

Single Inverse-designed Waveguide Enables Sub-picometer Resolution Spectrometer over 700 nm Bandwidth

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Abstract: We demonstrate a compact and high-performance on-chip spectrometer. By employing inverse design along the sidewalls of a single waveguide, this chip achieves a record full-width at half-maximum of 0.25 pm and an operation bandwidth over 700 nm.

High precision spectroscopy is essential for in situ measurements in applications ranging from atomic systems to astronomy. In most cases, such measurements still rely on bulky and expensive instruments, since resolving Doppler-broadened atomic spectra typically requires an ultrahigh resolution on the order of 0.1 to 1 pm [1]. Integrated spectrometers, while far more compact, have generally struggled to reach this regime and often face additional limitations in sensitivity and system complexity [2,3]. Here, we present a simple waveguide-based computational spectrometer that achieves sub-picometer resolution on a CMOS-compatible platform. We describe the inverse-designed device architecture and experimentally evaluate its performance for a range of spectral features. The spectrometer achieves a full width at half maximum of 0.25 pm, a double-peak resolution of 1 pm, and an operating range from 1290 to 2000 nm. The same design strategy can also be readily extended to other wavelength bands and integrated photonic platforms.

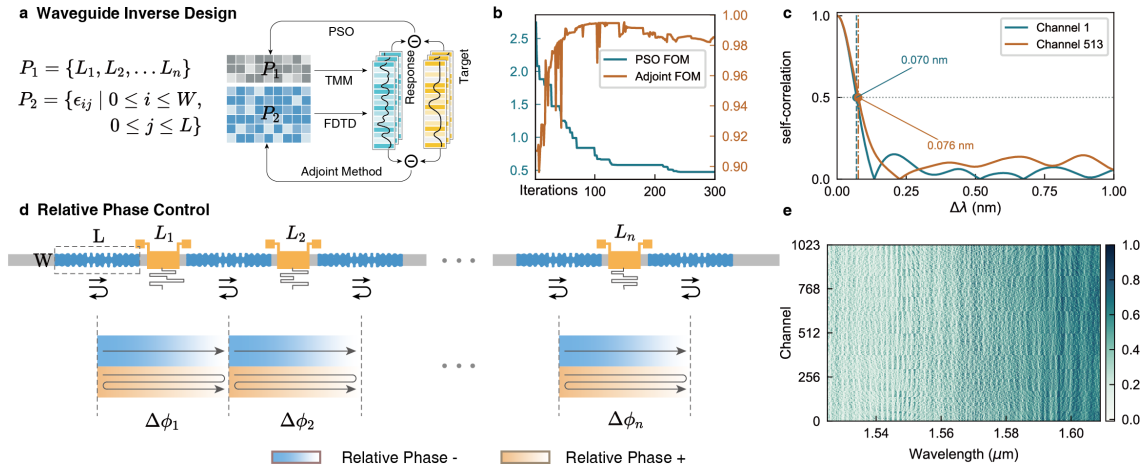


Fig. 1. (a) Inverse design optimization for proposed waveguide spectrometer. (b) The figure of merit evaluation during the inverse design. (c) Measured auto-correlation of two randomly selected channels. (d) The schematic of the spectrometer and its phase control process. The phase shifters change the spectrum response by adjust the relative phase between two optical paths. (e) Channel footprint of the spectrometer.

As shown in Fig. 1(a), the spectrometer is built on a straight waveguide incorporating multiple inverse-designed segments, each of which introduces partial reflection of the input signal. This structure maps spectral information from the input light into intensity patterns, which are then detected by photodiodes and used for spectral reconstruction. To maximize the spectral resolution, we adopt two main design strategies. First, the waveguide geometry is optimized through inverse design to generate spectral responses that are both sharp and weakly correlated. As detailed in Fig. 1(a), the device is parameterized by P_1 and P_2 . P_1 denotes the lengths of the $N - 1$ waveguide sections separated by N inverse-designed regions. P_2 represents the permittivity distribution, with each element corresponding to the dielectric constant of one grid cell in the device region. In the optimization process, P_1 and

