

Integrated photonic spectrometers: a critical review

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Abstract. Integrated photonics, where optical components are fabricated on a chip-scale platform leveraging standard microfabrication technologies, has transformed telecommunications and data communications, quantum optics, and molecular sensing. Optical spectrometry is yet another field that integrated photonics is poised to revolutionize. Unlike traditional bulky, costly benchtop spectrometers, integrated photonics promises miniaturized, rugged, and low-cost spectrometer-on-a-chip modules with broad application prospects ranging from communications to medical imaging. In this review, we survey the various designs of integrated photonic spectrometers through the lens of their underlying operating principles, aiming to reveal quantitative performance scaling laws that transcend specific implementations. This approach enables a general, physically grounded comparison of spectrometer capabilities without being bogged down by device-level details. We further provide guidance on selecting appropriate spectrometer architectures for different applications, taking into account not only their reported advantages but also the practical limitations and implementation challenges.

Keywords: integrated photonics; waveguide; spectrometry; spectroscopy.

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1 Introduction

Optical spectrum analysis is the cornerstone of spectroscopic sensing, optical network performance monitoring, hyperspectral imaging, astronomical spectroscopy, and spectral domain optical coherence tomography (SD-OCT). Such analysis traditionally involves bulky and costly benchtop instruments only found in dedicated laboratories. Emerging market opportunities ranging from point-of-care diagnostics to sensor network deployment are now increasingly demanding spectrometers with reduced size, weight, power, and cost (SWaP-C) metrics.^[1–4]

Photonic integrated circuits (PICs),^[5–9] the optical analog of electronic integrated circuits, offer a promising route towards miniaturized spectrometers. Compared to conventional spectrometers based on bulk optics, PIC technologies promise several critical performance advantages in addition to their apparent SWaP-C benefits. Photonic integration defines devices on-chip with lithographic precision, thereby largely obviating the need for stringent alignment between discrete optical elements and dramatically boosting the ruggedness of spectrometer modules. The advent of ultralow-loss optical waveguides^[10] allows long optical paths to be folded onto a small chip, enabling spectrometers with exceptional spectral resolution. PICs also provide access to ultra-compact, high-speed optical switches to route light between different paths through thermo-optic (TO), electro-optic (EO), or micro-electromechanical systems (MEMS), an essential feature for time-domain modulated spectrometers.^[11]

Finally, PICs facilitate interfacing with other chip-scale micro-modules such as electronics for signal processing and microfluidics for analyte handling, potentially leading to full system-in-a-package solutions.

In this review, we aim to provide a comprehensive survey of the state-of-the-art in PIC-based spectrometers. The review is organized as follows. We will start with describing a generic model of optical spectrometers, followed by an overview of the spectrum reconstruction methods. Next, we will proceed to review different variants of PIC-based spectrometer designs and assess their relative merits. Given the focus on PIC technologies, we limit the scope of this review to waveguide-based spectrometers, and we direct interested readers to other reviews that cover non-PIC spectrometers (which may still leverage chip-scale microsystem technologies).^[12–17] Beachhead markets where PIC-based spectrometers are likely to make a disruptive impact are then evaluated.

2 Generic Model of Optical Spectrometers

In its generic incarnation, a spectrometer is a linear optical device involving a set of photodetectors, each with distinct spectral responses (Fig. 1). The different spectral responses are customarily defined by optical filters concatenated with the detectors. The photodetectors can be a spatial array of detector pixels, or a single-pixel detector integrated with a time-varying filter, effectively creating a time-domain sequence of the detector set (or

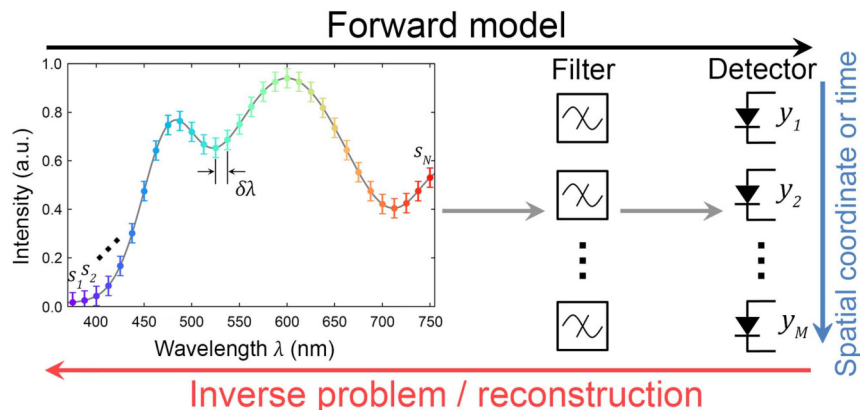


Fig. 1 Generic model and inverse problem for an optical spectrometer comprising a set of photodetectors coupled to optical filters. To numerically describe the spectrometer, the input spectrum is approximated by intensities s_j at a set of discrete wavelengths λ_j . The photodetectors collect signals y_i , which are used to reconstruct the input spectrum.

some combination of the two configurations). This distinction defines two major classes of optical spectrometers: classical dispersive spectrometers based on prisms or gratings are examples of the former configuration, whereas Fourier-transform infrared (FTIR) spectrometers epitomize the latter time-domain modulated design.^[11]

The wavelength-dependent optical transmittance for each of the detectors is denoted by $T_i(\lambda)$, where λ is the wavelength and i denotes the detector number in either the spatial- or time-domain. The index i takes a value between 1 and the number of measurements M . The signal intensity on the i th detector is therefore

$$I_i = \int R_i(\lambda) T_i(\lambda) S(\lambda) d\lambda + \eta_i, \quad (1)$$

where $R_i(\lambda)$ denotes the responsivity of the photodetector, $S(\lambda)$ gives the input spectrum or more specifically the power spectral density of the input signal received through the spectrometer's input aperture, and η_i is the noise at the i th detector.

In order to reconstruct the input spectrum, it is customary to discretize over a discrete set of wavelength points λ_j , with $1 \leq j \leq N$, where N is the spectral channel count. Equation (1) can then be approximated as a weighted sum at these discrete wavelength points λ_j (a quadrature rule^[18–20]):

$$I_i = \sum_j w_j R_i(\lambda_j) T_i(\lambda_j) S(\lambda_j) + \eta_i \Leftrightarrow y = Gs + \eta, \quad (2)$$

where on the right, we have expressed the weighted sum in a matrix form: y is the column vector with I_i as its elements, the elements of column vector η represent the noise at each detector, the column vector s has length N and contains the power spectral density at each wavelength λ_j , and G is a matrix with entries $G_{ij} = w_j R_i(\lambda_j) T_i(\lambda_j)$ (analogous to the “point spread function (PSF) matrix” in imaging). The simplest quadrature rule is a Riemann sum, with equally spaced $\lambda_j = \lambda_0 + j\delta\lambda$ and equal weights $w_j = \delta\lambda$.^[21,22]

Discretizing the integral into a finite number of points λ_j is closely related to discretizing the unknown spectrum $S(\lambda)$ into a finite vector s of discrete $S(\lambda_j)$ samples. Given these samples $S(\lambda_j)$, one must then interpolate them somehow to obtain $S(\lambda)$. In fact, the choice of quadrature scheme usually implicitly defines a corresponding interpolation: Riemann sums correspond to piecewise constant interpolation, a trapezoidal rule^[18–20] corresponds to piecewise linear interpolation, and more sophisticated schemes like Gaussian quadrature or Clenshaw–Curtis quadrature^[19,20] correspond to higher-order polynomial interpolants (from carefully chosen, unequally spaced points λ_j). Alternatively, one could explicitly expand $S(\lambda) \approx \sum_{\ell} b_{\ell}(\lambda) x_{\ell}$ in some finite set of basis functions b_{ℓ} (e.g., polynomials and radial basis functions^[23] such as Gaussians^[24–26]) and unknown coefficients x_{ℓ} . The matrix equation and the spectrum vector in Eq. (2) can be expressed in terms of this basis:

$$y \approx Ax + \eta, \quad A = GB, \quad s \approx Bx, \quad (3)$$

with B a matrix with elements $B_{j\ell} = b_{\ell}(\lambda_j)$ and x a column vector of length L composed of x_{ℓ} .

Even more generally, $S(\lambda)$ could be expressed as a nonlinear function of unknown coefficients, such as some type of neural network^[27–33]—this complicates the reconstruction problem by

making it nonlinear and nonconvex, so we focus on linear models Ax in this review.

Setting B to an identity matrix yields $x = s$ and makes the matrix equation for y in Eq. (3) identical to that in Eq. (2). This is, for example, the case for classical dispersive spectrometers, where there is a one-to-one correspondence between wavelength and detector pixel and thus the matrices A and G are square. For classical dispersive spectrometers with low crosstalk, A and G can be well approximated as diagonal matrices whose diagonal elements are determined by the wavelength-dependent insertion loss and detector responsivity.

In the case of a square matrix A , x may be inferred straightforwardly by inverting A . When the matrix A is not square, e.g., because the number of detector pixels M is not equal to the number of wavelength points N (and $B \notin \mathbb{R}^{N \times M}$), Eq. (3) is either over- or underdetermined and the inverse reconstruction task becomes a problem of linear algebra and optimization. In the following section, we will treat this optimization problem in more detail before moving on to discuss the performance metrics of spectrometers.

3 Spectrum Reconstruction

Previously, we noted that A becomes a square matrix when the spectrum coefficient vector x and the measurement vector y have the same number of elements. In this case, x could be estimated as $\hat{x} = A^{-1}y$. There are two complications. First, the presence of noise means that one must be concerned with the “conditioning” of the matrix A :^[34] if A is close to singular (“ill-conditioned”), then the solution can be very sensitive to noise. For an ill-conditioned A , different spectra x can yield nearly the same measurements y and will be impossible to distinguish once noise is added. This issue is addressed by (1) designing the optics to yield a well-conditioned A (different input spectral components should form very different intensity patterns on the detector array) or related figures of merit for the inference error, through, e.g., inverse design^[35] or “end-to-end” optics/inference co-design;^[36–43] and/or (2) adding regularizations based on prior knowledge.^[44–52] The second complication is that, in practice, A will often be non-square: it is either overdetermined (more measurements than unknowns) or underdetermined (more unknowns than measurements, which also requires additional prior knowledge). We discuss the over/underdetermined situations in more detail below.

