Performance analysis of different slot waveguide structures for evanescent field based gas sensor applications

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Abstract
Slot waveguide has emerged as a potential candidate for the design of evanescent field absorption based photonic gas sensors, etc. In this paper, three different slot waveguide structures, i.e., conventional slot, partial-strip-loaded slot, and full-strip-loaded slot waveguides have been explored, to analyze their sensing performance for methane gas. In anticipation of improvement in evanescent field ratio in slot region, and hence, the sensing capabilities of the gas sensor, the slot waveguide structures have been designed by depositing the germanium layer over the calcium fluoride in different manners. Several waveguide parameters, such as evanescent field ratio, propagation loss, and sensitivity have been considered for the analysis and comparison of the presented slot waveguide structures, by varying the arm-width and thickness of germanium layer. Simulation results have demonstrated that the full-strip-loaded slot waveguide has the superior performance, in terms of higher evanescent field (28%), and higher sensitivity (73.76 L/Mol), which is closely followed by the partial-strip-loaded slot waveguide, for a target value of propagation loss (3 dB/cm). However, the conventional slot waveguide provides slightly larger optimum waveguide length (0.86 cm), as compared to other presented slot waveguides.

Keywords Slot waveguide · Sensitivity · Evanescent field · Propagation loss · Methane gas

1 Introduction
The photonic waveguide based sensor applications are very popular due to its low cost, ultra-compact size, high sensitivity, easy to fabricate, and CMOS compatibility (Bogaerts et al. 2005), which can be used in various applications, such as bio-medical (Dai et al. 2020), chemical detection, gas detection, etc. Usually, the absorption property based photonic sensing approach is preferred over the effective index based sensing. In presence of the material/sample taken for the sensing, the change in the effective index is quite smaller than the change in the evanescent field, which is mainly due to the absorption of light/evanescent field by the sensing material (Butt et al. 2017; Ranacher et al. 2018a; Vlk et al. 2021; Kazanskiy et al. 2016).
Further, the extent of light absorption depends on the dimension/material of the sensor device, the operating wavelength, and the material to be sensed. The authors in Ranacher et al. (2018b), Datta et al. (2021), Cherouana et al. (2019) and Ashkavand et al. (2020) have presented the idea of an evanescent field based photonic gas sensor using different types of photonic waveguides, namely strip, rib, and slot, in the mid-infrared region. The percentage of evanescent field/light in upper cladding/slot region of the photonic waveguide changes during its interaction with the molecules of the sensing material. Therefore, the photonic sensors are required to be designed with the waveguides having comparatively larger evanescent field in the upper cladding region. The authors in Butt et al. (2018) and Huang et al. (2014) have demonstrated that the slot waveguide has the highest evanescent field ratio (EFR) in the slot (upper cladding) region, as compared to the other photonic waveguide structures, which comes at the cost of higher propagation loss (Ding et al. 2010; Almeida et al. 2004; Debnath et al. 2016; Rifat et al. 2019). In the slot waveguide, the light is mostly confined in the slot region, therefore, it has reasonably higher value of EFR (Soref et al. 2006; Tien et al. 2010; Baehr-Jones et al. 2010; Li et al. 2011; Xu et al. 2020; Nacer et al. 2012; Parriaux and Veldhuis 1998). Moreover, to compensate the propagation loss, a light source of comparatively high input power may be used with optimized waveguide geometry (Butt et al. 2020), to achieve the high sensitivity (Frumin et al. 2020). Further, a photo-detector (Yazici et al. 2020), integrated at the end of the device can be used to detect the output light from the sensing device. Since, the sensitivity of the photonic sensor is mainly dependent on the percentage of evanescent field/light in the upper cladding region; therefore, it can be anticipated that the slot waveguide can offer significantly higher sensitivity, as compared to the other photonic waveguide structures.

