Invited Paper

Ultralow-threshold neodymium-doped microsphere lasers on a silicon chip

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A B S T R A C T
We demonstrate ultralow-threshold neodymium-doped silica microsphere lasers on a silicon chip with lasing wavelengths of ~900 nm and ~1060 nm. Neodymium-doped microsphere cavities are fabricated with a series of doping concentrations using silica sol–gel films. Experimentally, we observe single-mode lasing emissions from the high-Q microsphere cavities with a threshold of as low as 1.2 μW.

1. Introduction

In the past decade, whispering-gallery-mode (WGM) optical microcavities have drawn extensive interest in the applications of cavity quantum electrodynamics [1], cavity optomechanics [2], biosensors [3], microlasers, Kerr frequency comb [4], on-chip optical nonreciprocity [5,6], as well as parity-time symmetry [6], due to their high quality factors and small mode volumes. In particular, glass WGM microcavities including micropsheres [7,8], microtoroids [9], microdisks [10,11], microbottles [12], and microbubbles [13] have been considered as an important kind of microcavities because of their easy fabrication, ultra-low optical loss, broadband transparency as well as full compatibility with complementary metal-oxide-semiconductor (CMOS) technique [9–11]. To date, ultra-high quality factors of ~8 × 109 have been achieved with silica microsphere cavities [7,8] and greater than 1010 with chip-based microtoroid/microdisk cavities [9,10], respectively. When incorporating the WGM microcavities with different rare-earth ions, such as Nd3⁺ [14–17], Er3⁺ [18–21], Yb3⁺ [22], and Tm3⁺ [23–25], such glass microcavities have been used for ultralow threshold microlasers with lasing wavelengths from visible to mid-infrared. Among them, Nd3⁺-doped glass microsphere lasers with a record threshold of 65 nW have been reported from Nd3⁺:Gd2O3 nanocrystals functionalyzed silica microsphere cavities [15].

Recently, Nd3⁺-doped silica microtoroid lasers have been fabricated on a glass chip by three-dimensional femtosecond laser micromachining process [16] and on a silicon chip by the sol–gel process [17].

Here, we demonstrated Nd3⁺-doped silica microsphere lasers on a silicon chip using silica sol–gel film. We observed single-mode and multi-mode lasing emissions at the wavelength of ~900 nm and ~1060 nm, respectively, and their measured lasing thresholds are as low as 2.4 μW and 1.2 μW.

2. Experiments and results

To fabricate the chip-based Nd3⁺-doped microsphere cavities, we prepared the silica sol–gel film with a thickness of approximately 1.3 μm (For details, please refer to Refs. [19,20]). During the sol–gel process, Neodymium (III) nitrate hexahydrates (Nd(NO3)3·6H2O) with different doping concentrations were added into the solution. Then, Nd3⁺-doped silica microdisks with a diameter of ~200 μm and a small top pedestal diameter were created with the combination of photolithography, HF wet etching and XeF2 dry etching. At the final stage, a high power CO2 laser at the wavelength of 10.6 μm was employed to reflow the silica microdisk to form the microsphere structures [19,20]. The diameters of microspheres that we achieved in our experiment were approximately ranged from 36 μm to 42 μm. Fig. 1 shows a typical side-view scanning electron microscope image of an Nd3⁺-doped silica microsphere cavity with a diameter of 37 μm.

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The experimental setup for the measurements of the Nd$^{3+}$-doped microsphere lasers is depicted in Fig. 2. A tapered optical fiber [26], pulled from a single-mode optical fiber (780 HP), is used to evanescently couple the pump laser light into the microsphere cavity to excite the neodymium ions, and meanwhile to couple the laser emission out of the microsphere cavity. The distance between the microsphere cavity and the fiber taper is finely adjusted by using a three-axis piezoelectric nanopositioner to optimize the coupling condition and hence the lasing performance. The microsphere laser is pumped by a tunable, narrow-linewidth laser operating at the wavelength of $\sim 780$ nm. A variable optical attenuator and a fiber polarization controller are used to adjust the pump power and its polarization. After passing through two fused optical fiber couplers, the lasing emissions (coupled out from the microsphere cavity via the fiber taper) are measured by an optical spectrum analyzer, while the pump light is measured by an optical power meter and a photodetector whose output is monitored by an oscilloscope. Note that the absorbed pump power is obtained through the power difference between the input and output pump measured via two optical power meters (PM1 and PM2).

To characterize the lasing performance of the Nd$^{3+}$-doped silica microspheres, the pump light is thermally locked [27] into the cavity modes to resonantly pump the microcavity and excite the neodymium ions. In the experiment, single-longitudinal mode lasing emissions are observed at the 1060 nm wavelength from the Nd$^{3+}$-doped silica microsphere cavities with different doping concentrations. As an example, Fig. 3(a) shows the typical single mode laser spectrum at the wavelength of 1096.5 nm from a 37-µm-diameter microsphere cavity with a doping concentration of $2.3 \times 10^{19}$ cm$^{-3}$. The intrinsic optical quality factor is $2.6 \times 10^{6}$ at the pump wavelength of 777.8 nm, which is limited by the absorption of the neodymium ions [28]. By changing the coupling condition and the pumped optical power/laser frequency detuning, multi-mode lasing emissions are also obtained in our system (see Fig. 3(b)).

Fig. 4(a) shows the laser output power as a function of the absorbed pump power for the Nd$^{3+}$-doped silica microsphere laser. The measured lasing threshold is 1.2 µW, same as that for the Nd$^{3+}$-doped silica microtoroid laser on a silicon chip without incorporating the aluminum ions [17]. In addition, we have obtained lasing emissions from the silica microsphere cavities with doping concentrations of $3.8 \times 10^{19}$ cm$^{-3}$ and $5.7 \times 10^{19}$ cm$^{-3}$, and the measured lasing thresholds are 6.6 µW and 7.1 µW, respectively. As illustrated in Fig. 4(b), the lasing threshold of the microsphere laser increased with the increase of the neodymium-doping concentration. This can be understood by noticing the fact that increasing the doping concentration results in the increase of the absorption of the neodymium ions [28]. The Nd$^{3+}$-doped silica microsphere laser with lower threshold might be achieved by further optimizing the doping concentration of the neodymium ions.

Besides the observation of the lasing emission at the wavelength of 1060 nm band, we also achieved lasing emission of $\sim 900$ nm from Nd$^{3+}$-doped silica microsphere cavities with a...
doping concentration of $2.3 \times 10^{19} \, \text{cm}^{-3}$. Fig. 5(a) shows a typical lasing spectrum from a 39-μm-diameter silica microsphere cavity, measured at the pump mode with an intrinsic quality factor of $2.4 \times 10^6$. As shown in Fig. 5(b), the measured threshold for the 900-nm-wavelength lasing is 2.4 μW.

3. Conclusions

In summary, we have experimentally demonstrated the Nd$^{3+}$-doped silica microsphere lasers on a silicon chip using the sol–gel process. Lasing emissions at the wavelengths of 1060 nm and 900 nm bands are observed from the Nd$^{3+}$-doped silica microsphere cavities. Importantly, in the experiment we achieved a threshold of 1.2 μW at the lasing wavelength of 1060 nm band from a 37-μm-diameter microsphere cavity with a doping concentration of $2.3 \times 10^{19} \, \text{cm}^{-3}$. Such a chip-based Nd$^{3+}$-doped silica microsphere laser is expected to find useful applications in active sensors with ultra-high sensitivity.

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