

Subwavelength-engineered silicon-on-sapphire photonics for broadband interferometric mid-infrared spectroscopy and sensing

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Abstract. Mid-infrared integrated photonics offers a promising route toward compact spectroscopy and sensing, yet system-level implementation remains limited by the lack of a platform-consistent set of broadband and tunable photonic devices. We address this challenge on a silicon-on-sapphire platform using sub-wavelength-grating engineering. We develop and connect the key functions required by a spectroscopy-driven sensing architecture, including broadband optical splitting/recombination, thermo-optic phase control, resonant wavelength-selective interaction, and interferometric spectral reconstruction. A subwavelength-grating 1×2 3-dB multimode-interference splitter is designed for 2.5 to 4.5 μm operation with simulated per-output excess loss below 0.15 dB, whereas a subwavelength-grating 2×2 3-dB multimode-interference coupler is designed for 2.75 to 3.55 μm with simulated per-output excess loss below 0.25 dB and low output imbalance. Experimentally, their operation is verified within the accessible source-limited windows of 3.1 to 3.2 μm and 3.68 to 3.78 μm , rather than across the full simulated design bands. We further demonstrate thermo-optic modulation based on a Mach–Zehnder interferometer and resonance tuning based on uniform strip-waveguide and subwavelength-grating (SWG) micro-ring resonators. Finally, we apply a thermo-optic/dispersion-corrected Mach–Zehnder interferometer Fourier-transform spectrometer framework and numerically validate spectral reconstruction. These results show that subwavelength-grating-engineered silicon-on-sapphire photonics can provide the broadband routing, active interferometric control, and resonant interaction functions required for future on-chip mid-infrared spectroscopy and sensing systems.

Keywords: mid-infrared integrated photonics; silicon-on-sapphire; subwavelength gratings; broadband multimode interference couplers; on-chip spectroscopy.

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1 Introduction

The 3 to 5 μm mid-infrared (mid-IR) spectral window is highly attractive for chemical sensing and spectroscopy because many molecules exhibit strong vibrational absorption fingerprints in this range.^{1,2} Although compact and field-deployable mid-IR sensing instruments have emerged, many spectroscopy-based implementations still rely on hybrid assemblies of sources, interaction cells, detectors, and optical/readout components. Photonic integration therefore offers a path toward further reducing footprint, improving robustness, and enabling more highly integrated sensing architectures.

From a system perspective, an integrated mid-IR sensing circuit typically requires broadband routing components to distribute optical signals, optional resonant or wavelength-selective elements to enhance light–matter interaction or perform channel selection. In addition, on-chip spectrometers are required to map spectral information into a measurable domain that can subsequently be reconstructed through digital processing. Substantial progress has been made in mid-IR integrated photonics, including low-loss passive waveguides and components,^{3–12} optical modulators and phase shifters,^{13–18} on-chip sources,^{19–21} detectors,^{22–25} and spectrometers.^{26–31} Recent micro-electro-mechanical system (MEMS)-enabled computational spectrometers have further demonstrated chip-scale mid-IR spectral reconstruction for gas analysis,³⁰ highlighting the potential of integrated spectrometers for sensing-oriented applications. Toward more highly integrated sensing circuits, spectral readout should be developed together with compatible routing and interaction components on the same photonic platform. In particular, broadband and well-balanced integrated interferometric components remain challenging in high-index-contrast mid-IR platforms, especially when low excess loss, low output imbalance, and compact footprint must be maintained simultaneously. Although several integrated mid-IR multimode-interference (MMI) couplers have been reported,^{5,6,8} their bandwidth, footprint, and platform compatibility remain strongly dependent on the specific material system and device geometry. These issues become even more critical for mid-IR interferometric spectrometers, where usable spectral bandwidth may be constrained not only by the spectrometer architecture itself but also by narrowband sub-components within the optical circuit.

Structured photonic media based on engineered spatial or temporal refractive-index modulations—which have been widely explored across fiber photonics,^{32,33} metasurface-based free-space optics,^{34,35} and integrated photonics^{36,37}—offer an effective route to address this challenge. As a representative class of structured photonic media in integrated photonics, subwavelength-grating (SWG) structures have become an important design tool, enabling functions such as broadband beam routing,^{8,38,39} grating,⁴⁰ Bragg filtering/resonance,^{11,41} polarization handling⁴² and evanescent-field sensing.^{43–45} Depending on the device function, the relevant performance metrics include operating bandwidth, excess loss, output imbalance, footprint, and modal-overlap enhancement. When the grating period is sufficiently below the Bragg condition, SWG waveguides can be treated as effective anisotropic media whose refractive index and dispersion can be tailored through geometry.^{36,46} For MMI devices in particular, this additional degree of freedom is especially attractive, as their self-imaging behavior is strongly governed by wavelength-dependent modal propagation. By modifying the dispersion characteristics of the multimode

region, SWG design offers a natural means to broaden operating bandwidth and reduce device length. Beyond broadband routing, SWG structures can also enhance sensing-related performance by modifying modal overlap with the surrounding environment and strengthening light–matter interaction. Practical mid-IR implementation of SWG-enabled devices, therefore, requires a material platform with an appropriate transparency window and sufficient refractive-index contrast for compact mode confinement and effective-index engineering.

Among the available mid-IR material platforms, silicon-on-sapphire (SOS) is especially attractive because it combines high refractive-index contrast (~ 1.7), compatibility with complementary metal-oxide-semiconductor process, and broad transparency window. In contrast to silicon-on-insulator (SOI) platforms where silicon waveguide is supported by a buried SiO_2 layer, SOS uses sapphire as the substrate, thereby avoiding the mid-IR absorption associated with the oxide layer. In addition, as demonstrated in prior SOS mid-IR waveguide studies,^{47–49} the relatively low refractive index and broad transparency window of sapphire contribute to alleviating substrate-leakage constraints in parts of the mid-IR band, making SOS attractive for mid-IR photonic circuits. Free-carrier-related optical loss can also be reduced by using high-resistivity silicon.⁴⁷ Nevertheless, the usable wavelength range of SOS devices is ultimately limited by the wavelength-dependent absorption of the sapphire substrate, especially toward the longer-wavelength side of the mid-IR. These characteristics make SOS a suitable platform for developing mutually compatible mid-IR passive and tunable building blocks, while SWG engineering provides an additional geometrical degree of freedom for tailoring effective index, modal dispersion, and device footprint.

In this work, we investigate SWG-engineered SOS building blocks for broadband interferometric mid-IR spectroscopy and sensing. Specifically, we design SWG MMI splitters/combiners for broadband optical routing and recombination. Their wide operating bands are supported by numerical simulations, whereas experiments verify their performance within the accessible source-limited wavelength windows. We further demonstrate a thermo-optic (TO) Mach–Zehnder interferometer (MZI) for active phase control, together with uniform strip-waveguide, SWG, and thermo-optically tunable micro-ring resonators (MRRs) for wavelength-selective and resonance-enhanced interaction. Finally, we apply an MZI-based Fourier-transform spectrometer (MZI-FTS) framework to the SOS implementation and numerically verify spectral reconstruction using the designed SOS waveguide parameters and SWG-MMI responses. As illustrated in Fig. 1, these experimentally characterized building blocks and the numerically verified spectrometer concept are mapped onto a conceptual workflow for future co-integrated mid-IR sensing and spectrometry. The full cascaded system and analyte-sensing experiments are beyond the scope of this work.

2 Design of SWG Structures

In the broadband sensing workflow of Fig. 1, broadband interferometric routing, recombination, and phase-control components are required. On the high-index-contrast SOS platform, however, strong waveguide modal dispersion can make the phase response and modal-interference condition strongly wavelength dependent, thereby limiting the operating bandwidth of conventional interferometric devices. We therefore introduce SWG engineering as a geometrical approach to tailor the modal

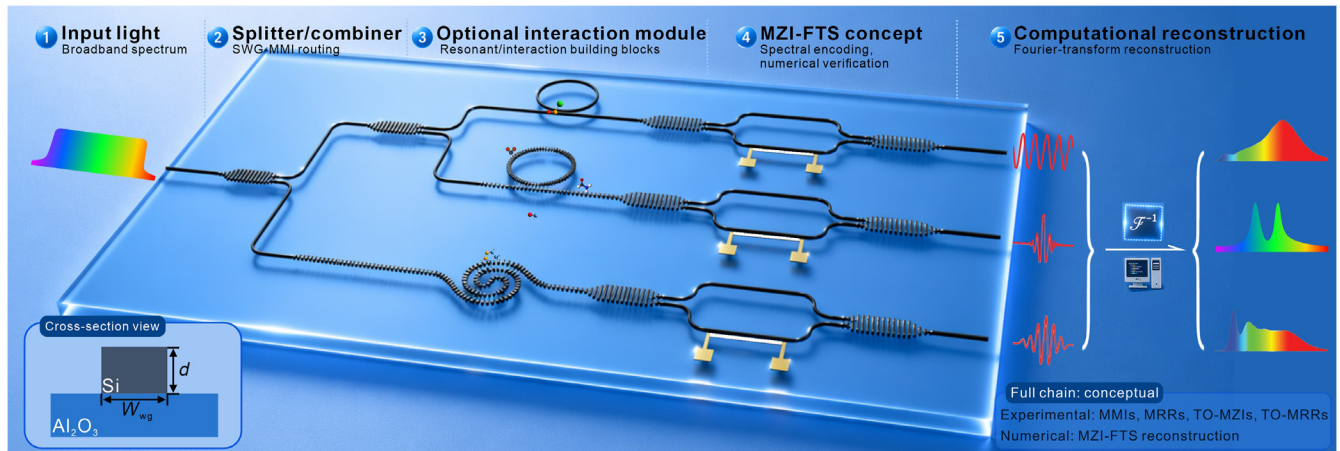


Fig. 1 Conceptual workflow and role map of the SOS building blocks investigated in this work for future mid-IR spectroscopy-enabled sensing. Broadband input light can be routed by MMI splitter/combiner devices, optionally pass through resonant or wavelength-selective interaction modules, and then be processed by an MZI-based spectrometer concept followed by computational reconstruction. Inset: representative cross-section of an SOS waveguide with silicon thickness $d = 600$ nm and W_{wg} is device-dependent and specified in the corresponding device sections.

effective index and dispersion. This provides an effective route toward broadband components for the targeted mid-IR spectroscopy and sensing workflow.