The current work explores the possibilities of different slot waveguide structures, designed with germanium (Ge) and calcium fluoride (CaF$_2$) materials, for gas sensor applications. In this analysis, two important waveguide parameters, evanescent field and propagation loss have been investigated, in order to determine the sensitivity of the gas sensor. As the main peak absorption of methane gas is in the mid-infrared region, ~ 3.31 μm; therefore, for the current analysis the operating wavelength has been considered as 3.31 μm.

The authors in Kai-he et al. (2019) and Khonina et al. (2020) have presented the analysis of silicon-on-insulator (SOI), i.e., Si-SiO$_2$ based methane gas sensor using the slot micro-ring resonator structure. Moreover, beyond the wavelength of 3.6 μm, the SiO$_2$ material becomes highly absorbing; and hence, the SOI based waveguides cannot be used in the range of mid-IR region. Therefore, the materials having the wide transparency range in mid-IR region (Mere et al. 2016; Soref 2010; Kim et al. 2018), along with high-index contrast, like Ge and CaF$_2$, can be suitably used for methane gas sensing applications, as compared to the SOI materials. The gas sensor analysis for different gases have been provided in Dong et al. (2017), Zheng et al. (2017), Rouxel et al. (2015), Fabricius et al. (1992) and Yebo et al. (2010).

The outline of the paper is as follows. Section 2 presents the design structures of different slot waveguides and its parameters, which is followed by the simulation results in terms of different waveguide parameters in Sect. 3. The comparison and performance analysis of all the three slot waveguide structures have been presented in Sect. 4. Finally, the work has been concluded in Sect. 5.
2 Waveguide structures and parameters

2.1 Design of waveguide

The cross-sectional view of three different structures of Ge-on-CaF$_2$ materials based slot waveguides have been presented in Fig. 1, where ‘$W$’ is the arm width (of Ge), ‘$H$’ is the total height of the Ge-layer, ‘$t$’ is the thickness of Ge-layer, which has been developed above the CaF$_2$, and ‘$G$’ is the slot gap of the slot waveguides. The conventional slot waveguide has been depicted in Fig. 1a, whereas, the partial-strip-loaded and full-strip-loaded slot waveguides have been shown respectively in Fig. 1b, c.

The material used for the lower cladding layer is CaF$_2$, having the refractive index of 1.40, and the same for the Ge is 4.02, at the operating wavelength of 3.31 μm (Kim et al. 2018). For the slot waveguides presented in the current work, only quasi-TE mode has been investigated, as the evanescent field in the slot region is enhanced in this mode (Huang et al. 2014), and hence, mainly the quasi-TE mode can propagate with a significant amount of power; while, the quasi-TM mode can propagate through the horizontal type of slot waveguides (Chandra et al. 2020). Therefore, the presented analysis has been done only for the quasi-TE mode, with the TE light source. Further, to get the stronger evanescent field in slot region, the slot waveguide with smaller dimension is desirable. With the decrease in arm widths, the amount of evanescent field increases, which leads to better sensing capabilities (Katti et al. 2018). However, further decrement in ‘$W$’ may cause the leakage of the quasi-TE mode, and it may no longer remain as a guiding mode (Huang et al. 2016). Therefore, it is essential to investigate the suitable waveguide dimension for all the considered slot waveguide structures for the effective propagation of quasi-TE mode. Out of the three slot waveguide structures presented in the current work, the partial-strip-loaded, and full-strip-loaded slot waveguides have been developed respectively by depositing a thin Ge-layer, partially and fully, on CaF$_2$ material, as depicted in Fig. 1, in anticipation of further enhancement of evanescent field in the slot region. Here, it is assumed that the upper cladding region is surrounded by the air or gas to be sensed. In the current work, among the different waveguide materials, the material, germanium has been preferred, due to its high refractive index, and in combination with low-index material, CaF$_2$, it can provide the compact, high-contrast integrated photonics platform with higher sensitivity, smaller device footprint, etc. The CMOS compatible germanium-on-insulator (GOI) based devices can be fabricated using the GOI substrate with a SiO$_2$ BOX, as discussed in Kim et al. (2018). The authors in Ranacher et al. (2016) have presented the experimental set-up for the evanescent-wave

![Fig. 1 Structures of three different slot waveguides using Ge-on-CaF$_2$ materials a conventional slot waveguide, b partial-strip-loaded slot waveguide, and c full-strip-loaded slot waveguide](image-url)
absorption sensor for the gas detection, using the silicon slab waveguide fabricated with MEMS technology.

