



Designing absorbers for graphene based mid-infrared wide band waveguide photodetectors

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Abstract: The mid-infrared (MIR) spectral region is of great importance in scientific and real-world applications ranging from detecting forming planets to identifying molecular species for industrial process control. Existing instrumentation to perform analyses is neither low cost nor compact, robust, or low power consumption, presenting opportunities for a planar integrated MIR sensing device to cost effectively detect and extract information on a widespread scale and in handheld devices. A key missing element in this vision is low cost waveguide photodetectors, which can cover the necessary wavelength range and are made with a wafer scale process. Graphene based detectors could fill this void. A parametric study is presented on broadband light absorption in graphene on waveguide devices of varied designs, index contrasts and dimensions. Generic design information is provided, and Genetic Annealing algorithms combined with Finite Element modal analysis provide a shortest design of 121 μm long that absorbs >90% of light from 1 to 10 μm , and a wide range of designs under 500 μm long. This shows for the first time that 2-D material based broadband waveguide MIR photodetectors could be viably integrated in MIR planar optics devices.

1. Introduction

The potential of MIR spectroscopy for molecular compositional analysis and bond structure sensing is of great scientific and technological importance. Traditionally, work in the MIR region has relied on the Fourier Transform Infrared (FTIR) spectrometer, but this is not a system suitable for mass deployment, low cost devices, or systems operating in mechanically noisy environments due to the need for precision linear scanning mechanical stages. The advent of high power quantum cascade laser diodes [1], MIR supercontinuum sources [2], and promising compact dual comb sources [3,4] offer new opportunities for MIR detection, but do not address low cost wideband sensing in their current incarnations. The rapidly developing field of MIR planar waveguide integration promises small, robust, low cost, vibration insensitive MIR sensors, and recent advances in on-chip broadband MIR supercontinuum generation [5] and CW pumped MIR comb generation [6] are suggesting high power, broad bandwidth, on-chip sources for analysis may become feasible. Demonstrations of many important MIR sensor system components have been made, for example, low loss wide bandwidth waveguides principally in Germanium and Chalcogenide glass based systems [7–12], high power broadband sources [5], planar MIR spectrometers [13] and integration of high power Quantum Cascade Lasers on chip [14] have drawn the reality of chip scale MIR sensor systems closer. However, the key missing element to attaining a MIR sensor on-chip is low cost, broadband MIR waveguide detectors, especially in an array form as needed for spectrometers. Ideally, such detectors should leverage the relatively high power MIR sources available to avoid the need for cooling, and possess high linearity at up to tens of milliWatt input levels for accurate photometric measurements with wide dynamic range.

To this end, a new low cost wafer scale planar photonics MIR detection technology is needed. Two dimensional materials show great promise for integrated photonics [15–18], and graphene in particular is a strong potential candidate as an MIR detector material due to its zero band gap and linear dispersion relations [19,20], having demonstrated a wavelength independent ~2%

normal incidence absorption throughout the MIR region [21,22]. However, the low normal incidence absorption significantly limits detector efficiency and to get strong absorption it is necessary to integrate graphene with waveguides to increase the interaction length by many orders of magnitude. Importantly, graphene is compatible with established integrated electronics and photonics [23–25], making low cost and large scale integration into planar circuits feasible [26,27].

To date there have been some waveguide based graphene photodetector demonstrations at NIR wavelengths [23,24,28–33], and a limited number in the MIR [25,34–36]. An absorption up to 9350 dB/cm and 7860 dB/cm for TE and TM mode respectively was obtained with graphene-on-silicon slot waveguides at a wavelength of 1.55 μm [30]. An integrated Chalcogenide glass waveguide with graphene detector reached 80 dB/cm absorption at 2.03 μm for TE polarization [34]. The operating wavelength was further extended to 3.8 μm with 150 dB/cm for the TE mode absorption by an asymmetric electrode graphene-on-silicon waveguide detector [36]. However, no graphene-based waveguide device design covers the 1–10 μm band. A knowledge gap exists regarding suitable device designs for broadband absorption and integration methodologies with broadband MIR waveguide technologies.

This paper presents the results from a detailed design study aimed at filling this knowledge gap. Parametric design information is presented and made available covering several waveguide designs, geometry variations, graphene configurations, and refractive index (RI) contrast regimes across the 1–10 μm spectral range. From this several alternative designs offering high absorption, but differing degrees of fabrication difficulty are presented showing that broadband MIR waveguide photodetectors are viable. To the author's knowledge this is the first parametric study of broadband absorption in graphene on waveguide devices, and the first time that optimised wideband detector absorber designs of practical dimensions are presented.

2. Simulation method

Numerical simulation of graphene photodetector structures was performed based on the Finite Element Method (FEM) as embodied in RSoft FemSIM. In each simulation the fundamental modes of the waveguide were selected and analysed. An example of a simulated structure is shown in Fig. 1. For this graphene covered, fully etched waveguide, the geometry dependence (the waveguide width and height) and RI contrast dependence (of the top and bottom cladding and the waveguide core material) were investigated to determine the absorption in the wavelength range 1–10 μm for both TE and TM polarization. The wavelength range matches most of the commercially available MCT detectors and FTIR instruments, also covering the scientifically and industrially important molecular fingerprint region.

