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Mid-infrared integrated resonators on a III–V platform with Q-factors beyond half a million ^{EP}

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Mid-infrared integrated resonators on a III-V platform with Q-factors beyond half a million

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ABSTRACT

We demonstrate mid-IR integrated race-track resonators on a III-V semiconductor platform: InGaAs core epitaxially grown on InP. We have performed a complete characterization of the optical propagation losses at $\lambda = 4.6 \mu\text{m}$ and $\lambda = 8.5 \mu\text{m}$, two representative wavelengths for the first and second atmospheric transparency windows, respectively. We measured losses of $\alpha \sim 1 \text{ dB/cm}$ (TE polarization) and $\alpha \sim 1.3 \text{ dB/cm}$ (TM polarization) at $8.5 \mu\text{m}$. Substantially lower losses $\alpha \sim 0.3 \text{ dB/cm}$ were measured at $\lambda = 4.6 \mu\text{m}$ (TM polarization). We then implemented racetrack resonators with straight evanescent couplers. We obtained loaded quality factors larger than 600 000 at $\lambda = 4.6 \mu\text{m}$. These results are promising toward the development of non-linear mid-IR integrated devices with Q factors beyond 10^6 , where the onset of stimulated parametric processes could be reachable.

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I. INTRODUCTION

The invention and development of the frequency comb has opened a vast range of possibilities in several application domains.¹ In the VIS/NIR (visible, near-infrared) spectral ranges, such technology has led to radical advances in metrology and spectroscopy.² In the mid-infrared (mid-IR, $3 \mu\text{m} < \lambda < 30 \mu\text{m}$) spectral range, dual-comb spectroscopy has become a particularly valuable technique. One major advantage is the possibility to acquire broadband spectra at much faster speeds than conventional FTIR spectrometers (hundreds of us instead of tens of seconds).^{3,4}

Frequency combs are traditionally generated via mode-locked lasers. When the phases are all equal, an amplitude modulated comb is produced (TiSa, for instance)⁵ and pulses are generated. If the phases are locked, but not equal, it is possible to obtain frequency modulated (FM) combs. FM combs are typically favored in lasers with upper state lifetimes shorter than the photon lifetime, such as quantum cascade lasers (QCL). As a matter of fact, QCL-based FM combs have recently seen an intense development.^{6–9}

About 15 years ago, an alternative strategy to generate frequency combs was discovered, based on the Kerr effect in very high Q-resonators.^{10,11} They offer broader spectral coverage, higher coherence, and lower phase noise than QCL combs. Now referred to

as “Kerr combs,” it relies on the interaction between a continuous-wave pump laser with a monolithic high-Q resonator and it exploits the onset of four-wave-mixing (FWM) gain under specific conditions. The discovery enabled the development of integrated micro-comb sources at telecom wavelengths.¹² Integrated photonics circuits (PICs) offer major advantages by guiding light through on-chip waveguides instead of using bulky lenses and mirrors; it enables much smaller and more compact systems where integrated components are permanently aligned, which provides greater stability and reliability compared to free-space setups that are sensitive to vibrations and temperature changes. In addition, PICs can be mass-produced at low cost using semiconductor fabrication processes and can be easily co-integrated with electronics, allowing fast, efficient, and highly scalable optical systems. With the current trend to develop PICs in the MIR, pushed by spectroscopy and trace-gas sensing applications, it is natural to try and develop integrated micro-combs operating at long infrared wavelengths.

A high Q factor resonator is one of the big key elements to have in Kerr combs. Indeed, the minimum pump power threshold for parametric gain is inversely proportional to the square of the resonator total Q-factor (Q_{tot}), where it is inversely proportional to the non-linear index of refraction (n_2).¹⁰

