

Graphene-enabled coherent terahertz wave detection and thickness determination

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Abstract

Coherent detection and interferometry in the terahertz (THz) regime are key capabilities that enable applications ranging from astronomy to non-destructive testing. Phase-sensitive THz detection is currently achieved using nonlinear crystals or external interferometers and photomixers. However, the former approach requires femtosecond pulsed radiation, and all approaches suffer from a large footprint and sensitive alignment. Here, we demonstrate a graphene-enabled, on-chip, integrated THz detector-interferometer with optical cavity and antenna, exhibiting high sensitivity to the phase of incident THz light. We exploit this by determining the thickness of thin films placed in front of the detector-interferometer, obtaining a strongly sub-wavelength thickness accuracy of ~ 5 nm, while we predict that an accuracy of 10 nm is within reach. This is relevant for a range of industrial application domains, including automotive, construction, and health. The detector-interferometer moreover exhibits a record-high external responsivity – without any normalization to a diffraction-limited spot size – of 73 mA/W and a noise-equivalent power of 79 pW Hz^{-1/2}. This performance is due to enhanced absorption at the cavity mode around 89 GHz, in agreement with multi-physics simulations. These results pave the way to exploiting coherent wave detection in the THz regime with utility in spectroscopy, next-generation wireless communication, and beyond.

Keywords: terahertz, photodetection, graphene, interferometer, thickness determination

Coherent wave detection, which exploits phase information instead of the amplitude or intensity of incident light, is an essential tool that lies at the core of many scientific and engineering fields. A common way to implement coherent wave detection is through wave interference [1, 2]. Phase-sensitive detectors and interferometers in the THz regime are particularly desirable for a wide range of applications, where the use of conventional ranges of the electromagnetic spectrum is limited [3, 4]. For example, in astronomy, the detection of specific cosmic THz radiation allows diving into the formation of planets and galaxies in the far regions of the Universe [5–7]. Coherent THz detection also reinforces security applications [8–10] and non-destructive testing in the automotive, building and construction, and electronics industries. A prime example is the determination of the thicknesses of thin, visible-opaque coatings and

films, such as car paint layers [11–14]. Coherent THz detection can also lead to a speed-up of wireless telecommunication systems [15, 16], where phase-sensitive data transfer schemes are combined with a high-frequency carrier wave [17], and in quantum key distribution systems [18, 19].

In the most common coherent THz detection approaches, the amplitude and phase of weak THz signals are measured through heterodyne and homodyne detection [7, 20–22]. This is the case for THz time-domain spectroscopy, where THz pulses are detected through electro-optic sampling in nonlinear crystals followed by balanced photodetection [23–25]. This is also the case for continuous wave spectroscopy in photomixers [26, 27]. For coherent THz detection through interferometry, typically external optical setups, such as Michelson and Fabry-Pérot interferometers, are used, after which a photodetector registers the interference pattern of the mixed waves [28, 29]. These approaches generally have a large footprint, as they require external optical components, such as a delay line, nonlinear crystals, additional light emitters, *etc.* They are also sensitive to precise alignment, consume significant power, and can be rather costly.

We overcome these limitations by developing an integrated graphene THz detector that is simultaneously an interferometer through its combination with a vertical THz cavity that is formed between a metallic antenna and a metallic back mirror (see Fig. 1). The absorption enhancement in the cavity, together with the strong photo-thermoelectric response of graphene, gives rise to an external responsivity of 73 mA/W and an external noise-equivalent power of 79 pW Hz^{-1/2}. The detector does not require any bias voltage, resulting in minimal power consumption. Because of the large responsivity, the interference effects in the cavity, and the ultrathin photoactive area formed by the graphene, this integrated THz detector-interferometer

enables highly phase-sensitive THz photodetection. Scanning the detector along the THz propagation path enables determination of the thickness of optically opaque materials, which we demonstrate using silicon, paper, kapton, and polypropylene. The thickness accuracy we achieve is limited by the phase stability of our THz setup and electronic noise, while a phase-stable THz source and Johnson-noise-limited detector would lead to an accuracy down to 10 nm. Beyond thickness determination, this coherent THz detector-interferometer opens up a myriad of possibilities.

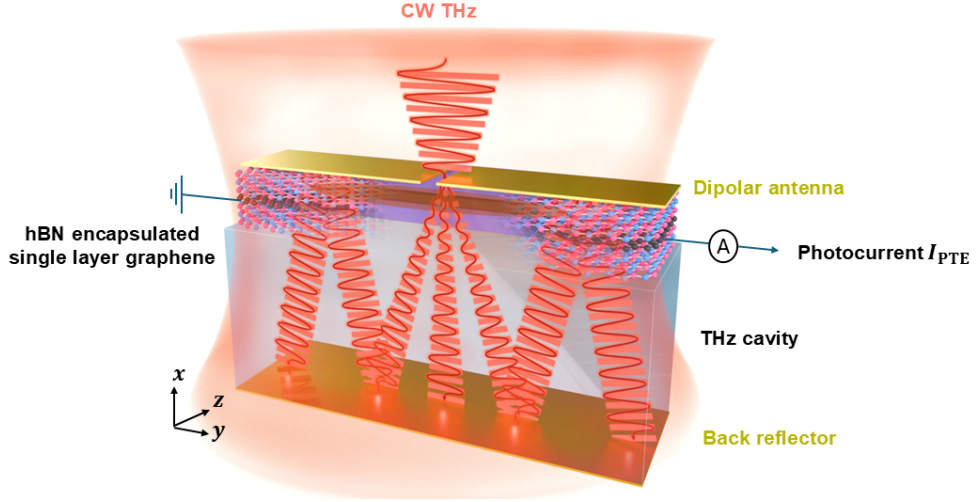


Fig. 1: Schematic of the integrated graphene-based THz detector-interferometer. The device contains hBN-encapsulated graphene underneath a dipolar antenna. The photo-active region is the graphene channel below the gap of the dipolar antenna. This channel has side contacts (not shown) that enable us to measure photocurrent. The antenna and the metallic back mirror form an optical cavity, where incident (THz) light can travel back and forth and interfere. The THz cavity consists mostly of silicon.

