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Wafer-scale waveguide-integrated graphene optoelectronic mixers

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Optoelectronic mixers enable efficient frequency conversion and are essential components of future communication modules, radar systems, antenna arrays, and high-speed signal processing. A promising material for optoelectronic mixing is graphene, offering significant advantages over traditional electrical or optoelectronic mixers, such as higher operational frequencies, lower power consumption, broader bandwidths, and a smaller device footprint. Here, we report the wafer-scale realization of graphene-based optoelectronic mixers integrated on a 150 mm silicon-on-insulator photonic platform, achieving a mixing performance of -47 dB up to 67 GHz. The performance of our devices exceeds that of reported wafer-scale graphene optoelectronic mixers by 20 dB. This enhanced efficiency results from the direct integration of graphene onto optical waveguides, which increases the optical absorption of graphene through evanescent field coupling along the waveguide. The wafer-scale approach resulted in approximately one thousand fully functional mixers, and enabled a

statistically relevant number of measurements across the wafer to assess the mixers' performance. Furthermore, our approach facilitates the miniaturization of optoelectronic mixers into integrated optoelectronic circuits on chip.

Introduction

The increasing demand for broader bandwidth in wireless networks, driven by the growth of 5G and the future rollout of 6G technology, calls for the utilization of higher carrier frequencies (30–300 GHz).^{1,2} This frequency range provides the large signal bandwidths necessary for ultrafast data rates and low-latency communication. Additionally, it can support emerging applications of next-generation wireless systems, avoiding frequency congestion.¹

In communication systems, information is typically upconverted to high frequencies at the transmitter. At the receiver, the signal is downconverted back to lower baseband frequencies, where standard (low-frequency) electronics process the signals. Frequency mixing is implemented via the superheterodyne concept, which typically involves mixers.^{3–6} A mixer is a device or a circuit that multiplies an input signal with a local oscillator (LO) signal, producing an output modulated with the sum and/or difference of the two signals' frequencies. The higher-frequency signal is referred to as the radio frequency (RF), whereas the lower-frequency signal is known as the intermediate frequency (IF). In systems in use today, the conventional approach still relies on fully electrical mixers. However, as carrier frequencies are pushed higher to mitigate frequency congestion and to enable the large bandwidths necessary for 6G telecom and internet of things (IoT) future applications, fully electronic mixers encounter limitations in bandwidth and power consumption. A major contributor to power consumption in fully electronic architectures is the LO distribution loss, which increases with operating frequency and prohibits large-bandwidth electrical-LO systems.⁷ One route to

overcoming these limitations is to employ optical signals for the mixing process. If at least one of the input signals is optical, the mixer is referred to as an optoelectronic (OE) mixer. OE mixers offer the advantage of delivering input signals through optical fibers, which significantly reduces propagation losses compared with high-frequency RF transmission lines and simplifies front-end receiver architectures. A common approach in microwave–photonics mixers employs heterodyne mixing of purely optical LO and RF signals that are coupled to a photodetector,^{8–11} providing an upconverted or downconverted optical heterodyne signal as the output. This scheme typically requires two separate high-frequency optoelectronic components, a photodetector and a modulator, often interconnected via optical fibers. In such heterodyne mixing schemes, the photodetectors commonly rely on III–V compound semiconductors, which require high-temperature epitaxial growth and are generally incompatible with standard complementary metal–oxide–semiconductor (CMOS) processing.^{3,12,13} Another OE mixing approach is directly combining an optical LO signal with an electrical RF signal, known as self–mixing¹⁴ as in our graphene-based OE mixers (GOEMs). This eliminates the need to convert the electrical RF signal into an optical carrier. An efficient OE mixer must simultaneously provide high-speed photodetection, fast carrier transport, and excellent linearity. Graphene fulfills all these requirements owing to its high carrier mobility,^{15–18} broadband absorption,^{19,20} and low photocarrier lifetime.^{21,22} As a consequence, ultrafast graphene photodetectors,^{23–25} modulators,^{26–28} mixers,^{3,29–31} and samplers³² have been reported in the literature, with graphene photodetectors exhibiting bandwidths up to 500 GHz,³³ and theoretical predictions extending beyond this limit.

Graphene-based OE mixers have been demonstrated in planar device geometries with normal-incidence illumination, initially with chemical vapor deposition (CVD)–grown graphene,^{29,30} and later with exfoliated, hBN-encapsulated high-mobility graphene,³¹ which achieved the

highest reported conversion efficiency. GOEMs can also be realized by integrating graphene with photonic waveguides. This configuration mitigates the low intrinsic optical absorption of monolayer graphene of approximately 2.3% per transmission,¹⁹ as absorption through evanescent field coupling between the guided mode and the graphene layer enables nearly 100% absorption.^{24,34–36} While high-mobility graphene mixers with bandwidths up to 100 GHz have been demonstrated on photonic wafers,³ their reliance on exfoliated, hBN-encapsulated graphene limits compatibility with scalable industrial processes. In contrast, CVD-grown graphene can be produced at wafer scale^{37,38} encapsulated with dielectric oxides, and integrated into the back end of the line (BEOL) of CMOS technology platforms. This enables the miniaturized active optoelectronic components directly cointegrated with electronic integrated circuits,³⁹ which could drive the next paradigm shift in the performance and scalability of integrated systems. Compared with electrical and fully optical mixers, GOEMs thus could show significant advantages in terms of power consumption, bandwidth capacity, and footprint.

