Octave-spanning low-loss mid-IR waveguides based on semiconductor-loaded plasmonics

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Abstract: Plasmonic waveguides are crucial building blocks for integrated on-chip mid-infrared (mid-IR) sensors, which have recently attracted great interest as a sensing platform to target enhanced molecular sensing. However, while hosting a wide range of applications from spectroscopy to telecommunication, the mid-IR lacks suitable broadband solutions that provide monolithic integration with III-V materials. This work reports a novel concept based on hybrid semiconductor-metal surface plasmon polariton waveguides, which result in experimentally demonstrated low loss and broadband devices. Composed of a thin germanium slab on top of a gold layer, the waveguiding properties can be directly controlled by changing the geometrical parameters. The measured losses of our devices are as low as 6.73 dB/mm at 9.12 µm and remain <15 dB/mm in the mid-IR range of 5.6–11.2 µm. The octave-spanning capability of the waveguides makes them ideal candidates for combination with broadband mid-IR quantum cascade laser frequency combs and integrated spectroscopic sensors.

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1. Introduction

Scientific progress and development are a constant source of novelties comforting and easing our life. It has brought us sensors for measuring, monitoring, and controlling countless quantities to significantly increase the quality and convenience of our everyday lives. This includes small and compact portable devices for medical diagnostics of severe diseases [1–4], handheld sensors for sensitive on-site detection of (greenhouse) gases [5–7] and liquids [8], as well as consumer-oriented security applications, e.g., in wearables [9]. It is also true for large and highly complex detection systems, e.g., being used in radio-astronomy [10]. The listed applications all share the common basic concept of being dependent on optical detection schemes and the need to access the mid-infrared (mid-IR) to THz spectral range to unlock their full potential. This region is the so-called fingerprint region, where many molecules have their fundamental absorptions [11,12]. When analyzing and comparing the sensor performance for various settings in molecule detection, several figures-of-merit can be evaluated, including (i) sensitivity and specificity, (ii) robustness and versatility as well as (iii) compactness and compatibility with existing concepts and with target analytes (e.g., when in direct contact to the sensor). While successfully addressing individual elements of this list results in high-performance sensors, novel disruptive approaches are typically marked by significant progress in multiple of those figures-of-merit. Hereby, recent examples for the latter can be divided into three groups: (i) device and instrument-based improvements, e.g. the realization of (novel) high-performance mid-IR laser sources, i.e. quantum cascade laser (QCL) [13–15] and interband cascade laser
[15,16], (ii) new (spectroscopic) concepts, e.g. QEPAS [11], BICAPS [17] and others [18] for gases and Mach-Zehnder interferometers [19] or balanced detection paired with external-cavity quantum cascade lasers (EC-QCLs) [20] for liquids [21], and (iii) a mixture of (i) and (ii), e.g. QCL-based frequency comb spectroscopy [22–25] (significant improvements on the device and measurement concept level). In this context, the realization of sensors relying on plasmonic structures at Vis/near-IR wavelengths implemented into semiconductor-based systems is another of such disruptive approaches [26,27]. It results in a new class of spectroscopic devices that tick all the above-mentioned boxes. The only step missing for a wide use e.g., in molecule spectroscopy, was finally taken by just recently extending this approach to mid-IR frequencies by first proof-of-concept experiments [8,27]. In this paper, we can further significantly extend this approach by showing the first realization of novel low-loss and broadband mid-IR waveguides based on hybrid semiconductor-loaded surface plasmon polariton (SLSPPs) cavities. They cover the entire long-wave infrared (LWIR) spectral range between $\sim 5.6$–$11.2 \mu m$ (broadband), with total experimental losses as low as $\sim 5.0$ dB/mm to 14.1 dB/mm (low-loss) when using the best geometry for each wavelength and between $\sim 8.8$ dB/mm to 22 dB/mm for using one single device with particular device geometry, respectively. We discuss how our approach improves regular mid-IR plasmonic waveguides and compare it to different approaches from the literature. By aiming at realizing a plasmonic platform with maximum flexibility, we tackle the following important figures-of-merit: i) large spectral bandwidth, ii) simultaneous Si-integrated-photonics- (and to a certain degree with back-end of line complementary metal-oxide-semiconductor (CMOS-)) and III-V-compatibility, iii) bio-compatibility for sensing applications and iv) simplicity in fabrication complexity. Addressing all those features simultaneously, allows us to demonstrate one of the most versatile and flexible plasmonic platforms addressing the LWIR spectral range and possibly beyond.

