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Optical biochemical sensor based on half-circled microdisk laser diode

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Abstract: In this study, a half-circled cavity based microdisk laser diode is proposed and demonstrated experimentally for an integrated photonic biochemical sensor. Conventional microdisk sensors have limitations in optical coupling and reproducibility. In order to overcome these drawbacks, we design a novel half-circled micro disk laser (HC-MDL) which is easy to manufacture and has optical output directionality. The Q-factor of the fabricated HC-MDL was measured as 7.72×10^6 using the self-heterodyne method and the side mode suppression ratio was measured as 23 dB. Moreover, gas sensing experiments were performed using the HC-MDL sensor. A wavelength shift response of 14.21 pm was obtained for 100 ppb dimethyl methylphosphonate (DMMP) gas and that of 14.70 pm was obtained for 1 ppm ethanol gas. These results indicate the possibility of highly sensitive gas detection at ppb levels using HC-MDL. This attractive feature of the HC-MDL sensor is believed to be very useful for a wide variety of optical biochemical sensor applications.

OCIS codes: (130.0130) Integrated optics; (130.6010) Sensors; (140.3948) Microcavity devices.

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1. Introduction

Recently, various integrated optical-resonator-based, high-sensitivity biochemical sensors with ultra-high Q-factors, such as micro-toroids [1–3], micro-spheres [4–6] and micro-disks [7,8], have been studied and developed. However, because tapered optical fibers must be precisely coupled, it is difficult to fabricate and utilize ultra-high Q sensors. The coupling factor affects the Q-factor of the resonator, and it cannot be easily integrated with other devices. Owing to the necessary of precise alignment of the fibers, the properties are significantly influenced by the external factors, such as pressure and vibration. However, deformed micro disk lasers with high Q factor and unidirectionality do not suffer from this drawback [9–11]. However, this structure is very difficult to design and has a very small process tolerance in fabrication. Therefore, it is not suitable for the mass production of low-cost, highly reproducible high-sensitivity sensors.

In order to overcome these limitations of resonator-based sensors, we propose and demonstrate a bended Fabry-Pérot(BFP) cavity-based half-circled micro disk laser(HC-MDL) sensors. HC-MDL sensors have many advantages such as simple design, simple fabrication, high Q-factor, high sensitivity, and high reproducibility. An HC-MDL sensor consists of a half-circled cavity, deep-etched mirror, and probing pad with an air-bridge metal line. In the half-circled cavity, the traveling wave propagates repeatedly along the boundary between cavity and air by means of a deeply etched mirror. The traveling wave is similar to the whispering gallery mode(WGM). The high sensitivity of the HC-MDL sensor results from the open sensing area of the core waveguide by the deep etching. Morevere, the proposed HC-MDL structure can be easily combined with various integrated optical structures such as y-branch, multimode interference, and photo-detector. In this paper, we describe the fabrication and characterization results of the proposed HC-MDL structure, and discuss the results of dimethyl methylphosphonate(DMMP) gas detection experiment using the fabricated HC-MDL. Consequently, gas detection was confirmed by measuring the laser wavelength shift of the HC-MDL. This wavelength change is caused by the effective refractive index change around the sensor, and the gas concentration can be estimated from the variation of the laser wavelength.

2. Design and fabrication

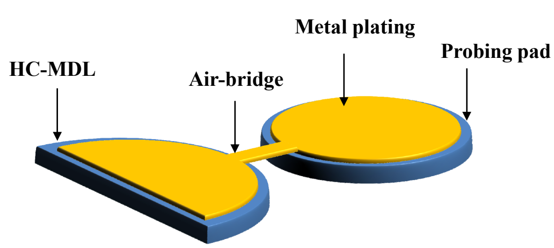

Fig. 1. Schematic of the proposed HC-MDL sensor structure.

