

Dense Frequency-Comb Spectral Reconstruction Using an Integrated Interferometric Waveguide Mesh

Hao He,¹ Zengji Tu,¹ and Lin Chang^{1,*}

¹State Key Laboratory of Photonics and Communications, School of Electronics, Peking University, Beijing, 100871, China.

*linchang@pku.edu.cn

Abstract: We demonstrate an integrated computational spectrometer based on a reconfigurable interferometric mesh. Accurate reconstruction of frequency comb spectra with a minimum frequency spacing of 25 GHz is achieved based on a physics-informed U-Net++ convolutional neural network.

1. Introduction

Over the past decade, the rising demand for portable and low-cost sensing devices has accelerated the development of integrated spectrometers. Among various approaches, computational spectrometers have drawn significant attention due to high spectral resolution and compact footprint simultaneously [1, 2]. However, existing spectrometer reconstruction algorithms often rely on sparsity or smoothness assumptions, which limits them to simple or smooth spectra [3]. Their ability to handle complex spectral patterns has not been fully demonstrated. Here, we propose a spectrometer based on single-mode interference within a waveguide array, achieving an ultrahigh spectral resolution of 4 pm on a silicon nitride chip at sub-second scanning speed. With a U-Net-based spectral reconstruction algorithm, the spectrometer enables accurate real-time reconstruction of dense optical frequency combs with 25 G to 125 G free spectral range, showcasing substantial potential for real-world applications.

2. Principle and Device

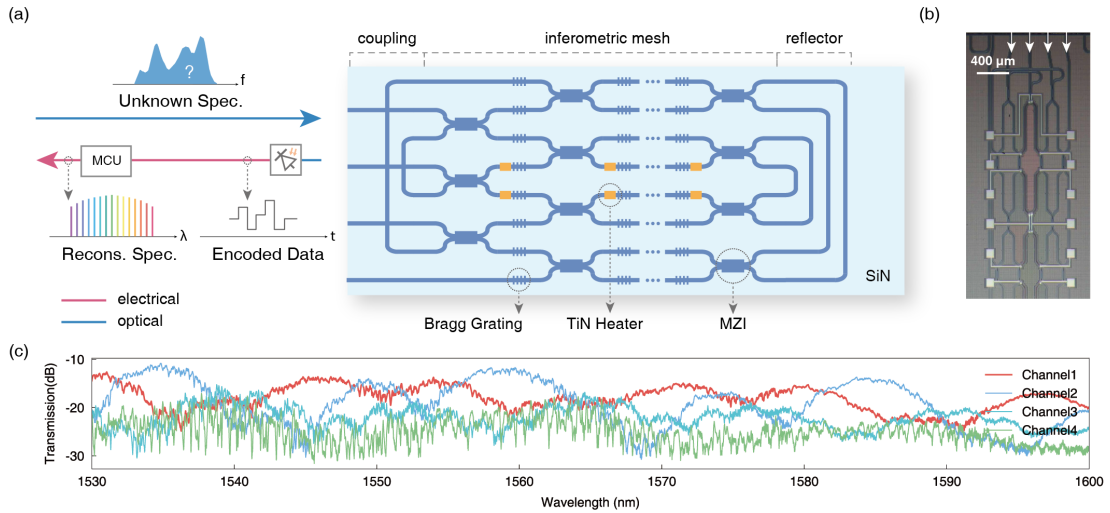


Fig. 1. (a) Schematic of proposed high-resolution spectrometer (b) Microscope Image of the chip and fiber array coupling (c) Selected channel response.

As shown in Fig. 1(a), the proposed on-chip spectrometer is built on a six-layer MMI mesh, with weakly reflective Bragg gratings distributed along its waveguides. Light entering the network from a single input port is split into multiple paths and partially reflected within the mesh, generating a characteristic interference speckle pattern. The resulting signal is collected at the output ports and measured using power detectors (PDs). Four ports

are placed on the same side of the chip, enabling six distinct spectral responses through different input–output combinations. As illustrated in Fig. 1(b), the device was fabricated on a 300-nm silicon-nitride-on-insulator platform, which ensures low propagation loss and high thermal stability. A 100 nm TiN heater layer is deposited on the waveguides to control the interference states of the mesh, thereby providing a sufficient number of independent spectral channels. Recycling paths are incorporated at both ends of the mesh to recapture residual optical power. Fig. 1(c) shows representative responses measured at different ports, with insertion losses of 20.6 dB, 20.5 dB, 25.3 dB, and 29.1 dB. Each channel exhibits a slowly varying spectral envelope superimposed with fine speckle features, together forming the physical basis for dense spectral reconstruction.

