Four-Wave Mixing in a High-*Q* Aluminum Oxide Microcavity on Silicon

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Abstract: We demonstrate *Q* factors of > 10^6 and parametric frequency conversion in Al_2O_3 micro-trench resonators co-integrated with Si_3N_4 waveguides on silicon. Under 1550-nm pumping we show oscillation at wavelengths ranging from 1135 to 2445 nm. © 2018 The Author(s)

OCIS codes: (130.3120) Integrated optics devices; (230.5750) Resonators; (190.4390) Nonlinear optics, integrated optics.

1. Introduction

Optical microcavities are important photonic structures because they confine light to small mode volumes, achieve high power densities and have narrow spectral widths [1]. As such they offer exceptional performance for a number of applications, including devices that rely on nonlinear optical phenomena, low-threshold microlasers and efficient optical sensors [2]. Optical microcavities have been widely studied on silicon photonic platforms, which enables their use in compact, low-cost and energy efficient silicon photonic circuits [3]. However silicon photonic devices and microsystems are traditionally limited to a handful of materials compatible with complimentary metal-oxide-semiconductor (CMOS) processing, including silicon itself, silicon nitride and germanium. Recently, we have been investigating methods in which new materials can be built into wafer-scale silicon photonic processes by performing additional processing steps outside the foundry with the aim of introducing new functionalities to silicon photonic microsystems. In one such study we demonstrated a novel monolithic silicon-based laser based on rare-earth-doped aluminum oxide microcavities co-integrated with silicon nitride waveguides [4]. In similar passive microcavities we showed *Q* factors of up to 5.7×10^5 at 1550 nm. However, for efficient nonlinear devices, sensors and lasers, higher *Q* factors are desired. Here, in an optimized Al_2O_3 cavity structure we show quality factors of >10^6 and optical parametric oscillation in the near- and mid-infrared. The results demonstrate that high-*Q* Al_2O_3 optical microcavities are of interest as monolithic nonlinear optical light sources for silicon photonic microsystems.

2. Microcavity Design and Fabrication

We fabricated the 300-µm-diameter Al_2O_3 microcavities using a 300-mm CMOS foundry with a 65-nm technology node. Figure 1(a) shows a schematic of the Al_2O_3 microcavity and co-integrated double-layered Si_3N_4 waveguide. All processing steps (which are described in detail in [4] and [5]) are silicon-photonics compatible, including straightforward post-processing deposition of the resonator material (a 1.2-µm-thick reactively-sputtered amorphous Al_2O_3 film) within a circular trench etched into the SiO_2 top cladding. The design is highly-flexible and can enable integration of a wide variety of potential resonator materials beyond Al_2O_3 onto a silicon photonic platform. SEM images of the microcavity and waveguide cross-sections are displayed in Figs. 1(b) and (c).

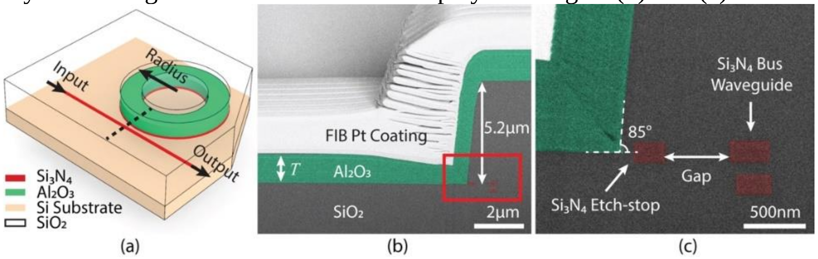
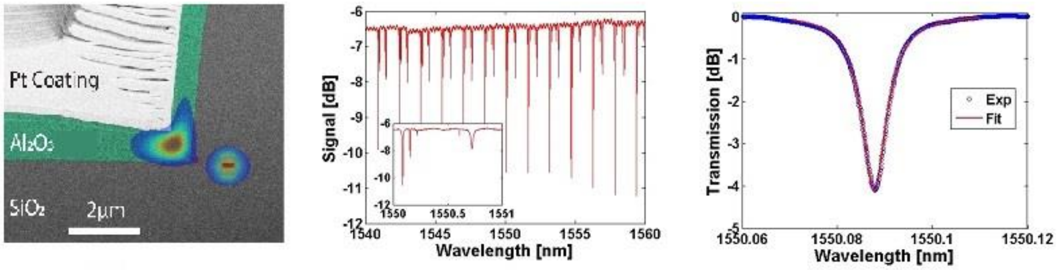


Fig. 1. (a) Diagram of microcavity and integrated Si_3N_4 waveguide. (b) SEM cross sections of cavity and (c) zoomed-in view of bus waveguide.

