Flexible compact microdisk lasers on a polydimethylsiloxane (PDMS) substrate

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Abstract: Compact microdisk cavities were fabricated on a polydimethylsiloxane substrate. The lasing of the flexible compact cavity was achieved with a low threshold power. The whispering-gallery mode of the microdisk was also characterized with three-dimensional finite-difference time-domain simulation. The curvature dependence in output power and threshold was also demonstrated by bending the microdisk cavity.

OCIS codes: (140.5960) Semiconductor lasers; (140.3948) Microcavity devices; (250.2080) Polymer active devices; (280.4788) Optical sensing and sensors.

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1. Introduction

In recent years, semiconductor microdisk cavities have attracted a lot of attention for applications in photonic integrated circuits due to their promising and versatile optical functions. The extensive studies and discussions with varied microdisk cavities had been reported including filter [1-3], demultiplexer [4, 5], modulators [6, 7] and lasers [8-13]. The type cavities with whispering gallery mode (WGM) became one of excellent candidates for compact semiconductor lasers for the chip scale integrated systems. The polymer/organic photonic devices had been studied widely because of their special spectral properties and application flexibility. There are demonstrations in the flexible platform for light sources [14-19], modulators [20, 21], sensors [22, 23] and etc. In past years, the III-V microdisk lasers on the different substrates had been studied [24-27] for varied applications, however there is no report for a compact flexible laser/sensor on a bendable surface. In this paper, we demonstrated a flexible compact InGaAsP microdisk laser on a polydimethylsiloxane (PDMS) substrate. Figure 1 shows the illustration of an InGaAsP microdisk cavity on a PDMS substrate. The InGaAsP microdisk is embedded inside the low index (n=1.41) PDMS layer which is benefit to optical confinement of the whispering gallery mode in the disk layer. The lasing action was observed from the semiconductor-polymer hybrid compact cavity with a low threshold power. The laser intensity can also be coupled into waveguides efficiently with the reported structures [1, 5, 26, 27] in photonic integrated circuits. With a flexible platform, this novel laser can function not only as a light source for the photonic integrated circuits on the non-flat surface, but also as a sensing device for the curvature of the bent substrate.

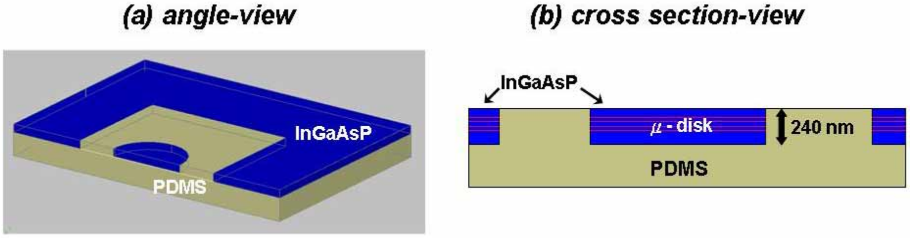
(a) angle-view **(b) cross section-view**

Fig. 1. The illustration of an InGaAsP microdisk cavity on a PDMS substrate from (a) angle-view and (b) cross-section view.

2. Fabrication procedures

In order to fabricate the proposed structure, the microdisk cavities were implemented in a 240nm thick InGaAsP layer on the InP substrate which is growth by a metal organic chemical vapor deposition (MOCVD) system. The InGaAsP layer contents four 10nm thick strained InGaAsP quantum wells (QWs) which is designed for the lasers operated near 1550nm wavelength. A silicon nitride (SiN_x) layer and a polymethylmethacrylate (PMMA) layer are deposited on the top of the wafer for the dry etching processes and electron beam lithography. The microdisk patterns were defined by the electron beam lithography, followed by two dry etching steps with CHF_3/O_2 and $CH_4/Cl_2/H_2$ mixture gases in the inductive couple plasma (ICP) system. The microdisk structures then flipped and mounted to an 80 μm thick PDMS substrate. The InP substrate was removed by a wet etching step with HCl solution. Figure 2(a) shows a SEM image of an array of fabricated disks on the PDMS substrate with varied diameters of 1.80, 2.85, 3.80 and 4.75μm. Figure 2(b) is the magnified SEM image of a microdisk laser with 4.75 μm diameter. The area outside the square is InGaAsP membrane which is reserved for electrical contacts in the future electrically-pumped scheme. The adhesion between the InGaAsP disk and the PDMS substrate is good enough for the small angle bending, and the InGaAsP microdisk isn't damaged during the bending process.

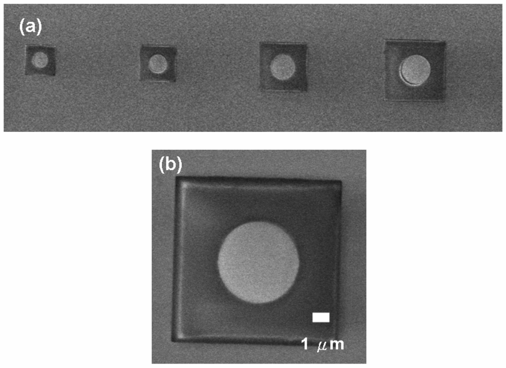

Fig. 2. (a). A SEM image of an array of fabricated disks on the PDMS substrate with varied diameters of 1.80, 2.85, 3.80 and 4.75 μm. (b) The magnified SEM image of a microdisk laser with 4.75 μm diameter.

