Monolithic Integration of Si_3N_4 Ring Resonator and On-Chip Fourier Transform Spectrometer for The Lab-On-A-Chip Biosensor

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Abstract: We demonstrated the monolithically integrated biosensor with micro-ring-resonator (MRR) and spatial-heterodyne Fourier-transform-spectrometer (SH-FTS) on Si_3N_4-on-SiO_2, substituting the external optical spectrum analyzer. The spectrum is retrieved from SH-FTS with the bulk sensitivity of 42.9 nm/RIU. © 2022 The Author(s)

As the needs of the accurate and fast point-of-care portable bio-detection systems are growing rapidly for the clinical and health-monitoring applications, various of micro- and nano-scale optical biosensors have intrigued a significant attention as compact, highly selective, and sensitive real-time biosensor platforms. Among them, micro-ring-resonator (MRR) based optical sensors have been demonstrated in numerous applications due to their advantages of high sensitivity and small footprint [1]. Also, the near-infrared (NIR) tissue transparency wavelength from 600 nm to 1200 nm is beneficial for the non-invasive in-vivo mammalian bio sensing applications, and silicon nitride (Si_3N_4) is known as one of the best candidates for the visible to NIR wavelength applications due to its low material absorption loss in this wavelength range as well as moderately high refractive index (n~2) [2]. The general sensing principle of MRR bio sensing is based on the detection of the resonance wavelength shift ($\Delta\lambda$). Based on the evanescent field sensing mechanism, the resonance condition of the MRR is changed when the refractive index of the functionalized layer is changed due to the binding between the target molecules and the receptors, leading to a resonance wavelength shift. Several research have introduced Si_3N_4 MRR bio-sensing applications [3,4] but utilizing external optical spectrum analyzer (OSA) was inevitable to read the spectrum and detect $\Delta\lambda$, making the overall system bulky and expensive. To miniaturize the whole system into a chip for the lab-on-a-chip biosensor, the integration of MRR and on-chip spectrometer benefit from the photonic integrated circuits (PICs) is highly demanded. In this paper, we demonstrated the monolithic integration of MRR and spatial-heterodyne Fourier transform spectrometer (SH-FTS) on the Si_3N_4-on-SiO_2 platform.

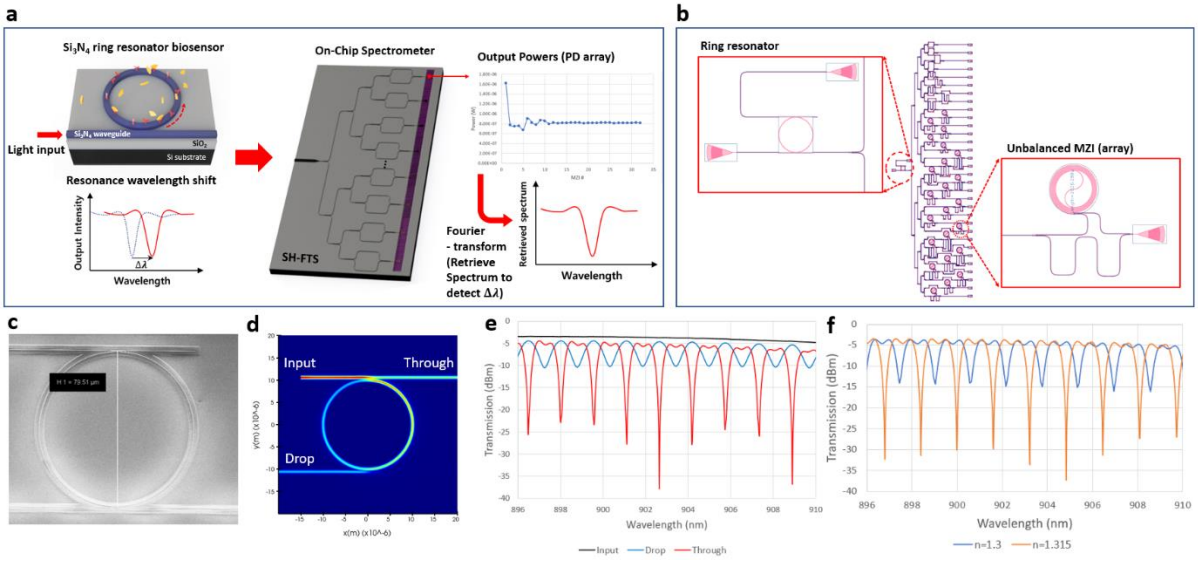

Fig. 1. (a) Conceptual diagram of the MRR and SH-FTS integrated biosensor system. (b) The outlook of the integrated device footprint including MRR and an array of MZI. (c) The SEM image and (d) electrical field simulation of the Si_3N_4 MRR. (e) The transmission spectrum of the MRR including input, drop port, and through port signals with $n_{clad} = 1$. (f) The through port transmission spectrum with $n_{clad} = 1.3$ and $n_{clad} = 1.315$ showing $\Delta\lambda = 643$ pm.

