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Propagation Loss Measurements in Sputter Coated Titanium Oxide waveguides

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ABSTRACT

The accurate analysis of propagation losses is key as optimization tool for the development of new integrated optical waveguides. Channel waveguide propagation losses can be determined by studying the resonances of microring resonators. In this work, we study the propagation losses of TiO_2 channel waveguide by analyzing the transmission of microring resonators in the wavelength range from 1460 to 1640 nm. Propagation losses as low as 1.0 dB/cm at 1550 nm of wavelength have been experimentally demonstrated.

Keywords: Titanium Dioxide, Sputtering, Low Loss, Coupling, Simulation

1. INTRODUCTION

TiO_2 is a promising material for optical devices due to the high refractive index at low frequencies of light for linear and non-linear optics [1], its negative dn/dT coefficient and the high transparency window from the visible to mid-infrared wavelengths. Compared to other optical materials, the low transition temperature to the crystalline phase, anatase, and the high propagation loss hinders the exploitation of its full potential in integrated photonics. The sputtering deposition process has been optimized to achieve layers with minimal slab losses (<0.1 dB/cm at 978 nm). By analyzing the resonances of microring resonators fabricated on this slab, channel propagation losses can be obtained. In this work, the details of this analysis will be discussed.

2. EXPERIMENTAL PROCEDURE

When using microring resonators to characterize the losses of optical channel waveguides, a loaded Q value can be extracted from the fit of the resonance dips, as $Q = \frac{\lambda}{FWHM}$, where λ is the center wavelength of the dip and $FWHM$ is its full width at half maximum, both extracted from a Lorentian fit to the resonance dip. The loaded Q can be expressed as $\frac{1}{Q} = \frac{1}{Q_{ext}} + \frac{1}{Q_{int}}$, where Q_{ext} is the external quality factor of the resonator, which is related to the losses due to the outcoupling of power from the ring to the bus waveguide and Q_{int} is the intrinsic quality factor, mainly affected by the propagation losses inside the microring [2]. The propagation losses can be extracted from the Q_{int} as $\alpha = \frac{\lambda \cdot Q_{int}}{FSR \cdot R}$, where λ is the resonance dip center wavelength, Q_{int} is the intrinsic Q factor, FSR is the freee spectral range and R is the radius of the ring. The propagation loss, α, is given in cm^{-1}. The internal quality factor can be calculated as $Q_{int} = \frac{Q}{2 \cdot (1 \pm \sqrt{\frac{1}{ER}})}$, with ER the extinction ratio of the ring. It is important to note the ± sign in the denominator. A positive sign is used if the ring is undercoupled (i.e., the transmission coefficient of the coupler, t, is larger than the round-trip transmission loss of the ring, a) while a negative sign is used if the ring is overcoupled (i.e., a>t). From the measurements, two Q factors can be extracted, one of them being the external and the other the internal one, the values of which are exactly exchanged depending on whether a + or a – is used in the equation of Q_{int}. In order to differentiate them, it is necessary to know whether a ring is under or over coupled. Only then it is possible to extract the propagation

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losses from the resonance spectrum. Ideally, a series of rings with the same waveguide cross-section, same radii and varying coupling gaps should be analyzed. By extracting the two quality factors and plotting them as a function of coupling gap, the Q_{int} should not vary while the Q_{ext} should increase as the coupling gap increases. The ring is critically coupled when $Q_{ext} = Q_{int}$.

If only one ring is available for the analysis, a scan over the wavelength range will help evaluating whether the ring is over or under coupled. As the wavelength increases, the coupling from the bus waveguide into the ring increases (i.e., t decreases). Since the extinction ratio increases as the ring approaches critical coupling, a decreasing ER with wavelength indicates undercoupling while an increase of ER towards longer wavelengths indicates overcoupling.

Careful analysis of the transmission spectrum [2] of a microring can also help determining whether the ring is over or undercoupled. The transmission spectrum is given by:

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

Where a and t are the round-trip transmission losses of the ring and the transmission through the coupler, as discussed above, and ϕ is the phase accumulated by the light in a round trip around the ring. As it can be seen in equation 1, a and t are interchangeable. However, if knowing the value of t, it can be seen from Figure 1 that for t>a (i.e., undercoupled ring), the resonance dips have a wider shape than in the range for which t<a (i.e., overcoupled ring).

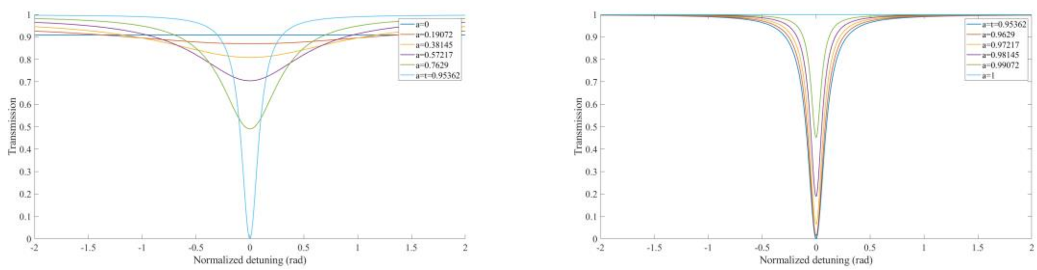

Figure 1. (left) Under-coupled transmission spectrum vs. normalized detuning in radians for different "a" values. (right) Over-coupled transmission spectrum vs. normalized detuning in radians for different "a" values. A value of t=0.95362 was used in these simulations.

