High-Throughput, Multimode Spectroscopy Using Cross-Dispersive Serpentine Integrated Grating Arrays

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Abstract: We demonstrate a high-resolution, crossed-dispersion integrated photonic spectrometer capable of high-etendue, multimode operation. The first experimental single-mode design achieves record performance per volume with 1.5 GHz resolution and 13 THz band-width in a 0.5 mm^2 footprint.

Modern bulk-optic spectrometers measure fine spectral features over a broad bandwidth with spatially incoherent input from a multimode fiber or slit. The use of spatially incoherent light, and measuring the entire bandwidth simultaneously, are essential to these spectrometers' utility in photon-starved applications, such as astronomy or remote-sensing, to ensure that every incident signal photon contributes to the instrument's sensitivity. Integrated photonic spectrometers designed for these applications must similarly operate using spatially incoherent light and cover a large number of simultaneous bins. Numerous dispersive and Fourier transform spectrometers, capable of simultaneously measuring the entire bandwidth, have been demonstrated on-chip [1]. Integrated spectrometers using a spatially incoherent input have been demonstrated [2] but no clear path forward to operation with 10s or 100s of incident modes has been identified.

In this work, we propose and demonstrate a novel 2D crossed-dispersive integrated photonic spectrometer design which achieves a record number of simultaneously measurable spectral bins amongst integrated photonic designs. We refer to the dispersive element as a serpentine integrated grating (SIG), which is based on a previously demonstrated 2D wavelength-steered serpentine optical phased array (SOPA) [3]. The SIG design folds a long delay line with out-coupling gratings in a compact on-chip footprint for high spectral resolution, large bandwidth, and small spectrometer volume. The SIG's 2D emission pattern with orthorgonal coarse and fine resolution axes and compact form-factor are uniquely suited for arraying many SIGs on a chip. The SIG array can be fed with spatially incoherent light to realize high-etendue spectroscopy in an integrated photonic platform. We demonstrate a preliminary SIG spectrometer design which achieves 1.5 GHz resolution over a 13 THz bandwidth for 8,600 simultaneously measured spectral bins using only 0.5 mm^2 on-chip footprint, a record-setting number of bins amongst integrated photonic spectrometers.

The SIG design, SIG spectrometer operation, and high-etendue concept are depicted in Fig. 1. The SIG is composed of a 1D array of long, weak gratings each fed by the output of the previous grating to create a serpentine delay line [3]. The fabricated SIG chip containing 12 variants, and the specific variant demonstrated here, is shown in Fig. 1(a). The SIG is shown schematically to the right with gratings represented in blue and routing waveguides

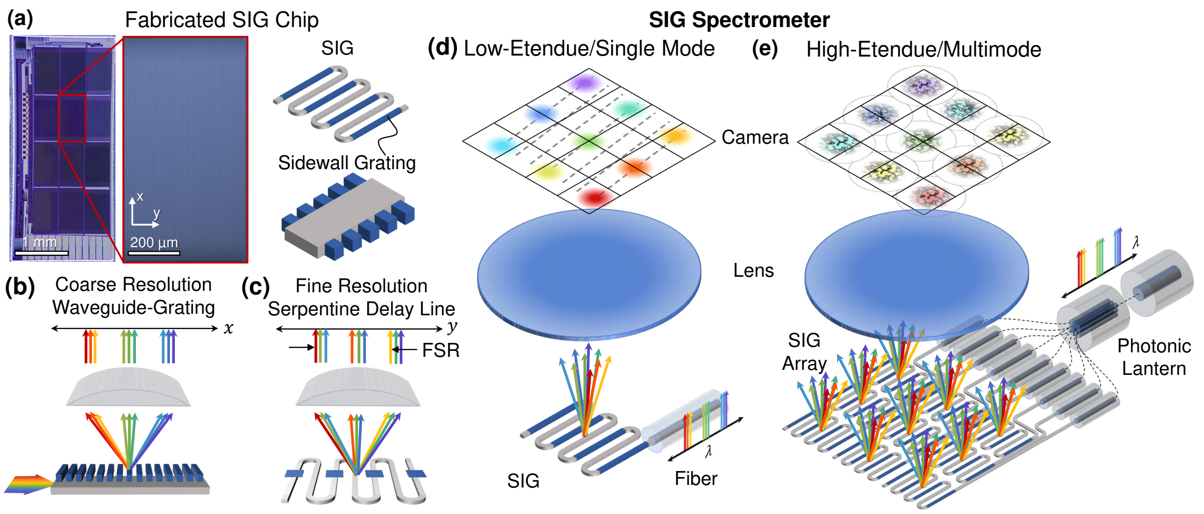

Fig. 1: High-etendue spectroscopy with serpentine integrated gratings (SIGs). (a) Fabricated SIG chip with a micrograph of the SIG variant demonstrated in this paper and schematic depictions of the SIG and sidewall grating used here. The grating provides coarse wavelength resolution along one dimension (b) while the serpentine structure provides fine wavelength resolution along the orthogonal dimension (c). (d) A single SIG, requiring a single mode input, creates a 2D emission pattern which is focused by a Fourier-transforming lens onto a camera. (e) An array of SIGs fed by a photonic lantern each emit with a random, time-varying amplitude and phase such that for each input wavelength a speckled spot with constant envelope is created on the Fourier plane which is averaged by the intensity-detecting camera pixels, allowing for high-etendue spectroscopy with spatially incoherent multimode input light such as that produced by turbulence.