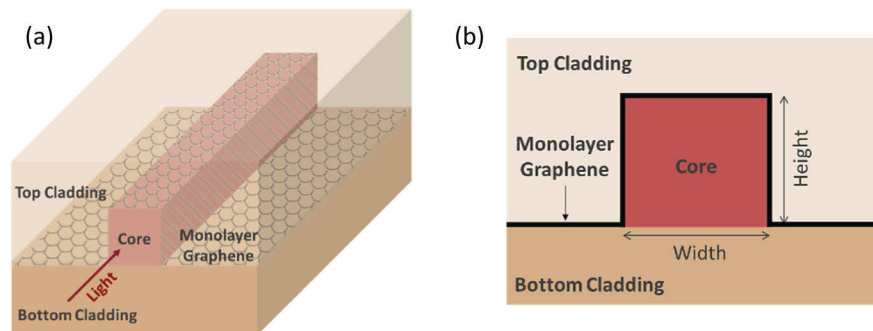


Fig. 1. The simulated graphene covered fully etched waveguide design. (a) Schematic of the waveguide structure. (b) Cross-section of the waveguide design.

The direction of incident light, for all subsequent simulations, is annotated in Fig. 1. The thickness of the monolayer graphene was modelled according to [30] with Fermi level $E_F = 0$ eV. The zero Fermi energy case was chosen as this offers the best opportunity for wideband absorption. The waveguide absorption (optical loss) was calculated from FEMSIM using the refractive index of graphene derived from the optical conductivity using the Kubo formula [37]. Figure 2 shows the complex dielectric constant of graphene calculated from the model and the absorption as a function of wavelength.

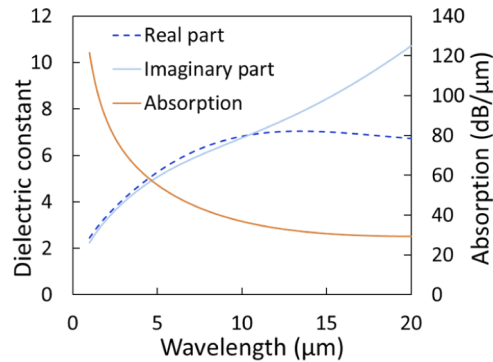


Fig. 2. Graphene dielectric constant real part, imaginary part and the absorption plot for Fermi level $E_F = 0$ eV in dash blue, light blue and orange respectively.

Using the model as shown in Fig. 1 to study the geometry dependence, simulation of the absorption for different waveguide designs with width and height both varying from 0.1 to 5 μm was carried out to determine the high absorption regions for different wavelengths. Larger waveguide designs were also simulated, but the absorption reached a saturated threshold beyond 5 μm in low index contrast devices and the high absorption region was contained in this domain for higher index contrasts. In the model, the solution grid was graded at the interfaces to provide a much finer grid so that even the graphene had at least five grid points through its thickness to ensure the complex propagation constant took full account of the graphene layer. The refractive indices investigated were 1, 1.5, 2.5 for claddings and 2.6, 3.5 and 4.5 for the waveguide cores. These correspond to a range of MIR transparent materials from air claddings through membrane suspension to Fluorides and various chalcogenides to Germanium as core materials, examples of such materials being listed in Table 1.

Table 1. MIR transparent waveguide core and cladding material refractive indices at 5 μm

Cladding Materials	Cladding RI	Core Materials	Core RI
Air (Membrane suspended)	1	$\text{Ge}_{11}\text{As}_{24}\text{Se}_{65}$	2.6
		Si	3.5
CaF_2	1.4	$\text{Ge}_x\text{Te}_{1-x}$	3.4-4
		Ge^a	4.5
$\text{Ge}_{33}\text{As}_{12}\text{Se}_{55}$	2.5	$\text{Pb}_x\text{Se}_{1-x}$ ($>5 \mu\text{m}$)	4.5-4.9
		$\text{Pb}_x\text{Te}_{1-x}$ ($>5 \mu\text{m}$)	4.8-5.8

^aThe RI of Ge from Ref. [38]

Absorption maps were produced across the 1 to 10 μm wavelength range as functions of width and height for both fundamental mode polarizations for each waveguide design and several

graphene configurations. Rib and fully etched waveguides were studied, and the graphene location was varied from covering the core to being embedded under the core.

3. Simulation results and analysis

Absorption maps were produced for the parameter ranges set out above. There are considerable variations in the map topographies, and here the two extreme examples are presented. The first is a waveguide with a cladding RI of 2.5 and a core RI of 2.6, giving a refractive index contrast (RIC) of 0.1 which corresponds to a typical core/clad material set for a moderate index contrast single mode chalcogenide glass waveguide. The absorption map is shown at 5 μm and 10 μm wavelengths and for both TE and TM polarisations in Fig. 3(a)–3(d).