3. Spectrum Reconstruction

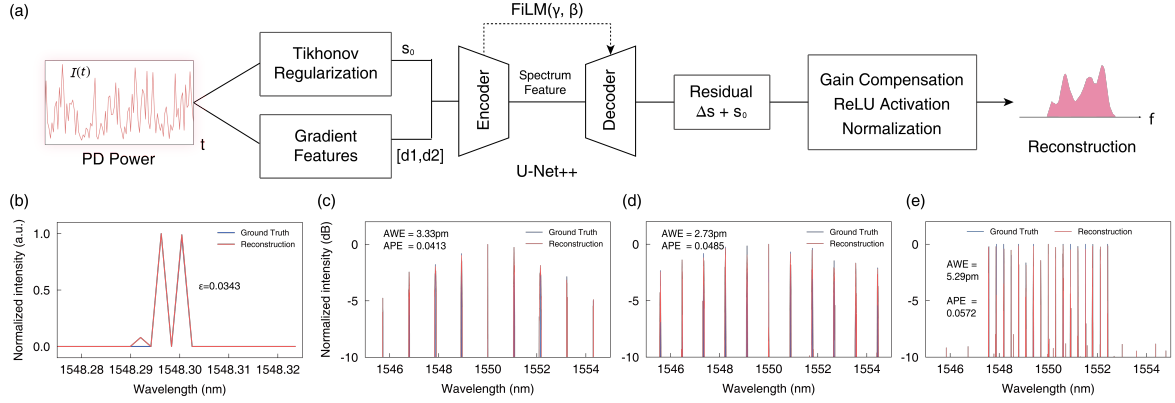


Fig. 2. (a) Structure of the reconstruction algorithm based on U-Net++. (b) Reconstruction results of double-peak spectrum, with performance measured by relative error ϵ [4]. (c-e) Reconstruction results of frequency-comb spectra. Average wavelength error (AWE) is defined as the mean deviation between the reconstructed and true wavelength of each comb line, and average power error (APE) is defined as the mean deviation between the reconstructed and true normalized power of each comb line.

Instead of using convex optimization methods that work only for simple or smooth spectra, we develop a physics-informed U-Net++ convolutional neural network (CNN) for reconstructing dense frequency-comb spectra [5]. This approach is a combination of chip-based inverse problem solving with data-driven refinement.

As illustrated in Fig. 2(a), the measured spectral responses and photodetector signals are first processed by a Tikhonov-regularized linear inverse operator to form an initial guess. A residual correction is then applied by a 1D U-Net++ enhanced with feature-wise linear modulation (FiLM). The network receives the spectrum together with its first- and second-order finite differences, allowing it to explicitly encode peak slopes and curvature. The U-Net++ architecture, with multi-scale encoders, decoders, and skip connections, captures long-range spectral structures while preserving the localization of individual lines. A final gain-compensation step corrects amplitude biases introduced during reconstruction.

The network is trained on 10,000 simulated comb datasets with realistic noise. By embedding the underlying physics and suppressing peak broadening and artifacts, the method accurately recovers not only simple dual-peak signals but also comb-line wavelengths and relative amplitudes across various experimental conditions, as shown in Fig. 2(b)–(e).

4. Conclusion

In conclusion, we have demonstrated an integrated spectrometer that combines spatial and temporal encoding to enable robust reconstruction of complex optical signals. Leveraging a U-Net based algorithm, we experimentally verified accurate recovery of densely spaced frequency-comb spectra. This work represents an important step toward the practical deployment of computational spectrometers in real-world applications.

References

1. H. He et al., “Recursive Inverse Design Enables Hyper-spectral Photonic Integrated Circuits”, Oct. 14, 2025, *arXiv:2510.12104*. doi: 10.48550/arXiv.2510.12104.

2. B. Redding, S. F. Liew, R. Sarma, and H. Cao, "Compact spectrometer based on a disordered photonic chip", *Nature Photon*, vol. 7, no. 9, pp. 746–751, Sept. 2013, doi: 10.1038/nphoton.2013.190.
3. Y. Li et al., "Inverse-Designed Linear Coherent Photonic Networks for High-Resolution Spectral Reconstruction", *ACS Photonics*, p. acsphotronics.2c01172, Jan. 2023, doi: 10.1021/acsphotronics.2c01172.
4. Z. Zhang, Y. Li, Y. Wang, Z. Yu, X. Sun, and H. K. Tsang, "Compact High Resolution Speckle Spectrometer by Using Linear Coherent Integrated Network on Silicon Nitride Platform at 776 nm", *Laser & Photonics Reviews*, vol. 15, no. 11, p. 2100039, 2021, doi: 10.1002/lpor.202100039.
5. O. Ronneberger, P. Fischer, and T. Brox, "U-Net: Convolutional Networks for Biomedical Image Segmentation", in *Medical Image Computing and Computer- MICCAI*, 2015, pp. 234–241. doi: 10.1007/978-3-319-24574-4_28.