An SWG waveguide consists of periodically arranged silicon segments with period Λ and duty cycle DC, as schematically illustrated in Fig. 2(a). A representative scanning electron microscope (SEM) image of the fabricated SWG waveguide is also included in Fig. 2(a), confirming the periodic structure on the SOS platform. The effective index of an SWG waveguide can be tuned flexibly by adjusting Λ and DC, thereby providing additional design freedom for optimizing MMI performance. To realize broadband subwavelength photonic circuits with low optical loss, the SWG parameters must be chosen such that the structure remains in the subwavelength-guided regime across the operational bandwidth, whereas diffraction, slow light, and Bragg reflection effects are suppressed. Considering fabrication constraints, we fix DC = 0.5 to simplify fabrication and improve process robustness. The grating period Λ , therefore, needs to be optimized and kept sufficiently small, particularly for the wider waveguides used in the MMI sections. Consistent with the simulations in Fig. S1 in the [Supplementary Material](#) (Sec. 1 of the [Supplementary Material](#)), smaller Λ generally enlarges the subwavelength operating window for a given width W_{wg} . By contrast, wider SWG waveguides require smaller Λ to avoid band-edge slow-light behavior and Bragg reflection within the same spectral range. Based on these considerations, the period is chosen as $\Lambda = 400$ nm for all SWG device designs in this work.

To verify the subwavelength operating regime, we simulate the dispersion characteristics of an SWG waveguide with width $W_{wg} = 2.5$ μm using the finite-difference time-domain (FDTD) solver in Lumerical. The calculated band structure is shown in Fig. 2(b), indicating a guided transverse electric (TE) fundamental mode over an angular-frequency range of ~ 420 to 750 rad/ps, corresponding to a wavelength range of $\lambda \approx 2.5$ to 4.5 μm . The absence of pronounced band flattening in this range indicates that the structure does not approach a strong band-edge slow-light regime or Bragg-reflection condition.

Figure 2(c) compares the simulated normalized electric-field intensity profiles $|E|^2$ of the SWG waveguide and a uniform strip waveguide at $\lambda = 3.5$ μm . Both waveguides have the same nominal width $W_{wg} = 2.5$ μm and silicon thickness $d = 600$ nm, and both cross-sectional and top-view field profiles are shown using the same color scale. Compared with the uniform strip waveguide, whose optical field is mainly confined within the continuous silicon core, the SWG waveguide redistributes part of the optical field into the low-index gaps and surrounding region. This modal redistribution is relevant for sensing-oriented interaction sections while maintaining guided-mode confinement. The corresponding effective index n_{eff} and group index n_g in Fig. 2(d) further show that the SWG geometry substantially reduces and tailors the modal index compared with the uniform strip waveguide. Therefore, the selected SWG geometry operates in the subwavelength-guided regime over the target band and provides a suitable dispersion-engineered basis for broadband interferometric routing functions on the SOS platform.

3 Interferometric Devices

3.1 Broadband MMI Design and Characterization

For the sensing workflow in Fig. 1, the first functional requirement is a broadband and well-balanced beam splitter/recombiner. MMI couplers are attractive candidates because they offer compact footprints and relaxed fabrication tolerance. Their operation relies on the self-imaging principle,⁵⁰ in which replicas of the input field are formed at specific propagation distances inside a multimode section. In high-index-contrast silicon waveguides, the self-imaging distance drifts rapidly with wavelength due to strong modal dispersion, thereby limiting the operating bandwidth. To mitigate this limitation, we introduce SWG engineering to tailor the wavelength dependence of the modal propagation constants in the multimode region. As detailed in Sec. 2 of the [Supplementary Material](#), the SWG multimode region reduces the wavelength dependence of the beat length, making the

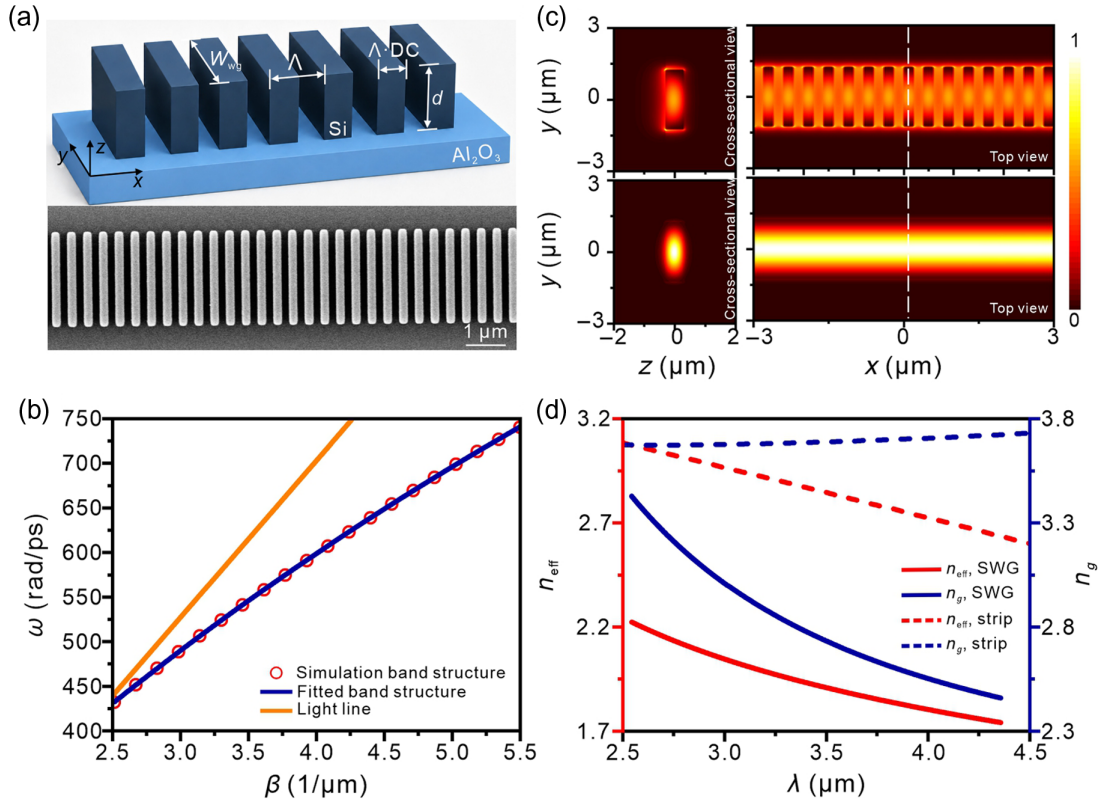


Fig. 2 Design and verification of the SWG waveguide. (a) Three-dimensional schematic of the SWG waveguide and representative SEM image of the fabricated structure on the SOS platform. The SWG period, duty cycle, waveguide width, and silicon thickness are denoted by Λ , DC, W_{wg} , and d , respectively. (b) Simulated band diagram of the SWG waveguide with $W_{\text{wg}} = 2.5\ \mu\text{m}$, $\Lambda = 400\ \text{nm}$, and DC = 0.5. The vertical axis is the angular frequency ω , and the horizontal axis is the propagation constant $\beta = 2\pi n_{\text{eff}}/\lambda$. The light line corresponds to propagation in vacuum with $n_{\text{eff}} = 1$. (c) Simulated normalized electric-field intensity profiles $|E|^2$ at $\lambda = 3.5\ \mu\text{m}$ for the SWG waveguide and a uniform strip waveguide with the same nominal width $W_{\text{wg}} = 2.5\ \mu\text{m}$ and silicon thickness $d = 600\ \text{nm}$. For each structure, the cross-sectional view is shown on the left and the top view is shown on the right, and the dashed white line in the top view indicates the cross-sectional position. (d) Simulated effective index n_{eff} and group index n_g of the SWG waveguide and the uniform strip waveguide.

self-imaging position more stable over wavelength than in a uniform strip multimode waveguide. This dispersion control enables MMI devices that are simultaneously shorter and broader-band while maintaining low insertion loss and low imbalance.

