Microlaser based on a hybrid structure of a semiconductor nanowire and a silica microdisk cavity

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Abstract: We experimentally demonstrate a hybrid structure microlaser on chip with a single CdSe nanowire attached to a high-Q silica microdisk cavity at room temperature. When pumped by a 532 nm pulse laser, both single-longitudinal mode and multi-longitudinal mode lasers with linewidth of 0.18 nm are obtained from the hybrid structure with a 58-µm-diameter microdisk and a 250-nm diameter nanowire. The measured lasing threshold of the microlaser is as low as 100 µJ/cm².

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References and links

1. Introduction

Semiconductor nanowires have attracted much attention for their applications in nanophotonic circuits [1, 2], such as subwavelength waveguides [3], LED [4], nanolasers [5–11], all-optical switching [12] and so on. In particular, single semiconductor nanowire lasers have been realized in various materials, with emission wavelengths ranging from ultraviolet to infra-red for their widely available bandgaps [6–10]. Recently, a new class of lasers based on semiconductor nanowires, called spacers, has been demonstrated at deep subwavelength scale making the nanowire lasers working beyond the diffraction limit [13, 14].

Usually, the semiconductor nanowire laser works in a Fabry-Perot (F-P) cavity formed by reflections from the end facets of the nanowire which is used both as the gain medium and the optical cavity [6, 7]. However, due to the low reflectivity from the end facets of the semiconductor nanowire [15], the demonstrated Q-factor of the F-P mode in single nanowire is below 1000, which limits its application for low-threshold lasing operation. To avoid this obstacle, a hybrid approach has been proposed [16, 17] and experimentally investigated including single semiconductor nanowire coupled to a racetrack resonator [16], a microstadium resonator [18], a silica microfiber knot cavity [19], a photonic crystal microcavity [20] and a dielectric microcavity [21] for demonstrating lasers for photons [18–20] and polaritons [21].

Here, we propose and demonstrate a new kind of hybrid structure consisting of a single CdSe semiconductor nanowire and a silica microdisk cavity for low-threshold nanowire laser operation. This kind of hybrid structure combines the advantages of the large gain in the semiconductor nanowire and the high-Q whispering-gallery modes (WGMs) in the microdisk cavity [22, 23]. Effective coupling between the nanowire and the WGMs of the microdisk cavity is investigated in both simulation and experiment. A Q-factor higher than $10^5$ at the wavelength of 1.5 μm is obtained in this hybrid structure and lasing on chip with low threshold is achieved at room temperature. The Q-factor of the hybrid structure is more than one order of magnitude higher than the previously reported hybrid structures [16–21]. Also, such hybrid structure will be useful for applications in cavity-QED, nonlinear optics and low power integrated photonic devices.
2. Experiment

As shown in Fig. 1(a), the hybrid structure consists of a single CdSe nanowire and a high-Q silica microdisk cavity. The CdSe nanowires with diameters of 100-500 nm are synthesized via the well-established physical vapor deposition method [24]. The silica microdisk cavities with diameters in the range of 20-80 μm and thicknesses of 0.5-2 μm are fabricated by a combination of photolithography, HF wet etching and XeF₂ dry release [22, 23]. To assemble the hybrid structure, the CdSe nanowires are first dispersed on a silicon substrate, then a selected nanowire with an appropriate size is lifted from the substrate and moved towards a silica microdisk cavity using a fiber probe. This process is similar to the one used in Ref. 19. To maximize the coupling between the nanowire and the microdisk cavity, the CdSe nanowire is positioned on the edge of the silica microdisk (Figs. 1(b) and 1(c)) where parts of the WGMs of the microcavity are located. In the experiment, the typical silica microdisk diameter and thickness are 58 μm and 800 nm, respectively, while the length and diameter of the CdSe nanowire are 10 μm and 250 nm.

This hybrid structure supports evanescently coupled WGMs with the nanowire in the overlapped region and normal microdisk WGMs in the other region (no semiconductor nanowire area) [22, 23]. For better understanding of the coupling between the nanowire and the silica microdisk in the interacting region, finite-element method (FEM) simulation is performed for a 45 degree angled device. Figure 2(a) shows the intensity profile for a typical fundamental TE-like mode of the hybrid structure in the coupling region. According to
simulation, around 2% mode intensity is present in the CdSe nanowire in the coupling region, indicating an efficient coupling between the nanowire and the microdisk WGMs. Also, the coupling can be optimized by using thinner and smaller microdisk cavities.

In order to characterize the loss of the hybrid structure, an adiabatically pulled fiber-taper with a diameter of ~1 μm is employed to measure the Q-factor of the device at the wavelength of ~1.5 μm [25, 26]. Figure 2(b) shows the transmission spectrum of the hybrid structure consisting of a 58-μm-diameter microdisk and a 10-μm-length nanowire. The thickness of the microdisk is 800 nm and the diameter of the nanowire is around 250 nm. The measured intrinsic Q-factor is $6.2 \times 10^4$, which is higher than the previously achieved hybrid structures on chip [16, 18, 20]. In addition, the Q-factor of the hybrid structure is improved up to $2 \times 10^5$ (Fig. 2(c)) when a 2-μm-thickness microdisk is used. It needs to be mentioned that the Q-factors of the hybrid structures are degraded around one order of magnitude from the initial Q-factors of the silica microdisk cavities. This is mainly caused by the contamination during the assembling process, during which some tiny CdSe fragments (Fig. 3(b)) from the CdSe nanowire or small particles from the fiber probe will be attached on the silica microdisk. For the Q factor of the hybrid structure at the lasing wavelength, it should be slightly lower than that at the 1.5 μm wavelength due to the absorption of the CdSe nanowire.