Figure 1 shows the proposed device based on III-V semiconductors. The radius of the half-circled cavity, radius of the probing pad, and etching depth are 50 μm, 40 μm and 4 μm, respectively. The HC-MDL and the electrical probing pad are connected via an air-bridge metal line. In order to ensure the stability of the HC-MDL against external factors such as pressure and vibration duaring electrical pumping, an external probing pad is designed. Moreover, the probing pad and the HC-MDL are connected by an air-bridge metal line. Moreover, since the core waveguide is exposed to the outside, it is very high sensitive to changes in external refractive index. The p-metal under-metal plating is designed for the selective pumping for the WGM-like BFP mode along the boundary of the HC-MDL.

The microscope image of the fabricated HC-MDL sensor is shown in Fig. 2(a). The key aspect of this fabrication is the inductively coupled plasma(ICP) etching process. In the deep etching for exposing the core to the outside, a 4000 Å thick SiO_2 thin film was used as a mask, and a deep etching process was performed for 150 seconds at a ratio of Cl_2: H_2: Ar = 9: 19:2 through ICP equipment. A vertically etched facet affects the operating characteristics of the HC-MDL because it directly affects the Q-factor. Figure 2(b) shows the scanning electron microscope(SEM) image of the etched facet. The photograph shows that the roughness of the surface is very good owing to the quantum well region. The effect of roughness on the laser facet is negligible(less than λ/15) [12]. The fabricated device satisfies this condition. Moreover, it can be observed that the air-bridge connecting the HC-MDL and the probing pad is well formed.

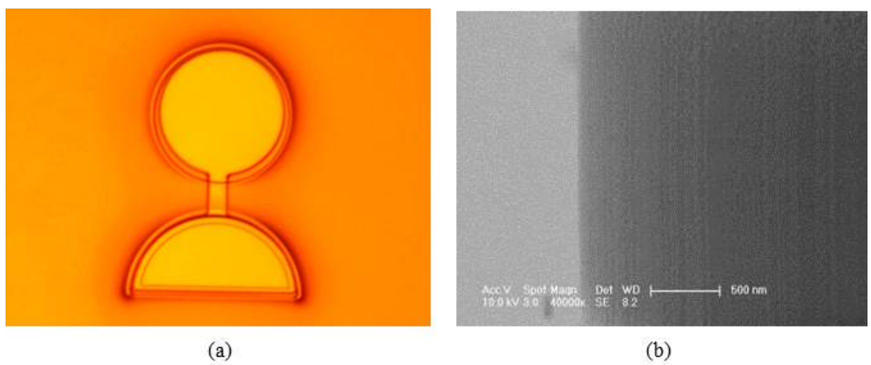

Fig. 2. Microscope images (a) The photolithography image of the HC-MDL to obtain the air-bridge (b) Deep-etched facet image of the HC-MDL using SEM

3. Operation characteristics

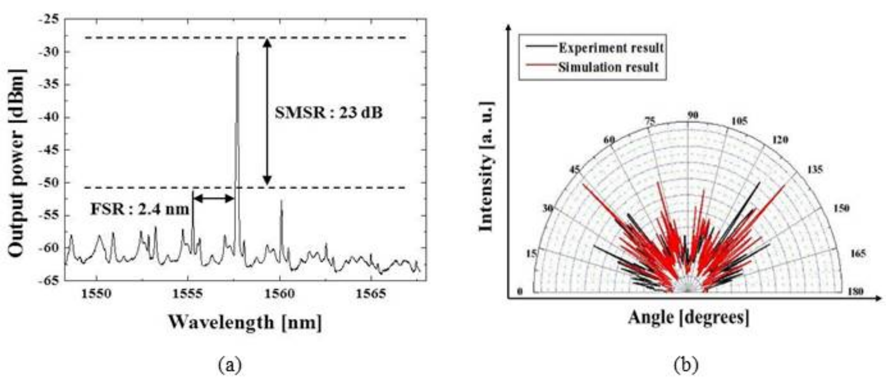

Fig. 3. Operation characteristics of the HC-MDL. (a) Lasing spectrum of the HC-MDL. (b) Far field pattern