3.1 Overdetermined Reconstruction

A straightforward approach to overdetermined reconstruction solves the least squares^[53,54] to find the coefficients:^[55–59]

$$\hat{x} = \arg \min \|Ax - y\|_2^2. \quad (4)$$

If the basis functions are nonnegative, one may also wish to impose the constraint $x \geq 0$ (i.e., all elements of x are nonnegative) in order to ensure that the reconstructed spectrum is nonnegative at all frequencies. In many cases, however, we have found that this additional constraint seems to be unnecessary to obtain a nonnegative spectrum, and we omit it below. Least-squares problems, with or without nonnegativity constraints (and other variations such as weighting for unequal or correlated noise between different sensors), are convex quadratic optimization problems that can be solved by many well-known efficient algorithms.^[54,60–62]

To mitigate vulnerability to noise, one may trade off model error $\|Ax - y\|_2$ for denoising. A common practice is Tikhonov regularization (also known as ridge regression):

$$\hat{x} = \arg \min_x \|Ax - y\|_2^2 + \alpha \|x\|_2^2, \quad (5)$$

where $\alpha \geq 0$ is a regularization coefficient^[44–46] and the term $\alpha \|x\|_2^2$ penalizes the magnitude of the reconstructed spectrum. More generally, the regularization term can be written as $\alpha \|\Phi x\|_2^2$, with Φ being a matrix chosen according to prior knowledge of the spectrum and the features that should be suppressed or enhanced. Two or more regularization terms may be used simultaneously,^[63] including terms with other norms such as the L_1 norm discussed below [Ref. [57] used L_1 regularization, similar to Ref. [50] (private communications with Hui Cao, 2024)]. Ideally, Eq. (5) requires the noise η on each detector to be identical and uncorrelated. If the requirement is not satisfied, Eq. (5) may still be applicable, while a corrected version of Eq. (5) may be available given sufficient knowledge about the noise.^[64] A regularization trade-off very similar to Tikhonov is achieved by a truncated singular value decomposition (discarding singular values of A below some threshold),^[58,65] which is related to principal component regression.^[66]

3.2 Underdetermined Reconstruction

In an underdetermined inverse problem (reconstructing more unknowns x than measurements y), infinitely many solutions exist. Although one may still use Tikhonov regularization for reconstruction and denoising, prior knowledge about the measured spectrum is generally needed for meaningful reconstruction.

As a simple example, if we assume that the spectrum consists only of a few bright peaks/lines in a dark background, or perhaps comprises a few spectral patterns out of a large set of possibilities, so that the solution $\hat{x}$ is “sparse” (mostly zero) in an appropriate basis, the well-known techniques of “compressed sensing” can be applied.^[47–52] The most common such technique is least squares with L_1 regularization (also called LASSO, for “least absolute shrinkage and selection”):^[67,68]

$$\hat{x} = \arg \min_x \|Ax - y\|_2^2 + \alpha \|x\|_1, \quad (6)$$

where $\|x\|_1 = \sum_j |x_j|$ penalizes non-sparse solutions with penalty strength $\alpha \geq 0$. There are many variations on this idea; e.g., if one also adds a Tikhonov (L_2) regularization, it is called an “ElasticNet”.^[68] A key point is that all of these variants are still convex problems with many efficient solution algorithms.^[60,62] Hyperparameters are sometimes determined with the help of validation against additional data not used for training/fitting.^[69–71]

Recall from Eq. (3) that x contains the expansion coefficients of the spectrum $S(\lambda)$ in a basis described by B (also called a dictionary in compressed sensing). Unlike the overdetermined case, the basis here may be overcomplete (i.e., B ’s columns may be linearly dependent).^[72] The sparseness of x relies on the choice of B . If prior knowledge about an appropriate B is unavailable or insufficient, the optimization can include the basis B itself in the optimization parameters, as in “dictionary learning”.^[72,73]

Other machine-learning methods have also been used, especially in the related problem of imaging,^[74–76] in which neural

networks provide nonlinear regularization and reconstruction. These techniques have the advantage that they can learn to reconstruct spectra that are similar to a given training set, even if the characteristics of the training data are not easily described by a simple formula such as those involving L_2 or L_1 regularization. Their disadvantage is that a much larger training set is typically required, and it is often unclear how well the resulting algorithm and trained parameters will generalize to new out-of-sample data.^[77,78]

In the succeeding sections, we will discuss various types of PIC-based spectrometers. The discussion focuses on the performance metrics that relate to the spectral features, including the spectral channel count N , i.e., the number of data points comprising the optical spectrum, spectral resolution $\delta\lambda$, characterizing the minimum resolvable wavelength spacing between the data points (Fig. 1), and bandwidth $\Delta\lambda$, the operational wavelength range of the spectrometer, which is classically given by the product of N and $\delta\lambda$ when the wavelength points are roughly equally spaced. Metrics related to the signal-to-noise ratio (SNR) are separately discussed in Sec. 8.

4 Spatially Dispersed On-Chip Spectrometers

In this part of the review, we discuss the different types of on-chip spectrometers that have been proposed. We first consider spatially dispersed spectrometers, where the spectral response is spread out in space (Fig. 1). We distinguish four categories of spatially dispersed spectrometers, i.e., classical dispersive spectrometers, resonator array spectrometers, wavelength multiplexing spectrometers, and stationary-wave integrated Fourier-transform spectrometers.

4.1 Classical Dispersive Spectrometers

In a classical dispersive spectrometer, the incident light is split into different spectral components using a dispersive element, such as a grating, prism, or hologram. Each of these components is then captured using detectors in an array to give the optical spectrum. For a well-designed classical dispersive spectrometer with low optical crosstalk, the signal at each detector y_i thus directly correlates to spectral intensity s_i (at wavelength λ_i). Most on-chip implementations of such spectrometers make use of planar waveguide gratings, in particular echelle gratings [Fig. 2(a)]^[79–88] or arrayed waveguide gratings [AWGs, Fig. 2(b)].^[80,81,89–93] Other approaches include photonic crystal (PhC) gratings,^[94] digital planar holograms,^[95,96] PhC superprisms^[97], and in-plane metalenses.^[98]

Let us now have a look at the performance metrics (Table 1). The scaling behavior of N and $\delta\lambda$ is important for on-chip integration. For classical spectrometers, the spatial separation between wavelengths scales with the optical path length (OPL) between the dispersive element and the detector array. In other words, both the spectral channel count and resolution improve linearly with the OPL and most likely also scale linearly with the geometric dimensions of the spectrometer. Consequently, on-chip classical dispersive spectrometers typically suffer a performance loss compared to their benchtop counterpart.

The next metric we discuss is the operating bandwidth $\Delta\lambda$. Consider a very broadband signal incident on a grating or other dispersive element. Due to the emergence of different diffraction orders, different wavelengths can couple into the same output channel. The free spectral range (FSR) is defined as the spacing

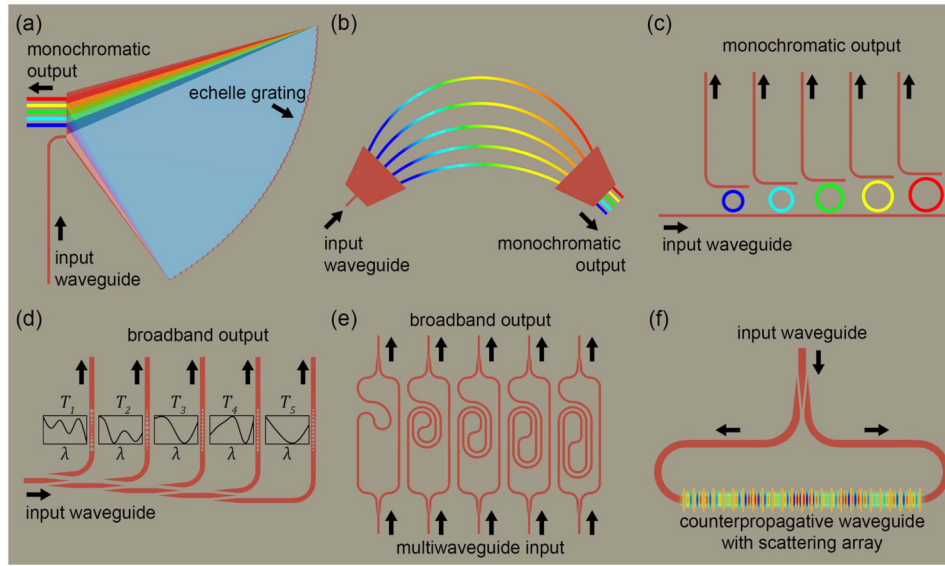


Fig. 2 Schematic representations of the types of spatially dispersed on-chip spectrometers. (a) Classical dispersive spectrometer based on an echelle grating. (b) Classical dispersive spectrometer based on an arrayed waveguide grating. (c) Resonator array spectrometer comprised of microring resonators. (d) Wavelength multiplexing spectrometer based on a broadband filter array. Examples of (uncorrelated) transmission spectra T_i are plotted next to each filter. (e) Stationary Fourier-transform (FT) spectrometer with multiple input waveguides. (f) Stationary-wave integrated Fourier-transform spectrometer (SWIFTS) in the counterpropagative configuration. A prototypical standing wave electric field profile is plotted in the SWIFTS.

between two consecutive wavelengths that are coupled into the same spectral channel (Fig. 3). The maximum $\Delta\lambda$ of the spectrometer is determined by this FSR. The FSR is determined by the design of the dispersive element, e.g., for a grating, the FSR is inversely proportional to the diffraction order m . To increase the operating bandwidth in echelle gratings, neighboring diffraction orders can be suppressed by specifically engineering each individual grating facet.^[79] Another strategy to extend the bandwidth of the spectrometer (Table 1) is cascading dispersive elements.^[93,126] First, a low-resolution dispersive element splits the broadband light into multiple wavelength bands. Then, a second set of elements splits each band into the high-resolution optical channels (where high resolution refers to small $\delta\lambda$). Finally, we note that for some dispersive elements, such as an AWG, a trade-off arises between bandwidth and resolution. This trade-off results from a decrease in both $\delta\lambda$ and the FSR when the optical path length difference (OPD) between the waveguides in the AWG increases (for fixed free propagation regions).

Finally, we discuss the influence of fabrication imperfections. In classical dispersive spectrometers, such imperfections generally result in optical crosstalk, i.e., the spillover from one wavelength into the neighboring spectral channels. When it comes to arrayed waveguide gratings, the crosstalk is usually induced by the non-uniformity of the waveguides across the linear waveguide grating. This non-uniformity is usually caused by variation in waveguide width across the chip, leading to a distortion of the wavefront compared to the design.^[127] For echelle gratings, as well as other grating-based or holographic spectrometers, the light propagates through a slab waveguide, rather than a strip waveguide. In this case, width variations do not pose an issue, and the device generally exhibits less optical

crosstalk.^[86] Optical crosstalk in this case arises from inaccurate placement and size variation in the grating or PhC elements^[85] or from non-uniformity in the thickness of the waveguide layer.

4.2 Resonator Array Spectrometers

The second approach to spatially dispersed on-chip spectrometers uses optical resonator arrays. In this case, each resonator will be tuned to a different resonant wavelength [Fig. 2(c)]. So, when a broadband signal comes in, each resonator will now split off a spectral component and funnel it into a photodetector. Proposed types of resonators include microdonut or microring resonators (MRRs)^[99,101,128] and PhC cavities.^[100,129] One advantage of such a design is that the spectral resolution is not directly limited by the physical size of the optical components. Instead, $\delta\lambda$ is determined by the quality factor Q of the resonator. On-chip resonators can achieve very high Q , allowing for compact spectrometers with a high spectral resolution (small $\delta\lambda$) and a small footprint (Table 1).

Similar to the classical dispersive spectrometers, the bandwidth of the device is limited by the FSR of the resonator (Fig. 3). Furthermore, there still is a linear scaling behavior, but it now applies to N . Each resonator corresponds to one spectral channel or wavelength, so for a large N , a large resonator array is needed.

