Ultra-high resolution on-chip reconstructive spectrometer

(Student paper)

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We present a novel design of on-chip reconstructive spectrometer with ultra-high resolution and broad bandwidth. Based on a multi-stage reconfigurable network, our method permits a scalable number of sampling channels that avoids passive splitting loss. Distinct micro-ring resonators are distributed over the network to enable diverse channel spectral responses with high sampling efficiency. Using the silicon nitride photonic integration platform, we experimentally demonstrate a 50 pm resolution over a 120 nm bandwidth with 128 sampling channels.

Keywords: *On-chip spectrometer, reconfigurable, ultra-high resolution, broadband, SiN platform*

Introduction

The past decades have seen miniaturized optical spectrometers addressing numerous applications, such as in situ chemical detection, astronomical sensing, wearable biological monitoring, and etc[1,2]. Nevertheless, the size reduction of spectrometers inevitably brings strong trade-off between the resolution and bandwidth. For example, some demonstrations based on narrowband filters or spatial heterodyne Fourier-transform can achieve high resolutions but suffer from limited bandwidths since the scales of their filter or interferometer arrays are physically restricted by the passive power splitting scheme and the footprint[3,4]. A clear technical bottleneck can be observed that none of the miniaturized spectrometers so far demonstrated can simultaneously achieve < 0.1 nm resolution and > 100 nm bandwidth, which are often required for biomedical sensing, industrial chemical monitoring scenarios[5,6].

In recent years, the reconstructive spectrometer (RS) has drawn extensive attention from the community. Via a number of sampling channels with distinct spectral responses, RSs can convert an arbitrary incident spectrum into a set of aggregated optical power intensities, allowing the recovery of the incident spectrum by solving linear equations. With proper engineering of the channel spectral responses, RSs can resolve a large number of spectral pixels with a moderate number of sampling channels. Nevertheless, the reported miniaturized RSs typically rely on lumped passive spectral filter designs which bonds the number of sampling channels [7]. Here, we present the design of an on-chip reconstructive spectrometer that achieves both ultra-high resolution and broad bandwidth. The passive power fan-out in conventional RS designs is replaced by a reconfigurable optical network which allows the incident light to be actively routed into different sampling channels without sacrificing the power intensity. Over-coupled micro-ring resonators (MRRs) with varying spectral properties are distributed over the network, and act as broadband spectral filters to create distinctive spectral responses for each channel. Based on a commercial silicon nitride (SiN) photonic integration platform, we experimentally demonstrate a ~50 pm resolution over a 120 nm bandwidth using 128 sampling channels.

Design and principle

Figure 1(a) shows the system schematic of our reconstructive spectrometer based on a multi-stage reconfigurable network and distributed MRR filters. Each stage (except for the fan-out) consists of two vertically arranged 2×2 MZIs followed by a waveguide crossing that interconnects the upper and lower MZIs between adjacent stages. MRRs are distributed after the output ports of each MZI, and serve as broadband spectral filters. Thereby, an incident signal can be actively routed through different optical paths (i.e., by reconfiguring the cross/bar state of the MZIs). As each MZI cell is set in a binary fashion, the number of total sampling channels grows exponentially with the increase of stage number, as:

$$\begin{cases} N_{channel} = 2^{N+1} \\ N_{MZI} = 2N + 1 \end{cases} \quad (1)$$

where $N_{channel}$, N_{MZI}, and N are the channel number, number of MZIs, and stage number respectively. Following this topology, a high number of sampling channels (with no splitting loss) can be readily created. A successful RS also requires proper tailoring of the channel spectral responses. Detailed mathematical elaboration of the

