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Demonstration of an erbium-doped microsphere laser on a silicon chip

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Abstract
We demonstrate a low-threshold microsphere laser on a silicon chip, fabricated from erbium-doped silica sol–gel film. Single-longitudinal mode lasing emission is observed from a 37 µm diameter microsphere cavity with an erbium ion concentration of 2 × 10¹⁹ cm⁻³. The measured lasing threshold of the silica microsphere laser is as low as 4.8 µW.

1. Introduction
High quality (high-Q) factor whispering-gallery mode (WGM) optical microcavities, including microdroplets, microdisks, microspheres or microtoroids, have been widely used in many fundamental as well as applied fields such as cavity quantum electrodynamics, cavity optomechanics, nonlinear optics and biosensors [1, 2]. Among them, silica microsphere cavities formed by surface tension have been shown with extremely high optical quality factors of ∼10¹⁰, due to their ultra-low material absorption and nearly atomic-scale surface roughness [3, 4]. When incorporated with active gain media such as rare-earth ions [5–13], dyes [14], semiconductors [15] or nanocrystal quantum dots [16, 17], WGM optical microcavities can be used for low-threshold microlasers and microlaser-based label-free sensors [18]. So far, typical spherical microlasers have been obtained by directly heating rare-earth-doped optical fiber tips using a CO₂ laser [6–8] or by doping pure silica microspheres by coating rare-earth-doped sol–gel films [9, 13] or by using rare-earth ion implantation [12], all of which have been realized with different lasing wavelengths [19]. Recently, silica optical microsphere cavities fabricated on a silicon chip have been realized and used for cavity optomechanics [20–22]. Here, by fabricating a rare-earth-doped microsphere cavity on a silicon chip using erbium-doped silica sol–gel film, we demonstrate a chip-based spherical high quality microcavity laser operated at a wavelength of 1.5 µm.

2. Experiment
To fabricate such an erbium-doped microsphere cavity on a silicon chip, we first prepare the erbium-doped silica film by the sol–gel process. The fabrication process of the sol–gel film is similar to that used in [9]. The only difference is that here we add formamide into the tetraethoxysilane (TEOS) solution, to prevent the cracking of the silica sol–gel film, which also speeds up the reaction of the solution [23]. Then, the microsphere cavity is fabricated by a combination of photolithography, buffered HF wet etching, XeF₂ dry etching and CO₂ laser reflow [24]. Typically, to get a high quality spherical structure, a silica microdisk with a very small top pedestal diameter (<5 µm) should be prepared before the CO₂ laser reflow [22]. Figure 1(a) shows a typical scanning electron microscope (SEM) image of a 37 µm diameter erbium-doped silica microsphere cavity which is fabricated from a four-layer silica sol–gel film with a thickness of 1.3 µm.

Figure 2(a) gives the schematic diagram of the experimental setup for the measurements of the erbium-doped
silica microsphere laser on a chip. A narrow linewidth tunable laser operating in the 1480 nm band is used to pump the erbium-doped microsphere cavity. The optical power and the polarization of the pump light are adjusted by a variable optical attenuator (VOA) and a polarization controller, respectively. After passing through a fiber circulator, the pump light is coupled into the microsphere cavity via a low loss optical fiber taper which is also used to couple the laser light out of the microcavity via the evanescent field around the fiber taper [25, 26]. The generated laser signal is measured from the reflected port of the circulator to avoid the noise of the pump laser at the 1550 nm band by an optical spectrum analyzer, since the lasing emission is coupled into the fiber taper in both the forward and backward directions. In addition, two optical power meters, at the 10% port of the fused fiber couplers with a 90:10 split ratio, are used to measure the input and output powers of the pump light.

To characterize the erbium-doped silica microsphere cavity, we first scan the frequency of the pump light to identify a proper mode to resonantly pump the erbium-doped microsphere laser at a wavelength of around 1480 nm. Figure 2(b) shows a typical single-longitudinal mode laser spectrum of the erbium-doped silica microsphere at a wavelength of 1598 nm. Multi-longitudinal mode laser has also been observed (inset of figure 3) under different pump and tapered optical fiber coupling conditions.

To measure the threshold of this silica microsphere laser, we gradually change the optical power of the pump light while fixing the loaded quality factor of the microcavity by controlling the position of the optical fiber taper and monitoring the transmission power of the pump mode.
During the experiment, the pump light is thermally locked to the cavity mode (figure 2(b)) with a fixed slight blue-detuning [28]. Due to the thermal effect of the silica microcavity [28], when the pump power becomes larger, we also need to slightly increase the pump wavelength within the cavity mode to keep the detuning of the pump laser and make sure we have the same build-up factor for pump light in the cavity. Figure 4 shows the measured laser output power as a function of the absorbed pump power, which is calculated from the difference between the measured optical powers of the two power meters (figure 2(a)). The measured lasing threshold is around 4.8 µW, which is comparable to the value obtained in an erbium-doped microtoroid laser on a chip [27, 29].

3. Conclusion

In conclusion, we have demonstrated a low-threshold microsphere laser on a silicon chip for the first time. The microsphere cavity is fabricated from erbium-doped silica sol–gel film. A lasing threshold as low as 4.8 µW has been achieved from a 37 µm diameter microsphere cavity. Such chip-based silica microsphere lasers can find applications in integrated silicon photonics for optical communications and highly sensitive active biosensors.

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