For some resonators, e.g., MRRs, the trade-off between bandwidth and resolution is also present.^[130] This trade-off results from the scaling of the performance metrics with the radius R of the MRR. The FSR of the resonator increases as we reduce R . The quality factor on the other hand depends on the optical loss in the resonator. When the bending loss exceeds the other

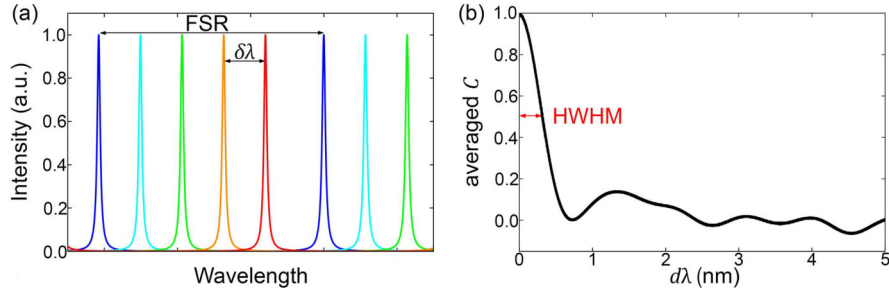


Fig. 3 (a) Each color represents the transmission into one spectral channel of a spectrometer based on a classical dispersive element or resonator array. Wavelengths separated by the FSR of the dispersive element are collected by the same detector. (b) Typical example of the averaged spectral correlation function [Eq. (7)] as a function of wavelength spacing. The spectral resolution relates to the half-width at half-maximum (HWHM) of the curve.

sources of optical loss in the MRR, the reduction of R and thus an increase in FSR is accompanied by an increasing loss, thus reducing Q and increasing $\delta\lambda$. Therefore, bending loss sets a practical limit to size downscaling of MRR-array-based spectrometers.

Fabrication imperfections, such as sidewall roughness and variation in waveguide dimensions, influence the resonator array spectrometers in two ways. Firstly, fabrication imperfections introduce losses that decrease the quality factor of the resonator, resulting in increased crosstalk or reduced resolution of the device. Secondly, imperfections result in reduced control over the resonant frequency of individual resonators and again increased crosstalk between the channels. The second issue, however, can potentially be mitigated by active tuning of the resonant frequencies at the expense of device complexity.

4.3 Wavelength Multiplexing Spectrometers

So far, we have discussed the use of dispersive elements or resonators to separate the different spectral components into individual wavelength channels. Alternatively, the principle of wavelength multiplexing can be utilized to realize on-chip spectrometers. Figure 2(d) sketches the working principle of such a device. Unlike narrowband-resonator-array-based spectrometers, the wavelength multiplexing spectrometer employs broadband filters. The operating principle of the device is therefore distinctively different. Nevertheless, recent work shows that the same principles (discussed below) can be applied to classical dispersive spectrometers^[98] and resonator array spectrometers.^[101,129] In these cases, the dispersive or resonator elements are effectively treated as broadband filters in order to achieve a higher spectral channel count with a limited number of detectors or to reduce the required quality factor Q of the resonators.

Classical dispersive spectrometers and resonator array spectrometers traditionally operate under the assumption that G is a square, diagonal matrix [Eq. (2)]. In other words, the functions $T_i(\lambda_j)$ are assumed to be zero for all $\lambda_j \neq \lambda_i$. For wavelength multiplexing spectrometers, however, each $T_i(\lambda_j)$ represents a broadband filter transmittance and is composed of a linear combination of many wavelengths. To allow determination of an unknown input spectrum $S(\lambda)$, the matrix A is generally calibrated with a tunable laser (or a known broadband source in conjunction with a calibrated spectrometer). Once the matrix A is known, the wavelength multiplexing spectrometer can be used to measure and reconstruct unknown input spectra based on the

methods described in Sec. 3. Wavelength multiplexing spectrometers are thus the first type of spectrometers we encounter that belong to the class of so-called computational spectrometers. Computational spectrometers generally suffer from longer reconstruction times than classical dispersive and resonator-based spectrometers. On the other hand, computational spectrometers are generally more robust against fabrication imperfections, since potential imperfections, such as variations in waveguide thickness throughout the chip, are captured in the calibration of matrix A .

The operating bandwidth $\Delta\lambda$ of wavelength multiplexing spectrometers is determined by the wavelength range over which the matrix A is calibrated. For a given $\Delta\lambda$, the resolution $\delta\lambda$ and the spectral channel count N are then dictated by the choice of filters as well as the reconstruction algorithm. Taking advantage of the computational reconstruction and prior knowledge of the spectrum, the number of filters M can be significantly smaller than N .^[102,105,106] Multiplexing spectrometers thus allow for a reduced device footprint with similar resolution to classical dispersive spectrometers. Increasing the resolution of the device, however, is not as straightforward as just increasing the number of filters. It is important that the functions $T_i(\lambda)$ give a unique response across the operating bandwidth. The uniqueness of an individual filter's response with wavelength is generally quantified with the spectral correlation function:^[131]

$$C(d\lambda, i) = \frac{\langle T_i(\lambda)T_i(\lambda + d\lambda) \rangle}{\langle T_i(\lambda) \rangle \langle T_i(\lambda + d\lambda) \rangle} - 1, \quad (7)$$

with $d\lambda$ representing the spacing between wavelength points and where $\langle f(\lambda) \rangle$ represents the averaging of the function $f(\lambda)$ with respect to λ . When averaged over all filters, the spectral correlation function should peak at $d\lambda = 0$ [Fig. 3(b)]. The half-width at half-maximum (HWHM) can then be used as a proxy for the spectral resolution $\delta\lambda$.^[57] Here, we note that one can experimentally achieve a $\delta\lambda$ much smaller than the HWHM of the averaged spectral correlation function^[124] when the optical SNR is sufficiently high. Nevertheless, C remains a key figure-of-merit when comparing the spectral resolving power of different spectrometer designs.

The choice of filters determines the scaling behavior of the device. Broadband filter implementations include random scattering,^[57,104,132] Mach-Zehnder interferometers (MZIs),^[51,133–143] multimode interference,^[102,144,145] stratified waveguides,^[105]

Table 1 Overview of Performance Metrics for Representative Examples of Each Spectrometer Type^a

Ref.	Category	Method	λ_c (nm)	$\delta\lambda$ (nm)	$\Delta\lambda$ (nm)	F (mm ²)	D
[84]	Classical	Echelle grating	1550	0.5	60	9	121
[86]		Echelle grating	1300	4.5	18	0.02	4
[87]		Echelle grating ^b	1300	7	1400	4	
[89]		AWG	1545	0.2	20	64	50
[93]		Cascaded AWGs	1550	1	195	110	195
[95]		Planar holograms	740	0.15	148	200	926 ^c
[98]	Resonator array	Metallenses ^d	1550	0.14	50	0.01	32
[99]		MRR	1580	0.6	50	1	84
[100]		PhC cavity	840	0.3	35	0.004	100
[101]		MRR ^d	809	0.17	12	0.15	3
[51]	Multiplexing	FT	1550	0.03	0.78		14
[102]		Multimode spiral	1520	0.01	2	0.25	40
[103]		Speckle-enhanced FT	1556	0.003	12	100	600 ^e
[104]		Scattering	1556	0.25	30	0.0004	8
[105]		Stratified waveguides	1560	0.45	180	0.009	32
[106]		Coherent network	776	0.02	12	0.11	8
[107]	SWIFTS	Disordered lattice	1545	0.015	40	1	4096 ^c
[108]		Lippmann	633	0.16	256	0.032	2000 ^f
[109]		Tunable SWIFTS	1500	40	1000	0.001	5
[110]		Multi-aperture Lippmann	842.5	0.2	75	5.12	160
[111]	Tunable narrowband	MRR	1580	0.15	19	0.6	1
[112]		PhC cavity	1455	0.5	12.3		1
[113]		FP cavity array	1472	0.43	73.2	0.026	5
[114]		MRR + MRR array	1550	0.005	9.7	0.35	11
[115]		Photonic molecule ^d	1550	0.04	100	0.004	1
[116]		Microdisk ^d	1505	0.01	0.3	0.24	1
[117]		Cascaded MRRs ^d	1550	0.1	200	0.004	3
[118]		Cascaded MRRs ^d	1440	0.008	520	0.6	1
[52]	FT	dFT ^g	1560	0.2	20	1.9	1
[119]		Thermo-optic	1550	0.9	56	0.9	1
[120]		MRR assisted TO	1571	0.47	90		1
[121]		MEMS	1550	0.2	100	0.075	1
[122]	Tunable broadband	2D FT	1550	0.125	200		128
[123]		Multimode spiral	1554	0.015	2	3.36	12
[124]		Cascaded MZIs	1510	0.01	200	8	1
[125]		Cavity-enhanced mode mixing	1550	0.005	100	1.5	1

^aFor each example, the spectrometer category, implementation method, center wavelength λ_c , spectral resolution $\delta\lambda$, bandwidth $\Delta\lambda$, footprint F , and number of detectors D are listed. A more complete overview can be found in Appendix A.

^bRequires cryogenic temperatures and NbN superconducting nanowires for single-photon detection.

^cMakes use of an off-chip camera.

^dEmploys computational spectral reconstruction based on a calibrated A matrix.

^eEach data point consists of an average over a column of off-chip camera pixels.

^fNumber of metal scattering centers.

^gDigital Fourier transform (dFT).

coherent networks,^[106,146] self-coupled waveguides,^[147] disordered MRR lattices,^[107] and disordered in-plane metasurfaces.^[148] For a straightforward filter-array approach,^[105,147] linear scaling of the footprint with the number of measurement channels M holds. As a result, either the resolution or bandwidth will scale linearly with the filter array footprint. For other approaches, the spectral correlation of the filter transmittance depends on the OPL.

Spatial heterodyne or stationary Fourier-transform (FT) spectrometers [Fig. 2(e)]^[51,133–143] consist of an array of MZIs with a unique OPD. In the case that $N = M$ with linearly spaced OPDs, the inversion of matrix G becomes equivalent to a classical Fourier transform,^[133,134] hence the name FT spectrometer. The resolution of such a spectrometer is dictated by the FSR of the MZIs. This FSR scales inversely proportional with the OPD of the MZI. A long path length will give a small FSR and thus allow for a high spectral resolution. Additionally, stationary FT spectrometers again follow a linear scaling law. For high spectral resolution a large number M of interferometers is needed, which again results in a trade-off between footprint and $\delta\lambda$.

For random-scattering-based spectrometers, due to the occurrence of multiple scattering events, the effective path length on-chip can be much longer than the length of the scattering region. As a result, the resolution no longer improves linearly with the geometric dimension of the device. Instead, in the diffuse regime, a quadratic scaling is observed.^[57] Similarly, evanescent coupling between waveguides in a spiral^[102] or coupling to MRRs^[106,107,146] can be employed to increase the OPL and thus modify the scaling behavior of the spectrometer.

Alternatively, cascading broadband filter elements, such as disordered metasurfaces,^[148] can achieve a more narrowly peaked spectral correlation function. In this case, the performance metrics of the device are still expected to scale linearly with the number of filter elements.