The cross-coupling coefficient of the ring and, therefore, the external Q factor, can be calculated using the following equation [2]:

$$Q_{ext} = \frac{2\pi R n_g}{\lambda \kappa^2} \quad (2)$$

Where R is the radius of the microring resonator, n_g is the group refractive index, λ the wavelength of the resonance dip, and κ is the coupling coefficient. The coupling coefficient, κ, can be calculated by following the methodology described in [3]. By comparing the calculated Q_{ext} with the measured values it is possible to differentiate between the two measured Q factors, determine Q_{int} and extract the propagation losses as described above.

3. FABRICATION PROCESS

TiO_2 layers are deposited on 100 mm silicon wafers with 8 mm of thermal oxide by reactive DC magnetron sputtering with a 4-inch titanium target. The deposition process was optimized as discussed in [4]. In the final process, 97.5% of relative discharge voltage, 500 W of power in the Ti target, 80 cm3/min of Ar, 9.0-9.7 cm^3/min of O_2 with a base pressure of 1.0E-6 mbar, process pressure of 6.0E-3 mbar, and chuck rotation of 5 rpm, lead to the films with lowest propagation losses. The substrates were kept at room temperature during the deposition. The thickness of the deposited layer was 200 nm. The Cauchy parameters, A and B, as measured by ellipsometry, were 2.288 and 0.00266, respectively. Microring resonator devices with gaps varying between 300 nm and 700 nm and channel waveguides of width 1.8 μm were patterned by electron-beam lithography and reactive ion etching. A 1 μm thick cladding of PMMA was then deposited over the singulated chips for characterization.

4. CHARACTERIZATION

An Agilent 8164B light measurement system was used for the characterization of the samples, with the additional PM500 set-up for accurate positioning. Light was coupled to the waveguides by using polarization maintaining fibers optimized for 1550 nm wavelength. The laser input fiber was set on the TM polarization mode. Figure 2. shows a photo of the setup.

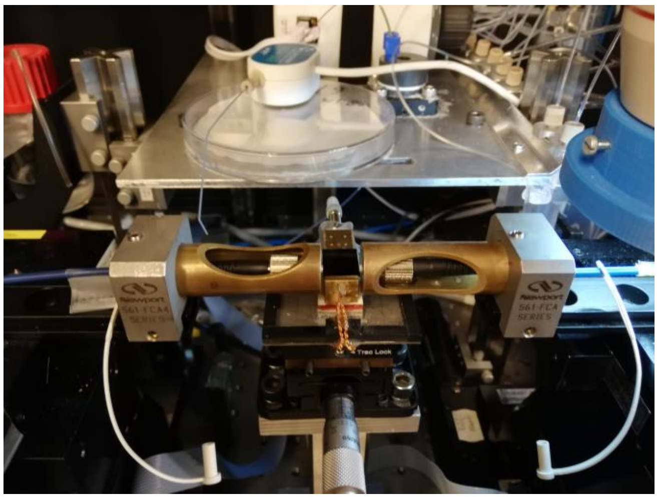

Figure 2. Set-up used for the characterization of the samples.

To improve fiber to chip coupling, index matching gel was applied between the fiber and the chip. The wavelength was scanned 1460 to 1640 nm wavelength with a step size of 1 pm and a speed of 5 to 10 nm/s. For this study, a low laser input power of 3 mW was utilized.

5. RESULTS

Table 1 shows the measured values for the two Q factors of the rings, Q_1 and Q_2. As discussed above, following the methodology described in [3] the expected Q_{ext} was calculated for the given geometry, TM polarization and at a wavelength of 1550 nm. Comparing the calculated Q_{ext} with the measurements, it is possible to assign Q_1 as the external Q factor and Q_2 as the internal Q factor. All the rings in this experiment are overcoupled, approaching critical coupling as the gap increases. From the measured values of Qint, propagation losses from 1-1.5 dB/cm were measured in the waveguide.

Table 1. Variation of the external quality factor from the simulated structure and the measured sample over different gap distances.

Gap (nm)	Q_{ext}(TM) Simulated	Q_1(TM) Measured	Q_2(TM) Measured
700	1.235E5	8.9E4	2.3E5
600	6.757E4	5.6E4	2.0E5
500	3.787E4	4.6E4	1.2E5
400	2.2E4	2.8E4	2.8E5
300	1.4E4	2E4	2.2E5

6. CONCLUSION

Optical propagation losses were measured in TiO_2 waveguides by analyzing the resonance spectrum of microring resonators. The rings in this study were all overcoupled approaching critical coupling for coupling gaps approaching 700 nm. The proposed methodology, combining simulations of the external Q factors of the rings to distinguish between the two measured Q factors appears robust and permits determining the propagation losses of the waveguides from the intrinsic Q factor. In this work, propagation losses in the range 1-1.5 dB/cm were measured from the different waveguides.

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