In this work, we fabricated approximately one thousand graphene optoelectronic mixers on silicon (Si) waveguides, each embedded with an RF coplanar waveguide (CPW), using standard mask-based photolithography compatible with foundry-level and cost-effective fabrication. The devices were made in parallel by fabricating waveguides on a 150 mm silicon on insulator (SOI) wafer and transferring CVD-grown graphene with a mobility of approximately $1500 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ onto the Si waveguides, followed by graphene patterning and encapsulating with aluminum oxide (Al_2O_3). We achieved a mixing conversion efficiency of -47 dB over a bandwidth of 67 GHz, corresponding to an efficiency increase of more than 20 dB compared with wafer-scale planar mixers based on graphene with similar carrier mobility.^{30,31} This

substantial increase arises from the integration of graphene into optical waveguides. Finally, we discuss the performance repeatability obtained from statistical wafer-scale measurements.

Device fabrication, layout, and initial characterization

The mixers were fabricated on commercial 150 mm SOI wafers with 220 nm top Si and a 3 μm buried oxide (BOX) layer, and a photograph of the fabricated wafer is shown in Fig. 1a. A schematic cross-section and top-view of a GOEM are shown in Fig. 1b, c. It consists of a photonic layer and an RF coplanar waveguide. The optical waveguides with widths of 800 nm and etch depths of 50 nm (rib waveguides) were realized using optical lithography (i-line stepper) and reactive ion etching (RIE). Grating couplers, designed for TE-polarized light, were patterned via high-resolution electron beam lithography (e-beam) followed by RIE. A 10 nm Al_2O_3 layer was deposited using plasma-assisted atomic layer deposition (ALD) to electrically isolate the graphene and the Si. CVD-grown graphene with an average carrier mobility $\mu \approx 1500 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ on copper foil was coated with polymethyl methacrylate (PMMA) and transferred to the wafer using a semi-dry method⁴⁰ (Supplementary Note 1). The graphene layer was patterned by optical lithography and oxygen plasma etching. The electrodes were fabricated using an evaporation and lift-off process that involved 5 nm titanium (Ti) and 65 nm gold (Au) as the contact materials. The graphene was then encapsulated with a 400 nm thick ALD Al_2O_3 layer. Subsequently, vias were defined with photolithography and RIE to access the contact electrodes with needle probes.

The graphene channel width (W) along the waveguide was varied between 10 and 60 μm , whereas channel lengths (L) between the metal electrodes ranged from 2–3 μm . The graphene channel was integrated into the CPW, which consists of 60 μm wide signal electrodes (source and drain) and 240 μm wide ground electrodes (Fig. 1c). This ground-signal-ground (GSG) RF

waveguide architecture is preferred due to lower propagation losses at high frequency, better electromagnetic shielding from exterior sources, and a shorter current return path compared to simpler transmission lines such as microstrip. The distance between the signal and ground electrodes was designed to $35\text{ }\mu\text{m}$ to maintain continuity of the ground electrodes and minimize bending losses in the Si rib-waveguide⁴¹. The CPW impedance varies between 55 and $72\text{ }\Omega$ across the different designs. The 10 nm Al_2O_3 film between the Si waveguides and CPW is too thin to affect the RF mode confinement; therefore, the impedance is primarily determined by the permittivity of the underlying silicon slab. Optical and scanning electron microscopy (SEM) images of the fabricated device are shown in Fig. 1d, e. Wrinkles are clearly visible in the SEM images of the transferred graphene, and the graphene does not conformally cover the waveguides, leaving small airgaps on the waveguide sidewalls. These effects are commonly observed in wet-transfer and semi-dry transfer processes owing to the limited flexibility of the transfer polymer. In our devices with a waveguide height of 50 nm, air gaps of approximately 100 nm formed (Fig. 1e).