4.4 Stationary-Wave Integrated Fourier-Transform Spectrometers

The last type of spectrometer we discuss in the category of spatially dispersed spectrometers is the stationary-wave integrated Fourier-transform spectrometer or SWIFTS, which can also be considered a special class of wavelength multiplexing spectrometers. The SWIFTS operates by creating a standing-wave interference pattern in the waveguide [Fig. 2(f)]. By integrating a linear array of detectors, the spatial intensity distribution of the standing wave can be mapped. From this intensity distribution, the input spectrum can be inferred. Similar to the spatial heterodyne FT spectrometers, spectral reconstruction based on a standing-wave interferogram sampled at constant pitch is equivalent to a classical Fourier-transform.

We distinguish three SWIFTS configurations: the Lippmann configuration,^[108,110] the counterpropagative configuration,^[149] and the copropagative configuration.^[150] In the Lippmann configuration, the standing wave is created by means of a reflector, such that the reflected light interferes with the incident light. In the counterpropagative configuration, light is propagating in both directions of the spectrometer waveguide. In the configuration, two parallel waveguides with different effective indices are used to generate a standing-wave interference pattern in between the two waveguides.

Regardless of the configuration, the resolution of an SWIFTS is limited by the length of the interferogram. Again, a linear

relation emerges where the resolution improves with increasing device length. The bandwidth at a given device length depends on the sampling rate, i.e., the spacing between the detectors Δx .^[151] Given the relatively large footprint of currently available integrated photodetectors,^[152] demonstrated SWIFTSs employ scattering arrays in combination with off-chip detector arrays to achieve a narrower on-chip sampling pitch. As a result, Δx and consequently $\Delta\lambda$ are diffraction-limited.

One method to increase $\Delta\lambda$ is to couple the input spectrum into multiple waveguides^[110] or a slab waveguide^[108] (Table 1). This allows the detectors/scattering centers to be spread out laterally, enabling an enhanced sampling rate along the standing-wave pattern. Additionally, the coupling of the input light into multiple waveguides [Fig. 2(e)] or a slab waveguide allows for an increased spectrometer etendue, a topic we explore further in Sec. 6.

As an alternative approach, one can improve $\Delta\lambda$ by applying a phase shift to the input light, e.g., with a tunable MZI,^[115] electro-optic modulators,^[109,153] or thermo-optic modulators.^[154] By implementing a phase delay between the two inputs (in a counterpropagative configuration), one is able to shift the location of the center of the interferogram. By stepwise increasing the phase delay and consecutive sampling of the interferogram, the entire interferogram can be sampled even at a large detector pitch. Note that this measurement technique requires active tuning of the spectrometer, and we have effectively changed the spatially dispersed SWIFTS into a combined spatially dispersed and time-domain modulated device. The matrix G now must incorporate the transmission functions for every wavelength in both space and time.

5 On-Chip Spectrometers Based on Time-Domain Modulation

We have discussed spatially dispersed on-chip spectrometers in the previous section. In the final paragraph, we encountered an example of a spectrometer that utilizes time-domain modulation. In this section, we explore other on-chip spectrometers based on time-domain modulation. Instead of spatially spread static filters (Fig. 1), tunable filters are used in time-domain modulated spectrometers. This allows for modulation of the filter's spectral response as a function of time. As a result, instead of a detector array, only a single detector is required. Now the photodetector readout y gives a time sequence of intensity readings from the single detector, instead of the signal readout of the detector array. Each element y_i thus gives the readout at one particular point in time or, in other words, at one specific state of the tunable filter. Each row in the matrix G now corresponds to a filter transmittance function $T_i(\lambda)$ for one particular tunable filter state i .

5.1 Narrowband Tunable Filter Spectrometers

The first variant of such a time-domain modulated spectrometer we discuss is a spectrometer based on a narrowband tunable filter.^[111–113,115,116,118,155,156] A common choice of narrowband filter is an MRR or microdisk resonator integrated with an optical phase modulator, such as a thermo-optic phase shifter [Fig. 4(a)].^[111,116,156] Other filter choices include Fabry–Pérot (FP)^[112,113] and PhC cavities.^[155]

Tunable-filter-based spectrometers tend to have an advantage over resonator arrays in terms of optical crosstalk. The advantage arises from the fact that only a single resonator is used.

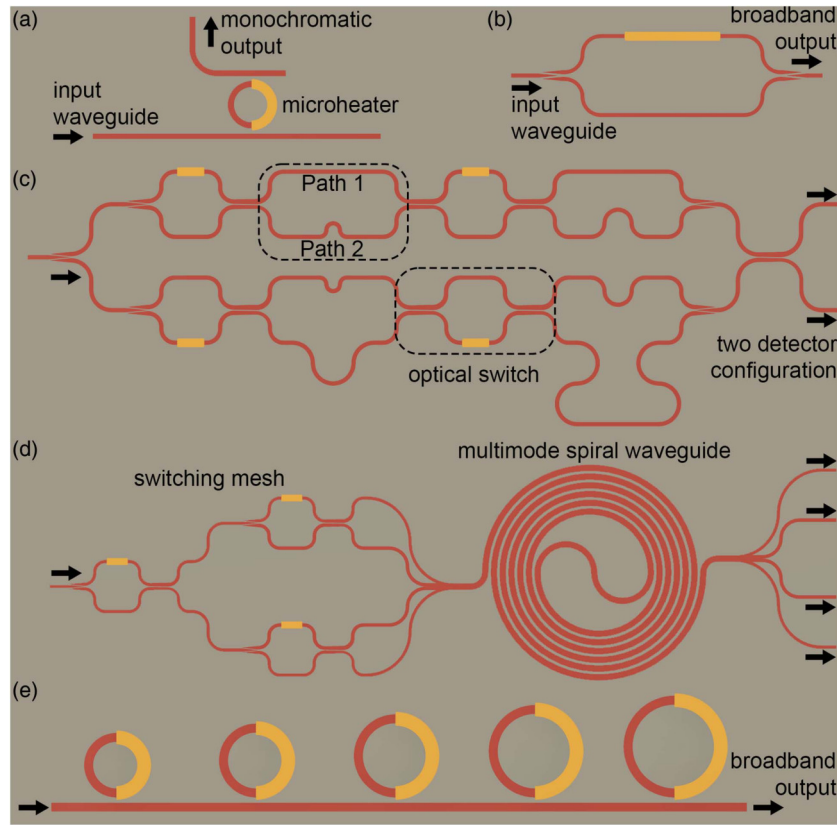


Fig. 4 Schematic representations of the types of time-domain modulated spectrometers. (a) Narrowband filter spectrometer based on an MRR with a thermo-optic phase shifter. (b) FT spectrometer consisting of an MZI with a tunable delay in one of the arms. (c) dFT spectrometer architecture^[52] with double detector configuration. In each arm of the main MZI, optical switches route the light to one of two possible paths (either path 1 or path 2). Each combination of switch states gives a unique OPD at the main MZI output. (d) Tunable broadband filter spectrometer, where a wavelength multiplexing spectrometer based on an evanescently coupled multimode spiral waveguide is combined with an optical switching matrix.^[123] (e) Cascaded tunable MRR spectrometer.^[118]

Consequently, we do not have to worry as much about fabrication imperfection and the resulting resonator-to-resonator variation.

Similar to resonator array spectrometers (Sec. 4.2), the operating bandwidth of a tunable narrowband filter is limited by the FSR of the resonator. In addition to the FSR, the attainable wavelength tuning range can limit $\Delta\lambda$. The resolution is again not directly limited by the physical size. Instead, $\delta\lambda$ is determined by the quality factor Q . Since only a single narrowband filter and photodetector are required, the footprint of the spectrometer can be much smaller than that of spatially dispersed spectrometers (Table 1). Furthermore, we have a unique scaling behavior, where both N and $\delta\lambda$ do not scale with the device footprint, but instead depend on the resonator's Q and the phase modulation range.

In the case of a tunable MRR,^[111] we again have that reducing the ring radius leads to an increasing FSR, but decreasing Q when radiative bending loss takes over. Hence, a similar trade-off between resolution and bandwidth arises as for MRR arrays. FP and PhC cavities, on the other hand, can exhibit high Q with a large FSR. These large FSR cavities, however,

generally still exhibit a limited $\Delta\lambda$, due to a limited tuning range.

There again exist several approaches to achieving both a broad bandwidth and a high resolution. First, the operating bandwidth can be extended by cascading multiple tunable cavities,^[113,155] in which the wavelength tuning range of each is centered around a different part of the total bandwidth, or by co-integration of a resonator with a tunable lattice filter^[157,158] or tunable FT spectrometer (Sec. 5.2).^[120] A third approach entails co-integration of a tunable narrowband filter with a dispersive element.^[114,159–162] Such a co-integrated design is similar to cascaded dispersive spectrometers (Sec. 4.1). The dispersive element is used to split the broadband signal into multiple wavelength bands. Each output of the dispersive element is now routed to a tunable filter (instead of a second dispersive element), where we perform a high-resolution scan of the wavelength band. Alternatively, the order of co-integrated components can be reversed.^[120,159,161,162] In that case, the broadband signal first passes a resonator, where a set of wavelengths with a spacing equal to the FSR is filtered out of the input. The filtered wavelengths are then sent through a coarse dispersive

splitting element, which routes each of the filtered wavelengths to a specific detector. Both the cascaded cavity as well as the co-integrated approaches, however, require multiple photodetectors as well as an increased device footprint. The final approach we discuss is the engineering of the MRR system to obtain operation spanning multiple FSRs. A broadened $\Delta\lambda$ could, for example, be obtained by the Vernier effect^[163,164] or using microgear resonators.^[165] Recent works employ dispersion engineering in photonic molecules,^[115] selective mode coupling,^[166] or cascaded MRRs.^[117,118] Note that in these cases, the narrow-band filter is effectively converted into a (sparse) broadband filter (Sec. 5.3) and reconstruction of the input spectrum is based on a measured matrix A (Sec. 3).

5.2 Fourier-Transform Spectrometers

The second type of spectrometers based on time-domain modulation is the FT spectrometer [Fig. 4(b)], which can be regarded as the time-domain modulated counterpart of the stationary FT spectrometer that we discussed in Sec. 4.3. An FT spectrometer consists of a variable MZI, where in one or both of the arms a tunable delay is integrated to generate a tunable OPD between the two arms. The tunable delay can be implemented in various ways, including electro-optic modulators,^[167,168] thermo-optic modulators,^[119,120,169–171] or MEMS.^[121,172] The resolution is inversely proportional to the maximum OPD that can be achieved by the tunable delay. As a result, for a given choice of modulator, we again observe a linear scaling behavior, where the resolution improves with increasing device footprint.

