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Compact Optical Curvature Sensor with a Flexible Microdisk Laser on a Polymer Substrate

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In this paper, a chip-scale compact optical curvature sensor was demonstrated. It consists of a low threshold InGaAsP microdisk laser on a flexible polydimethylsiloxane polymer substrate. The curvature dependence of lasing wavelength was characterized by bending the cavity at different bending radii. The measurements showed that the lasing wavelength decreases monotonously with an increasing bending curvature. A good agreement between experiment and three-dimensional finite-difference time-domain simulation was also obtained. The sensitivity of the compact device to the bending curvature is -23.7 nm/mm form the experiment.

OCIS codes: 140.5960, 140.3948, 250.2080, 280.4788

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, for instance, lasers [1-5], modulators [6-8] and sensors [9-12]. In addition, the optical curvature sensor had been studied widely with the long period fiber grating system [13-17]. This optical fiber technology can be applied in the curvature monitoring for larger structures such as bridges and buildings. However, these fiber gratings are not suitable for curvature sensing in either chip-scale integrated circuits or two-dimensional in-plane detection due to its structure size and special geometry. In this study, we demonstrated a compact optical curvature sensor with the InGaAsP microdisk laser on a polydimethylsiloxane (PDMS) substrate. The dimension of the sensor is less than 10 microns. This small size makes it suitable not only for monitoring the local curvature within few μm region, but also for performing the curvature detection or mapping in two-dimensional planes with the microdisk sensor array. Fig. 1 shows the illustration of an InGaAsP microdisk cavity on a PDMS substrate. The InGaAsP microdisk is embedded inside a flexible PDMS layer which is benefit to the bending ability of the cavity. The low index (n=1.41) of the PDMS also improve the vertical confinement of the optical mode in the disk, compare to microdisks on Si or GaAs substrates. 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 compact sensing device for the curvature of the bent substrate.

The microdisk cavities were implemented in a 240nm thick InGaAsP layer on the InP substrate. The InGaAsP layer consists of four 10nm thick strained InGaAsP quantum wells (QWs) which is designed for the lasers operated near 1550nm wavelength. A silicon nitride (SiNx) layer and a polymethylmethacrylate (PMMA) layer are deposited subsequently for the dry etching processes and electron beam lithography. The microdisk patterns were defined by electron beam lithography followed by two dry etching steps with CHF_3/O_2 mixture and $CH_4/Cl_2/H_2$ mixture gas 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 HCl solution. The size of the fabricated microdisk array is from 0.5 to 10μm in diameter for studying the compact lasers. Fig. 1(c) shows the SEM images of a microdisk array with varied diameters on the PDMS substrate. Fig. 1(d) is a close-up view of a microdisk cavity with a diameter of 4.75 μm. ~~The adhesion between the InGaAsP microdisk and the PDMS substrate is shown to be reliable for bending up to 10 mm radius.~~

The microdisk lasers were optically pumped at room temperature by 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 2 μm in diameter. The output power was collected by a multi-mode fiber connected to an optical spectrum analyzer. The lasing action of the microdisk cavities was achieved with a low threshold. Fig. 2(a) shows a lasing spectrum from a microdisk laser with 4.75 μm diameter. The lasing wavelength is around 1571.9 nm. The light-in-light-out (L-L) curve of this laser is shown in the Fig. 2(b). The threshold of the laser happened at 0.18 mW of incident pumped power. We roughly estimated the absorbed power in 240nm InGaAsP layer by considering the material absorption (~2 μm^{-1}) and surface reflectivity (~0.29). From the estimated values, only 5.4% of incident power is absorbed by the QWs. Therefore the effective threshold power is approximately 9.8 μW. This low threshold power of a single laser will benefit the further integration of the laser array. In order to understand the cavity mode of the flexible microdisk cavity, three-dimensional (3-D) finite-difference time-domain (FDTD) method was used to perform the simulation with a domain of **up to 10 μm x 10 μm x 5 μm** and 4 nm grid size for all three dimensions. The lasing mode from the measured microdisk was verified to be the first-order mode by comparing the measured and simulated spectra. The calculated Hz components of the first-order mode of a 4.75 μm microdisk cavity at the flat surface is shown in Fig. 2(c).