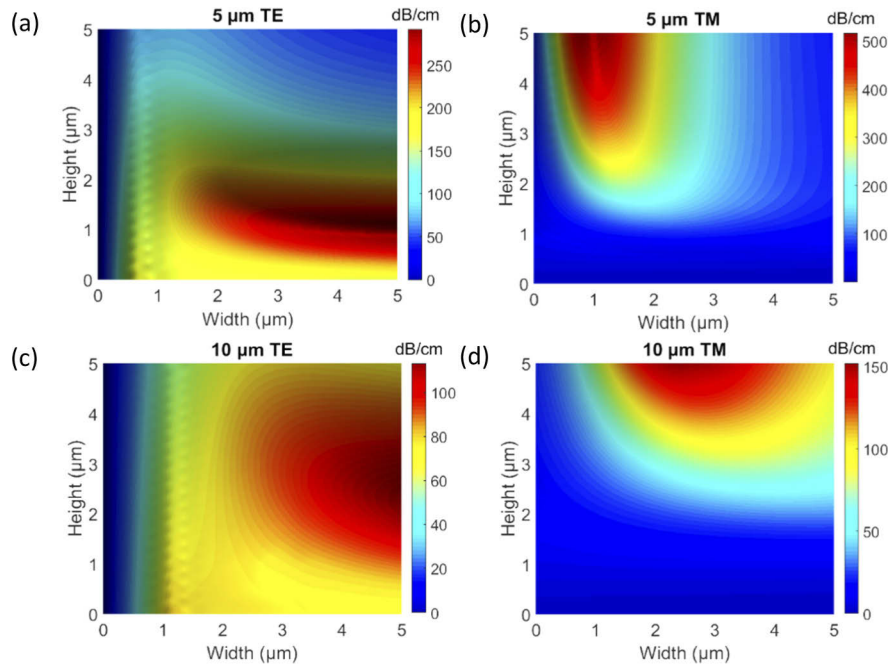


Fig. 3. Absorption maps for cladding RI of 2.5 and a core RI of 2.6 for TE and TM modes at 5 μm (a)–(b) and 10 μm (c)–(d) as a function of waveguide height and width, step size is 0.15 μm .

At 5 μm the peak absorption of the TE mode is 312 dB/cm, which occurs where the waveguide height (H) and width (W) are 0.95 μm and 4.8 μm respectively. To make sure the peak absorption had been reached, a scan of the absorption with fixed height 0.95 μm and width beyond 5 μm was taken with the result showing the absorption did not increase further remaining at about this level. Similar scans were carried out for TM polarization (fixed width 0.95 μm and increased height) also at other wavelengths with the same conclusion. This might be explained as the total absorption is proportional to the product of the electric field and the graphene cross sectional area. The electric field at the graphene interface decrease almost linearly with further increases in width/height for TE/TM modes at the edge of the domain as the waveguide mode asymptotes towards a 1-D slab waveguide. This is compensated for by a linearly increased width/height of the waveguide, as well as the graphene area to interact with leading to an almost constant absorption. This was a property restricted to low index contrast devices, as will be seen. For the TM mode the highest absorption is 551 dB/cm at H and W of 4.8 and 0.95 μm respectively. The peak absorption area for TE mode shifts to larger widths and for TM mode it shifts to increased

heights as the wavelength increases as shown in Fig. 3(c)–3(d). At 10 μm the peak absorption of the TE mode and TM mode are 121 dB/cm (at $H = 2.25 \mu\text{m}$ and $W = 4.9 \mu\text{m}$) and 161 dB/cm (at $H = 4.92 \mu\text{m}$ and $W = 2.52 \mu\text{m}$) respectively, significantly lower than at 5 μm and exceeding the $\sim 2\times$ reduction in the graphene absorption itself shown in Fig. 2. By comparing the absorption data for both TE and TM polarization, the locus where the TE mode absorption equals the TM mode absorption could be found, this producing a detector with no polarization dependence which is important for many real world optical systems where wide optical bandwidth polarization control is challenging. The highest absorption under this condition is 212 dB/cm ($H = 1.8 \mu\text{m}$ and $W = 1.95 \mu\text{m}$) at 5 μm and 94 dB/cm ($H = 3.51 \mu\text{m}$ and $W = 3.8 \mu\text{m}$) for 10 μm respectively.

The highest absorption for TE mode, TM mode and TE absorption = TM absorption over the 1–10 μm wavelength range are plotted in Fig. 4. At short wavelengths, much higher absorption can be achieved. From a wavelength of 1 μm this absorption drops off by just over one order of magnitude by 10 μm , likely as the electric field at the graphene is reducing as the mode field grows larger at longer wavelengths and as the graphene absorption falls with wavelength. This indicates that detector designs will need comparatively long sections of waveguide designed specifically to absorb the light at the longer wavelengths in low index contrast devices.

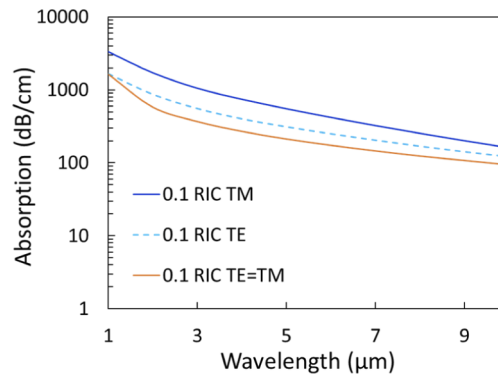


Fig. 4. Absorption plot of the RI=2.5 cladding and RI=2.6 core waveguide design as a function of wavelength.