To increase the OPD beyond the typical on-chip phase modulators' tuning range, a combination of spatial heterodyne and time-domain modulated FT can be used.^[170,172,173] In this case, each MZI is used to tune the OPL over a unique range of OPDs. A different combination of spatial heterodyne and time-domain modulated FT can be implemented by cascading a tunable FT with a spatial heterodyne FT spectrometer.^[122] An alternative device architecture, the on-chip digital FT (dFT) spectrometer [Fig. 4(c)],^[11,52,171,174–178] has also been proposed. In a dFT spectrometer, we integrate a cascaded array of optical switches on each arm of the interferometer. Each switch allows for toggling the optical path between two waveguides. Each permutation of the optical switch states results in a unique OPD. Since switching of waveguide paths presents a far more efficient way to introduce phase delay compared to electro-optic or thermo-optic modulation, the waveguide lengths needed in dFT spectrometers to achieve the same OPD can be more than two orders of magnitude shorter. Instead of a linear scaling with footprint, the number of optical states M is proportional to 2^k , where k is the total number of optical switches. As a result, the spectral resolution also scales with 2^k . This exponential scaling allows for a compact integrated device with a high optical performance. It is worth highlighting that the dFT spectrometer represents the first example of a more generic class of time-domain modulated spectrometers based on cascaded tunable elements to achieve exponential scaling, where the total number M of optical states scales with the product of state numbers across all elements. We shall see more examples of this class of spectrometers in other sections.^[118,124,125,179]

Finally, we note that for both stationary as well as time-domain modulated FT spectrometers in a single-detector configuration, on average, half of the photons in a broadband signal will be tossed out, since only constructively interfering photons

are retained. These “lost” photons can be reclaimed by implementing a two-detector configuration. In this two-detector configuration, instead of a 2×1 combiner at the end of the MZI, a 2×2 coupler is used [Fig. 4(c)]. By doing so, we can actually double the signal. If the spectrometer noise is dominated by the detector noise,^[180] the two detector approach achieves a net gain of the SNR by a factor of $\sqrt{2}$ compared to the single-detector configuration.

5.3 Tunable Broadband Filter Spectrometers

In this class of spectrometers, a broadband transmission spectrum is tuned. These spectrometers employ the same principles as wavelength multiplexing spectrometers (Sec. 4.3), with the addition of active modulation of the broadband filters to vary the signal at one^[124,125,181] or multiple photodetectors.^[123,179,182–184]

Similar to the dFT spectrometer, a photonic-switching-based approach has been applied to multimode-interference-based wavelength multiplexing spectrometers [Fig. 4(d)].^[123,179,182] Here, the switches are used to selectively launch modes into a multimode waveguide. Since the effective OPL in the multimode waveguide is independent of the optical switches, the spectral resolution does not directly depend on the number of optical switches k . Instead, M and $\Delta\lambda$ change with the number of optical switches. The relation between M and k depends on the exact device implementation. Scaling with k , 2^k ,^[179] and k^2 ^[182] has been demonstrated.

Alternative tunable broadband filter implementations include tunable coherent networks,^[181,183] tunable-cavity-enhanced mode mixing,^[125] and disordered metalenses with beam steering.^[184] Similar to their stationary counterparts, these approaches employ resonators, evanescent coupling between waveguides, and cascaded filter elements to increase the effective OPL and decrease the correlation of transmission functions $T_i(\lambda)$ [Eq. (7)]. As a result, a complicated scaling behavior is recovered. In the case of cavity-enhanced mode mixing, for example, the resolution is found to be relatively independent of the overall size of the resonator, but instead scales approximately linearly with the size of the mode mixing region.^[125]

Finally, another tunable-MZI-based spectrometer was recently proposed.^[124] Instead of an FT spectrometer with a single MZI, multiple cascaded MZIs were used to generate a complicated interference signal at the output. As a result, the resolution is no longer limited by the maximum OPD that can be achieved in a single MZI. An exponential scaling is recovered, where the scaling depends on the number of cascaded elements k and the number of states per element. An alternative approach to this type of exponential scaling employs cascaded MRRs [Fig. 4(e)],^[118] which can be used to implement a broadband tunable filter (Sec. 5.1). With four tuning states per ring, M is proportional to 4^k . With a dispersion-engineered six-ring design ($M = 4096$) a record-high resolution-to-bandwidth ratio was achieved (Table 1).

6 Constraints to On-Chip Spectrometer Implementation

Now that we discussed the different types of PIC-based spectrometers and their performance metrics, we proceed to assess some fundamental constraints and design considerations for on-chip spectrometers. These constraints determine the applicability of on-chip spectrometers under different circumstances.

In the following section, we treat the application areas where PIC-based spectrometers promise a significant impact.

The most significant limitation of waveguide-based spectrometers is the optical throughput: compared to free-space spectrometers, PIC-based spectrometers generally exhibit significantly reduced optical throughput due to the small etendue of on-chip waveguides. In some spectrometer designs, such as resonator array spectrometers,^[100] SWIFTS,^[108] and specific wavelength multiplexing spectrometers,^[103,106,139,140,146] the spectrometer etendue can be increased by coupling into multiple waveguides or slab waveguides. Nonetheless, the etendue generally remains small compared to free-space spectrometers, such as 2D filter-detector array spectrometers.^[185,186] Therefore, PIC-based spectrometers work best with light sources that have a high degree of spatial coherence. When dealing with a large-area light source with low spatial coherence, the performance of on-chip spectrometers is severely limited.

Another important consideration relating to spectrometer applicability is the material platform on which to implement the spectrometer. Firstly, the wavelength range covered by PIC spectrometers is limited by the material platform. Silicon-on-insulator (SOI), which, due to its compatibility with standard complementary metal-oxide-semiconductor (CMOS) processing, allows for low-cost and scalable manufacturing, is the most widely used platform for PICs in the near-infrared (near-IR). However, due to considerable absorption in the visible range and at longer mid-IR wavelengths ($>3.5\ \mu\text{m}$ for oxide-cladded devices and $>6.7\ \mu\text{m}$ for suspended Si waveguides), the SOI platform is not suited for spectrometry outside of the short-wavelength part of the IR spectrum. In the visible range, silicon nitride (SiN) has emerged as a CMOS-compatible alternative.^[8,187] Other material platforms are required for spectroscopic sensing in the so-called “fingerprint region” (7–20 μm , containing the primary absorption bands of many chemical and biological molecules).^[7,188]

Beyond the transparency window, the choice of material can influence spectrometer performance. Waveguide losses are generally dominated by scattering loss, due to sidewall roughness.^[10] Processing capabilities and the resulting sidewall roughness are related to the choice of material platform. In the near-IR, SiN has emerged as a low sidewall roughness and thus ultralow-loss waveguide platform.^[8,10] Lower waveguide losses not only promise higher optical throughput, but can directly influence spectrometer performance metrics. For example, due to these ultralow losses, the SiN platform promises higher Q resonators^[189] than SOI, allowing for higher resolution in resonator-based spectrometers. Because of the lower refractive index contrast with the oxide cladding, however, SiN waveguides exhibit larger bending losses than Si waveguides. Consequently, SiN waveguides require larger bending radii, resulting in a larger device footprint and limited microring FSR.

Finally, we discuss the thermal stability of on-chip spectrometers. Changes to the on-chip temperature generate refractive index changes in the waveguide through the thermo-optic effect. As the TO coefficient in most PIC platforms is positive, an increase in temperature generally yields redshifted transmittance functions $T_i(\lambda)$.^[124,147,190–192] The most straightforward solution is active monitoring and regulation of the temperature of the PIC, e.g., with a thermo-electric cooler. Such thermal control, however, increases the power consumption of the device.

Alternatively, monitoring the on-chip temperature allows for compensation for temperature variations by applying a

correction to the matrix G that accounts for the thermally induced shift in $T_i(\lambda)$.^[192,193] Consider the case of a classical dispersive or resonator-based spectrometer with a square, diagonal G as a concrete example. At higher temperatures than designed for, wavelength λ_j can be collected at detector channel $i < j$ instead of the intended channel $i = j$. When the chip temperature at the time of measurement is known, this offset between the detector and the wavelength channel can be corrected. A drawback in this case of a diagonal G matrix (especially for designs with a larger FSR than $\Delta\lambda$) is potential loss of spectral information,^[147] resulting from the fact that the signal at the edge of the bandwidth is no longer collected at any detector. Spectrometer designs based on non-diagonal G matrices, i.e., spectrometers implementing broadband filters, are better equipped to handle large temperature changes, since even though $T_i(\lambda)$ changes with temperature, light from all wavelengths continues to reach the detector. By performing calibration over a large range of temperatures, the entire input spectrum can thus be recovered over a larger temperature range.^[147,193]

Finally, thermal stability can be taken into account during the design of the spectrometer.^[142] Firstly, the material platform in which the spectrometer is integrated is important. The TO coefficient for SiN, e.g., is significantly smaller than the TO coefficient for Si. Consequently, spectrometers implemented on SiN are generally more thermally stable than on SOI. Secondly, one can aim to design the spectrometer such that the spectral response does not change with temperature, e.g., by adding an extra optical component that compensates for the temperature dependence of the filters.^[190,194] In a recent work, an athermal echelle grating^[194] was implemented by compensating for the thermally induced tilt in the phase front in the grating with the thermal response of an asymmetric MZI at the input of the device.

7 Integrated Photonic Spectrometer Applications

We discuss four application areas where PICs promise key advantages and opportunities as a result of their reduced SWaP-C metrics.

7.1 Biological and Chemical Sensing

Both absorption and Raman spectroscopy are powerful techniques to directly identify chemical and biological samples.^[1,14] Due to the size and cost of traditional spectrometers, this spectroscopic analysis is historically performed in a laboratory setting. There is however an increasing demand for spectrometers that can be brought out into the field, enabling on-site analysis for a wide range of applications, including industrial, environmental, or toxic gas sensing,^[195] point-of-care diagnostics,^[196] bioprocess monitoring,^[197,198] and forensics.^[199]

Integrated photonics provides a unique opportunity for so-called lab-on-chip system integration, wherein the light source, sensing element, and detector are all integrated into the same platform [Fig. 5(a)].^[200–203] Spiral waveguides and on-chip resonators allow for long interaction lengths with a small footprint.^[204,205] Compared to other (on-chip) sensing techniques, such as refractive index sensing [Fig. 5(b)],^[200] spectroscopic sensing [Fig. 5(c)] offers high selectivity without the need for target-specific functionalization or labeling. Unlike sensors relying on surface functionalization coatings, which are typically for single-use only due to the irreversible binding nature

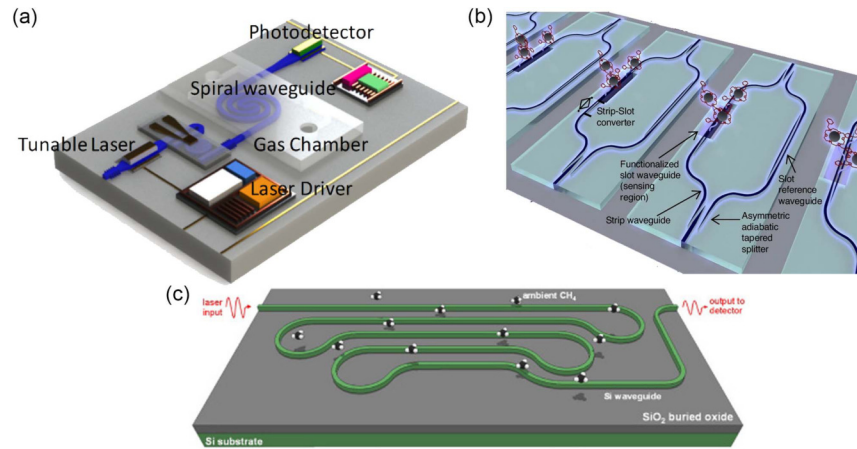


Fig. 5 (a) Example of an integrated photonic lab-on-chip system. Reprinted with permission from Ref. 210 © Chinese Laser Press. (b) Refractive index sensing for lead detection using functionalized MZIs. Adapted from Ref. 211 under Creative Commons license.^[212] (c) Waveguide-based methane absorption sensor. Reprinted with permission from Ref. 213 © Optical Society of America.

of the coatings, lab-on-chip systems based on spectroscopic sensing can be repeatedly used, e.g., for applications where continuous monitoring is needed. Furthermore, waveguide-based sensing can provide enhanced sensitivity in Raman spectroscopy.^[206–209]

Recent work in integrated spectrometers for sensing applications includes gas sensing,^[162,172] sensing of volatile organic compounds,^[128] absorption sensing,^[118,138] and Raman spectroscopy.^[110] One specific example focused on a spectrometer for sensing multiple gases, such as HF, CO, H₂S, and CO₂, at wavelengths between 1310 and 1930 nm.^[162] The proposed design consisted of a multimode-waveguide-grating-based filter array in combination with tunable MRRs. The authors were able to implement a chip-scale spectrometer for high-resolution sensing (0.08–0.37 nm) over this broad bandwidth using four multimode waveguide gratings as bandpass filters, each centered on a narrow wavelength band of interest (6–10 nm at 1310, 1560, 1570, and 1930 nm). In another study,^[118] a cascaded MRR spectrometer is used to measure the reflectance spectra of various plastic and coffee samples as well as the concentration-dependent transmission spectra of various solutions (such as ethanol or glucose aqueous solutions). The authors train a support vector machine to identify the different plastic or coffee samples on the reconstructed spectra. Additionally, the integrated spectrometer achieves a detection limit of 0.1% glucose in solution, comparable to that of a benchtop dispersive and a benchtop FT spectrometer.