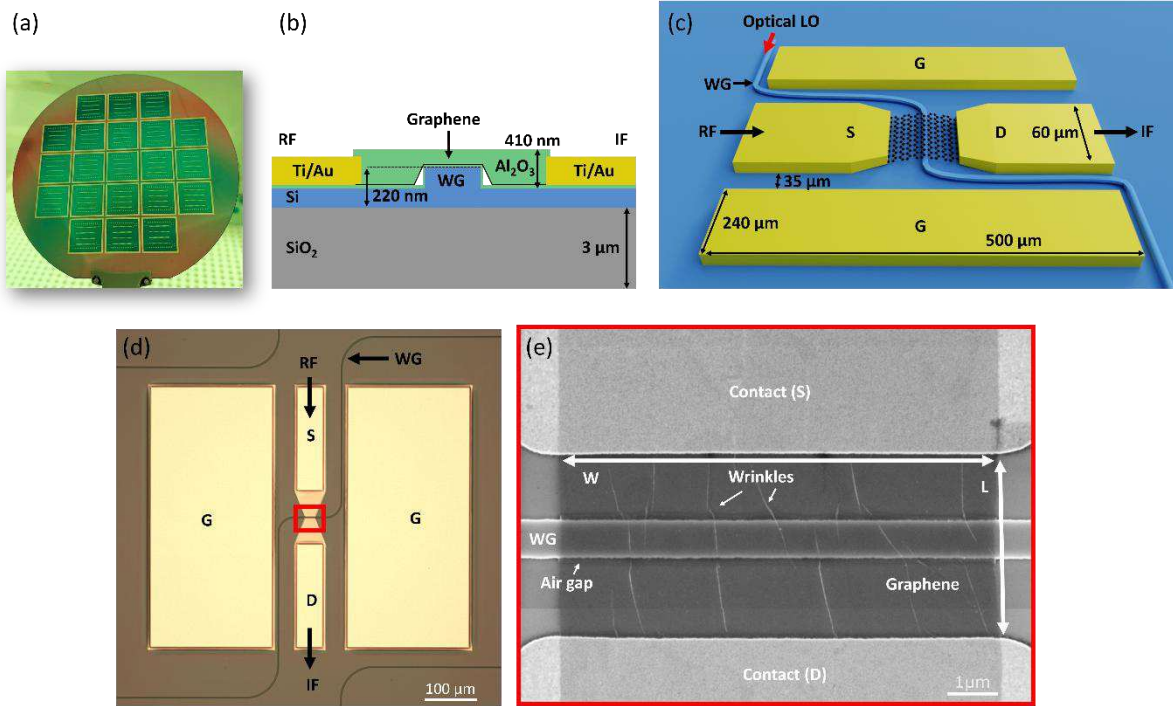


Fig. 1 | GOEM layout. **a** Photograph of the 150 mm SOI wafer containing the integrated GOEMS. **b** Cross-sectional schematic of the device, showing the rib waveguide (blue), the metal electrodes (yellow) and the graphene layer (black), positioned between the two metal contacts of the signal line (RF and IF terminals). **c** Schematic diagram of the waveguide-integrated graphene optoelectronic mixer. An optical LO signal is injected at one end of the waveguide (denoted by WG) and supplied to the GOEM. The electrical RF signal is fed into the device from the source electrode (S), and the downconverted IF signal is extracted through the drain electrode (D). The ground electrodes are indicated as G. **d** Optical image of a fabricated GOEM, tilted by 90° compared to **b** and **c**. The red square indicates the area of the SEM image shown in panel e. **e** SEM image of the graphene on the waveguide. The width and length of the graphene channel are denoted by W and L, respectively. Wrinkles and an approximately 100 nm lateral air gap between the waveguide sidewalls and the graphene resulted from the wet transfer process and are marked in the image.

The losses of the waveguides and grating couplers were measured after fabrication. The waveguides exhibited an average loss of -3 dB/cm, while the grating coupler losses were approximately -5 dB. An absorption coefficient of 0.077 dB/ μm for graphene was extracted by incrementally increasing the graphene-covered width along the waveguide. Additionally, the metal electrodes contributed to losses due to their proximity to the waveguides: for the $L = 2$ μm channels with 0.6 μm distance between the contact electrodes and the waveguides, the loss was 1.14×10^{-2} dB/ μm , while it was 6.94×10^{-5} dB/ μm for $L = 3$ μm and 1.1 μm distance to the waveguide) (Supplementary Note 2).

We assessed the graphene quality using Raman spectroscopy with a $\lambda = 512$ nm excitation laser directly after graphene transfer onto the waveguides and again at the end of the GOEM fabrication. Raman spectra, along with the 2D-peak full-width-at-half-maximum (FWHM) distributions and the relative positions of the G and 2D peaks extracted from Raman maps of multiple devices, are presented in Supplementary Note 3. The 2D peak is highly sensitive to strain, which strongly influences carrier mobility.^{42–44} Following transfer, most devices exhibited a 2D-peak FWHM of approximately 35 cm^{-1} , whereas encapsulated devices showed values exceeding 40 cm^{-1} , consistent with increased strain and the corresponding mobility degradation, likely arising from the substrate topography and the amorphous Al_2O_3 encapsulation layer. In addition to strain, our measurements (Supplementary Fig. 3c) indicate that Al_2O_3 encapsulation introduces enhanced p-doping in graphene.^{45,46} The doping level, however, remains spatially inhomogeneous across individual devices.

Optoelectronic Characterization

Optoelectronic graphene-based mixers exploit the change in graphene conductance under illumination in the presence of an applied RF voltage. The photocurrent is defined as $I_{ph} = G_{ph} \cdot V_{ch}$, where G_{ph} denotes the channel differential photoconductance and V_{ch} is the source to drain bias voltage applied to the channel. G_{ph} is modulated by the optical signal (here: the intensity-modulated 1550 nm laser light) at the LO frequency (f_{LO}), which modulates the carrier density in the graphene. If the applied bias is a DC voltage, the resulting photocurrent is modulated at f_{LO} , and the device acts as a photodetector. When V_{ch} is modulated at an RF frequency, the current through the graphene is correspondingly modulated and contains intermodulation products of the optical (LO) and RF frequencies, thereby enabling mixing. A detailed description of the measurement setup is provided in the Methods section.

The channel photoconductance in graphene can be either positive or negative, depending on the dominant physical mechanism. When the Fermi level is close to the charge neutrality point (Dirac point), the photovoltaic effect dominates and the incoming light creates electron–hole pairs, increasing the conductance and leading to a positive channel photoconductance. When the graphene channel is highly doped, the thermobolometric effect dominates, where at high–frequencies the scattering between the carriers and charged impurities increases due to photothermal-induced reduced screening, leading to negative photoconductivity.⁴⁷ Therefore, intrinsic channel doping with $E_F < 0.1$ eV or > 0.15 eV leads to positive or negative photoconductance, respectively.⁴⁸

