External Cavity Lasers Based on Photonic Crystal Nanobeam For Refractive Index Sensing

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***Abstract*—We propose an external cavity laser based on a nanobeam cavity and RSOA for sensing. The detection limit of the refractive index change is improved by a factor of 175 compared to its passive counterpart.**

***Keywords*—Photonic crystal nanobeam cavity, External cavity laser, Sensor**

I. INTRODUCTION

In recent years, optical microresonators have greatly enhanced the interaction between light and matter due to their ultra-high quality factor(Q factor) and extremely small mode volume, which has attracted widespread attention in the field of sensing [1]–[3]. The detection limit of optical microsensors is primarily influenced by the cavity mode linewidth, which impacts the resolution of resonance wavelength. In passive resonators, this linewidth is restricted by geometric structure, scattering loss, and material absorption. Adopting advanced fabrication processes can further reduce the radiation and scattering losses and increase the Q factor of the microresonators. Nevertheless, the linewidth of a passive cavity remains ultimately constrained by material absorption. Unlike pasive devices, active cavities with optical gain can compensate intrinsic losses, and significantly reduce the mode linewidth [4]. Moreover, compared to passive sensors, active sensors have a simplified structure, which reduces system complexity and cost. When lasers are used as a key component in the optical sensing system, the sensing resolution and detection limit can be significantly improved. On-chip lasers with external cavities pave a promising way for small-footprint High-Q optical sensing with attractive scalability [5]–[7].

In this work, we propose a single-wavelength external cavity laser based on a photonic crystal nanobeam. Utilizing a single nanobeam side-coupled to a bend waveguide as the external cavity, our scheme has small footprint. Using FDTD numerical method, the simulated intrinsic Q factor of the photonic crystal nanobeam cavity is 5×10^6. The simulated 20 dB linewidth of the external-cavity laser is less than 0.004 nm and the refractive index sensitivity of the laser sensing system is about 113 nm/RIU.

II. RESULTS AND DISCUSSION

We propose an on-chip external cavity laser based on a photonic crystal nanobeam cavity and a reflective semiconductor optical amplifier (RSOA) for the optical sensing application. The nanobeam cavity is designed on a SOI wafer with 220 nm-thick top silicon layer and 2 μm-thick buried oxide layer, which is widely applied in the standard silicon photonic foundries. The circular air holes of the nanobeam cavity are etched into a strip silicon waveguide with a width of 700 nm as shown in Fig.1(a). The radius of the air hole is 135 nm and the device has an air cladding. Based on the deterministic nanobeam design principles reported in [8], we can design a Gaussian-shape-mirror-like nanobeam cavity to reduce the

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intrinsic loss. In the tapered region of the nanobeam cavity, the lattice constant ($a(i)$) varies from 350 nm ($a(1)$) at the center to 390 nm ($a(N_{taper})$) at the ends of two sides according to the following transforming pattern:

$$a(i) = a(1) - \frac{a(1) - a(N_{taper})}{(N_{taper} - 1)^2}(i - 1)^2. \quad (1)$$

The period part has N_{mirror} holes with a lattice of $a(N_{taper})$. In this paper, N_{taper} = 15 and N_{taper} = 10, the coupling gap is g = 185 nm and the waveguide width is w = 500 nm. The resonance wavelength of the nanobeam microcavity is 1556.97 nm. The simulated power transmission and reflection spectra of the nanobeam-based external cavity are shown in Fig.1(b, c), and the inset in the right of Fig.1(c) shows the electric field distribution in the xy plane (z = 0) at the nanobeam resonance wavelength.

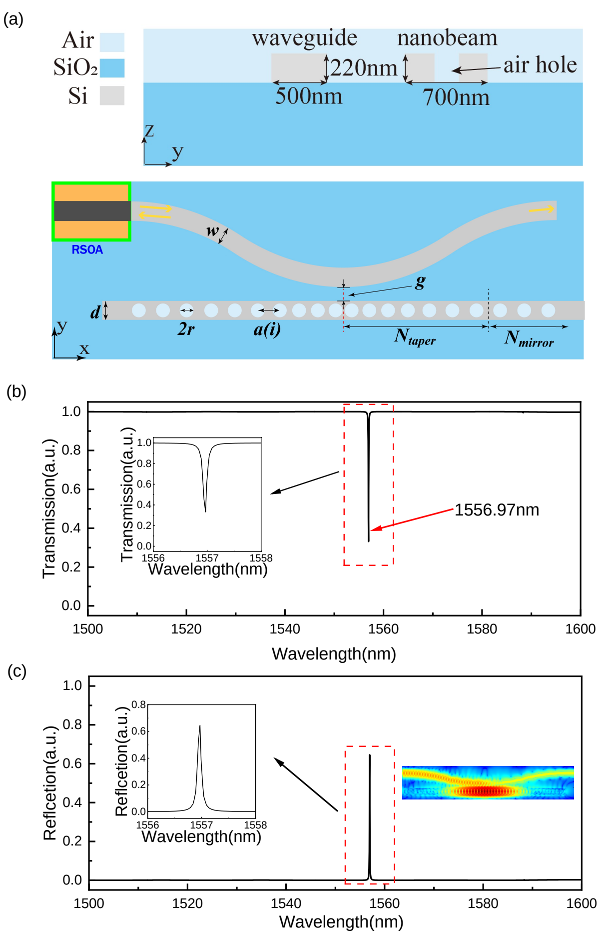

Fig. 1. (a) Schematic of the on-chip external cavity laser using a nanobeam micoresonator and a reflective semiconductor optical amplifier (RSOA). (b-c) Simulated transmission and reflection spectrum of the nanobeam-based external cavity. The insert shows the details of the spectrum close to the resonance wavelength. The inset in the right of (c) is the simulated electric field on the xy (z = 0) plane at the resonance wavelength.