As a comparison, using the same core and cladding combination, simulations were run for various different waveguide structures and graphene locations, the results being plotted for the maximum absorption with varied waveguide dimensions vs wavelength in Fig. 5. As shown in Fig. 5(a) for the TE mode, the fully etched waveguide with graphene on top possess the highest absorption at shorter wavelengths, then has similar absorption to the other designs at longer wavelengths. For the TM mode, there is an obvious advantage to using graphene on top of the fully etched waveguide compared to the other two designs over all wavelengths, as shown in Fig. 5(b). For devices operating in a single polarisation, it is clear that TM mode is optimum and that fully etched is the best option. For the TE polarisation, at longer wavelengths the graphene at the bottom of a fully etched waveguide could be a better choice for detection due to decreased fabrication difficulty when low temperature physical vapour deposition can be used. For broadband TE/TM absorption, the fully etched waveguides with graphene on top possess the highest absorption among all the designs. Devices with such structure have been experimentally demonstrated and the measurement results are in good agreement with the simulations [24,25,32]. Considering there might be a small gap between the graphene and the waveguide sidewall due to the imperfect graphene transfer simulations with an angle between graphene and sidewall up to 30 degrees were performed to identify the influence of the gap. The results indicate the TM absorption is not impacted as most of the TM absorption occurs at the waveguide top surface. The

difference in TE absorption is typically around 5 - 10% (depending on the waveguide cladding and core materials) and therefore not a significant concern.

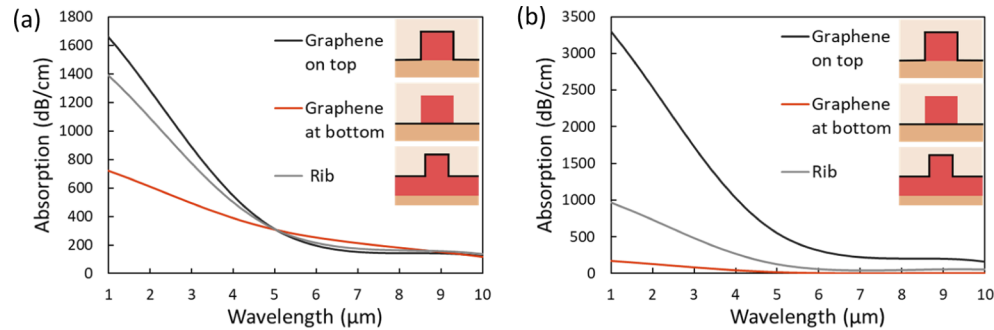


Fig. 5. Maximum absorption plot as a function of wavelength of the RI 2.5 cladding and RI 2.6 core with a fully etched waveguide with graphene on top (black), with graphene at bottom (red) and a 50% etched rib waveguide with graphene on top (grey) for TE (a) and TM (b) modes.

To examine how the RIC impacts the waveguide absorption; simulations of the fully etched waveguide with graphene on top, but with higher RIC, were performed. At the extreme, results for a waveguide with an air cladding and core RI of 4.5 (equivalent to a membrane suspended Ge or telluride chalcogenide cored waveguide), giving an RIC of 3.5, is illustrated in Fig. 6. The absorption map at 5 μm and 10 μm wavelengths and for both TE and TM polarizations are shown. The highest absorption for the TE and TM modes at 5 μm is 6235 dB/cm and 4263 dB/cm respectively and 2670 dB/cm and 1968 dB/cm respectively at 10 μm . These are approximately two orders of magnitude higher than the RIC 0.1 design. The significant increase of single polarization absorption also enables an area with higher TE = TM absorption, the maximum TE = TM absorptions found were 3207 dB/cm and 1594 dB/cm at 5 μm and 10 μm respectively.

As can be seen from Fig. 6 as the refractive index contrast rises, so too does the peak absorption which is likely due to better mode confinement increasing the intensity of the light at the point where it interacts with the graphene. The peak absorption occurs across a much narrower area of the modelled domain with only a very limited height and width combination. To better judge the impact of the RIC, which is the key potentially controllable factor to influence the absorption, it is useful to compare different RICs ranging from 0.1 to 3.5 as a function of wavelength.

To simplify the data presentation, the peak absorptions for both polarizations and the TE = TM absorption were extracted and plotted against wavelength for all RICs studied as shown in Fig. 7. Having mapped the absorption across a range of waveguide designs and wavelengths, some key points emerge. First, high waveguide core and cladding RI contrast will dramatically increase the absorption over all wavelengths. Hence, the 3.5 RIC design at 2 μm gives a TE mode peak absorption 14604 dB/cm, nearly 200 times larger than the reported value of an Chalcogenide glass rib waveguide with air cladding, giving RIC around 1 [34]. Second, TM absorption is larger than TE when RIC is lower than 2; TE, TM absorptions reach a similar level when RIC is around 2~3, and TE takes over for the highest value when RIC is greater than 3. Lastly, the results in Fig. 6 also show that the maximum absorption waveguide profile varies considerably with wavelength which suggests that delicate design of the waveguide geometry is required to maximise broadband absorption, thus tapered waveguide designs become a necessity. The absorption map is available for download in the supplemental materials [Dataset 1](#) (Ref. [39]).