Fig. 1a shows the overall concept of the MRR and SH-FTS integrated biosensor system. The output port of MRR is directly connected to the SH-FTS, consist of an array of unbalanced Mach-Zehnder interferometers (MZIs). By measuring the output powers of each MZI and reconstruct the MRR spectrum from the spatial interferogram of output powers using the discrete Fourier transform (DFT) equation before and after the binding, the resonance wavelength shift can be measured. The theory and principle of SH-FTS have been demonstrated by Florjańczyk et al. previously [5]. The spectral resolution and the bandwidth of SH-FTS are determined by the number of MZIs (N_{min}) and the maximum optical path length delay (ΔL_{max}) as follows: $N_{min} = 2\frac{\Delta\sigma}{\delta\sigma}\cdots$ (1) $\Delta L_{max} = \frac{1}{\delta\sigma \cdot n_{eff}}\ldots$ (2), where n_{eff} is the effective index of Si_3N_4 waveguide, $\delta\sigma$ and $\Delta\sigma$ are the wavenumber resolution and bandwidth of the spectrometer. We previously demonstrated the Si_3N_4 SH-FTS device with 24-MZI array for the spectral retrieval resolution of 5 nm with the bandwidth of 60 nm centered at λ_o =900 nm [6], but the resolution should be < 1 nm to detect the resonance wavelength shifts induced from minute variations of the analyte's concentration. Following the previous result [6], we used the Si_3N_4 strip waveguide with 500nm width and 220nm height, but for the biosensing application, we designed the SH-FTS with 32-MZI array (N=32) and $\Delta L_{max} = 1.86\ mm$ for the resolution of 0.285 nm with the spectral bandwidth of 4.55 nm. The final outlook of the integrated device footprint is shown in Fig. 1b. And the MRR is designed with $r = 40\ \mu m$ and the gap between the ring waveguide and bus waveguide is 200 nm to have free spectral range (FSR) = 1.5 nm. The SEM image of fabricated Si_3N_4 MRR and the E-field simulation result are shown in Fig. 1c and d. Using the 3D-FDTD simulation, we extracted the S-parameters of the MRR device to characterize the transmission characteristics as shown in Fig. 1e. To verify the bulk sensitivity of MRR biosensor, we simulated the molecule binding condition by changing the refractive index of the top cladding (n_{clad}) from n_{clad}=1.3 to n_{clad}=1.315 ($\Delta n_{clad} = 0.015$), and observed the $\Delta\lambda$ =643 pm as shown in Fig. 1f, representing the bulk sensitivity of 42.9 nm/RIU.

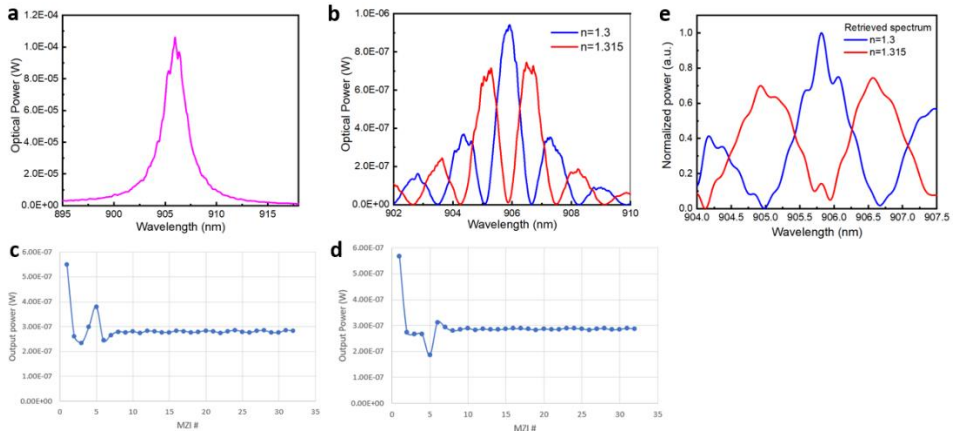

Fig. 2. The interconnect model simulation results. (a) The spectrum of input light source centered at λ_o =906 nm. (b) The spectrum of MRR output with two different n_{clad} conditions; blue line is n_{clad}=1.3, red line is n_{clad}=1.315. (c) The output powers from the 32 MZIs of SH-FTS with n_{clad}=1.3 and (d) n_{clad}=1.315. (e) The retrieved spectrum of MRR from SH-FTS using DFT equation.

Then, using the extracted S-parameters of optimized devices, we designed and simulated the MRR integrated SH-FTS device by Lumerical Interconnect. Fig. 2a shows the spectrum of the input light source centered at λ_o = 906 nm with the linewith of 10 nm. Then, the light is connect to the MRR model, and the output spectrum from the MRR output is shown in Fig. 2b. Two different n_{clad} values represent the refractive index of functionalized layer of MRR with and without binding molecules. Then, the output powers of 32-MZIs are measured as shown in Fig. 2c and d for both cases. Finally, the spectrum of MRR can be retrieved for both cases using DFT equations as shown in Fig. 2e. As a result, we could examined that the retrieved spectrum (Fig. 2e) is matched well with the directly measured spectrum (Fig. 2b), showing the resonance wavelength shift $\Delta\lambda$ =643 pm from the $\Delta n_{clad} = 0.015$, representing the bulk sensitivity of 42.9 nm/RIU.

In conclusion, we demonstrated the monolithically integrated biosensor with MRR and SH-FTS substituting the external OSA measurement system, and the first prototype design is examined to have 42.9 nm/RIU sensitivity. The design modification and experimental measurements are in progress to improve the sensing sensitivity. This research was supported by the Air Force Research Laboratory (AFRL) Contract # FA864920P0971.

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