Lasing in a Neodymium-doped Aluminium Oxide Taiji Resonator

Student paper

Dahnée Wojcik*, Bjorn Jongebloed, Carlos Osornio-Martínez, Sonia M. García-Blanco

Integrated Optical Systems, MESA+ Institute for Nanotechnology, University of Twente, 7500 AE Enschede, The Netherlands.
* d.j.m.wojcik@student.utwente.nl

In many applications in integrated optics, high output power and mode stability are required for an on-chip laser. This could be achieved by using unidirectional lasing. However, on-chip lasers with a microring cavity are either not stable or prone to spontaneous switching. In this contribution, a low-cost design for stable unidirectional lasing is proposed: a Nd^{3+}-doped Al_2O_3 Taiji resonator. Moreover, lasing is experimentally shown.
Keywords: *Laser, Taiji resonator, neodymium, Aluminium Oxide*

INTRODUCTION

Unidirectional lasing leads to higher output power, increased mode stability and a single frequency spectrum [1] in comparison with a simple microring resonator (MRR) laser. Moreover, it obviously has the advantage of one stable direction of laser light. These advantages are necessities for many applications in integrated optics, like for instance optical isolators based on four-wave mixing [2], coherent (on-chip) communication and sensing [3].

It has been attempted to create unidirectional lasers with simple MRRs. However, these MRR lasers have stability issues and are prone to spontaneous switching between clockwise and counterclockwise modes, due to backscattering effects. Stable unidirectional lasing has been shown in photonic integrated circuits (PICs), by using an MRR with an S-shaped bus waveguide in its cavity connected with a Y-junction to the ring [4]–[6]. The designs were, however, electrically pumped and had to be either pumped with a relative high current or were very sensitive to the pump current. Furthermore, unidirectional lasing can be achieved by breaking chiral symmetry in the context of sensing [7].

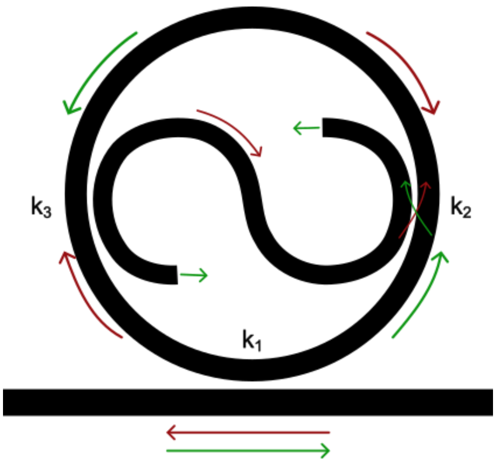

Fig. 1. The design for the Taiji resonator. The clockwise (CW) mode is indicated with red and the counterclockwise (CCW) mode with green. The ends of the S-waveguide are tapered with a skewed end facet.

In this work, a Taiji resonator (TJR) is studied. While the TJR is interesting for sensing applications, due to its predicted exceptional point sensitivity [8], when the waveguide material is doped with rare-earth ions, the TJR also allows for unidirectional lasing [1]. The TJR is formed by embedding an S-shaped waveguide inside the cavity of an MRR. In that regard, it is a simple device structure. Fig. 1 shows the schematic design of the TJR. Here, the clockwise (CW) mode can couple to the counterclockwise (CCW) mode, but not the other way around. This leads to a preferred mode with a lower laser threshold.

A theoretical investigation has been done, which states that stable unidirectional lasing occurs for a certain coupling to the S-waveguide [1]. There should be enough coupling compared to the inherent loss in the ring to create enough back-reflection. This creates a non-chirality with a preferred lasing mode. However, coupling of the CW mode to the CCW mode will also lead to a loss of the CCW, such that the laser threshold can become too high.

Neodymium has a broad emission cross-section at 1064 nm wavelength when pumped at 800 nm. Moreover, it has no reabsorption, and it constitutes a four-level system gain medium [9]. Since light with a 1064 nm wavelength is not absorbed by water, a 1064 nm laser in integrated optics is relevant. Therefore, there are various biological imaging applications, applications for sensing and for fluid dynamic visualisation [10].

Aluminium oxide is the base core material. It has a very wide transparency window (from UV to IR), which makes it interesting in many integrated optic applications. Furthermore, Al_2O_3 has a high solubility for rare-earth ions and it has a high refractive index, which leads to more compact designs in PICs.

METHODS

We deposit a Nd^{3+}:Al_2O_3 layer on a silicon wafer covered by an 8 µm thick thermal oxide layer, with RF reactive co-sputtering (AJA ATC 1500) from metallic targets in oxygen atmosphere. The oxygen flow was kept constant. The power on the neodymium target was 14 W. In this way, a Nd^{3+}:Al_2O_3 layer with a thickness of 390 nm is deposited. The Nd^{3+}:Al_2O_3 is covered with a negative resist (ARN7520.18) and conductive coating (AR-PC 5090.02) by spin-coating, after which the resist is patterned with E-beam lithography (RAITH EBPG5150). After development, the Nd^{3+}:Al_2O_3 is etched using reactive ion etching (Oxford PlasmaPro 100 Cobra). Then, residual photoresist is removed and a SiO_2 cladding is deposited (Oxford PECVD 80).