After the characterizing the microdisk lasers on a flat surface, the cavity was bended along the diameter of the disk on a bent metal surface. Fig. 3(a) illustrates the the microdisk cavity with the curvature 1/R after bending. We expected the lasing characteristics of the microdisk can be manipulated by varying the bending radius R. The microdisk was mounted on the metal plates with different bending radius. These curved metal surfaces were formed by bending the metal plates in the slots with varied bending radii with a homemade curvature component. Fig. 3(b) shows the curvature component and the curved metal plates. We also verify the surface curvature of the device with optical microscope and SEM images after the device is mounted on the bent metal surface. In the experiment, the variation of lasing wavelength was observed by bending the microdisk cavity and fixing the pumped conditions and power. Fig. 3(c) shows the lasing spectra of a 4.75 μm microdisk laser at the varied bending curvatures (1/R = 0, 0.022, 0.066 and 0.080 mm^{-1}) under the same pumping conditions and fixed 2.0 mW incident pumped power. The microdisk achieved lasing at all these bending curvatures. According to the data, the lasing wavelength reduces as the bending curvature increases. This special blue shifted characteristic can be applied to compensate the red shift of lasing wavelength due to the operating temperature increase, especially for the compact lasers and laser arrays. The InGaAsP/PDMS hybrid microdisk cavity is shown to be reliable for bending up to 10 mm radius, according to the SEM images and lasing data after several bending processes. The 3-D FDTD

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method was also used to perform the simulation for the wavelength of the bent microdisk at varied curvatures. Here the FDTD simulations only calculated the resonant modes for a cold cavity. The change of material gain due to physical strain and the anisotropy due to photoelastic effect were not considered in the calculations. Fig. 4(a) shows the comparison of the 3D-FDTD simulation and measurement at different curvature. The blue curve is the calculated wavelength of the bended microdisk cavity on a PDMS substrate at varied curvatures. The wavelength of the operated mode is blue-shifted linearly as the bending radius decreases from flat to 20 mm, and the wavelength decrease dramatically once the bending radius is smaller than 20 mm. The measured lasing wavelength is also shown in the Fig. 4(a) with the red triangular dots. The experiment results agree with the FDTD simulation very well. The difference between the simulation and measurement in wavelength is approximately 2 nm, which is less than 0.2%. This difference is believed to be caused by the small discrepancy in refractive index used in the simulation and experiment. The lasing wavelength is varied linearly in a wide bending region between flat to 20 mm radius which is suitable for the curvature sensing. Fig. 4(b) shows the curvature dependence of lasing wavelength in this linearly region. The sensitivity of the curvature sensor is approximately -23.7 nm/mm^{-1} . Although it is not higher than other larger size curvature sensors [16,17], this value is good enough for the micrometer-size sensor to detect the local curvature variation within the few μm region. The micrometer size, flexible platform also stands on a vantage point for the high-density integration of the sensor arrays in a single chip.

In summary, we fabricated compact flexible microdisk lasers on a PDMS substrate with a very low threshold of 9.8 μW. The curvature sensing ability of the compact laser was demonstrated based on the lasing wavelength at different curvatures. It can detect the local curvature variation due to the compact size of the microdisk. The compact flexible microdisk laser and its very low threshold power promise the chip-scale integration of the high density sensor array for future applications.

Figure captions

Fig. 1

The illustrations of an InGaAsP microdisk cavity on a polydimethylsiloxane (PDMS) polymer substrate from (a) angle-view and (b) cross section-view. (c) A SEM image of a microdisk lasers array on a PDMS substrate. (d) A magnified SEM image of a 4.75μm microdisk laser on a PDMS substrate.

Fig. 2

(a)The lasing spectrum and (b) light-in-light-out (LL) curve of a 4.75μm microdisk laser on a PDMS substrate. The lasing wavelength is 1571.9 nm, and the incident threshold power is 0.18 mW. (c)The calculated Hz mode profile for a 4.75μm microdisk laser on a PDMS substrate form 3-D FDTD simulation.

Fig. 3

(a)The illustration of a bent microdisk cavity on a PDMS substrate with a bending radius of R. (b) The home-made curvature component (right) and the bendable metal plates (left) for characterization. (c) The measured lasing spectra from a microdisk laser on a PDMS substrate at varied curvatures under the fixed pumped conditions and 2 mW incident pumped power.