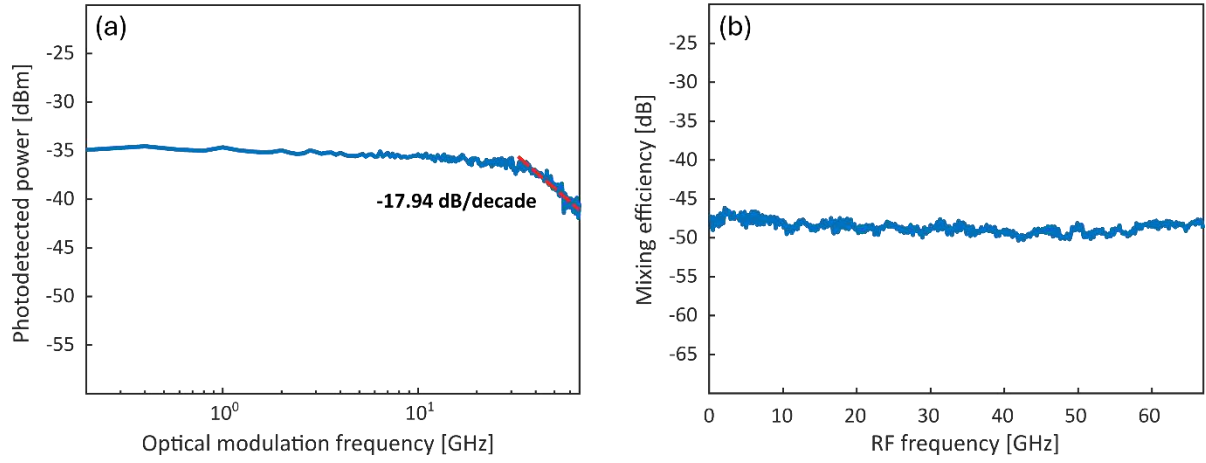


Fig. 2| Best-performing optical and electrical responses among the measured devices.

a Photodetected power versus optical modulation frequency (f_{LO}) for a bias voltage of 0.5 V.

The photoresponse of the device shows a 17.94 dB/dec drop for frequencies above 37 GHz. **b**

Mixing efficiency versus input RF frequency for $f_{LO} = 67$ GHz and an RF power of -5 dBm. The

mixing efficiency is flat up to 67 GHz, with an average value of -47 dB.

Figure 2 presents the photodetection and mixing performance of the best-performing device, with a channel width of 40 μm and a channel length of 2 μm , measured under a laser input power of 107 mW. Figure 2a shows the frequency photoresponse of this device with -35 dBm photodetected power at f_{LO} values between 1 and 67 GHz with an applied DC bias voltage of 0.5 V. A corner frequency of ~ 37 GHz separates two regimes with contrasting roll-off rates: the small -1.09 dB/dec slope at low frequencies changes to -17.94 dB/dec at high frequencies. This frequency response is consistent with the measurements over the whole wafer and is not due to frequency-dependent variations in the laser light modulation (Supplementary Fig. 4).

The mixing efficiency of one of our best-performing GOEMs, defined as the power ratio of the output IF and input RF signals ($\frac{P_{\text{IF}}}{P_{\text{RF}}}$), is shown in Fig. 2b for an optical $f_{\text{LO}} = 67$ GHz and an input RF power of -5 dBm, with f_{RF} swept up to 67 GHz. The LO frequency, which is above the photoresponse cutoff frequency, was chosen to evaluate our device's performance at frequencies similar to those previously reported mixers.^{31,32} The mixing efficiency is flat up to an RF frequency of 67 GHz, with an average value of -47 dB, indicating that this GOEM has a bandwidth larger than 67 GHz. Notably, the mixing efficiency is more than 20 dB greater than that reported for top-illuminated wafer-scale graphene GOEMS^{30,31} and is close to the record value (-40 dB) obtained with high mobility ($28,000 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$) h-BN-encapsulated graphene (currently a non-scalable method),³² which highlights the benefits of illumination through integrated waveguides.

Figure 3a presents the photocurrent of a typical GOEM, averaged over the DC–37 GHz bandwidth, as a function of the laser input power at a bias voltage of 0.5 V. The photocurrent begins to saturate for optical laser powers exceeding 100 mW. In this experiment, the input optical power was chosen to ensure that the optical power coupled into the waveguides

remained below the nonlinear threshold of Si, considering the average grating coupler insertion losses of -5 dB. Figure 3b shows a representative measurement of the input and output optical power through a device, which remains linear, indicating that the observed photocurrent deviation from linearity cannot be attributed to losses in the optical waveguide or to Pauli blocking. Instead, the nonlinear behavior of the photocurrent as a function of the optical input power can be qualitatively understood by considering the underlying photodetection mechanism. In our devices, photodetection is predominantly governed by the photobolometric effect, as the graphene layer is heavily doped by the thick Al₂O₃ encapsulation. Upon light absorption, in addition to electron-hole pair generation, electronic heating also occurs in graphene. In low-mobility graphene, such as in our devices, energy transfer is dominated by supercollision cooling due to short-range scatterers (disorders or defects).^{29,47,49} The relationship between conductivity and electronic temperature is inherently nonlinear, as observed in the negative photoconductance in Fig. 3a: as the electron temperature increases, the screening of these scattering centers decreases,⁵⁰ accelerating hot carrier cooling and contributing to nonlinear or saturating behavior in the photocurrent, an observation referred to as negative photoconductance.⁴⁷ A more comprehensive understanding of this mechanism would require precise electrostatic tuning of the graphene doping level via a gate electrode, which is beyond the scope of this study.