2.2 Evanescent field ratio (EFR)

The EFR is a crucial parameter for the realization of evanescent field absorption based devices/sensors. The EFR is defined as the amount of power in upper cladding/slot region, interacting with the environment/material to be sensed, to the total incident power on the device. The EFR mainly depends on the geometry and operating wavelength of the photonic waveguide. Mathematically, the EFR can be expressed as Chandra et al. (2020), in the Eq. (1) below,

\[
\eta = \frac{\iint_{\text{evan}} \vec{S} \cdot \vec{n} dxdy}{\iint_{\text{Total}} \vec{S} \cdot \vec{n} dxdy}
\]  

where \( \eta \) is the EFR, \( \vec{S} \) is the Poynting vector of the mode field in the waveguide, and \( \vec{n} \) is the normal vector to the waveguide cross-section.

2.3 Propagation loss

Beside the EFR, the propagation loss in the waveguide plays a critical role to analyze the performance of the sensor designs. The waveguide propagation loss is mainly dependent on the waveguide geometries, and it is highly reliant on the imaginary part of the effective refractive index \( (n_{\text{eff}}) \) of the propagating mode, i.e., \('Im(n_{\text{eff}})'\), as expressed in Eq. (2) below (Du et al. 2013; Lindecrantz et al. 2014; Huang et al. 2016),

\[
\text{Loss (dB)} = 10 \times \log_{10}(e) \times \frac{4\pi \times \text{Im}(n_{\text{eff}})}{\lambda}
\]  

From the Eq. (2), it is clear that for a fixed operating wavelength, the propagation loss, and hence, the propagation length depends only on \( \text{Im}(n_{\text{eff}}) \). However, the value of the imaginary part of \( n_{\text{eff}} \), i.e., \( \text{Im}(n_{\text{eff}}) \) has been obtained from the COMSOL Multiphysics simulations.

2.4 Sensitivity

The photonic sensors are required to be designed with waveguides having comparatively high sensitivity. The sensitivity can be estimated by the Eq. (3) (Butt et al. 2018; Huang et al. 2014) below,

\[
\text{Sensitivity} = -\eta e L \exp(-\eta e C L - \alpha_{\text{wvg}} L)
\]  

where \( \eta, e, C, \alpha_{\text{wvg}}, \) and \( L \) are the EFR, absorption coefficient, concentration, intrinsic waveguide loss, and length of the waveguide, respectively. Hence, the sensitivity of a photonic device is highly dependent on EFR (\( \eta \)) and concentration (\( C \)) of the material to be sensed. However, by measuring the EFR and propagation loss (Vlk et al. 2021), the sensitivity can be estimated experimentally, with the help of Eq. (3). Further, the optimum waveguide
length \((L_{opt})\) is a waveguide length at which the sensitivity is maximum, and beyond that the sensitivity starts to decay due to waveguide loss. For a photonic sensor/device, it can be obtained by solving the equation, \(\frac{dt}{dL} = 0\), from Eq. (3) above. Therefore, the optimum waveguide length can be expressed, as noted in Eq. (4) below,

\[
L_{opt} = \frac{1}{\eta e C + a_{wvg} L}
\]

3 Simulation results

The simulation analysis has been done using the finite element method (FEM) based COMSOL Multiphysics simulation platform. During the simulation, the extremely fine mesh size has been considered in the COMSOL Multiphysics, and the scattering boundary condition has been applied, in order to analyze the different modal characteristics for all the three considered slot waveguide structures. The scattering boundary condition is usually applied to absorb the scattering electromagnetic fields, in order to avoid its interference with the propagating modes.