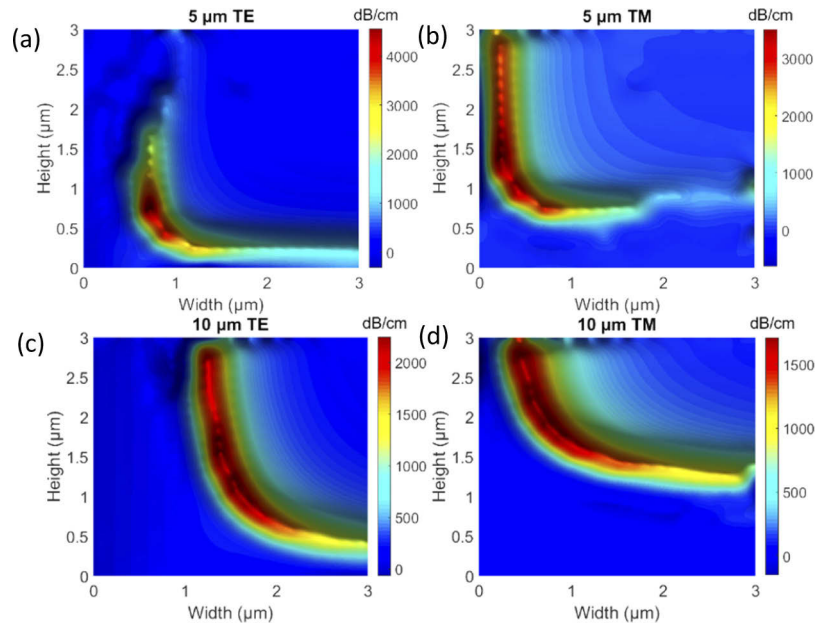


Fig. 6. Absorption maps of the RI 1 cladding and RI 4.5 core waveguide design for TE and TM modes at 5 μm (a)-(b) and 10 μm (c)-(d) as a function of waveguide height and width.

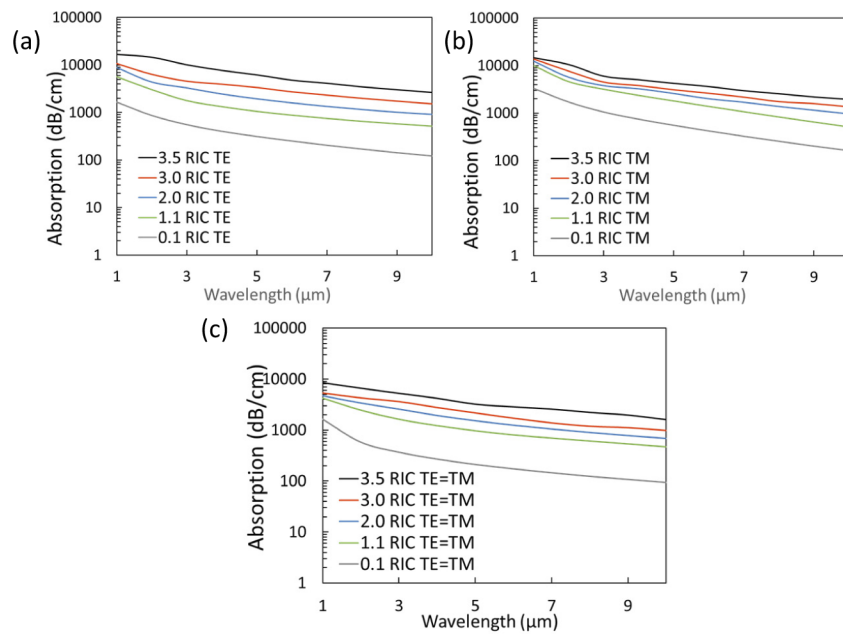


Fig. 7. Absorption over wavelength plot of RIC 0.1 –3.5 designs for (a) TE mode, (b) TM mode, (c) TE = TM absorption.

4. Tapered waveguide design

The data presented above illustrate that the waveguide dimensions for optimal absorption vary considerably with wavelength, so a tapered waveguide design is optimal but the required taper function is unknown. Based on the absorption maps, an initial simplistic approach to the design of tapered waveguides is to segment the waveguide length into ten sections, each section designed optimally for one wavelength. If the required absorption of each segment is 10 dB, then the segment length can easily be calculated from the peak absorption. The dimensions were then determined by the height and width of the peak absorption. Each segment of the waveguide was tapered and linearly connected to the nearest sections. One constraint placed on the taper shape was that it has to be monotonically decreasing in the height dimension so that it is a potentially physically realisable shape by methods such as shadow masked deposition [40]. Waveguide propagation loss was assumed to be negligible in these calculations, which is reasonable given that the lowest absorptions noted above are in the hundreds of dB/cm at 10 μm and much higher at shorter wavelengths compared for example with 0.4 dB/cm for silicon nanowire waveguides (RIC 2.5) at 1550 nm [41]. Further sidewall scattering induced losses that are normally the dominant loss source in high RIC waveguides are roughly inversely proportional to wavelength squared and so becomes less significant at longer wavelengths anyway. Following the lead of the previous section, detailed results for the two extremes are again presented; the 4.5 RI core with a cladding index of 1 (RIC of 3.5 simulating a hypothetical Ge or Tellurium chalcogenide glass on membrane air clad waveguide) and the waveguide with an RIC of 0.1 utilising a core index of 2.6 with a cladding index of 2.5 (equivalent to commonly used single mode chalcogenide MIR waveguides). Waveguide taper length for the simplistic approach versus RI contrast is plotted in Fig. 8. The high RIC design dramatically reduces the length of the device. It is also noted that by increasing the RIC up to 1.1 or higher, the waveguide taper total length for TE, TM mode and TE = TM detection could be shortened to less than 1 mm, making it much easier to fabricate as large areas of defect free graphene are challenging.