The dependence of the photocurrent on applied bias voltage (V_{ch}) on a GOEM was measured at a 67 GHz LO frequency with a laser input power of 107 mW, as shown in Fig. 3c. The photocurrent initially increases linearly with V_{ch} , but deviates from linearity at higher bias voltages. This stems from the origin of the photoresponse, which is solely the result of a change in the device's conductance when exposed to optical power P_{opt} . This cause-consequence chain translates into the mathematical relation $I_{ph} \simeq G_{ph} \frac{\partial I_{ch}}{\partial G_{ch}}$, as long as $G_{ph} \ll$

G_{ch} , a hypothesis that is met in practice. In the above formula, I_{ph} is the photocurrent, I_{ch} stands for channel current, G_{ch} and G_{ph} are the differential channel conductance and photoconductance, respectively. The origin of the above relation appears as a simple derivation chain rule in the limit of vanishing optical power as $\frac{\partial I_{ph}}{\partial P_{opt}} = \frac{\partial I_{ph}}{\partial G_{ch}} \frac{\partial G_{ch}}{\partial P_{opt}}$, and we have $I_{ph} \simeq G_{ph} \frac{\partial I_{ch}}{\partial G_{ch}}$, where $G_{ph} = \frac{\partial G_{ch}}{\partial P_{opt}} P_{opt}$.³² As a result, the transistor nonlinearity, which is encoded in the channel current–voltage (I_{ch} – V_{ch}) characteristic under dark conditions (Supplementary Fig. 5), is reflected in the voltage dependence of the photocurrent (see Supplementary Note 5 for a detailed discussion), which can be written in the explicit form as:

$$I_{ph} \simeq \frac{G_{ph} V_{ch}}{1 - \frac{I_{ch} \partial V_{ch}}{V_{ch} \partial I_{ch}}} \quad (1)$$

The measured data in Fig. 3c are compared to this model's expectations given by Equation 1, in which only the coefficient G_{ph} is used as a fit parameter for the low-bias data. The resulting fit, shown as a green line in Fig. 3c, is in excellent agreement with the measured data, confirming that the observed nonlinearity in the photocurrent as a function of bias voltage arises solely from the DC response of the GOEM.

In mixing mode, no DC bias voltage is applied to the device. Instead, an RF signal with a power of –5 dBm (equivalent to a maximum bias voltage of 0.13 V, which remains within the linear regime) is applied, whereas an optical LO signal is simultaneously directed onto the GOEM, generating a photocurrent. The mixing current (IF signal) can be expressed as described by Hamidouche *et al.*²⁹:

$$I_{mix}(f_{IF}) = \frac{1}{2} G_{ph}(f_{LO}) \cdot V_{RF}(f_{RF}) \quad (2)$$

where V_{RF} denotes the applied RF voltage and $G_{ph} = \frac{\partial I_{ph}}{\partial V_{ch}}$, as described above, represents the first-order differential photoconductance with respect to the bias voltage and additionally

depends on both the optical power and optical frequency (f_{LO}). This term also accounts for the phenomena related to the contact resistance and system impedance mismatch. The factor of $\frac{1}{2}$ arises because the IF frequency (f_{IF}) corresponds to either an up- or downconverted frequency, where $f_{IF} = f_{LO} \pm f_{RF}$. The RF voltage can be expressed in terms of the RF power delivered to the device, considering the combined impedance of the device and the measurement system. By neglecting the reactance in our GOEM, we can model the mixing efficiency as follows:²⁹

$$\frac{P_{IF}}{P_{RF}} = \left(R_0 G_{ph} \frac{R_T}{R_T + 2R_0} \right)^2 \quad (3)$$

where R_T is the total impedance of the device and R_0 is the impedance of the measurement system (our system is adapted to 50 Ω impedance). Figure 3d represents the mixing efficiency of a GOEM with a channel width of 40 μm , length of 2 μm , and total resistance of 90.75 Ω . The device was characterized by an RF signal with a power of $P_{RF} = -5$ dBm and an optical LO signal with $P_{opt} = 107$ mW at $f_{LO} = 67$ GHz. The mixing efficiency data were analyzed using Equation 3, and the first-order G_{ph} was empirically extracted from the linear regime of the photocurrent-DC diagram shown in Fig. 3c. As all the parameters except the RF frequency were held constant during the mixing measurement, G_{ph} remained constant at a value of 94 μS . This analysis yields a mixing efficiency of -53 dB, which is in good agreement with the measured average value of -52.3 dB (indicated in green).