3. Microcavity Characterization Results

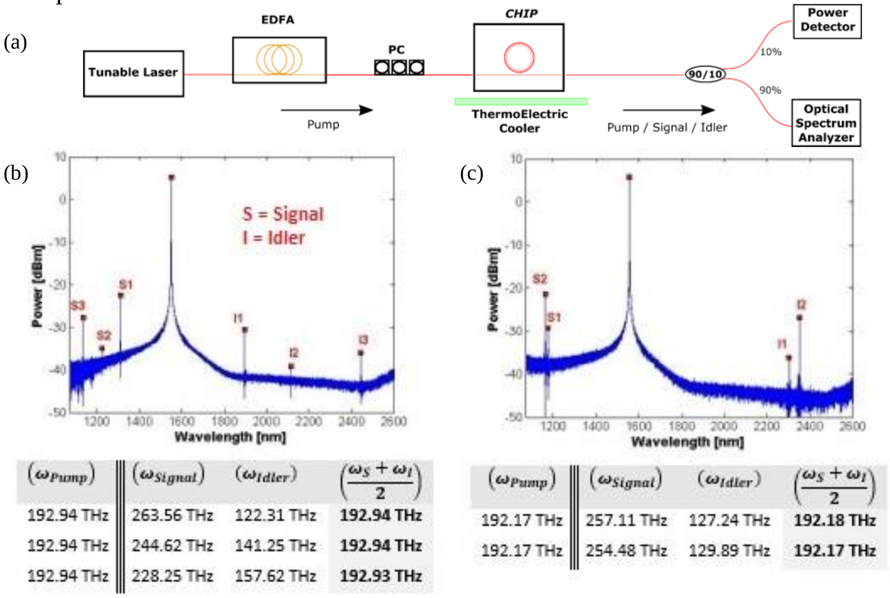
We carried out transmission measurements by coupling light from a tunable laser on and off the chip via edge-coupling from a tapered fiber to the Si_3N_4 bus waveguide. The calculated mode profiles in the cavity and waveguide for quasitransverse electric (TE) polarization and at 1550 nm are shown in Fig. 2(a). A typical measured transmission spectrum is displayed in Fig. 2(b), showing multiple resonant modes and a free spectral range of 1.5 nm. A zoomed-in view and Lorentzian fit to the highest Q mode (the fundamental mode) is shown in Fig. 2(c), from which we obtain an internal Q factor of 1.7×10^6.



(a) (b) (c)

Fig. 2. (a) Calculated mode profiles of an Al_2O_3 microcavity (left) and S_3N_4 bus waveguide (right) at 1550 nm and for TE polarization. (b) Measured transmission spectrum of a microcavity. (c) Transmission data for the highest Q mode and fitted Lorentzian function.

To investigate the potential of such resonators as nonlinear devices we pumped the microcavity using a tunable laser cascaded with an erbium-doped fiber amplifier (EDFA), with up to 90 mW power incident on the chip, and an estimated 45 mW coupled into the bus waveguide. The emitted light was then measured using a near/mid-infrared optical spectrum analyzer as illustrated in Fig. 3(a). The measured spectra demonstrate phase-matched oscillation of sideband signal and idler photons in the resonant cavity, as shown in Figs. 3(b) and (c). The frequencies of the signal and idler photons are equal to two times the pump frequency ($2\omega_{Pump} = \omega_{Signal} + \omega_{Idler}$), representing the process of parametric four wave mixing, where two pump photons annihilate to generate an upconverted signal photon and a downconverted idler photon.



(ω_{Pump})	(ω_{Signal})	(ω_{Idler})	$\left(\frac{\omega_S + \omega_I}{2}\right)$
192.94 THz	263.56 THz	122.31 THz	**192.94 THz**
192.94 THz	244.62 THz	141.25 THz	**192.94 THz**
192.94 THz	228.25 THz	157.62 THz	**192.93 THz**

(ω_{Pump})	(ω_{Signal})	(ω_{Idler})	$\left(\frac{\omega_S + \omega_I}{2}\right)$
192.17 THz	257.11 THz	127.24 THz	**192.18 THz**
192.17 THz	254.48 THz	129.89 THz	**192.17 THz**

Fig. 3. (a) Experimental setup for generating and measuring nonlinear optical response from microcavities. (b), (c) Two measured transmission spectra from microcavities demonstrating sideband emission of signal and idler photons. The tables show that the addition of signal and idler photon frequencies are equal to that of two pump photons.

In conclusion, we have demonstrated four-wave mixing in the near- and mid-infrared in a novel high-Q Al_2O_3 micro-trench cavity. The results demonstrate the potential for this cavity structure to be applied in monolithic nonlinear optical light sources on a silicon photonic platform.

4. References

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