2. Materials and methods

2.1. Materials

In order to realize plasmonic waveguide concepts in the mid-IR spectral range, several steps need to be taken. First of all, a proper material system has to be selected by analyzing the refractive index in the spectral region of interest. In our case, this range is the LWIR located between $\sim 6$–$12 \mu m$ wavelength. It can be divided into i) a region of low attenuation from water-vapor absorption ($\sim 8$–$12 \mu m$) [12], which is suitable for free-space-optical telecommunication, and ii) a region addressing particular molecules with strong absorption lines of gases like O$_3$ ($\sim 9.4$–$9.9 \mu m$) and SO$_2$ ($8.2$–$9.1 \mu m$) [11] as well as characteristic absorption bands of liquids like: e.g., proteins ($\sim 6$–$6.6 \mu m$) [28] and glucose ($\sim 10.0$–$8.5 \mu m$) [29,30], and which is consequently of relevance for highly-sensitive spectroscopy. Here, we want to focus on high atmospheric transmissibility for long-range applications and therefore select a wavelength of interest of 9.12 $\mu m$ [12,31]. Noble metals have often been used to realize large Q-factor SPPs in the mid-IR, however, resulting in poor mode-confinement to the metal surface (mode extends $\sim 10$–$1000 \mu m$ into the surrounding dielectric) at a metal-air interface [8,32]. Consequently, such devices are highly unsuitable for (sub-) wavelength mid-IR optics. Therefore, in recent years, also other materials have been investigated, including heavily-doped epitaxial semiconductors like Ge, Si, and III-Vs, transition metal nitrides, transparent conductive oxides, silicides, or even graphene [33,34]. While designed to address silicon photonic integration, most of them lack simple fabrication protocols for implementation into III-V substrates, which is a necessary pathway towards new on-chip approaches based on matured QC (Quantum Cascade) technology [8]. To surpass all those difficulties mentioned above, we follow another novel approach. While Pendry et al. suggested a pretty complex resonant sub-wavelength patterning of the plasmonic metal layer for a strongly bound SPP mode in so-called spoof SPP waveguides [35], we exploit a simpler but nonetheless very effective approach. By merging the previously often used noble
metals with the concept of dielectric loading on their topside, so-called dielectric-loaded SPPs (DLSPPs) are obtained [8]. While this concept shows some resemblance with hybrid plasmonic approaches [36–38] and has already been used at telecom wavelengths [39,40], mainly yielding an increased SPP propagation length, it as well helps to reduce the vertical mode extension by about one order of magnitude in the mid-IR. This stems from the fact that the permittivity in the mid-IR is far more negative as compared to visible and near-IR wavelengths, and the additional dielectric layer increases the effective mode index significantly. The result is the observed vertical squeezing of the mode [8]. Depending on the relation of refractive index and thickness of the dielectric layer, the vertical mode extension can be confined to a range of between a few up to tens of micrometers only. In addition, the dielectric layer also helps to increase the lateral mode confinement (comparable to the visible/near-IR). However, as most of the mode (>95%) is still guided outside of the waveguide (including the additional dielectric layer), this configuration is nonetheless highly suitable for spectroscopic measurements [8]. Based on the DLSPP concept we will show in this paper, that by substituting the dielectric topside layer with a (low-doped) semiconductor layer, the result is a SLSPP waveguide with broadband low-loss capabilities, and which covers one full octave in the mid-IR spectral range, as carried out with a single device only. Hereby, one fundamental advantage of most semiconductors over dielectrics is their better thermal behavior [39], making them suitable for an even wider range of applications. For this concept to be successful, we need the right choice of (semiconductor) material, i.e., a material with suitable refractive index n together with low extinction coefficient k in the LWIR. While typical dielectric materials like SiN, SiOx, Al2O3 show rather high losses in the LWIR [41], chalcogenides and halides have difficult processing protocols. Germanium, in contrast, shows low losses in the LWIR [42] and has already been studied as heavily doped (∼10^20–10^21 cm-3) single layer SPP waveguide with similar properties as noble metals like Au at shorter wavelengths. However, its epitaxial deposition is rather complex and sets tight boundaries to the substrates onto which it can be grown, mainly preventing direct III-V integration as needed for QC-devices-based monolithic concepts. Similarly, germanides and silicates require high-temperature annealing together with some difficulties addressing III-V material integration [43,44]. We will show in the following that, in contrast to that, low-doped, sputtered Ge can be used as a semiconductor-loaded layer on top of noble metals like Au. Based on this architecture, we are exploiting its low-loss and suitable refractive index properties of amorphous Ge in the LWIR while circumventing the need for an epitaxial deposition combined with high doping levels. In addition, Ge shows bio-compatible properties [45,46], which makes Ge-based sensors interesting candidates for biological and medical studies and applications.