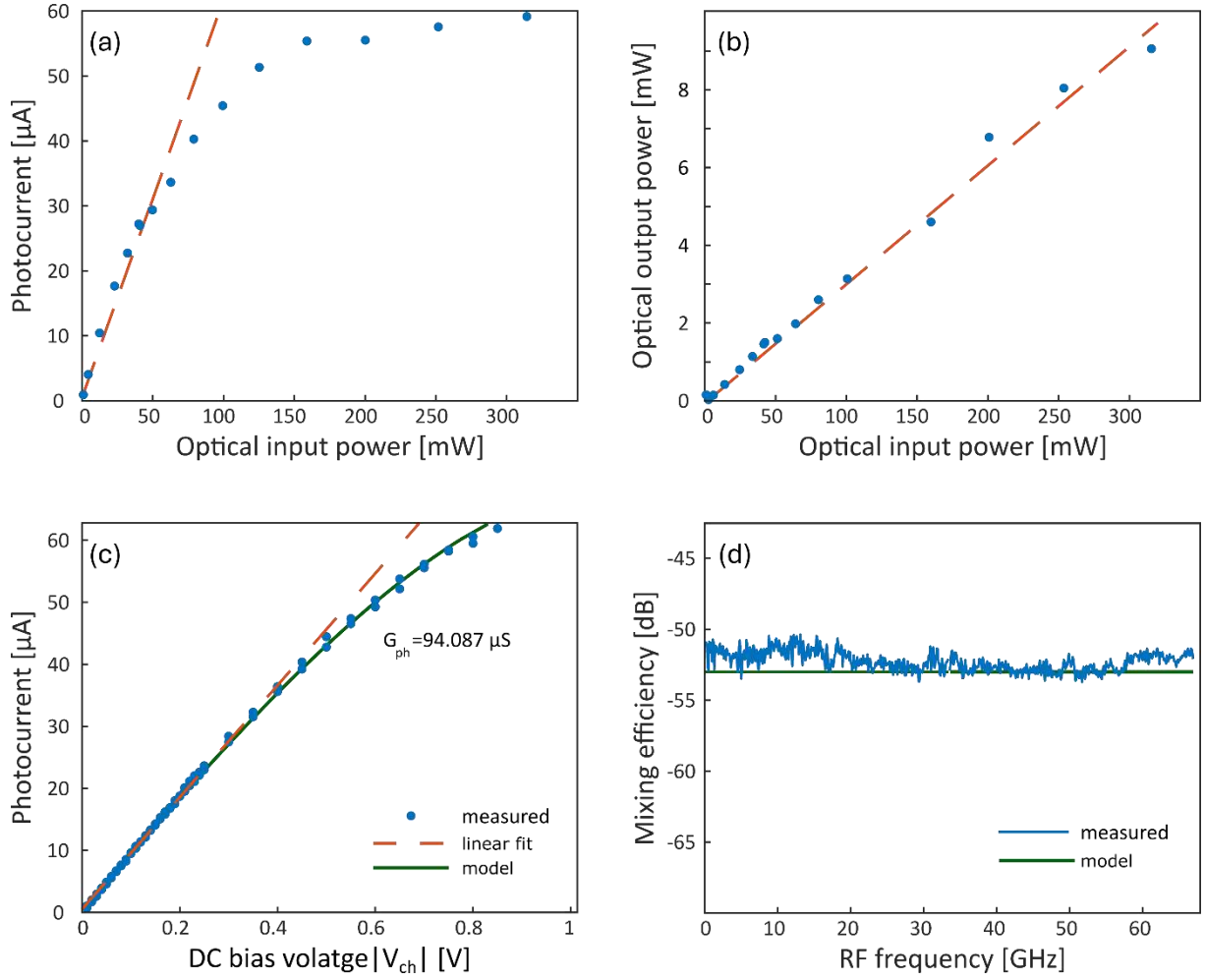


Fig. 3| GOEM optoelectronic characterization. All measurements were taken on a representative device. **a** Photocurrent as a function of laser input power at an applied DC bias voltage of 0.5 V. The photocurrent is averaged over the photodetection bandwidth from DC to 37 GHz. **b** Measurement of input and output optical powers. **c** Photocurrent as a function of the DC bias voltage (V_{ch}). Experimental data are shown as blue points, with the model fit from Equation 1 indicated by a solid green line and the linear fit by an orange dashed line. The linear fit provides first-order photoconductance G_{ph} , from which the mixing efficiency can be calculated via Equation 3. **d** Measured mixing efficiency for $P_{\text{RF}} = -5$ dBm compared with the model value derived from the photodetected power in panel c. Panels c and d were obtained from the same device under identical optical powers $P_{\text{opt}} = 107$ mW and optical frequencies $f_{\text{LO}} = 67$ GHz.

We studied the dependence of mixing efficiency on device geometry by analyzing measurements from 300 devices distributed across the wafer (solid black lines in Fig. 4a, b). As the channel width increases from 10 to 40 μm , the mixing efficiency increases, which is attributed mostly to better impedance matching in wider channels. However, as shown in Fig. 4a and b, increasing the width does not continuously improve the performance. Instead, the mixing efficiency decreases as the width increases from 40 μm to 60 μm , despite the increase in total optical absorption (see Supplementary Fig. 6 and Supplementary Note 6 for photodetected power distribution). This behavior arises from a nonuniform illumination profile across the graphene channel. For a 60 μm -wide channel, the region near the light input experiences higher optical LO power, while the opposite side receives reduced illumination due to optical absorption along the propagation path (Supplementary Note 7). Such spatial nonuniformity in illumination can induce variations in the local channel conductance, which explains the observed decrease in mixing efficiency of GOEMs with channel width larger than 40 μm . This observation indicates the existence of an optimal channel width for maximum efficiency. Additionally, devices with 2 μm -long channels exhibit slightly greater performance than those with 3 μm -long channels. This improvement is due to a reduction in the non-modulated resistance outside the waveguide region. In longer channels, a larger portion of the graphene lies outside the optically active region, acting as parasitic lower resistance channels that lower the effective bias applied across the illuminated section of the graphene channel. Notably, 2 μm -long channels are more sensitive to fabrication errors (particularly the lift-off process for contact electrodes), which leads to greater variation in the performance. Table 1 summarizes the average photodetection and mixing efficiencies for all investigated geometries, together with their standard deviations.