Results

Device and signatures of interference

We fabricated a graphene-based detector that includes a built-in vertical optical cavity, which leads to multiple reflections and constructive and destructive wave interference. The choice for graphene is based on its large Drude absorption [30, 31], and the promising THz photodetection performance that has recently been demonstrated [32–38]. The atomically thin photoactive region furthermore minimizes the broadening of interference peaks. We optimized the detector specifically for the photo-thermoelectric effect, which simultaneously offers high sensitivity, fast response, broad spectral response, and passive operation [39–45]. The detector contains a dipolar antenna that funnels THz radiation to the photoactive graphene area, and its two branches serve as electrostatic gates to create a junction in the graphene channel [39, 46]. The antenna also serves as one of the two reflecting surfaces of the optical cavity, while the other surface consists of a metallic back mirror. In between the two reflecting surfaces, there is mainly silicon with a thickness of 279 μm , in addition to hBN-encapsulated graphene, which is directly below the antenna, as shown in Fig. 1 (see [Methods](#) for details).

We first characterize our device by measuring the photocurrent I_{PTE} as a function of frequency f using a commercial continuous-wave THz setup (see [Methods](#)). The results in Fig. 2a show a strong photocurrent peak at $f_{\text{peak}} = 89$ GHz, corresponding to a free-space wavelength of $\lambda_0 = 3.35$ mm. We ascribe this to positive interference at the location of the photoactive graphene area, which occurs for a cavity with a length L equal to $\frac{\lambda_0}{4n_{\text{THz}}}$. This gives a THz refractive index of $n_{\text{THz}} = 3.1$, which is close to the expected refractive index of silicon of 3.4 in the THz range [47]. Examining the width of the photocurrent peak f_{width} , we extract a quality factor of $Q = f_{\text{peak}}/f_{\text{width}} = 74$ for the internal cavity formed between the metallic antenna and the metallic back

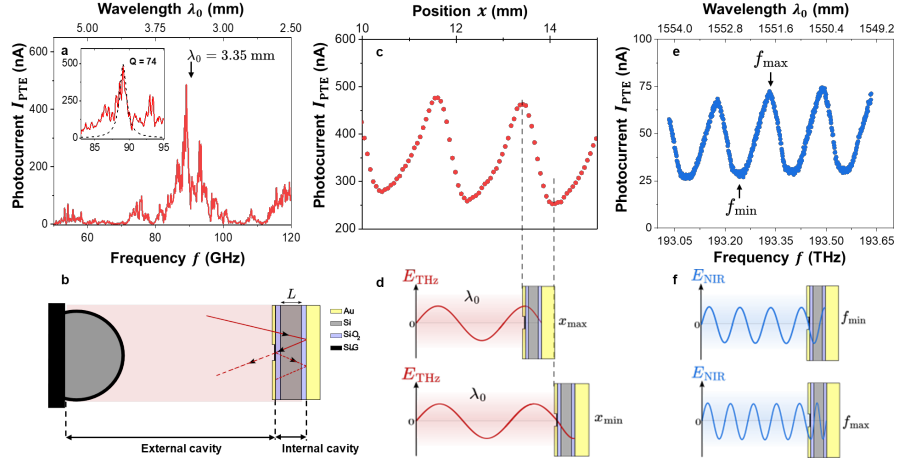


Fig. 2: Spectral and spatial signatures of interference. **a**, Measured photocurrent as a function of frequency f (wavelength λ_0), where a main peak occurs at 89 GHz (3.35 mm). The inset presents a zoom of the main peak with a Lorentzian fit (dotted black line). **b**, Schematic of the relevant internal and external cavities. The photocurrent peak corresponds to the situation where reflections in the internal cavity lead to constructive interference at the graphene location. The thinnest cavity for which this occurs is when $L = \frac{\lambda_0}{4n_{\text{THz}}}$. **c**, Measured photocurrent at 89 GHz while moving the detector along the light propagation direction x . The oscillatory pattern has a maximum (minimum) at position x_{max} (x_{min}), with $|x_{\text{max}} - x_{\text{min}}| = \lambda_0/4$. **d**, Schematic of the experimental geometry when moving the detector in the x -direction. Maxima (minima) occur when the incident field at the graphene position has a maximum (minimum). **e**, Measured photocurrent as a function of frequency in the near-infrared (NIR) range, showing periodic oscillations with maxima f_{max} and minima f_{min} . **f**, Representation of the interference conditions at telecom frequencies, where the frequency spacing is determined by the internal cavity via $|f_{\text{max}} - f_{\text{min}}| = c/4n_{\text{NIR}}L$.

mirror. In addition to the main photocurrent peak, we observe periodic peaks around the central frequency. We attribute these to the external cavity that is formed between the detector and the THz source, as shown in Fig. 2b. We will discuss this in more detail in the subsection that describes the finite-difference time-domain simulations.

To further study interference effects in our device, we map the occurrence of constructive and destructive interference by moving the detector position along the THz propagation axis (out-of-plane direction x , see Fig. 1) for incident light at 89 GHz, see Fig. 2c. The result looks like a typical interferogram with maxima and

minima. The periodicity of the signal is 1.79 mm (see Appendix Fig. 1), which is very close to $\lambda_0/2$. For incident light with a frequency of 160 GHz, we observe a similar interference pattern, now with a periodicity of 0.98 mm, which is again very close to $\lambda_0/2$ (see Appendix Fig. 1). We therefore ascribe the observation of the occurrence of maxima and minima in photocurrent to the occurrence of maxima and minima in the intensity of the electric field of the incident THz light at the graphene position, as shown in Fig. 2d. This confirms that our detector works as an interferometer.

As final evidence of interference, we measure the photocurrent response using a tunable telecom laser in the wavelength range between 1549 and 1554 nm. Figure 2e shows clear oscillations with a frequency spacing around $\Delta f = 80$ GHz, where the frequency spacing of the oscillations matches the constructive ($f_{\max}$) and destructive ($f_{\min}$) interference conditions at the graphene position, due to the internal cavity, in the near-infrared (NIR) regime. This is given by $\Delta f = f_{\max} - f_{\min} = c/4n_{\text{NIR}}L$, where c is the speed of light and n_{NIR} the refractive index of silicon in the near-infrared. This gives a refractive index of 3.3, which is close to the reported values [47]. This shows that the internal cavity leads to interference effects over a broad range of frequencies, spanning at least 80 GHz to 200 THz.