The lasing characteristics of the fabricated HC-MDL are shown in Fig. 3(a). Stimulated emission is observed near the telecommunication wavelength and side mode suppression ratio characteristics of 23 dB are observed. The characteristic of operating in a single mode plays a very important role in the applicability to biochemical sensors. When the sensor performs peak tracing to observe the wavelength shift, confirming the fine movement of the peak becomes difficult when a multimode is present. Figure 3(b) shows a far-filed pattern of the HC-MDL. The light traveling along the circumference of the HC-MDL is output at both ends through a deep-etched mirror such as the FP laser. Moreover, the free spectral range of the HC-MDL is 2.4 nm, which is exactly the same as the calculation according to the length of

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light traveling along the circumference. Therefore, the cavity mode inside the proposed HC-MDL can be called the WGM-like BFP mode.

The Q-factor of the proposed HC-MDL cannot be measured owing to the wavelength bandwidth resolution limit of the optical spectrum analyzer equipment. Therefore, we measure the Q-factor of the fabricated device using the self-heterodyne method [13, 14]. Figure 4 is a schematic diagram of the experimental set-up of the self-heterodyne used for Q-factor measurements. An optical modulator was used to avoid 1 / f noise and a delay line was used to break the coherence. The modulation frequency of the optical modulator and the length of the delay line were 40 MHz and 10 km, respectively. The measured results are shown in Fig. 5. It can be observed that the full width at half maximum (FWHM) of the HC-MDL using the beating signal with a 3 dB bandwidth of 50 MHz is 25 MHz. Therefore, the Q-factor of HC-MDL is 7.72×10^6, which shows that the structural loss is compensated by the active medium and moreover, the loss in the deep-etched mirror is extremely small.

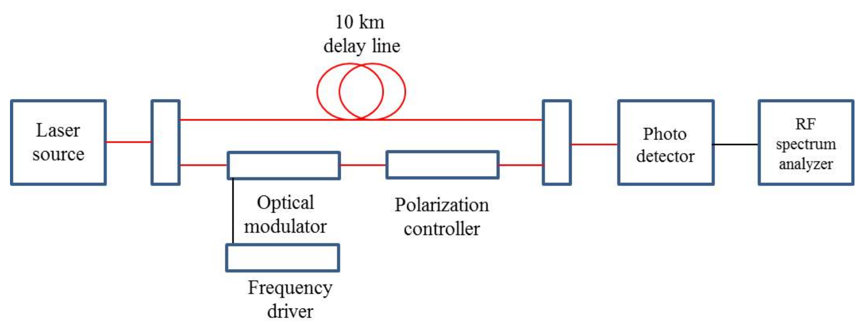

Fig. 4. Experimental setup of the self-heterodyne to detect a high Q-factor.

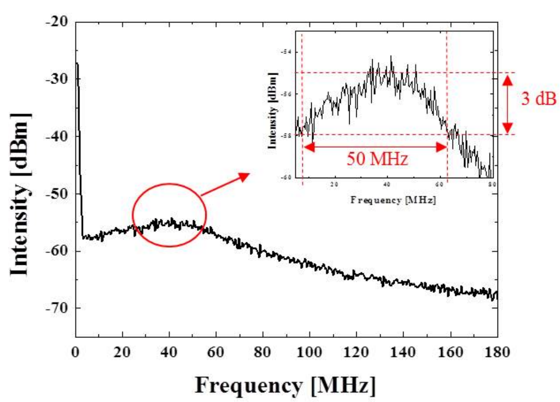

Fig. 5. Self-heterodyne beating signal of the HC-MDL.

4. Gas sensing results of the HC-MDL sensor

Figure 6(a) shows the experimental setup for gas sensing using a vacuum chamber and a mass flow controller (MFC). The proposed sensor is fixed in the chamber through the vacuum contact, and the lasing characteristics of the HC-MDL are measured using a lensed fiber and a DC probe tip as shown in Fig. 6(b). We align the lensed fiber based on the measured far field pattern and inject the current into the HC-MDL using the probe tip to measure the change in the lasing wavelength of the HC-MDL detected by the lensed fiber. The injected target gases 1 ppm of DMMP, 10 ppm of ethanol gas and N_2 gas injected-into the chamber are controlled by the MFC.