The lasing spectra of the TJR is measured. The setup depicted in Fig. 2 allows for pumping the TJR and observing the lasing modes. The pump laser is a Ti:Sapphire laser, that can be tuned to emit light at 800 nm. This is a suitable wavelength to excite the gain medium. An optical spectrum analyser (Hewlett Packard 70950B) is used as spectrometer to measure the light emitted by the TJR laser with a resolution of 0.1 nm. The CW lasing mode is observed by optically pumping the TJR from the right (as indicated in Fig. 1), while the CCW mode is observed when the TJR is pumped from the left. The pump light is butt-coupled with a polarization-maintaining (PM) fibre into our waveguides.

To promote stable lasing, the chip will be placed on a temperature-controlled stage. By keeping the temperature constant, the resonance wavelengths of the TJR are more constant. The stable resonance wavelengths, then, support in stable lasing.

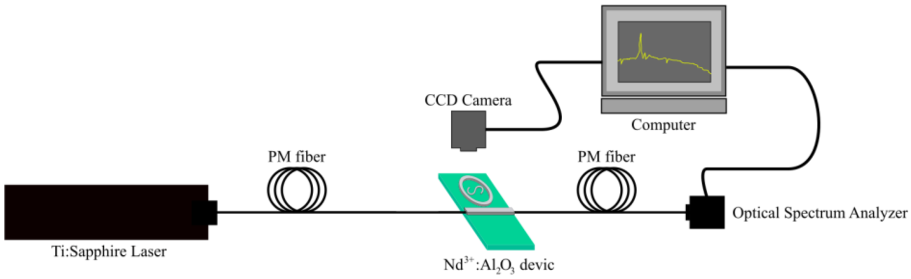

Fig. 2. Schematic overview of the set-up for measuring the transmission spectrum of a resonator in a PIC.

RESULTS

The lasing spectra from the CW mode and CCW mode of the TJR is shown in Fig. 3, for an incident pump power of approximately 25.3 mW. The TJR shows multimode lasing near 1076 nm which corresponds to the emission peak of Nd^{3+} that is centred around 1064 nm. In Fig. 3c, a black-and-white picture can be seen of the TJR, during the experiment. The white pixels indicate the signal wavelength.

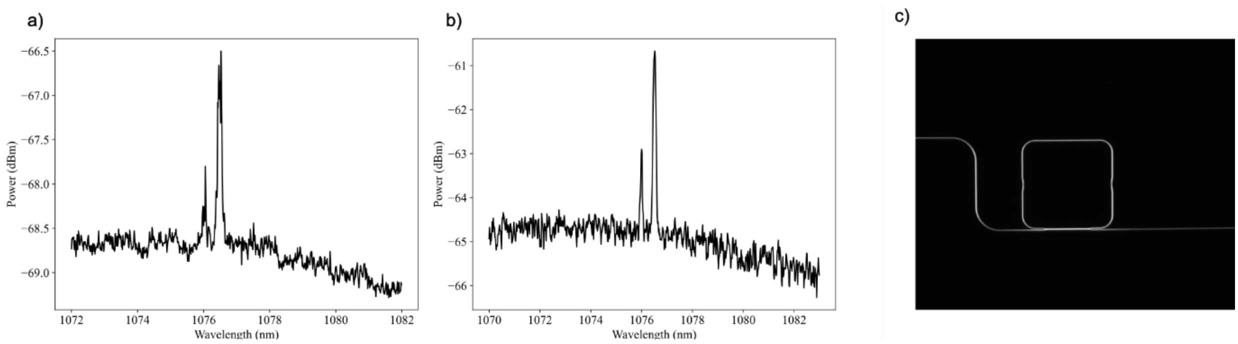

Fig. 3. The laser spectra of the CW mode (a) and the CCW mode (b) of the TJR near the 1064 nm gain peak. A black-white picture was made (c) while the Taiji was pumped from the left. The white pixels indicate scattered light of the signal intensity. The pump wavelength is filtered by cut-on filters from 900 nm, 850 nm and 800 nm.

The power of the lasing peak as seen in Fig. 3, was measured for multiple pump powers for both the CW and CCW modes. The resulting measurements and linear fit can be seen in Fig. 4. It should be noted that the slope efficiency of the CW mode is an order of magnitude higher than the slope efficiency of the CCW mode.