For this reason, the community is devoting a vast, coordinated effort to explore, and optimize, material platforms for very low waveguide losses and elevated n_2 . Although the Kerr non-linear coefficient n_2 has not been extensively characterized at longer wavelengths ($\lambda > 3 \mu\text{m}$), recent studies indicate that a range of materials, including SiGe, Ge, III-V compounds, and chalcogenides, exhibit comparable n_2 values on the order of $1\text{--}2 \times 10^{-17} \text{ m}^2/\text{W}$.^{17a,18a,18b} This suggests that these materials can all provide significant optical nonlinearity for integrated mid-infrared photonic applications. To this day, losses in the (sub)-dB/cm range have been reported in SiGe-on-Si,¹³ graded SiGe on Si,¹⁴ and in III-V materials (InGaAs/InP^{15,16,20}). Studies on fiber-based^{17b} and in-plane deposited^{17c} chalcogenide materials showed very low loss propagation losses (sub dB/m). As per Q-factors, mid-IR resonators have been reported in III-V platforms with Q-factors of more than a few hundred thousand,^{15,20} in an Si platform with one million Q-factors,²³ and at short mid-IR wavelengths in chalcogenides with several tens of millions Qs.^{17b} Although chalcogenide glasses offer a unique transparency advantage in the mid-IR, they also present limitations compared to semiconductor platforms for PICs. Their low thermal conductivity and environmental instability lead to performance degradation under high optical power injection, making futures-based devices more fragile and harder to package. Silicon-based platforms offer significant advantages in terms of cost due to mature and highly scalable fabrication processes, and they are fully compatible with CMOS technologies, making them attractive for large-scale manufacturing and integration with electronic circuitry. However, integrating active devices on silicon often requires hybrid integration or transfer printing, which can be challenging. In contrast, III-V semiconductors platforms can more easily incorporate active components in the mid-infrared, such as sources, detectors, and modulators in mature processing and a highly scalable fabrication process.

In this letter, we report mid-IR low-loss waveguides and race-track resonators in a metal-organic vapor-phase epitaxy (MOVPE)-grown lattice-matched $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ -on-InP materials platform with measured high Q-factors exceeding 600 000 (corresponding to intrinsic Qs exceeding 700 000) at $\lambda = 4.6 \mu\text{m}$. The result is corroborated by a full characterization of the optical propagation losses in this system at representative wavelengths in the two atmospheric windows (4.6 and $8.5 \mu\text{m}$). Our findings suggest that the $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ -on-InP platform is a promising system to demonstrate mid-IR Kerr combs, with eventual full integration with active components, such as quantum cascade lasers and quantum cascade detectors.

II. WAVEGUIDE LOSS

The device wafer was grown in a MOVPE reactor on a Fe-doped InP substrate, also acting as waveguide bottom cladding. A $3.5 \mu\text{m}$ thick InGaAs layer was grown as a waveguide core on top of the Fe-InP substrate, and a $1.3 \mu\text{m}$ non-intentionally doped InP top layer acts as waveguide top cladding.

A. Waveguide design and fabrication

The design of the waveguides was created to achieve single-mode operation for both TE and TM polarizations at $\lambda = 8.5 \mu\text{m}$. Finite difference eigenmode (FDE) simulations were used to obtain the mode effective indices and the final ridge width was fixed to $6 \mu\text{m}$. Adiabatic tapers that are $20 \mu\text{m}$ -wide and $750 \mu\text{m}$ -long were designed using eigenmode expansion (EME) simulations for optimized mid-IR light injection and collection. The minimum bending radius was set to $700 \mu\text{m}$ to avoid radiation losses in the bent sections. To ease the experimental alignment and measurement procedures, the input-output facets of each spiral were offset by 3 mm . Details on the waveguide, tapers and bending losses can be found in [supplementary material](#).

To assess the performances of our InP platform, we performed loss measurements on dielectric waveguides using spiral waveguides of different lengths (1.8, 3.8, and 5.6 cm , each repeated 3 times on the same chip). A top view optical microscope image of the final fabricated sample is shown in [Fig. 1\(b\)](#). The sample fabrication starts with deposition of a Si_xN_y hard-mask by plasma-enhanced chemical vapor deposition (PECVD). Subsequently, the waveguides are defined with electron-beam lithography (EBL) and the pattern is transferred to the hard-mask with reactive ion etching (RIE). The semiconductor stack is etched using inductively coupled plasma RIE (ICP-RIE) based on HBr/O_2 chemistry. Finally, the Si_xN_y hard-mask is removed in pure hydrofluoric acid. The sample is then cleaved to obtain clean facets on both input and output (reducing the final length by $\approx 0.1 \text{ cm}$). [Figure 1\(a\)](#) shows a scanning electron microscope (SEM) image of the waveguide cross section with the calculated electric field intensity profile of the fundamental TM_{00} mode overlaid on it.