3.1 Mode field distribution

For all the three considered slot waveguide structures, the mode field distributions have been illustrated in Figs. 2, 3 and 4 respectively. Figure 2 shows the mode field distribution and corresponding normalized electric field distribution for the conventional slot waveguide, where, \(W=550\) nm, \(G=80\) nm, and \(H=500\) nm. The figure clearly depicts that the light/mode field and hence, corresponding normalized electric field distribution is mostly confined in the slot region of the waveguide, which is mainly due to the discontinuity of electric field in high refractive index regions (Liu et al. 2015; Verma et al. 2017); whereas, the optical field intensity in high refractive index regions is extremely low. Further, with the other suitable values of ‘\(W\)’ and ‘\(G\)’, such as \(W=510\) nm, and \(G=80\) nm, the similar mode field and its corresponding electric field distributions can be obtained that are useful for the analysis of different waveguide parameters.

Fig. 2 a Mode field distribution, and b plot of corresponding normalized electric field distribution, for conventional slot waveguide, at \(W=550\) nm, \(G=80\) nm, and \(H=500\) nm
Likewise, Fig. 3 shows the mode field distribution and corresponding normalized electric field distribution for the partial-strip-loaded slot waveguide. Due to the development of additional layer of Ge, of thickness ‘\( t \)’, except in between the waveguide arms, over the lower cladding layer, more light is confined in the slot region of partial-strip-loaded slot waveguide, which leads to higher EFR, as compared to the conventional slot waveguide. Hence, the amplitude of the normalized electric field in the slot region is significantly larger than that recognized with conventional slot waveguide. This is desirable to attain the high sensing performance. For the design of partial-strip-loaded slot waveguide, the comparable waveguide parameters have been considered, such as \( W = 510 \) nm, \( G = 80 \) nm, \( H = 500 \) nm, and \( t = 101 \) nm.

Subsequently, the distributions of mode field and corresponding normalized electric field for the full-strip-loaded slot waveguide have been illustrated in Fig. 4, which once again confirms its confinement in the slot region. For this particular slot waveguide structure, a thin layer of Ge-material has been deposited over the entire lower-cladding layer, including the slot region between the two arms. This structure offers the further improvement in mode field/normalized electric field amplitude over the previous two slot waveguides. Hence, by inserting a thin layer of Ge, over CaF\(_2\), the high light confinement/strong electric field confinement, in slot region can be achieved, as observed with
partial-strip-loaded and full-strip-loaded slot waveguide structures, as compared to the conventional slot waveguide.

3.2 Evanescent field ratio (EFR) versus waveguide dimension

It is well known that due to high EFR in slot region, the slot waveguide is one of the popular structure to realize the evanescent field based photonic sensor devices. The presence of amount of evanescent field in slot region is highly dependent on the appropriate choice of the waveguide structure and dimension; therefore, it is essential to visualize the impact of variations in waveguide dimension on EFR, for all the three considered slot waveguide structures. For the conventional slot waveguide, ‘W’ has been varied from 450 nm to 650 nm for two different slot gaps (G) of 80 nm and 120 nm, as depicted in Fig. 5a. From the figure, it is clear that the percentage of EFR first decreases with the increase in ‘W’. Moreover, for G = 80 nm, it has been observed that the EFR increases abruptly at W = 510 nm, and achieves the maximum EFR (of 0.3), at around W = 520 nm. However, before W = 510 nm, the light confinement is mostly either in side arms (Ge) or in lower-cladding regions, and from W = 510 nm, the light starts propagating mainly through the slot region. Furthermore, after W = 520 nm, the light confinement in the slot region decreases gradually with the increase in arm widths. A similar observation has been made for G = 120 nm, and the light confinement in the slot region starts with W = 530 nm, which attains the peak EFR.