Enhanced sensitivity of combined THz detector-interferometer

Having reported evidence of interference occurring in our THz detector due to a built-in optical cavity, we explore how this enhances the performance of the detector in terms of responsivity and noise-equivalent power. Figure 3a shows the measured photocurrent *vs.* incoming THz power P_{in} . The slope gives an external device responsivity of $\mathbb{R}_{\text{ext}} = I_{\text{PTE}}/P_{\text{in}} = 73$ mA/W (36 V/W). Considering Johnson noise as the main noise source, this gives an external noise-equivalent power (NEP_{ext}) of 79 pW Hz^{-1/2}

(see [Methods](#)). These numbers are not corrected for the amount of THz absorption or the ideal case of a diffraction-limited spot size, which means that they are truly external performance parameters without any normalization. In terms of external responsivity and NEP, our detector outperforms all bias-free, graphene-based photodetectors in the (sub-)THz regime published to date (see Appendix Table 1).

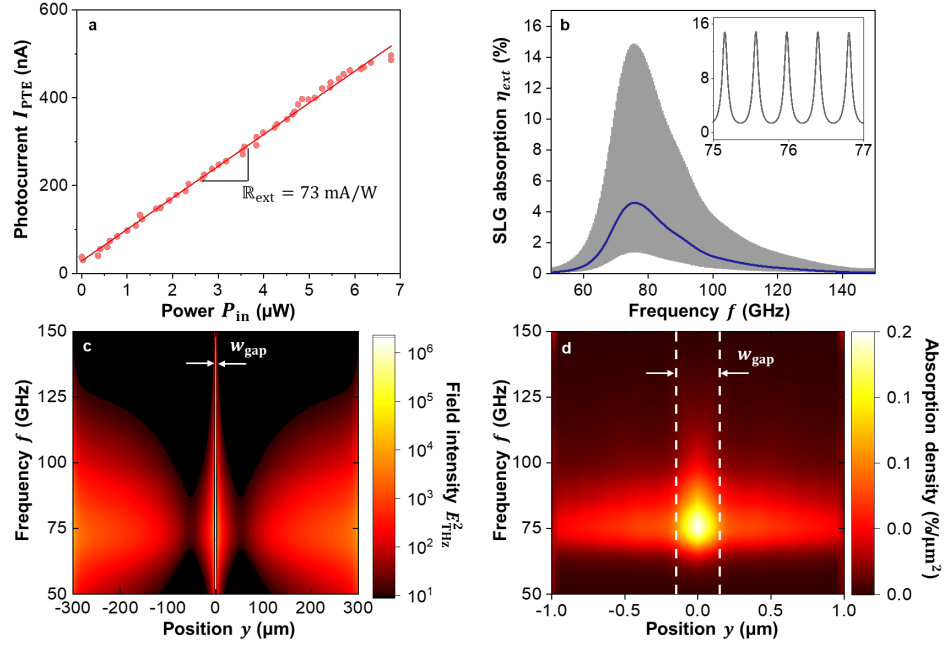


Fig. 3: Enhanced responsivity and absorption from experiment and simulation. **a**, Measured photocurrent I_{PTE} at 89 GHz *vs.* incoming THz power P_{in} , giving an external responsivity of 73 mA/W. **b**, Simulation of the THz absorption *vs.* frequency for incident THz light that is focused with a numerical aperture of 0.5, as in the experiment. The absorption gives a peak value due to interference in the internal cavity (blue curve), in agreement with the experimental results of Fig. 2a. Additional enhancement occurs due to the external cavity (grey curve), which gives rise to a substructure that is shown in the inset. **c,d**, Maps of the electric field intensity E_{THz}^2 (**c**) and absorption density (**d**) as a function of frequency and lateral position y , along the source-drain direction. These maps show strong enhancement inside the gap of the dipolar antenna around the resonance frequency. The dashed lines indicate the gap of the dipolar antenna with width w_{gap} .

The large responsivity of the detector could be due to a long cooling time τ_{cool} of hot carriers in graphene, or due to strong THz absorption. To explore the first hypothesis, we determine the cooling time by performing time-resolved photocurrent measurements (see [Methods](#), and Appendix Fig. 2). We extract a mean cooling time around 3.4 ps, which is a typical value for hot carrier cooling in hBN-encapsulated graphene [48, 49]. From the experimentally determined photocurrent and cooling time, we estimate a THz absorption coefficient η of 20% for our THz focus spot (see [Methods](#)). This large absorption is the combined result of the antenna, the internal cavity, and the external cavity, as we show in the next section. Importantly, this is the absorption for the case of the experimental, non-diffraction-limited focus area A_{focus} . It is common practice to extrapolate the performance of (THz) photodetectors to the situation for a diffraction-limited spot with area A_{diff} by multiplying the responsivity by $A_{\text{focus}}/A_{\text{diff}} \approx 13$. Interestingly, our detector already absorbs so strongly that such an extrapolation would result in a nonphysical absorption above 100%.

Simulations of absorption and responsivity

To support our experimental findings, we simulate the photoresponse of our device using finite-difference time-domain simulations. We simulate the spectral response in terms of absorption in the graphene layer and the device responsivity in two cases: *i*) considering the internal cavity only, and *ii*) including both the internal and external cavities. The results in Fig. 3b show that the internal cavity increases the graphene THz absorption by one order of magnitude. By adding the external cavity, the total absorption in the graphene channel increases by another factor of three, reaching a maximum of 15%. This is very close to the 20% obtained from the measured photocurrent and cooling time. Furthermore, we extract $\mathbb{R}_{\text{ext}} = 24 \text{ mA/W}$ from the simulation with only the internal cavity, and $\mathbb{R}_{\text{ext}} = 120 \text{ mA/W}$ by including internal

and external cavities, as shown in Appendix Fig. 3. This is close to the experimentally obtained value of $\mathbb{R}_{\text{ext}}$ of 73 mA/W.

The inset of Fig. 3b shows the effect of the external cavity formed between the THz source and the detector-interferometer, which is the appearance of additional maxima and minima in absorption. The periodicity of this substructure is determined by the source-detector distance. We observe this substructure also in the experimental photocurrent data, as shown in the inset of Fig. 2a. Indeed, Fourier analysis of the experimental photocurrent spectrum for two different emitter-detector distances reveals the periodicity of the additional peaks around the resonant frequency. This periodicity matches the spectral substructure found in the simulations (see Appendix Fig. 4).

