Non-evanescently pumped Raman silicon lasers using spiral-shaped microdisks

Hui Chen, Jonathan Y. Lee, and Andrew W. Poon

Photonic Device Laboratory, Department of Electronic and Computer Engineering
The Hong Kong University of Science and Technology, Kowloon, Hong Kong SAR, China
Tel: (852)-2358-7905; Fax: (852)-2358-1485; Email: eeawpoon@ust.hk

H. K. Tsang

Department of Electronic Engineering, The Chinese University of Hong Kong,
Shatin, N.T., Hong Kong SAR, China
Tel: (852)-2609-8254; Email: hktsgang@ee.cuhk.edu.hk

Abstract: We propose non-evanescently pumped Raman silicon lasers using spiral-shaped microdisks. Our simulations suggest that pump lightwave can be seamlessly butt-coupled at the spiral notch, whereas the Stokes lightwave can be out-coupled either evanescently or non-evanescently.

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Unidirectional lasing from spiral-shaped microdisks has been demonstrated by optical pumping [1] and electrical injection [2] from the microdisk top surfaces. The unidirectional lasing from the spiral notch can be seamlessly butt-coupled to a waveguide [3], which is then favorable for potential integrated light source applications in high-density-integrated photonic circuits. Most recently, some of us proposed and demonstrated spiral-shaped microdisk filters using the spiral-notch coupled waveguide for non-evanescent input- and output-coupling [4]. The implication is that spiral microdisk is a promising, albeit alternative, monolithic integrated microresonator which can be non-evanescently coupled, thus signaling a paradigm shift from the conventional evanescently coupled microresonators that impose critical coupling [5]. In this summary, we propose a spiral-shaped microdisk Raman silicon laser that can be non-evanescently pumped through the spiral notch from a seamlessly butt-coupled waveguide. We also highlight possible asymmetry between the Stokes clockwise (CW) and counterclockwise (CCW) traveling modes that can result in unidirectional Raman lasing.

Fig. 1(a) shows the schematic of a spiral-shaped microdisk that is butt-coupled with a waveguide at the spiral notch for optical pumping, and is evanescent-coupled with another lateral waveguide for out-coupling. The gray region shows the spiral shape cross-section given by \( r(\phi) = r_0(1 - \varepsilon \phi / 2\pi) \) [1], where \( r_0 \) is the spiral radius at azimuthally angular position \( \phi = 0 \), and \( \varepsilon \) is the so-called deformation parameter. Optical pumping is expected to be efficient in case the notch waveguide is nearly impedance matched with the spiral microdisk [6]. It is desirable to align both the pump wavelength and the Raman Stokes wavelength to different spiral microdisk resonances. Note that the notch-coupled waveguide and the side-coupled waveguide can have different widths for pumping and Stokes output coupling optimization [4].

Fig. 1 (a) Schematic of the proposed non-evanescently pumped Raman silicon laser using a spiral-shaped microdisk. Pump (CCW): blue arrow; Stokes (CCW): red arrow; Stokes (CW): green dashed arrow. (b) – (d) FDTD-simulated time-average TE-polarized intensity pattern for (b) pump CCW at 1419.9 nm, (c) Stokes CCW resonance at 1533.1 nm, and (d) Stokes CW resonance at 1533.1 nm. The Stokes lightwave in the passive cavity simulation is launched from the side-coupled waveguide. \( r_0 = 10 \mu m, \varepsilon = 0.04 \).
In contrast to conventional symmetric resonators, CW and CCW traveling modes in spiral microdisks can be uniquely different both in terms of Q and resonance field patterns [1-4]. It is generally believed that the CW traveling modes as depicted here support a lower Q than the CCW traveling modes (as the CW traveling modes tend to preferentially escape through the spiral notch). Should CW and CCW traveling modes display different cavity losses, it is conceivable that the CW and CCW traveling modes then exhibit different lasing thresholds [1-2]. The implication is that the hypothetical higher-Q CCW traveling modes are likely to first lase (assuming CCW and CW traveling modes see largely the same cavity gain) and deplete the gain, enabling possible unidirectional Raman lasing emission in the evanescently coupled waveguide. In contrast, a critically-coupled symmetric microring resonator Raman silicon laser gives evanescently coupled lasing emission in both directions of the coupled waveguide [5].

Fig. 1(b) shows the finite-difference time-domain (FDTD) simulated intensity pattern for the CCW traveling-wave mode at the pump wavelength 1419.9 nm. Figs. 1(c) and (d) show the FDTD-simulated intensity patterns for the CCW and CW traveling-wave resonance modes at the silicon Stokes wavelength 1533.1 nm.

![Fig. 1](image_url)

**Fig. 1** (a) Pulsed pump and probe experimental setup. The light is input-coupled to the silicon chip by a lensed fiber. (b) Optical micrograph of a fabricated silicon spiral micodisk. (c), (d) Scanning electron micrographs of (c) the evanescent coupling waveguide region and (d) the notch coupling region. PC: polarization controller, EDFA: erbium-doped fiber amplifier, PMF: polarization maintaining fiber, BPF: band-pass filter, NF: notch-filter, TOD: tunable optical delay line.

Our on-going experiments use pump-probe pulses to study the proposed Raman silicon lasing from spiral microdisks. The technique of using short few-hundred-fs pulses in a low repetition rate (20 MHz) essentially reduces the undesirable two-photon-absorption induced free-carrier-absorption effects that can suppress the Raman lasing. Fig. 2(a) shows the experimental setup for generating pulsed pump and probe sources [7]. The pump pulses are EDFA-amplified pulses from the fiber pulse laser (centered around 1560 nm). The probe pulses are generated by soliton self-frequency shift effect by propagating through a ~400-m polarization-maintaining fiber. Fig. 2(a) inset shows our measured combined pump and probe spectrum. The probe pulses are centered at around 1689 nm wavelength in order to cover the silicon Raman Stokes shifts. Fig. 2(b) shows the optical micrograph of a fabricated spiral microdisk of radius $r_0 = 500 \, \mu m$ ($\varepsilon = 0.005$) on a silicon-on-insulator substrate of 2-μm device layer. The fabricated rib waveguides has a slab height of 1 μm and a width of 1.5 μm (for both the side-coupled and notch-coupled waveguides). Figs. 2(c) and (d) show the scanning electron micrographs of the coupling gap (~0.4 μm) between the side-coupled waveguide and the spiral microdisk and of the notch coupling region (notch size is 2.5 μm).