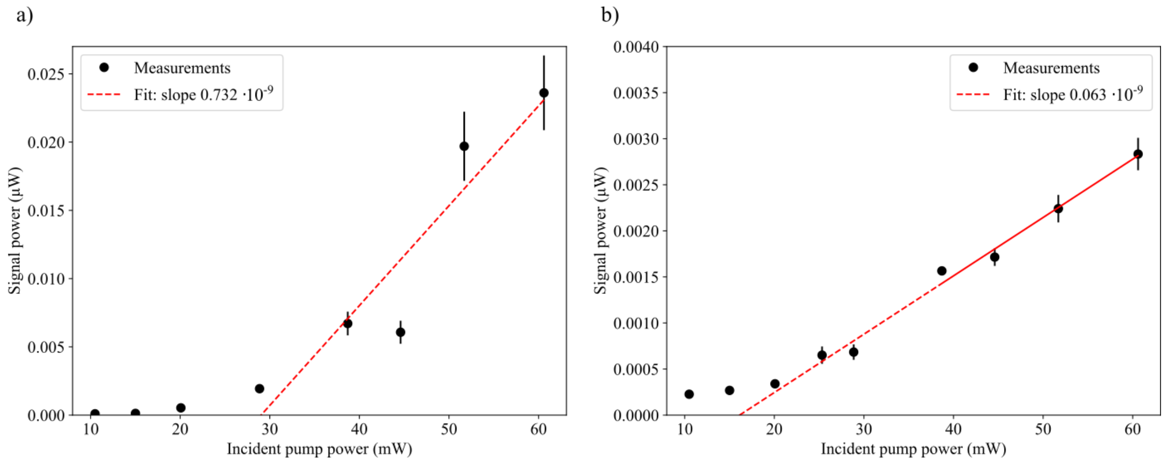

Fig. 4. The signal power measured for different incident pump powers, when the TJR was pumped from the right (a) and from the left (b), measuring the CW mode and CCW mode, respectively.

DISCUSSION AND CONCLUSION

The multimode lasing is mainly due to the combination of a small free spectral range (FSR) and a high pump power. In future design iterations, the FSR can be increased by reducing the circumference of the ring.

The slope efficiency of the CW mode is an order of magnitude larger than the CCW mode slope efficiency, as can be seen in Fig. 4. This indicates a weak directional-dependent emission. However, the CCW mode is expected to be the preferred lasing mode. The difference is therefore attributed to more scatter points in the bus waveguide to the right.

The observation of lasing modes in a Nd^{3+}: Al_2O_3 TJR is a promising result in the search for on-chip unidirectional lasing. To show that the TJR clearly exhibits unidirectional lasing, more investigation is necessary. The first step is to increase the coupling from the laser cavity to the S-waveguide. More coupling from the ring to the S-waveguide should increase the non-chirality of the TJR and, therefore, the TJR prefers one mode more strongly above the other.

References

[1] A. Muñoz de las Heras and I. Carusotto, “Unidirectional lasing in nonlinear Taiji microring resonators,” Phys Rev A (Coll Park), vol. 104, no. 4, p. 043501, Oct. 2021, doi: https://doi.org/10.1103/PhysRevA.104.043501.

[2] A. Muñoz de las Heras and I. Carusotto, “Optical isolators based on nonreciprocal four-wave mixing,” Phys Rev A (Coll Park), vol. 106, no. 6, p. 063523, Dec. 2022, doi: 10.1103/PhysRevA.106.063523.

[3] J. Lin et al., “Electro-optic tuning of a single-frequency ultranarrow linewidth microdisk laser,” Advanced Photonics, vol. 4, no. 3, May 2022, doi: 10.1117/1.AP.4.3.036001.

[4] J. P. Hohimer, G. A. Vawter, and D. C. Craft, “Unidirectional operation in a semiconductor ring diode laser,” Appl. Phys. Lett, vol. 62, p. 1185, 1993, doi: 10.1063/1.108728.

[5] J. P. Hohimer and G. A. Vawter, “Unidirectional semiconductor ring lasers with racetrack cavities,” Appl. Phys. Lett, vol. 63, p. 2459, 1993, doi: 10.1063/1.110474.

[6] W. D. Sacher, M. L. Davenport, M. J. R Heck, J. C. Mikkelsen, J. K. S Poon, and J. E. Bowers, “Unidirectional hybrid silicon ring laserwith an intracavity S-bend,” Laser Photon. Rev, vol. 6, pp. 511–517, 2012, doi: 10.1364/OE.23.026369.

[7] B. Peng et al., “Chiral modes and directional lasing at exceptional points,” Proc Natl Acad Sci U S A, vol. 113, no. 25, pp. 6845–6850, Jun. 2016, doi: 10.1073/PNAS.1603318113/SUPPL_FILE/PNAS.1603318113.SAPP.PDF.

[8] R. Franchi, S. Biasi, F. Mione, and L. Pavesi, “On the response of the Taiji microresonator against small perturbation of the counter propagating mode,” p. 13, Mar. 2022, doi: 10.1117/12.2608157.

[9] J. Yang, “Neodymium-doped Waveguide Amplifiers and Lasers for Integrated Optical Applications,” University of Twente, Enschede, 2010.

[10] G. N. Palafox, R. B. Wicker, and C. J. Elkins, “Rapid In-Vitro Physiologic Flow Experimentation Using Rapid Prototyping And Particle Image Velocimetry,” 2003, pp. 0419–0420. Accessed: Feb. 03, 2023. [Online]. Available: https://www2.tulane.edu/~sbc2003/pdfdocs/0419.PDF