Fig. 4

(a) The comparison of the FDTD simulated and measured lasing wavelength at varied bending radii. (b) The measured lasing wavelength versus the device curvature within the linear sensing region. The sensitivity is approximately -23.7 nm/mm^{-1}.

Figure 1.

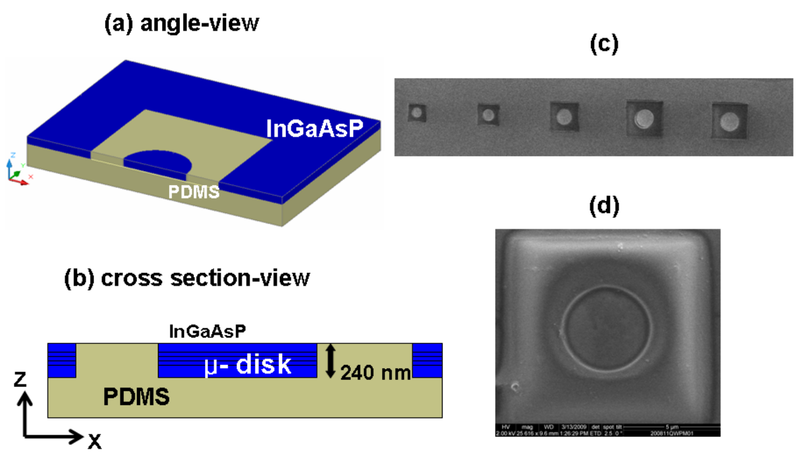
(a) angle-view
InGaAsP
PDMS
(c)
(d)
(b) cross section-view
InGaAsP
μ- disk
240 nm
PDMS
z
x

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Figure 2.

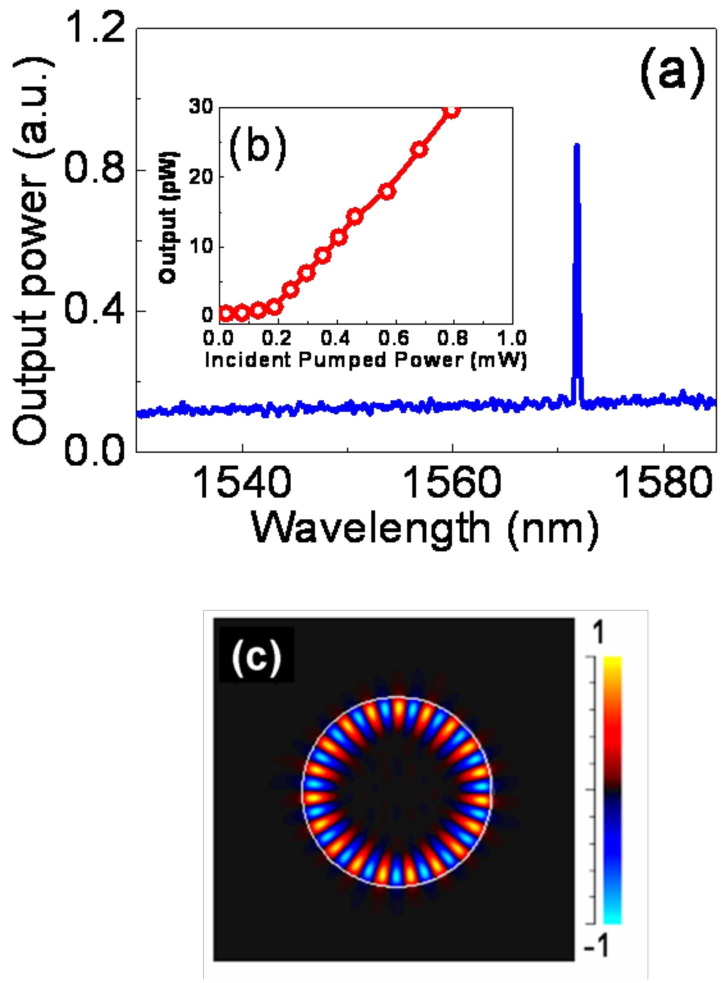


Figure 3.