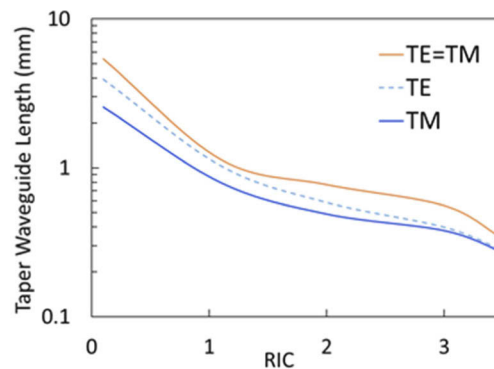


Fig. 8. Taper waveguide total length as a function of RI contrast using segment method.

For a 0.1 RIC, the waveguide taper shape has the profile shown in Fig. 9(a)–(c), giving a total length 3.93 mm for TE mode, 2.56 mm for TM mode and 5.4 mm for both polarizations. Whilst this design certainly provides high absorption, it is not ideal for chip integration and it would be advantageous to minimise the detector length to better improve the electrical bandwidth, noise, integration density, ease of fabrication and cost. For comparison, Fig. 9(d)–(f) shows the height and width of the 3.5 RIC design. The total waveguide length was reduced to 0.19 mm and 0.27 mm for TE and TM respectively, and 0.33 mm for absorbing both TE and TM modes. Due to the narrow peak absorption area of the high RIC design at each wavelength and discretisation

flaws in the absorption map, the height and width profile are less smooth compared with the low RIC ones.

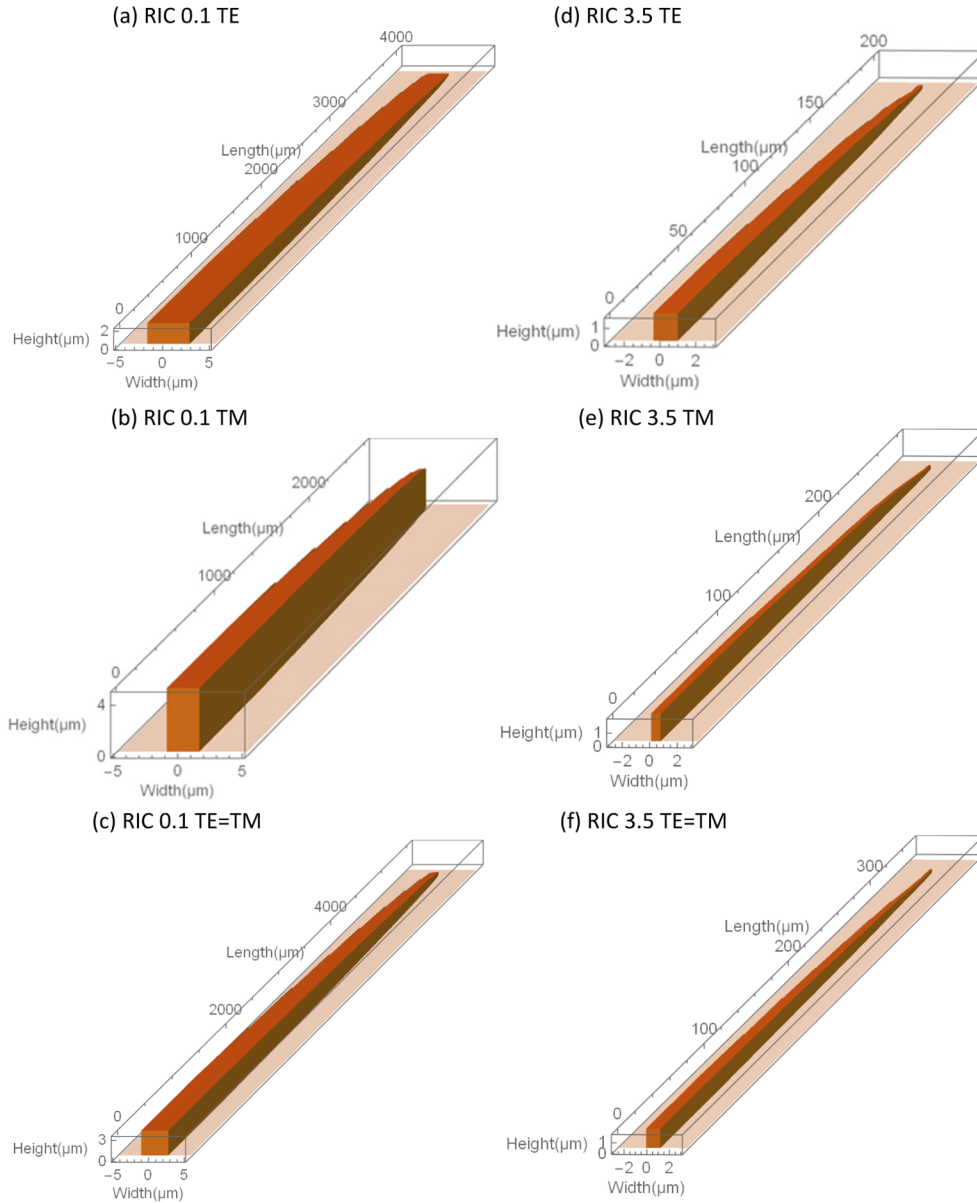


Fig. 9. Taper waveguide profile for RIC 0.1 designs (a) TE mode, (b) TM mode and (c) for both TE and TM mode detection. Taper waveguide profile for RIC 3.5 designs (d) TE mode, (e) TM mode and (f) for both TE and TM mode detection.