3.1.1 1×2 MMI design and characterization

Figure 3(a) shows an SEM image of the fabricated 1×2 3-dB SWG MMI splitter designed for fundamental TE_0 -mode input, comprising one input and two symmetric outputs. To balance footprint and imaging quality, we select a multimode width of $W_c = 10\ \mu\text{m}$. Linear tapers are introduced at the input and output interfaces to reduce mode-mismatch loss ($L_t = 16\ \mu\text{m}$, $W_t = 5\ \mu\text{m}$), and the two output tapers are separated by $S_t = W_c/2$. To further suppress loss and enhance bandwidth, an apodized entrance section is incorporated at the beginning of the multimode region. The apodization length and multimode length are optimized via 3D FDTD simulations (Lumerical) to $L_a = 2.4\ \mu\text{m}$ and $L_c = 11.2\ \mu\text{m}$, respectively. The simulated per-output transmission spectra of the two outputs are plotted as dashed lines in Fig. 3(b). Across the full simulated band

of 2.5 to 4.5 μm , both transmissions maintain better than $-3.15\ \text{dB}$, indicating near-balanced splitting with low excess loss (0.15 dB). The inset shows the simulated field intensity distribution $|E|^2$ at 3.1 μm .

Experimental characterization was carried out using two source-detection configurations, with light coupled into and out of the chip through vertical grating couplers. For the 3.1 to 3.2 μm measurement window, an in-house supercontinuum source was used, and the output spectra were recorded using an optical spectrum analyzer (OSA, YOKOGAWA AQ6377) with a wavelength resolution of 5 nm. For the 3.68 to 3.78 μm window, a tunable quantum cascade laser (QCL) was used, and the output power was recorded using a thermal power sensor (MKS Ophir, 3A-FS). Before chip coupling, input polarization control was applied to preferentially excite the TE_0 mode and suppress residual non-TE components. TE and TM polarizations have different modal indices and self-imaging lengths in the MMI region. Therefore, residual non-TE components are not optimally imaged by the TE-designed MMI and can contribute to additional loss, output imbalance, or reduced interferometric

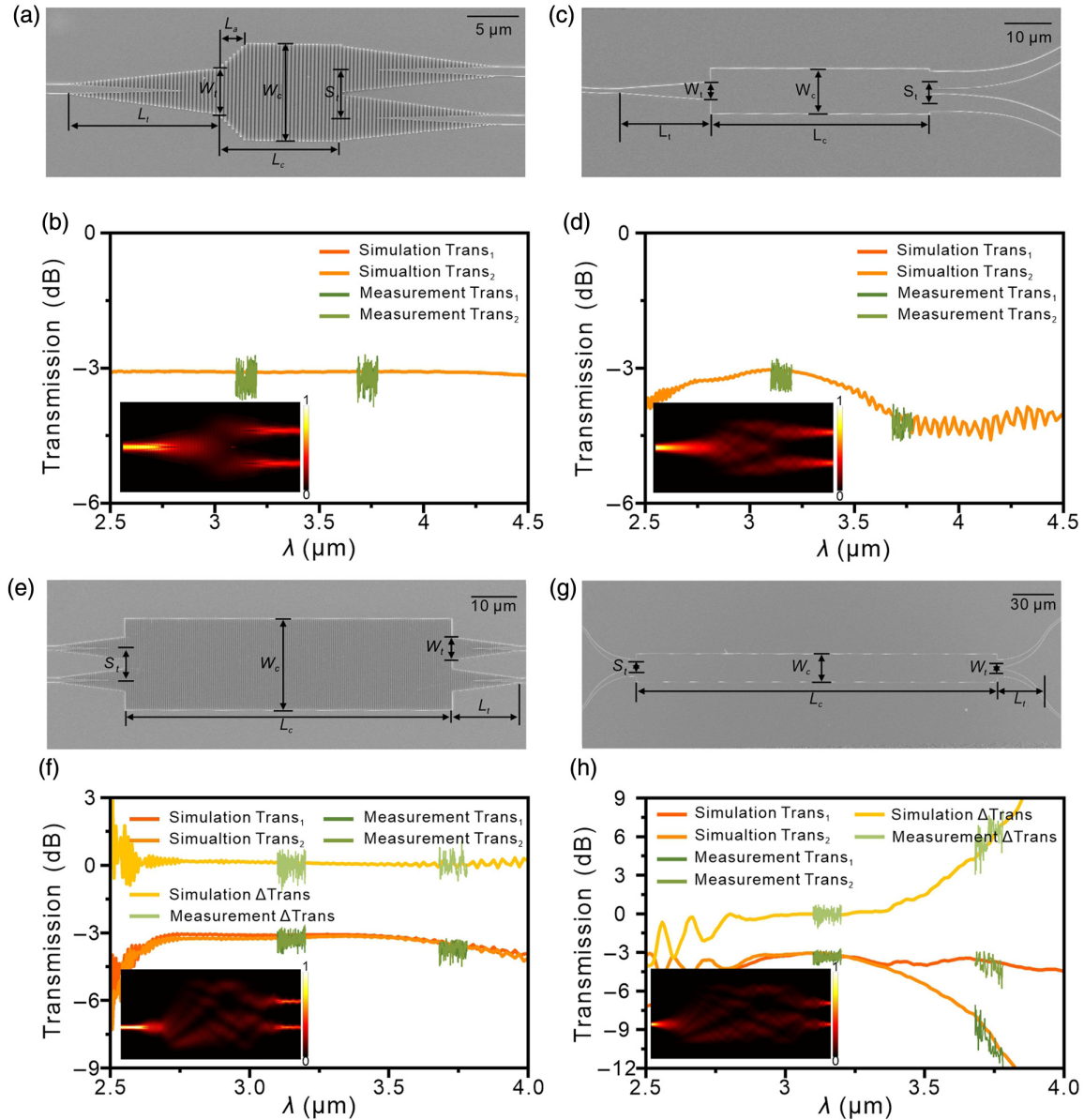


Fig. 3 MMI performance: SWG versus conventional designs on SOS. Experimental data are plotted in the accessible 3.1 to 3.2 μm and 3.68 to 3.78 μm windows, and simulations are shown over the broader wavelength range. (a), (b) SEM image and normalized transmission spectra of the 1×2 SWG MMI. (c), (d) SEM image and normalized transmission spectra of the conventional 1×2 MMI. (e), (f) SEM image, normalized transmission spectra, and output difference ΔTrans of the 2×2 SWG MMI. (g), (h) SEM image, normalized transmission spectra, and output difference ΔTrans of the conventional 2×2 MMI. Insets: simulated field intensity $|E|^2$ at 3.1 μm .

visibility in cascaded circuits. Additional details on the optical delivery paths, detection equipment, and fabrication process are provided in Sec. 6 of the [Supplementary Material](#). As shown in Fig. 3(b), the measured per-output transmissions of the SWG 1×2 MMI are ~ -3.25 dB in both the 3.1 to 3.2 μm and 3.68 to 3.78 μm measurement windows, corresponding to a per-output excess loss of ~ 0.25 dB. The measured traces exhibit fluctuations of ± 0.4 dB, mainly associated with time-dependent source-power variations during the measurements.

For comparison, a conventional (non-SWG) 1×2 MMI is designed and characterized on the same SOS platform. The multimode section width is kept identical ($W_c = 10$ μm) to

ensure a fair comparison, whereas the multimode length is optimized to $L_c = 46$ μm . Other parameters are given in Table S1 in Sec. 2 of the [Supplementary Material](#). Figure 3(d) shows the simulated and measured per-output spectra. The simulated -3.15 dB per-output bandwidth is 2.95 to 3.33 μm , corresponding to a bandwidth of 0.38 μm . In the 3.1 to 3.2 μm measurement window, which overlaps with the optimized operating band, the measured per-output transmissions are -3.2 dB, corresponding to a per-output excess loss of ~ 0.2 dB. In the 3.68 to 3.78 μm measurement window, which lies outside the optimized band of the conventional design, the per-output transmission decreases to ~ -4.18 dB in simulation and ~ -4.27 dB in

measurement, corresponding to an increased excess loss of ~ 1.27 dB per output. This wavelength-dependent degradation is consistent with the simulated bandwidth limitation of the conventional MMI. By contrast, the SWG 1×2 MMI maintains ~ -3.25 dB per output in both measurement windows. Compared with the conventional design, the SWG 1×2 MMI reduces the multimode length from 46 to $11.2 \mu\text{m}$ and extends the -3.15 dB per-output bandwidth by more than $1.5 \mu\text{m}$, confirming its advantage for compact broadband power splitting.

3.1.2 2×2 MMI design and characterization

The 2×2 coupler addresses the complementary requirement of broadband routing and interferometric signal processing in sensing systems. Figure 3(e) shows an SEM image of the fabricated 2×2 SWG MMI, which adopts a paired-interference configuration and is designed for fundamental TE_0 -mode input. The device is optimized for low loss and low imbalance over the target band, with multimode width and length of $W_c = 21 \mu\text{m}$ and $L_c = 73.6 \mu\text{m}$, respectively. Figure 3(f) shows the simulated per-output transmission spectra (dashed lines) together with the output difference ($\Delta\text{Trans} = \text{Trans}_1 - \text{Trans}_2$) between the two output ports. The simulation predicts per-output transmission better than -3.25 dB (corresponding to excess loss of 0.25 dB) from 2.75 to $3.55 \mu\text{m}$, while keeping output imbalance $|\Delta\text{Trans}|$ below 0.1 dB across the same range. The inset shows the simulated field intensity distribution $|E|^2$ at $3.1 \mu\text{m}$. Within the accessible measurement windows (3.1 to $3.2 \mu\text{m}$ and 3.68 to $3.78 \mu\text{m}$), the two outputs exhibit per-output transmissions of ~ -3.37 and -3.39 dB (corresponding to excess loss of 0.37 and 0.39 dB), respectively, consistent with the simulated trend. The modest additional loss is mainly attributed to fabrication-induced scattering.