7.2 Telecommunications

Optical fibers provide high-bandwidth, low-loss optical communications worldwide. Recent years, however, have seen a significant increase in data traffic and a demand for even faster (6G) data transmission, due to the rise of big data, artificial intelligence, and the internet of things. To keep up with these increasing demands, network communication is being extended from the C+L-bands into the S-, E-, O-, and U-bands. Dynamic control is essential for energy-efficient operation of a multi-band

network, allowing for scaling up or scaling down the network depending on the network traffic.^[214–216]

Dynamic (software-based) control of modern networks (Fig. 6) is only possible with optical network monitoring.^[217,218] Efficient monitoring throughout the entire network requires low-cost, compact monitors that are able to track the individual wavelength channels. Integrated photonic spectrometers have the potential to fulfill these requirements for low-cost large-scale manufacturing and can provide real-time monitoring of the individual channels. Initial proposals for such optical channel monitors rely on classical dispersive elements such as echelle gratings^[219] and AWGs^[220] to directly monitor the optical power, SNR, and wavelength drift in the channels. An alternative monitoring approach is so-called “homodyne detection”, for which monitoring is based on the interference spectrum between the monitored signal and a tunable laser.^[214,221] In a recent work,^[222] a spectrometer design using a tunable MRR cascaded with two interlaced AWGs was proposed for high-resolution (~1.4 GHz or ~0.01 nm) optical network monitoring in the C-band (1530–1565 nm) on a SiN platform.

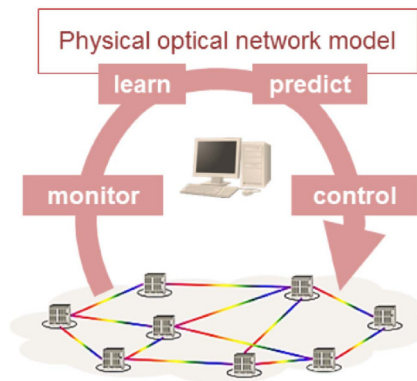


Fig. 6 Dynamic software-based control and management of optical networks. Reprinted with permission from Ref. [223] © Optical Society of America.

7.3 Spectral Domain Optical Coherence Tomography

Optical coherence tomography (OCT) is an interferometric 3D imaging technique that provides high-resolution, cross-sectional imaging for a wide range of scientific and medical applications.^[224] It is the gold standard for retinal imaging (Fig. 7) in ophthalmology and is increasingly used in cardiology, dermatology, and other medical fields. Additionally, OCT is applied in non-destructive testing (NDT) to provide information on subsurface structures and uniformity in manufacturing, aviation, automotive, display panels, and medical devices.

While there are a few embodiments of time-domain and Fourier-domain OCT, spectrometers play a crucial role in spectral-domain optical coherence tomography (SD-OCT). The bandwidth and resolution of the spectrometer directly influence the axial resolution and signal-to-noise ratio of the OCT system, making it an essential component in the performance of OCT. Traditionally, benchtop dispersive spectrometers are used in OCT systems, but there have been recent investigations into integrated photonic approaches. PICs allow for the miniaturization of OCT systems, making them more portable and accessible for various applications, including point-of-care diagnostics and field use. Additionally, the integration of photonic components onto a single chip can lead to substantial cost reductions by simplifying manufacturing processes and reducing the need for bulky, discrete optical elements. In recent years, there has been an effort to bring other components of the OCT system onto PICs,^[226] including beam splitters,^[227,228] delay lines,^[227,229] and light sources.^[230]

Notably, one of the latest works in the field developed two OCT spectrometer designs based on AWGs on a SiN platform. The devices featured sufficiently broad bandwidths (22 and 48 nm centered around 800 nm) to provide high axial resolution (10.7 and 6.5 μm , respectively).^[225] These were the first instances where PIC-based spectrometers were used to provide *in-vivo* retinal OCT imaging (Fig. 7) and achieved sensitivity above 90 dB. High sensitivity is crucial for medical applications due to the critical importance of accurate diagnosis, as it ensures detailed and precise imaging necessary for identifying and monitoring medical conditions. This innovation builds on AWG-based spectrometers^[92,126,231] and OCT demonstrations,^[161,232,233] which focus on wavelengths around 800 or 1300 nm, including imaging demonstrations of human skin.^[228] In a follow-up work,^[234] an OCT spectrometer comprised of a single, 512

channel AWG was used for *in-vivo* imaging of zebrafish, larvae, and human skin with a sensitivity of 92 dB.

7.4 Astronomy

Spectroscopic techniques are fundamental to astronomy and are used to determine chemical composition, measure motion, and detect exoplanets, among other applications.^[235,236] These astrophysical studies require large-diameter (D) telescopes to collect light from faint and distant sources. Conventional spectroscopic instrumentation scales in size with D and consequently scales with D^2 to D^3 in terms of volume, mass, and cost.^[235,237] The field of astrophotonics provides a path towards spectroscopic instrumentation at reduced SWaP-C.

In astrophotonics, light is coupled from a (large) telescope into a fiber and can then be coupled further into an integrated circuit. Although light coupling from the telescope into a fiber was already proposed in 1988,^[238] the coupling efficiency has been limited by atmospheric turbulence.^[236] With recent developments in adaptive optics, the coupling efficiency to fibers has significantly improved,^[239] and astrophotonics is becoming increasingly important to astronomical instrumentation. For a more complete overview of the field of astrophotonics, we direct interested readers to other review articles.^[236,240] Here, we briefly discuss integrated photonic spectrometers developed for astronomical purposes.

Although there is interest in using echelle gratings (due to their larger finesse)^[235,237] or FT spectrometers (for high-resolution, broadband operation),^[235] most demonstrations of integrated spectrometers for astronomy have so far focused on AWGs (Fig. 8).^[91,237,241] One notable study^[242] found that by removing the input waveguides and instead coupling light directly from a fiber into the free propagation region of an AWG, the resolution increased ($\delta\lambda$ reduced from 0.63 to 0.22 nm at 1540 nm wavelength) while simultaneously allowing for light injection from multiple fibers or sources into the same spectrometer. Similarly, on the output side of the AWG, the different spectral channels were not collected in a set of output waveguides. Instead, for these astronomical spectrometers, the focal plane of the output coupler was aligned with the edge of the chip, and the spectrum was imaged with an off-chip camera.^[91,242] In another recent study,^[144] the solar spectrum was collected with a telescope and routed to a multimode interference spectrometer. The authors showed accurate reconstruction of the Fraunhofer A absorption line in the solar spectrum (located at a wavelength of 760 nm).

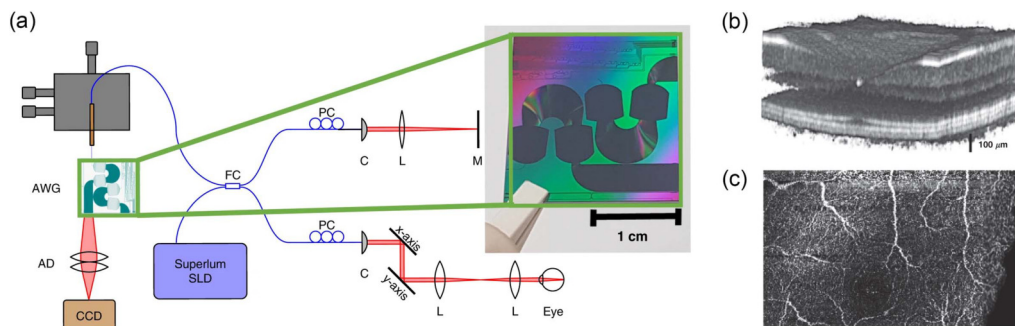


Fig. 7 (a) OCT set-up for retinal imaging with an AWG-based dispersive spectrometer. (b) 3D image of the retina as recorded with this set-up. (c) Corresponding OCT angiography (OCTA) image calculated from B-scan repetitions. Adapted from Ref. 225 under Creative Commons license.^[212]

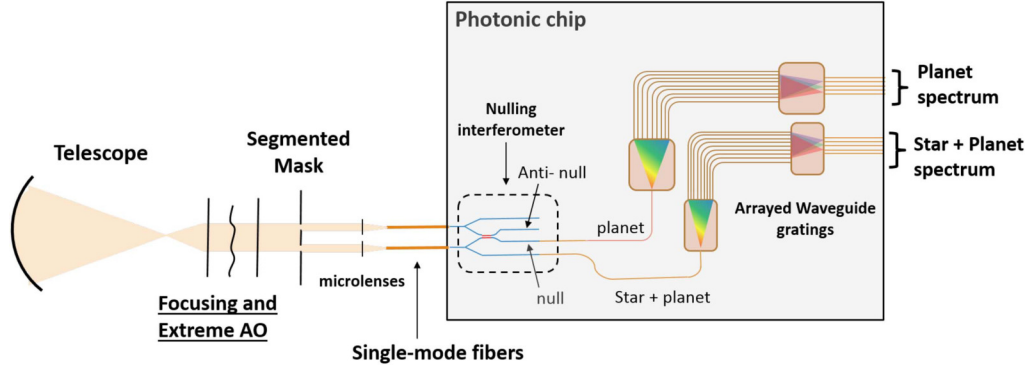


Fig. 8 Schematic of a telescope set-up integrated with AWG-based on-chip spectrometers for exoplanet spectroscopy. Reprinted from Ref. [235] under Creative Commons license.