2.2. Simulations

A schematic representation of the proposed plasmonic waveguide is illustrated in Fig. 1(a), and consists of a narrow and un-doped sputtered Ge-stripe deposited onto an un-patterned gold layer supported by a silicon substrate.

We studied this waveguide architecture and the impact of geometrical factors via numerical simulations. During simulations, several figures-of-merit were analyzed in order to reveal the potential of such structure in offering low loss transmission and a good degree of confinement for optical sensing. The simulations were centered around the wavelength of interest of 9.12 µm and extended to a wider spectral range covering the LWIR. For this, we used the eigenmode solver of the FEM-based commercial software COMSOL (v5.5). The modal characteristics were investigated by solving the Helmholtz equation and extracting the complex wavevector of the E-field for out-of-plane propagation. For time-harmonic problems, it can be expressed as:

\[ \hat{E}(r, t) = \text{Re}[\hat{E}(r)e^{i(\omega t - \gamma z)}] \] (1)
Fig. 1. (a) 3D-sketch of the Ge-based semiconductor-loaded SPP waveguide. (b) A detailed schematic description of the device fabrication flow and picture of the cleaved final samples containing up to 21 waveguides per chip. Scanning electron microscope images of a typical fabricated waveguide: (c) top-view of multiple waveguides (gray vertical lines), (d) and (e) show close-ups of the diagonal top-view of typical facets from both sides.

where $z$ is the known out-of-plane direction. The modal characteristics are extracted by the propagation constant $\gamma = \alpha + j\beta = -\tilde{\lambda}$, where $\alpha$ and $\beta$ are respectively the attenuation and the phase constants, and $\tilde{\lambda}$ is the eigenvalue returned by the solver.

The effective mode index is defined as $n_{\text{eff}} = i\tilde{\lambda}/k_0$, where $k_0$ is the vacuum wavevector. The propagation length was calculated as:

$$L_p = \frac{1}{2\alpha}$$

(2)

defined as the 1/e-decay distance of a propagating mode. The attenuation in dB scale is calculated from the propagation constant using the formula:

$$\alpha_{\text{dB/m}} = 20\alpha \log_{10} e$$

(3)

In addition, the effective mode area $A_{\text{eff}}$ is defined [47]:

$$A_{\text{eff}} = \frac{1}{\text{Max}\{W(r)\}} \int_{A_{\text{in}}} W(r) dA$$

(4)

with the energy density $W(r)$ at position $r$ as expressed in Eq. (5),

$$W(r) = \frac{1}{2} \text{Re} \left\{ \frac{d[\omega \varepsilon(r)]}{d\omega} \right\} |E(r)|^2 + \frac{1}{2} \mu_0 |H(r)|^2$$

(5)

where $E(r)$ is the electric field, $H(r)$ is the magnetic field, $\varepsilon$ is the permittivity, and $\mu_0$ is the permeability. In order to mimic the open boundary, we applied a second-order scattering boundary condition and convergence tests ensured that the numerical boundaries did not interfere with the solutions.