3. Characterization for microdisk lasers

The microdisk lasers were optically-pumped at room temperature by using an 850 nm wavelength diode laser at normal incidence with a 1.5% duty cycle and a 30 ns pulse width. The pump beam was focused on the devices by a 100x objective lens. The pump beam spot size is approximately 1.5 μm in diameter. The output power was then collected by a multi-mode fiber connected to an optical spectrum analyzer.

The lasing action was observed from the varied size microdisk cavities, and the size of the smallest lasing cavity is 1.8μm in diameter. Figure 3(a) shows a lasing spectrum from a microdisk laser with 4.75μm diameter. The lasing wavelength is around 1577.6 nm. The light-in-light-out (L-L) curve of this microdisk laser is shown in the Fig. 3(b). The incident threshold power is approximately 0.55 mW. The effective threshold power is only 60 μW after estimating the material absorption, surface reflectivity of the cavity structure. Although the cavity quality factor (Q) value is lower than the free-standing structure, the threshold power is still very low because of circularity of the disks and smoothness of sidewall.

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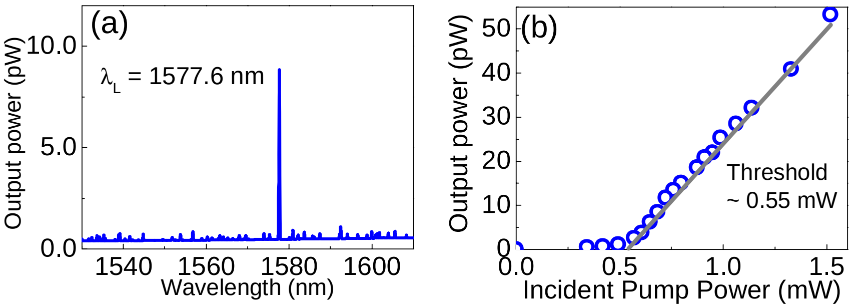

Fig. 3. (a). The lasing spectrum from a mcrodisk laser with 4.75μm diameter. The lasing wavelength is 1577.6 nm. (b). The light-in-light-out (L-L) curve of this microdisk laser. The incident threshold power is approximately 0.55 mW.

In order to identify the whispering gallery modes in the microdisk cavity, three-dimensional finite-difference time-domain (FDTD) method was used to perform the simulation. The simulated domain is 10μm x10μm x2μm for this structure. The indices of air, InGaAsP and PDMS layers are 1.0, 3.4 and 1.41, respectively. The simulation was processed with TE polarized sources and 20 nm grid size. The red curve in Fig. 4(a) is the calculated spectrum for a 4.75μm microdisk from FDTD simulation. The higher peaks (A_1, A_2 and A_3) at 1528.5, 1580.1 and 1634.8 nm are the first-order whispering gallery modes, and the small peaks (B_1, B_2 and B_3) are the second-order modes. The other higher-order modes have very low Q values according to the simulation; therefore they are not obvious in the spectrum. The blue curve in Fig. 4(a) is the 1577.6 nm lasing spectrum from the measurement. The observed lasing mode from measurement spectrum is verified to be the first-order mode by comparing the measured and simulated spectra. Figure 4(b) shows the top view of H_z mode profile for the lasing mode from the FDTD simulation. Figure 4(c) shows the cross-section view of the calculated H_z profile around the edge of the microdisk cavity. The second-order modes of the microdisk have lower Qs according to our simulation. Therefore, the second-order modes were not observed in the experiments. The optical mode is confined in the InGaAsP disk layer well, and the vertical mode distribution is not symmetric in the InGaAsP layer due to the index difference of top and bottom materials. We can reduce threshold power by modifying QW position in the InGaAsP layer, in advanced. The microdisk cavity Q can be evaluated from the ratio of the resonant peak wavelength to the linewidth (i.e. $Q\sim \lambda/\Delta\lambda$). The FDTD calculated Q value of the operated mode is close to 6000, and the experimental Q value is approximately 3000 which is estimated from the resonant peak around the transparency. We obtained a good agreement between experiment and simulation not only in wavelength, but also in cavity Q value. Approximately 0.2 % in wavelength between measurement and model prediction was observed. We attributed it to the imperfection of fabrication and the inaccuracy of indices used in the FDTD simulation.