In addition to internal and external cavities, the device also contains a dipolar antenna that enhances the absorption in the graphene channel, as demonstrated earlier [39]. To observe its effect, we simulate the electric field distribution along the graphene channel at different frequencies, see Figs. 3c,d. The distribution of the THz electric field on the device surface demonstrates the funneling of THz light into the antenna gap. Since the graphene channel is located directly below this gap, this leads to strong THz absorption enhancement and therefore a large device responsivity. In Appendix Fig. 3, we summarize the relative contributions to the absorption enhancement from the antenna, the internal cavity, and the external cavity.

Using phase sensitivity to determine film thicknesses

Having established that the THz detector has a high sensitivity and acts as an interferometer, we now combine this to demonstrate sensitive phase measurements. In

particular, we exploit the phase sensitivity to determine the thickness of thin films. In order to do so, we measure the generated photocurrent while moving the detector along the out-of-plane direction x , with and without a thin sample material placed between the THz source and our THz detector-interferometer, as shown in Fig. 4a. Since the sample material has a THz refractive index n_s , this gives rise to a spatial shift Δx in the interference pattern. From this spatial shift, we extract the sample thickness d using: $\Delta x = (n_s - n_{\text{air}})d$ with $n_{\text{air}} = 1$.

We confirm the validity of this approach by simulating the absorption in graphene when moving along the x -position. We use the case where a material of thickness d and refractive index $n_s = 1.6$ (for paper) is placed between the source and the detector. The results in Fig. 4b show that maximum absorption occurs for specific combinations of thickness d and position x . These maxima occur with a periodicity of $\lambda_0/2$ and satisfy the relation $\frac{\partial x}{\partial d} = (n_s - n_{\text{air}})$. This simulation confirms that our experimental approach to determine sample thicknesses is valid.

Figure 4c shows the results of the phase-enabled thickness measurements on three different materials widely used in industrial sectors: a high-resistive double-side polished Si wafer (Si, $n_s \approx 3.5$ [47]), paper ($n_s \approx 1.6$ [50]), and a Kapton polyimide thin film ($n_s \approx 1.8$ [51]). In all cases, the oscillating pattern is displaced by a spatial shift Δx between the case without and the case with the sample. The shift depends on the thickness and refractive index of the inset material. The thicknesses we obtain are consistent with the independently determined thickness values, as shown in Fig. 4d (see Methods for details). This also includes a measurement of a polypropylene (PP) film with a thickness of 40 μm and refractive index of 1.5 (see Appendix Fig. 5).

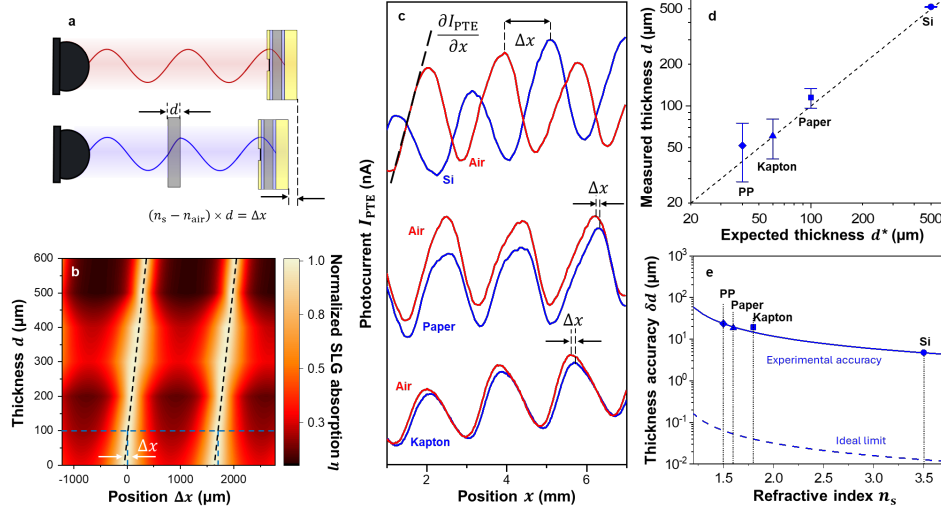


Fig. 4: Thickness determination using coherent THz detector-interferometer. a, Scheme of the THz thickness determination measurements, where the spatial shift Δx is related to the thickness d of the material placed between the emitter (left) and detector (right). **b,** Simulation of the absorption in the graphene channel, while moving the detector along the direction of the wave propagation, for the case that a material with $n_s = 1.6$ is placed between the THz source and the detector. The black dashed line shows the maximum absorption of the graphene depending on the thickness of the material d . The slope is equal to $(n_s - n_{\text{air}})$. The intersection between the blue and black dashed line represents the position of maximum absorption for a thickness of 100 μm. The spatial shift Δx is the distance between the position of the intersection and the position where there is no sample, *i.e.* $d = 0$. **c,** Photocurrent I_{PTE} interference patterns (y axis offset for clarity) *vs.* position x , measured for three combinations: thin films of silicon, paper and kapton (blue), each combined with a reference measurement without sample (red). The spatial shift Δx in the interference pattern is the result of the phase delay induced by the higher refractive indices of the samples compared to air. The slope $\frac{\partial I_{\text{PTE}}}{\partial x}$ determines the phase sensitivity. **d,** Extracted thicknesses d for silicon, paper, kapton, and polypropylene (PP) films (blue markers) *vs.* expected thicknesses d^* . The error bars represent the 68% confidence interval. **e,** Determination of the thickness accuracy δd *vs.* refractive index n_s in the experimental case (solid line). The dashed line shows the ideal thickness accuracy for a phase-stable source, where the photocurrent noise is only limited by Johnson noise.

The precision of the thickness measurement depends on how much the photocurrent changes due to a change in thickness of material with a certain refractive index, compared to the smallest observable change in photocurrent: $\delta d = \left(\frac{\partial I_{\text{PTE}}}{\partial x} \right)^{-1} \times \frac{I_{\text{noise}}}{(n_s - 1)}$. Here, $\frac{\partial I_{\text{PTE}}}{\partial x}$ is the largest slope of the photocurrent as a function of position x , which occurs halfway between a maximum and a minimum, and I_{noise} is the photocurrent

noise. We determined this noise by measuring the variation in photocurrent with x positioned halfway between a maximum and a minimum for the same period of time that it takes to record an interference pattern (see Appendix Fig. 6). Figure 4d shows the calculated thickness accuracy as a function of the refractive index, which closely matches the thickness error bars that we obtained experimentally for the four different materials that we studied. We obtain the highest accuracy for silicon, which is a few micrometers. If the photocurrent noise were limited by Johnson noise, we would reach a thickness accuracy close to 10 nm, which is six orders of magnitude smaller than the wavelength. This requires a phase-stable THz source, faster scanning of the detector position, and packaging of the detector to minimize electronic noise. A more intense THz source will lead to a further improvement of the thickness accuracy.