The results of the simulations take into account the attenuation losses (i.e., radiation losses due to the material absorption of Au and Ge). Therefore, as the calculations strongly depend on the involved materials’ optical constants, we first measured the materials’ complex permittivity after fabrication via mid-IR ellipsometry (for details, see Supporting Information, section 1.2), and used these values as parameters for the simulations.

However, additional loss mechanisms must be considered in order to compare the simulations with the experimental measurements. The main additional loss mechanisms not accounted for in the model are i) the optical scattering losses induced by surface and edge roughness along the Ge film and ii) coupling losses. In this paper, we used the effective cut-back technique to measure the coupling losses (see Section 2.4), showing that the sum of attenuation (from the simulations)
and coupling losses account for the major part of the total measured losses. Additional remaining deviations to the measured losses can be mainly attributed to additional scattering losses from imperfections in device fabrication.

2.3. Fabrication

The fabrication of the SLSPP waveguides was conducted in our in-house cleanroom facilities, using state-of-the-art semiconductor fabrication techniques. We used Silicon substrates (2-inch size, 275 µm thick) as carrier wafers, which shows the compatibility of our approach with silicon integrated photonics as well as to a certain degree with back-end of line CMOS-processing. The formation of an Au/Ge eutectic below 300°C is a certain limitation in this respect. For the fabrication of our devices, first, we deposited a 5 nm thin Ti adhesion layer directly on top of the plasma-cleaned Si surface, followed by a 200 nm thick Au layer. Both layers were deposited by HV e-beam evaporation (p ~ 1e-7 mbar). To improve the surface Ltd “G3-9000-D25”, 99.999%) was sputtered on top of the Au with a nominal thickness of 300 nm. The Ge sputtering was conducted in multiple cycles (typically 12 cycles of 60 s per cycle) alternating with cool-down periods (1 min. each) at low rates of 24.6 nm/cycle (25 W, pwork = 8e-3 mbar) for best results in terms of material quality and surface roughness. For patterning the Ge layer only, we used a photoresist mask and selectively etched the Ge in an SF6-O2-based ICP-RIE process to the desired geometry. After removing the remaining resist, we cleaved the individual devices perpendicular to the ridges into 1.0, 1.5, and 2.0 mm long waveguides. For this, they were scribed along the whole sample length (JFP Microtech, S-100 Scriber Breaker). This way, we obtained good cleaving results with identical straight facets and only rarely observed “steps” at the plane of cleaving along the crystallographic structure of the substrate. The fabrication process is outlined in Fig. 1(b), while Fig. 1(c), (d), and (e) show scanning electron microscope images of the typical fabricated devices. We want to stress that even though we got already good results concerning the cleaving of the facets when scribing along the whole sample length, this process can be further improved, e.g. by only partial-scribing with the diamond tip, to reduce the obtained coupling losses.

2.4. Experimental characterization

A schematic representation of the experimental setup used to characterize the waveguides is shown in Fig. 2(a). The light of a tunable (5.66 to 11.24 µm) EC-QCL (“MIRcat” from Daylight Solutions Inc., San Diego, CA) emitting 500 nm / 100 kHz pulses with a maximum output power of 27 mW was used to excite the plasmonic mode in an end-fire style configuration.

