRs have been fabricated in a 360-nm-thick amorphous TiO$_2$ film, which is deposited on a 2.2-μm-thick oxide layer on a silicon wafer by an ion-beam deposition method. Details of the deposition can be found in our previous work [10]. Waveguide patterns are firstly defined by electron beam lithography on the ZEP520A e-beam resist and then transferred to an 80-nm-thick chromium (Cr) layer by inductively coupled plasma (ICP) etching with the gas mixture of oxygen (O$_2$, 15 sccm) and chlorine (Cl$_2$, 65 sccm) with a platen power of 20 W. Then gas mixture of Cl$_2$ (30 sccm) and boron trichloride (BCl$_3$, 12 sccm) are used in the same ICP machine to etch the TiO$_2$ with Cr as the hard mask and a platen power of 100 W. After stripping the residual Cr, the TiO$_2$ waveguides are formed with air as the cladding. Note that Cr diffusion shouldn’t be an issue since the highest process temperature used in the fabrication flow is 110 °C for pre-baking ZEP520A resist for 5 min. Figures 1(a) and 1(b) show the scanning electron microscope (SEM) images of the fabricated TiO$_2$ racetrack MRR and the coupling region, respectively. The ring radius, distance from the MRR to the bus waveguide and the length of the straight coupling region are denoted as $R$, $g$, and $L$, respectively. The inset SEM image in Fig. 1(b) shows the close-up morphology of the TiO$_2$ waveguide sidewall, which, yet not perfectly smooth, exhibits a big improvement on the surface roughness compared with our previous work where fluorine-contained etchant gases were used [10]. Figure 1(c) shows the SEM image of the cross-section of the fabricated TiO$_2$ waveguide with a width of 1450 nm and one can see the waveguide sidewalls are almost vertical. The improvements of the etching may be ascribed to the chlorine-contained etchant gases used in the present optimized etching recipe which might introduce stronger chemical etching than the fluorine-contained etchant gases. However, this is only an assumption and needs to be further investigated. We have also calculated the mode profile of the fundamental transverse-electric (TE$_0$) mode as shown on the top of the SEM image in Fig. 1(c), from which we can see that light field is mostly confined in the TiO$_2$ core. Furthermore, the corresponding effective mode area $A_{\text{eff}}$ is calculated to be 0.58 μm$^2$ by using the commercial software MODE Solutions from Lumerical Inc.
Fig. 1. Characterization of a fabricated TiO$_2$ racetrack MRR. SEM images of the MRR (a), the coupling region (b) and the cross-section of the MRR waveguide with a width of 1450 nm and a height of 360 nm (c). Inset SEM image in (b) shows the close-up morphology of the waveguide sidewall. Shown on the top of the SEM image in (c) is the calculated mode profile of the TE$_0$ mode of the waveguide at the wavelength 1550 nm. (d) Measured and normalized transmission spectrum for the MRR with $R = 130 \ \mu$m, $L = 20 \ \mu$m and $g = 250$ nm. The MRR will be pumped at the marked resonance (red-circle) in the following weak-signal FWM experiments. (e) Measured spectrum and Lorentzian fitting around the resonant wavelength at 1548.019 nm. (f) Extracted $Q_{\text{int}}$ (red dot) and waveguide loss (light blue triangular) at each resonant wavelength. Dashed lines show the $Q_{\text{int}}$ value of $1.4 \times 10^5$ and the loss of 3.1 dB/cm.

Linear characterizations of the TiO$_2$ MRRs have been carried out by sweeping the laser (Ando AQ4321D) wavelength from 1480 nm to 1580 nm and recording the transmissions with an optical spectrum analyzer (OSA, Ando AQ6317B). Since the 1450-nm-wide waveguide can hardly confine the high-order modes, we hereinafter focus on the TE$_0$ mode. Figure 1(d) shows the measured normalized (to a straight waveguide) spectrum around 1550 nm of a TiO$_2$ MRR. The red circle indicates the resonance where the MRR will be pumped in the following weak-signal FWM experiments. The under-test MRR has a waveguide width of 1450 nm, $R = 130 \ \mu$m, $L = 20 \ \mu$m and $g = 250$ nm. Such a coupling region profile puts the MRR at over-coupling at the measured wavelengths. The free spectral range (FSR) is read out as 1.13 nm from the measured spectrum, from which one can extract the waveguide’s group index $n_g$ to be 2.48 which agrees well with the calculated value of 2.45.