The simplistic design is however expected to be far from optimal as it ignores the absorption of other wavelengths in preceding sections of the taper. A typical approach to improving the design would be to use an optimiser with a propagation solver based on either the Beam Propagation Method (BPM), Eigenmode Expansion Analysis (EEA), or Finite Difference Time Domain (FDTD) methods in 3D full vector mode. However, the very thin graphene layer and many wavelength long structures cause a considerable problem with this way forward. The commercially

available BPM code cannot operate with a non-uniform grid in full vector mode meaning it cannot capture the graphene effects, and is not computationally stable as well as requiring massive computational resources with the grid size required to include the graphene. The EEA method can overcome the issue with the graphene layer as it can incorporate a non-uniform mesh, but as each simulation for a specific design at a given wavelength required several hours of computation it was too slow to be usable with an optimiser. FDTD can again use a variable mesh but the resources required for the domain sizes considered again made this approach too slow.

A simpler approximate waveguide detector optimization tool based on Genetic Annealing (GA) algorithms was therefore implemented to find the shortest detector designs. The program segmented the waveguide length and varied the cross-sectional dimensions of each segment, utilising the absorption map data to minimise the required device length to absorb at least 90% of the light at each wavelength and polarisation (i.e. 10 dB absorption). When the absorption was equal or higher than the required value at a wavelength, the cost value at that wavelength was set to zero. The cost function for the annealing process was the sum of the cost values for each wavelength. When the cost function equalled zero, the design iteration met the requirements and all the parameters were saved. The segments were then shortened by 10% and an improved solution sought, the process repeating until an improved solution did not emerge. One constraint placed on the taper shape was that it had to be monotonically decreasing in the height dimension so that it was a shape potentially physically realisable by methods such as shadow masked deposition [40]. A further constraint was placed on the amount by which the height of each

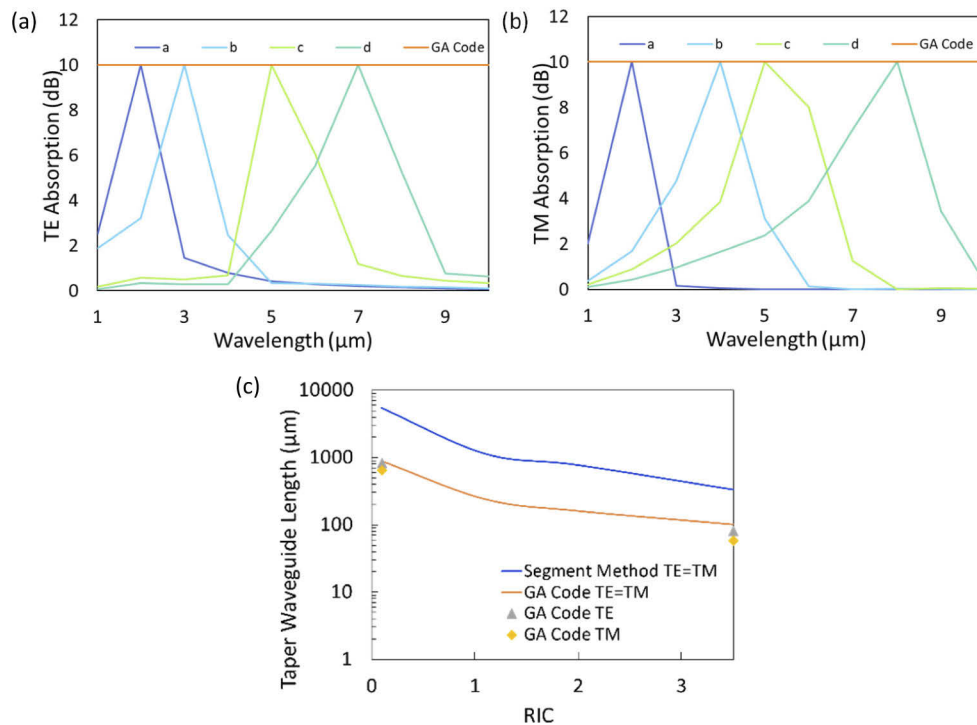


Fig. 10. Comparisons of GA RIC 3.5 waveguide taper absorption (a) TE and (b) TM mode for ≥ 10 dB absorption across the 1–10 μm waveband with the same length, fixed height and width waveguides a, H: 0.33 μm W: 0.3 μm , b, H: 0.72 μm W: 0.45 μm , c, H: 0.85 μm W: 0.78 μm , d, H: 1.24 μm W: 0.99 μm . (c) Detector length vs RIC for GA tapers having ≥ 10 dB absorption across the 1–10 μm waveband for TE = TM (orange line) and single polarization (grey and yellow dots), compared with segment method (blue line).

segment could decrease relative to the previous one to reduce the number of inappropriate designs generated by the mutation process to speed up convergence. This simplified model assumed that there was no mode conversion in the taper as it considered only the fundamental modes, and also assumed that no light was lost to radiation coupling. The validity of these approximations was checked on several of the final designs using the EEA method (Photon Design FIMMprop) and this indicated minimal impact of the above effects and the EEA model produced equal or larger absorption than the simplified model for the devices tested indicating the designs do indeed have ≥ 10 dB of actual absorption at all wavelengths.

