Polycrystalline Anatase Micro-Ring Resonators at Telecommunication Wavelengths

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Abstract: We fabricate and characterize integrated polycrystalline anatase TiO_2 micro-ring resonators at around λ = 1550 nm. We obtain quality factors of 1.5×10^4 and calculate a propagation loss of 8.0 ± 1.3 dB/cm.
OCIS codes: 130.0130,130.3130

1. Introduction

Titanium dioxide (TiO_2) is a new, promising material for integrated photonics[1–4]. Its large transparency (for λ >400 nm), matched with a relatively large linear refractive (n_0 = 2.4–2.7) and nonlinear Kerr index ($n_2 = 1.6\times10^{-14}$ cm^2/W), make it ideal for applications in nonlinear optics. Recently, waveguides comprised of the anatase phase of TiO_2 have been used to demonstrated spectral broadening and third harmonic generation[5, 6].

Nonlinear processes, such as second and third harmonic generation, can be enhanced using resonant cavities [7]. Micro-ring resonators have solely been demonstrated in amorphous TiO_2, which has yet to reveal nonlinear properties [1]. Additionally, there has been no accurate measurement of the propagation loss of optical waveguides fabricated of polycrystalline anatase in the telecom wavelengths, and these resonators can be used to extract these factors [1, 8]. In this study we demonstrate integrated micro-ring resonators made of anatase TiO_2 and use them to accurately measure the propagation loss of this material in the telecommunication band.

2. Experimental

The fabrication procedure follows previously reported methods [2]. A thin film is first deposited by radio frequency magnetron sputtering of a titanium target in a 2:1 argon:oxygen environment. The chamber pressure and temperature are held at 2 mT and 625 K, respectively. The RF power is set to 200 W and the complete deposition takes 1390 minutes, yielding a 250-nm thick anatase thin film on an oxidized silicon wafer.

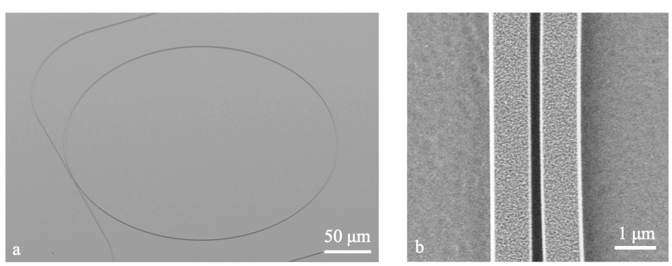

Fig. 1: (a) Scanning electron micrograph of a polycrystalline anatase micro-ring resonator. (b) Close-up image of the coupling region, showing a waveguide width of 900 nm, a 300 nm gap, and the polycrystalline waveguide surface.

We structure waveguides using conventional lithography and lift-off techniques: a 300-nm thick positive tone electron-beam (e-beam) resist layer (ZEP-520a) is spin-coated and the patterns are written using e-beam lithography. A 50-nm thick chromium layer is then deposited using e-beam evaporation and is subsequently lifted off using ultra-sonication, forming a metal etch-mask. This pattern is then transferred onto the thin film using reactive ion etching in a 4:1 CF_4:H_2 environment, after which the chromium mask is finally removed using a Cr-etchant. Lastly, the sample is spin-coated with a 1.6-μm thick protective transparent fluoropolymer (CYTOP). The ends are cleaved to produce input facets. The resulting structures that compose the device are 900nm-wide waveguides with a 75 degree sidewall angle. The resonator has a ring radius of 150 μm and a gap of 300 nm (**Fig. 1**).

We couple into the input waveguide using tapered lensed fibers with a spot size of 1.7 μm. Using a tunable laser source with an input power of 3.2mW, we sweep from 1525 nm to 1575 nm with a resolution of 0.05 nm. The output spectrum is measured using an optical spectrum analyzer.

3. Results and Discussion

We show the resulting output spectrum in Figure 2. We observe dips at equally spaced resonance frequencies corresponding to whispering gallery modes of the resonator with a free spectral range of 1.4 nm and quality factors as high as 1.5×10^4. We can extract propagation losses by fitting to the transmission spectrum of a ring resonator [8]:

$$T = \frac{t^2 + \alpha^2 - 2\alpha t\cos(\phi)}{t^2 + \alpha^2 + 2\alpha t\cos(\phi)} \quad (1)$$

where T is transmission spectrum, t and α are the coupling coefficients and total loss coefficient of the resonator, respectively, and ϕ is the propagation phase. We obtain a propagation loss of 8.0 dB/cm. We have carefully selected a ring with a bend radius large enough to neglect bend losses. Thus, any losses in the system should be entirely due to propagation losses caused by surface and volumetric scattering and material absorption due to defects.

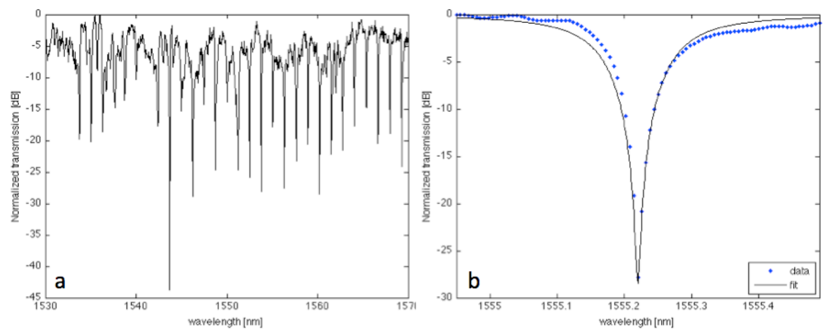

Fig 2: (a) Output spectrum of the fabricated device, displaying characteristic resonance dips with a free spectral range of 1.4 nm. (b) Close-up image of a dip at around λ = 1555 nm and a fit to Equation 1.

Extracted values of t and α cannot be differentiated in Equation 1 due to their symmetry. However, we find that by interchanging α and t we obtain a propagation loss of 26.7 dB/cm. Given a total transmission loss of 19 dB off-resonance, this necessitates an unphysical insertion gain and allows us to differentiate t and α.

A slight asymmetry can be seen in the resonances, as shown in Figure 2b. We believe it is either due to partially reflecting elements in the waveguide or to facet defects caused by an imperfect cleave, leading to the propagation of both polarizations. By fitting to either side of the resonance individually and assuming a symmetric plane at the center, we obtain losses of 5.9 dB/cm for the left-hand side of the dip and 10.3 dB/cm for the right-hand side. These values suggest a standard error of 1.3 dB/cm. A propagation loss of 8.0 ± 1.3 dB/cm is comparable to measurements of polycrystalline silicon [9] and suggests that improvements can be made with the help of surface passivation.

In conclusion, we have presented the fabrication and characterization of micro-ring resonators comprised of polycrystalline anatase. We observe a quality factor of 1.5×10^4 and a propagation loss of 8.0 ± 1.3 dB/cm. These values are encouraging for further studies in integrated nonlinear optics with anatase TiO_2.

4. References

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