A conventional 2×2 MMI with the same multimode-section width ($W_c = 21 \mu\text{m}$) is designed and characterized. Figures 3(g) and 3(h) show the SEM image and the corresponding spectra. The conventional design achieves per-output transmission better than -3.25 dB over 3.01 to $3.17 \mu\text{m}$ ($0.16 \mu\text{m}$ bandwidth), with $|\Delta\text{Trans}| < 0.12$ dB in the same band. In the 3.1 to $3.2 \mu\text{m}$ measurement window, which overlaps with this optimized operating band, the measured per-output transmissions are -3.31 and -3.34 dB, corresponding to excess losses of ~ 0.31 and 0.34 dB, respectively. These results confirm near-balanced operation of the conventional 2×2 MMI within its designed wavelength range. In the 3.68 to $3.78 \mu\text{m}$ measurement window, which lies outside the optimized operating band, the conventional 2×2 MMI exhibits clear degradation in both excess loss and output imbalance. One output port shows a measured transmission of ~ -3.98 dB, whereas the other output decreases to ~ -9.83 dB near the center of the measurement window. The measured spectra follow the simulated degradation trend, in which one output remains moderately transmissive, whereas the other output rapidly decreases with increasing wavelength. This behavior is consistent with the wavelength dependence of the self-imaging condition in the conventional MMI. By contrast, the SWG 2×2 MMI maintains near-balanced output transmissions in the same accessible measurement window.

Compared with the conventional 2×2 MMI, the SWG design shortens the multimode-section length from 268 to $73.6 \mu\text{m}$ and broadens the low-loss operating band by $0.64 \mu\text{m}$ while maintaining similarly low imbalance. Together with the 1×2 result, this confirms that SWG-engineered MMIs can provide

the broadband routing and recombination functions needed for SOS interferometric sensing circuits.

In addition, supplementary tolerance simulations were performed to assess the influence of representative SWG fabrication variations on the MMI response. As detailed in Sec. 7 of the [Supplementary Material](#), duty-cycle variation has a more pronounced impact than moderate multimode-region-width variation, whereas changing W_c by ± 100 nm produces only a weak influence on the simulated spectra and imbalance.

3.2 TO-MZI Design and Characterization

The TO-MZI on SOS serves as the thermo-optically tunable interferometric core of the spectrometer in the targeted sensing architecture. A schematic cross-section of the TO-MZI is shown in Fig. 4(a), and an optical microscope image of the fabricated device is shown in Fig. 4(b). The MZI is formed by two SWG 1×2 MMI couplers and two unequal-length waveguide arms. The use of SWG MMI splitters/combiners broadens the accessible spectral window of the MZI because the splitter/combiner bandwidth is no longer the dominant limitation.

In this device, the waveguide width is set to $W_{\text{wg}} = 1 \mu\text{m}$. Thermo-optic tuning is realized by placing a platinum (Pt) microheater adjacent to one arm of the MZI. The heater has a width $W_h = 1.5 \mu\text{m}$ and thickness $d_h = 50$ nm and is separated from the heated arm by an air gap of $s = 0.8 \mu\text{m}$. This spacing is chosen as a compromise between optical loss induced by the metal heater and thermal coupling efficiency (the simulated heater-induced optical loss is summarized in Sec. 3 of the [Supplementary Material](#)). The Pt heater is connected to larger gold pads to facilitate electrical probing. The simulated temperature distribution, calculated using the HEAT solver in Lumerical under an applied heating power of $2 \text{ mW}/\mu\text{m}$, is shown in Fig. 4(a).

For static characterization, different steady-state electrical voltages are applied to the $200 \mu\text{m}$ -long heater using a source meter, and the corresponding interference spectra are recorded with an OSA. As shown in Fig. 4(c), increasing the applied electrical power induces a red shift of the interference fringes, consistent with the positive thermo-optic coefficient of silicon. An extinction ratio of ~ 10 dB is obtained, mainly limited by imperfect input polarization purity, propagation-loss mismatch, measurement spectral resolution, fabrication-induced phase and amplitude errors, nonideal splitting/recombination, and local perturbations introduced by the adjacent heater. From the relationship between electrical power and the phase shift extracted from the spectral shift in Fig. 4(d), the tuning efficiency is determined to be $\eta = 0.095 \text{ nm}/\text{mW}$. Here, P_π is defined as the electrical power required to shift one interference dip by half of the MZI free spectral range (FSR), corresponding to a π -phase change, yielding $P_\pi = 168 \text{ mW}$.

For dynamic characterization, a square-wave signal generated by an arbitrary waveform generator is applied to the heater. A single-wavelength input is modulated by the MZI and detected by a photodetector (Thorlabs, PDAVJ10). As shown in Fig. 4(e), the device exhibits a 10% to 90% rise time of $23 \mu\text{s}$ and a 90% to 10% fall time of $24 \mu\text{s}$ at 3157 nm . The displayed trace is a representative dynamic response, and its signal-to-noise ratio is mainly limited by the available output optical power and the noise of the mid-IR photodetection/electrical readout chain. The relatively high P_π is primarily attributed to the heater-to-waveguide spacing, which weakens thermal coupling. Heat dissipation into the high-thermal-

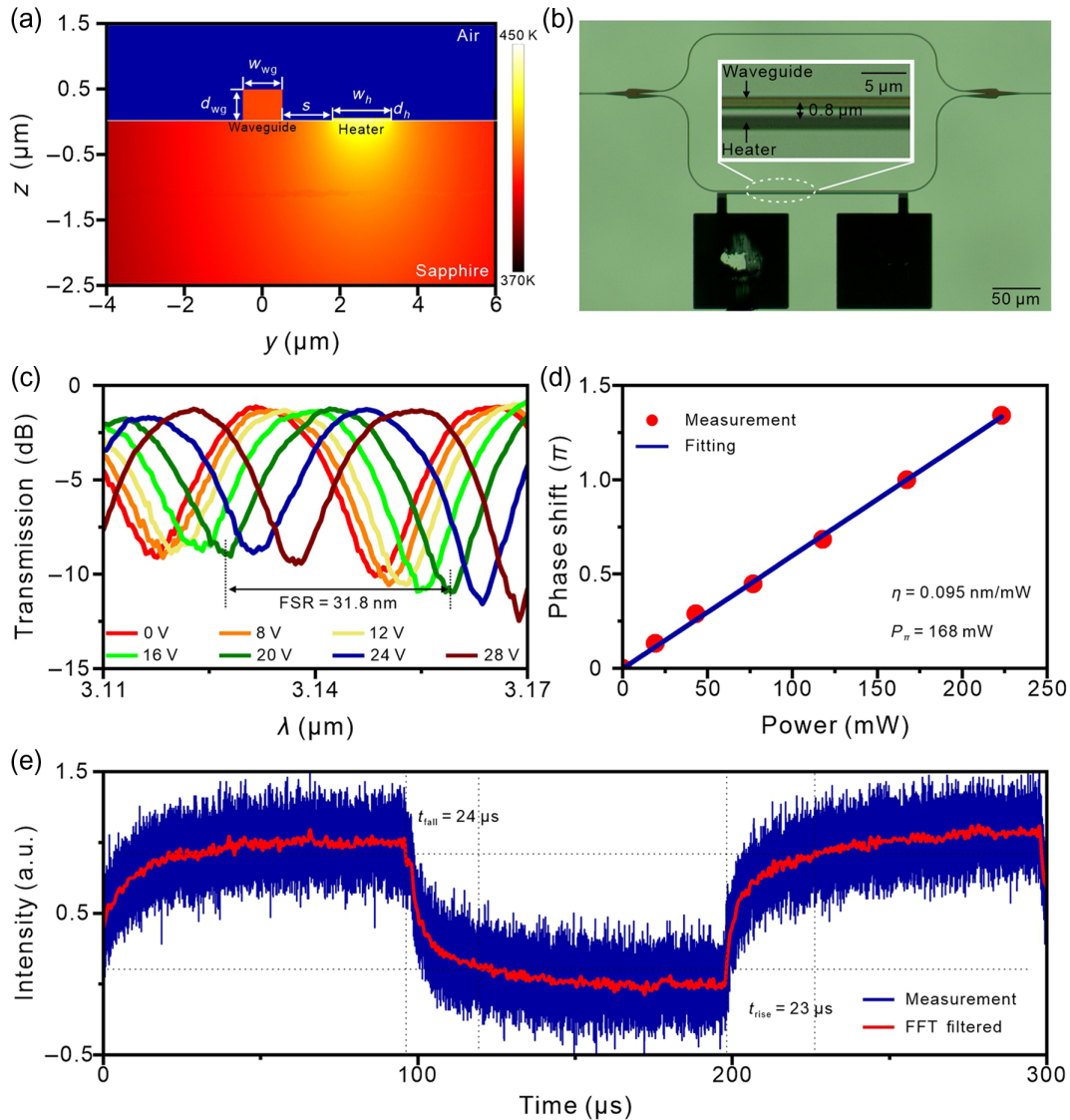


Fig. 4 Design and characterization of the MZI-based thermo-optic modulator. (a) Simulated temperature distribution of the TO-MZI cross-section under heating. (b) Optical microscope image of the fabricated TO-MZI. (c) Measured transmission spectra of the TO-MZI under different applied voltages. (d) Extracted phase shifts as a function of applied electrical power, from which the tuning efficiency η and π -shift power consumption P_π are obtained. (e) Dynamic response of the TO-MZI under square-wave electrical excitation.

conductivity sapphire substrate also contributes to the increased tuning power. Therefore, this value reflects the current low-loss heater layout rather than a fundamental platform limit.