B. Loss measurements and results

The waveguide loss measurements were performed using two continuous wave distributed feedback quantum cascade lasers (DFB-QCL) emitting at $\lambda = 8.5 \mu\text{m}$ and $\lambda = 4.6 \mu\text{m}$, respectively. The emission wavelength was tuned by finely changing the laser driving current. The transmission spectrum of each waveguide was recorded

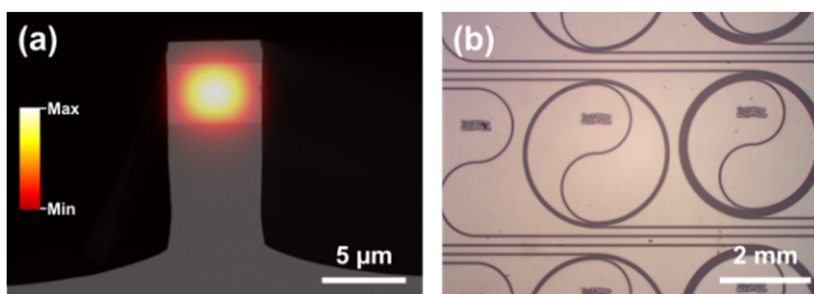


FIG. 1. Profile and geometry of the spiral waveguides. (a) SEM image of the etched waveguide profile, overlaid with the simulated electric field intensity profile of the fundamental TM_{00} mode at a $8.5 \mu\text{m}$ wavelength. (b) Optical microscope image (top view) of the spiral waveguides with varying lengths.

using a liquid nitrogen-cooled mercury cadmium telluride (MCT) detector and a lock-in amplifier. The setup is shown in Fig. S1, and the details are available in the [supplementary material](#).

The waveguide losses were inferred using the method described in Ref. 19. The waveguide transmission as a function of the laser emission wavelength presents Fabry–Perot (FP) oscillations stemming from the cavity induced by the cleaved facets. A typical FP spectrum measured around $\lambda = 8.5 \mu\text{m}$ is shown in the insets of Figs. 2(a) and 2(b) for the shortest spiral in both TM and TE polarization, respectively. The waveguide losses can be related to FP maxima, minima, and facet reflectivity through the following equation:

$$\alpha = -\frac{1}{L} \ln \left(\frac{1}{R} \frac{\sqrt{r}-1}{\sqrt{r}+1} \right), \quad (1)$$

where $r = \frac{I_{\text{max}}}{I_{\text{min}}}$ is the ratio between the maxima and minima of the FP oscillations and $R = \sqrt{R_1 R_2}$ (with R_1 and R_2 being the reflectivity of each facet). An equivalent way to express Eq. (1) is

$$\ln \left(\frac{\sqrt{r}-1}{\sqrt{r}+1} \right) = -\alpha L - \ln \left(\frac{1}{R} \right). \quad (2)$$

Having measured the FP oscillations for spirals with different lengths, the quantity $\ln \left(\frac{\sqrt{r}-1}{\sqrt{r}+1} \right)$ is known and can be plot as function of the waveguide length according to Eq. (2). A linear curve is obtained from the plot, whose slope is α , the loss per unit length. The intercept with y axis yields the facet reflectivity. This

method is more reliable than estimating α from a single FP transmission spectrum using Eq. (1). The reason is that it *directly measures* the facet reflectivity and avoids assuming a value, usually calculated with numerical simulations. The mean and standard deviation of the fringe contrast for each spiral was measured at $\lambda = 8.5 \mu\text{m}$ and used to perform a linear fit with Eq. (2). As a result of the first run of measurements, and following an additional HF deoxidation, we obtained $\alpha = (1.3 \pm 0.05) \text{ dB/cm}$ for TM and $(1.04 \pm 0.04) \text{ dB/cm}$ for TE polarization [see Figs. 2(a) and 2(b)]. These results validate ICP-etched InP-based semiconductor platform as a valid low-loss system for mid-IR PICs. Note that judicious deoxidation steps play a crucial role in reducing the waveguide losses, especially for TE polarization, which exhibits the highest overlap with the waveguide sidewalls.