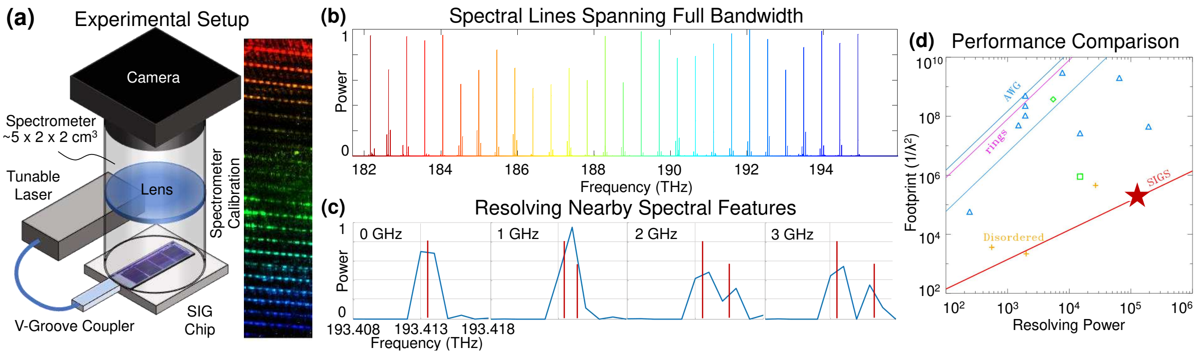

Fig. 2: Experimental demonstration of SIG spectrometer bandwidth and resolution. (a) Experimental setup for demonstrating the SIG spectrometer, occupying approximately 20 cm^2 (neglecting the bulky camera housing). An image composed of every $\sim 30^{\text{th}}$ spectrometer calibration point is shown on the right in the region of interest on the camera. (b) Reconstructed spectra of 28 individual lines spanning the 13 THz (110 nm) bandwidth of the spectrometer limited by the lens NA. (c) Reconstructed spectra of 2 nearby lines which are separated by 0, 1, 2, and 3 GHz respectively demonstrating the $\sim$ 1.5 GHz spectral resolution. (d) Comparison of SIG resolving power and footprint to other integrated photonic spectrometers [1].

in gray, consisting of 30 gratings, each 6.5 µm wide and 690 µm long, operating in the TE0 mode and spaced at 16 µm pitch. The SIG creates a 2D emission pattern where the gratings provide coarse wavelength resolution along one dimension [Fig. 1(b)] and the large time delay of the serpentine structure provides fine wavelength resolution along the orthogonal dimension [Fig. 1(c)] similar to conventional crossed-dispersed spectrometers.

The SIG spectrometer uses a detector array placed in the focal plane of a Fourier lens which captures the SIG emission pattern to extract spectral information from the resulting image. A spectrometer using a single SIG (which takes a single mode input) is depicted in Fig. 1(d) with the dashed lines denoting the locus of the emission pattern. For many applications, the light captured by the optical system is not single mode and therefore a spectrometer using a single SIG will inherently have optical losses associated with the low etendue. To overcome this limit, the emission from multiple mm-scale SIGs in a 2D array can be combined onto the same detector array by feeding each SIG with a single mode input using a photonic lantern [4] as shown in Fig. 1(e). Photonic lanterns provide a low-loss fan-out between a multimode (spatially incoherent) input and multiple single mode outputs, such that one SIG is needed per incident mode to achieve high-etendue operation. The random phases of the SIGs interfere on the camera plane to create a temporally fluctuating speckle pattern which is averaged by the camera pixels. The corresponding total signal power of the spectrometer will scale with the number of SIGs in the array up to this total number of incident modes. The 2D emission pattern out of the chip plane inherent to the SIG design is naturally suited to 2D detector arrays, and its small size allows for many SIGs to be arrayed on a chip, providing a clear path to multimode operation without stacking multiple chips, off-chip dispersive optics, or 1D detector arrays.

We demonstrate a preliminary SIG spectrometer as an initial step towards high-etendue spectroscopy with an array of SIGs using the experimental setup shown in Fig. 2(a). A 0.45 NA achromat captures the SIG emission and focuses it onto a detector array. The spectrometer is calibrated by stepping the tunable laser at 1 GHz increments across the entire 13 THz bandwidth and using the corresponding image set to generate a calibration matrix which maps a measured image to a reconstructed spectrum. A composite image composed of every $\sim 30^{\text{th}}$ calibration wavelength is shown to the right in the region of interest on the camera, showing the tilted emission pattern locus. To demonstrate the bandwidth of the SIG spectrometer, we step the tunable laser to 28 different wavelengths (located randomly in between calibration wavelengths) spanning a 13 THz bandwidth limited by the NA of the lens [Fig. 2(b)]. To demonstrate the spectral resolution of the SIG spectrometer, we use two tunable lasers coupled into a single SIG with a 50:50 coupler. One laser is held constant at 193.4135 THz while the other is stepped by 1 GHz increments, showing the lines are not resolved with 1 GHz spacing and clearly resolved with 2 GHz spacing for $\sim$ 1.5 GHz resolution consistent with the 6 cm delay line length [Fig. 2(c)].

The demonstrated SIG spectrometer achieves 8,600 simultaneously measurable bins and 1.5 GHz resolution in a 0.5 mm^2 chip footprint and 20 cm^3 optical volume. This is a record combination of number of bins amongst integrated photonic spectrometers [Fig. 2(d)] due to the enhanced capacity of the 2D folded spectrum output format on a 2D detector array. Crucially, the small system volume, high resolution, and large number of bins can be extended to multimode (spatially incoherent) inputs using the SIG-array spectrometer design for the high-etendue operation necessary in photon-starved applications. We believe this spatially incoherent operation, and the high resolution per footprint of the SIG design, is an exciting step forward for integrated photonic spectrometers along the path to replacing bulk-optic designs.

References

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