P_2 are simulated using the transfer matrix method (TMM) and the finite-difference time-domain (FDTD) method, respectively, and are optimized using particle swarm optimization and the adjoint method. The objective function is defined based on the autocorrelation of the spectral responses. As shown in Fig. 1(b), after 300 optimization iterations, the figure of merit in both parameter spaces is substantially improved. The measured autocorrelation performance of the fabricated spectrometer is presented in Fig. 1(c), showing good response independence. Nine waveguides are designed for different bands, enabling an aggregate bandwidth from 1290 to 2000 nm. Second, we introduce relative phase control. As shown in Fig. 1(d), each waveguide section supports both directly transmitted light and round-trip light, and the interference between these two components determines the spectral fingerprint of the device. To tune the spectral response, we place a thermo-optic phase modulator on each waveguide section. As shown in Fig. 1(e), by combining the states of 10 phase modulators, the spectrometer provides 1024 mutually independent responses, which substantially enhances its resolving capability.

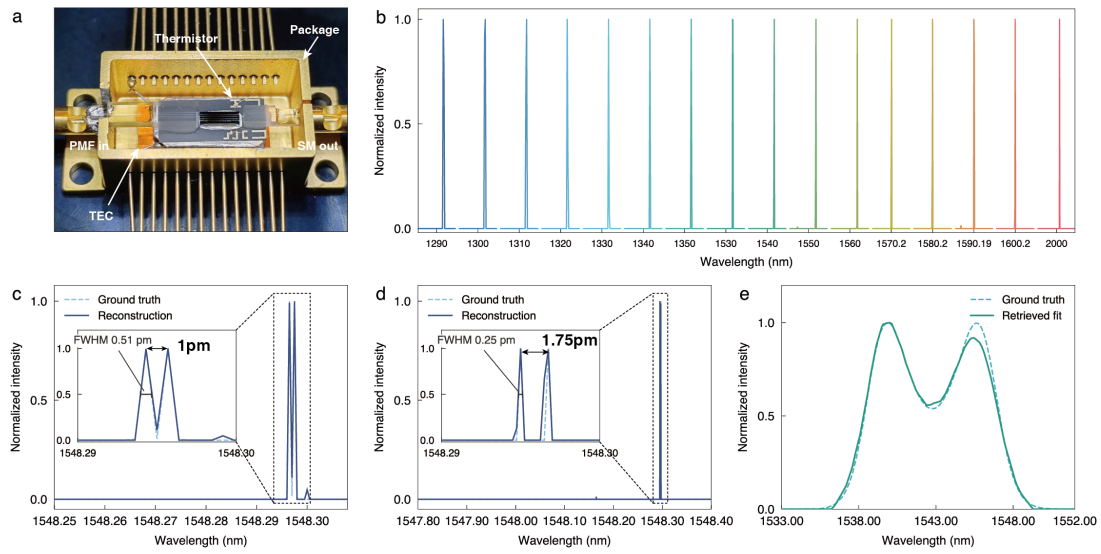


Fig. 2. (a) Package of the spectrometer. (b-e) Reconstruction results of (b) single-peck signal, (c-d) dual-peck signal, and (e) broadband signals.

Fig. 2(a) shows the fabricated spectrometer on a 330 nm silicon nitride on insulator platform after packaging. The packaged chip exhibited an end-to-end optical loss of 11.2 dB, measured with an amplified spontaneous emission (ASE) source around 1550 nm, which was sufficient for sensitive detection. To evaluate its performance, we used least squares regression to reconstruct single peak, double peak, and broadband spectra [4]. As shown in Fig. 2(b) through 2(e), the single peak measurements exhibit good reconstruction uniformity across the operating band. In the dual-peak measurements, two spectral lines with well controlled spacing were generated using a narrow linewidth laser and an acousto-optic frequency shifter. The spectrometer accurately reconstructed double-peak signals with separations down to 125 GHz and achieved a full width at half maximum of 0.25 pm. The broadband results further confirm its ability to reconstruct wideband spectra.

In conclusion, we have demonstrated a simple integrated spectrometer based on a single sidewall-engineered waveguide. Using inverse design together with relative phase control, the device experimentally achieves a state-of-the-art resolution of 0.25 pm among integrated spectrometers over an 800 nm operating bandwidth. These results bring integrated spectrometers closer to applications in atomic precision measurements.

References

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