By fitting the spectrum around the resonant wavelength at 1548.019 nm, with a Lorentzian curve as shown in Fig. 1(e), an intrinsic quality factor $Q_{\text{int}}$ of $\sim 1.4 \times 10^5$ and a corresponding waveguide loss ($\alpha$) of $\sim 3.1$ dB/cm (i.e., 0.71 cm$^{-1}$) are extracted by using $Q_{\text{int}} = 2Q_L/(1 + \sqrt{T_0})$ and $\alpha = 2\pi \cdot n_g/(Q_{\text{int}}\lambda_0)$ [23], where $Q_L$ is the loaded quality factor, $T_0$ is the transmission at the resonant wavelength $\lambda_0$. The distortion of the spectrum is due to the interference of the Fabry-Perot cavity formed between the two facets of the bus waveguide, which yet introduces little influence on the fitting accuracy since the MRR resonances possess large extinction ratios. The intrinsic $Q_{\text{int}}$ and linear loss at all resonances from 1480 nm to 1580 nm are also extracted as shown in Fig. 1(f). It is found that $Q_{\text{int}}$ distributes around the value of $\sim 1.4 \times 10^5$ and loss around 3.1 dB/cm in the investigated wavelength range, which is a significant improvement compared with our previous work ($Q_{\text{int}} \sim 0.74 \times 10^5$) [10], and stands in the highest level for the
high confinement TiO$_2$ MRRs up to now. The waveguide loss can be divided into the material loss and the confinement loss with the former one being $\sim 1.6$ dB/cm according to our previous work [29] and the latter one extracted to be $\sim 1.5$ dB/cm. Thus, in order to further increase the Q values, both the recipes for TiO$_2$ deposition and waveguide etching require further optimization.

3. FWM experiments with one FSR detuning

Four-wave mixing experiments have been carried out with the above characterized high-Q TiO$_2$ MRR and the setup is illustrated in Fig. 2. The signal light beam (hereinafter referred to as signal) and the pump light beam (hereinafter referred to as pump) are generated from two individual CW tunable lasers, amplified by EDFAs and adjusted by variable optical attenuators (VOAs). Then, the beams are filtered by band-pass filters to reduce the out-of-band amplified spontaneous emission (ASE) and improve the output spectral signal-to-noise ratio (SNR). After passing through fiber polarization controllers (PCs), the two beams are combined by a 10 dB coupler and then injected into the waveguides by the lensed fibers. A polarization beam splitter (PBS) is positioned before the input lensed fiber to make sure that both the signal and the pump are injected into the waveguide with TE polarization. The output beam is collected by another lensed fiber and measured by a power meter (PM) and an OSA.

![Fig. 2. Schematic of the experimental setup for FWM measurements.](image)

3.1. Weak-signal FWM scheme

The FWM experiments with the weak-signal scheme, i.e., a high-power pump and a low-power signal, are firstly carried out. The pump wavelength and the signal wavelength are finely tuned around the resonant wavelengths of 1548.019 nm and 1546.891 nm, respectively, and their separation corresponds to one FSR of the MRR. The coupled input signal power is fixed to $-4.6$ dBm during the measurements while the input pump power is varied.

Figure 3(a) shows the measured output spectra for the coupled input pump power (hereinafter referred to as the power in the bus waveguide) of 16 dBm when both the pump and the signal wavelengths are on resonance (red) or off resonance (blue). Here, a conversion efficiency (CE) of $-31$ dB is obtained when both the pump and the signal are on resonance, where the CE is defined as the ratio of the output idler power to the output signal power for the off-resonance case [31]. As a comparison, for the off-resonance case, the CE achieved in the straight bus waveguide which equals the length of the sample chip of $\sim 4$ mm is $-49.6$ dB. Thus, we can calculate the CE of a 0.857-mm-long waveguide (equivalent to the perimeter of the measured MRR waveguide) to be $-62$ dB with the same pump power of 16 dBm by considering $CE \propto L_{eff}^2$ and $L_{eff} = (1 - e^{-\alpha L})/\alpha$ [31], where $L$ is the waveguide length. It should be noted that the fibers before the waveguide also contribute to the FWM, though the contribution to the CE is 6-8 dB smaller than that of the waveguide according to Ref. [32]. Therefore, over 31 dB enhancement of the CE can be obtained by using the resonator. Basically, this enhancement is due to the elongated interaction of the two beams circulating in the ring resonator, which can be described by the power enhancement factor defined as [33,34]:

$$FE^2 = \frac{P_{\text{ring}}}{P_{\text{bus}}} = \frac{FSR}{\pi \cdot \Delta f_{\text{FWHM}}} \frac{2Q_t}{Q_c}.$$ (1)
Here, $FE$ is the field enhancement factor and $FE^2$ is the power enhancement factor defined by the ratio between the circulating power in the resonator ($P_{\text{circ}}$) and the power in the bus waveguide ($P_{\text{bus}}$). $\Delta f_{\text{FWHM}}$ and $Q_c$ are the MRR’s linewidth of the resonance and coupled quality factor, respectively. The power enhancement factor of the under-test MRR is calculated to be 15. As a comparison, if the previous fabrication flow which gave a waveguide loss of $\sim5.4\,\text{dB/cm}$ had been used [10], $FE^2$ for the TiO$_2$ MRR with the same structure would have been around 9.4 at the most when operating at the critical coupling condition. The CEs with respect to different coupled pump powers are also measured and shown with blue circles in Fig. 3(b). A slope of $\sim2$ of the linear fitting (red line) in Fig. 3(b) indicates the stable coupling between the bus waveguide and the resonator, and the negligible nonlinear loss of our fabricated TiO$_2$ MRR under different coupled pump powers.

![Fig. 3. FWM measurements with a weak signal. (a) Output spectra with both the signal and the pump wavelengths being on-resonance (red) and off-resonance (blue). (b) Wavelength conversion efficiency as a function of the pump power.](image)

### 3.2. Strong-signal FWM scheme

Although the resonator can greatly enhance the wavelength conversion efficiency, the power of the generated idler in the weak-signal FWM scheme is still quite low, i.e., $-38.6\,\text{dBm}$ in the bus waveguide, considering a power of $-44.6\,\text{dBm}$ read out from the OSA and 6 dB coupling loss between the waveguide and the lensed fiber, which will hinder such FWMs for practical applications. The coupling loss has been extracted by normalizing the transmission of the bus waveguide to that of the fiber-to-fiber and the propagation loss of the bus waveguide. In order to increase the idler power, and also to study more details of the nonlinear characterization of the MRR, strong-signal FWM scheme is demonstrated by increasing the signal power significantly to the pump power level.

Figure 4(a) shows the measured output spectra when the coupled signal and pump powers are both 14.6 dBm (red line) and both 16.6 dBm (blue line), respectively. Since the two coupled lights are in the same power level, hereinafter the signal and pump will be denoted as P1 and P2, respectively. Obviously, four idler wavelengths can be observed on both spectra, i.e., I1, I2, I3 and I4. For the case of 16.6-dBm pump powers (blue line), the powers of the first-order idlers I1 and I2 are as large as $-24.8\,\text{dBm}$ (i.e., $-18.8\,\text{dBm}$ in the bus waveguide) and $-22.8\,\text{dBm}$ (i.e., $-16.8\,\text{dBm}$ in the bus waveguide) respectively, which are around 20 dB larger than that of the weak-signal FWM. Furthermore, when such strong first-order idlers circulate in the MRR, they will interact with the other concomitant beams to generate second-order idlers (I3 and I4). At the same time, we can find that the idler powers will be remarkably raised nonlinearly with the increasing pump power.

According to Fig. 4(a), only 2-dB power increment of the two pumps P1 and P2 can lead to about 6-dB power increment of the first-order idlers and 10-dB power increment of the second-order idlers, which should be resulted from the cascaded FWMs driving by two or
more different pumps [35]. Here, the generation of the second-order idlers mimics the direct phase-matched fifth-order nonlinear process or 6-photon interaction process, i.e., the frequencies satisfy the relationship:

$$\omega_{I(4)} = 3\omega_{P(2)} - 2\omega_{P(1)}.$$  

which demonstrates that the power increment of the second-order idler $P_{I(4)}$ are threefold of the power increment of $P_{P(2)}$ plus twofold of the power increment of $P_{P(1)}$. The powers of the two first-order idlers as a function of the coupled pump powers are shown with the red dots for I1 and blue dots for I2 respectively in Fig. 4(b). Obviously, according to the linear fittings shown in Fig. 4(b), the slopes of $\sim 3$ agree quite well with the aforementioned theoretical expectations. Cascaded FWM processes of such are of great importance for various applications [16, 35] and the observation of them in the TiO$_2$ MRRs further unfolds the great potentials of the TiO$_2$ nonlinear waveguide platform.