In addition, a second TO-MZI with a wider arm waveguide ($W_{wg} = 2.5$ μm) is presented in Fig. S4 in the [Supplementary Material](#), and it exhibits a lower tuning efficiency and a higher P_π consistent with the reduced overlap between the heated region and the optical mode. Further optimization of the thermo-optic phase-control section could reduce the required tuning power by decreasing the heater-waveguide spacing, optimizing the heater geometry, introducing localized Al_2O_3 -assisted top-heater integration, or adding thermal isolation trenches to suppress heat leakage and thermal crosstalk. These strategies should be applied primarily to nonsensing phase-control

sections, whereas sensing-oriented interaction regions should remain sufficiently exposed to the surrounding medium. Nevertheless, the present result already demonstrates the key active interferometric function required for spectral encoding on SOS, namely, controllable thermo-optic phase modulation within a broadband interferometric circuit.

4 Resonant Devices: Design and Characterization

Wavelength-selective and resonance-enhanced optical functions are also essential in integrated mid-IR sensing systems, as they enable filtering, channel selection, and enhanced light-matter interaction. We therefore implement SWG and uniform strip-waveguide MRRs together with thermo-optically tunable MRRs,

to assess how resonant interaction modules can be incorporated into the workflow of Fig. 1.

4.1 MRR Design and Characterization

The implementations of SWG and conventional uniform strip-waveguide all-pass MRRs operating near 3.1 μm are shown in Figs. 5(a)–5(d). The MRR transmission spectra were recorded using the supercontinuum-source/OSA configuration with a wavelength resolution of 0.2 nm. Compared with a uniform strip-waveguide MRR, the SWG MRR offers an additional geometrical degree of freedom for tailoring the modal distribution and the group index.

As shown in Fig. 5(a), the fabricated SWG MRR consists of a straight SWG bus waveguide with a width of 2 μm and an SWG ring with a radius of 50 μm . The bus-ring air gap is 100 nm and is chosen to approach near-critical coupling around the operating wavelength. Figure 5(b) shows the measured transmission spectrum of the SWG MRR (dotted line) together with the Lorentzian fit (solid line). The resonance exhibits an extinction ratio (ER) of ~ 9.2 dB. From the fitted resonance, the full width at half-maximum (FWHM) is about 0.60 nm and the FSR is ~ 9.93 nm, corresponding to a loaded quality factor Q_l of 5166 and an intrinsic quality factor Q_i of 10,332. Following the standard MRR loss analysis,⁵¹ the FSR-derived group index and fitted intrinsic quality factor give a ring-derived propagation-loss estimate of ~ 26 dB/cm.

For comparison, a uniform strip-waveguide all-pass MRR was also fabricated on the same platform, as shown in Fig. 5(c). In this design, the waveguide width is 1 μm and the ring radius is again 50 μm . The measured transmission spectrum at a near-critical coupling gap of 50 nm, along with its Lorentzian fit, is shown in Fig. 5(d), yielding an ER of ~ 5.7 dB. From the fitted linewidth (FWHM ≈ 0.28 nm), the loaded quality factor is extracted as $Q_l = 11,046$. Under the near-critical-coupling assumption, the corresponding intrinsic quality factor is estimated to be on the order of 2.2×10^4 , but this value is resolution-limited because the measured linewidth is close to the OSA resolution of 0.2 nm. The corresponding FSR is ~ 7.22 nm, giving a ring-derived propagation-loss estimate of ~ 17 dB/cm using the same method. This ring-derived loss is higher than the optimized SOS ridge-waveguide loss reported by Baehr-Jones et al. at 4.5 μm .⁴⁷ However, the comparison is not strictly one-to-one because that work used $1.8 \mu\text{m} \times 0.6 \mu\text{m}$ waveguides and length-dependent transmission measurements, whereas the present value is inferred from microring resonances of $1.0 \mu\text{m} \times 0.6 \mu\text{m}$ strip waveguides near 3.1 μm . The extracted group indices are $\sim n_g = 3.08$ for the SWG MRR and $n_g = 4.24$ for the uniform strip-waveguide MRR. Because the two rings have the same radius, the lower n_g of the SWG MRR corresponds to its larger measured FSR and is consistent with the expected dispersion-engineering effect of the SWG structure. The extracted n_g of the SWG MRR is slightly larger than the simulated value of the straight SWG waveguide in Fig. 2(d), which may be attributed to the fabricated SWG duty cycle being slightly larger than the nominal value. The measured ER is governed by the coupling condition of the all-pass ring and is also affected by the finite spectral resolution of the OSA. In particular, the 0.2 nm OSA resolution spectrally averages the resonance response. For narrow resonances such as the conventional MRR with a fitted FWHM of ~ 0.28 nm, this averaging can raise the measured resonance minimum and therefore underestimate the measured ER.

These results show that the present SWG MRR operates in a modest- Q regime and exhibits higher ring-derived propagation loss than the uniform strip-waveguide MRR. This additional loss is mainly attributed to the segmented SWG geometry, which introduces a larger etched sidewall area, repeated silicon/air interfaces, and accumulated scattering from the periodic silicon segments. Consequently, the SWG waveguide is more sensitive to sidewall roughness, etched-interface imperfections, duty-cycle deviations, and local dimensional nonuniformity. Further optimization of lithography, dry etching, sidewall/interface roughness, duty-cycle control, and postfabrication cleaning or smoothing is expected to reduce both the baseline strip-waveguide loss and the additional SWG-induced loss.

Nevertheless, the SWG geometry provides stronger interaction with the surrounding medium. As detailed in Sec. 4 of the [Supplementary Material](#), the calculated modal-overlap factor with the surrounding air/cladding increases from 15.2% for the uniform strip waveguide to 56.4% for the SWG waveguide. Cladding-index sensitivity simulations (detailed in Sec. 4 of the [Supplementary Material](#)) further show that, under simulated Q values close to the experimental values, the SWG MRR still exhibits a higher sensitivity of ~ 1148 nm/RIU, compared with ~ 97.7 nm/RIU for the uniform strip-waveguide MRR. Although the lower Q of the SWG MRR broadens the resonance linewidth, its larger sensitivity gives a higher sensitivity-to-linewidth figure of merit of $\sim 1.9 \times 10^3$ RIU $^{-1}$, compared with $\sim 3.2 \times 10^2$ RIU $^{-1}$ for the uniform strip-waveguide MRR. Therefore, even with the current moderate Q , the SWG MRR can provide appreciable sensing response. Further optimization of the SWG fabrication process, including improved lithography and reduced interface roughness, is expected to reduce propagation loss, improve the resonator Q , and further enhance the sensing performance of SWG MRRs.

4.2 TO-MRR Design and Characterization

For sensing-oriented resonant modules, static spectral selectivity alone is often not sufficient. Practical systems typically require reconfigurability, enabling controlled resonance positioning for drift compensation and channel alignment. We therefore implement a thermo-optically tunable SWG MRR. An optical microscope image of the fabricated SWG MRR-based TO modulator is shown in Fig. 5(e). A 200 μm -long Pt heater with the same width and thickness as in the TO-MZI is placed adjacent to the ring, with a heater-to-waveguide spacing of $s = 1$ μm . The SWG ring waveguide width is 2.0 μm .

Static and dynamic characterizations are carried out using the same measurement setup described above. Figures 5(f) and 5(g) show the resonance shift as the applied electrical power increases. A clear red shift of the resonance dip is observed, with an extinction ratio of ~ 14 dB. From the measured shift in resonance wavelength versus electrical power [Fig. 5(g)], the spectral tuning efficiency is extracted as $\eta = 0.016$ nm/mW. For consistency with the MZI analysis, P_π is defined here as the electrical power required to shift one resonance dip by half of the ring FSR, and the resulting value is $P_\pi = 297$ mW. The dynamic characterization result is shown in Fig. 5(h), indicating a rise time of 18 μs and a fall time of 20 μs at 3177 nm.