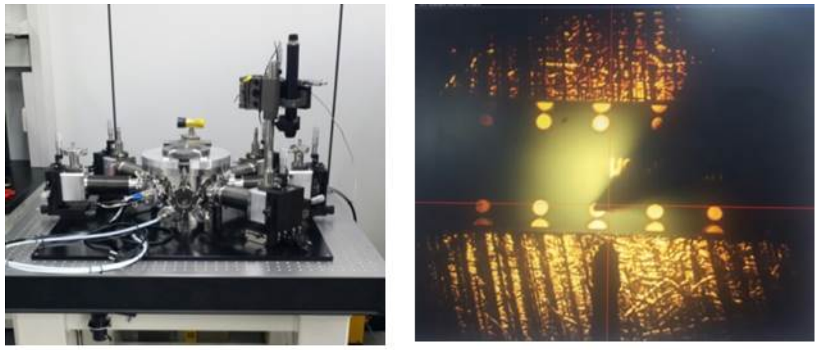

Fig. 6. Experiment setup for gas sensing using the vacuum chamber. (a) Measurement stage on the optical table. (b) Measurement of the HC-MDL in the vacuum chamber.

First, the chamber is evacuated and N_2 gas is injected at 1000 sccm for 30 min to stabilize the characteristics of the HC-MDL. Second, the target gas to be measured is mixed with N_2 gas at a ratio of 9:1, and the concentration is adjusted to 10%. Further 1 ppm DMMP gas and 10 ppm ethanol gas are used as the target gas, and injected at the concentrations of 100 ppb and 1 ppm, respectively. Finally, the HC-MDL is regenerated by injecting N_2 gas similar to the first step. The effective refractive index around the HC-MDL changes according to the concentration and mass of the injected target gas. Therefore, the lasing characteristic of the HC-MDL changes accordingly because the resonance condition of the HC-MDL is changed by the variation of the external effective refractive index. Figure 7 illustrates the change in the wavelength depending on the change of gas injected into the chamber. The gas flow unit over time is shown in Fig. 7(a). The sample stabilized through the injection of N_2 gas is measured for 5 min, and after the target gas is injected, it is regenerated using N_2 gas after 40 min. This was followed by a method of detecting the two target gases. DMMP which has a high molecular weight of concentration 1 ppm was used, and ethanol of concentration 10 ppm was used. According to the injection of the target gas, the DMMP gas reacted 3 min after the injection; further, the red shift of the lasing wavelength was generated at 14.21 pm, and the ethanol gas reacted after 15 min to show the wavelength change of 14.7 pm as shown in Fig. 7(b). The loss of the cavity owing to the gas molecules attached to the periphery of the HC-MDL causes the output power to increase as shown in Fig. 8(c). When ethanol gas was injected, the output power of the HC-MDL increased by 7 dB. In the case of DMMP, this has a smaller concentration than ethanol, the output power increased by approximately 3 dB at the point of reaction of the target gas. Figures 7(d) and 7(e) show the variation of the wavelength spectrum. The lasing wavelength of the HC-MDL changes depending on the gas change in the chamber. The proposed sensor could detect a very small amount of DMMP gas by showing a wavelength shift of 14.21 pm and an output power change of 3 dB for 1 ppm of DMMP gas at the concentration of 10%, which corresponds to 100 ppb.