Light-coupling into and out of the waveguides under investigation was achieved using an optical system consisting of two lenses (C037TME-F, Thorlabs) to focus and collimate the free-space optical mode, respectively. The rough alignment of the waveguide to the focal point of the lenses was obtained with the help of a digital microscope (“Dino-Lite Edge” Digital Microscope). A piezoelectric transition stage was then used to move the waveguide with respect to the lenses with nanometer precision. Using a 50:50 ZnSe beamsplitter (BSW711, Thorlabs), we aligned the beam profile simultaneously on an IR camera (Pyrocam, Ophir-Spiricon, USA) and onto a thermoelectrically cooled (−78°C) HgCdTe detector (“PVI-4TE-10.6”, Vigo Systems S.A., Poland; detectivity: ≥2.0×10^9 cm √Hz/WHz1/2/W at 10.6 µm, window: wedged AR-coated ZnSe). The obtained detector signal was amplified using a pre-amplifier and the signal-to-noise ratio was increased significantly by using a lock-in amplifier. A standard method used in integrated optics to measure the attenuation and coupling loss of a waveguide is the effective “cut-back” technique, where the total losses of a waveguide are acquired as a function of its length by repeatedly measuring the same waveguide while cutting its length between two successive measurements. The resulting loss-vs-length fit allows extracting the coupling loss of the waveguide configuration under investigation as the y-offset of a linear fit to the
As it is nearly impossible to cleave or polish back the facets of 1-2 mm long plasmonic waveguides, we used a similar approach as was used in [48–51], where the losses of end-fire coupled plasmonic waveguides were determined experimentally with the same approach. In the case of plasmonic waveguides, the cut-back technique is slightly adapted, and instead of cutting the same waveguide, different (but nominally similar) waveguides of different lengths are used. The underlying assumption is that different individual waveguide facets, and thus the coupling losses in dB and total losses in dB/mm, are identical among waveguides of different lengths. To confirm the validity of this approach, we first measured multiple waveguides of each length and identical additional parameters, including Ge layer thickness and width, and ensured that the resulting values were similar within reasonable (processing- and alignment-dependent) deviations. In addition, we checked that the obtained values fit a linear model and compared them to the simulations. As will be shown in the results section, we got good agreement between simulations and experimental data by using this technique.

To measure the losses, the following procedure was used: The measurement of the reference voltage was taken prior to every measurement, while controlling that the IR camera was showing a Gaussian beam. Then, each waveguide was carefully aligned with respect to the focal point of the lenses. The intensity of each waveguide was measured at least three consecutive times and then averaged. We repeated this procedure for each selected waveguide and for every length to extract the coupling losses from the effective cut-back technique. For the spectral bandwidth characterization, we selected a representative 1-mm device per type (= particular geometry) and the alignment procedure was repeated for each measured wavelength.

3. Results and discussion

Figure 3 illustrates the results of the simulations of our ridge waveguide structure. The performance of such waveguides can be characterized by their total attenuation (or similarly their propagation length $L_p$) and confinement (i.e., mode size). We calculated the vertical mode confinement (Fig. 3(a)), propagation length (Fig. 3(b)), and the effective mode index (Fig. 3(d)) for different Ge thicknesses and widths at a wavelength of 9.12 µm. For a Ge layer thickness of around 300 nm, the plasmonic configuration allows mm-range propagation for ~9 µm wide Ge waveguides, while providing good vertical (Ly ~6 µm, i.e., below the extension of one
wavelength) and lateral confinement (the mode profile is well within the width, see Fig. 3(b) (inset), dashed vertical lines).

These results show that the obtained values for this geometry are especially suitable for integrated sensing applications such as lab-on-chip optical sensors [8], where typically distances of some hundreds of microns need to be overcome, while a considerable portion (>95%) of the optical mode needs to be guided outside the Ge layer in the surrounding medium (i.e., air or liquids) for the detection of the molecular species of interest.

Figure 3(c) confirms excellent (lateral and vertical) mode confinement for a 300 nm thick and 9 µm wide Ge waveguide together with a mode propagation length of 663 µm, i.e., well within the range needed for liquid spectroscopy [8]. Figure 3(d) shows that increasing the Ge thickness above ~300 nm significantly increases the effective mode index for typical Ge-width of the waveguide between 4–9 µm, thus resulting in an also significantly reduced overlap of the mode with the surrounding medium. The simulations in Fig. 4 show that it is possible to preserve relatively similar device performances, represented by the effective mode index $N_{eff}$, the propagation length $L_p$, and $A_{eff}$ for different mid-IR wavelengths, by simply adjusting...
geometrical factors. For example, thicker germanium structures lead to higher mode confinement and therefore increasing effective mode index at the expense of lower propagation length.

But as shown in Fig. 4(c), a thicker and wider Ge waveguide can balance the effects of an increased wavelength in a way that $N_{eff}$ remains the same and $L_p$ is changed by less than 20% and remains on the order of $>600 \mu m$. Consequently, the simulations show that the entire LWIR range (6–12 $\mu m$) can be covered with this material system and concept at similar performance. As we will see later, this even holds true for a single Ge-SLSPP device measured throughout the entire wavelength range of the EC-QCL (5.66–11.24 $\mu m$), still showing relatively low total propagation losses for the plasmonic mode (for more details, see Supporting Information, section 1.1).