For comparison, we also implement a conventional MRR-based TO device (Sec. 3 in the [Supplementary Material](#)). The conventional device exhibits a higher tuning efficiency of

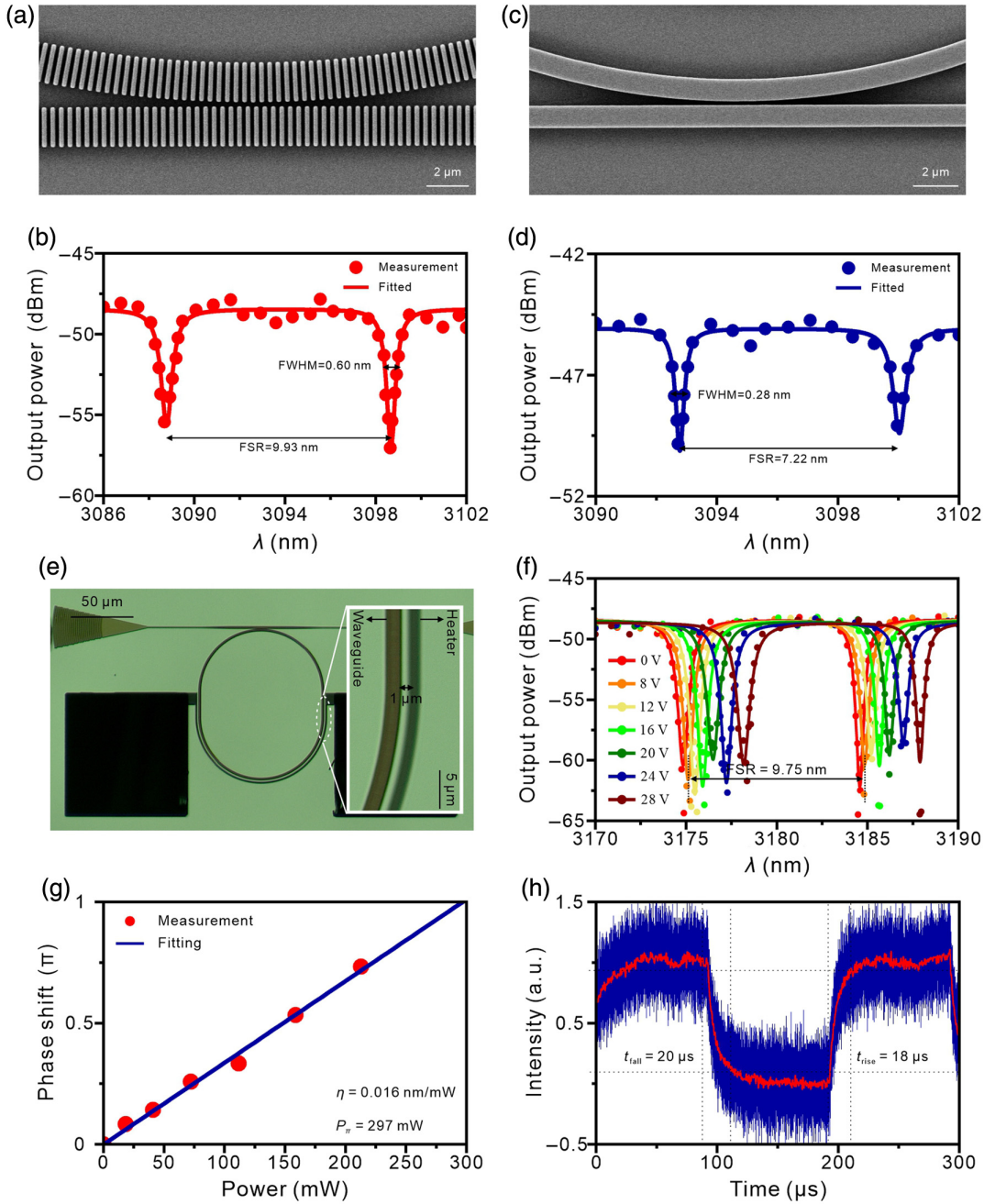


Fig. 5 Performance of resonance devices. (a) SEM image of the fabricated SWG MRR, showing the coupling region. (b) Measured output-power spectrum of the SWG MRR (dotted) and the corresponding Lorentzian fit (solid). (c) SEM image of the fabricated conventional MRR, showing the coupling region. (d) Measured output-power spectrum of the conventional MRR (dotted) and the corresponding Lorentzian fit (solid). (e) Optical microscope image of the fabricated SWG TO-MRR. (f) Measured output-power spectra under different applied voltages, showing the thermally induced resonance shift. (g) Extracted phase shifts as a function of applied electrical power, from which the tuning efficiency and π -shift power consumption are extracted. (h) Dynamic response of the TO-MRR under square-wave electrical excitation.

0.027 nm/mW and a lower P_π of 150 mW. This trend is mainly attributed to geometry-dependent thermo-optic phase accumulation: under the same heater configuration, the conventional ring provides a longer continuous silicon path overlapping the heated region, whereas the SWG ring contains air gaps with negligible thermo-optic contribution.

5 TO-MZI-Based Spectrometer: Theory and Numerical Verification

A broadband spectrometer sub-system is an essential requirement of the sensing architecture, as it enables spectral readout and reconstruction after the optional interaction stage. Here,

following the thermo-optic nonlinearity and dispersion-correction framework previously reported for SOI MZI Fourier-transform spectrometers, we numerically apply this reconstruction approach to an SOS-based thermo-optically tunable MZI implementation. The ultra-broadband SWG 1×2 MMI developed above is incorporated to extend the operational spectral range, whereas a $2.5 \mu\text{m}$ -wide and 30-mm -long waveguide arm design is adopted for practical low-loss operation with reduced sensitivity to fabrication-induced effective-index perturbations. Time-dependent heating applied to one interferometer arm introduces a controllable optical path difference, thereby generating an interferogram for spectral reconstruction. The spectrum is then reconstructed using this thermo-optic/dispersion-corrected Fourier-transform framework, which accounts for the dominant effects of thermo-optic nonlinearity, modal dispersion, and thermal expansion within the target operating window.

Figure 6(a) summarizes the spectral-reconstruction workflow of the TO-MZI-based spectrometer. For a TO-MZI-based FTS, the interferometric output $I(\Delta\varphi)$ is obtained by integrating the PSD(ν) weighted by the $T_{\text{tf}}(\nu)$ and the phase factor $[\Delta\varphi(\nu)]$ over frequency (ν):⁵²

$$I(\Delta\varphi) = \int_{-\infty}^{+\infty} T_{\text{tf}}(\nu) \text{PSD}(\nu) e^{i\Delta\varphi(\nu)} d\nu, \quad (1)$$

where PSD(ν) is the input power spectral density, $T_{\text{tf}}(\nu)$ is the transfer function of the interferometer (in our implementation, $T_{\text{tf}}(\nu) \approx 1$ after normalization), and $\Delta\varphi(\nu)$ is the phase difference between the two arms. The phase difference $\Delta\varphi(\nu)$ is determined by the thermo-optically induced change in modal

effective index and dispersion, together with the thermally induced length variation. These nonlinear contributions become non-negligible when the temperature excursion is large and the operating bandwidth is broad.

To quantify the influence of higher-order terms on the phase delay, the TE₀ mode effective index $n_{\text{eff}}(\nu, T)$ of the arm waveguide is extracted using the FDE solver in Lumerical MODE (Fig. S6 in the [Supplementary Material](#)) with Sellmeier dispersion models for sapphire⁵³ and silicon,⁵⁴ and the resulting data are fitted to obtain the dispersion and thermo-optic coefficients listed in Table S2 in the [Supplementary Material](#). By evaluating the higher-order contribution to the phase delay (Fig. S8 in the [Supplementary Material](#)) within the specified frequency and temperature window [$\nu = 83.28$ to 99.93 THz (corresponding to $\lambda = 3\text{--}3.6 \mu\text{m}$) and $T = 300$ to 400 K], the relationship between the interferogram and input PSD can be simplified to the following form:

$$\begin{cases} I(\Gamma) = \mathcal{F}[\text{PSD}(u) e^{i\varphi(u)}] \\ \text{PSD}(u) = |\mathcal{F}^{-1}[I(\Gamma)]| \end{cases}, \quad (2)$$

where u and Γ are the modified frequency and modified time delay terms parameterized by the coefficients χ_1 , χ_2 and ς_1 , and $\varphi(u)$ is a frequency-dependent but time-delay-independent phase contribution term (definitions and derivations are in Sec. 5 of the [Supplementary Material](#)). Using Eq. (2), the input PSD can be retrieved via Fourier-transform-based inversion and the frequency-coordinate transformation once the coefficients are identified.