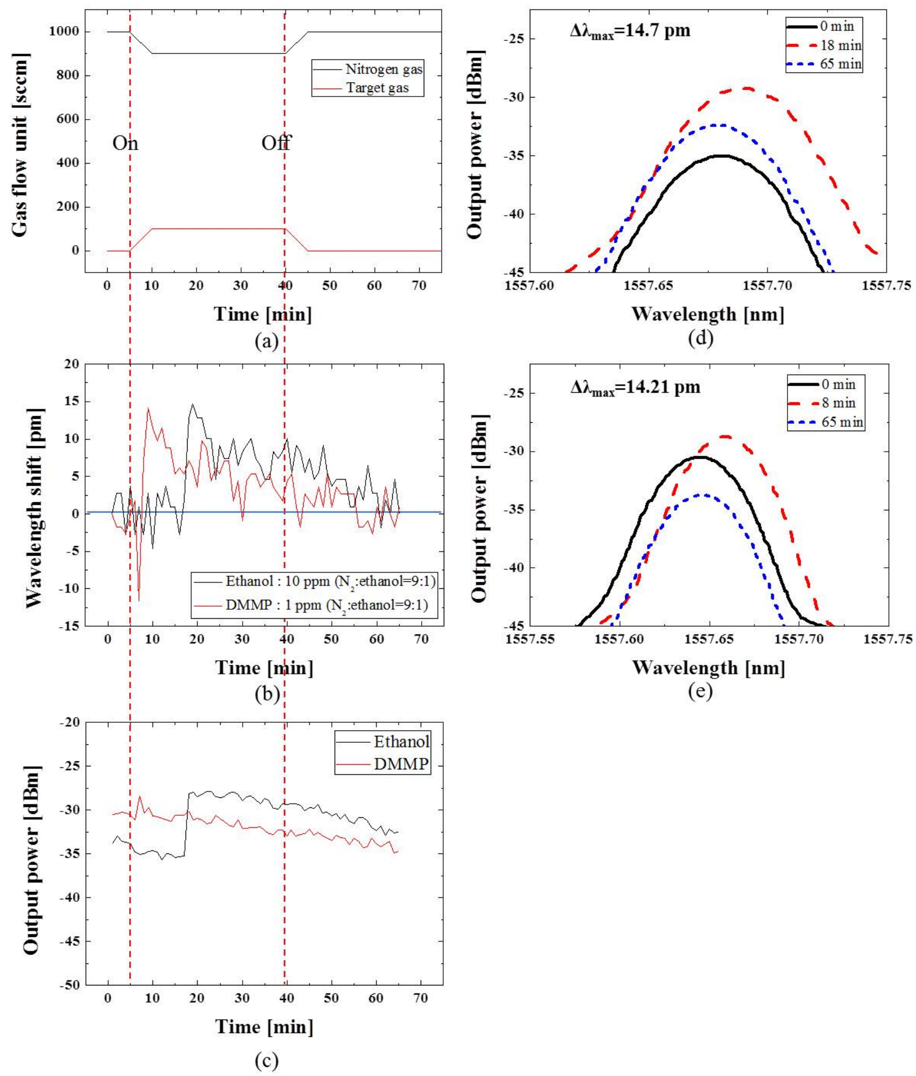

Fig. 7. Gas sensing experiment. (a) Target gas flow chart. (b) Wavelength shift of the HC-MDL according to the changes in the gas concentration in the chamber. (c) Output power variations according to the target gas injection (d) Changes of the lasing wavelength for the ethanol gas injection. (e) Changes of the lasing wavelength for the DMMP gas injection.

5. Conclusions

In this paper, an integrated chemical gas sensor, which we refer to as the HC-MDL, with a WGM-like BPF cavity has been demonstrated and characterized. The demonstrated HC-MDL has a high Q-factor of 7.7×210^6, which is measured using the self-heterodyne method. With its simple design and easy measurement, the HC-MDL can be used as a sensor capable of measuring 100 ppb of DMMP with the wavelength shift of 14.21 pm and 1 ppm of ethanol with the wavelength shift of 14.7 pm. Moreover, it was observed that the output power of the HC-MDL changes owing to the scattering loss caused by the gas molecules. Therefore, the proposed HC-MDL sensor exhibits high Q-factor and high sensitivity by loss compensation through electrical pumping and a significant advantage in integration with other devices owing to its fixed lasing directionality.

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