![Fig. 5](image-url)

Fig. 5 Variations in EFR at two different ‘G’ a with ‘W’, in conventional slot waveguide, b with ‘t’, in partial-strip-loaded slot waveguide, and c with ‘t’, in full-strip-loaded slot waveguide
(of 0.28), at $W=540$ nm, before the start of gradual decrement of light confinement in slot region. Further, through the extensive simulation analysis, it has been observed that for the lower value of ‘$G$’, it is difficult to achieve the light confinement in the slot region, and the light may get leaked in to the upper/lower cladding and high index regions. Moreover, the significant amount of light propagation has been observed for the value of ‘$G$’, near around 80 nm, which leads to the substantial values of EFR, etc. On the other hand, for the evanescent field analysis in the partial-strip-loaded slot waveguide, and full-strip-loaded slot waveguide, the ‘$t$’ of Ge-layer has been varied from 0 to 140 nm, in order to search the optimal thickness of Ge-layer to achieve the maximum EFR in the slot region. Again, the two slot gaps of 80 nm, and 120 nm have been considered for the analysis, and depicted in Fig. 5b, c respectively, for partial-strip-loaded, and full-strip-loaded slot waveguide structures. In literature, the similar nature of graph has been recently reported by Babakhani-Fard et al. (2020), to illustrate the variations in confinement factor in the slot waveguide. Further, some other authors Fan et al. (2020), Mu et al. (2008) and Penades et al. (2015) have also shown the similar type of transitions in their results, in terms of confinement factor of the slot waveguide.

Based on the previous analysis with conventional slot waveguide and from the meticulous simulations with partial-strip-loaded and full-strip-loaded slot waveguides, here, the ‘$W$’ for has been fixed at 510 nm. From Fig. 5b, for partial-strip-loaded slot waveguide, the maximum level of evanescent field has been observed as ~ 30.22%, and ~ 28.31% respectively, for the slot gaps of 80 nm, and 120 nm, at their respective ‘$t$’ of 10 nm, and 60 nm. Likewise, for full-strip-loaded slot waveguide, Fig. 5c shows the variations in EFR with respect to ‘$t$’. The maximum EFR have been noted as ~ 31.4%, and ~ 28.77% for the same respective slot gaps with its corresponding ‘$t$’ values of 0 nm, and 40 nm. After attaining the highest EFR values in both partial-strip-loaded and full-strip-loaded slot waveguide structures, the increase in ‘$t$’ leads to decrease in EFR. Moreover, these obtained values of ‘$W$’ and ‘$t$’ for the considered slot waveguides are corresponding to the maximum EFR value in slot region. Nevertheless, along with the EFR, the propagation loss has significant impact to turn up with the optimal dimension of waveguides with higher sensitivity and lower propagation loss, which have been discussed in the subsequent sub-sections below.

### 3.3 Propagation loss versus waveguide dimension

Propagation loss is mainly dependent on the materials used and geometry of the photonic waveguide. From the previous analysis, it can be anticipated that the deposition of Ge-layer on CaF$_2$ may results in decrement in propagation loss in the slot waveguide structures. To visualize the effect of variations in waveguide dimension on propagation loss, the ‘$W$’ of the slot waveguide has been again varied from 450 to 650 nm, for $G=80$ nm and 120 nm. Using the simulation analysis, the imaginary part of effective refractive index ($\text{Im}(n_{\text{eff}})$) has been obtained. Further, utilizing these values of $\text{Im}(n_{\text{eff}})$ for different dimensions of slot waveguides, in Eq. (2), the propagation loss in slot waveguides have been obtained. Figure 6a illustrates the relationship between the propagation loss and ‘$W$’ in the conventional slot waveguide. With the increase in ‘$W$’, the propagation loss starts to decrease. However, as mentioned in last sub-section, for $G=80$ nm, the significant light confinement in slot region starts with $W=510$ nm, and it reaches to maximum confinement at $W=520$ nm. Correspondingly, the propagation loss starts to increase at $W=510$ nm and reaches to maximum value at $W=520$ nm, and afterwards, it continuously decreases. Therefore, it can be predicted that in slot waveguides the high light confinement/EFR can be realized at
the cost of high propagation loss. Moreover, to realize both low propagation loss and significant light confinement, the ‘W’ must be chosen very judiciously, such as for G = 80 nm, at W = 550 nm, the EFR decreased by 3% only, while corresponding to this, there is significant decrement in propagation loss, of nearly 7 dB/cm, as compared to that at W = 520 nm. Similarly, for G = 120 nm, by choosing W = 560 nm, the reduction in EFR, and corresponding propagation loss are respectively, of around 2.4%, and 7.6 dB/cm, as compared to W = 540 nm.