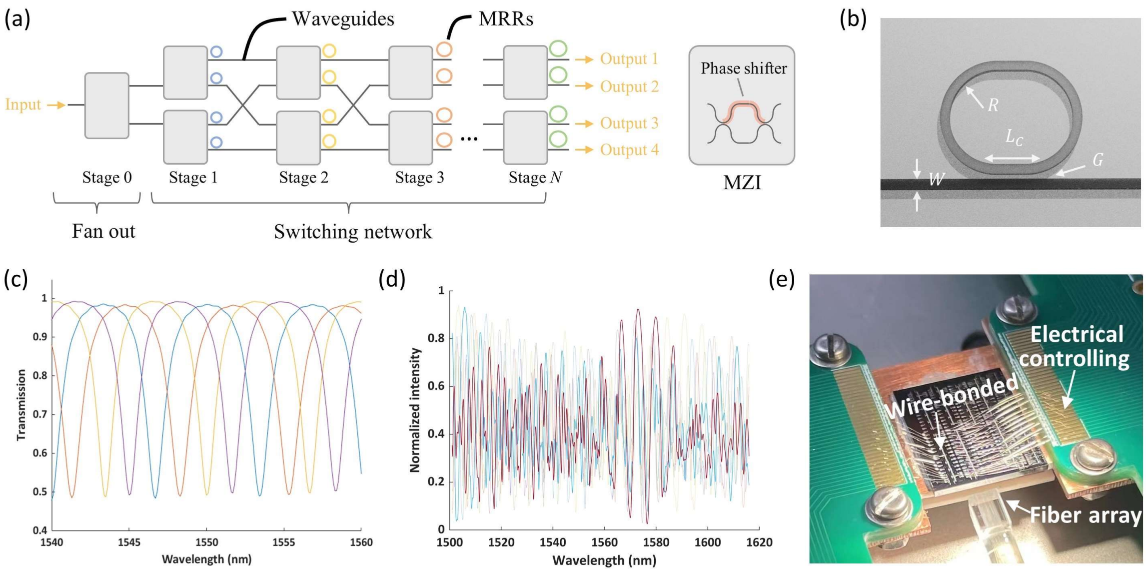

Fig. 1. (a) System schematic of the proposed reconstructive spectrometer. (b) Schematic of the racetrack MRR. (c)Simulated transmission spectra of the four MRRs at a certain stage. (d) Simulated spectral responses of a few sampling channels. (e) Photograph of our packaged on-chip reconstructive spectrometer

computational spectrum reconstruction can be found in ref[1,2]. In general, there are two key requirements for the channel spectral responses of RSs: 1) small self-correlation length, i.e., rapid fluctuations in the wavelength domain to enable high sampling efficiency; 2) high orthogonality between channels. To fulfill these two targets, we develop a distributed spectral filtering method with over-coupled racetrack MRRs. By adjusting the geometry, Fig. 1(b), of each MRR, its spectral response, including the FSR, finesse, and resonance wavelength can be fully manipulated. Here we set the FSR of the MRRs for the different stages to increase from ~4 nm to ~8 nm and maintain their finesse at ~7 to enable rapid spectral fluctuations (resulting in high sampling efficiency). The resonant wavelength of each MRR is also fine adjusted to differ from all the other, as shown by Fig. 1(c). Since different sampling channel passes through different combinations of MRRs, the cascaded spectral responses can therefore be highly distinctive. Figure 1(d) shows several examples of the channel spectral responses. It can be clearly seen that the abovementioned two requirements have been successfully achieved. Based on such design scheme, we implemented a 6-stage reconstructive spectrometer (i.e., 128 sampling channels) on a SiN platform, as shown by Fig 1(e). A microcontroller unit with customized driving broads is developed for the electrical control of the reconfigurable system. An ultra-high NA fiber array with a mode diameter of about 3.5 µm is used to match the edge couplers for the optical IO, which achieves an about 3 dB loss per facet. The measured total on-chip loss is around 5 dB at 1550 nm.

Experimental results

To test the performance of our fabricated spectrometer, we first calibrate the spectral responses of all 128 sampling channels by launching an ASE broadband light source through the chip and measuring the transmission spectra with a benchtop spectrum analyzer, as shown by Fig 2(a). The calculated spectral self-correlation is about 0.57 nm (see ref[8]), indicating a high sampling resolution. We then apply DFB lasers (with linewidths < 10 MHz, i.e., spectral widths < ~1 pm) at different wavelengths as narrowband inputs and use an optical power meter to detect the aggregated power intensities at the output ports. The sampling spectral window is set between 1500 nm to 1620 nm (i.e., a bandwidth of 120 nm). Based on the pre-calibrated channel spectral responses (also referred as the transmission matrix) and the vector of detected power intensities, we use a nonlinear optimization algorithm, namely the CVX algorithm[9], to reconstruct the incident laser signals. Figure 2(c-e) shows the reconstructed spectra (references obtained using a benchtop spectrum analyzer). The FWHM of the resolved peaks is maintained at ~50 pm for the different wavelength inputs, illustrating that our spectrometer can detect narrow spectral components with an ultra-high resolution down to 50 pm. The slight reconstruction errors can be attributed to the measurement inconsistencies between the calibration and testing.