Discussion

In summary, we have developed a chip-scale, integrated THz detector-interferometer with a high responsivity and a high sensitivity to the phase of the incident THz light. This is enabled by combining the strong photo-thermoelectric response of graphene with a planar THz dipolar antenna and a vertical optical cavity. We have demonstrated interference effects in the spectral, spatial, and temporal domain, and for both THz and near-infrared light. Finally, we have exploited the phase sensitivity to determine the thickness of thin films with deep sub-wavelength accuracy. This makes the graphene-based detector-interferometer a promising alternative to THz time-of-flight measurements using femtosecond pulses, aimed at determining film thicknesses, for example. While our optical cavity led to the largest absorption enhancement and phase sensitivity for light around 80-90 GHz, it is possible to optimize the optical cavity for other frequencies, or incorporate a tunable cavity [37]. Beyond thickness measurements, the phase sensitivity of our THz detector-interferometer opens up a

myriad of possibilities to exploit phase information, including non-destructive industrial testing, beyond-fifth-generation wireless data transfer, and quantum technologies.

Methods

Device fabrication. The starting point of the fabrication was a highly resistive double-side polished silicon substrate with a thickness of 279 μm , with thermally grown SiO_2 of thickness 300 nm on both sides. We placed hBN-encapsulated graphene on top, and contacted the graphene to source and drain electrodes via side contacts using etching and metal evaporation. The graphene channel has a width of $w_{\text{dev}} = 30$ μm . We deposited a dipolar antenna on top of the hBN-graphene-hBN stack. The antenna has a gap width w_{gap} of 300 nm, a width w_{ant} of 30 μm , and a length L_{ant} of 681 μm . The substrate with graphene, contacts, and antenna was placed on a metal support, forming the back mirror.

Terahertz photocurrent setup. The terahertz photocurrent setup is based on a “Terascan 1550” continuous wave terahertz spectroscopy system [52] (Toptica Photonics AG), which has an accessible range from 0 to 1.2 THz, with a THz power around 7.6 μW at 89 GHz. The divergent THz beam generated on the emitter side of the commercial THz setup is collimated using a first parabolic mirror and then focused onto the graphene-based detector-interferometer by a second parabolic mirror. Both parabolic mirrors have a focal distance of 50.8 mm and a diameter of 50.8 mm, corresponding to a numerical aperture (NA) of 0.5. The sample is mounted on a motorized *xyz*-stage, whose maximum range along one axis is 25 mm and minimal step resolution of 1.25 μm . We collect the demodulated photocurrent via a lock-in amplifier (Zurich Instruments MFLI). The reference frequency to perform the lock-in

detection is based on the AC bias applied to the THz emitter (39.7 kHz). All measurements are performed with $V_g^A = V_g^B = 0$ V. For the THz thickness measurements, the samples of interest (Si wafer, paper, Kapton, polypropylene film) are placed close to the THz focal point in front of the graphene-based detector-interferometer. In all measurements, a polystyrene foam is placed in the collimated beam path to absorb any remaining non-THz light that was used to generate THz radiation.

Time-resolved photocurrent setup. We use a femtosecond laser ($\simeq 100$ fs pulse duration, 76 MHz repetition rate, 1030 nm central wavelength) split into two pump beams to excite the device. We modulate one of these pump beams at 240 Hz using a mechanical chopper. This beam passes through a mechanical delay line that controls the time delay τ_{delay} between both pump pulses. For both pump beams, we adjust the power at the sample location to a few hundreds of μW . We set the polarization of the pump beams perpendicular to each other. We combine both beams using a non-polarizing beam splitter, and a 50x objective ($\text{NA} = 0.42$) focuses the beams onto the photo-active region of the graphene-based detector-interferometer, with typical spot sizes of $\simeq 1$ μm . We use closed-loop *xyz*-nanopositioners to move the sample with respect to the laser beams. We collect the generated photocurrent from the device using lock-in detection by demodulating the signal at the chopper frequency. Additionally, we can collect the reflected probe light using a biased InGaAs photodetector to simultaneously obtain reflectance and photocurrent maps of the device. For the time-resolved photocurrent measurements, we scan the delay line to achieve a time delay window of ± 30 ps, with sub-ps temporal resolution. We perform all measurements under ambient conditions without applying any gate voltage to the device. To extract the cooling time, we fit the photocurrent signal as a function of delay time to exponentially decaying functions.

Photoresponse simulations. We perform all the simulations using Lumerical software. We first simulate the frequency response of the cavity using a 2D model with a plane wave for three cases: *i*) without a back mirror, *ii*) with back mirror, *iii*) including a Si lens in the point source. In the three cases, we change the distances of the point source with respect to the device to observe the cavity effects induce by the source and the THz cavity. Then, we perform a simulation using a 3D model and use a focused THz beam as a source to determine the absorption on the graphene. The descriptions of the thermoelectrical and electrostatic models are available in [53] and [44].

Obtaining the detector responsivity and NEP. The external responsivity for our experimental THz spot size is defined by $\mathbb{R}_{\text{ext}} = I_{\text{PTE}}/P_{\text{in}}$, where I_{PTE} is the peak-to-peak value of the demodulated PTE photocurrent signal measured with the lock-in amplifier and P_{in} is the incoming power measured at the focus position. We calculate the peak-to-peak value of the photocurrent using $I_{\text{PTE}} = 2\sqrt{2}\pi/4I_{\text{lock-in}}$, where $I_{\text{lock-in}}$ is the root mean square value of the demodulated photocurrent signal measured by the lock-in amplifier. The external noise-equivalent power is $\text{NEP}_{\text{ext}} = I_{\text{noise}}/\mathbb{R}_{\text{ext}}$, where $I_{\text{noise}} = \sqrt{4k_{\text{B}}T\Delta f/R}$ is the Johnson noise, k_{B} is the Boltzmann constant, $T = 300$ K is the temperature, $\Delta f = 1$ Hz is the measurement bandwidth and $R = 500 \Omega$ is the channel resistance. In the experiment, the non-diffraction-limited focus area was around 57.8 mm^2 (see Appendix Fig. 7). The ideal diffraction-limited focus area is given by [39] $A_{\text{diff}} = \frac{\lambda_0^2}{\pi} \approx 4.5 \text{ mm}^2$. This gives a ratio $A_{\text{focus}}/A_{\text{diff}} \approx 13$. Since the absorption is already 15-20% in the non-diffraction-limited case, we can expect 100% absorption for a (near-)diffraction-limited spot, giving an ideal responsivity $\mathbb{R}_{\text{diff}}$ (ideal NEP_{diff}) that is increased (decreased) by at least a factor five.