Figure 10(a)-(b) show the comparison between the GA generated RIC 3.5 taper waveguides (the orange line indicating a minimum 10 dB absorption in the 1–10 μm wavelength range) with several fixed height and width fully-etched waveguide designs with the same length as the GA taper designs. The fixed H/W waveguide profiles were chosen from the single wavelength peak absorption map. These indicate the relative absorptions of different sections of the taper with wavelength and also show how detectors optimised for particular wavelengths are possible for use in spectrometer arrays for example. The GA taper waveguide design both enables shortening of the waveguide length and broadband absorption.

A comparison between the GA taper waveguide total length and the simple segment method as a function of RIC is plotted in Fig. 10(c). The GA method reduced the waveguide length significantly for all RIC designs. It was more effective for the lower RIC cases: for RIC 0.1 the waveguide length was shortened from 5403 μm to 880 μm . For the RIC 3.5 case the waveguide length was shortened from 334 μm to 121 μm . These length reductions significantly increase the

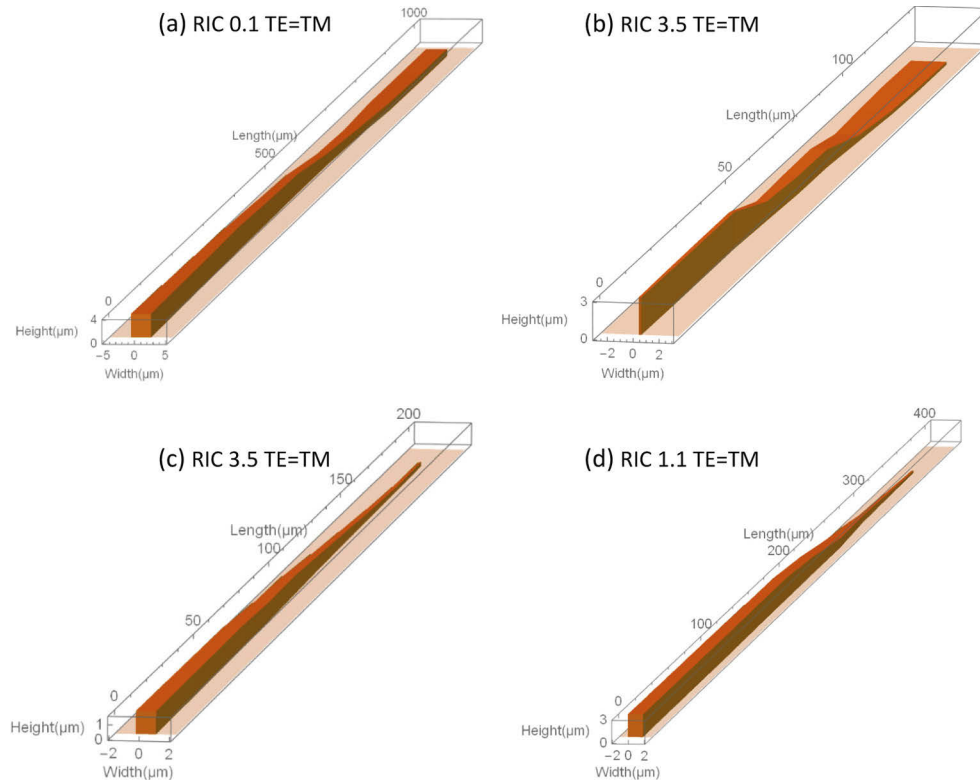


Fig. 11. GA taper waveguide profiles for TE and TM detection with (a) RIC 0.1 and a length of 880 μm , (b) RIC 3.5 and a length of 121 μm , (c) RIC 3.5 and a length 187 μm . (d) RIC 1.1 and a length 361 μm .

actual detector fabrication feasibility as single crystal high mobility domain sizes using CVD graphene growth are currently limited to a few hundred microns [42]. Given this practical limit, Fig. 10(c) also shows the RIC of the taper waveguide design should be greater than 1 to achieve a detector length shorter than 200 μm .

Figure 11(a,b) shows the spatial profiles of a GA designed polarisation insensitive RIC 0.1 taper waveguide with a total length of 880 μm , and a RIC 3.5 taper waveguide with a total length of 121 μm respectively. From the profile it is clear to see that the RIC 0.1 waveguide is achievable in terms of fabrication, however the shortest RIC 3.5 design with high aspect ratio structures dramatically increases the fabrication difficulty. A slightly longer RIC 3.5 taper waveguide with a total length 187 μm and a 361 μm RIC 1.1 taper waveguide with more easily fabricatable profiles were generated by the GA code and are presented in Fig. 11(c) and (d), indicating that it should be possible to realise practical devices with available waveguide and high quality graphene fabrication technologies.

5. Conclusion

This paper presented the first, to the author's knowledge, deep geometry and RIC analysis of broadband MIR graphene waveguide detector absorber designs. It verified that it is possible to make relatively short length, high absorption broadband devices. By using a Genetic Annealing algorithm, tapered waveguide designs which absorb 90% of all light from 1 to 10 μm were developed for the first time. A range of practical length taper designs absorbing both TE and TM modes for different index contrasts were identified with total device lengths of ranging from 121 μm to 880 μm , dimensions that are feasible based on current graphene and waveguide fabrication technology. An index contrast greater than one is required to attain lengths 300 microns and less. This work provides the foundation stone for the development of broadband graphene-based MIR waveguide detectors and arrays and presented possible architectures to achieve the first broadband MIR waveguide detectors.

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Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are available in [Dataset 1](#), Ref. [39].

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