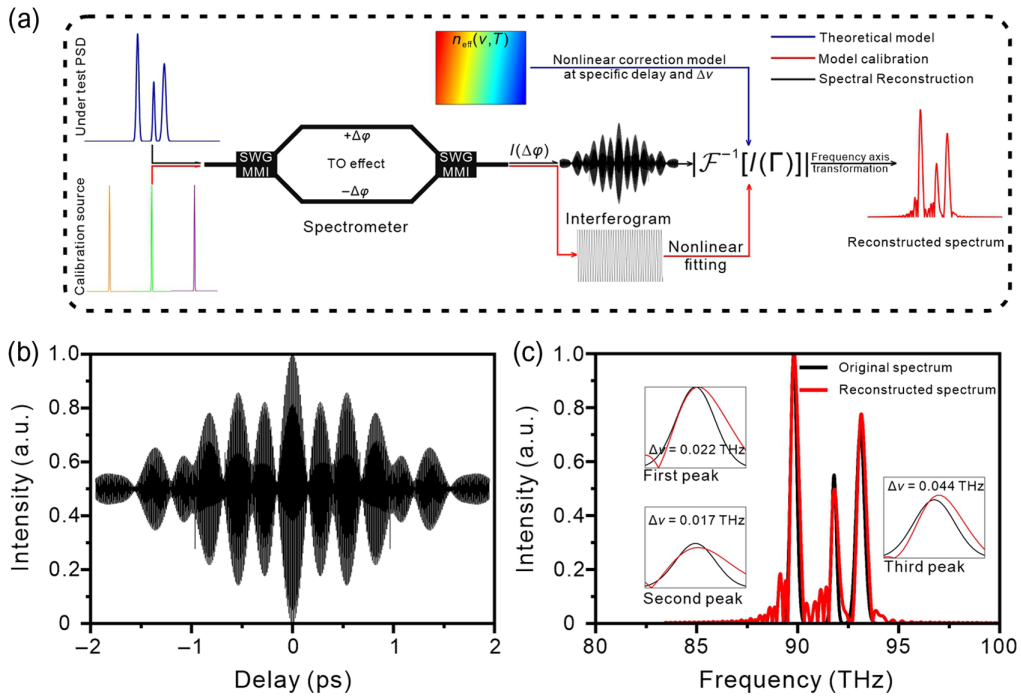


Fig. 6 Numerical verification of spectral reconstruction. (a) Workflow of the TO-MZI-based spectrometer model. The effective-index-based nonlinear calibration model is first established over a defined delay and frequency window (blue path), then calibrated with multiple narrowband laser sources (red path), and finally used to reconstruct an unknown input spectrum (black path). (b) Interferogram corresponding to the test spectrum. (c) Ground-truth and reconstructed spectra obtained with the nonlinear-corrected TO-MZI FT spectrometer. Insets show zoomed-in peaks and the residual error ($\Delta\nu$) between the input and recovered spectra.

Next, a TO-MZI interferogram matrix is generated in Lumerical INTERCONNECT for each frequency and temperature point using the extracted $n_{\text{eff}}(\nu, T)$ and S-parameters of the ultra-broadband MMI described above. The simulated interferograms exhibit a chirped cosine form with an almost constant envelope (a typical interferogram at $\nu_0 = 91.603$ THz is shown in Fig. S10 in the [Supplementary Material](#)). The coefficients are then calibrated using multiple single-frequency inputs. Although three nondegenerate frequency points are the theoretical minimum required to identify the three coefficients, 21 frequency points are used in this work to improve fitting robustness and reduce sensitivity to numerical or measurement noise. By fitting the interferogram for each single-frequency input according to Eq. (2), the modified frequency and time delay are extracted as $u \approx 90.61 + 1.10645 \Delta\nu$ and $\Gamma \approx 0.01797 \Delta T + 1.53247 \times 10^{-5} \Delta T^2$ (details are provided in Sec. 5 of the [Supplementary Material](#)).

Finally, we numerically verify the spectral-reconstruction performance of the designed SOS TO-MZI-based spectrometer. The interferogram [Fig. 6(b)] is generated by multiplying the interference matrix at each frequency and temperature point by a test input spectrum consisting of three Gaussian features with different amplitudes and linewidths [black line in Fig. 6(c)]. Specifically, the two reciprocal thermo-optic scans are represented by phase-difference terms $+\Delta\varphi$ and $-\Delta\varphi$ in the interference matrix. The spectrum is then reconstructed according to Eq. (2) together with the interferogram and the calibrated coefficients, and converted back from the modified frequency coordinate to the original optical frequency. The reconstructed PSD [red line in Fig. 6(c)] agrees well with the ground truth, confirming that the nonlinear corrections enable accurate broadband reconstruction on the SOS platform. The slight drift at the peak and the oscillation at the bottom can be attributed to small contributions from higher-order terms and to apodization of the time delay. In the present simulated configuration, the achievable spectral resolution is governed by the maximum accessible modified delay $\Delta\Gamma \approx 3.9$ ps, corresponding to a resolution of ~ 0.23 THz, or ~ 8.2 nm around $\lambda \approx 3.27$ μm .

Although this verification is numerical, it shows that the broadband routing and thermo-optic interferometric functions demonstrated above can support the spectral-processing function required by future on-chip mid-IR spectroscopy and sensing systems. Channelized spectrometer architectures, such as arrayed-waveguide-grating demultiplexers^{9,10} and MRR-assisted³¹ filter-bank spectrometers, can provide high spectral selectivity and potentially higher resolution within designed wavelength channels. By contrast, the TO-MZI Fourier-transform approach considered here operates through broadband interferometric encoding and computational reconstruction, with its spectral resolution determined by the maximum tunable optical delay. This operating principle makes it suitable for continuous broadband spectral readout within the SWG-MMI-based interferometric architecture developed in this work.

In practical implementations, the SOS TO-MZI-FTS can be realized by adding an Al_2O_3 over-cladding after silicon-waveguide formation, followed by heater electrodes and metal contact pads fabricated on top of the cladding for thermo-optic tuning. The over-cladding provides electrical isolation and allows top-heater integration with reduced optical absorption and enhanced heating efficiency, whereas local windows can be opened above sensing-oriented interaction regions to preserve

access to the surrounding analyte. Thermal isolation trenches can also be introduced around the heated sections to reduce heat spreading and thermal cross-talk. For the TO-MZI-FTS itself, the interferometer arms can be implemented as spiral waveguides to increase the effective optical delay within a compact footprint, as demonstrated in prior integrated Si-FTS implementations.^{52,55} Wider MZI arm waveguides can be used to reduce propagation loss and suppress fabrication-induced effective-index perturbations, and spiral heaters placed above the spiral arms can provide a more uniform thermal field along the delay path. These design strategies are expected to improve heating efficiency, reduce thermal power consumption, suppress thermal cross-talk, increase the accessible optical delay, and improve long-term phase stability.

In this architecture, the achievable spectral resolution is limited by the maximum calibrated delay, whose relationship with the arm length and heating temperature is derived in Eq. (S22) in the [Supplementary Material](#). The accessible delay is determined by the thermo-optic tuning efficiency, heater power budget, allowable temperature rise, and thermal diffusion. Increasing the delay through a longer interferometer arm or/and a larger heating-temperature excursion can improve the spectral resolution, but this must be balanced against propagation loss, chip footprint, thermal power consumption, thermal cross-talk, and the resulting signal-to-noise ratio. Therefore, improving practical performance will require co-optimization of waveguide loss, heater efficiency, thermal isolation, delay-line length, and optical power budget. In addition, polarization drift and unintended higher-order-mode excitation can reduce interferometric visibility and should be controlled through polarization-selective coupling and mode filtering. Furthermore, reference-wavelength-based calibration, similar to that used in bench-top Fourier-transform spectrometers, will be needed to track temperature-dependent dispersion drift and maintain long-term reconstruction accuracy.

6 Conclusion

This work addresses a central requirement for future on-chip mid-infrared spectroscopy and sensing: the realization of a broadband, tunable, and mutually compatible interferometric photonic front-end on silicon-on-sapphire. We show that SWG-engineered SOS photonics can provide key component-level functions required by such a sensing workflow, including broadband optical routing and power splitting, active thermo-optic phase control, resonance-based wavelength selectivity, and interferometric spectral reconstruction. The SWG MMIs provide a simulated broadband routing foundation for wideband interferometric operation, and their operation is experimentally verified within the accessible source-constrained wavelength windows. The thermo-optic MZI demonstrates controllable phase modulation compatible with spectral encoding, and conventional as well as SWG MRRs provide candidate interaction modules for filtering and enhanced light-matter interaction. Building on these component-level results, we further apply a thermo-optic/dispersion-corrected MZI Fourier-transform spectrometer framework to the SOS platform and numerically verify spectral reconstruction using the designed SWG-MMI-based interferometric architecture. Taken together, these results establish a platform-consistent set of experimentally demonstrated SOS building blocks, together with a numerically verified spectrometer concept, for future integrated mid-infrared spectroscopy and sensing systems. At the same time, full system-level

integration will require further reduction of waveguide and resonator losses, improved fabrication uniformity, and optimized optical power budgets to ensure sufficient signal-to-noise ratio and optical power per spectral channel.

Disclosures

The authors declare no conflicts of interest.