Obtaining the absorption from experiments. We first extract the increase in temperature from the photocurrent using $I_{\text{PTE}} = (S_1 - S_2)\Delta T/R$ [39], where $S_1 - S_2$ is the Seebeck coefficient ($160 \mu\text{V K}^{-1}$, known from previous reports [38, 39]), and $R = 500 \Omega$ is the resistance of the device. This gives $\Delta T = 1.55 \text{ K}$ for the highest THz power. The following equation describes the relationship between the increase in temperature and the absorption η : $\Delta T = \frac{\eta P_{\text{in}} \tau_{\text{cool}}}{2l_{\text{cool}} w C_{\text{el}}}$, where $C_{\text{el}} = 1 \times 10^{-4} \text{ Jm}^{-2}\text{K}^{-1}$ is the electronic heat capacity, τ_{cool} is the cooling time of graphene, $l_{\text{cool}} = 500 \text{ nm}$ is the cooling length in graphene and $w = 30 \mu\text{m}$ the width of the photoactive area. The cooling length is estimated from the cooling time and the momentum relaxation time [48]. Using these parameters, which are all known, we extract the absorption coefficient.

Thickness measurements. We perform statistical averaging to improve the accuracy of the thickness determination and to simultaneously mitigate the intrinsic phase drift of our THz system. Concretely, we measure around twenty consecutive scans close to where a local maximum is located. To determine the peak position of the curve, we find the maximum value of all the curves and extract Δx from each consecutive scan (air and material). Then, the thickness d is given by $\Delta x/(n_s - n_{\text{air}})$. Finally, we calculate the averaged thickness and its standard deviation. This procedure was applied to two groups of data: the first group is the acquired data without any treatment, and the second group is the acquired data treated by smoothing.

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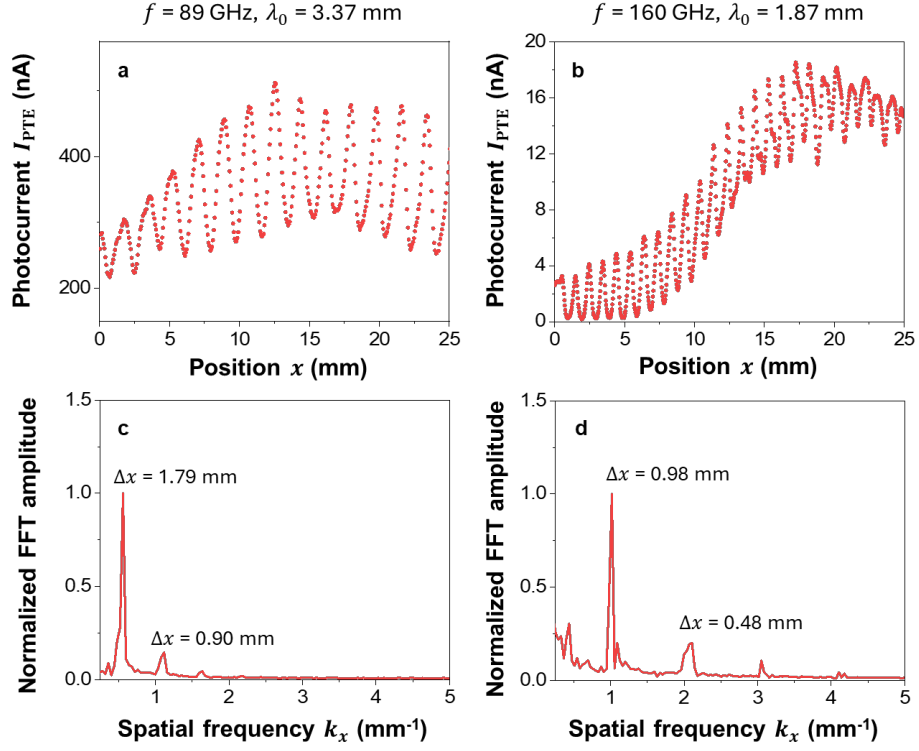
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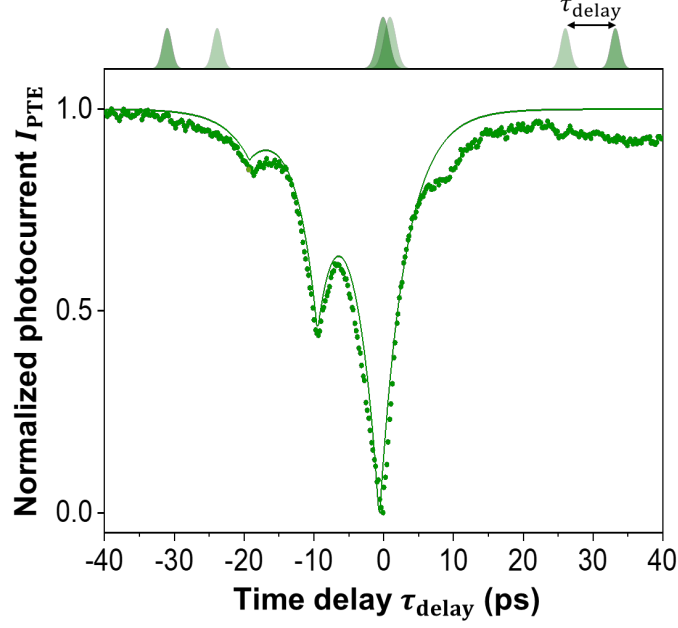
Appendix