8 Selecting the Right Spectrometer

In this section, we discuss how to select the right spectrometer for an intended application. Per application, the ideal spectrometer type depends on the requirements with respect to the performance metrics ($\delta\lambda$, $\Delta\lambda$, and SNR). Here, we start with the

spectrometer of choice when resolution is the most important metric. In Secs. 4 and 5, we discussed the relationship between resolution and footprint for the different types of spectrometer designs [Fig. 9(a)]. In this section, we focus on whether the intended application requires narrowband or broadband operation [Fig. 9(b)].

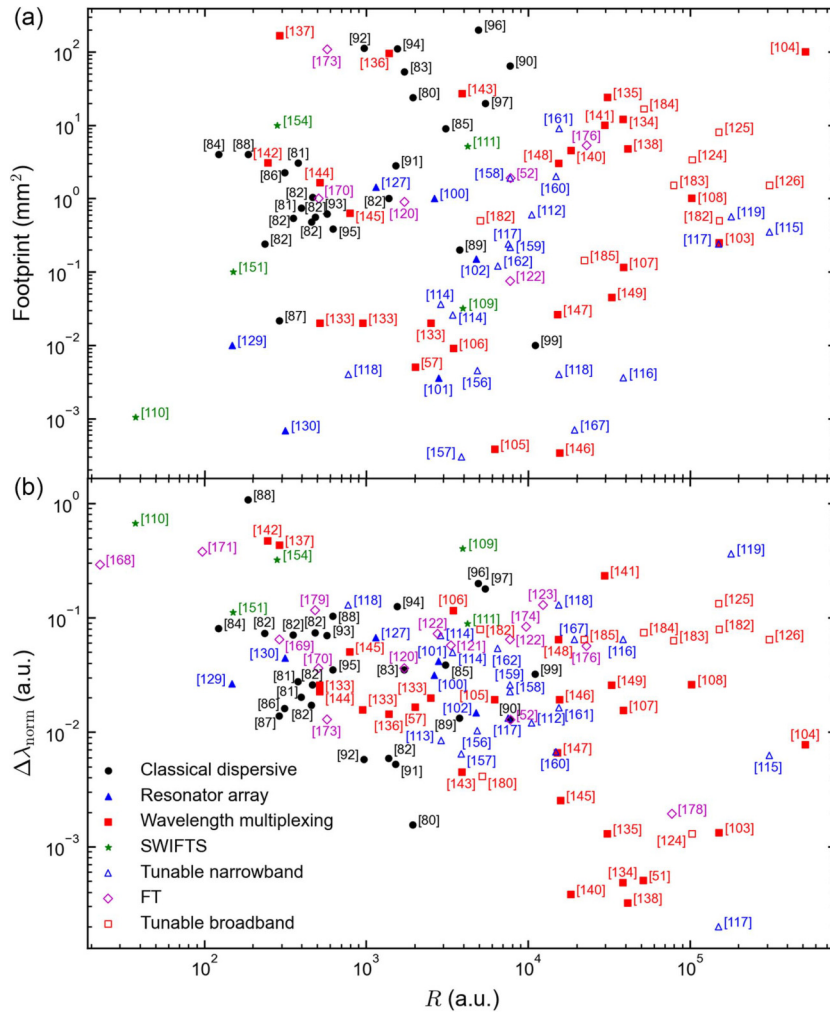


Fig. 9 Here we plot (a) the spectrometer footprint and (b) the normalized bandwidth ($\Delta\lambda_{\text{norm}} = \frac{\Delta\lambda}{\lambda}$) as a function of the resolving power ($R = \frac{\lambda}{\delta\lambda}$) for various integrated spectrometers. An overview of the plotted data can be found in Appendix A.

For narrowband operation, resonator-based spectrometers are promising candidates. Resonator-based spectrometers allow for very high resolution that is only limited by the resonators' Q . Additionally, due to the narrow transmission function of a resonator, these spectrometers are able to selectively measure the target wavelengths without interference from any of the background. Notably, in recent work, a tunable MRR in combination with an MRR array was used to achieve a high resolution of 5 pm over a bandwidth of 9.7 nm.^[114] Alternatively, spatially dispersed wavelength multiplexing spectrometers, such as stationary FT^[51] or multimode-interference-based spectrometers,^[102] are well-suited for high resolution under narrowband operation. With a so-called speckle-enhanced FT spectrometer,^[103] a high resolution of 3 pm over a 12 nm bandwidth was achieved (Table 1). However, we do note that this speckle-enhanced FT relies on the detection of light propagating both in strip waveguides as well as the substrate of the SOI PIC. Therefore, an off-chip camera is required to detect the spectrometer's output signals.

For broadband operation, due to the bandwidth-resolution trade-off, resonator-based spectrometers generally are not the best choice. Instead, a design that allows for exponential scaling with device footprint is needed to achieve high-resolution, broadband operation on-chip. Designs that allow for such scaling include cascaded MRRs,^[118] dFT, and tunable broadband filter spectrometers.^[124] The unique scaling in these types of spectrometers is ideal for achieving a large number of optical states M , thus enabling enhanced broadband performance. Furthermore, we note that these spectrometers' bandwidth is actually not limited by the bandwidth of the individual components, such as the optical switches. A switching-based device, for example, does not require perfect power switching between the different waveguides, as long as each switch permutation generates a unique spectral transmittance $T_i(\lambda)$. Ultimately the bandwidth and resolution of these spectrometers will only be limited by the waveguide single-mode condition and the SNR.

In the remainder of this section, we discuss the best choices for integrated spectrometers based on the SNR. Time-domain FT and tunable broadband filter spectrometers exhibit a theoretical SNR advantage over spatially dispersed and time-domain modulated narrowband filter spectrometers, known as the "multiplex advantage" or "Fellgett's advantage".^[243] This SNR advantage occurs when the main source of noise is from the photodetector (as opposed to light-intensity-dependent noise contributions, such as photon shot noise or background noise).^[180] For classical dispersive and resonator-based spectrometers, the input spectrum is split into many spectral channels and each spectral channel is detected separately. Multiplexing spectrometers and SWIFTS similarly spread the optical intensity over multiple detectors. As a result, the signal at the detector is diminished. Time-domain FT and tunable broadband filter spectrometers concentrate the light on a single or a few detectors, allowing for superior SNR. This SNR enhancement holds when comparing the same measurement bandwidth or, in other words, the same integration time. The enhancement factor depends on the spectrometer configuration, and the specific formalisms can be found elsewhere.^[180] It is important to note that this SNR advantage is generally non-existent when working with a sparse spectrum that only offers a few discrete spectral lines. In the spatially dispersed wavelength multiplexing designs, however, due to the use of

broadband filters, the diminished SNR persists even in the case of sparse spectra.

When optical noise spillover becomes significant, time-domain modulated FT and tunable or spatially dispersed multiplexing spectrometers suffer from "Fellgett's disadvantage". When the matrix G is non-diagonal, optical noise from all wavelength channels can impact the measurement. In this case, low-intensity signals can be overshadowed by large photon shot noise from another wavelength with high light intensity, for example, in the case of laser spectroscopy.

9 Future Directions

Finally, we discuss the direction in which the field of integrated spectrometry is headed. We first discuss expected developments in terms of spectrometer design, before discussing expected innovation in terms of signal analysis.

Integrated spectrometer designs have moved from classical dispersive and resonator-based designs with a one-to-one correspondence between detector i and spectral channel j , towards underdetermined A matrices and computational reconstruction (Sec. 3). Recently, we have seen the emergence of spectrometer designs whose number of optical states M and thus performance metrics scale exponentially. This exponential scaling promises integrated spectrometers with both ultrahigh resolution and ultrabroad bandwidth. Early demonstrations of such architectures, such as the dFT spectrometer,^[52] employ optical switches to achieve this exponential scaling (2^k for k switches). More recent work has demonstrated the potential for further enhanced scaling by cascading tunable elements, such as MZIs^[124] or MRRs.^[118] With n states per tunable element, the scaling factor is increased to n^k . We expect this trend to continue, with future breakthroughs in spectrometer designs that allow for exceptional performance improvements with the number of integrated elements.

These types of exponentially scaling spectrometers generally suffer from Fellgett's disadvantage. Co-integration of these spectrometers with additional filters or careful design of the spectrometer's spectral filters can overcome this disadvantage. In the case of laser spectroscopy, for example, the SNR can be significantly improved with a notch filter, filtering out the undesired laser line.

Furthermore, we note that current on-chip spectrometer demonstrations rely heavily on off-chip functionalities. A large portion of the research discussed in this review employs off-chip photodetectors or cameras for data collection. Moreover, the discussed spectrometers generally only collect the data, while post-processing and spectral reconstruction are then performed on a computer. As integrated photonics technology matures, we anticipate that more and more components of the spectrometer will be integrated on-chip.

On-chip/waveguide-integrated photodetectors are an ongoing topic of research.^[244,245] Currently, integrated photonic foundries offer Ge photodetectors^[246] directly integrated on Si waveguides. Unsurprisingly, a large portion of the spectrometers covered in this review that use on-chip photodetectors employ such Ge-on-Si diodes.^[52,139,160,179] Other implementations are based on metal-semiconductor-metal photodetectors,^[82] two photon absorption,^[156] and single-photon detectors.^[87,88] Out of these, on-chip single-photon detectors offer an obvious advantage in terms of SNR. However, the demonstrated spectrometers with single-photon detectors require cryogenic temperatures for operation, limiting the spectrometer's application and increasing

the costs. Integrated avalanche photodetectors offer a promising alternative. These avalanche photodetectors offer sensitivity up to the single-photon level at or near room temperature^[247–249] and have been shown for ultraviolet,^[250] visible,^[249,251] near-IR,^[248,252] and mid-IR wavelengths.^[253,254]

The next step towards full on-chip integration is the integration of the electronic control and read-out circuit with the photonic circuit. There are two approaches towards this co-integration. In the first approach, for example, proposed by TSMC,^[255] an electronic die is directly bonded onto the PIC. The second approach, as, for example, offered at GlobalFoundries,^[256] consists of monolithic integration of electronic and photonic circuits onto a single die. As these platforms mature, they will enable true “end-to-end” spectrometer design, where the optical circuit, signal read-out, and signal processing are co-designed and integrated onto a single chip.

Finally, we note that spectrometers have so far mainly focused on direct reconstruction of a discretized equally spaced input spectrum s ,^[51,52] while some works employ radial basis functions^[23] (such as Gaussians^[116,155]), separation of sparse narrowband and smooth broadband spectral components,^[124,166] and

neural networks.^[117,144] Reconstruction can potentially be improved by exploring other, carefully chosen basis functions for unknown spectra. Additionally, sampling of the input spectrum at unequally spaced wavelength points^[35] and various regularization techniques can be explored. Such choices in basis and discretization require prior knowledge of the input spectrum and are likely to be application specific. For applications that rely on spectral information but do not require explicit knowledge of the spectrum itself, one could opt to train a model or neural network to directly perform the task at hand.^[107,257]

Appendix A: Performance Metrics

In this appendix, we provide an overview of the experimentally demonstrated performance metrics for the various categories of integrated photonic spectrometers. Some of the data listed here is plotted in Fig. 9. For each category of integrated photonic spectrometer, a separate table is compiled.