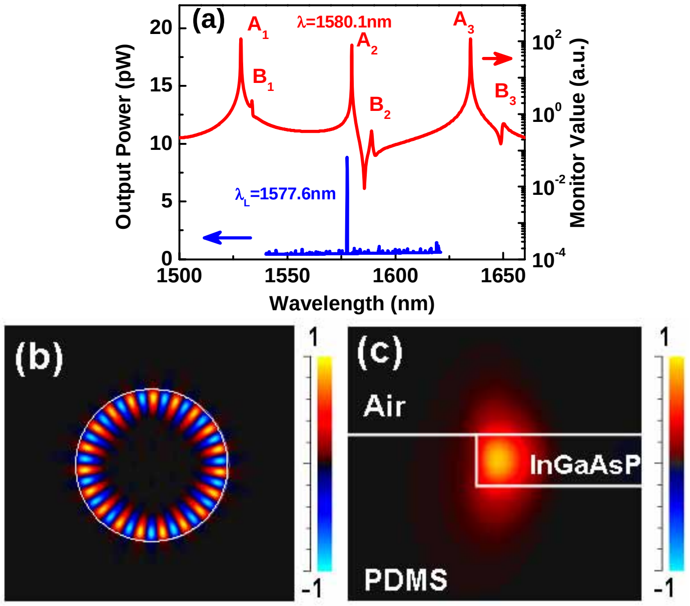

Fig. 4. (a). Comparison of FDTD simulation and measurement. The Red curve is simulated spectrum from FDTD simulation, and the blue curve is the measured spectrum for a 4.75μm microdisk laser. (b) The top view of Hz mode profile for a 4.75μm microdisk cavity at 1580.1 nm from the FDTD simulation. (b) The cross-section view of the calculated Hz profile around the edge of a microdisk cavity.

4. Lasing power and threshold versus bending curvature of the microdisk cavity

One of advantages of this type laser is that the optical properties can be manipulated by deforming the structure. With the flexible PDMS substrate, the variation of lasing power was observed by slightly bending the microdisk cavity and fixing the pumped conditions. The structure was bended along a diameter of the disk with a small curvature (1/R). Figure 5 shows the illustration of a bent microdisk cavity, and the R is the radius of the curve of the cavity surface. The bending curvature was verified carefully with optical microscope and SEM system. Figure 6 shows the measured lasing power of a 4.75μm disk at different bending curvatures. The lasing peak value dropped from 75 pW to 46 pW as the bending curvature increases from zero (flat substrate) to 0.053 mm^{-1} under the fixed pumped conditions which are the same pumped position, same pumped spot size and the fixed 2 mW pumped power. The curvature sensitivity in power of the compact laser, about 540 pW-mm, provides a high possibility in the sensing applications.

We also characterized the threshold power of the bent microdisk cavity. Figure 7 shows the L-L curve comparison of a 4.75 μm microdisk laser before and after bending. The blue and red L-L curves were obtained from this laser with zero and 0.053 mm^{-1} curvature, respectively. The threshold power increases from 0.55 mW to 0.81 mW when the cavity is bended slightly. The 45% raise of threshold power from the bent laser is because the quality factor decreases when the curvature of the bent cavity is increased.

There are points we should note here. The first issue is the microdisk laser still has good performance with the reasonable low threshold after the bending. It indicates this compact microdisk laser can be applied in integrated photonic systems on the non-flat or flexible substrates. However, it also can be used as the mechanical or curvature sensors because of its notable variation of optical properties at different curvatures.

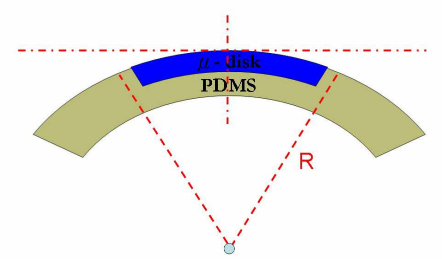

Fig. 5. The illustration of a bent microdisk cavity, and the R is the radius of the curve of the cavity surface.

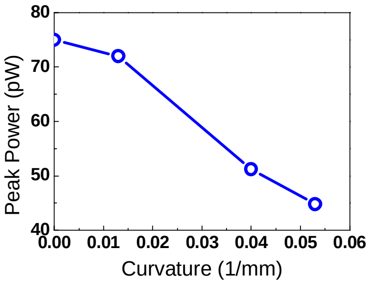

Fig. 6. The measured lasing power of a 4.75μm disk at different bending curvatures.

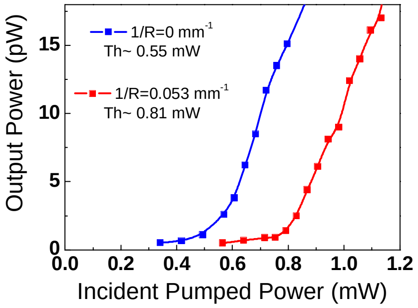

Fig. 7. The L-L curve comparison of a 4.75 μm microdisk laser before and after bending.

5. Summary

In summary, the compact size, flexible microdisk lasers on a PDMS substrate had been demonstrated. The lasing near 1550 nm wavelength was achieved with a low threshold power of 60 μW. The curvature dependence in lasing power and threshold were also characterized with the small bending of the cavities. This novel flexible microdisk laser can benefit to compact light source or sensor in the future photonic integrated systems.

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