Device design	Frequency	Responsivity	NEP	Reference
Square-spiral antenna without cavity	80–120, 140, 300 GHz	1.4 mA/W** (2.8 mV/W*)	35 mWHz ^{-1/2}	Guo <i>et al.</i> [54]
Log-periodic antenna	120 GHz	0.84 mA/W** (840 mV/W*)	33.3 nWHz ^{-1/2*}	Liu <i>et al.</i> [55]
Dipolar antenna without cavity	1.8–4.25 THz	0.42 mA/W* (1.76 mV/W**)	4.8 nWHz ^{-1/2*}	Castilla <i>et al.</i> [39]
Bow tie antenna with cavity	2.86 THz	≈ 0.1 mA/W ** (≈ 2 V/W*)	5.4 nWHz ^{-1/2*}	Viti <i>et al.</i> [56]
Integrated sub-THz cavity and dipolar antenna	89 GHz	73 mA/W (36 V/W)	79 pWHz ^{-1/2}	This work

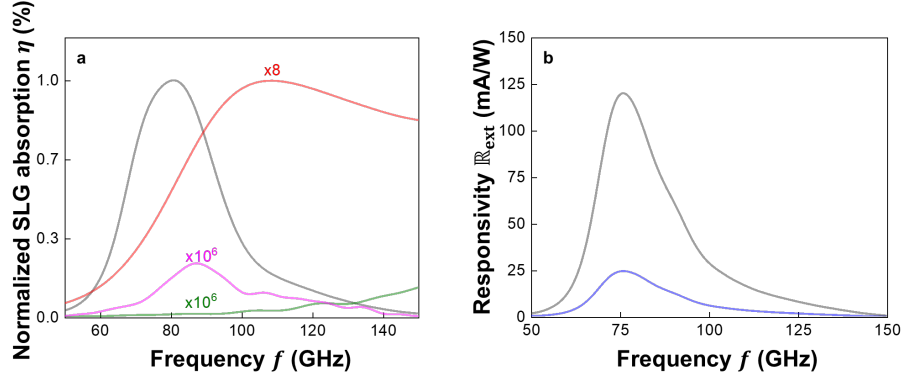
Appendix Table 1: Comparison of the *external* performance of graphene-based, bias-free photodetectors. * Maximum external responsivities calculated considering the experimental focus area using the normalization factor provided in the referenced papers. **These values were converted using the values reported in the referenced papers, such that they correspond to values without normalization.



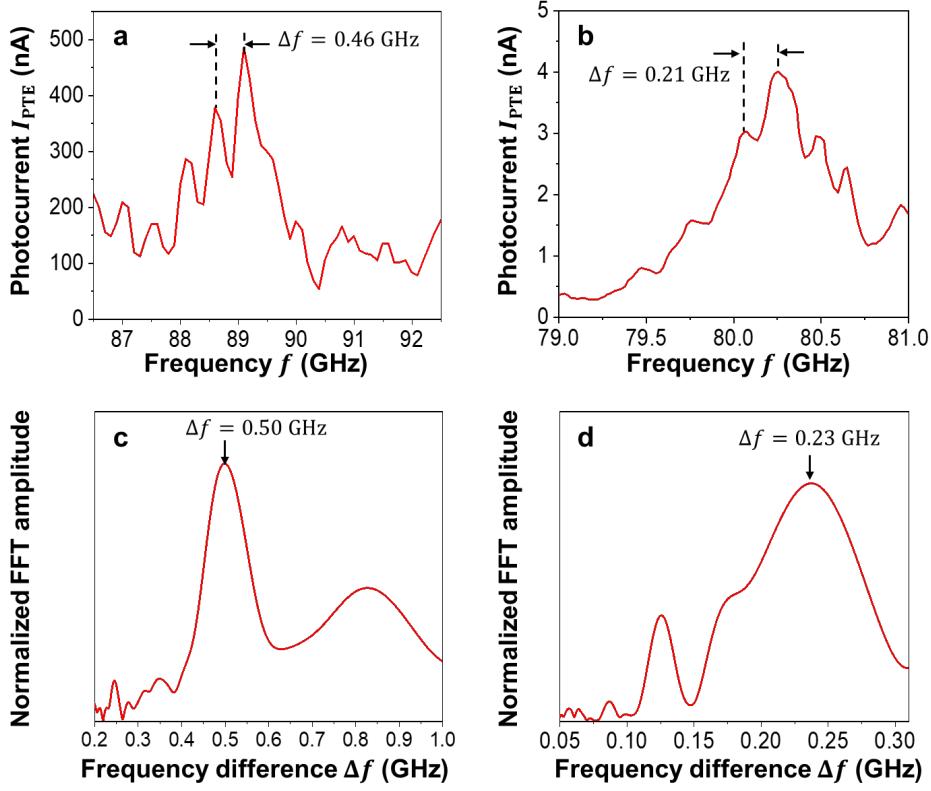
Appendix Fig. 1: Interference pattern observed when scanning the detector position. **a,b,** Photocurrent measured while moving the detector along the travel direction of the light for incident radiation at 89 GHz (**a**) and 160 GHz (**b**), together with the Fourier transforms of these interference patterns (**c,d**). The Fourier transforms are performed to determine the periodicity of the signals and give main peaks at 1.79 mm and 0.98 mm for 89 and 160 GHz, respectively. This is close to half of the wavelength of the incident light, which is 1.69 mm and 0.94 mm, respectively. The fact that we observe oscillations for both frequencies shows that the occurrence of interference is not limited to the resonance frequency of the internal cavity.