The reconfigurable optical network of our device also permits a user-definable resolution by differently grouping sampling channels, allowing a programmable performance to balance the computational complexity, measurement time, and resource consumption. Thus, in experiment, we investigate the relationship between the resolution and channel number by applying different numbers of sampling channels to reconstruct the narrowband inputs and resolve the resolutions. As shown by Fig. 2(e), a clear downward trend can be observed that the spectrometer

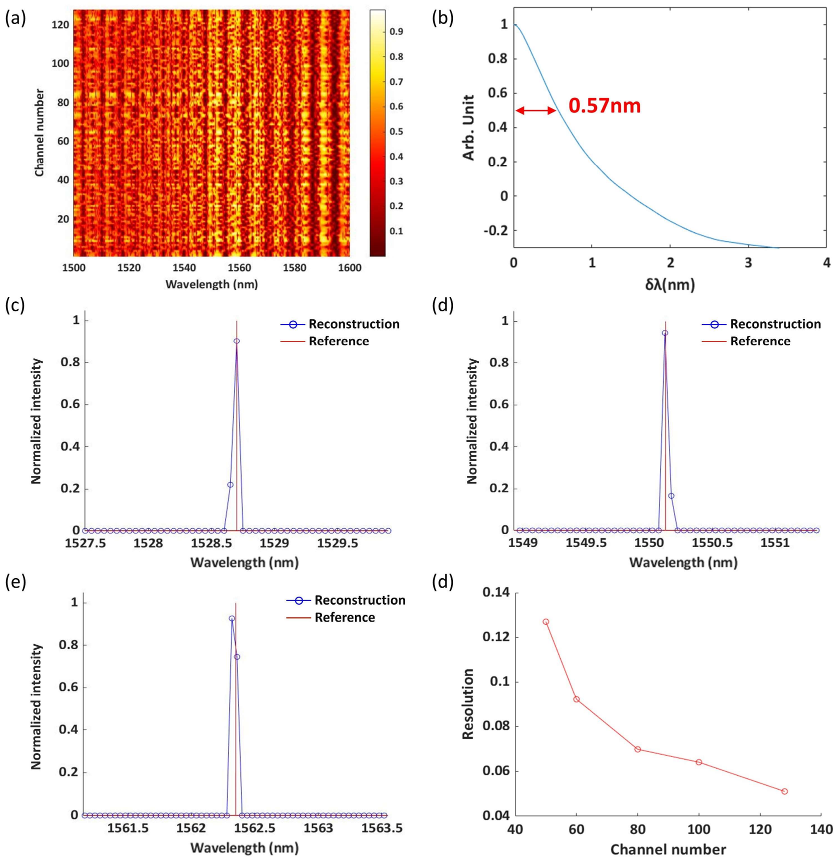

Fig. 2. (a) 2D map of the measured spectral responses of the 128 sampling channels. The scale bar represents the normalized transmission intensity. (b) Calculated spectral self-correlation function C(Δλ) (c-e) Reconstruction results of the narrowband incident signals at different wavelengths, respectively. (f) Spectrometer resolution vs. channel number

resolution continuously improves as the sampling channel increases. Accordingly, we foresee that the resolution of our design can be further extended by scaling up the network with more sampling channels.

Conclusion

In this paper, we present a novel design of on-chip reconstructive spectrometer with ultra-high resolution and broad bandwidth. The passive splitting-to-detection schemes is replaced by a reconfigurable network to create a scalable number of sampling channels. We also develop a distributed spectral filtering method using various MRRs to generate diverse channel spectral responses with high sampling efficiency. Experimentally, we demonstrate a 128-channel spectrometer on a SiN platform and realize an ultra-high resolution of ~50 pm resolution with 120 nm bandwidth.

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