The attenuation values obtained through the effective “cut-back” technique for 1.0, 1.5, and 2.0 mm long SLSPP waveguides (width $\sim 9.0 \mu m$, thickness $\sim 290$ nm) at $\lambda = 9.12 \mu m$ are shown in Fig. 5(a).

![Fig. 4. 2D simulations of the mode profile at the waveguide facet with the respective figures-of-merit for different waveguide widths and wavelengths.](image)

![Fig. 5.](image)

The experimentally extracted total propagation loss of the fabricated waveguides is 6.73 dB/mm (red, solid line), corresponding to a propagation length $L_p$ of 645 $\mu m$. The agreement between the regression line extracted from the data (red, solid line) and the simulation (blue dashed) is very good. The total coupling losses for both facets combined, are extracted from the linear
model. We obtain for the total coupling losses a value of 6.28 dB. The inset in Fig. 5(a) shows excellent agreement between the measurements of the lateral mode profile and the corresponding simulations, in this case for the 1 mm long device. However, in our study, we performed the cut-back technique at one selected wavelength (9.12 µm). It should be noted that the mode area in this waveguide configuration monotonously increases when the wavelength is larger than the Ge stripe width, leading to additional wavelength-dependent coupling losses.

This effect is shown in Fig. 5(b), where the lateral Mode Field Diameter (MFD), defined as the $1/e^2$ width of the lateral profile of the electric distribution, is plotted against the Ge-layer-width at a fixed wavelength (for more details, see Supporting Information, section 1.3). To the best of the authors’ knowledge, this is the first experimentally demonstrated plasmonic waveguide in the LWIR (8-12 µm) spectral range. The above-presented results for the total propagation losses of our Ge-SLSPP waveguides (e.g. 6.73 dB/mm for a 9 µm wide waveguide at 9.12 µm) show that our proposed architecture has comparable if not superior performance to previously proposed, and only theoretical, LWIR plasmonic waveguides based on, e.g., heavily doped semiconductors (predicted losses around 100 dB/mm at 9 µm) [52], germanides (predicted Lp around 410–615 µm) [44] and silicides [53] (predicted Lp in the millimeter-range but mode extends >> 10 µm into the above dielectric (= air)). In addition, our geometry with the deposition of the Au layer onto the substrate opens the pathway for integration of this waveguide architecture into basically any substrate, including Si and III-Vs. Thus, the Ge-SLSPP is a geometry simultaneously back end of line CMOS- and III-V-compatible. In addition, its implementation and deposition are much more simple than other concepts, which are often based on epitaxy and/or limited in their compatibility to a few types of carrier substrates only.

To demonstrate the broadband capabilities of the proposed waveguide structure, we measured the losses for different wavelengths of a typical 9 µm and 6 µm wide and 290 nm thick waveguides and of a 4 µm wide and 220 nm thick one. The results are shown in Fig. 6(a), (b), and (c). The dashed lines represent the attenuation losses extracted by the 2D-simulations, while the data points are the losses calculated after subtracting the coupling losses measured at 9.12 µm from the experimental measurements. In Fig. 6(a) we used a 9 µm wide waveguide and analyzed its spectral bandwidth between 8.5 µm and 11.2 µm. As expected, when calculating the attenuation losses of such waveguides and subtracting from the measurements the coupling losses from Fig. 5(a), we obtain excellent overlap for wavelengths extending from 8.5 µm to ~10 µm. Above that value, the wavelength becomes much larger than the waveguide width, leading to a larger mode area and thus higher coupling losses, as previously discussed (Fig. 5(b)). Similarly, the 6 and 4 µm wide waveguides in Fig. 6(b) and (c) show good agreement between measured and calculated values between ~5.6 µm and ~7.5 µm. However, as the spectral region between 5.6 and 7.0 microns is a range of strong absorptions from water vapor in the atmosphere, the humidity variations in the lab could be one source for the higher “scattering” of the measurements in this wavelength region. In the case of Fig. 6(c), we can observe that above this wavelength range, the experimental data diverge monotonously from the theoretical values also when including the previously extracted coupling losses at 9.12 µm.