The same measurements were performed at $\lambda = 4.6 \mu\text{m}$. However, because the waveguides were designed for single mode operation at $8.5 \mu\text{m}$, they are multimode at shorter wavelengths. As a consequence, depending on the position of the laser beam on the input taper ridge, multiple mode excitation is possible. Whenever multiple modes are excited, we consistently see smaller mean values of the fringe contrast with respect to single mode excitation (the multimode operation was clearly visible on the mid-IR camera when looking at the mode profile at the output facet of the waveguide). To account for this effect, different loss values were calculated with Eq. (1) for the shortest spiral at $4.6 \mu\text{m}$. Figure 2(c) shows that the loss values range from a minimum of 0.3 dB/cm (when the fringe contrast is the highest) to a maximum of 1 dB/cm , depending on the excitation condition. In the same graph, the value measured at

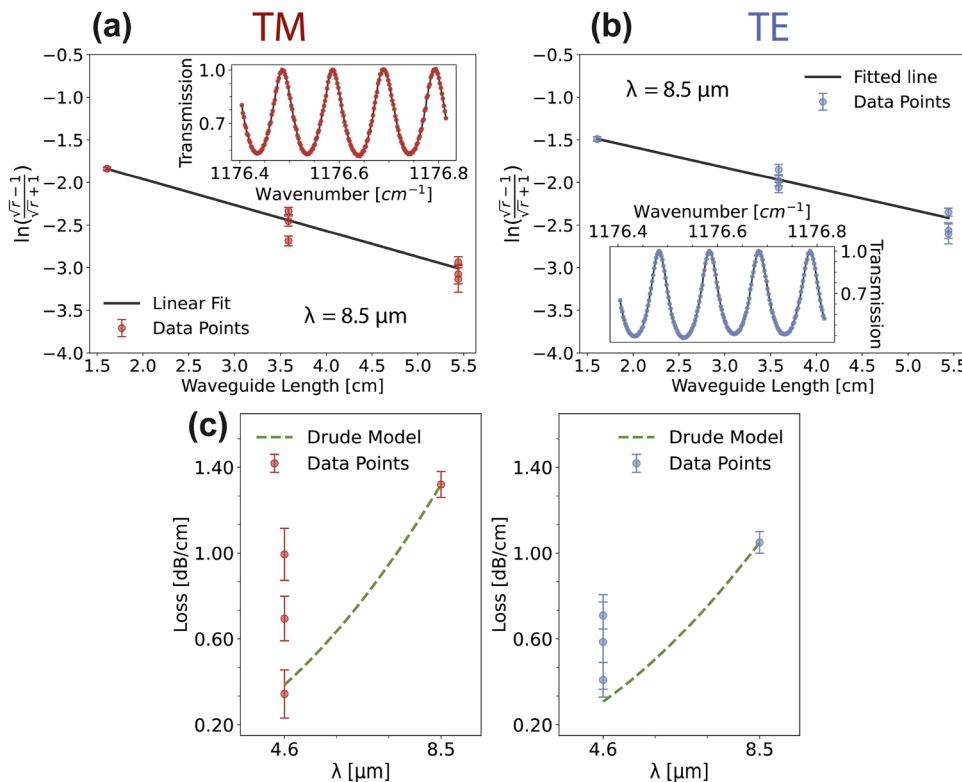


FIG. 2. Propagation loss analysis of the fabricated waveguides. (a) Plot of $\ln \left(\frac{\sqrt{r}-1}{\sqrt{r}+1} \right)$ as a function of waveguide length for three different lengths in TM polarization at a $8.5 \mu\text{m}$ wavelength. The linear fit (solid black line) yields $\alpha = 1.33 \pm 0.05 \text{ dB/cm}$ and $R = 0.26 \pm 0.02$. The inset shows a typical transmission spectrum with Fabry–Perot oscillations. (b) Same analysis as (a) for TE polarization, yielding $\alpha = 1.06 \pm 0.06 \text{ dB/cm}$ and $R = 0.33 \pm 0.01$. Different data points are associated with different spirals. (c) Comparison of measured loss values at a wavelength of 8.5 and $4.6 \mu\text{m}$ for TM (left) and TE (right) polarization. The dashed curve represents the predicted loss change, based on the $8.5 \mu\text{m}$ loss value, considering free carrier absorption as the main source of losses. Variability in the estimated loss value at $4.6 \mu\text{m}$ is ascribed to waveguide multimode operation. Very low losses, down to 0.3 dB/cm , are predicted at $\lambda = 4.6 \mu\text{m}$.

8.5 μm is also shown. Considering free carrier absorption as the primary source of losses in our platform, a simple Drude model can provide an estimate of the expected losses at 4.6 μm . The calculated trend [green dashed line shown in Fig. 2(c)] is ~ 0.3 dB/cm, aligning more closely with the minimum losses (corresponding to single-mode operation) measured rather than the maximum losses.

