nature COMMUNICATIONS

Article https://doi.org/10.1038/s41467-026-71087-7

Achieving sub-pm wavelength regression via minimum-phase in a single-stream photonic IC

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Photonic chips are powerful tools for measuring and analyzing light, but most compact spectrometers face a fundamental trade-off: improving resolution usually requires larger devices or sacrifices in signal quality. Here, we introduce a chip-scale architecture that overcomes this limitation by extracting phase information corresponding to the hidden timing of light waves using only simple intensity measurements. Our method generalizes earlier minimum phase designs to allow sparse and non-sequential optical delays, enabling accurate phase reconstruction on a single circuit. By engineering these delays, the device can determine the wavelength of an unknown laser with sub-picometer precision, all while using just one input and one output. This single-stream design reduces loss, improves robustness, and avoids the complexity of traditional spectrometers. The result is a compact, scalable platform that enables high-accuracy wavelength metrology and opens possibilities for on-chip sensing and computational spectroscopy.

The field of computational spectroscopy has recently received a great deal of attention in the photonic integrated circuit research community[1–3]. The main reason behind this is the ability to incorporate functionalities that, in the past, required large footprints[4–10]. Photonic integrated circuits (PICs) allow the miniaturization of all these bulky systems while maintaining their functionality and desired performance[11]. In addition to the size advantage, the ability to mass-produce these miniaturized spectrometers enables a more cost-effective solution for the consumer market.

PIC spectrometers have been implemented using three primary architectures: Mach-Zehnder interferometers (MZIs) with multiple optical path lengths[12–21], optical cavities that partition the spectrum into discrete channels[22–27], and dispersive elements that spatially spread the spectrum for reconstruction[28–33]. Each offers distinct strengths but faces fundamental trade-offs between resolution, bandwidth, footprint, and signal fidelity. Dispersive designs can access a broad bandwidth, but they require many spatial channels, which increases size and loss. Optical cavity spectrometers achieve high resolution with large quality factors, yet wide-band operation demands multiple cavities. MZI-based approaches are broadband, but resolution scales directly with path length, and intensity-only regression near interferometric nulls produces error bias. In all three cases, the multi-path nature of the architecture inherently reduces SNR, as optical power is divided among multiple channels or paths.

Using the light's phase overcomes the drawbacks of interferometric fringes for spectroscopy. However, accessing the phase information in a photonic circuit is nontrivial. For example, it is common to utilize integrated 90° hybrids[13], but they require a large footprint and are highly susceptible to manufacturing variations. In contrast, Xu et al. showed that the phase in a photonic circuit can be extracted solely from intensity measurements using minimum-phase systems[34,35]. Specifically, the phase is determined directly from the magnitude via their fundamental relationship in a minimum phase system, enforced by the Hilbert transform[36–38].

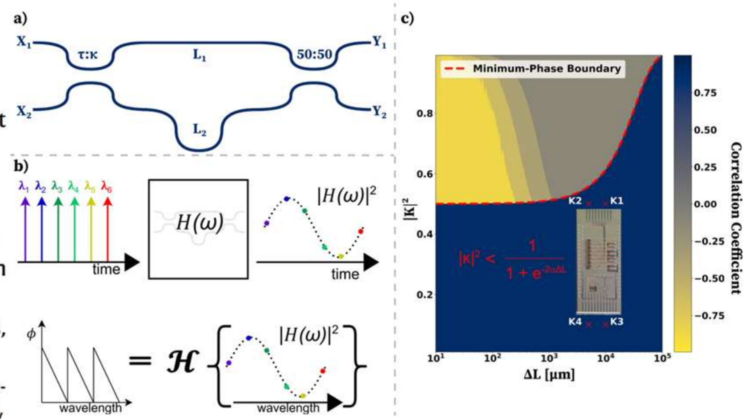

Fig. 1 | Minimum-phase Mach-Zehnder inteferometer for phase retrieval from intensity measurements. a Asymmetric Mach-Zehnder Interferometer(MZI) with a variable input coupling coefficient κ and a 50: 50 output coupler used to analyze the minimum-phase boundary condition. **b** Phase retrieval process using a wavelength-swept laser, where the $H(\omega)$ intensity response is related to the phase response through a Hilbert transformation owing to the minimum-phase nature of the system. **c** The simulated correlation coefficient between the retrieved phase (by Hilbert transform) and the simulated phase shows excellent agreement with the derived minimum-phase boundary condition (red-dashed line). All points in the blue region meet the minimum-phase condition. The red X marks inside the contour plot show the chosen four design points used to test this condition experimentally using a PIC (microscope image). K1 and K2 are near the minimum-phase boundary and K3 and K4 strongly meet the minimum-phase condition.

Here we generalize the work of Xu et al., who applied the minimum phase concept specifically to optical FIR (Finite-Impulse Response) filter implementations[34]. Our generalization extends the applicability of the minimum-phase approach to high-performance wavelength metrology and spectroscopy applications, as well as to general circuit parametric extraction (key for the development of PIC process design kits, an area of growing commercial importance). Specifically, Xu et al. demonstrated that the full complex response of a circuit can be reconstructed from intensity-only measurements by leveraging the minimum-phase Kramers-Kronig relationship[36]. However, their implementation was limited to sequential tap filter configurations ($n = 1,2,3,\ldots$). This conceptual limitation would prohibitively increase a spectrometer circuit's footprint by n-fold (n delays paths needed to go from bandwidth-defining FSR to higher-resolution FSR). Here, we overcome this through the use of non-sequential tap increases, uncovering the necessary optical signal processing needed to achieve high-performance wavelength metrology. This work enables arbitrary and sparse tap filter configurations, where n can be any integer, removing the footprint requirements from n delay paths to any $m < n$. Enabling this arbitrary increase in delay length significantly enhances spectral resolution, proving particularly valuable for wavelength metrology applications. Specifically, in this work, we utilize large tap values to achieve sub-picometer (sub-pm) wavelength resolution in a single-stream circuit. As a result, our approach overcomes the fundamental trade-offs faced by traditional multi-path architectures, which must balance resolution, footprint, and signal/noise ratio.

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