In principle, the RSOA provides the necessary optical gain to balance the loss of the inner and external cavities. The tapered edge coupler is used to couple the light between the RSOA and the external nanobeam cavity as reported by [9]. The light of the out-of-resonance will bypass the nanobeam cavity and emit out of the external cavity through the bend waveguide. On the other hand, the light of the on-resonance wavelength will be coupled into the nanobeam cavity and be partially reflected back to the RSOA. Thus, there is a highly wavelength-selective optical feedback in the on-chip external cavity laser system as shown in Fig.1(b, c). The Full Width at Half Maximum(FWHM) of the resonance peak is narrow and there is no side mode across a wide range around 100 nm. From the simulation, the laser operates in a single-longitudinal mode under a broad optical bandwidth unlike other external cavity lasers [5]–[7] that have small free spectral range (FSR). Our design shows a promising way to achieve a single-mode lasing with a simple external cavity configuration.

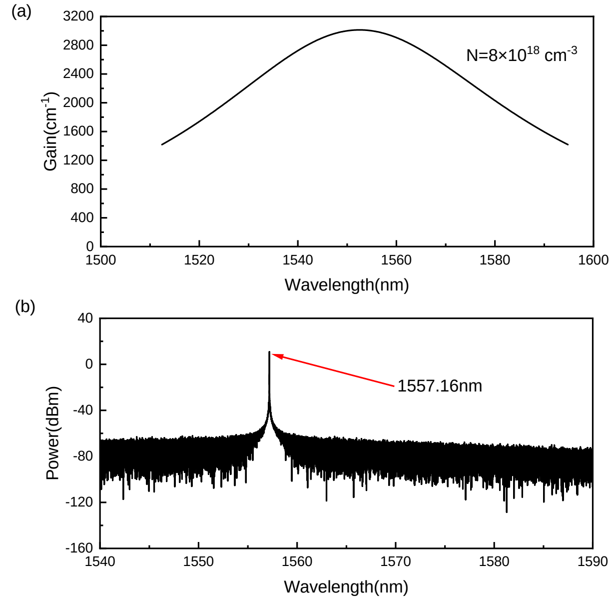

Fig. 2. (a) The simulated gain spectrum of the RSOA. (b) The simulated laser emitting spectrum

We model the external cavity as a two-port optical S-parameter component. Within the given wavelength range (1500 - 1600 nm in this study), the S-parameters are used to represent the transmission, reflection, and phase characteristics of the external cavity. For obtaining the emission spectrum of the laser, we employed the transmission line (TL) model to simulate our laser. In simulation, the gain material is set to typical InP, the active region has a length of 400 µm, a width of 2.5 µm, and a thickness of 40 nm, initial gain coefficient $g_0 = 1.8 \times 10^3$ cm^{-1}, the transparency carrier density $N_{tr} = 1.5 \times 10^{18}$ cm^{-3}. The logarithmic gain curve is given by the following formula:

$$g = g_0 \frac{ln\frac{N}{N_{tr}}}{1 + \frac{Q(\lambda - \lambda_c)}{2\lambda_c}}. \quad (2)$$

Where N is carrier density; Q = 20 is the Lorentzian linewidth quality factor; λ_c = 1552.6 nm is the central wavelength of gain curve. Fig.2(a) shows the logarithmic gain curve which we set in simulation, in this work, the carrier density is set to $N = 8 \times 10^{18}\ \mathrm{cm}^{-3}$, corresponding drive current is 60 mA. The simulated lasing wavelength is 1557.16 nm and the emission spectrum of the external cavity laser is shown in Fig.2(b).