An alternative way to gauge the losses is to estimate the intrinsic quality factor ($Q_{\text{intrinsic}}$) of resonators. This quantity is directly linked to the propagation losses (losses per unit length) through the following equation:^{15,19}

$$Q_{\text{intrinsic}} = \frac{2\pi n_g}{\alpha \lambda}, \quad (3)$$

where n_g is the mode group index estimated to be $n_g \approx 3.5$ from FDE simulations of the current geometry and α is the power loss in cm^{-1} . Furthermore, losses as low as 0.3 dB/cm, at $\lambda = 4.6$ μm , yield a $Q_{\text{intrinsic}}$ value well beyond 500k. To the best of our knowledge, the highest $Q_{\text{intrinsic}}$ measured on an InP platform in the mid-IR is 175,000 at $\lambda = 5.2$ μm ,²⁰ corresponding to $\alpha = 1.17$ dB/cm. This was a further motivation to design and measure racetrack resonators and test them at both $\lambda = 8.5$ μm and $\lambda = 4.6$ μm in our semiconductor platform.

III. HIGH-QUALITY FACTOR RACETRACK RESONATORS

As mentioned above, an alternative way to generate frequency combs involves pumping high-Q optical resonators with embedded Kerr nonlinearities using a continuous-wave laser. An efficient way to model these systems relies on the Lugiato-Lefever equation (LLE),²¹ which is a form of non-linear Schrödinger equation. This approach models the dynamics of the total intracavity field and permits to infer a simple, closed-form formula for the minimum power needed to achieve parametric gain, as developed in Ref. 10,

$$P_{\min} = 2\pi a \frac{\omega_L^2}{8\gamma v_g^2} \frac{Q_{\text{ext},t}}{Q_{\text{tot}}^3} = 2\pi a \frac{\omega_L^2}{8v_g^2} \frac{cA_{\text{eff}}}{\omega_0 n_2} \frac{Q_{\text{ext},t}}{Q_{\text{tot}}^3}, \quad (4)$$

where a is the resonator radius, ω_L is the input laser frequency, ω_0 is the cavity mode frequency, Q_{ext} is the coupling Q-factor, Q_{tot} is the total Q-factor, A_{eff} is the effective surface of the waveguided mode, and n_2 is the Kerr non-linear index. While a numerical study of the LLE is necessary to optimize a micro-comb device, this formula permits to rapidly grasp the crucial parameters that need to be considered: (i) Q factor, as $P_{\min}$ scales as $1/Q^2$; (ii) effective volume ($A_{\text{eff}} \cdot 2\pi a$); and (iii) non-linear index. We have, therefore, implemented racetrack resonators not only to precisely measure the waveguide losses but also to gauge the potential of our material platform for mid-IR frequency comb generation.

A. Design strategies

Racetrack resonators were designed and optimized to operate at $\lambda = 8.5$ μm . The bus and the resonator waveguide ridge width were set to 6 μm , similarly to the spirals described in Sec. II A. The bus waveguide is shorter than the spiral waveguides, with a total nominal length of ≈ 8 mm. FDTD simulations were performed to estimate the minimum bending radius that would make radiation and mode mismatch losses in the bent sections negligible. We found a minimum radius of 300 μm , hence we set it to 350 μm . The design of the coupler [Fig. 3(a)] was performed by combining coupled mode theory (CMT)²² and FDE simulations, where gaps and coupling lengths L_c were tailored to achieve different coupling regimes. To assess the impact of the platform losses on the estimated L_c , a range of propagation losses between 1.87 and 0.87 dB/cm was considered. To improve accuracy, the calculation is performed assuming a 4.8 μm deep etch in the gap, simulating the profile obtained from previous etching recipe optimizations. The final result is presented in Fig. 3(b), where the discrepancy in L_c between TM and TE polarizations is ascribed to stronger mode coupling in TM because of