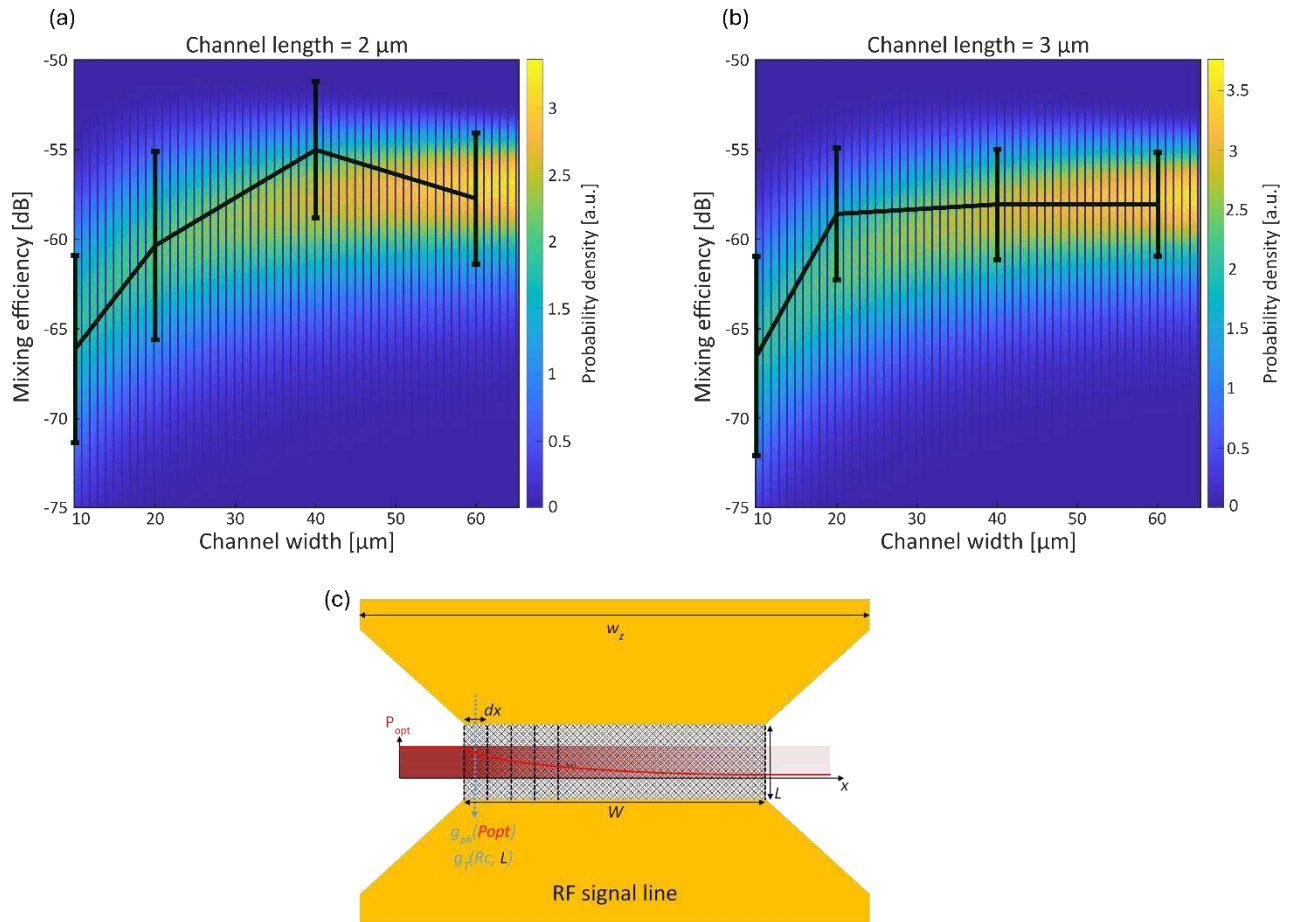


Fig. 4| Statistical performance analysis of GOEMs. **a,b** Mixing efficiencies averaged over the DC–67 GHz bandwidth as a function of channel width for devices with channel lengths of $2\ \mu\text{m}$ (a) and $3\ \mu\text{m}$ (b). The solid black lines indicate the statistical mean, and error bars denote the standard deviation across all measured devices. The background color maps show the corresponding Monte Carlo simulations. The color scale represents the probability density of the mixing efficiency in arbitrary units (each channel width treated independently). **c** Schematic of the distributed model proposed along the channel width.

Table 1. Statistical summary of photodetection power and mixing efficiency as a function of channel geometry. Values correspond to the mean and standard deviation obtained from 300 devices measured across the wafer, highlighting the dependence of performance on channel width and length.

Channel length [μm]	2				3			
Channel width [μm]	10	20	40	60	10	20	40	60
Photodetection [dBm]	-61.7 ± 8.3	-51.2 ± 8.2	-42.1 ± 4.7	-43.6 ± 4.5	-56.5 ± 8.1	-48.7 ± 4.8	-45.8 ± 4.0	-45.3 ± 3.2
Mixing [dB]	-55.1 ± 5.2	-60.3 ± 5.3	-55.0 ± 3.8	-57.7 ± 3.7	-66.5 ± 5.6	-58.6 ± 3.7	-58.0 ± 3.1	-58.0 ± 2.9

To understand the effect of geometry on mixer performance, we propose a distributed model along the width W of the channel, shown in Fig. 4c. We assume that the device is uniform, and its linear conductance per unit width is given by g_T . In g_T , both the length of the channel and the contact resistance are included. Therefore, the total impedance (resistance) of the device can be expressed as $R_T = (g_T \cdot W)^{-1}$. Then, we assume that the differential photoconductance is linear to the optical LO power (although this linearity is not strictly satisfied under experimental conditions). Each segment of the channel width contributes to the total photocurrent through a linear differential photoconductance given by $g_{ph} = \frac{\partial g_{ph}}{\partial P_{opt}} P_{opt}$. The incident optical power (P_{opt}) is assumed to undergo exponential attenuation due to the absorption of the graphene channel, described by $P_{opt}(x) = e^{-x/w_0}$, where x is the coordinate along the width (i.e., waveguide direction), and w_0 is the characteristic absorption width along the waveguide defined as the reciprocal of the absorption coefficient (Supplementary Fig. 7). The total differential photoconductance is subsequently obtained by integrating the photoconductances of each segment across the entire width: $G_{ph} = \int_0^W g_{ph}(P_{opt}(x)) \cdot dx$. Accordingly, for this distributed model, Equation 3 can be rewritten as:

$$\frac{P_{IF}}{P_{RF}} = \left[R_0 \frac{\partial g_{ph}}{\partial P_{opt}} w_0 P_{opt}(0) \left(1 - e^{-\frac{W}{w_0}} \right) \frac{1}{1 + \frac{W}{w_z}} \right]^2 \quad (4)$$

where $w_z = (2R_0 g_T)^{-1}$ represents the characteristic width at which approximate impedance matching is achieved. In the regime where $W \ll w_0$, the efficiency increases quadratically with

channel width, as $\frac{P_{IF}}{P_{RF}} \propto \left[\frac{\frac{W}{w_0}}{1 + \frac{W}{w_z}} \right]^2$. Conversely, for $W \gg w_0$, the efficiency decreases as

$\frac{P_{IF}}{P_{RF}} \propto \left[\frac{1}{1 + \frac{W}{w_z}} \right]^2$. This implies that the mixing efficiency peaks at an intermediate channel width,

balancing optical absorption and impedance matching.