Fig. 2. (a) Calculated mode intensity profile for the fundamental TE-like cavity mode of the hybrid structure in the coupling region at a wavelength of ~700 nm. The thickness of the silica microdisk is 800 nm and the diameter of the CdSe nanowire is 250 nm. (b) Normalized transmission spectrum of the hybrid structure consisting of a microdisk cavity (with 800 nm thickness and 58 μm diameter) and a 10 μm long CdSe nanowire. (c) Normalized transmission spectrum of the hybrid structure consisting of a microdisk cavity (with 2 μm thickness and 80 μm diameter) and a 15 μm long CdSe nanowire.

Fig. 3. (a) Schematic diagram of the measurement system. (b) Photoluminescence image of the hybrid structure above lasing threshold. NDF: variable neutral density filter, BS: beam splitter, PM: power meter.
Figure 3(a) shows the schematic diagram of the setup to examine the lasing properties of the hybrid structure. In the experiment, we use a 532 nm frequency-doubled Nd:YAG pulse laser (10 ns pulse width, 2 kHz repetition rate) to pump the devices at room temperature. The power of the pump laser is controlled by a variable neutral density filter (NDF). The pump laser is split into two paths by a beam splitter with one path to pump the sample and the other to monitor the power of the pump laser by a power meter. The pump laser is focused onto a 10-μm-diameter spot and illuminates on the CdSe nanowire (inset of Fig. 3(a)) through a 100× objective with a numerical aperture of 0.7. The photoluminescence (PL) is collected by the same objective from the top of the CdSe nanowire and measured by a grating spectrometer (HORIBA Jobin Yvon iHR 550) after passing through a notch filter centered at 532 nm. The resolution of the spectrometer is 0.045 nm. When pumped by the 532 nm laser, the generated PL from the CdSe nanowire is coupled into the silica microdisk and builds up in the microcavity (Fig. 3(b)) featuring a WGM (Fig. 2(a)).

![Emission spectra of the hybrid structure under different pump powers.](image)

Fig. 4. Emission spectra of the hybrid structure under different pump powers.

Lasing emission has been observed in several hybrid structures with silica microdisk thicknesses of ~0.8 μm, 1 μm and 2 μm, respectively. The diameters of the microdisks are 50 μm-80 μm while the lengths of the CdSe nanowires are 10-20 μm. Figure 4 shows the typical PL spectra under different pump powers from the hybrid structure with a 58-μm-diameter microdisk and a 10-μm-length CdSe nanowire. The thickness of the silica microdisk is 800 nm and the diameter of the nanowire is 250 nm. When the pump power starts to exceed the...
threshold value, single-longitudinal mode lasing at the wavelength of ~712 nm is observed. When the pump power is further increased (to ~120 μJ/cm²), lasing with multi-longitudinal modes starts to appear. The measured linewidth of the laser mode is around 0.18 nm with all the lasing modes nearly the same. Also, narrower linewidth as low as 0.08 nm can be obtained when a 2-μm-thickness microdisk is used in the hybrid structure. As shown in Fig. 4, the measured free spectral range (FSR) of the laser is ~1.80 nm, which is in well agreement with the calculated WGM mode spacing. It is worth noting that during the experiment, no F-P cavity modes (FSR = 8.9 nm) of the CdSe nanowire are observed, indicating that the WGMs are dominant in such hybrid structures. Figure 5 plots the integrated intensities of the emission from 710.0 nm to 714.3 nm at different pump power densities. The measured threshold is around 100 μJ/cm² nearly the same level to the bare nanowire laser [11], which is mainly due to the much large mode volume of the hybrid structure comparing to the bare nanowire laser. Further lowering the threshold is possible by using silica microdisks with smaller diameters and thin thickness while maintaining the Q factor.

Fig. 5. Integrated emission intensity vs pump power density for the hybrid structure.

3. Conclusion

We have realized a hybrid structure consisting of a CdSe nanowire evanescently coupled to a high-Q WGM microdisk cavity. Q-factors as large as $6.2 \times 10^5$ and $1.2 \times 10^5$ are demonstrated when 800-nm and 2-μm thick microdisk cavities are used to form the hybrid structure. Due to the large gain of the semiconductor nanowire and the high Q-factor of the silica microdisk cavity, lasing operation on chip with a threshold value as low as 100 μJ/cm² is observed in such hybrid structure at room temperature. We believe that by further improving the Q factor of the hybrid structure or optimizing the coupling between the semiconductor nanowire and the cavity modes of the silica microdisk, it may lead to continuous-wave operation of the semiconductor nanowire laser [14] or microlaser-based sensor with high sensitivity [27]. In addition, by embedding a quantum dot into the
semiconductor nanowire [28, 29], this structure can be very useful for quantum information processing [30].

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