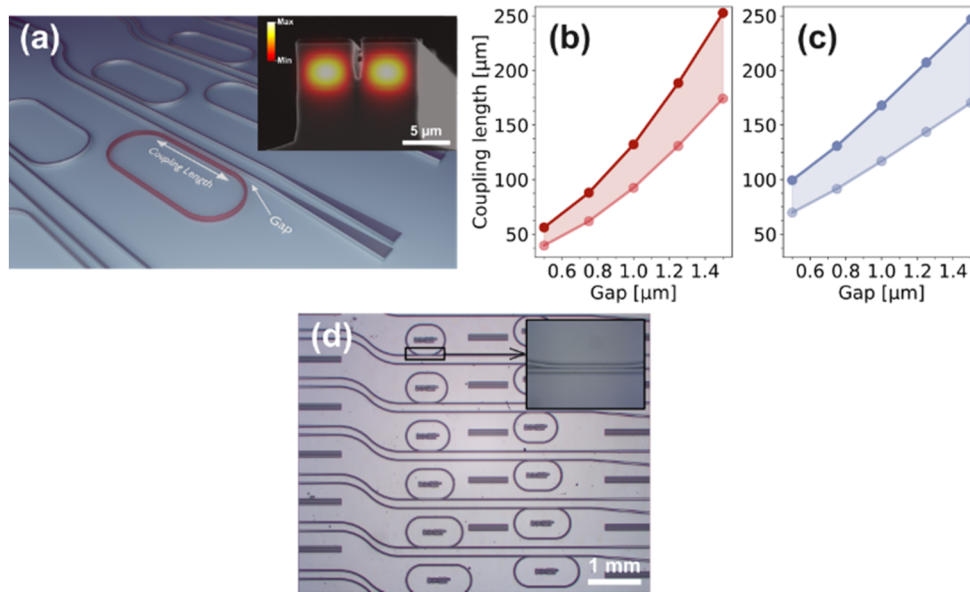


FIG. 3. Design and geometry of the racetrack resonators. (a) Schematics of the resonators. The inset shows a cross-section SEM image of the region between the racetrack and the bus waveguide, overlaid with the TM super-mode electric field profile. (b) Calculated critical coupling lengths as a function of the gap between the racetrack and the bus waveguide for the TM fundamental mode. Two loss values are considered: 1.87 dB/cm and 0.87 dB/cm. (c) Same as panel (b), but for the TE fundamental mode. (d) Optical microscope image (top view) of the chip with resonators of varying sizes and coupling lengths. The inset is a close-up of the coupling region.

a lower confinement factor with respect to TE polarization. Coupling lengths in the (100–1000) μm range were selected for the final fabrication to span all the coupling regimes (critical-, under-, and over-coupling). The gap is fixed to 1 μm due to limitations imposed by the fabrication process. The bus waveguide geometry is the same as the one in Sec. II B. However, the output facet of odd-numbered waveguides is tilted by 5° : this reduces the reflectivity (see Fig. S3 in the [supplementary material](#)) and reduces the amplitude of the Fabry–Pérot oscillations, simplifying the analysis of the racetrack resonators resonances.

The inset of Fig. 3(a) displays an SEM image of the coupling section right before the hard mask removal step. The etching penetrates only partially in the gap, leaving 30% of the core layer unetched. This yields a stronger mode coupling, thus modifying the critical coupling condition (L_c should be shorter). A top view image of the sample is shown in Fig. 3(d).

B. Q factors at 4.6 and 8.5 μm wavelengths

Figure 4 reports the measurements of the loaded Q-factors of the racetrack resonators at 4.6 μm wavelength, obtained via transmission measurements of waveguides coupled to racetrack resonators, in TM (upper panels) and TE (lower panels) polarizations. The measurements were performed as above, by spectrally tuning the emission of a commercial DFB QC laser with the injection current. The current-wavelength correspondence was initially calibrated using a Fourier transform infrared (FTIR) spectrometers. Panel (a) shows a relatively large spectral scan: sample and background signals are reported and a narrow resonance (circled in dashed) is evident. Panel (b) is a high-resolution close-up of the resonance: the FWHM is only 101 MHz, which translates in a loaded Q-factor (Q_{tot}) of 6.4×10^5 .

Using the standard formula $Q_{\text{intrinsic}} = (2 * Q_{\text{tot}}) / (1 \pm \sqrt{T})$, where T is the transmission at resonance (and assuming under-coupling operation), we obtain an intrinsic Q-factor ($Q_{\text{intrinsic}}$) of 7.4×10^5 . This is a record-high value for high Q-factor resonators in a III–V semiconductor platform, and furthermore, it corresponds to waveguide losses of 0.24 dB/cm, in full agreement with the measurements performed with the Fabry–Pérot method (see Fig. 2).

