Single-Shot Ultra-Broadband Spectrometer with Cascaded Nanobeam Mirrors

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Abstract: We present a novel reconstructive spectrometer with cascaded nanobeam mirrors. A compact SiN spectrometer is demonstrated achieving <0.5 nm resolution across 160 nm bandwidth with only 15 sampling channels, yielding a record-high spectral pixel-to-channel ratio.

1. Introduction

Reconstructive spectrometers (RSs) have received extensive research interest, since they globally sample the entire incident spectrum and are able to resolve a large number of spectral pixels with the aid of algorithms [1,2]. This is fundamentally different to conventional dispersion- or narrowband filtering-based spectrometers that linearly decode and detect slices of spectrum. This feature makes RSs particularly suitable for miniaturized chip-scale implementations as a considerably smaller number of building components are required [3,4]. Rapid evolving in situ and in vivo spectroscopic applications, such as wearable healthcare monitoring or portable chemical sensing, not only demand superior device performance, including high resolution, large operational bandwidth, and low sampling loss, but also prioritize compactness, low power consumption, and cost [5]. Finding an effective method to engineer the channel responses of the RS for efficient spectral sampling remains a challenge, especially when striving to balance all above-mentioned factors.

In this work, we introduce a single-shot ultra-broadband RS design using photonic crystal nanobeams that are tailored to create broadband, low-loss, partial-reflective mirrors. By cascading such mirrors with designated spacings, the resultant multi-mirror system is capable to produce high-performance sampling responses featuring highly complex spectral fluctuations, in a footprint smaller than 200 μm^2. Utilizing only 15 sampling channels, we experimentally demonstrate a high resolution of <0.5 nm over a 160 nm bandwidth, covering 1445 nm to 1615 nm. This yields a spectral pixel-to-channel ratio of 21.3 (i.e. the division of bandwidth over resolution and channel number), which, to the best of our knowledge, is a new performance record for single-shot integrated spectrometers.

2. Device principle and design

The working principle of RSs can be found in [1,2,7]. Figure 1(a) shows the schematic of our single-shot RS design, where an incident spectrum is split and fed into different channels for parallel sampling. The output power aggregations, which are the integrals of the incident signal and different samplers' spectral responses over wavelength, are subsequently collected by photodiodes (PDs) and used to reconstruct the incident spectrum. Each sampling channel contains a series of partial-reflective mirrors spaced at varying spacings. This multi-mirror system can be readily modeled via the transfer matrix method [6]. By optimizing the number of mirrors, their partial reflectance, and the intermediate spacing, the resultant transmission spectra can produce complex, dense spectral fluctuations, enabling highly efficient and decorrelated sampling responses. Here, the channel self-correlation width [7] is used as a major criterion to evaluate the sampler performance. Rigorous simulation results indicate that a 6-mirror system, each mirror with a reflectance near 0.15 and an average spacing of approximately 30 μm, provides an optimal balance between the footprint, sampling loss, and sampling efficiency.

To realize partial-reflective mirrors with broad bandwidth and low insertion loss, we introduce elliptical etching holes onto single-mode waveguides to form photonic crystal nanobeams for the fundamental TE mode, as depicted in Fig. 1(b). All the geometric parameters, including the major axes of the holes (denoted as L_1 to L_3), the gap G between holes, and the minor axis W of the holes, are systematically optimized using the Particle Swarm Optimization (PSO) algorithm, aiming to maximize the working bandwidth while suppressing the scattering loss. Figure 1(c) presents the finite-difference time-domain (FDTD) simulated reflectance/transmittance of the optimized nanobeam mirror. It can be seen that the mirror reflectance is maintained between 0.1 to 0.18 from 1440 nm to 1650 nm, with the insertion loss being around 0.3 dB. Accordingly, we further simulate the spectral responses of multi-mirror systems. As examples, Fig. 1(c) shows the transmission spectra of a few sampling channels with 6