In this case, the coupling losses are only a rather rough estimate since the waveguide used in these measurements was much smaller than the measured wavelength. This deviation can be explained with the increasing mode size given by exceeding wavelength with respect to the Ge stripe width (as discussed previously in Fig. 5(b)) Nevertheless, the measured spectral-dependent waveguide losses of such single waveguides demonstrate the low-loss (<15 dB/mm) broadband capabilities of this waveguide geometry, covering a full octave through almost the entire LWIR range. With this, we have demonstrated that our plasmonic waveguide is indeed low loss in the octave-spanning region 5.6-11.2 µm, by remaining <15 dB/mm in the whole region.
Fig. 6. (a) Spectral bandwidth of a 9 µm wide and 290 nm thick plasmonic waveguide in the spectral range of ∼8.5–11 µm. (b) Spectral bandwidth of a 6 µm wide and 290 nm thick plasmonic waveguide in the spectral range of 5.5–7.0 µm (c) The spectral bandwidth of a 4 µm wide and 220 nm thick Ge-loaded plasmonic waveguide covering the entire LWIR. Solid lines are added as a guide to the eye.

In addition, we want to also stress that the coupling losses are contributing a major part to the measured total losses and can consequently be reduced significantly by on-chip approaches, where laser, plasmonic waveguide, and detector are monolithically integrated [8].

4. Conclusion

We designed, fabricated, and characterized novel hybrid semiconductor-loaded SPP (i.e., SLSPP) waveguides based on the Ge-Au material system, resembling that of DLSPP waveguides. These cover almost the entire LWIR spectral range, in particular between 5.6 and 11.2 µm. The measured losses are as low as 6.73 dB/mm at 9.12 µm, and ∼8.8 dB/mm at 7 µm (4 µm wide waveguide, when including the coupling losses). Using a single device (4 µm waveguide), we could show that it can cover a full octave in the LWIR range between 5.6 µm – 11.2 µm with losses below 15 dB/mm. Therefore, with this, we give the first experimental demonstration of a low loss plasmonic waveguide operation in the wavelength range of 8.5 -11 µm. This corresponds to propagation lengths that can exceed 500 µm, excellent for on-chip spectroscopy-based applications.

Further optimization can be achieved by balancing the trade-off between low loss propagation and confinement through carefully adjusting the SLSPP waveguide’s geometrical factors. As it was shown in the paper, it is possible to increase the Neff by increasing the Ge thickness, allowing a high degree of confinement at the expense of lower propagation length. Consequently, by carefully selecting the proper Ge ridge geometry, it is possible to obtain subdiffraction mode confinement and simultaneous low loss on-chip s-bend guiding with propagation lengths on the order of multiple wavelengths. For this reason, the concept presented herein can become the preferred choice when strong field confinement and mode propagation and guiding over only small distances are required for LWIR integrated photonics applications.

The excellent agreement observed between theory and experiment validates the well-understanding of our SLSPP waveguide’s broadband and low loss propagation capabilities for the long-wave mid-IR. Besides the large spectral bandwidth and relatively simple fabrication scheme, our devices are compatible with both Si integrated photonics (including back end of line CMOS-) and III-V integration as well as are bio-compatible for sensing applications, e.g., in liquids. Owing to the large portion of the evanescent field propagating in the surrounding air, this waveguide design constitutes the perfect candidate for lab-on-chip style sensors in the mid-IR. This is especially true for on-chip absorption spectroscopy, where the optical mode needs to be attached, but still with its main portion guided outside of the waveguide along the chip surface.
Most notably, this study reveals the large potential of the proposed Au-Ge based semiconductor-loaded SPP waveguide configuration throughout the entire mid-IR transparency window of Ge, which paves the way for a wide range of on-chip integrated optics and spectroscopic applications, especially for mid-IR sensing applications. Additionally, we want to stress that our new hybrid concept is not limited to the investigated wavelength-range and devices presented here, but can also be used in other wavelength ranges and settings together with other materials.

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Data availability. 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.

Supplemental document. See Supplement 1 for supporting content.

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