Moreover, for the analysis of propagation losses in partial-strip-loaded, and full-strip-loaded slot waveguides, ‘W’ is again considered as 510 nm, and the ‘t’ has been varied up to 140 nm, with G = 80 nm, and 120 nm, as depicted in Fig. 6b, c, respectively. From the figures, it is clear that for G = 80 nm, the propagation loss continuously decreases with the increase in ‘t’, without any jump in propagation loss at some mid value of ‘t’, as observed with G = 120 nm. Similar to the previous analysis, the value of ‘t’ must be chosen very carefully, to realize the significant EFR with low propagation loss. From Fig. 6, it has been observed that the propagation loss decreases with the increase in values of ‘W’ and ‘t’, and considerably less propagation loss can be recognized for the smaller ‘G’. Moreover, from the propagation loss point of view, the performance of full-strip-loaded slot waveguide is quite better than that of the partial-strip-loaded slot waveguide, and appreciably superior than the conventional slot waveguide. Therefore, both partial-strip-loaded and

Fig. 6 Variations in propagation loss versus a ‘W’ for conventional slot waveguide, b ‘t’ for partial-strip-loaded slot waveguide, and c ‘t’ for full-strip-loaded slot waveguide, at G = 80 nm, and 120 nm
full-strip-loaded slot waveguides can be suitably utilized for the design of the gas sensors based on the absorption of evanescent field.

3.4 Sensitivity variations for CH$_4$ gas sensor

In order to achieve the higher sensitivity with photonic waveguide, the EFR, and propagation loss should be respectively, high, and low. However, normally in the slot waveguide, the higher EFR results in high propagation loss. Therefore, there must be a trade-off between the values of EFR and propagation loss, to achieve the decent value of sensitivity. By utilizing the Eq. (3), the values of sensitivity for all the three slot waveguide structures have been estimated. The value of the absorption coefficient has been considered as, 960.96 L/Mol-cm (Kai-he et al. 2019), to calculate the sensitivity of the device. The variations in sensing abilities with respect to the waveguide lengths have been depicted in Fig. 7a–c, respectively for different EFR in slot region, propagation losses, and gas concentrations, for all the three slot waveguides. For $G=80$ nm, Fig. 7a shows the nature of sensitivity variations for three different EFRs of 0.22, 0.27, and 0.28, that are obtained for the three respective slot waveguide structures, i.e., conventional, partial-strip-loaded, and full-strip-loaded slot waveguides, at a fixed propagation loss of 3 dB/cm.