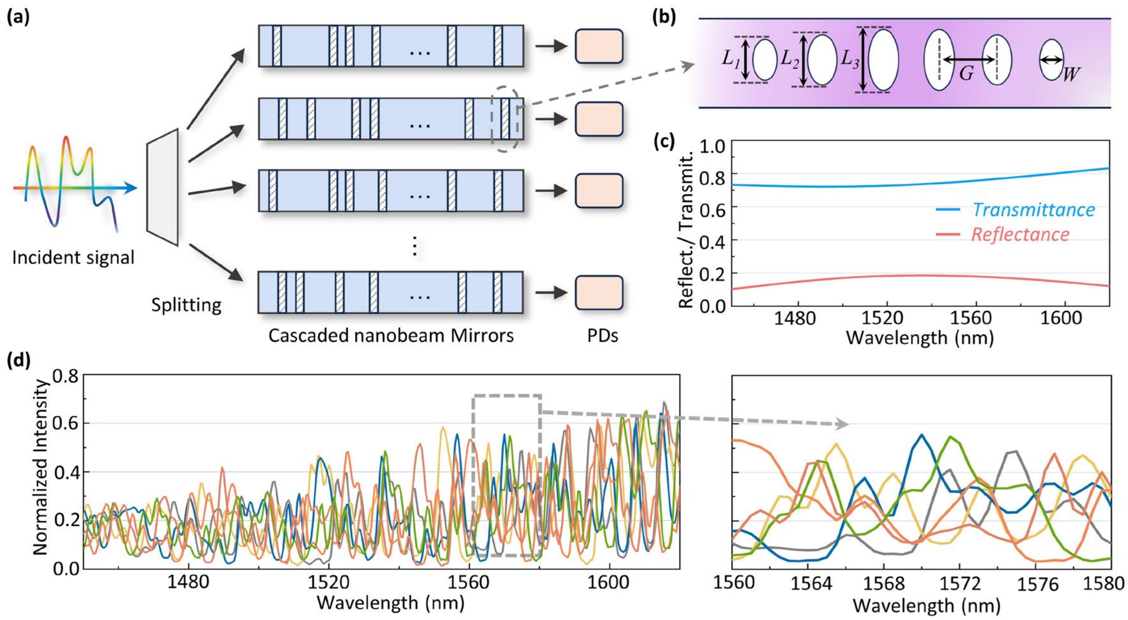

Fig. 1. (a) Schematic diagram of the proposed RS design. (b) Schematic of the nanobeam mirror. (c) Simulated reflectance of the nanobeam mirror. (d) Simulated transmission spectra of several 6-mirror sampling channels. The inset highlights the complex spectral fluctuations.

cascaded nanobeam mirrors, illustrating a high degree of spectral decorrelation between channels.

3. Experimental results

Figure 2(a) shows the microscope image of the fabricated RS with 15 sampling channels based on the CORNERSTONE silicon nitride (SiN) integration platform, with insets showing enlarged views of a 1×2 MMI coupler and a sampling channel with 6 cascaded nanobeam mirrors, respectively. The transmission matrix is pre-calibrated using a super luminescent diode in tandem with a commercial optical spectrum analyzer, as presented by Fig. 2(b). The sampling spectral window is designed between 1455 nm to 1615 nm, as determined by the sampler transmission loss, thereby defining the operational bandwidth of 160 nm. The inset of Fig. 2(b) shows several representative channel responses, aligning well with the simulation results depicted in Fig. 1(d).

As part of the device evaluation, we first launch a series of laser signals at different wavelengths as narrowband inputs. A nonlinear optimization algorithm, namely the CVX algorithm [8], is employed to conduct the spectrum

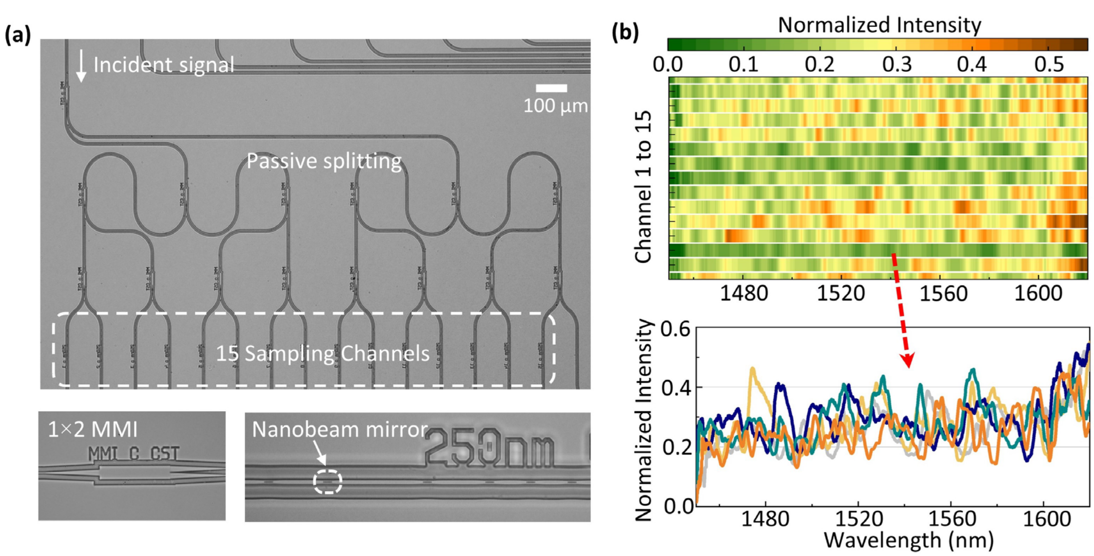

Fig. 2. (a) Microscope image of the fabricated RS. The insets show the 1×2 MMI and a sampling channel composed of cascaded nanobeam mirrors. (b) Normalized transmission matrix of the 15-channel RS. The inset plots a few representative channel responses.