Panels (c) and (d) report the same measurements, albeit in TE polarization. We obtain a Q_{load} value of 2.1×10^5 , with an estimated $Q_{\text{intrinsic}}$ of 2.4×10^5 . These lower Q-factors could stem from the relatively shallow etch of the gap between access waveguide and racetrack resonator that add scattering losses [Fig. 3(a), inset]. Because of the multimode operation at such a short wavelength, this effect may be more pronounced for the TE polarization due to the higher overlap with the waveguide sidewalls. This effect of partial etching on the Q-factor has also been observed in SiGe on the Si platform.²³

While the core result of the work is the record-high Q-factor at $\lambda = 4.6 \mu\text{m}$, we also performed Q-factor measurements at 8.5 μm wavelength; Fig. 5 shows the normalized transmissions, in TM and TE polarizations, around a racetrack resonator resonance. Intrinsic Q-factors of 85,000 (54,000) in TM (TE) polarization, respectively, are observed. These lower values with respect to what is obtained at shorter wavelengths are in agreement with previous findings in the literature:^{15,24} the waveguide losses dramatically increase moving from the 4 μm to the 9 μm region. This result also suggests that our devices are most probably limited by free-carrier absorption, leaving ample opportunities for further Q-factor improvement by working on the material quality. For instance, the background doping—and, therefore, the propagation losses—could be further reduced by iron-doping the semiconductor material during the epitaxy.^{15,16}

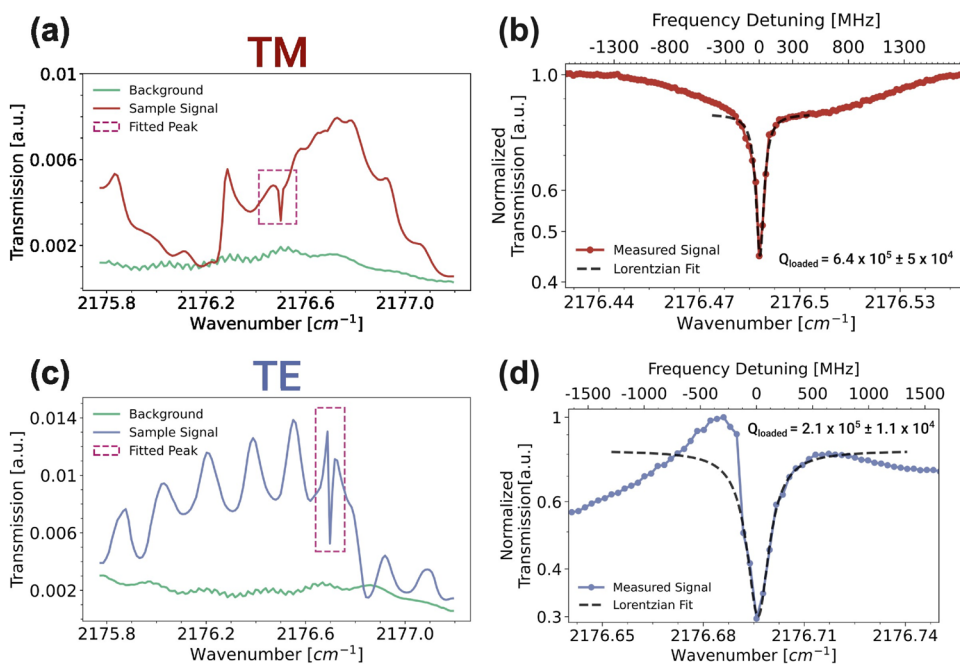


FIG. 4. Experimental transmission spectra at $\lambda = 4.6 \mu\text{m}$ —via the bus waveguide—of a racetrack resonator with $L_c = 100 \mu\text{m}$. (a) Transmission spectrum (red curve) in TM polarization, showing a single resonance within the measurement span (limited by the DFB laser tuning range). The green curve represents the reference signal, measured without the sample. (b) Close-up of the resonance highlighted by the dashed rectangular region in panel (a). The normalized transmission spectrum (signal/reference) is shown. The black dashed curve is a Lorentzian fit, yielding a record-high Q_{loaded} of 6.4×10^5 and an estimated $Q_{\text{intrinsic}}$ of 7.4×10^5 , assuming an undercoupling operating regime. The top horizontal axis corresponds to the frequency detuning with respect to resonance center. Panels (c) and (d) are the same as panels (a) and (b) but in TE polarization. The measured Q_{loaded} value is 2.1×10^5 , with an estimated $Q_{\text{intrinsic}}$ of 2.4×10^5 .