![Figure 7a](image1.png)

![Figure 7b](image2.png)

![Figure 7c](image3.png)

Fig. 7 Sensitivity versus waveguide lengths for a three slot waveguide structures at their respective EFR values for fixed propagation loss of 3 dB/cm and $G=80$ nm, b three slot waveguide structures at their respective propagation loss for a fixed EFR of 0.30 and $G=80$ nm, and c four different methane gas concentrations for full-strip-loaded slot waveguide, at $G=80$ nm and EFR = 0.28

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The figure clearly depicts that the full-strip-loaded slot waveguide has the highest sensing ability, among the three structures. However, the variations in sensitivities of both partial-strip-loaded and full-strip-loaded slot waveguides are very close to each other, as their respective EFR values are very close, at the propagation loss of 3 dB/cm. Further, the impact of variations in waveguide length have been illustrated in Fig. 7b for different propagation losses of approximately 14 dB/cm, 7 dB/cm, and 5 dB/cm, realized respectively for conventional slot, partial-strip-loaded slot, and full-strip-loaded slot waveguides, for a fixed EFR of 0.30 and \( G = 80 \) nm. Under the considerations of the same EFR values for all the three slot waveguides, their propagation losses are different due to their specific design structures. Moreover, the partial-strip-loaded and conventional slot waveguides have reduced sensing abilities respectively by, 5–15 L/Mol, and 20–40 L/Mol, as compared to the full-strip-loaded slot waveguide. Therefore, from Fig. 7a, b, it is clear that the sensitivity increases with the increasing propagation loss, as well as with the decreasing EFR value. This also recognizes the superiority of full-strip-loaded slot waveguide. Similarly, for different concentrations of methane gas, such as 50 ppm, 100 ppm, 500 ppm, and 1000 ppm, the variations in sensitivity have been analyzed in terms of waveguide lengths for full-strip-loaded slot waveguide, and shown in Fig. 7c. From the figure, it has been observed that with the increase in gas concentrations, the sensitivity decreases. This is mainly due to the fact that with the increase in gas concentration, more gas molecules will interact with the evanescent field, which leads to more absorption of light/evanescent field, and hence, it increases the loss and correspondingly decreases the sensitivity. However, for a particular gas concentration value, the sensitivity first increases, then at the optimum length it reaches to its maximum value, and beyond this length, it starts to decrease.

4 Discussion and comparison

The conventional structure of the slot waveguides has been reported several times in the literature for different devices/applications. In the current work, the analysis of different slot waveguide structures based on Ge-on-CaF_2 materials have been explored, in order to search the possibilities to further enhance the performance of the slot waveguide in terms of EFR, propagation loss, and sensitivity. The current analysis has been done by varying the different geometrical parameters, namely ‘\( W \)’, ‘\( G \)’, and ‘\( t \)’, with a fixed waveguide height, \( H = 500 \) nm. Moreover, the impact of variations in ‘\( H \)’, on different waveguide parameters can be extended as the future work. The variations in EFR in slot region have been realized, by varying ‘\( W \)’ of slot waveguide. It has been observed that at \( W = 510 \) nm, the light confinement in slot region has started, and it reaches to maximum at \( W = 520 \) nm, beyond that the light confinement/EFR decreases, for \( G = 80 \) nm. Based on this analysis and careful simulations with partial-strip-loaded and full-strip-loaded slot waveguides, their ‘\( W \)’ has been fixed as 510 nm, and the variations in EFR have been observed by varying ‘\( t \)’. The simulation results have exhibited that the significant light confinement (maximum EFR) can be achieved at some specific values of ‘\( t \)’, such as 60 nm and 40 nm, respectively for partial-strip-loaded and full-strip-loaded slot waveguides, at \( G = 120 \) nm, and beyond this value of ‘\( t \)’, the EFR decreases. However, it has also been observed that the high EFR/light confinement in slot region is always with the penalty in terms of high propagation loss. The low propagation loss is essentially required, in order to achieve the longer length as well as higher sensitivity. Therefore, to accomplish the significant EFR with low propagation loss, the values of ‘\( W \)’ and
‘t’ must be chosen very cautiously, for all the considered slot waveguides. Further, the analysis of sensitivity variations has been carried out for a substantial range of waveguide lengths, by varying the gas concentrations and waveguide parameters, such as EFR, and propagation loss. The higher sensitivities have been achieved with the higher EFR and lower values of gas concentration and propagation loss.