### 4. Broadband FWM wavelength conversion in the TiO$_2$ MRR

Broadband FWM wavelength conversion is essential for many applications [36, 37]. Here, we first measure the FWM conversion bandwidth of the fabricated TiO$_2$ MRR with the weak-signal scheme. During the measurements, the pump wavelength is fixed at 1551.3 nm and the signal wavelength is swept from 1512.8 nm to 1550.3 nm with a step of one FSR, i.e., 1.13 nm. Meanwhile, the coupled powers of the signal and the pump are fixed at $-6$ dBm and 12 dBm, respectively. Figure 5(a) shows the measured CEs with respect to the signal wavelength detuning. With direct read-out single-side bandwidth of $\sim 20$ nm, we can extract a 3-dB conversion bandwidth up to $\sim 40$ nm, which is believed to be benefited from the relatively low dispersion as well as the high FWM efficiency of the waveguide.

We have also measured the dispersions ($D$) of the under-test TiO$_2$ MRR waveguide by using a similar setup in Ref. [38, 39], where a low-dispersion high-finesse free-space cavity performs as the reference to accurately determine the resonant wavelengths of the TiO$_2$ MRR. The simulated (solid lines) and the measured (red star) dispersions are shown in Fig. 5(b). The measured dispersion agrees well with the simulated results (green line) and is found to be very small, e.g., $\sim 183$ ps/nm/km at 1580 nm, which determines the broadband operation of our fabricated TiO$_2$ MRR. Simulations also unfold that, by increasing the waveguide height from 360 nm to 460 nm, anomalous dispersion can be realized in the 1450-nm-wide waveguide around 1550 nm, as shown by the purple line in Fig. 5(b). The thicker waveguide is expected to be demonstrated in the near future and foreseen to achieve even broader FWM conversion bandwidth.

To further demonstrate the broadband capability of the TiO$_2$ MRRs, FWM measurements with the strong-signal scheme are then done under different wavelength detuning of the two pumps. Figures 6(a) and 6(b) show the measured output spectra when the wavelength detuning is 21 nm.
and 12 nm, respectively, while the coupled pump powers are kept at around 15 dBm. The idler powers vary 3 dB at most when the two pump wavelengths are detuned from 12 nm (−34.10 dBm @1526.853 nm and −34.13 dBm @1563.893 nm) to 21 nm (−34.20 dBm @1509.517 nm and −37.04 dBm @1573.156 nm), clearly exhibiting the broadband characteristics of our fabricated TiO$_2$ MRR. By increasing the two pump powers to 18 dBm for the 12 nm detuning, higher-order idlers can also be clearly observed as shown in Fig. 6(c). Based on these results, we can foresee that, if more pump powers could be coupled into the MRR by overcoming the limited bandwidth of the EDFAs, the higher-order idlers are still possibly generated even under a very large wavelength detuning, e.g., larger than 21 nm, which will expand the bandwidth of the idler channels. Meanwhile, during the measurements, no degradation of the fabricated TiO$_2$ MRR has been found even when two 18-dBm pumps are applied and the corresponding total circulating power in the cavity is ∼2 W, which suggests that our fabricated TiO$_2$ MRRs can maintain high stability for high powers.

5. Conclusion

In summary, we have demonstrated the TiO$_2$ MRRs with high Qs (∼1.4 × 10$^5$) on highly confined TiO$_2$ waveguide platform by using optimized nano-fabrication processes to produce smoother and vertical waveguide sidewalls. The four-wave mixing measurements of the resonators have been performed with weak and strong signal powers respectively. An enhancement (31 dB) of the FWM conversion efficiency can be achieved with a power enhancement factor of 15. The idlers with high powers can be produced and, consequently, more new wavelengths are generated from
the cascaded FWMs when double high-power pumps are applied. The dispersion of the proposed TiO$_2$ waveguides can be precisely engineered and here the waveguide with a small dispersion is exemplified to exhibit the broadband wavelength conversion capability, i.e., ~40 nm of the 3-dB bandwidth. These achievements strongly support TiO$_2$ MRRs as an efficient platform for nonlinear photonic applications and suggest that the TiO$_2$ MRRs are very promising to achieve high-end nonlinear devices like the frequency comb generators.

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**Disclosures**

The authors declare no conflicts of interest.

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