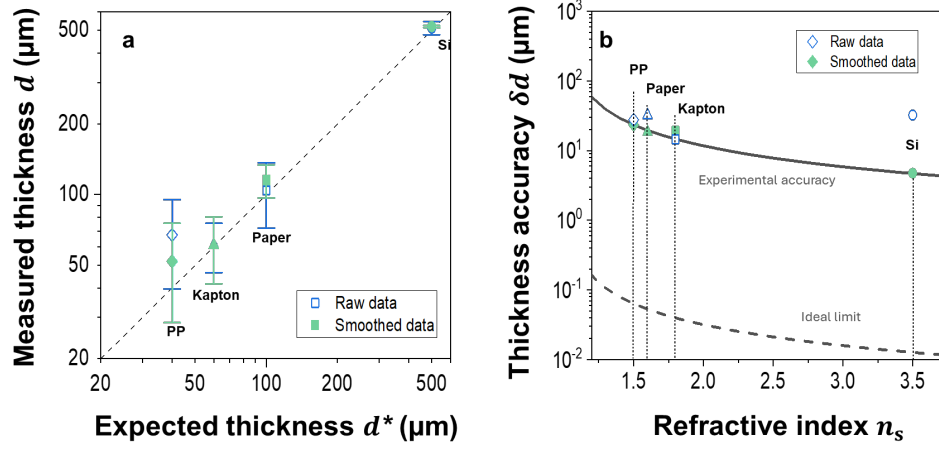
Appendix Fig. 2: Time-resolved photocurrent measurements. In order to determine the cooling time of the hot electrons in the graphene THz detector, we perform time-resolved photocurrent measurements with an incident wavelength of 1030 nm. For details on the technique, see [Methods](#) and Ref. [57]. We observe a pronounced main dip at zero time delay, and secondary periodic dips that are likely related to reflections inside the sub-THz cavity. To extract the cooling time from the time-resolved photocurrent, we describe the photocurrent using a sum of exponential decay functions of the form $I_{\text{PTE}} \propto (T_e - T_l) \exp\left(-\frac{\tau_{\text{delay}}}{\tau_{\text{cool}}}\right)$ [57, 58], where T_e , T_l , τ_{delay} , τ_{cool} are the electronic temperature, lattice temperature, the delay time, and the cooling time, respectively. Each dip has two exponentially decaying functions – to positive and to negative time delays. We obtain a cooling time of 3.4 ps for the main dip around time zero.



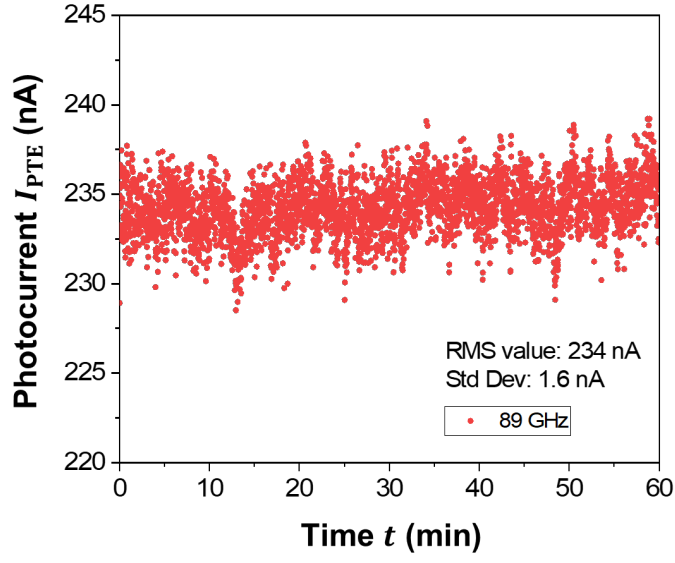
Appendix Fig. 3: Simulation results for absorption and responsivity. **a**, Calculated THz absorption in the graphene channel, taking into account both the internal cavity (metallic back reflector) and the dipole antenna (grey); only dipole antenna without internal cavity (red); only internal cavity without dipolar antenna (pink); and without the internal cavity nor dipolar antenna (green). We multiply each curve by the factor written above it for better visualization. These values correspond to THz light focused with an NA of 1, which is higher than the NA of 0.5 that was used in the experiment. **b**, Calculated external responsivity as a function of frequency with (grey) and without (blue) the external cavity, with a NA of 0.5 similar to our experiments.



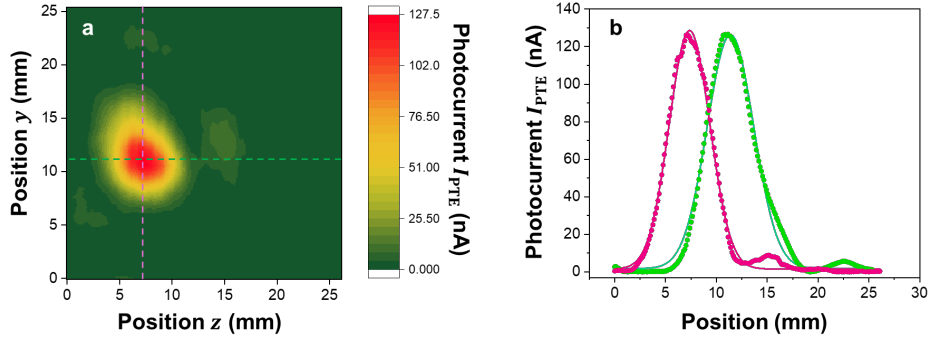
Appendix Fig. 4: Experimental signatures of the external cavity. **a,b** Photocurrent signal for source-detector distances L_{ext} of 36 cm (**a**) and 61 cm (**b**), showing a spectral substructure. **c,d** Fourier transforms of the photocurrent signals for L_{ext} of 36 cm (**c**) and 61 cm (**d**), showing a periodicity of 0.5 GHz and 0.23 GHz, respectively. The expected periodicity due to the external cavity is given by $c/2L_{\text{ext}}$, which gives 0.4 GHz and 0.25 GHz, respectively.



Appendix Fig. 5: Comparison of thickness estimation using two different methods. **a**, Extracted thickness d vs. expected thickness d^* using the raw data (open blue symbols) and smoothed data (solid green symbols). **b**, Obtained thickness accuracy δd as a function of refractive index for the different materials, using the raw data (open blue symbols) and smoothed data (solid green symbols).



Appendix Fig. 6: Evaluation of the graphene detector noise. Photocurrent variation as a function of time at 89 GHz using our graphene-based THz detector-interferometer, measured during a period that is equal to the time it takes to perform a thickness measurement. The noise of the signal is 1.6 nA.



Appendix Fig. 7: Determination of the experimental focus area. **a**, Photocurrent profile when scanning the detector position in the plane perpendicular to the travel direction of light. This is taken at 80 GHz at the best focal distance after the second parabolic mirror, and gives the experimental focus spot size. **b**, Determination of the focus spot size by describing the photocurrent extracted along the vertical (y) and horizontal (z) lines (purple and green data points, respectively) with Gaussian functions (solid lines). We obtain a beam radius $w_{0,y} = 4.58$ mm and $w_{0,z} = 4.01$ mm, corresponding to a full-width at half-maximum of $\text{FWHM} = \sqrt{2 \ln 2} w_0$. We calculate the focus area as $A_{\text{focus}} = \pi(w_{0,z}w_{0,y})$ giving $A_{\text{focus}} = 57.8 \text{ mm}^2$.