Table 1 shows values of maximum achievable EFR and sensitivity, for all the three slot waveguide structures for a relatively lower propagation loss of 3 dB/cm, and gas concentration of 50 ppm, with $G=80$ nm, and compared with the recently reported works. As noted in Table 1, the highest EFR value has been realized as 0.28, for full-strip-loaded slot waveguide, which is closely followed by partial-strip-loaded slot waveguide with its corresponding EFR of 0.27. From the perspective of sensitivity, the highest sensitivity of 73.76 L/Mol has been achieved for full-strip-loaded slot waveguide, which is pursued by partial-strip-loaded slot waveguide with sensitivity of 72.50 L/Mol. Moreover, the $L_{opt}$ of conventional slot waveguide has the largest value, of 0.86 cm, among the three slot waveguide structures, and hence, the comparatively miniaturized photonic sensor can be realized with the full-strip-loaded and partial-strip-loaded slot waveguides. Therefore, Table 1 clearly validates the fact that the full-strip-loaded and partial-strip-loaded slot waveguides have reasonably better performance over the conventional slot waveguide. In general, the comprehensive analysis of this kind of sensors can be sorted into three parts namely, light source, sensing element, and photodetector. The current work mainly focused on the sensing element part for the light source having wavelength of 3.31 μm. However, photodetector is another important aspect for the design and analysis of photonic sensors. For the detection of light from these methane gas-sensing devices, the PbTe type of photodetector (Su et al. 2019) can be efficiently designed, and used to detect the wavelength of 3.31 μm from the sensor device. This type of detector can provide the monolithic integration capability (i.e., integrated photodetectors), which makes it more reliable to detect the mid-IR lightwave.

| Waveguide structures | α [dB/cm] | $\eta$ (EFR) | Maximum sensitivity (L/Mol) | $L_{opt}$ (in cm) | References |
|----------------------|-----------|--------------|----------------------------|------------------|------------|
| Slot waveguide       | 3         | 0.22         | 66.93                      | 0.86             | This work (CH₄ sensor) |
| Partial-strip-loaded slot waveguide | 0.27 | 72.50 | 0.762 | |
| Full-strip-loaded slot waveguide | 0.28 | 73.76 | 0.745 | |
| Strip                | 2–5       | 0.10         | –                          | –                | (Huang et al. 2014) (CO₂ sensor) |
| Rib                  | 0.9–1.9   | 0.15         | –                          | –                | (Ranacher et al. 2018a) (CH₄ sensor) |
| Slot                 | ~ 10      | 0.20         | –                          | –                | (Ranacher et al. 2018b) (CO₂ sensor) |
| Strip                | 3.98      | 0.14–0.16    | –                          | –                |            |
| Strip                | –         | 19.5         | –                          | –                |            |
5 Conclusions

In this work, the evanescent field absorption based methane gas sensors have been explored using three different slot waveguide structures, to investigate the sensing capabilities of the photonic gas sensors. Among the three structures of waveguide, the partial-strip-loaded and full-strip-loaded slot waveguides have been realized by depositing the Ge-layer on CaF$_2$, in different ways, in anticipation of further improvement in sensing performance of the slot waveguides. The simulation analysis has been done by varying the ‘$W$’ and ‘$t$’, to achieve the efficient dimension of the slot waveguide structures. It has been observed that to achieve the high sensitivity, the higher EFR in slot region is required, which comes at the cost of higher propagation loss. Therefore, the dimension of slot waveguides must be chosen very judiciously to achieve the significantly low propagation loss. The obtained results have depicted that for a fixed value of propagation loss (3 dB/cm), the full-strip-loaded slot waveguide has the highest EFR (0.28), as well as highest sensitivity (73.76 L/Mol), which is closely followed by the partial-strip-loaded slot waveguide, with their respective values of 0.27 and 72.5 L/Mol. Further, the current work can be extended for design and analysis of the efficient and reliable photodetector with high sensitivity, to increase the performance of the gas sensors.

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