Data Availability Statement

The data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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References

1. H. Lin et al., “Mid-infrared integrated photonics on silicon: a perspective,” *Nanophotonics* **7**(2), 393–420 (2018).
2. M. A. Butt, D. P. Abellán, and R. Piramidowicz, “Mid-infrared integrated photonics: material platforms and emerging applications,” *Laser Photonics Rev.* **20**(6), e00099 (2026).
3. R. Shankar, I. Bulu, and M. Lončar, “Integrated high-quality factor silicon-on-sapphire ring resonators for the mid-infrared,” *Appl. Phys. Lett.* **102**(5), 051108 (2013).
4. P. Ma et al., “High Q factor chalcogenide ring resonators for cavity-enhanced MIR spectroscopic sensing,” *Opt. Express* **23**(15), 19969–19979 (2015).
5. J. S. Penades et al., “Suspended silicon mid-infrared waveguide devices with subwavelength grating metamaterial cladding,” *Opt. Express* **24**(20), 22908–22916 (2016).
6. V. Vakarin et al., “Ultra-wideband Ge-rich silicon germanium integrated Mach-Zehnder interferometer for mid-infrared spectroscopy,” *Opt. Lett.* **42**(17), 3482–3485 (2017).
7. T.-H. Xiao et al., “Mid-infrared high-Q germanium microring resonator,” *Opt. Lett.* **43**(12), 2885–2888 (2018).
8. C. J. Stirling et al., “Broadband 2×2 multimode interference coupler for mid-infrared wavelengths,” *Opt. Lett.* **46**(21), 5300–5303 (2021).
9. T. S. Karnik et al., “High-efficiency mid-infrared InGaAs/InP arrayed waveguide gratings,” *Opt. Express* **31**(3), 5056–5068 (2023).
10. T. S. Karnik et al., “Mid-infrared arrayed waveguide gratings using a quantum cascade laser gain medium as core material,” *Appl. Opt.* **63**(33), 8548–8554 (2024).
11. Y. Si et al., “Realization and simulation of silicon-on-sapphire mid-infrared one-dimensional photonic crystal cavities,” *Appl. Phys. Lett.* **126**(2), 021101 (2025).
12. M. Perestjuk et al., “One million quality factor integrated ring resonators in the mid-infrared,” *Nanophotonics* **14**(7), 1009–1015 (2025).
13. M. Nedeljkovic et al., “Silicon-on-insulator free-carrier injection modulators for the mid-infrared,” *Opt. Lett.* **44**(4), 915–918 (2019).
14. Q. Li et al., “High-speed mid-infrared graphene electro-optical modulator based on suspended germanium slot waveguides,” *Opt. Express* **31**(18), 29523–29535 (2023).
15. S. Xu et al., “Mid-infrared silicon-on-lithium-niobate electro-optic modulators toward integrated spectroscopic sensing systems,” *Adv. Opt. Mater.* **11**(4), 2202228 (2023).
16. J. Lim et al., “Thermally tunable microring resonators based on germanium-on-insulator for mid-infrared spectrometer,” *APL Photonics* **9**(10), 106109 (2024).
17. R. Guo et al., “Foundry-processed mid-infrared thermo-optic phase shifters,” *J. Lightwave Technol.* **43**(7), 3358–3365 (2025).
18. P. Didier et al., “Thin film lithium niobate on sapphire for integrated mid-infrared modulator,” *Nat. Commun.* **17**(1), 3050 (2026).
19. P. Wang et al., “Broadband mid-infrared supercontinuum generation in dispersion-engineered As_2S_3 -silica nanospire waveguides pumped by 2.8 μm femtosecond laser,” *Photonics Res.* **9**(4), 630–636 (2021).
20. R. Wang et al., “Monolithic integration of mid-infrared quantum cascade lasers and frequency combs with passive waveguides,” *ACS Photonics* **9**(2), 426–431 (2022).
21. D. Burghart et al., “Multi-color photonic integrated circuits based on homogeneous integration of quantum cascade lasers,” *Nat. Commun.* **16**(1), 3563 (2025).
22. J. Goldstein et al., “Waveguide-integrated mid-infrared photodetection using graphene on a scalable chalcogenide glass platform,” *Nat. Commun.* **13**(1), 3915 (2022).
23. J. Shim et al., “Room-temperature waveguide-integrated photodetector using bolometric effect for mid-infrared spectroscopy applications,” *Light: Sci. Appl.* **14**(1), 125 (2025).
24. L. Mancini et al., “Atto-Watt photo-detection at mid-infrared wavelengths by a room-temperature balanced heterodyne set-up,” *Laser Photonics Rev.* **20**(3), e01339 (2026).
25. C. Lemieux-Leduc et al., “Waveguide-coupled mid-infrared GeSn membrane photodetectors on silicon-on-insulator,” *ACS Photonics* **12**(11), 6343–6351 (2025).
26. M. Nedeljkovic et al., “Mid-infrared silicon-on-insulator Fourier-transform spectrometer chip,” *IEEE Photonics Technol. Lett.* **28**(4), 528–531 (2016).
27. Q. Liu et al., “Integrated broadband dual-polarization Ge-rich SiGe mid-infrared Fourier-transform spectrometer,” *Opt. Lett.* **43**(20), 5021–5024 (2018).
28. E. Heidari et al., “On-chip Fourier transform spectrometer on silicon-on-sapphire,” *Opt. Lett.* **44**(11), 2883–2886 (2019).
29. T. T. D. Dinh et al., “Mid-infrared Fourier-transform spectrometer based on metamaterial lateral cladding suspended silicon waveguides,” *Opt. Lett.* **47**(4), 810–813 (2022).
30. Q. Qiao et al., “MEMS-enabled on-chip computational mid-infrared spectrometer using silicon photonics,” *ACS Photonics* **9**(7), 2367–2377 (2022).
31. J. Zhou et al., “Mid-infrared serial microring resonator array for real-time detection of vapor-phase volatile organic compounds,” *Anal. Chem.* **94**(31), 11008–11015 (2022).
32. Z. Ran et al., “Fiber-optic microstructure sensors: a review,” *Photonic Sensors* **11**(2), 227–261 (2021).
33. X. Hu et al., “Observing the collapse of super-Bloch oscillations in strong-driving photonic temporal lattices,” *Adv. Photonics* **6**(4), 046001 (2024).
34. T. Gu et al., “Reconfigurable metasurfaces towards commercial success,” *Nat. Photonics* **17**(1), 48–58 (2023).
35. S. Yasir et al., “Deep learning in metasurfaces: from automated design to adaptive metadevices,” *Adv. Photonics* **7**(3), 034005 (2025).

36. P. Cheben et al., "Subwavelength integrated photonics," *Nature* **560**(7720), 565–572 (2018).
37. A. Ma et al., "Reconfigurable and programmable integrated topological photonics," *Nat. Rev. Phys.* **8**, 327–343 (2026).
38. A. Maese-Novo et al., "Wavelength independent multimode interference coupler," *Opt. Express* **21**(6), 7033–7040 (2013).
39. R. Halir et al., "Ultra-broadband nanophotonic beamsplitter using an anisotropic sub-wavelength metamaterial," *Laser Photonics Rev.* **10**(6), 1039–1046 (2016).
40. R. Guo et al., "Blazed subwavelength grating coupler," *Photonics Res.* **11**(2), 189–195 (2023).
41. C. Ranacher et al., "Design of a mid-infrared bandpass filter with large rejection bandwidth for silicon photonics," *J. Lightwave Technol.* **37**(15), 3770–3776 (2019).
42. H. Xu, D. Dai, and Y. Shi, "Ultra-broadband and ultra-compact on-chip silicon polarization beam splitter by using hetero-anisotropic metamaterials," *Laser Photonics Rev.* **13**(4), 1800349 (2019).
43. J. G. Wangüemert-Pérez et al., "Evanescent field waveguide sensing with subwavelength grating structures in silicon-on-insulator," *Opt. Lett.* **39**(15), 4442–4445 (2014).
44. J. G. Wangüemert-Pérez et al., "Subwavelength structures for silicon photonics biosensing," *Opt. Laser Technol.* **109**, 437–448 (2019).
45. R. Guo et al., "High-Q silicon microring resonator with ultrathin sub-wavelength thicknesses for sensitive gas sensing," *Appl. Phys. Rev.* **11**(2), 021417 (2024).
46. J. M. Luque-González et al., "A review of silicon subwavelength gratings: building break-through devices with anisotropic metamaterials," *Nanophotonics* **10**(11), 2765–2797 (2021).
47. T. Baehr-Jones et al., "Silicon-on-sapphire integrated waveguides for the mid-infrared," *Opt. Express* **18**(12), 12127–12135 (2010).
48. F. Li et al., "Low propagation loss silicon-on-sapphire waveguides for the mid-infrared," *Opt. Express* **19**(16), 15212–15220 (2011).
49. A. Spott et al., "Silicon waveguides and ring resonators at 5.5 μm ," *Appl. Phys. Lett.* **97**(21), 213501 (2010).
50. L. B. Soldano and E. C. M. Pennings, "Optical multi-mode interference devices based on self-imaging: principles and applications," *J. Lightwave Technol.* **13**(4), 615–627 (1995).
51. W. Bogaerts et al., "Silicon microring resonators," *Laser Photonics Rev.* **6**(1), 47–73 (2012).
52. M. C. M. M. Souza et al., "Fourier transform spectrometer on silicon with thermo-optic non-linearity and dispersion correction," *Nat. Commun.* **9**(1), 665 (2018).
53. Y. Di et al., "Infrared refractive index measurements using a new method," *Proc. SPIE* **4103**, 42–52 (2000).
54. H. H. Li, "Refractive index of silicon and germanium and its wavelength and temperature derivatives," *J. Phys. Chem. Ref. Data* **9**(3), 561–658 (1980).
55. A. Li et al., "Fabrication-tolerant Fourier transform spectrometer on silicon with broad bandwidth and high resolution," *Photonics Res.* **8**(2), 219–224 (2020).

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