A.1 Classical Dispersive Spectrometers

Table 2 Overview of Performance Metrics for On-Chip Classical Dispersive Spectrometers^a

Ref.	Year	Method	λ_c (nm)	$\delta\lambda$ (nm)	$\Delta\lambda$ (nm)	M	F (mm ²)	D
[89]	2007	AWG	1545	0.2	20	50	64	50
[79]	2010	Echelle grating	1550	0.8	2.4	3	24	3
[94]	2010	PhC grating	1560	2.5	55	22	0.384	22
[80]	2013	AWG	3800	9.6	77	6	0.75	6
[80]	2013	Echelle grating	3800	10	105	8	3.06	8
[81]	2013	Echelle grating	1550	3.2	115	8	0.56	8
[81]	2013	Echelle grating	1650	7	121	14	0.24	14
[81]	2013	Echelle grating	2125	6	150	16	0.54	16
[81]	2013	Echelle grating	2320	5	60	8	1.04	8
[81]	2013	AWG	2200	1.6	13	6	1	6
[81]	2013	AWG	2200	4.8	38	6	0.48	6
[82]	2013	Echelle grating	850	0.5	30	60	54	60
[83]	2014	Echelle grating	1550	12.7	125	15	4	15
[95]	2014	Planar holograms	740	0.15	148	926	200	926
[96]	2014	Hologram + interferometers	790	0.145	142		20	
[90]	2016	AWG	760	0.5	4	8	2.8	8
[91]	2017	AWG	1550	1.6	9	5	112	5
[84]	2018	Echelle grating	1550	0.5	60	121	9	121
[85]	2018	Echelle grating	1545	4.9	25	5	2.25	5
[86]	2019	Echelle grating	1300	4.5	18	4	0.02	4
[87]	2019	Echelle grating	1300	7	1400		4	
[87]	2019	Echelle grating	1550	2.5	160			
[92]	2019	AWG	860	1.5	60	40	0.62	40
[93]	2020	Cascaded AWGs	1550	1	195	195	110	195
[88]	2023	Echelle grating	1505	0.4	20	16	0.2	16
[98]	2023	Metalenses	1550	0.14	50	32	0.01	32

^aFor each example, the year of publication of the referenced paper, implementation method, center wavelength λ_c , spectral resolution $\delta\lambda$, bandwidth $\Delta\lambda$, number of measurements M , footprint F , and number of detectors D are listed.

A.2 Resonator Array Spectrometers

Table 3 Overview of Performance Metrics for On-Chip Resonator Array Spectrometers^a

Ref.	Year	Method	λ_c (nm)	$\delta\lambda$ (nm)	$\Delta\lambda$ (nm)	M	F (mm ²)	D
[99]	2011	MRR	1580	0.6	50	84	1	84
[100]	2012	PhC cavity	840	0.3	35	100	0.004	100
[126]	2021	MRR + AWG	860	0.75	57.5	70	1.4	70
[129]	2021	PhC cavity	1580	5	70	38	0.0007	38
[128]	2022	MRR	3410	23	90	4	0.01	4
[101]	2023	MRR	809	0.17	12	3	0.15	3

^aFor each example, the year of publication of the referenced paper, implementation method, center wavelength λ_c , spectral resolution $\delta\lambda$, bandwidth $\Delta\lambda$, number of measurements M , footprint F , and number of detectors D are listed.

A.3 Wavelength Multiplexing Spectrometers

Table 4 Overview of Performance Metrics for Spatially Dispersed Wavelength Multiplexing Spectrometers^a

Ref.	Year	Method	λ_c (nm)	$\delta\lambda$ (nm)	$\Delta\lambda$ (nm)	M	F (mm ²)	D
[57]	2013	Scattering	1512	0.75	25	33	0.005	33
[133]	2013	FT	1550	0.04	0.75	32	12	18
[134]	2013	FT	1550	0.05	2	32	24	32
[135]	2015	FT	3750	2.7	54	42	95	42
[102]	2016	Multimode spiral	1520	0.01	2	40	0.25	40
[51]	2017	FT	1550	0.03	0.78	14		14
[136]	2017	FT	1400	4.8	600	201	165	201
[137]	2019	FT	1550	0.038	0.5	34	4.75	34
[103]	2020	Speckle-enhanced FT	1556	0.003	12	640	100	640
[132]	2020	Scattering	755	0.3	15	13	0.02	13
[132]	2020	Scattering	955	1	15	13	0.02	13
[132]	2020	Scattering	1550	3	40	13	0.02	13
[104]	2021	Scattering	1556	0.25	30	8	0.0004	8
[105]	2021	Stratified waveguides	1560	0.45	180	32	0.009	32
[106]	2021	Coherent network	776	0.02	12	8	0.11	8
[139]	2021	FT	1568	0.09	0.6	16	4.5	16
[140]	2021	FT	1460	0.05	340	16	10	16
[141]	2022	FT	850	3.4	400	32	3.06	32
[107]	2023	Disordered lattice	1545	0.015	40	4096	1	4096
[142]	2023	FT	1560	0.4	7	32	27	32
[143]	2023	FT	1550	3	35	16	1.64	16
[146]	2023	Coherent network	1520	0.1	10	25	0.026	5
[147]	2023	Self-coupled waveguides	1550	0.1	100	64	3	64
[144]	2024	Multimode interference	795	1	40		0.625	
[144]	2024	Multimode interference	795	0.05	2	144000		144000
[145]	2025	Multimode interference	1570	0.1	30	12	0.0003	12
[148]	2025	Metasurfaces	1550	0.047	40	1200	0.045	1200

^aFor each example, the year of publication of the referenced paper, implementation method, center wavelength λ_c , spectral resolution $\delta\lambda$, bandwidth $\Delta\lambda$, number of measurements M , footprint F , and number of detectors D are listed.

A.4 Stationary-Wave Integrated Fourier-Transform Spectrometers

Table 5 Overview of Performance Metrics for Stationary-Wave Integrated Fourier-Transform Spectrometers^a

Ref.	Year	Method	λ_c (nm)	$\delta\lambda$ (nm)	$\Delta\lambda$ (nm)	M	F (mm ²)	D
[150]	2017	Copropagative	900	6	100		0.1	
[108]	2018	Lippmann	633	0.16	256	2000	0.032	2000
[109]	2018	Tunable SWIFTS	1500	40	1000	347	0.001	5
[153]	2020	Tunable SWIFTS	1550	5.5	500		10	87
[110]	2024	Lippmann	842.5	0.2	75	160	5.12	160

^aFor each example, the year of publication of the referenced paper, implementation method, center wavelength λ_c , spectral resolution $\delta\lambda$, bandwidth $\Delta\lambda$, number of measurements M , footprint F , and number of detectors D are listed.

A.5 Tunable Narrowband Filter Spectrometers

Table 6 Overview of Performance Metrics for On-Chip Tunable Narrowband Filter Spectrometers^a

Ref.	Year	Method	λ_c (nm)	$\delta\lambda$ (nm)	$\Delta\lambda$ (nm)	M	F (mm ²)	D
[159]	2010	MRR + AWG	1488	0.1	10	100	2	25
[111]	2016	MRR	1580	0.15	19	126	0.6	1
[160]	2019	MRR + AWG	1555	0.1	25.4	254	9	9
[112]	2022	PhC cavity	1455	0.5	12.3	25		1
[113]	2022	FP cavity array	1472	0.43	73.2	170	0.026	5
[113]	2022	FP cavity array	1472	0.51	102.7	201	0.036	7
[114]	2022	MRR + MRR array	1550	0.005	9.7	17389	0.35	11
[155]	2022	PhC cavity	1556	0.32	16	100	0.0045	3
[161]	2022	MRR + AWG	1300	0.2	70	350	0.12	10
[115]	2023	Photonic molecule	1550	0.04	100	2501	0.004	1
[116]	2023	Microdisk	1505	0.01	0.3	65	0.24	1
[116]	2023	Microdisk	1510	0.2	20	321	0.24	1
[166]	2023	Multimode MRR	1550	0.08	100	1250	0.0007	2
[117]	2024	Cascaded MRRs	1550	0.1	200	2187	0.004	3
[117]	2024	Cascaded MRRs	1550	2	200	192	0.004	3
[118]	2024	Cascaded MRRs	1440	0.008	520	4096	0.6	1
[156]	2024	MRR	1550	0.4	10		0.0003	1
[157]	2024	MRR + lattice filter	1550	0.2	35		1.9	8
[158]	2025	MRR + lattice filter	1550	0.2	40		0.21	4

^aFor each example, the year of publication of the referenced paper, implementation method, center wavelength λ_c , spectral resolution $\delta\lambda$, bandwidth $\Delta\lambda$, number of measurements M , footprint F , and number of detectors D are listed.

A.6 Fourier-Transform Spectrometers

Table 7 Overview of Performance Metrics for On-Chip Fourier-Transform Spectrometers^a

Ref.	Year	Method	λ_c (nm)	$\delta\lambda$ (nm)	$\Delta\lambda$ (nm)	M	F (mm ²)	D
[167]	2014	Lithium niobate	1550	68	450			1
[52]	2018	dFT	1560	0.2	20	64	1.9	1
[169]	2018	Thermo-optic	1550	3.0	56	18	1	1
[120]	2019	MRR assisted TO	1571	0.47	90			1
[170]	2019	Thermo-optic	7700	79	2900			
[175]	2019	dFT	2300	0.1	130	64	5.3	
[119]	2020	Thermo-optic	1550	0.9	56	63	0.9	1
[172]	2020	MEMS	1550	2.7	20		108	4
[173]	2021	Spatial heterodyne TO	1560	0.16	130			3
[177]	2022	dFT	1552	0.02	3	127		
[121]	2024	MEMS	1550	0.2	100	53	0.075	1
[121]	2024	MEMS	4150	1.5	300	53		1
[122]	2024	2D FT	1550	0.13	200			128
[168]	2024	Lithium niobate	1550	5.3	100			1
[178]	2024	dFT	3875	8	450	128		1

^aFor each example, the year of publication of the referenced paper, implementation method, center wavelength λ_c , spectral resolution $\delta\lambda$, bandwidth $\Delta\lambda$, number of measurements M , footprint F , and number of detectors D are listed.

A.7 Tunable Broadband Filter Spectrometers

Table 8 Overview of Performance Metrics for On-Chip Tunable Broadband Filter Spectrometers^a

Ref.	Year	Method	λ_c (nm)	$\delta\lambda$ (nm)	$\Delta\lambda$ (nm)	M	F (mm ²)	D
[123]	2017	Multimode spiral	1554	0.015	2	144	3.36	12
[179]	2021	Multimode interference	1565	0.3	6.4	64		4
[182]	2022	Multimode interference	1590	0.02	100	384	1.5	6
[124]	2023	MZIs	1510	0.01	200	729	8	1
[125]	2023	Cavity-enhanced mode mixing	1550	0.005	100	2001	1.5	1
[183]	2023	Coherent network	1559	0.03	115	256	16.65	4
[181]	2024	Coherent network	1520	0.01	120	400	0.5	1
[181]	2024	Coherent network	1520	0.3	120	132	0.5	1
[184]	2025	Beam-steered metasurfaces	1560	0.07	100	1200	0.1425	

^aFor each example, the year of publication of the referenced paper, implementation method, center wavelength λ_c , spectral resolution $\delta\lambda$, bandwidth $\Delta\lambda$, number of measurements M , footprint F , and number of detectors D are listed.

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