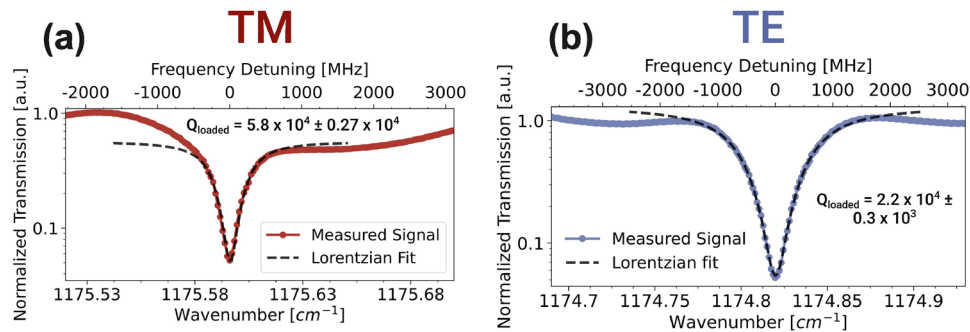


FIG. 5. Experimental normalized transmission at $\lambda = 8.5 \mu\text{m}$ of the racetrack resonators. (a) Normalized transmission of a TM resonance (close-up view), with a Lorentzian fit (black dashed curve), yielding $Q_{\text{loaded}} = 5.8 \times 10^4$ and $Q_{\text{intrinsic}} = 8.5 \times 10^4$, assuming an undercoupling operating regime. (b) Normalized transmission of a TE resonance (close-up view) for a different racetrack resonator, yielding $Q_{\text{loaded}} = 2.2 \times 10^4$ and $Q_{\text{intrinsic}} = 5.4 \times 10^4$, assuming an over-coupling operating regime.

IV. CONCLUSIONS/PERSPECTIVES

We have demonstrated mid-IR integrated race-track resonators in the InGaAs-on-InP semiconductor platform with measured quality factors larger than 600 000 at a wavelength of $4.6 \mu\text{m}$. In addition, we have performed a full characterization of the optical propagation losses in this system at two representative wavelengths for the first and second atmospheric transparency windows (4.6 and $8.5 \mu\text{m}$).

These results open realistic vistas for the development of integrated mid-IR devices based on InGaAs-on-InP where the onset of stimulated parametric processes could be reachable, with the long-term goal of demonstrating Kerr micro-combs in the first atmospheric window ($3\text{--}5 \mu\text{m}$). The next crucial steps to achieve this ambitious goal are (i) achieving Q-factors beyond one million and (ii) carefully engineering the waveguide dispersion in the proper parameter range for soliton generation. Plugging these values into formula (4) yields parametric threshold values at less than 50 mW of intracavity power, which are achievable, for instance, using commercial CW DFB QC lasers.

SUPPLEMENTARY MATERIAL

The supplementary material provides (I) experimental transmission setup, (II) modal reflectivity simulation, (III) Fabry–Perot measurement at $4.6 \mu\text{m}$ wavelength, (IV) considerations on the origin of the propagation losses, (V) measurements of the resonator free spectral range (FSR), (VI) Q factor scatterplots, and (VII) group velocity dispersion calculations.

ACKNOWLEDGMENTS

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

L. Lucia: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **G. L. Ngo:** Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **M. Urbain:** Data curation (equal); Investigation (equal); Validation (equal); Visualization (equal). **S. Pirotta:** Investigation (equal); Methodology (equal); Resources (equal); Validation (equal); Writing – review & editing (equal). **K. Pantzas:** Resources (supporting). **G. Beaudoin:** Investigation (equal); Methodology (equal); Resources (equal); Validation (equal); Writing – review & editing (equal). **J. M. Manceau:** Data curation (equal); Methodology (equal); Resources (equal); Validation (equal); Writing – review & editing (equal). **I. Sagnes:** Investigation (equal); Resources (equal). **R. Colombelli:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Resources (equal); Supervision (equal); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **A. Bousseksou:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Project administration (equal); Resources (equal); Supervision (equal); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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