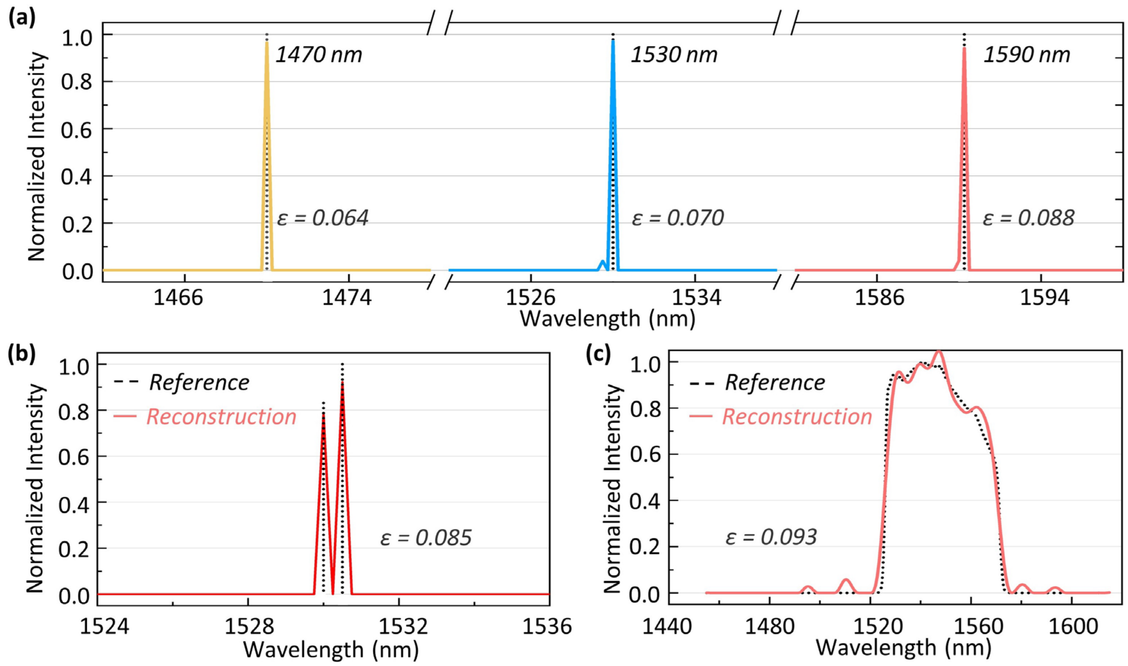

Fig. 3. (a) Reconstructed spectra of single spectral lines at different wavelengths. The black dotted lines mark their center wavelengths. (b) Reconstructed dual spectral lines with a spectral spacing of 0.5 nm. (c) Reconstructed spectrum for a continuous, broadband signal.

reconstruction and the L2-norm relative error ε [3,4] is used to quantify the reconstruction accuracy. Fig 3(a) shows the resolved single laser peaks with calculated relative errors ranging from 0.064 to 0.088. To verify its resolution, we then perform a dual-peak test, following the Rayleigh criteria, by simultaneously launching two laser signals. As shown by Fig. 3(b), the dual-peak spectrum with a <0.5 nm spectral spacing is well resolved with a low relative error ε of 0.085. Furthermore, we test its resolving capability for broadband inputs by launching a continuous ASE signal. Figure 3(c) presents the reconstruction result with a relative error ε of 0.093.

4. Conclusion

In this work, we present a single-shot, ultra-broadband RS design that innovatively leverages photonic crystal nanobeams to create highly efficient but decorrelated spectral samplers. Experimentally, we demonstrate an integrated spectrometer with <0.5 nm resolution and 160 nm bandwidth using only 15 sampling channels, achieving a record-breaking spectral pixel-to-channel ratio of 21.3. The proposed design scheme offers a novel solution for developing compact, cost-effective, high-performance spectrometers, holding great potential for miniaturized spectroscopic applications.

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