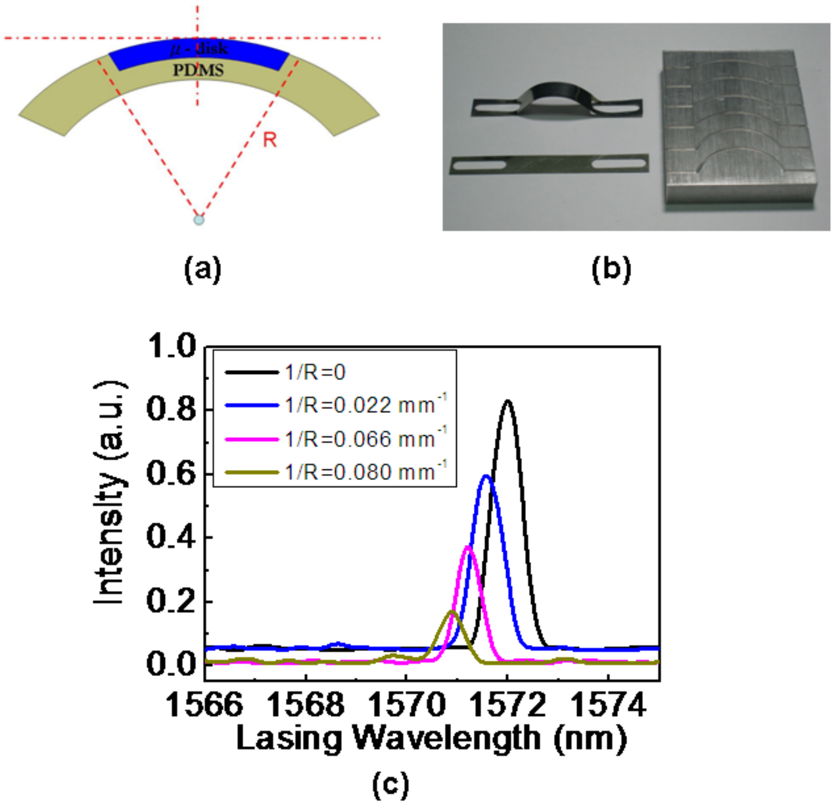
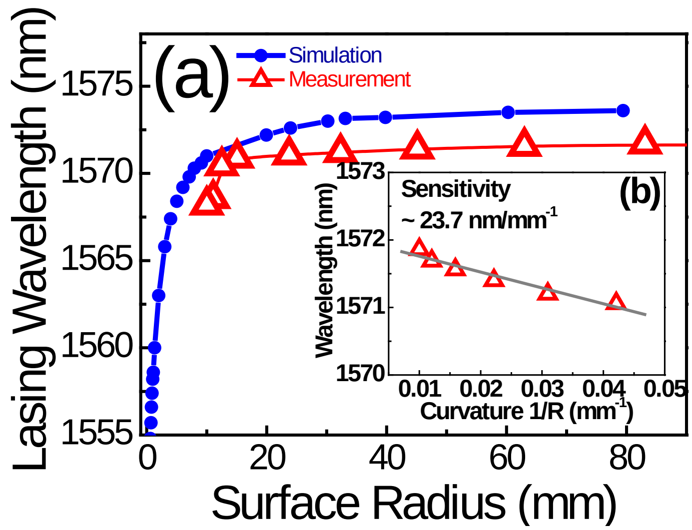

μ - disk
PDMS
R
(a)
(b)
1/R=0
1/R=0.022 mm⁻¹
1/R=0.066 mm⁻¹
1/R=0.080 mm⁻¹
Intensity (a.u.)
0.0
0.2
0.4
0.6
0.8
1.0
1566
1568
1570
1572
1574
Lasing Wavelength (nm)
(c)

Figure 4.


(a)
Simulation
Measurement
Lasing Wavelength (nm)
1575
1570
1565
1560
1555
0
20
40
60
80
Surface Radius (mm)
Sensitivity
~ 23.7 nm/mm-1
(b)
Wavelength (nm)
1573
1572
1571
1570
0.01
0.02
0.03
0.04
0.05
Curvature 1/R (mm-1)

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