To represent the variability in mixer efficiency shown in Fig. 4 with fluctuations in the total impedance (R_T), which spans nearly an order of magnitude across devices, we employed Monte Carlo simulations to compute the probability density of the mixing efficiency. A fixed optical absorption of 0.077 dB/ μm was assumed for graphene (Supplementary Fig. 2b), along with a Gaussian distribution for R_T centered at 238 Ω with a standard deviation of 147 Ω . The resulting simulated probability density distribution, shown in the background of the statistical curves in Fig. 4a, b, reproduces the experimental trends and exhibits a broad range of channel widths over which the maximum mixing efficiency is expected. However, the precise optimum value depends on the specific impedance matching and optical absorption characteristics of the devices. The experimentally determined optimal channel width is 40 μm , which is well matched to the design of our CPWs, where the signal line width is 60 μm . In contrast, previously reported mixers relied on top illumination via a laser beam, which constrains the graphene channel dimensions by the beam diameter. As a result, design variations are somewhat limited in top-illuminated configurations. Our integrated approach enables optimized device geometries, resulting in significantly higher efficiency observed in our devices.

Conclusion

Herein, we present the fabrication and in-depth study of integrated graphene-based optoelectronic mixers with both state-of-the-art performance and wafer-scale fabrication. More than 90% of the approximately 1000 devices fabricated across the wafer were fully functional, highlighting the scalability and reliability of the graphene processes. The demonstrated mixers achieve results close to those of high-mobility graphene-based mixers^{31,32} and 20 dB above the state-of-the-art mixing efficiency of a graphene-based OEM with a wafer-scale fabrication process³⁰. Our results pave the way for further exploration of graphene in practical optoelectronic applications, offering new avenues for high-speed, energy-efficient, and highly integrated devices.

Methods

Device fabrication

Device fabrication was carried out on a 150 mm SOI wafer (Soitec), featuring a 220 nm top silicon device layer, a 3 μm buried oxide, and a 675 μm handle wafer. The wafer was laser-diced to 150 mm format for processing at the AMO facility. Si waveguides were patterned using optical lithography with a Canon FPA-3000 i5+ stepper, followed by RIE using an Oxford Instruments Plasmalab-100 system. Grating couplers were defined using electron-beam lithography (Raith EBPG 5200) and etched via RIE. Graphene layer was transferred on top of the photonic layer via a wafer-scale wet-transfer technique by using PMMA (950K A6) as a support film. Metal contacts, consisting of 5 nm Ti and 65 nm Au, were deposited using an FHR Star 200 EVA e-beam evaporator and patterned via a lift-off process. Conformal Al_2O_3 layers were deposited both below (10 nm) and above (400 nm) the graphene monolayer using a

combination of water-based and plasma-based ALD techniques on an Oxford Instruments FlexAL system. Finally, the vias were opened through the Al₂O₃ encapsulation layer with use of optical lithography and RIE to reach the contact pads.

Structural device analysis

Optical microscopy was performed using a Keyence VK-X3000 laser scanning microscope, and scanning electron microscopy (SEM) was carried out with a Zeiss Supra 60VP system. The waveguide height and grating coupler profiles were characterized by atomic force microscopy (AFM) in tapping mode using a Bruker Dimension Icon system. Raman spectroscopy was conducted in mapping mode with a Horiba system, employing a 532 nm excitation laser at 1 mW power.

Optoelectronic measurement

All measurements were performed under ambient conditions. The experimental setup (Supplementary Fig. 8) employs a continuous-wave laser operating at 1550 nm (Amonics, Lightwave converter) modulated by a Mach–Zehnder modulator (Photline, MXAN-LN-40), driven by a sinusoidal electrical signal. The modulated optical signal is then directed to our mixer as the local oscillator (LO). The maximum optical frequency that our setup can probe is 67 GHz. This modulated beam is then amplified via an erbium-doped fiber amplifier (Lumibirds, CEFA-C-PB-HP) and coupled into the waveguide through grating couplers. A commercial photodiode (Thorlabs, PM100D) also measures the outcoupled light from the other end of the waveguide to monitor the fiber alignment and measure the losses of each waveguide-integrated GOEM. The CPW contact electrodes are connected to the Rohde & Schwarz (ZVA67) vector network analyzer (VNA) through two high-frequency RF probes (GSGs). The VNA also facilitates the measurement of DC currents and voltages via a

source-measure unit. The probes are connected to bias tees to decouple the DC from AC electrical signals, enabling the application of bias voltages while injecting and measuring high-frequency signals.

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Author contributions

S.P. and D.P. contributed equally to this work. S.P. designed and fabricated the devices and performed the initial characterization. D.P. performed the RF measurements and analyzed the data with the help of S.P. and E.B. E.B. developed the theoretical model. S.P. wrote the text with the help of D.P. and input from all authors. M.L., S.S., and P.L. supervised the project. All authors contributed to the discussions and reviewed the manuscript.

Competing interests

The authors declare no competing interests.

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