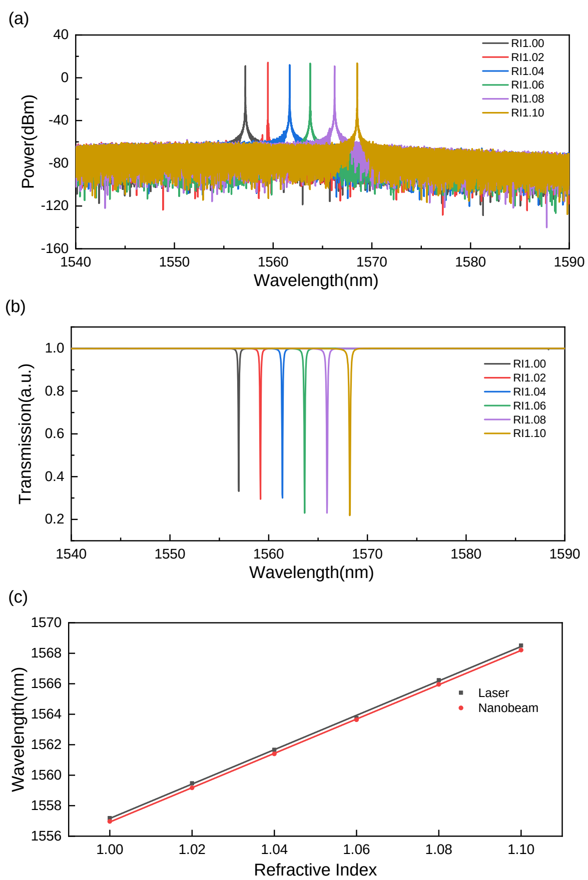

Fig. 3. The variation in the simulated laser emission spectrum (a) and the nanobeam transmission spectrum (b) as the refractive index changes from 1.00 to 1.10. (c) The change of simulated laser emission wavelength and nanobeam resonance wavelength with refractive index and their linear fit.

When we increased the refractive index (RI) of the cladding layer to simulate the change of the environment, both the resonance wavelength of the nanobeam cavity and the lasing wavelength of the external cavity laser redshifted. In this sensing scenario, the relationship between the change of the RI (1.00 to 1.10) and the lasing wavelength shift is shown in Fig.3(a). The sensitivity (S) of the nanobeam-based external cavity laser sensing system is also compared with the passive nanobeam cavity as shown in the Fig.3(b, c). They are almost the same around 113 nm/RIU with excellent linearity. The limit of detection (LoD) of the sensor refers to the minimum wavelength shift that can be detected. In general, the FWHM, also known as the 3 dB linewidth, is considered the minimum detectable shift in the central wavelength. So the LoD can be expressed as [10]:

$$LoD = \frac{FWHM}{S} \tag{3}$$

As shown in Fig.4, the FWHM of the passive external cavity is about 0.07 nm, while the 20 dB linewidth of the laser is about 0.004 nm. It can be calculated from the formula :

$$1 + (\frac{\Delta\lambda_{20dB}}{\Delta\lambda_{3dB}})^2 = 100 \tag{4}$$

that the 3 dB linewidth of the laser is about 0.4 pm. According to Eq.(3), we can calculate that the detection limit of the passive cavity is $LoD_p = 0.07/113 = 6.2 \times 10^{-4}$ RIU, while the detection limit of the laser is $LoD_g = 0.0004/113 = 3.54 \times 10^{-6}$ RIU. Thus, it can be inferred that the laser's detection limit is improved by a factor of about 175 compared to the passive cavity. It is noteworthy that due to simulation accuracy limitations, the resolution of the simulated laser spectrum is 25 GHz. Consequently, the actual laser linewidth may be narrower, and leading to an even better detection limit.

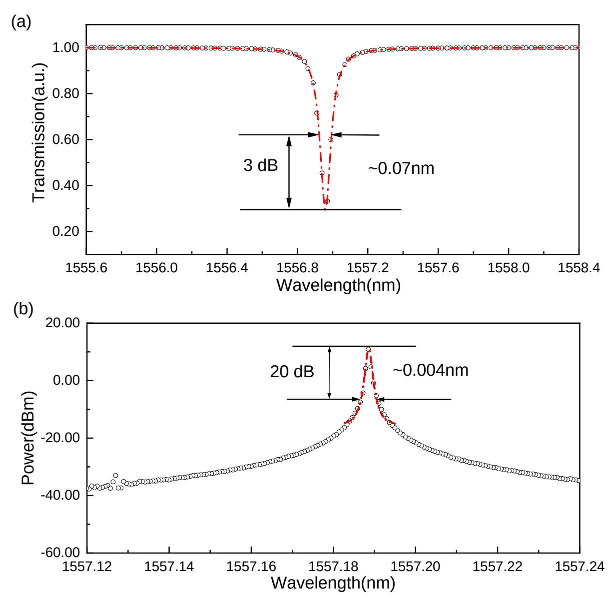

Fig. 4. Simulation data of the transmission spectrum of the nanobeam (a), emission spectrum of the laser (b), and their Lorentz fit.

III. CONCLUSION

In our design, the external cavity of the RSOA is made only by a nanobeam cavity side-coupled to a S-bend waveguide with small footprint of about a few tens of square micrometers. Under the simple configuration, the external cavity laser can also achieve excellent single-longitudinal mode operation across a broad spectrum range because the wavelength tunability is not limited by the FSR of the nanobeam cavity. The laser wavelength can be tuned by changing the refractive index of the cladding layer of the external cavity, which is related to the environment properties. Compared to the passive nanobeam cavity, the refractive index sensitivities of the external laser sensing system is in the same level around 113 nm/RIU. However, the detection limit of the active sensor is improved by a factor of 175 as a result of the optical feedback in the lasing mode. In conclusion, the photonic nanobeam cavity shows promising future for the high-performance large-scale integrated active optical sensors.

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